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Geological Resources of Tierra del Fuego

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Foreword

The CADIC's Geological Resources Program will soon turn 40 years of fruitful development. During this period, many projects were carried out and others remain to be implemented. In the course of time, three generations of researchers have been formed. Mentioning names would be unfair to those that could be involuntarily omitted. There is still a long way to go. The eagerness for knowledge should not stop.

This book is a tribute to all those people who have worked in the different projects, of pure and applied science, and educational, and human resources training, granted to this foundational program and associated laboratories of the regional center of CONICET in Ushuaia.

Ushuaia, Tierra del Fuego, Argentina — Rogelio Daniel Acevedo

Preface

Ignacio Subías Pérez, our kindhearted partner Natxo, Head of Mineral Resources of the Zaragoza University, died prematurely in February, 2019. The contributions that follow this foreword are intended as a memorial to his devotion to science and friendship.

Some articles of the present volume concern polymetallic ore deposits, the study of which had given him a well-deserved international reputation throughout his career. In 2007, ISP led a grant about massive sulfides ores in Tierra del Fuego funded by the Spanish Ministry of Education and Science and that support not only consolidated the basis for the spirit of this book but also of former and future studies.

The collaborations that constitute the present work have been written by different authors and everyone hopes that it will prove a fitting and lasting memorial to our colleague, whose personal influence to our knowledge of the geology of the end of the world was outstanding.

Ushuaia, Argentina Rogelio Daniel Acevedo

Acknowledgements

The editor is indebted to the *Centro Austral de Investigaciones Científicas* for the *Consejo Nacional de Investigaciones Científicas y Técnicas* and the *Instituto de Ciencias Polares* of the *Universidad Nacional de Tierra del Fuego* for give its facilities during the time it took to gather and organize the contributions received for this book.

Contents

An Introduction to the Geology of Tierra del Fuego

Luis Díaz Balocchi, Sebastián José Cao, and Erika Lorena Bedoya Agudelo

Abstract Tierra del Fuego is an island located at the southern tip of South America. It is one of the southernmost emerged lands on Earth, except for Antarctica. Its position is significant in terms of geologic environments both in the past and present times. During the Middle Jurassic, southern South America was exposed to regional extension and volcanism, associated with the breakup of the Gondwana supercontinent. In the Early Cretaceous, the Rocas Verdes back-arc basin (which included oceanic floor expansion) was developed. Contractional tectonics started in the Late Cretaceous, closing the back-arc basin and initiating the Andean orogeny. The crustal thickening led to the formation of the Austral (Magallanes) foreland basin. From the Late Cretaceous to the Eocene the Fuegian Andes went through a counterclockwise rotation that generated the bending of the South America–Antarctica connection and formed an orocline. Crustal extension responsible for the rupture of the continental bridge started at the Eocene and implied the relative displacement of South America to the north and Antarctica to the South. The contraction in the Fuegian Andes ended during the Miocene. Later, they were affected by a strike-slip faulting regime associated with transcurrence that started in the late Miocene. Nowadays, the island is placed over the South American and Scotia plates, separated by the Magallanes–Fagnano transform boundary (tectonically active) and is encircled by the Andes range to the west and south. Through the late Cenozoic, diverse agents sculpted the relief of Tierra del Fuego, mainly triggered by tectonic, climatic and eustatic action. Since the Late Miocene, the climate of southern South America entered the glacial cycles that are still active. Ice sheets covered the highest mountains in the southwestern portion of the island and fed four main ice lobes that occupied valleys in the lowlands. Late Pleistocene and Holocene glaciers were restricted to the higher and southern zones. Coastal landscapes of the island expose evidences of the oscillation of sea level through the late Cenozoic. Neotectonics related to the Magallanes–Fagnano

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Transform System is playing an important role in the landscape development in the central region.

Keywords Tierra del Fuego geology · Fuegian Andes · Rocas Verdes basin · Austral basin · Magallanes–Fagnano Transform System · Patagonian glaciations

1 Introduction

Tierra del Fuego is an island positioned at the tip of South America, in one of the southernmost emerged lands on Earth, except for Antarctica (Figs. 1 and 2). Enclosed by the Andes range to the west and south, and surrounded by the Atlantic, Pacific and Southern oceans, this location has unique significance in terms of climate, oceanography, ecology, human settlements and, indubitably, geology.

Its topography varies from gentle hills and plains in the northern part to a rocky mountainous environment in the south, with maximum elevations reaching over 2000 m a.s.l. Situated between 52° and 55° S, the climate is cold and oceanic,

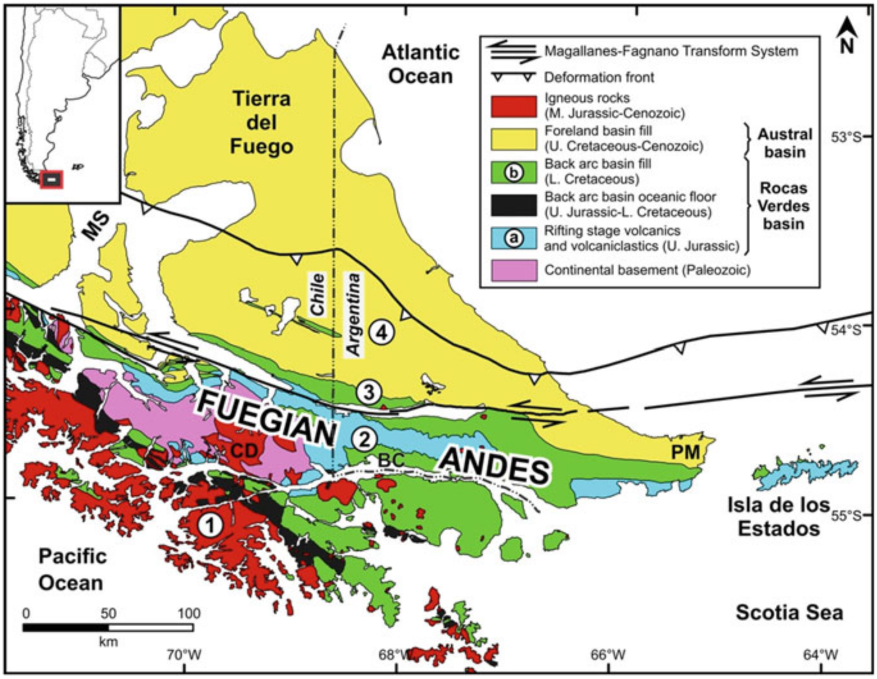

Fig. 1 Simplified geologic map of Tierra del Fuego and adjacent islands (modified from Torres Carbonell et al. 2014), indicating the main tectonostratigraphic units and structural elements. MS—Magellan Straits; CD—Cordillera Darwin; BC—Beagle Channel; PM—Península Mitre

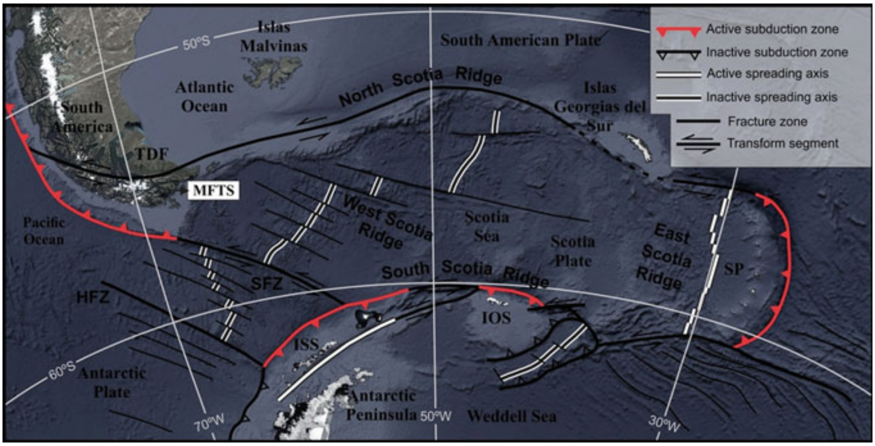

Fig. 2 Present-day geographic and tectonic situation of Tierra del Fuego with respect to the Scotia arc and the Antarctica Peninsula. TDF—Tierra del Fuego; MFTS—Magallanes-Fagnano Transform System; ISS—Islas Shetland del Sur; IOS—Islas Orcadas del Sur; SP—Sandwich Plate; SFZ—Shackleton Fracture Zone; HFZ—Hero Fracture Zone. Satellite image taken from Google Earth Pro. Structure based on Galindo-Zaldívar et al., Bohoyo et al. (2007), Dalziel et al. (2013) and Bohoyo et al. (2016)

with low thermal amplitude. Temperatures in winter usually fall below 0°C and not frequently rise above 20°C in summer. Winds coming from the west and southwest are constant and intense. Hydric regime shows a gradient from subhumid to humid in a southward direction (Coronato et al. 2008). All these differences induce a vegetation change from a grassy steppe in the northern zone to a deciduous *Nothofagus* forest with peat bogs in the Fuegian Andes further south (Coronato et al. 2008).

The island rests over the South American and Scotia plates, separated by the Magallanes–Fagnano transform boundary. During its geological history, Tierra del Fuego was affected by different tectonic regimes together with variations in paleogeography, sedimentary environments and climate that, in present times, configure a rich geology that we will try to briefly depict in the text below.

2 Mesozoic Rifting Stage and Back-Arc Basin Development

During the Middle Jurassic, southern South America was subjected to regional extensional faulting and associated volcanism, both related to the breakup of Gondwanaland. South of 50° S (present coordinates), crustal extension led to the opening of a submarine trough in Late Jurassic times, which by the Early Cretaceous evolved into a back-arc basin with oceanic floor development, known as the Rocas Verdes back-arc basin (Katz 1972; Dalziel et al. 1974; Bruhn et al. 1978; Gust et al. 1985).

The stratigraphy of the Rocas Verdes back-arc basin is best represented in the southern portion of Tierra del Fuego and in adjacent islands of the Fuegian Archipelago (Fig. 1). Exhumated relicts of the faulted continental basement are well exposed in Cordillera Darwin (Chilean Tierra del Fuego), encompassing greenschists to upper amphibolite facies metamorphic rocks, mostly Early Palaeozoic in age (Hervé et al. 2010). The Middle-Upper Jurassic Lemaire Formation (in Argentina), and its lateral equivalent, the Tobífera Formation (in Chile) comprise bimodal syn-rift lavas, shallow intrusive bodies and volcaniclastic successions deposited in a subaqueous environment (Hanson and Wilson 1991; Calderón et al. 2007; González Guillot et al. 2016) (unit "a" in Fig. 1). In southeastern Tierra del Fuego, the Lemaire Formation rocks portray very low to low-grade metamorphic grade, while in Cordillera Darwin the Tobífera Formation displays a wider range of metamorphic conditions, from lower greenschists to amphibolite facies, being higher in the southern sector of Cordillera Darwin (Nelson et al. 1980; Kohn et al. 1995; Maloney et al. 2011). The Lapataia Formation, restricted to the southwestern corner of Argentinian Tierra del Fuego, is thought to be a slightly higher metamorphic-grade equivalent of the Lemaire Formation (Olivero et al. 1997; Cao et al. 2018; Acevedo 2019). Between the latest Jurassic and the Early Cretaceous, oceanic crust generation took place. Rocas Verdes sea-floor remnants are preserved as incomplete ophiolite sequences, discontinuously distributed from the southern Patagonian Andes to the islands located south of Tierra del Fuego (Suárez 1977; Cunningham 1994; Stern and De Wit 2003; Calderón et al. 2012) (Fig. 1).

By the Early Cretaceous, the Rocas Verdes basin was rimmed by an active volcanic arc to the southwest and the South American continent to the northeast. Part of the Patagonian Batholith (labeled "1" in Fig. 1) is thought to represent the roots of this volcanic arc (Dalziel et al. 1974; Suárez 1979). Over a mixed crust of faulted basement blocks with partially developed oceanic crust and overlying the Upper Jurassic rift sequences, thick clastic and volcaniclastic deposits filled the Rocas Verdes basin during the Early Cretaceous (unit "b" in Fig. 1). In Argentinian Tierra del Fuego, the Yahgán Formation comprises Lower Cretaceous deep marine, flysch-like strata (very low-grade slates and meta-greywackes); while the Beauvoir Formation (black slates and mudstones) is considered its lateral equivalent to the north–northeast, representing outer platform sedimentary facies (Olivero and Martinioni 1996a; Olivero and Malumián 2008). The youngest fossil record known in the Rocas Verdes basin consists of late Albian inoceramids in the Yahgán Formation (Olivero and Martinioni 1996b), establishing a minimum age constraint for sedimentary activity, prior to tectonic contraction and the commencement of the Andean orogeny in Tierra del Fuego.

3 Late Mesozoic-Cenozoic Contraction: Back-Arc Basin Closure and Foreland Basin Development

The Fuegian Andes are the result of a long-lived, complex history of contractional tectonics, initiating in the Late Cretaceous. It has been proposed that the shift of tectonic regime (from extensional to contractional) responsible for the inversion of the Rocas Verdes basin and the beginning of the orogeny at the Pacific margin of southernmost South America was a consequence of global changes in plate kinematics, namely the increase in sea-floor spreading rates at the South Atlantic oceanic ridges (Dalziel 1986). Following structural criteria, the Fuegian Andes may be subdivided into an orogenic core or central belt of deformation (located hinterlandward, labeled "2" in Fig. 1), and a foreland thrust-fold belt—further subdivided into "internal" and "external," labeled "3" and "4," respectively, in Fig. 1 (Torres Carbonell et al. 2017a, b).

In a broad sense, the structure in the Fuegian Andes Central Belt domain reveals two main deformation phases, each related to different stages in the history of the Andean orogeny (Klepeis et al. 2010; Torres Carbonell et al. 2017a). The first phase of deformation initiated ca. 100 Ma, causing the obduction of the oceanic floor and volcanic/volcaniclastic fill of the basin to the northeast, and the underthrusting of the South American cratonic margin to the southwest (present coordinates). During this phase, the Rocas Verdes rocks experienced ductile deformation accompanied by regional metamorphism (Bruhn 1979; Klepeis et al. 2010; Torres Carbonell et al. 2017a). The second deformation event took place between the Late Cretaceous and the Miocene, and is characterized by brittle/ductile structures and the emplacement of regional-scale thrust systems, overprinting and crosscutting previous structures and metamorphic fabrics. This phase includes several deformation pulses, probably responsible for most of the uplift and shortening registered in the hinterland and the migration of the deformation front to the foreland (Klepeis 1994; Kohn et al. 1995; Gombosi et al. 2009; Torres Carbonell and Dimieri 2013). The crustal thickening achieved during the obduction of the Rocas Verdes basin exerted a tectonic load that caused the flexure of the lithosphere at the orogenic front; thus favoring sedimentation in the foreland region (to the northeast), with the adjacent growing orogen as the main source of detritus. This resulted in the initial development of the Austral (in Argentina) or Magallanes (in Chile) foreland basin (Biddle et al. 1986; Wilson 1991; Fildani and Hessler 2005).

The Fuegian thrust-fold belt is a thin-skinned orogenic wedge developed at the Fuegian Andes mountain front (Álvarez-Marrón et al. 1993; Torres Carbonell et al. 2011). According to differences in structural style, it has been subdivided into an internal thrust-fold belt and an external thrust-fold belt. The first one is located between the hinterland central belt and the external foreland thrust-fold belt, involves Upper Cretaceous (both Rocas Verdes basin and Austral basin) and Paleocene (Austral basin) strata, and marks the structural linkage between deformation and uplift in the orogenic core with the foreland propagation of structures toward progressively shallower structural levels in the external thrust-fold belt (Torres

Carbonell et al. 2017b). The latter comprises Cenozoic Austral basin units involved in a series of imbricate thrust systems with a predominantly brittle behavior. At least six contractional stages have been identified between the Maastrichtian-Danian and the Miocene in the Fuegian thrust-fold belt (Torres Carbonell et al. 2011).

From the uppermost Cretaceous through the Early Miocene, sedimentation in the Austral basin was accompanied by a significant tectonic control, evidenced in the occurrence of several synorogenic sequences with angular unconformities, as the foreland thrust-fold belt developed and the orogenic front advanced toward the foreland (Álvarez Marrón et al. 1993; Ghiglione and Ramos 2005; Rojas and Mpodozis 2006; Torres Carbonell et al. 2011). In Tierra del Fuego, the oldest sedimentary strata with clear provenance from an adjacent exhumed orogen are conglomerates in the Cerro Matrero, Río García (both localized in northern Cordillera Darwin) and the Bahía Thetis (in Península Mitre) Formations, all of them Campanian in age (Olivero et al. 2003; McAtamney et al. 2011). Overlying the Bahía Thetis Formation, the Policarpo Formation (Maastrichtian-Danian) is constituted by outer shelf and/or slope mudstones and sandstones (Olivero and Malumián 2008). The top of this unit shows an angular unconformity in the contact with the overlying strata, which may be Paleocene or Lutetian in different sectors of Tierra del Fuego (Torres Carbonell et al. 2011). The Paleocene and lower Eocene of the Austral basin are represented by the Río Claro Group, a regressive megasequence comprising turbiditic deposits at the base, and shallower facies to the top (Olivero and Malumián 2008). The La Despedida Group consists of a very thick clastic wedge (thinning to the north) that marks an extended transgression between the middle Eocene and the upper Eocene (Olivero and Martinioni 2001; Olivero and Malumián 2008), and the Cabo Domingo Group (Oligocene-middle Miocene) includes mostly subhorizontal strata, mainly exposed along the Atlantic coast from the thrust-fold belt deformation front boundary to the north (Olivero and Malumián 2008). The lower to upper Oligocene strata within the Cabo Domingo Group consist of folded marine conglomerates, sandstones and mudstones deposited below the calcite compensation depth; while the middle Miocene, upper part comprises shallow marine and deltaic mudstones of the Carmen Silva Formation and the chiefly fluvial deposits of the Cerro Castillo Formation (Olivero and Malumián 2008).

4 Oroclinal Bending and Rupture of the South America–Antarctica Continental Bridge

Although there is general consensus that the southern tip of South America and the Antarctic Peninsula where once joined forming a continuous continental "bridge," controversy still exists regarding the origin, timing and kinematics of their breakup and relative displacement (Diraison et al. 2000; Barker 2001; Dalziel et al. 2013; Torres Carbonell et al. 2014; Poblete et al. 2016; among many others). Paleogeographic reconstructions based on paleomagnetic data indicate that from the Late

Cretaceous to the Eocene the Fuegian Andes went through a large counterclockwise rotation, related to the closure of the Rocas Verdes basin (Poblete et al. 2016). Conversely, Antarctica experienced clockwise rotation with respect to South America, generating the bending of the South America–Antarctica connection and forming a cuspate orocline (Barker 2001; Torres Carbonell et al. 2014). Additionally, it has been proposed that from 110 Ma until 55 Ma both masses kept a similar relative position and a continuous southward displacement (Milanese et al. 2019).

The initiation of crustal extension and thinning responsible for the rupture of the South America–Antarctica continental bridge has been established at ca. 50 Ma (Livermore et al. 2005). This implied the relative displacement of South America to the north and Antarctica to the South, consistent with a northward thrust-front migration in the Fuegian thrust-fold belt recorded between the Eocene and the Miocene (Torres Carbonell et al. 2014). In that period, the Scotia Sea (Fig. 2) developed by extension at several spreading ridges, behind an east-migrating subduction zone at the boundary between the South American and Antarctic plates (Barker 2001). Contraction in the Fuegian Andes ended in the Miocene, coincident with a decrease in expansion rates at the West Scotia Ridge, which ceased definitely at around 7 Ma in the western and central Scotia Sea (Barker 2001).

5 Late Neogene–Recent Strike-Slip Faulting: The Magallanes–Fagnano Transform System

After contractional deformation ceased, the Fuegian Andes became subjected to a strike-slip faulting regime, associated with the Scotia plate northern transform boundary (Fig. 2). In Tierra del Fuego, a system of regional faults with an approximately east–west trend and sinistral kinematics is known as the Magallanes–Fagnano Transform System, located at the junction between the South American (to the north) and Scotia (to the south) tectonic plates (Figs. 1 and 2). The strike-slip displacement along the Fagnano system has been calculated at fairly 48 km (Torres Carbonell et al. 2008). Considering this value together with geodetic determinations of relative displacements documented at the plate boundary (Smalley et al. 2003; Mendoza et al. 2011), a maximum age between 7 and 11 Ma has been proposed for the initiation of transcurrence in Tierra del Fuego, which is still active (Torres Carbonell et al. 2008).

6 Late Cenozoic Landscape Evolution of Tierra del Fuego

Finally, through the late Cenozoic, Tierra del Fuego was affected by diverse agents that sculpted its relief (Rabassa et al. 2000, 2011; Coronato et al. 2008). Climatic and sea-level oscillations triggered different geomorphological events that left a footprint in the landscape. Since the Late Miocene, the climate of southern South America entered into the glacial cycles that are active until present (Mercer 1976; Wenzens 2006). The most prominent of these glacial episodes covered significant areas of the island, but is still in active discussion whether it has been fully covered at some time in the late Cenozoic (Malagnino and Olivero 1999; Rabassa et al. 2000; Coronato et al. 2004a; Bujalesky et al. 2001).

Over the highest mountains located in Cordillera Darwin, the ice sheets fed outlet glaciers and ice lobes that occupied lowlands. They dug wide valleys that follow an eastward direction taking advantage of depressions of tectonic origin (Diraison et al. 2000; Rabassa et al. 2000). The four main ice flow axes were the Magellan Straits, Bahía Inútil—San Sebastián, Lago Fagnano and Beagle Channel (Fig. 3). The several advances are recognized as a series of nested moraine ridges and belts that have been mapped and described since the nineteenth century (Darwin 1842; Nordenskjöld

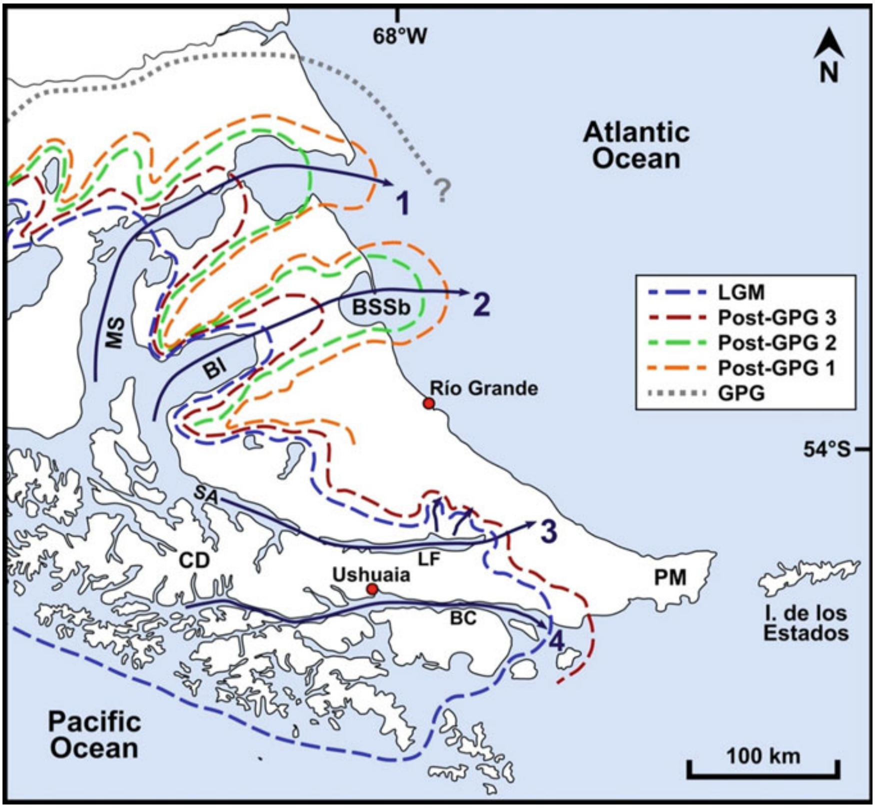

Fig. 3 Simplified map of Late Cenozoic ice flow axis and approximate ice lobes extension in Tierra del Fuego (based on Caldenius 1932; Meglioli 1992; Clapperton et al. 1995; Rabassa et al. 2000, 2011; Bentley et al. 2005; Glasser and Jansson 2008; Darvill et al. 2014, 2016). 1—Magellan Straits lobe; 2—Bahía Inútil—San Sebastián lobe; 3—Lago Fagnano lobe; 4—Beagle Channel lobe. MS—Magellan Straits; BI—Bahía Inútil; BSSb—Bahía San Sebastián; SA—Seno Almirantazgo; LF—Lago Fagnano; BC—Beagle Channel; PM—Península Mitre

1899; Caldenius 1932; Feruglio 1950; Auer 1956; Meglioli 1992; Clapperton et al. 1995; McCulloch and Bentley 1998; Rabassa et al. 2000, 2011; Coronato et al. 2004a, b; Bentley et al. 2005; Glasser and Jansson 2008; Darvill et al. 2014, 2016; among others).

The till plains and moraines of the oldest glaciations in Tierra del Fuego are found in the northern parts of the island (Meglioli 1992). They are possibly related to the Great Patagonian Glaciation (GPG, ca. 1.1 Ma BP, Mercer 1976), based on the correlation with landforms of known chronological age studied in continental Patagonia (Coronato et al. 2004a; Rabassa et al. 2011). The Post-GPG 1 (< 1 Ma, > 760 ka), 2 (< 760 ka, > 315 ka) and 3 (< 260 ka, > 150 ka) glaciations (Coronato et al. 2004b) are registered as well-defined morainic ridges and belts located on the margins of the northern ice lobes (Magellan Straits and Bahía Inútil—San Sebastián). Minor expressions of Post-GPG 3 advance are visible as moraines in the Río Fuego Valley, north of Lago Fagnano and in the Beagle Channel (Rabassa et al. 2011). Further field, mapping and dating studies over the central zone and the southeastern Atlantic coast are required to elucidate the extent and timing of glaciations prior to the Last Glacial Maximum (LGM) in these sectors.

The Late Pleistocene glaciations were restricted to the southern mountainous environments and the western coasts of Tierra del Fuego, surrounding the Magellan Straits, Bahía Inútil and Seno Almirantazgo (Fig. 3). The LGM (ca. 25 ka BP, Rabassa et al. 2011) ice limit is visible around the Chilean side of Tierra del Fuego, in the central Magellan Straits and Bahía Inútil, where minor readvances were identified (Bentley et al. 2005; McCulloch et al. 2005). Moraines produced by this glaciation are also located on the margins of the Lago Fagnano lobe, the Río Fuego and Ewan valleys (Coronato et al. 2009), the inner valleys of the Fuegian Andes (Coronato 1995), and in the coasts of the Beagle Channel (Rabassa et al. 2000, 2011). Moraines recording the Late Glacial minor ice readvances are found in inner and higher positions surrounding the same valleys affected by the LGM (McCulloch et al. 2005; Coronato et al. 2009; Rabassa et al. 2011).

Neoglaciation signals are limited to the higher sites of the Fuegian Andes, where climatic conditions allowed cirque glaciers to persist. Several Holocene and Little Ice Age moraines are preserved in the mountains located north of Ushuaia (Menounos et al. 2013).

During interglacial periods, the ice melting created vast gravel outwash plains and associated cut-in-fill terraces and fans. Examples of these landforms can be found in the proglacial zone of the Lago Fagnano lobe (Coronato et al. 2009) and in the steppes north and west of Río Grande (Codignotto and Malumián 1981; Bujalesky et al. 2001; Quiroga 2018). In these periods, the cold and humid climate together with the postglacial valleys topography led to the appearing of large peat bogs that dominate the southern and southeastern lowlands of the island (Rabassa et al. 1996; Iturraspe 2010).

The semiarid to subhumid conditions and westerly winds present in the northern part of the island allowed the aeolian modeling of the landscape. In the central portion of Tierra del Fuego, there are several examples of Holocene deflationary features. To the west of Río Grande, a group of ephemeral, brackish, shallow Lakes are set over blowouts (Codignotto and Malumián 1981; Coronato et al. 2011; Villarreal et al. 2014; Montes 2015; Villarreal and Coronato 2017; Quiroga 2018; Montes et al. 2020). They are encircled by depositional landforms formed by fine-grained sediments. Some of the recognized elements are sand and silt dunes (Coronato et al. 2011, 2020), lunettes (Villarreal and Coronato 2017; Montes et al. 2020) and sandy silt sheets (Villarreal et al. 2014). In the Bahía San Sebastián area, the interaction of aeolian processes acting over paleomarshes allowed the formation of ephemerally flooded pans, enlarged in an E-W direction (Arche and Vilas 1986, 2001; Villarreal and Coronato 2017).

Coastal landscapes of the island expose evidences of the oscillation of sea level through the Late Cenozoic, due to eustatic and tectonic processes (Bujalesky 2007; Ponce et al. 2011). These landscapes are found along the Atlantic coast as well as in the inner shores of the Magellan Straits and the Beagle Channel. They show a wide variety of landforms related to the emergence and submergence of the coasts at a local scale (Bujalesky 2007).

The northern Atlantic coast is part of a passive margin. It is dominated by cliffs that outline a straight wall positioned in a NNW–SSE orientation between Cabo Espíritu Santo and Cabo Nombre (Codignotto and Malumián 1981; Bujalesky 2007).

The Bahía San Sebastián (Fig. 3) is a wide bay (40 km diameter) of semicircular shape, developed over a glaciotectonic valley that was flooded during the early Holocene (Codignotto 1975). The northern part is characterized by supratidal fossil marshes and intertidal flats, the central and eastern shores are distinguished by Cheniers ridges, while the southern sector is recognized for its cliffs and sandy beach complexes (Vilas et al. 1986, 1999; Isla et al. 1991). The bay mouth is partially closed by El Páramo peninsula. It is a N-S oriented, 20-km long, gravel spit formed during the last 5 ka BP by the southward longshore drift (Codignotto 1975; Codignotto and Malumián 1981; Bujalesky 1990; Isla et al. 1991).

Southward, the central area of the Atlantic coast of Tierra del Fuego is defined by several Holocene gravel beach ridges plains. These landforms closed previous paleoembayments and estuaries, showing a relative sea-level descent (Bujalesky et al. 2001; Montes 2015; Bujalesky and Isla 2006). In addition, some of the southernmost Pleistocene raised beaches of the world are recognized there (Bujalesky 2007).

The Magellan Straits display diverse coastal landforms along its shores, related to glacial and eustatic oscillations. The coastal processes that affected its eastern mouth, in the north of the island, are similar to the ones that acted over the Atlantic margin. Thus, there appear cliffs, sandy beaches, spits, tidal mudflats, marshes and coastal dune fields (Simeoni et al. 1997). In the central section of the strait, there is a pattern of marine and glacio-lacustrine terraces and elevated shorelines (DeMuro et al. 2015, 2017).

The south and southwestern Tierra del Fuego shores, near Cordillera Darwin, Seno Almirantazgo and the western Beagle Channel (Fig. 3) were affected by tectonic and glacial processes different from the ones that acted in the eastern and northern part of the island (Bentley and McCulloch 2005), configuring coasts mainly occupied by fjords.

The central Beagle channel is surrounded by a rocky shoreline with cliffs and gravel beaches situated in the embayments (Gordillo et al. 1992). Several terrace levels are recognized along it, together with raised beaches of Holocene and Pleistocene ages (Gordillo et al. 1992; Rabassa et al. 2008). The coastline has suffered rapid modifications during the Holocene. The last postglacial flooding of the Beagle valley occurred about 11 ka BP, with a maximum sea-level rise of about 10 m above present day level at 6 ka BP (Bujalesky 2011), when low elevation Lakes were flooded and connected with the sea as paleofjords (Gordillo et al. 1993). The southeastern Peninsula Mitre (Fig. 3) shows rock cliffs and minor beaches, developed in bays and near river mouths (Isla 1994; Coronato et al. 2008).

Neotectonics related to the Magallanes–Fagnano Transform System is playing an important role in the landscape development in the central zone of the island. Several Quaternary fault scarps and pull-apart basins associated to strike-slip motion and transtension were recognized near Lago Fagnano (Costa et al. 2006; Perucca et al. 2016; Onorato et al. 2016, 2019).

To conclude, present-day active geomorphological processes are those inherited from the late Holocene, described above, in conjunction with fluvial, lacustrine, mass wasting, periglacial and anthropogenic activity (Coronato et al. 2008).

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Beatriz Mine: A Polymetallic Massive Occurrence in Tierra del Fuego

Silvia Ametrano, Ricardo Etcheverry, Horacio Echeveste, and Marta Godeas

Abstract The so-called Beatriz mine is located 15 km from Ushuaia and it was the first recognized polymetallic massive sulfide in Tierra del Fuego. The ore consists of a lens-shaped sulfide body with sedimentary and metamorphic textures, composed by chalcopyrite, sphalerite, galena and pyrite, and minor pyrrhotite, cobaltite, arsenopyrite, marcasite, magnetite and tetrahedrite. The lens is hosted in a volcano-sedimentary sequence of Jurassic age.

Keywords Polymetallic lens · Massive sulfides · Pyritic chert

1 Introduction

Many colored oxidized sulfide belts outcrops are known in Tierra del Fuego, which stretch along some 200 km within Andean Argentine territory. The first information regarding to metalliferous mineralizations in the region comes from Popper (in Kittl 1931) who assessed the auriferous placers discovered at Bahía Sloggett, which produced approximately 20,000 oz of gold. Kranck (1932) presented a systematic study of both sides of Canal de Beagle, where he surveyed different areas and found base metal sulfides (sphalerite, galena, chalcopyrite and pyrite). This author briefly refers to mineralizations located in Bahía Yendegaia, east coast of Lago Roca and Bahía San Juan. At the beginning and middle of 20´s century, some gold placer mining was developed in the Canal de Beagle and also rudimentary mining works were carried on in Beatriz mine. Since 1970, geological surveys (Caminos et al. 1981) determine several color anomalies (Arroyo Los Castores, Río Remolino-Túnel, Bahía Slogget, Bahía Aguirre). Many exploration and research works were also performed (Zubia et al. 1989; Broili et al. 2000; Biel et al. 2010; Biel 2011) that have allowed

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to typify these mineralizations as belonging to massive sulfide type, volcanic or sediments hosted (Acevedo et al. 2005).

The so-called Beatriz mine was the first recognized massive sulfide deposit in the area (Zubia et al. 1989), since the first geological surveys carried out by the Argentine Mining Geological Service (SEGEMAR) in the 70 s. Then the National University of La Plata (FCNyM) and the National Council of Science and Technology (CONICET) supported more studies. Nevertheless, others bigger colored zones and polymetallic lenses outcroppings, such as Arroyo Rojo, called the attention of companies for exploration surveys as well as research projects. The exploration has led to the recognition of several targets in the Sorondo and Alvear Range, which have reached the drill stage (Acevedo et al. 2005; Broili et al. 2000; Biel et al. 2010). This chapter summarized the knowledge reached on Beatriz polymetallic occurrence.

2 Regional Geological Setting

Beatriz mine is located in the western foothill of Monte Susana (54°51′30″ SL and 68°27′33″ WL) within Tierra del Fuego National Park (Fig. 1). This mineralization is 15 km from Ushuaia and 200 m from Bahía Ensenada in the Canal de Beagle. It is accessed through roads, although the last 1.5 km must be covered on foot.

The geological environment of Tierra del Fuego (Fig. 2) is characterized by a deformed metamorphic basement represented by accreted prisms, assigned to the Upper Paleozoic. In the southern part of South America, in Tierra del Fuego, during the Jurassic, there was an extensional episode (Dalziel et al. 1974; Bruhn et al. 1978), which originated a back-arc basin. During its evolution, a thick acid volcanism was deposited (Lemaire Formation, Borrello 1969), which was interbedded with marine sedimentary rocks. These sedimentary rocks correspond in their lower levels to high energy environments that evolved toward deeper environment facies represented by pelites and shales with no acid volcanic activity. These last sedimentary rocks with some rhyodacitic volcanic rocks correspond to Yahgán Formation (Kranck 1932).

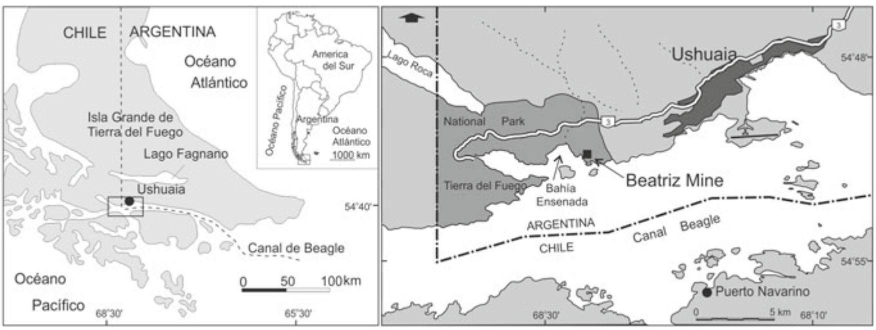

Fig. 1 Location of Beatriz mine

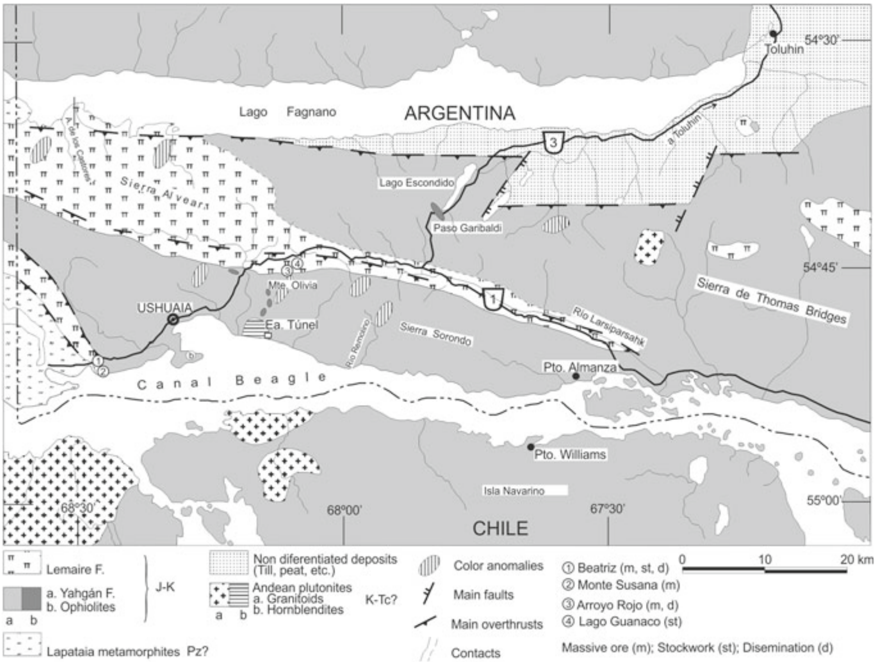

Fig. 2 Geology of Tierra del Fuego (compiled after Caminos et al. 1981; Kranck 1932; Suarez et al. 1985)

Later on, when attenuation and fracturing conditions were suitable, there was an overflow of basaltic dikes and bodies, which are the best exposure of the back-arc basin (Dalziel et al. 1987).

In the Argentine territory, the basement crops out only in the Argentine–Chilean border (Fig. 2) through the Lapataia Formation. The sedimentary and volcanic rocks of the back-arc basin were later affected by low grade and deformation metamorphism. It should be noted that the intercalation of the rhyolitic volcanic episode (Tuffaceous Series, Thomas 1949; Lemaire Formation, Borrello 1969, 1972) in the volcanic-sedimentary sequence of the back-arc is highly exposed in other sectors of the Andes. The age of the main units of this basin has been defined as Upper Triassic—Lower Cretaceous. Dark to greenish basic rocks, also metamorphosed, located at Paso Garibaldi and other sites represent the rift period according to Dalziel (1981); to the west, in Chilean territory, they have been named Rocas Verdes (Dalziel et al. 1974) and other authors relate them to Tortuga Complex (De Wit and Stern 1981).

The evolution is completed with a magmatic arc with plutonic rocks of the Late Cretaceous—Tertiary, when the closure of the basin is produced. These rocks form stocks and domes of various compositions (granite—syenodiorite—diorite—hornblendite). The current tectonic configuration is due to the Andean orogeny, whose compression effects appear in the different tectonic flakes, limited by reverse faults, which are characteristic of the Andes of Tierra del Fuego. According to Cingolani (1989) during the Tertiary there is a migration of the magmatic arc and a progressive deformation in depth, thus resulting strike displacement and thrust structures as a folded belt with frequent shearing effects. Finally, the region is bisected by transcurrent faults. During the Quaternary, there is a development of alluvial and glacial deposits mainly, as well as large peat plains.

3 Local Geology

In the Beatriz mine environment, three of the aforementioned units crop out. Pre-Jurassic basement rocks (Lapatia Formation) are present in the western which are very well known in the Chilean sector of the Isla Grande of Tierra del Fuego. The two other units are Jurassic acid volcanic rocks and metasediments of Lemaire Formation and sedimentary and marine volcaniclastic lithologies of the early Cretaceous of the Yahgán Formation.

The area was the object of a detailed study by Olivero et al. (1997) who consider that the Yahgán Formation is only represented to the eastern of the sector and assigns most of the sedimentary volcano sequence to the Lemaire Formation (Fig. 3).

The sequence has undergone low-grade regional metamorphism and deformation. Metamorphism reached prehnite–pumpellyite to greenschist facies

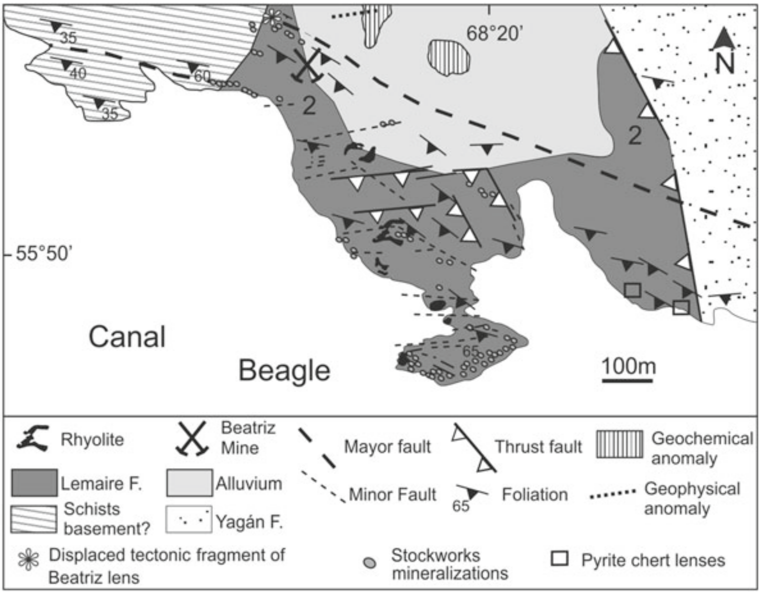

Fig. 3 Geology of Beatriz mine—Monte Susana area (compiled after Zubia et al. 1989; Olivero et al. 1997)

Fig. 4 Imbricated/interbeded rhyolites and detailed picture, Beatriz mine surroundings at the coast of Bahía Ensenada

(albite–sericite/muscovite–chlorite–biotite–stilpnomelane–pumpellyte). It consists of interbeded fine sedimentites (wackes, siltstones, shales) and rhyodacitic to dacitic pyroclastites within a euxinic environment represented by black shales levels showing abundant framboidal pyrite and graphite. Rhyolites bodies are present in the sequence (Fig. 4). They are considered tectonically imbricated units of Lemaire Formations by Olivero et al. (1997) or synsedimentary intruded by Zubia et al. (1989). These rhyolites are slightly porphyritic with a generally recrystalized matrix, without thermal effects in the contact zones. The cores of the major rhyolitic bodies present faulting with clearly observable scarps.

Rotated clasts and pressure shadows in silicates as well as disseminated pyrite are very frequent in the whole sequence and it has been affected by a quartz–sericite–pyrite alteration. The sequence has dominant E-W strike and deeps monoclinally to the south. Reverse and strike slip faults together with related close folding and microfolding are very frequent. Glacial sediments and turf soils complete the geological scheme.

This sector is part of an overthrust flake (Zubia et al. 1989) where the sequence monoclinally dips southward. Locally, the whole group is sometimes affected by axial cleavage. Foliation is basically coincident with stratification planes. Olivero et al. (1997) conclude that the structural disposition of the units suggests stratigraphic inversion, with the oldest units mounted tectonically on the youngest ones.

4 Mineralization

In this area, there are three types of sulfide mineralization: massive, disseminated and stockwork. Massive type is represented by the small occurrence of the polymetallic lens of Beatriz mine and by pyritic cherts lenses. Even though the body of Beatriz mine does not crop out, it can be observed by means of a prospecting undercut. Geology, petrology and mineralogy were described by Zubia et al. (1989), and chemical composition of the sulfides by Ametrano and Paar (1996a, b) and Ametrano et al. (2000).

4.1 Massive Sulfide Mineralizations

4.1.1 Beatriz Mine

Beatriz mine is a stratiform mineralization consisting of a small subconcordant lens with a length of 5 m and a maximum thickness of 0.8 m. It is estimated that the body has had a dimension at least twice that mentioned in the direction of the major axis, judging by the development of the entrance of the rudimentary mining work (Fig. 5). The western end of the lens is dismembered into veinlets along some 12 m due to

Fig. 5 Beatriz mine, entrance of undercut

the deformation. Besides this, the lens presents a fault displacement of about 300 m (Fig. 3).

This lens is hosted in sandstones and wackes of Lemaire Formation, at 200 m of rhyolitic bodies imbricated with it. The silicification and abundant pyritization in the wall rock are somewhat obscured by the metamorphism. Siliceous veins are important as a consequence of the metamorphism and deformation. The ore mineralogy consists of chalcopyrite, sphalerite, galena and pyrite as the main components, and minor or accessory pyrrhotite, cobaltite, arsenopyrite, marcasite, magnetite and tetrahedrite. Gold has been scarcely observed as 3–5 microns sparks within chalcopyrite. The gangue is integrated by quartz and very minor calcite. The sulfides constitute 50–80% of the lens.

The ore presents a marked compositional banding (chalcopyrite–sphalerite) subparallel to the regional foliation as the result of deformation, although some of the layerings may be primary sedimentary features. The grain size is very fine (5–10 microns) with relictic sedimentary characteristics such as disharmonic foldings. At a microscopic scale, metamorphic features are recrystallized pyrite grains (poikilitic megacrystals up to 150 microns), annealed texture (chalcopyrite/sphalerite) and peripheral redistribution of chalcopyrite blebs ("chalcopyrite disease") in recrystallized sphalerite. The deformation effects are the rotation of pyrite accompanied by "pressure shadows" constituted by the rest of the sulfide mass, also cracking and later filling of fractures by chalcopyrite. The frequent presence of cobaltite in cubic crystals has textural relations suggesting that this mineral was one of the first ones to be formed, with an almost stoichiometric chemical composition (42 wt% As, 32 wt% Co, 3.3 wt% Fe, 0.5 wt% Ni, Ametrano and Paar 1996b). These cobaltite crystals very often have their cores replaced by chalcopyrite, thus resulting in "atoll" crystals (Fig. 6 f).

The ore grades vary greatly along the Beatriz mine lens (Zubia et al. 1989), 0.03–19 Zn %, 0.02–4.73 Cu %, 0.02–4 Pb%, 5–175 Ag % and traces of gold.

4.1.2 Pyritic Chert

To the east of the area, on the coast of Canal de Beagle at the foot of Monte Susana (Fig. 3), black slates (Lemaire Formation) outcrop with abundant concordant intercalations of a pyritic chert. This chert is distributed within the 15 m thickness of the slates and extends along strike for more than 1 km. The microfolding and boudinage of the pyritic chert show a clear differential behavior after deformation as compared with that of slates (Fig. 7). Pyritic chert is mainly composed (more than 50%) of recrystallized pyrite with a great tendency to automorphism as well as pyritospheres (Fig. 6 d). These coastal outcroppings are accompained by strong limonitic oxidation. Preliminary chemical data allow interpreting this chert as an exhalite (Ametrano et al. 2000). Many other pyritic mineralizations have been described from Bahía Lapatia to Península Mitre in the east of Tierra del Fuego (Acevedo and Radoszta 1987). These pyritic coastal levels were used to make fire by the native peoples of Tierra del Fuego.

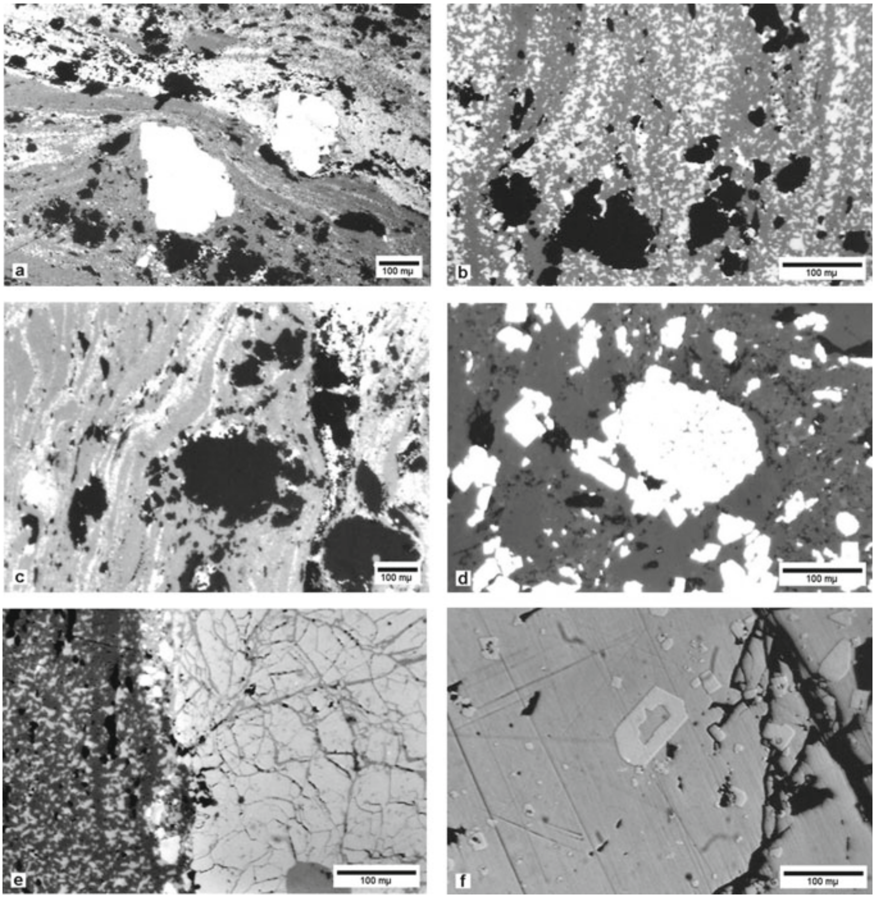

Fig. 6 **a** Beatriz lens, rotated poikilitic pyrite porphyroblasts with chalcopyrite inclusions and pressure shadows of fine-grained sulfides (chalcopyrite + sphalerite, annealed texture); **b** Beatriz lens, annealed texture, sphalerite (dark grey) and chalcopyrite (light grey), quartz (black); **c** Beatriz lens, fine-grained sulfides with banded/annealed texture (sphalerite dark grey, chalcopyrite light grey), porphyroblasts of pyrite (white), quartz (black) and lithoclasts (black); **d** Pyritic chert Monte Susana, framboidal and recrystallized pyrite (white), chert and clasts (black and dark grey); **e** Beatriz lens, fractured porphyroblast of pyrite, fractures filled with chalcopyrite; **f** Beatriz area stockwork, idiomorphic cobaltite crystals with cores replaced by chalcopyrite in coarse-grained chalcopyrite

4.2 Stockwork and Dissemination

The stockwork mineralization is observed in an area of approximately 1 km^2 near Beatriz mine. It is hosted in foliation planes and tensional structures (Fig. 8) of the metasedimentary rocks and in rhyolites, with frequent anastomosed pattern. The sulfides in the stockwork were observed in areas without vegetation cover, a

Fig. 7 Boudinage in pyritic chert lenses

greater distribution is not ruled out in covered areas. These veinlets present a variable thickness between 0.5 and 5 cm, and lengths that may reach 10 m. The gangue is almost exclusively quartz and its main components are chalcopyrite and pyrite, minor and secondary components are sphalerite, galena, cobaltite, covellite, malachite and azurite. The texture is typically that of open space filling. Cobaltite in these veinlets has usually "atoll" crystals with cores replaced by chalcopyrite.

Sulfide dissemination is observed in all of the mapped area (Fig. 3) and consists of pyrite, frequently framboidal, pyrrhotite and graphite, in concentrations not higher than 0.1%.

5 Geochemical and Isotopic Data

5.1 Chemical Data of Sulfide Minerals

Microprobe analyses of sulfide minerals were carried out (Ametrano and Paar 1996a, b; Ametrano et al. 2000). The sphalerites have FeS content between 5 and 9.70 mol% (highest values correspond to stockwork sphalerites), and cadmium (0.12–0.21 weight %) is below the epithermal range (Bortnikov et al. 1995). The correlation between Cd and FeS in sphalerites (Ametrano et al. 1997) shows a similar but weaker tendency to lower Cd values for sotckwork sphalerites when compared with data from the Iberian Pyritic Belt (Marcoux et al. 1996). Galena is the only silver carrier with an average of 0.30 weight % Ag, and a good Bi–Ag correlation. The selenium content

Fig. 8 Stockwork mineralization, Beatriz mine surroundings

in galena is high with an average of 1.41 weight % in the lens body and 0.95 weight % in the stockwork. Some significant Bi content has been also detected in galenas.

The content of cobalt in all pyrites fluctuates between 0.04 and 0.08 weight %. The high Co/Ni ratio found in pyrites is characteristic of those affected by metamorphism. Pyrites from pyritic chert have Zn contents between 100 and 700 ppm. The 100 microprobe analysis of pyrite carried out by Ametrano et al. (2000) from Beatriz

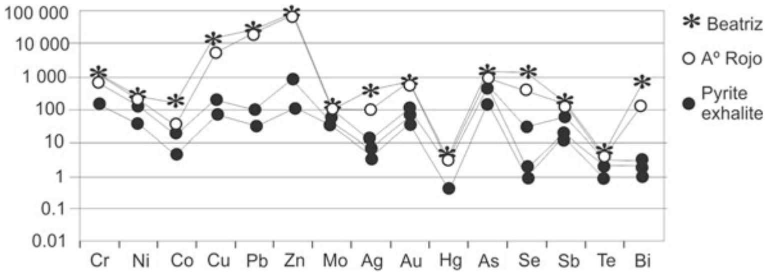

Fig. 9 Metal contents of massive sulfides ores (Arroyo Rojo and Beatriz mine) and pyritic cherts (Ametrano et al. 2000)

mine, Arroyo Rojo and pyritic exhalite allowed to conclude: pyrite from Arroyo Rojo has higher zinc content (up to 1.5 weight %); gold contents are variable, higher values are accompained by an arsenic increase; framboidal pyrites have higher arsenic values than the other pyrites, the recrystallization of framboidal pyrites has been accompained by a loss of arsenic.

5.1.1 Ore Chemical Composition

Ametrano et al. (2000) include comparisons of metallic content with those of Arroyo Rojo, a massive polymetallic deposit hosted in volcanics and volcaniclastics of Lemaire Formation. As seen in the Fig. 9, Arroyo Rojo has lower values of Co, Ag, Se and Bi. These contents are consistent with ore and mineral chemical data provided by Biel (2011), especially for galena that have less Ag, Bi and Se than those of Beatriz mine.

The REE pattern of pyritic chert resembles that of rhyolites (Ametrano et al. 2000). According to the Cu + Co + Ni/ Fe/ Mn discrimination diagram (Bonatti 1975), the pyritic chert of Monte Susana belongs to the hydrotermal field. On the other hand, zinc contents in pyrites from pyritic cherts could also be an expression of a hydrothermal episode in Lemaire Formation.

5.2 Lead and Sulfur Isotopes

Analysis of lead isotopes in a galena of Beatriz mine shows similar values to those of Arroyo Rojo (Table 1, Ametrano et al. 2000) and they are in good agreement with those of Biel (2011). In comparison with Stacey-Kramers (1975) average crustal evolution curve, both samples are within the curve error and model ages of less than 100 Ma, but this age could be influenced by the metamorphism that affected the sulfides.

Table 1 Isotopic Pb values in two galenas (Ametrano et al. 2000)

	$^{208}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{206}Pb/^{204}Pb$
Galena Beatriz	38.501	15.652	18.504
Galena A.Rojo	38.505	15.645	18.645

*2 sigma = ±0.012, 0.014, 0.048 Standard = NBS 981
**Data correction by fractionating + 0.13%/ atomic mass unit according to NBS 981

Table 2 S isotopes (Ametrano et al. 2000)

Mineral	$\delta^{34}S_{CDT}$ ‰
Py Beatriz	0.61
Py A.Rojo	1.60
Sph. Beatriz	−0.35
Sph.A.Rojo	0.79
Py chert Susana M.	7.88

Standard NBS 123

Ametrano et al. (2000) obtained some sulfur isotopic data for sulfides (Table 2). These values are similar to those of with greater statistical representation (−4 to 2.66‰) in Arroyo Rojo massive and semimassive ore obtained by Biel (2011). On the other hand, sulfur isotopes from pyrite in the pyritic chert differ markedly probably indicating a complementary contribution of seawater sulfur (Rollinson 1993) in the range of modern and ancient sedimentary pyrites of Seal (2006).

6 Final Remarks

The existing data and the geological framework allow assuming that the Beatriz mine responds to the model of deposits related to submarine volcanism of the massive sulfide type, with superimposed metamorphism, in a euxinic environment as suggested by the absence of barite and the presence of pyrrhotite and magnetite. Morphological features and ore textures of the lens-shaped mineralization show a syndiagenetic relationship with the host sequence and have been affected by the same metamorphism and deformation. The conspicuous ore textures from Beatriz lens are characteristic of others well-studied metamorphosed massive sulfides deposits and nearby Chilean occurrences such as Cutter Cove and Yendegaia (Ametrano et al.1997).

The disseminated and stockwork mineralizations do not depart from the model but could be part of the schemes already indicated for important districts in the world. Stockwork could be considered a feeder zone, as Biel et al. (2010) interpreted the mineralization of Lago Guanaco with respect to that of Arroyo Rojo. The stockwork in this area has higher Cu composition. Cu-rich stringer zones have been recognized for others big massive sulfide deposits such as Canadian Archean, Hokuroko and the Iberian Pyritic Belt.

According to Marcoux et al. (1996), Eldridge et al. (1983) and Large (1992) cobalt sulfoarsenides were formed at the beginning of massive sulfide genesis. The content of cobalt in the lens and stockwork of Beatriz mine could suggest a similar conclusion: it could be the basal zone when compared with Arroyo Rojo. The volcano sedimentary sequence has had other minor hydrothermal episode, the pyritic chert, with similar REE pattern as the Lemaire Formation rhyolites.

Biel et al. (2010) and Biel (2011) proposed a model of brine pool for Arroyo Rojo deposit supported by a very detailed study. The available data for Beatriz mine do not allow applying the criteria proposed by Solomon et al. (2004) to differentiate between brine pool-type from black smoker-type sulfide deposition in the volcanic-hosted massive sulfide deposits.

Although the lack of economic value of Beatriz mine, the two geophysical (IP and magnetometry) and geochemical (soil geochemistry) anomalies (Fig. 3) detected in the area by Zubia et al. (1989) could be reviewed.

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A Review of the Arroyo Rojo VMS Deposit, Tierra del Fuego

Constanza Lobo and Ignacio Gómez Vereda

Abstract The Arroyo Rojo VMS deposit is the most studied polymetallic ore of Tierra del Fuego, Argentina. The first mentions of its existence began in the 80s by Minera Aguilar, which has discovered a small nunatak containing a lens of polymetallic massive sulfides, since then various authors have studied the geology and mineralization of the site. Several anomalies of copper, lead and zinc were also identified in the region during regional prospection in the 70s. The deposit is within the Lemaire formation, a rhyolitic low-Jurassic marine volcano-sedimentary complex formed during the fragmentation of Gondwana. The mineralization consists of a massive sulfide lens that varies from 1.5 to 4 m in thickness in surface and two more massive sulfide lenses at depth with a thickness that varies between 3 and 18.6 m. The ore is composed mostly of pyrite and sphalerite, minor galena, chalcopyrite and pyrrhotite. Some of the original textures like framboidal, colloidal and euhedral type can be still recognized among other deformation and recrystallization textures. The hydrothermal alteration consists of a roughly concentric zonation with an inner silica and clorithic zone and an external sericitic zone. Even though previous works have classified the Arroyo Rojo deposit as Kuroko type, more recent studies have shown evidence that associates this deposit with a brine pool deposition.

Keywords Volcanic-hosted massive sulfide deposit · Mineralization · Polymetallic ore

1 Introduction

Inside the Fuegian Andes, several authors have identified and studied a series of Jurassic Volcanic Massive Sulfide (VMS) deposits known as Arroyo Rojo (Red Stream), named like this due to the characteristic red color of the surrounding rocks (Fig. 1a). Such deposits belong to a mineralized belt, yet barely studied, that extends in a NW–SE (Fig. 1a, b) sense within Lemaire formation (Low Jurassic). The ore is

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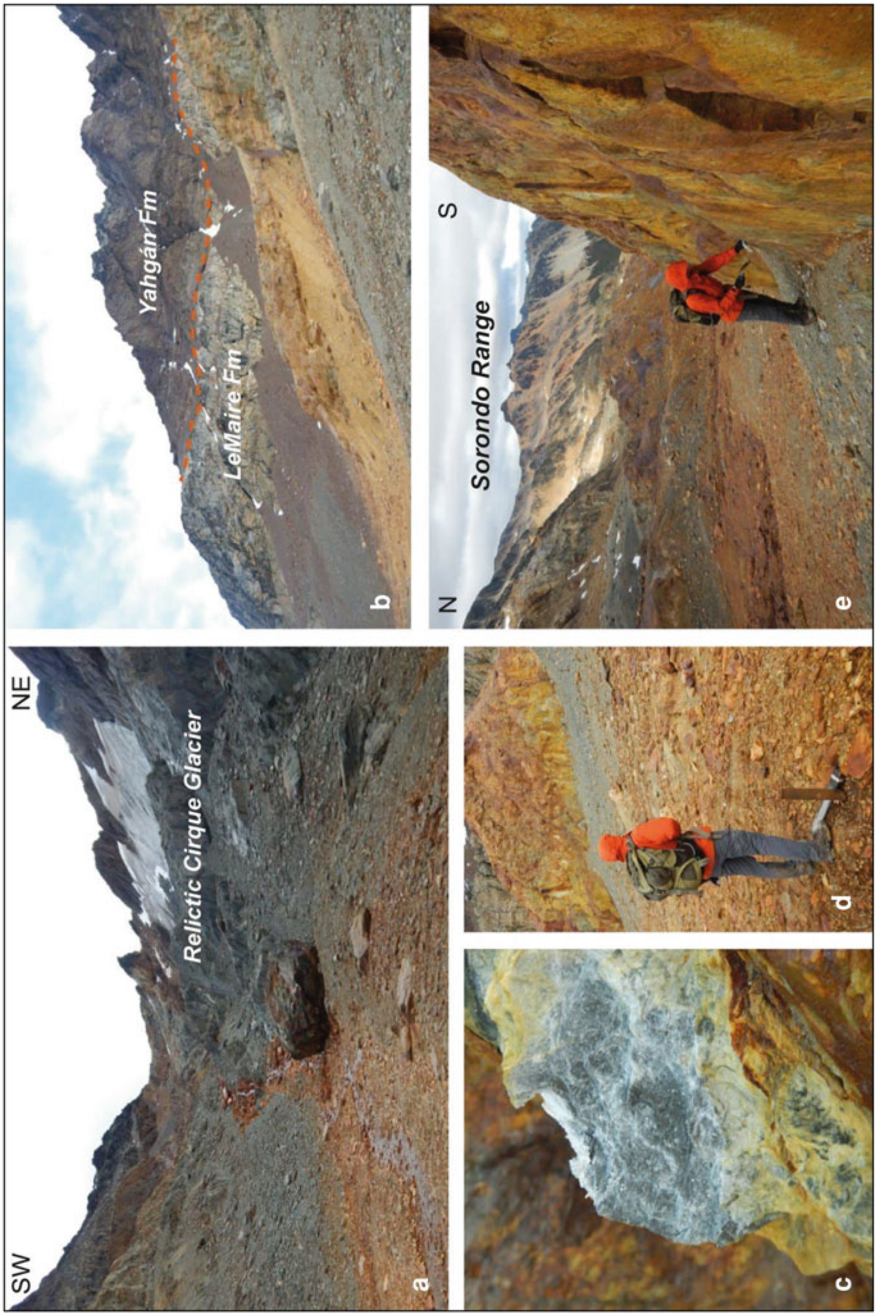

Fig. 1 **a** General view of the Arroyo Rojo valley with its cirque glacier; **b** Outcrops of the sulfured lenses contained in Lemaire formation; deduced contact between Le Maire and Yahgan formations (dash line); **c** Macro photo of the mineralization; **d** Rest of the drilling holes performed by Westmin; **e** General view of the intense red coloration of the Sorondo range

composed mostly of pyrite and sphalerite, minor galena, chalcopyrite and pyrrhotite, and trace amounts of tetrahedrite and bournonite (Fig. 1c). Some of the original textures like framboidal, colloidal and euhedral type can be still recognized among other deformation and recrystallization textures.

Many geological explorations took place in Tierra del Fuego in the 70s, 80s and 90s looking for VMS deposits since they were much appreciated to be exploited as Cu, Pb and Zn ore (Fig. 1d). Nevertheless the actual socioeconomical and legislative context of the province is different, and it does not promote the prospection and exploration of this type of mineral deposit.

The Arroyo Rojo deposit constitutes only a tiny fraction of the explored area, inside of a mineralized lenses belt throughout the Alvear and Sorondo range (Fig. 1e), which has not been studied deeply. The aim of this contribution is to provide a review of such studies and portray the actual state of knowledge of this deposit.

2 Location

The study area is located in the Argentinian side of the Isla Grande de Tierra del Fuego, which is part of the Fuegian Archipelago in southern South America. The deposit is placed at 15 km from Ushuaia city (Fig. 2), in the Arroyo Rojo valley within the Sierra Sorondo range in the Fuegian Andes. These highlands are delimited by the

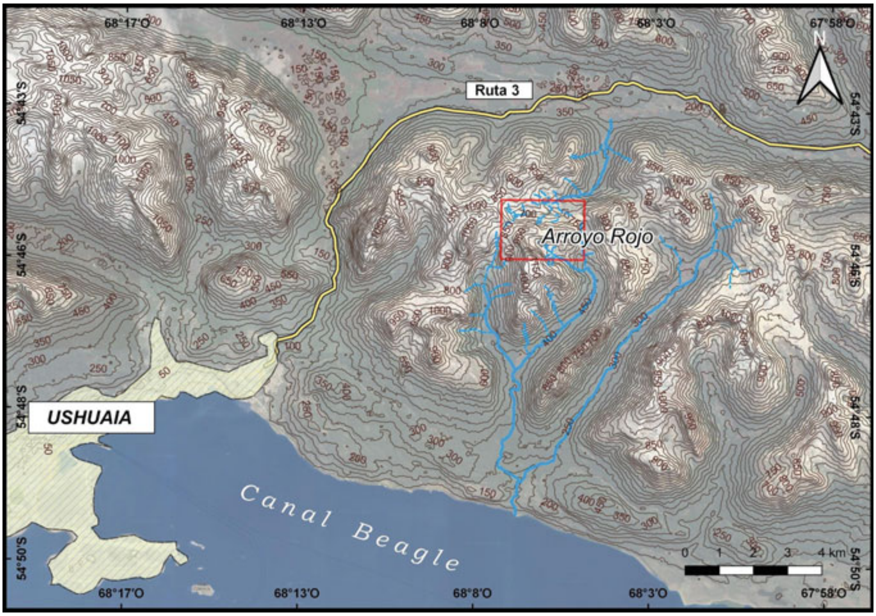

Fig. 2 Location of the study area (red square), at east of Ushuaia city and at north of Beagle channel

Carbajal valley in the north and by the Beagle channel (Canal Beagle) in the south. The place is characterized by a glacier modeled environment with hanging valleys, steep slopes, craggy ridges, horns and a still remaining cirque glacier. The valley is surrounded by the Submarino, Cinco Hermanos and Le Cloche mountains, the site can be accessed by air or on foot going upstream the Encajonado or the Submarine river.

3 Geological Setting

Arroyo Rojo VMS deposits belong to the low-Jurassic marine volcano-sedimentary complex described by Kranck (1932) and then named by Borello (1969) as Lemaire Formation. The composition of the Lemaire volcanism is ryolithic and its origin is associated with the opening of the Atlantic Ocean due to the fragmentation of Gondwana. Since this extensional event produced such fragmentation, a marginal basin named Cuenca de Rocas Verdes (CRV) was originated. The consolidation of this basin may have occurred up to the end of the Jurassic, starting with a rifting period followed by bimodal volcanism (predominantly acid) known as Lemaire formation. This formation is composed by an epiclastic basal member (turbidites, conglomerates, cherts, black limestones) and volcanic-volcaniclastics rocks (riolites, ignimbrites, breccias, tuffs, acretional lapilli and quartz porfides). During Cretacic, the basin was filled up by turbidites of Yahgan and Beauvoir formation. The closure of the marginal basin during Cretacic leads to the formation of the Austral Andes folded and thrust belt, which imposed low-metamorphic grade features over these formations (Dalziel et al. 1974; Nelson et al. 1980; Stern et al. 2003; Biddle et al. 1986; Olivero and Martinioni 2001).

4 Ore

According to Biel et al. (2010), the Arroyo Rojo deposit is the largest polymetallic massive sulfide deposit in Tierra del Fuego and it occurs as a series of lenses within Lemaire formation (Fig. 3).

5 Research

Previous descriptions of the Arroyo Rojo prospect have been provided by Broili et al. (2000), Ametrano et al. (2000, who considered Arroyo Rojo as a Kuroko-type VMS deposit), Acevedo et al. (2005), and Biel et al. (2010, 2012, 2016). Minera Aguilar was the first one to recognize the economic significance of the polymetallic massive sulfide occurrences in the Río Encajonado belt in the 70s during regional

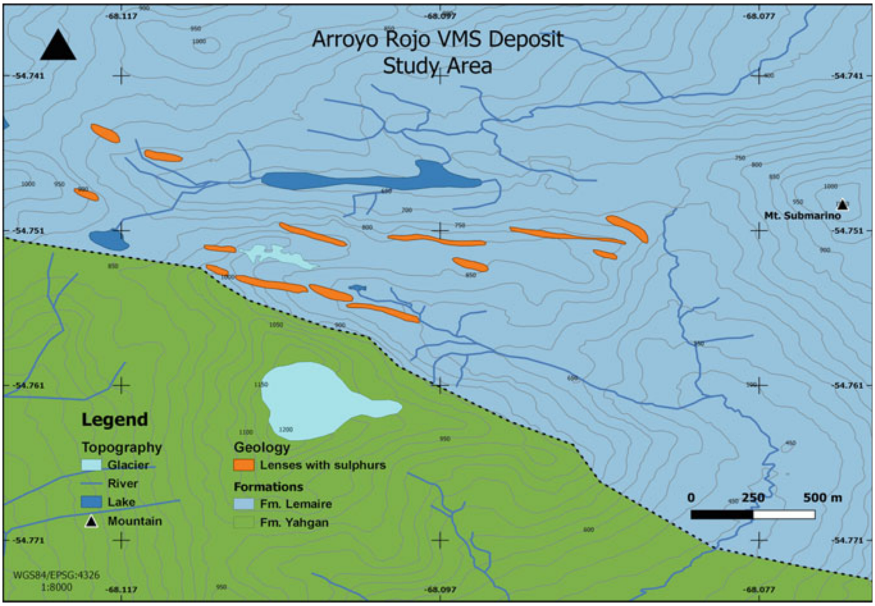

Fig. 3 Lenses distribution in the study area

reconnaissance exploration for base metals (Broili et al. 2000). Since then, base metals exploration was developed by several companies (Aguilar-St. Joe 1970–72, 1980–82; Noranda 1994–96; Yamana-Polimet 1995–96; Westmin 1996–97), nevertheless Westmin was the one that performed drillings in the area. Subsequently, Biel (2011) conducted a detailed study of such deposit, in the development of his PhD dissertation.

6 Structures and Lithology

In the study area, the contact between Lemaire and Yahgan formation is visible, and the outcrops show clear signs of deformation. Among these signs, the most conspicuous one belongs to a shear zone that dips in a S/SW direction and which is closed to the main mineralization and is considered as a regional detachment by Cao (2019). The deposit has a strong schistosity, but despite of this characteristic, the original stratification and the contacts with the surrounding rocks can be still recognized.

The mineralization containing rocks belongs to the volcanic portion of Lemaire formation and inside the study area Biel et al. (2010), Biel (2011) has identified, based on petrographic studies of outcrops and drilling samples from floor to roof, the following local stratigraphy

(a) Rhyolite: With different degrees of mylonitization, it contains millimetric elongate quartz and K-feldspar crystals and it does not show flow banding. It may be interpreted as a volcanic dome.
(b) Dacite: Microscopically, this rock is composed of Na-plagioclase phenocrysts showing twinning, growth zonation and sericite alteration, and some quartz phenocrysts.
(c) Ignimbrite: Characterized by the presence of fiammes and feldspar phenocrystals. The matrix and some of the fiammes are partially or totally replaced by chlorite and clinozoisite. Lithic clasts consist of rhyolite and rare dacite.
(d) Tuffs: This unit hosts the mineralization and is classified in four different types according to the amount of lithic, glassy or crystal fragments containing, these types are vesicular tuff, vitreous tuff, crystalline tuff and tuffy breccia.
(e) Vesicular tuff: These rocks show low-grade deformation, visible where elongated vesicles are weakly aligned with incipient mylonitization. These vesicles are infilled by a high density of rounded millimetric quartz eyes, surrounding by abundant quartz veinlets.
(f) Glassy tuff: Characterized by abundant glass shards with relictic glassy textures. Remanents of those textures are outlined by disseminated fine-grained, pyrite or iron oxides and locally, by micas, chlorite, and/or subrounded quartz grains.
(g) Crystalline tuff: Composed by quartz and feldspar crystals within a fine grain matrix. Pumiceous fragments are also seen.
(h) Tuffy breccia: It is characterized by a well-defined brechoid texture, composed of altered whitish fragmented clasts of a milimetric–centimetric size contained in a fine grain dark matrix.
(i) Ryolithic lava: Distinguished by its light color, aphiric texture and flow structures. These rocks were only observed in drilling samples.

Above this sequence, appear slates alternated with thin levels of foliated metagreywackes belonging to Yahgan formation (Cao 2019).

7 Morphology of Ore Deposits

According to Biel et al. (2010), the morphology of the mineralization consists of a massive sulfide lens that varies from 1.5 to 4 m in thickness, traced for over 250 m along strike. The orebody (Fig. 4) shows deformation evidenced by a pinch-and-swell structure, which has divided it into two minor portions. Two more massive sulfide lenses that occur at depth with a thickness that varies between 3 and 18.6 m were also described. According to Broili et al. (2001), mineralizations also occur as disseminations, stringers and semimassive lenses.

Even though lamination was formed previously to cleavage as a result of sedimentation and winnowing, the lack of evidence for ore deposition by replacement, presence of albite, lack of barite and Fe oxides and no significant change in FeS

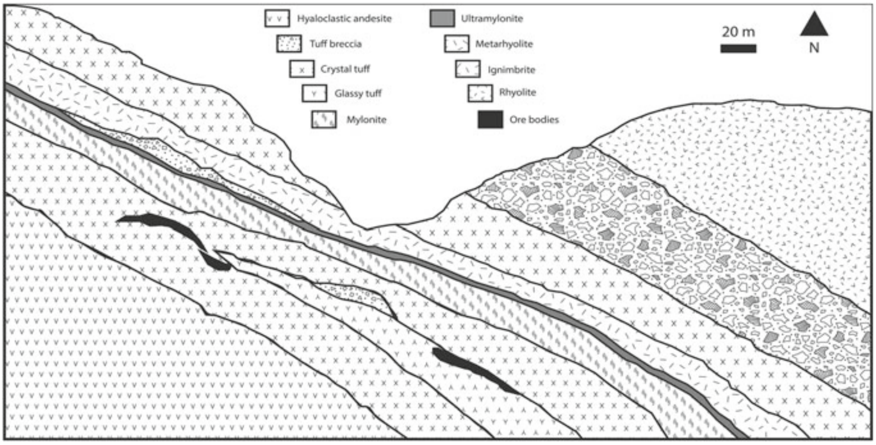

Fig. 4 Morphology of the Arroyo Rojo VMS deposit (Modified from Biel et al. 2010)

content of sphalerite passing from the massive sulfide lenses, suggest a brine pool deposition (Biel 2011).

8 Mineralization and Textures

The mineralization of the deposit is composed mostly of pyrite and sphalerite, minor galena, chalcopyrite and pyrrhotite, and trace amounts of tetrahedrite and bournonite (Biel et al. 2010).

8.1 Pyrite

Pyrite is the most abundant mineral of the deposit and it shows primary deformation and recrystallization textures. Fambroidal, euhedral (Fig. 5a) and colloform (Fig. 5b) are the only primary depositional textures preserved and are mainly concentrated in pyrite relict cores. Then, due to deformation, pyrite porphyroclasts are generally cracked and microfractured, aligned to a preferred or aleatory orientations and filling ductile phases by plastic injection (Fig. 5c). There are also pressure shadows of quartz, chlorite and muscovite manifested in pyrite. The signs of recrystallization in pyrite are shown in heterometric, granoblastic mosaics of fine-grained recrystallized with triples junctions near 120°.

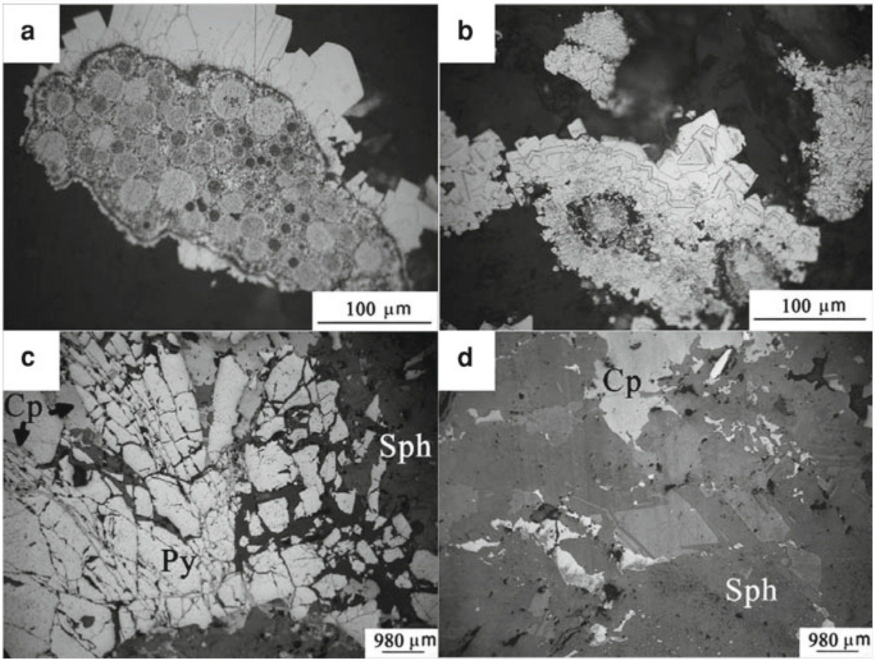

Fig. 5 **a** Euhedral pyritic radial overgrowths over polyframboidal cores; **b** Colloform overgrowth over framboidal core; **c** Oriented fractures in pyrite with incipient developing of cataclastic flow; **d** Growing twinning in sphalerite oblique to chalcopyrite disease (Modified from Biel et al. 2010)

8.2 Sphalerite, Galena, Chalcopyrite and Pyrrhotite

Sphalerite, chalcopyrite and pyrrhotite show a few relict primary textures even though they are less competent than pyrite and their microstructures are obliterated by deformation and recrystallization.

Sphalerite and chalcopyrite display deformation textures like twinning (Fig. 5d) and dislocations lattices, sometimes accompanied by subgrains. Sphalerite also shows a well-developed polygonal recrystallization to finer grain with triple junctions.

Galena only shows deformation and recrystallization textures. The first ones are related to a ductile behavior displayed by abundant lattice dislocations meanwhile the recrystallization signs, which are shared with pyrrhotite, are mainly triple junctions in polygonal grains of granoblastic textures.

9 Hydrothermal Alterations

Biel et al. (2010) describes rocks with hydrothermal alterations in the immediate footwall of the massive sulfide deposits. These alterations are shaped in a roughly concentric form with an inner silicic and clorithic zone and an external sericitic zone. The silicic alteration consists of quartz veins with pyrite and sphalerite within rhyolitic rocks, while the clorithic alteration is characterized by abundant dark green chlorite replacing felsic volcaniclastic rocks. The sericitic zone is the most extensive and widespread alteration and it is characterized by moderate to pervasive development of sericite in felsic volcaniclastic rocks.

10 Socioeconomical Remarks

In Tierra del Fuego, mining activity is regulated by the Secretaría de Minería (Mining Secretariat), which comes under the Ministerio de Producción y Ambiente (Production and Environment Ministry), mineral resources are classified by the mining code of Argentina (National Law N° 1919, 1887). This classification divides minerals in first, second and third order, being the first order, the category that contains metalliferous deposits and therefore, the Arroyo Rojo VMS deposit.

In turn, since 2011, the exploitation of first-order minerals is forbidden of account to the promulgation of the provincial law of application of the environmental principles of mining activity (Province Law N° 853, 2011). In this sense, if laws do not change, the Arroyo Rojo VMS deposit will remain untouched for exploitation purposes.

11 Conclusions

Even though polymetallic sulfide occurrences are widespread along the Sorondo range, Arroyo Rojo deposit is the largest polymetallic massive sulfide deposit in Tierra del Fuego (Biel et al. 2010). According to Broili et al. (2001), in general, these sulfide occurrences appear as disseminations, stringers and semimassive lenses of pyrite, pyrrhotite, sphalerite, galena and chalcopyrite, but the mineralization of Arroyo Rojo deposit is predominantly pyrite, sphalerite with lesser amounts of galena and chalcopyrite and rare pyrrhotite, tetrahedrite and bournonite. Also, the latest deposition model proposed by Biel et al. (2010) suggests that mineralization occurs in a brine pool mineral deposition in contrast to older theories that classified the deposit in a kuroko type VMS.

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Ornamental Rocks from Tierra del Fuego

Estefanía Picado and Raúl E. de Barrio

Abstract "Natural stone," a term that is frequently applied to ornamental rocks, it encompasses a wide range of stone materials used in the building industry. These rocks have been used by man for the manufacturing of different tools since ancient times. Today, these materials are used as raw materials for the construction of civil works, cladding of buildings, squares and streets. Tierra del Fuego Province, southern Patagonia Argentina, has metamorphic igneous rock complex, product of the magmatism that affected the region during the Cretaceous. It is mainly composed of magmatic bodies of small dimensions, between 3 and 25 km^2, and they are hosted by metasedimentary rocks of the Yahgán, Beauvoir and Lemaire Formations. The use of these natural resources has been evaluated only partially, with geotechnical tests, which resulted in very good data. In this work, the first laboratory tests performed on these rocks are detailed. Technological studies were focused on evaluating the suitability of several igneous materials for ornamental use. In specialized laboratories, different standardized petrophysical tests were performed to describe the properties of the rocks such as density, absorption and open porosity, resistance to compression and resistance to bending. Furthermore, the technological characteristics of the Fuegian rocks were contrasted with those published for other ornamental varieties marketed in Argentina. The level of geotechnical characterization reached allowed to establish that the Fuegian territory has different rocks susceptible to being used as ornamental rocks, among them the granitoids of the Cerro Jeu-Jepén stand out.

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Keywords Dimension stones · Geotechnical tests

1 Introduction

Application rocks are a resource that has been used by man since ancient times for the construction of tools and today, these elements are used as raw materials for the construction of civil works, building siding, squares and streets.

The name “application rocks” includes ornamental or lapidate, construction (used as stone aggregates) and industrial rocks, used for the manufacture of limes and cements (Ciccioli 2017).

Ornamental rocks are those used in building, generally being cut and polished, in plates of different shapes and sizes that allow to stand out its aesthetic characteristics, at the same time their functional properties are exploited (Secretaría de Minería 2012).

In 2005, the Government of Tierra del Fuego commissioned a survey and study of the basement rock of the province (Acevedo and González Guillot 2011) with the aim of knowing the potential of possible ornamental rocks.

The territory of Tierra del Fuego possesses different possible varieties of ornamental rocks due to the complex geological processes that have developed along the times. The magmatic arc of the Fuegian Andes is composed mostly of Upper Mesozoic to Cenozoic calc-alkaline plutons and subordinated lavas (González Guillot et al. 2011). Nowadays, these materials presume important mining resources to the Province of Tierra del Fuego, although they have not been globally evaluated yet. There is currently no active exploitation of granite (in the commercial sense of the word) or slates. The province of Tierra del Fuego has two small quarries that were exploited for specific purposes: one of them on Cerro Jeu-Jepén (Aguas Blancas quarry), where the rocks used for the building of the breakwater of Rio Grande Port were extracted, and the other one in Ushuaia Peninsula, in which of the materials used for the refill of the Bahía Encerrada were produced and as a housing lining (Acevedo and González Guillot 2011).

Historically, slate extraction occurred in Ushuaia on a small scale. Nevertheless, given the large extent of the outcrops of these rocks in the Cordillera Fueguina, there may be an important future resource.

The first geotechnical tests performed on Fuegian rocks are detailed in this work, emphasizing the lithological types that had the best results.

2 Materials and Methods

Figure 1 shows the geographic location of the points where the analyzed samples were obtained as follows:

(a) The hornblendite belonging to Ushuaia pluton,

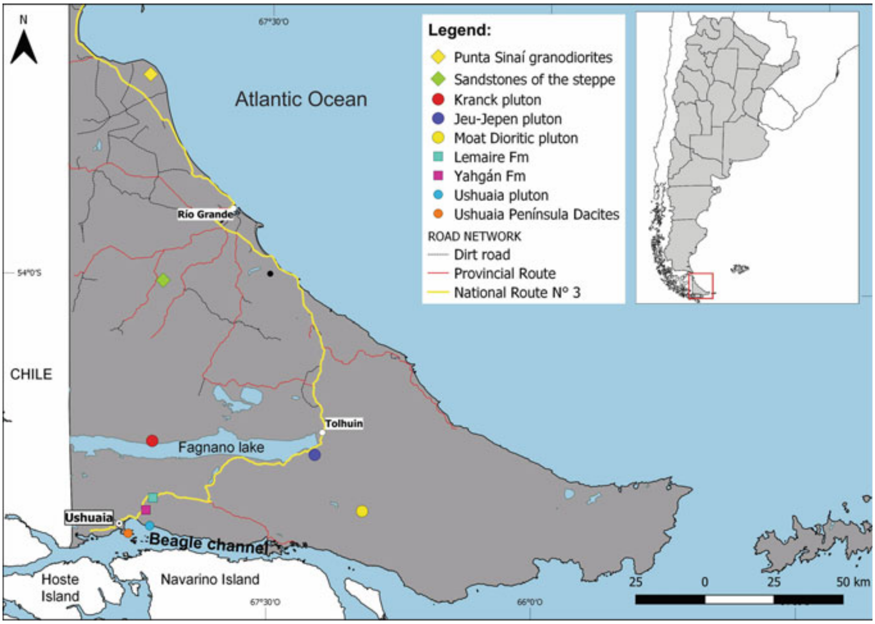

Fig. 1 Geographic location of sampled areas

(b) The dacites of the Ushuaia Península,
(c) The granitoids of Cerro Jeu-Jepén,
(d) The intrusive body of Mount Kranck, with its sienite and diorite types,
(e) Moat Dioritic pluton
(f) The basaltic rocks and the porphyric acid volcanic rocks, both lithologies belonging to the Lemaire Formation,
(g) The slates of the Yahgán Formation,
(h) The marine tertiary sandstones of the steppe and
(i) The erratic blocks of granodioritic composition of Punta Sinai.

The geotechnical tests were carried out in the laboratories of INTEMIN (Instituto de Tecnología Minera), belonging to the Servicio Geológico Minero Argentino and also in the INTI (Instituto Nacional de Tecnología Industrial). The tests were: density, absorption and open porosity, according to IRAM 10602 (IRAM 2013), dry condition compression resistance according to ASTM 170-09 (ASTM 2009a), wear resistance (Dorry method) and bending resistance according to ASTM C880/C880M-09 (ASTM 2009b).

3 Description of the Studied Rocks

3.1 Ushuaia Pluton

This intrusive body is located along the north coast of the Beagle Channel, 8 km east of Ushuaia city (Fig. 1).

The rocks of Plutón Ushuaia belong to a suite of monzonitic—mildly alkaline composition formed in a period of potassic magmatism (Fuegian Potassic Magmatism; González Guillot et al. 2009) that was emplaced to the rear of a Late Cretaceous arc in Tierra del Fuego. González Guillot et al. (2018) reported new LA-ICP-MS zircon ages from ~71 to 75 Ma. It mainly comprises whitish colored rocks ranging from a gabbro/diorite to a monzodiorite composition, which outcrop in the northwest sector and dark grey rocks made of hornblendites and pyroxenites of coarse grain and dark green color that outcrop at the southeast, comprising an approximate area of 8 km^2 (González Guillot 2009).

Acevedo and González Guillot (2011) carried out geotechnical tests only on the hornblendita rock, which emerges in the area of Estancia Túnel, where the best exposures are located on the cliffs of the coast.

The hornblendite presents dark green to blackish colors, sometimes with brown dyes produced by weathering, or greenish by epidotization.

Under the petrographic microscope, the texture is always grainy and its lithological composition varies between ultramafic (ultramelanocratic) and leucocratic terms (Acevedo 1992, 1996).

The pluton is intruded in the metaturbidites of the Yahgán Formation, which have metamorphosed by thermal contact with the formation of stoves of biotite, garnet, cordierite, and alusite and sillimanite (González Guillot and Acevedo 2009). The recrystallization of the fit file has produced a very firm and compact rock of extreme hardness.

3.2 Dacites of the Ushuaia Peninsula

In the Ushuaia Peninsula, igneous rocks appear as small apophyses, dykes and ridges (Acevedo 1990; González Guillot et al. 2008). They are mainly exhibited on two quarry fronts (Fig. 2) near Ushuaia City Airport. They were used for the construction of the Bahía Encerrada rock embankment.

The main lithological types are andesites and dacites (geotechnical tests were performed on the latter). Other lithologies correspond to quartz melagabbros, granodiorites and lamphrophyres. They show subvolcanic textures and intrude on the slates of the Yahgán Formation and Plutón Ushuaia (González Guillot et al. 2011). González Guillot et al. (2018) obtained LA-ICP-MS zircon ages in andesite of 84 Ma.

Fig. 2 North (CN) and South (CS) quarries on the Ushuaia Peninsula

The andesites have porphyritic texture with plagioclase phenocrystals, hornblende and biotite. Plagioclase shows marked multiple zoning and polysynthetic twinning. The hornblende also has zonation and twinning. The groundmass is aphanitic, composed of quartz, alkali feldspar ± plagioclase and hornblende, in a felsitic texture (González Guillot et al. 2008).

The dacites have porphyric texture with plagioclase phenocrystals (oligoclase-andesine) and few k-feldspar, in a leucocratic paste of quartz and k-feldspar rich allanite. It also features hornblende xenocrystals (Acevedo 2006).

Alteration is not ubiquitous and affects mainly plagioclase phenocrysts of some samples. Replacement products are sericite or clay minerals, or carbonates plus sericite to a lesser extent. Hornblende phenocrysts and the groundmass are rarely altered. Mafic minerals are replaced by chlorite, tremolite and epidote (González Guillot et al. 2011).

3.3 The Granitoids of Cerro Jeu-Jepén

The Cerro Jeu-Jepén is located at the head of Fagnano Lake, 10 km south of Tolhuin town (Fig. 1). It consists mainly of black metapelites from the Beauvoir Formation whose age is attributed from the content of Inoceramus and Aucellina sp., to the Lower Cretaceous (Olivero et al. 1999).

Topographically, it is a medium height mountain (704 m a.s.l.). A composite stock dominated by monzonites crops out in the western face of Jeu-Jepén hill. This is a small stock of 1.5 km^2, where a quarry front has been opened (Fig. 3) for the exploitation of blocks of up to 20 tons of weight that were carried to La Mission cove, north of Rio Grande city to build the seawall of a future harbor (Acevedo and González Guillot 2011).

Fig. 3 Panoramic view (CNES/Airbus Satellite Image, recovered with Google Earth) of Aguas Blancas Quarry

The intrusive Jeu-Jepén is composed of pyroxenites, hornblendites, gabbro-diorites, monzodiorites, monzonites, sienites and lamprophyres. The ultramafic rocks are represented by small scales of about 20–30 m in length and by 5–20 cm autoliths immersed in diorites–gabbros and also in monzonites. This location and the intrusive of the Mount Kranck are the only ones where the monzonites dominate over the rest of the lithologies (González Guillot 2009). Detailed descriptions of these igneous bodies can be found in Acevedo et al. (2000, 2004) and González Guillot et al. (2012).

3.4 Intrusive of Mount Kranck

It is located on the north coast of Lake Fagnano. The only access way is by boat, sailing from a Naval Argentina station, located on the south coast of the Lake. It is an intrusive body of approximately 3 km^2, located on Mount Kranck, at 1100 m.s.n.m. This body made of pyroxenites, hornblendites, gabbro–diorites, monzodiorites, monzonites, sienites and posthumous lamprophyre dykes is hosted by the sedimentites of the Beauvoir Formation (Acevedo and González Guillot 2011). Geotechnical tests were only conducted on the diorite and sienite types.

3.5 *Moat Dioritic Pluton*

The Moat Dioritic pluton is the largest outcrop of plutonic rocks in Tierra del Fuego. It is located at the Sierra de Lucio López, 23 km NW of the Moat farmhouse, isolated by extensive peatlands so its access must be by helicopter from the south. It covers an area of about 25 km^2.

The Sierra Lucio López is a mountain with a NW–SE orientation and consists basically of three geological units, besides the intrusive body, corresponding to the Lemaire, Yahgán and Beauvoir Formations (Caminos et al. 1981; Olivero et al. 1999).

The intrusive pluton has a subcircular shape at its NW end (main body), from which two arms (called SW and NE) split to the SE, separated by a glacial valley and several peripheral apophyses. The most important is the one outcrop at the Mount Rojo, of 0.5 × 1.3 km (González Guillot et al. 2009).

The diorites and to a lesser extent gabbros are the most representative rocks of this body, although monzodiorites, monzogabbros, monzonites, sienites, hornblendites and pyroxenites are also found. Detailed descriptions of these rocks can be found in González Guillot (2009) and González Guillot et al. (2009).

The high sample mass required for geotechnical testing did not allow the minimum amount required for their treatment. The inaccessibility of this body postpones for now its detailed study and possible utility.

3.6 *The Lemaire Formation*

The Lemaire Formation conforms a submarine volcanic sedimentary complex that includes epiclastic rocks (originally, turbidites, conglomerates, chert, and black radiolarian and carbonaceous mudstones); acid volcanic and volcaniclastic rocks (rhyolitic lavas, pyroclastic flows, breccias, tuffs, and accretionary lapilli; subvolcanic quartz porphyries). Interbedded in this sequence appear basaltic rocks (Kranck 1932; Caminos 1980; Hanson and Wilson 1991; Olivero and Martinioni 1996; Olivero et al. 1997, 1999).

Geotechnical tests were performed on acid volcanic and basalt rocks.

Acid volcanics are leucocratic rocks, whitish to yellowish green, with porphyric texture, with small plagioclase and quartz phenocrystals. They are strongly deformed and present sericitic, chloritic, and pyritic alterations (Acevedo and González Guillot 2011).

The basaltic rocks have microgranular texture and amygdaloid structure, with voids filled by carbonates, chlorite and quartz. Under a petrographic microscope, it is visible that the rock is among the basaltic–andesite–diabasa types, with a color index of less than 40 so it could be classified as leucobasalt (Acevedo and González Guillot 2011). González Guillot et al. (2016) distinguish accordingly to their primary paragenesis: plagioclase pyroxene lavas and sills, plagioclase lavas and sills, and hornblende-bearing sills. The former two are intercalated in the Late Jurassic Lemaire Formation, but do not extend into overlying units (Yahgán and Beauvoir Formations).

3.7 The Slates of the Yahgán Formation

The Yahgán Formation is well exposed in the Hoste, Navarino, Nueva, Lennox and Picton Chilean Islands (Dott et al. 1977; Winn 1978; Suárez et al. 1985) and in Argentina, in Sierra de Sorondo, along the north coast of the Beagle Channel, from Ushuaia city to Sloggett Bay (Olivero and Martinioni 2001).

This unit comprises breccias and conglomerates, sandstones, sandy and silly turbidites, black tuffites and tuffs, intruded by basaltic rocks of Tholeitic—calcoalcaline affinities (Olivero and Malumián 2007).

Its use (like that of the volcanites of Lemaire Formation) as a building material in Ushuaia city began more than 30 years ago (Fig. 4).

The slates of Yahgán Formation have huge economic potential due to their high wear resistance and its large exposition in the Fuegian territory.

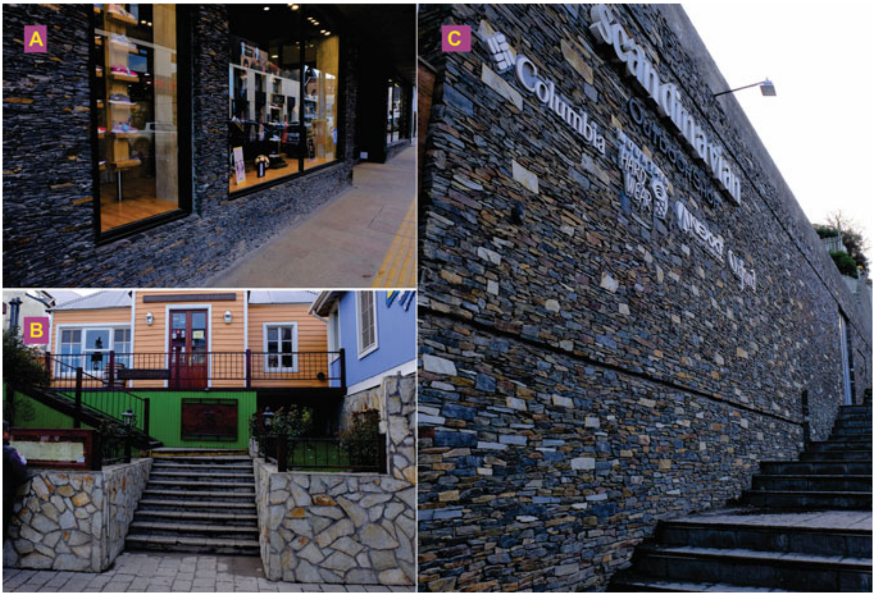

Fig. 4 Buildings located in the city center of Ushuaia, covered with **a** Yahgán Formation slates; **b** acidic volcanoes of Lemaire Fm; **c** Yahgán Fm. slates and volcanites of the Lemaire Fm

3.8 The Marine Tertiary Sandstones of the Steppe

Although they appear as the prevalent lithology of the island dominating the landscape of the steppe, this resource has not been used. Only sandstones extracted from the Don Bosco quarry, near La Mission cove were used for the construction of the breakwater core of Río Grande port. As it will be seen below, this lithology did not show good petrophysical results (high porosity and absorption) or mechanical (very low compression resistance), which constitutes its greatest demerit and determines its low unusefulness.

3.9 The Erratic Blocks of Granodioritic Composition of Punta Sinaí

In Punta Sinaí, east of Sara farmhouse, on the north of Tierra del Fuego Atlantic coast appear 200 huge erratic blocks (Fig. 5) of allochthonous origin that constitute a remarkable example of glacial accumulation from the Cordillera Darwin in Chile, transported along 150 km in NE direction, unloaded and weathered in the last half million years (Coronato et al. 1999).

The composition of these blocks is mainly granodioritic (quartz, k-feldspar, plagioclase and biotite) and has a grainy texture of coarse grain. The structure seems apparently massive and resilient. The rock highlights its beauty when polished (see Fig. 6f).

Acevedo and González Guillot (2011) recommend preserving these blocks since they represent a prominent landscape resource.

Fig. 5 Granodiorític erratic block on the beach of Sara farmhouse

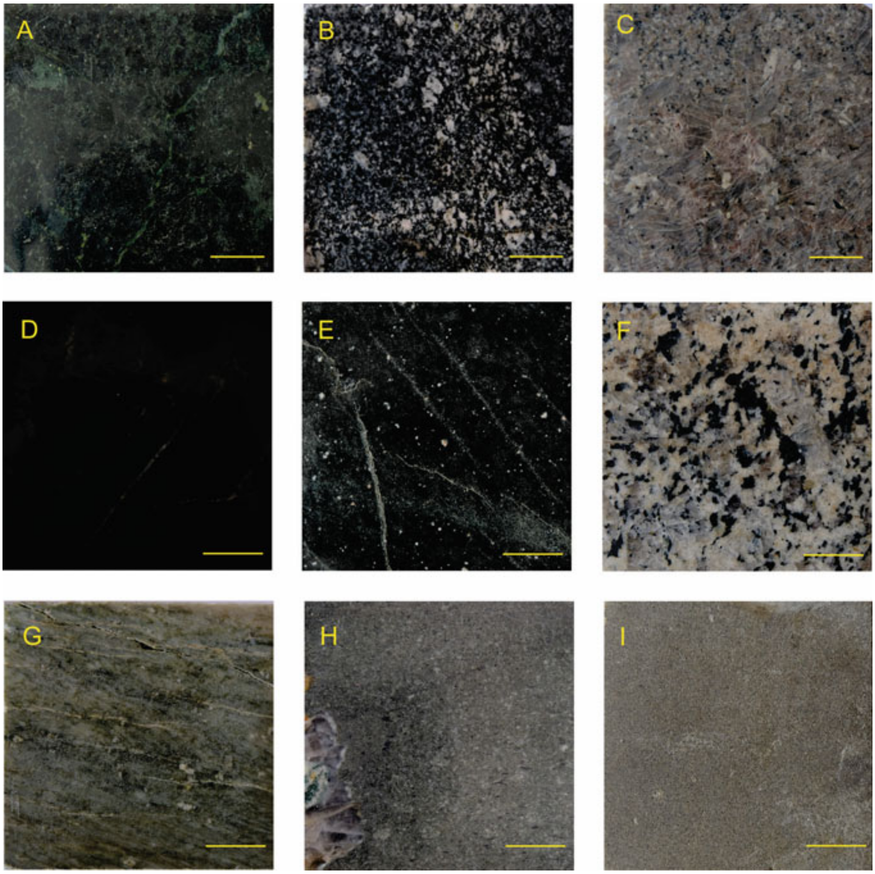

Fig. 6 Polished surfaces of the studied rocks. **a** hornblendite UP; **b** diorite-monzonite JJ; **c** syenite JJ; **d** hornfels JJ; **e** lamprophyre JJ; **f** granodiorite Punta Sinai; **g** acid volcanite Lemaire Fm; **h** basalt Lemaire Fm; **i** steppe marine sandstone. The reference bar corresponds to 1 cm

4 Petrophysical Results and Discussion

Ornamental use requires that the tested materials have certain technological characteristics that allow their application and guarantee their durability. The necessary tests to evaluate the ornamental features of a rock are defined according to the intended use. Table 1 shows the tests considered to be priority in relation to different applications, according to Frascá (2002).

Regarding the values of these properties, as reference, it is possible to cite the ranges consigned for some rocks marketed in the country, according to the Catálogo de Piedras Ornamentales Argentinas 2000 (De Maio et al. 2000). Thus, within the granitic rocks, the well-known variety Sierra Chica (Olavarría) has absorption values of 0.08–0.18%; density of 2.640–2.690 gr/cm^3; flexural strength of 8.3–12.0 Mpa

Table 1 Priority tests according to coating type (Frascá 2002)

Priority tests	Covering of					
	Floors		Wall		Facades	Countertops
	External	Internal	External	Internal		
Absorption	X	X	X	X	X	X
Porosity	X	X	X	X	X	X
Abrasion Resistance	X	X				
Flexural Strength	X	X			X	X
Compressive Strength	X		X	X	X	
Thermal Stresses	X	X	X	X	X	
Surface finishing	X	X			X	
Alterability	X	X			X	X

and compressive strength of 120.9–161.1 Mpa. In the field of ornamental volcanic rocks, we can mention the values given for some varieties of porphyry (produced in the Patagonian provinces of Argentina) those, according to the type, present porosity ranges from 0.68 to 3.67%; absorption from 0.25 to 2.19%; resistance to flexion from 8.9 to 23.9 MPa; resistance to compression from 98.8 MPa and resistance to abrasion from 0.51 to 1.44 mm × 1000 m.

For a preliminary evaluation of the ornamental aptitude of Fuegian rocks, physical properties (relative density, absorption and open porosity) and mechanical properties (resistance to flexion, compression and abrasion) were tested in order to consider the main requirements cited for the different uses. The results are shown in Tables 2 and 3.

As it can be seen, the type hornblendite, belonging to the Pluton Ushuaia showed the poorest technological data: high porosity and absorption, and low resistance to compression. The bending resistance test did not succeed due to the numerous veinlets that pass through the rock. However, these rocks possess a singular beauty when polished.

The granites of the Cerro Jeu-Jepén provided excellent results. Only the sienite registered a low resistance to compression and bending, possibly due to the foliated structure by localized deformation. It is important to highlight the seldom use of the hornfels, since being away from contact, it appears very dialist. The lamprophyre, which only comprises irregular dykes, also represents a limited resource.

The granite rocks of Mount Kranck are correlated with the monzonites and sienites of the Cerro Jeu-Jepén (Acevedo and González Guillot 2011). The physical and mechanical properties studied showed excellent results, however, their inaccessibility postpones effective use by the time-being.

The weathering that has been affecting the granodiorite blocks of Punta Sinai caused the physical–mechanical behavior of these rocks to have decreased. Also here it is recommended to preserve these erratic blocks as a provincial geological heritage of possible touristic activity.

Table 2 Results of the tests carried out on Fuegian igneous rocks

Technological tests	Ushuaia Pluton	Granitoids of Co. Jeu-Jepén				Kranck Pluton		Erratic blocks of Punta Sinaí
	Hornblendite	Diorite-Monzonites	Sienite	Lamprophyres	Hornfels	Diorite	Sienite	Granodiorite
Density gr/cm^3	3.23	2.85	2.89	2.8	2.39	3.07	2.64	2.91
Absorption %	0.46	0.16	0.58	0.12	0.13	0.26	0.41	0.72
Porosity %	1.46	0.45	1.67	0.34	0.33	0.8	1.07	2.08
Compressive Strength (Mpa)	70.51	131.21	87.23	146.54	177.2	208.44	211.83	77.38
Flexural Strength (Mpa)	N/D	25.92	10.39	23.44	44.43	ND	ND	7.88

ND, no data

Table 3 Results of the tests carried out in the Fuegian volcanic rocks

					Sedimentary rocks
Tests	Dacites of Ushuaia Peninsula.	Lemaire formation		Yahgán Formation	Steppe marine sandstones
		Basalts	Acidic porphyry volcanites	Slates	
Density gr/cm^3	2.83	2.79	2.96	ND	2.21
Absorption %	0.26	0.19	0.42	ND	9.5
Porosity %	0.73	0.51	1.24	ND	20.91
Compressive Strength (Mpa)	85.28	111.52	121.45	ND	27.96
Flexural Strength (Mpa)	9.76	25.31	ND	ND	ND
Abrasion Resistance (mm × 1000 m)	ND	2.01	ND	0,66	ND

ND, no data

The physical and mechanical properties of the Ushuaia Peninsula dacites and the basalts of the Lemaire Formation do not show great differences. Slates of the Yahgán Formation showed a high resistance to abrasion. Whereas the marine sandstones of the steppe yielded very poor results were observed.

Furthermore, in order to know the possibilities of surface finish of the Fuegian rocks, some mechanical polishing tests were carried out that revealed the surfaces and colors shown in Fig. 6.

Finally, in order to compare the values obtained with those published for other ornamental varieties marketed in Argentina, Table 4 contrasts the technological characteristics of samples from Cerro Jeu-Jepén with those of granite Rosa del Salto (produced in San Martín department, province of San Luis) and those of the Gris Mara variety (department of Punilla, Córdoba). In the first case, it is granite with porphyroid texture with megacrystals of k-feldspar, immersed in a quartz matrix, potassic feldspar, plagioclase, biotite and opaque minerals. The Gris Mara variety has a medium to fine granular texture, composed of quartz, orthose, biotite and plagioclase (De Maio et al. 2000).

The Fuegian volcanic rocks are comparable to the Porphyry Colum. It is a Patagonian basandesite of porphyric texture and gray color.

Table 4 Comparison of the technological characteristics of the studied rocks with commercial varieties of ornamental rocks from Argentina

Type of test	Granitoids of Co. Jeu-Jepén		Granito Rosa del Salto*	Granito Gris Mara*	Dacites of Ushuaia Peninsula	Basalts	Pórfido Colum*
	Diorite-Monzonite	Sienite					
Density gr/cm^3	2.85	2.89	2.61	2.63	2.83	2.79	2.34
Absorption %	0.16	0.58	0.20–0.30	0.31–0.40	0.26	0.19	2.19
Porosity %	0.45	1.67	0.35–0.52	0.30–0.80	0.73	0.51	3.67
Compressive Strength (Mpa)	131.21	87.23	ND	115–175	85.28	111.52	98.8
Flexural Strength (Mpa)	25.92	10.39	7–10.9	13.1–15.5	9.76	25.31	8.9
Abrasion Resistance (mm × 1000 m)	ND	ND	0.92–1.23	0.76–0.86	ND	2.01	1.44

*The values of commercial ornamental rocks were taken from the Catálogo de Piedras Ornamentales Argentinas 2000 (De Maio et al. 2000). ND, no data

5 Conclusions

This first contribution described the mineralogical and petrographic characteristics of the metamorphic igneous rock complex that are present in the Fuegian territory. These studies indicate preliminary features comparable in quality and aesthetics to the materials accepted as by the ornamental rock.

According to the results of the technological tests carried out, it can be concluded that the samples obtained on the Jeu-Jepén hill are those that have best responded to the physical and mechanical tests. In addition, all the rocks have acquired a particular beauty when being polished. Good quality and variety of ornamental rocks can be found in the Aguas Blancas quarry. In the plutonites of Monte Kranck, very good geotechnical results were obtained, however, the difficult accessibility prevents the exploitation of this resource.

On the other hand, the erratic blocks of Punta Sinai (σ_c 77 Mpa and σ_f 8 Mpa) and the hornblendite of Ushuaia Pluton (σ_c 85 Mpa and σ_f 10 Mpa) showed a poor mechanical resistance. The first ones attributed to the glacial meteorization to which they were subjected and the second ones due to fissure alteration.

The effusive rocks of the Lemaire Formation showed intermediate geotechnical indicators according to the state of alteration that they present. These rocks and slates of the Yahgán Formation showed a high resistance to abrasion. The marine sandstones of the steppe have shown a poor geotechnical behavior.

On the basic tests carried out, it can be concluded that the Isla Grande of Tierra del Fuego has igneous rocks suitable to be used as stone materials, especially for cladding walls and facades. However, the industrial studies and tests must be enhanced, with the application of modern technologies, to achieve an appropriate product with a surface finish according to the material, and with commercial possibilities of great importance at a regional or national level.

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Aggregates in Tierra del Fuego: Morphogenesis and Distribution

Juan Federico Ponce, Andrea Coronato, Diego Quiroga, Alejandro Montes, Luis Díaz Balocchi, and Mariana Vargas

Abstract This chapter presents a morphogenetic characterization and a distribution map of the main Quaternary sedimentary deposits in the argentine sector of Tierra del Fuego with potential for the exploitation of aggregates, classified according to large morphogenetic units. These deposits result from the intense glacial and glaciofluvial activity developed in a large part of the Isla Grande de Tierra del Fuego during the different Pleistocene glaciations and the coastal processes developed during the Pleistocene and Holocene interglacial periods. The morphogenetic units identified with potential for the extraction of aggregates are glaciofluvial plains and terraces, glaciofluvial fans, kame terraces and kame hills, kame deltas and sandy gravel beach ridges. Most of these deposits are concentrated in the northern part of the island, between the Lake Fagnano and San Sebastián Bay. This is due to the great development of the glaciofluvial systems during each of the glacial events and due to the morphodynamic characteristics of this sector of the Atlantic coast, which allowed the formation of a large number of sandy gravel beach ridge plains during the interglacial events.

Keywords Aggregates · Landforms · Sedimentology

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1 Introduction

The term “aggregate” is used in the field of construction and civil engineering to designate a rock or sediment, which is used for multiple applications, after an industrial treatment process. The treatment processes include a simple classification by size, in the case of sediments, or crushing, grinding and classification, in the case of rocks. The use of aggregates includes from concrete production, together with a binding material (portland cement, hydraulic lime, gypsum, tar, etc.), asphalt mortars and agglomerates, to the construction of bases and subbases for roads, ballasts and subballasts for railroad tracks, or breakwaters for the defence and construction of seaports (Suarez and Camacho 2017). The Mining Code of Argentina classifies aggregates as minerals of the third category and regulates their exploitation.

The landscape of the Argentine sector of Tierra del Fuego can be divided into two main regions: the Fuegian Andes in the south and the high plains toward the north (Fig. 1). The Fuegian Andes make up a mountain system with an E–W orientation in the south and a NW–SE in the center to northwest of the Isla Grande de Tierra del Fuego (Fig. 1). The argentine sector is mainly formed by metasedimentites and metavulcanites of the Jurassic-Cretaceous age (Olivero and Malumian 2008). The landscape of the northern high plains shows low, soft, rounded and plateau-shaped hills highly dissected and separated by depressions or pans of different extensions,

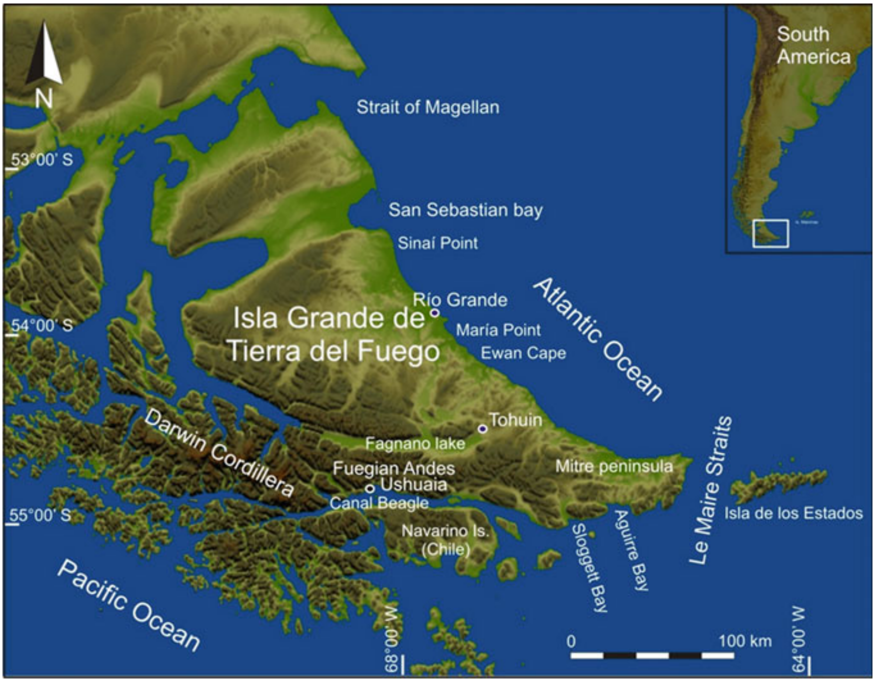

Fig. 1 Map location of Isla Grande de Tierra del Fuego

in many cases, constituted by ancient valleys of glacio-fluvial origin. This landscape was generated mainly on very friable marine sedimentary rocks of the Neogene. Most of them are mudstones, silty–claystone, sandstones and conglomerates (Olivero and Malumian 2008).

Sedimentary deposits with extractive potential for exploitation for aggregates in Tierra del Fuego are mostly sediments in which origin is associated with the presence of a large number of glacial events during the last million years. They are mainly fluvial paleoenvironments located principally in the northern sector and associated with the melting of glaciers during glaciations and with gravel beach ridges of Pleistocene and Holocene ages above the current sea level, generated by the relative sea level rise after the glaciations.

2 Glaciations and Interglacial Periods in Tierra Del Fuego

At least five glaciations, which occurred during the last million years, have been recognized in the north sector of the Isla Grande de Tierra del Fuego (Meglioli et al. 1990; Rabassa et al. 2000; Quiroga 2018) and at least the last two along the Beagle Channel (Rabassa et al. 2000). In each of these glaciations, several glaciers from the ice field of the Darwin Mountain Range (2,000 m a.s.l. Fig. 1) flowed north and eastward of the Isla Grande de Tierra del Fuego, reaching the current atlantic continental shelf (Porter 1990; Meglioli et al. 1990, Rabassa et al. 2000), along wide and deep valleys currently known as the Magellan Straits, Inútil Bay-San Sebastián Bay, Fagnano Lake, Carbajal-Lasifashaj Valley and the Beagle Channel (Figs. 1 and 2). Each of these glaciations was accompanied by a significant decrease in the sea level of the order of 100 m below the current sea level. Associated with these

Fig. 2 Tierra del Fuego during the Last Glacial Maximum (modified from Ponce and Rabassa 2012)

glaciers, extensive fluvial systems, which drained the meltwater into the Atlantic Ocean with an important sediment load of varied granulometry, were developed. In these fluvial systems, different sedimentation environments and landforms occurred, which constitute the main deposits with potential for the extraction of aggregates in Tierra del Fuego. These landforms include: glacio-fluvial plains, terraces and kame deltas, kames and kettles, glaciofluvial fans and glaciofluvial terraces.

The sedimentary deposits and landforms corresponding to the oldest glaciations are found mainly at the northern end of Tierra del Fuego and are associated with the glacial lobes of the Inutil Bay-San Sebastián Bay and Magellan Straits.

As a counterpart, the interglacial periods are related with high sea levels and warm climate conditions (Zazo 1999). The main landforms that indicate interglacial sea-level highstand periods are marine terraces, generally located in areas near the current coast (Murray-Wallace 2002). The marine terraces in paraglacial coastal areas are composed by gravel-dominated raised beaches (Ordford et al. 2002). Pleistocene-raised beaches occur in the north Atlantic coast of Isla Grande de Tierra del Fuego, along 100 km between Sinaí Point and Ewan Cape (Fig. 1).

In the Isla Grande de Tierra del Fuego, the surface covered by ice during the Last Glacial Maximum (LGM, 24000 cal yr BP; Rabassa 2008) was close to 50% (approximately 22,500 km^2) (Fig. 2). During the Last Glaciation, the sea level dropped to − 120 m approximately. As a result of this global decrease in the sea level, the Atlantic coast line of Tierra del Fuego was about 200 km east of its current position and an extensive coastal plain developed when part of the continental shelf emerged (Ponce et al. 2011).

The increase in temperature after the LGM caused a general retreat of the glaciers and the consequent rise in sea level on a global scale. The current configuration of the Atlantic coastline of Tierra del Fuego was made up around 8000–9000 cal yr BP. (Bujalesky et al. 2001; Bujalesky 2007; Ponce et al. 2011). A transgressive event is recorded on southern Isla Grande de Tierra del Fuego during the early middle Holocene with a maximum around 6,000 cal yr BP (Rabassa et al. 1986; Gordillo et al. 1993). After this event, a series of raised and regressive gravel beach ridges were deposited at different levels along almost the entire coast of the Beagle Channel and the Atlantic coast of Isla Grande de Tierra del Fuego (Bujalesky and Isla 2005; Montes 2015; Montes and Martinioni 2017; Montes et al. 2018).

3 Aggregates and Relief

Regardless of their classification by shape, size, materials, etc., aggregates are part of the deposits, which form certain landforms, resulting from the modeling processes of the relief.

3.1 Landforms and Deposits of Glacial and Glacio-Fluvial Origin

Among the modeling processes of glacial origin, the deposition of sediments transported by water currents, which evacuate the melting water of the ice bodies should be mentioned (Fig. 3).

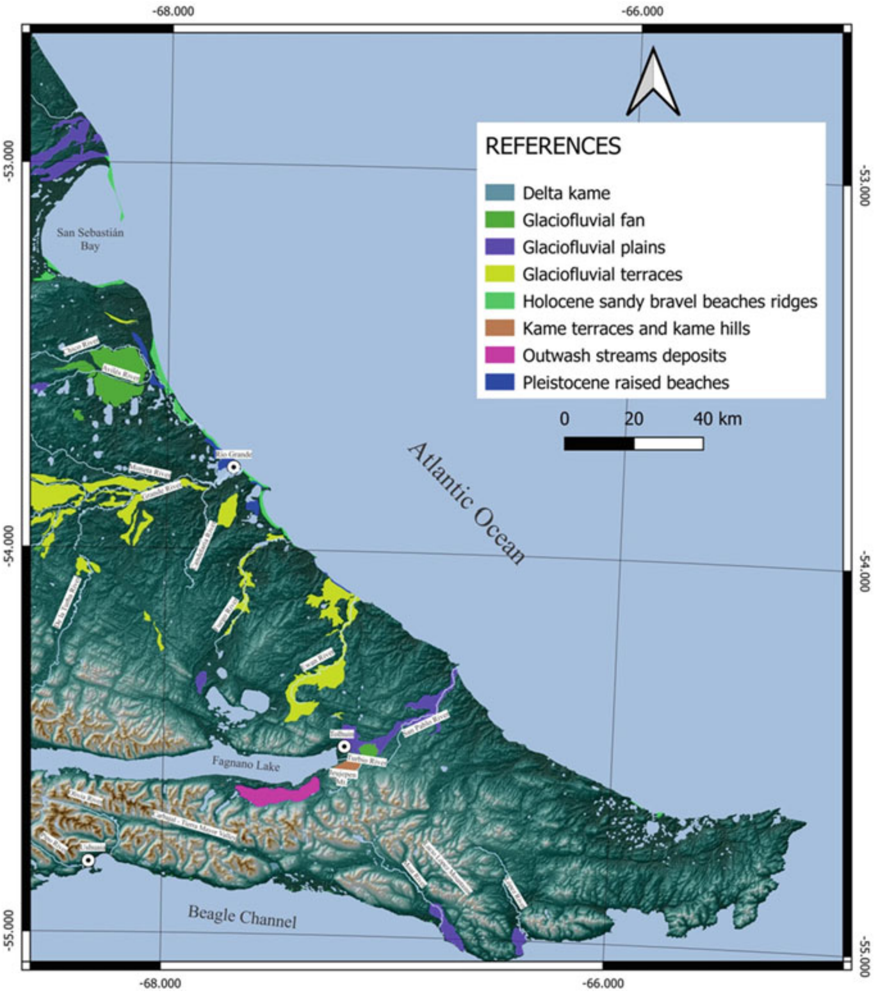

Fig. 3 Morphogenetic units in the argentine sector of Tierra del Fuego with potential for the exploitation of aggregates

3.1.1 Plains, Glaciofluvial Terraces and Outwash Streams Deposits

They are surfaces with very low or no slope, arranged throughout the valleys. The former occupies the lowlands along the bottoms of valleys and correspond to old floodplains, including bottom deposits of channels and different types of fluvial bars. Glaciofluvial terraces are old floodplains elevated by the progressive downcutting of a river channel forming stepped slopes in a wide valley previously modeled by glacial action. This morphogenetic unit represents the most extended deposits with potential for the exploitation of aggregates in the argentine sector of Isla Grande de Tierra del Fuego covering a total area of approximately 1100 km^2 (Fig. 1 and Table 1).

The sediment that constitutes them is mainly made up by gravel of different sizes alternated with sand strata; in general, it is thick and arranged in parallel or cross-bedding, forming old fluvial bars. The availability of the materials of sand or gravel size depends on the distance of the deposit from the ice body, which gave rise to the water course, on the speed of the water, the conditions of competition and transport capacity, usually conditioned by seasonal water variations.

In Tierra del Fuego, the most developed glaciofluvial plains extend east of the Fagnano Lake (Fig. 3), with an elevation of 100 m above the lake level (Coronato et al. 2002). These deposits were used as a quarry for road and urban infrastructure locally and in the area of Ushuaia (Fig. 4a). Moreover, most of the tributary rivers, which make up sub-basins of the Grande River, and those which flow into the Atlantic Ocean (Fuego, Ewan, San Pablo) formed their current course and associated landforms on extensive glaciofluvial plains, which were formed on the fronts of the existing glaciers during the Pleistocene glaciations (Fig. 3). Toward the southeast, the gravel deposits of the glaciofluvial plains of López River, Sloggett Bay and of the Aguirre Bay (Figs. 1 and 3) are remarkable.

Toward the north of the San Sebastián Bay, facies associated with Quaternary glaciofluvial plains are found in the sedimentary record (Fig. 3). These deposits

Table 1 Total area and aggregate composition of the main morphogenetic units with potential for the exploitation of aggregates

Morphogenetic units	Total área (km^2)	Aggregate type
Kame delta	5.5	Garvel and sand
Glaciofluvial fan	249.1	Gravel and sand
Glaciofluvial plains	470.2	Mainly gravel
Glaciofluvial terraces	622.0	Mainly gravel
Holocene sandy gravel beach ridges	93.0	Mainly gravel
Kame terraces and kame hills	20.9	Sand and gravel
Outwash streams deposits	91.8	Gavel and sand
Pleistocene raised beaches	40.5	Mainly gravel

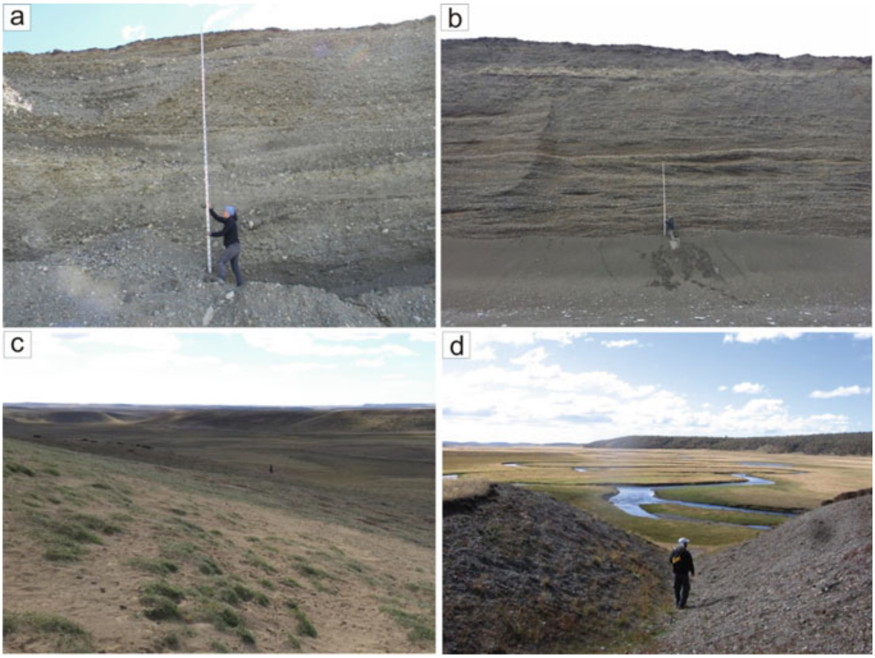

Fig. 4 **a** Glaciofluvial plain located at the east of Fagnano Lake; **b** Glaciofluvial deposits north of San Sebastian Bay, in marine cliffs of the Atlantic coast; **c** Fluvial terraces of Candelaria River; **d** Ewan River. See Fig. 3 for location

appear in subhorizontal strata of 5–15 m thicknesses, with lateral continuity over several kilometers, showing their formation in outwash plains that occupied large areas (Fig. 4b). The granulometry is predominantly gravel (pebbles and cobbles) with moderate to good selection and massive or stratified structure, occasionally alternated with lenticular banks of coarse sand and gravelly coarse sand. The exploitation of these materials is possible through quarries, which take advantage of the exposures in natural outcrops within incised valleys and coastal cliffs. These aggregates have already been used in road and civil construction related to the oil activity in the northern sector of Tierra del Fuego.

The main glaciofluvial terraces in Tierra del Fuego are distributed along the Candelaria (Fig. 4c), Fuego, Ewan (Fig. 4d) (Coronato et al. 2008), Cullen, Bella Vista, De la Turba, Onas, Candelaria, Herminita, Moneta and Grande rivers (Fig. 3). They are between 10 and 30 m above the current floodplains. The heterogeneity of the component materials is similar to that of the glaciofluvial plains since the depositional processes are practically the same (Fig. 4).

Outwash stream deposits are located along the south coast of the east sector of Fagnano Lake, at the foot of the northern slope of the Lucio Lopez Range (Fig. 3). They are confined between lateral morainic complex and ground moraines. The sediment that constitutes them is mainly sand and gravel of different sizes. They were deposited by melting water streams from Fagnano Lake paloeglacier and tributaries glacier located in the Lucio Lopez Range (Coronato et al. 2009).

3.1.2 Glaciofluvial Fans

They are landforms of low to medium slope, with triangular-shaped form (in plan view) and a well-defined apex and distal areas. Its sedimentological composition is based on sediments, which decrease distally in grain size. However, the alternation between gravelly coarse and sandy strata is recurrent across and throughout the landforms. The glaciofluvial condition is given by the glacial origin of the distributary streams forming the fan. They are generated from anastomosing or braided multichannel currents.

In the north of Tierra del Fuego, in the interfluve of the Chico and Avilés rivers (Fig. 3) an extensive glacio-fluvial fan extents from the upper basin of the Chico River (Bujalesky et al. 2001), close to the Sierras del Bosque Range, up to the vicinity of the Atlantic coast. Its origin is attributed to the discharge of melting water from glaciers, which occupied the northwestern area of Tierra del Fuego during the Middle Pleistocene glaciations (Bujalesky et al. 2001; Quiroga 2018). Figure 5a shows its

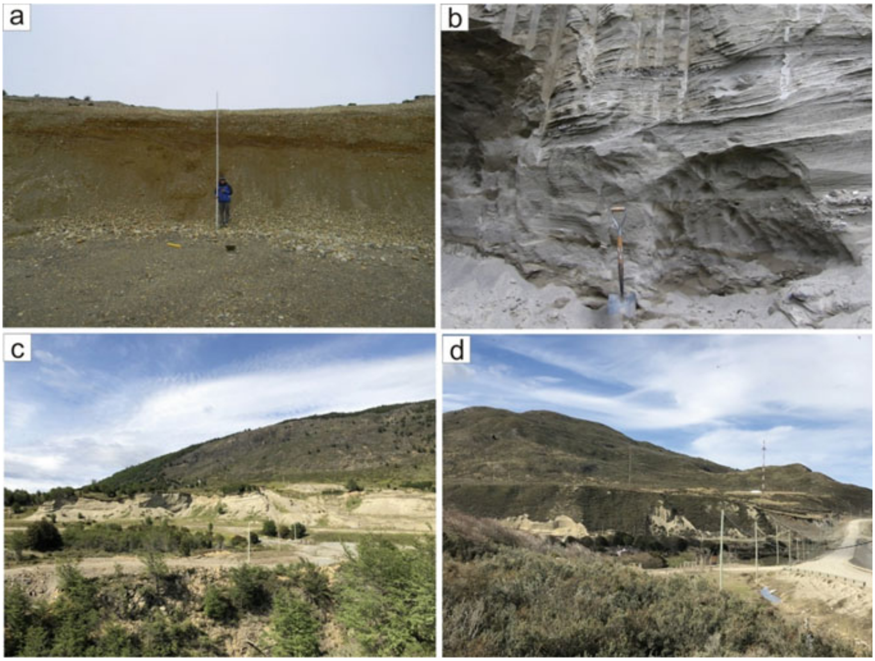

Fig. 5 **a** Glaciofluvial fan deposits in the north of Tierra del Fuego, in the interfluve area between Chico and Avilés rivers; **b** Sandy kame deposits located east of Fagnano Lake; **c** Kame terrace at Pipo River Valley; **d** Ancient kame delta of the Olivia River

sedimentological composition in proximity to the distal area. In general, medium to coarse gravel strata in a sandy matrix predominate, with cross-bedding structures. Some part of this deposit is being used as a quarry for road maintenance.

Another glaciofluvial fan with potential for the extraction of aggregates is also observed along the first kilometers of the Provincial Route 23, west of the crossing of the San Pablo River, where the fan of the Turbio paleoriver is located (Fig. 3). It was developed on the aforementioned glaciofluvial plain when, after the Last Pleistocene Glaciation, the Turbio River drained the melting water from the northern slope of the Lucio López mountain front (Fig. 3) to the Atlantic Ocean through the current San Pablo River basin. The decrease in the general slope of the land, resulting from the presence of the aforementioned glaciofluvial plain, caused the deposition of material from an apex formed at the foot of the mountain front (Coronato et al. 2002, 2009; Onorato 2018). The surface of the fan is dissected by several paleochannels, which are nonfunctional nowadays, giving the appearance of an altitudinal terrace-like surface descending toward the north. The deposit of the paleochannels and the terraces were both used as quarries for road and infrastructure construction.

3.1.3 Kames and Kettles

These landforms are typical of glacial melting environments, close to the front of the ice. It is a landscape constituted by low hills and depressions generated when stagnant ice blocks are completely or partially buried by glaciofluvial sediments and finally, they melt, leaving holes in the areas near to the ice of the glaciofluvial plain. This type of landscape is typical of the central area of Tierra del Fuego, along the National Route 3, near the town of Tolhuin (Figs. 1 and 3). They are low elevations interspersed with depressions, occupied by ponds and/or peat bogs nowadays. The hills are made up by gravel accumulations of different sizes, as a result of the deposition of the material which was transported from the front of the paleoglacier in Fagnano Lake, when its frontal position was located in Tolhuin town and from there, it produced large dead or stagnant ice blocks, disconnected from the glacier ice front (Coronato et al. 2009). These ice blocks were surrounded and/or buried by water currents with abundant sedimentary load which drained into the glacier during deglaciation. Depressions are the morphological result of collapses or total melting of the ice blocks while the hills are the result of the deposition of glacio-fluvial sediments generated by glacial melting currents, relatively high when the ice blocks disappeared (Fig. 6a).

3.1.4 Kame Terraces and Kame Hills

The kame terraces result from the deposition of sedimentary load of melting water in contact with glacial ice. The deposit occurs in areas of contact between the margins of the glacier and the rocky or morainic slopes previously formed. The deposition in these environments gives rise to terrace-like landforms (Fig. 6b) made up of medium to coarse gravels interspersed with sands.

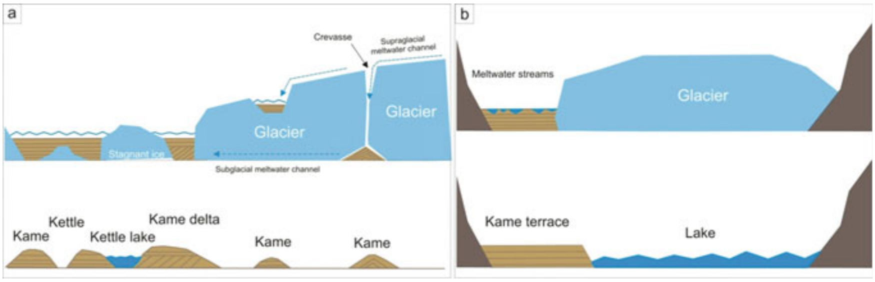

Fig. 6 Ice contact landforms formation: **a** kettles, kettle lakes and kames, **b** Kame terraces

The kame hills are small low hills generated by the deposition of sediments by melting water currents, which flow on the surface of the glacier. The sediments transported by these waters are usually of sand size (Fig. 5b) and their deposition occurs in depressions and cracks (creavesses) on the surface of the glacier (Fig. 6a). Although the presence of running water determines the laminar bedding, even having different grain sizes, the contact with ice determines the presence of large blocks and collapsing structures.

In the center of Tierra del Fuego, the development of kame terraces that make up the plains among the slopes of the Jeujepen Mt., Fagnano Lake and the surrounding fluvial valleys is significant. This deposit is at a maximum height of 200 m and covers an area of around 20 km^2. Nevertheless, kame terraces and hills are found along the Pipo River Valley (Coronato 1994), in the south of Tierra del Fuego (Figs. 3 and 5c). These were the source of construction material, which allowed the urban development of the Ushuaia city in the 1980s. Another example is the kame of the Grande Creek paleostream, which was built at the foot of the southern slope of the Cortéz Mt. (Coronato 1994) and used as a source of asphalt manufacturing material for Ushuaia in the 1990s. This type of landform does not have large dimensions in areas of alpine-type glaciations, in which glaciers flow in confined mountain valleys.

3.1.5 Kame Delta

The deposition of sedimentary load by glacial melting water in proglacial lakes with calm water causes the development of deltaic structures with high particle size variability ranging from gravels to fine sand and silt. These deposits are generated in contact with ice. As the glacier disappears, the topography of a gentle or plain slope, delimited by steep slopes upstream of the reservoir, appears. An example of this type of aggregate reservoir is the ancient delta of the Olivia River, with an elevation of 50 m above the current valley, which has been a source of sand and gravel for construction for several decades (Fig. 5d). Another important kame delta is located in the confluence of Carbajal-Lasifashaj and Canal Beagle valleys (Ponce et al. 2019 in press, Fig. 3). This landform presents a surface of 4 km^2 and is composed by sand and gravel of different sizes.

3.2 Landforms and Deposits of Marine Origin

Among the landforms that contain deposits with potential for the extraction of aggregates, it should be mentioned those ones resulting from the modeling processes caused by the action of waves in coastal areas, during interglacial periods in which the sea level was higher than the current one. The main marine landforms in glaciated mid- and high-latitude coastal areas are constituted by sandy gravel beach ridge plains, barriers and spits (Orford et al. 2002). These deposits are extensive in the adjacent areas to the current coast of the northern sector of Isla Grande de Tierra del Fuego (Bujalesky and Isla 2004, Bujalesky 2007, Montes et al. 2018). The different sea level highstands allowed the growth of these coastal landforms during the Pleistocene and Holocene.

3.2.1 Pleistocene Raised Beaches

The best example of deposits corresponding to raised beaches is La Sara Formation (Codignotto 1979). These deposits found mainly in the northern sector of Tierra del Fuego, adjacent to the current coast, along 100 km between Sinaí Point and Ewan Cape (Bujalesky 2007) (Figs. 1 and 3). They are old sandy gravel beaches elevated 7–8 m above the current sea level, together they make smoothly wavy to flat surfaces. The eastern margin of these deposits is an erosive escarpment, which was active during the maximum of the Holocene transgression (Montes 2015). These deposits are made up of medium to coarse gravel strata with planar cross-stratification, with very discoidal imbricated pebbles (Fig. 7a), with low angle inclination toward the sea (Bujalesky and Isla 2006).

3.2.2 Holocene Sandy Gravel Beach Ridges

Sandy gravel beach ridge plains and barrier spits are common geomorphological features of medium- to high-latitude coasts, where waves reworking alongshore heterogeneous glaciogenic deposits and previous coastal sediments are the main source of sediment supply (Isla and Bujalesky 2000). They are landforms with the appearance of rounded and low ridges, of great lateral continuity, arranged in parallel with each other. They consist mainly of gravels of different sizes and coarse sands. They are produced by the action of waves in old beaches corresponding to a sea level above the current one. Many of these landforms were generated during the regressive phase after the transgressive maximum of the middle Holocene. In Tierra del Fuego, these landforms are distributed in groups along old sea entrances, mainly in the northern sector of the Fuegian Atlantic coast, from María Point (Fig. 1) to the northern end of San Sebastián Bay (Bujalesky 2007, Fig. 3). The groups of sandy gravel beach ridges are arranged between the current coastline and up to 2.5 km inland, at a height which varies between the current sea level and 1–3 m. In this

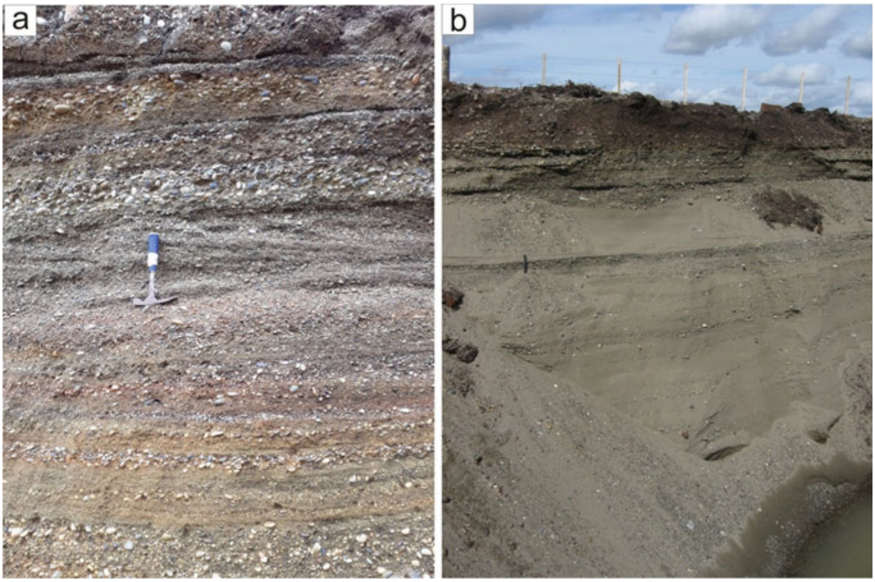

Fig. 7 **a** Pleistocene raised beach sediments composed of alternation of gravel in sand matrix strata and poorly sorted sand strata, La Sara formation; **b** Holocene sandy gravel beach ridges deposits at Río Chico locality, composed of alternation of pebbles in coarse sand matrix strata and poorly sorted sand strata

sector of Tierra del Fuego, these landforms cover an area of 93 km^2 (Table 1). A typical sedimentological exposure of beach ridge deposits consists of parallel-bedded sediments composed of alternation of pebbles in coarse sand matrix strata and poorly sorted sand strata (Fig. 7b). Strata range in thickness is 2–15 cm (Montes et al. 2018).

4 Final Remarks

The existence of aggregates in the argentine sector of the Isla Grande Tierra del Fuego is the result of several factors, which contributed to the current surface modeling. The availability of conglomerate sedimentary levels in the upper strata of sedimentary sequences of Miocene age, the repeated action of outlet and alpine-type glaciers, which eroded the Fuegian Andes and the folded belt hills, the genesis of the landforms of glaciofluvial and glacial accumulation with a high content of gravels and sands, and the repeated ingression of the sea into the current island interior, are the main factors which contributed to the current availability of these resources. Some fluvial valleys and depressed areas covered by peat bogs may also be still unknown reservoirs of gravel and sand sedimentary sequences.

The distribution of the resource is uneven. In the central and northern areas of Tierra del Fuego, there is a greater availability of landforms made up of gravel and sand, mainly, due to the extensive development of glacio-fluvial systems associated with Pleistocene glaciations and with the geomorphological characteristics of the coasts, which allowed a greater influence of transgressive-regressive events. However, in the southern mountainous area, the development of predominantly glacial erosive modeling processes was favored due to the proximity of the sources of accumulation of the glacial bodies and, in addition, the lower development of the marine coast.

The current knowledge about the potential and sedimentological characteristics of landforms described in the present study is still too scarce to evaluate the possibilities and advantages of their exploitation as aggregate quarries. Nevertheless, it is necessary to state that every mining action on these landforms and deposits requires environmental assessment, which takes into account the relation between geoconservation and economic exploitation, as well as the effective establishment of mitigation measures for environmental problems and landscape changes which arise after exploitation. Examples of deterioration of the landscape scenic beauty are frequent in the vicinity of the cities and along the National Route 3, among others, due to the abandonment of quarries without remedial actions. On the contrary, the landfills made for readaptation in urban, sports and recreational grounds in Ushuaia city are good examples of restoiration.

Finally, the extraction of sediments in coastal areas changes the beach dynamic promoting erosive processes along the coastlines. For that reason, environmental impact assessments that include coastal geomorphological studies are absolutely necessary when material extractions are carried out in deposits and landforms of current coastal areas. In addition, it should be noted the importance of archaeological impact studies when material extractions are carried out in these landforms, since these environments were widely used by marine hunter gatherers groups during the last 6,000 years and they contain valuable archaeological information in its surface.

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Didactic Tools in the Scope of Physical Geography in the Provincia de Tierra Del Fuego

Francisco Javier Labate

Abstract The current paper reviews the origins of General Didactics, its essence, as regard teaching, in order to deal specifically with didactics of Physical Geography. In the Provincia de Tierra del Fuego the "image" and "field trips" are particularly analyzed as privileged didactic resources in the training of future teachers of Physical Geography. The image has the ability to summarize a concept. Therefore, it is considered a powerful resource for teaching, which implies, like in any other decision in the field of education, an ethical positioning. The field trips allow an experiential connection between the environment and the man who inhabits it, making an indelible mark on both teachers and students alike. In that sense, Tierra del Fuego is a source of endless changing landscapes.

Keyword General didactics · Physical geography

1 Introduction

In principle, and as an introduction to the field, I would like to present Didactics as a scientific pedagogical discipline devoted to the study of and the intervention in the processes of teaching and learning.

Etymologically, Didactics comes from the Greek word "*didaktikós*", which means "in connection or belonging to teaching."

The Didactic Magna by John Amos Comenius, subtitled Universal Treaty on the Art of Teaching, published in 1657, proposes "to reform all issues of mankind through education" (Comenius 1959:97), posing since then a genuine concern as a response to the need to systematize education by proposing an educational reform in Bohemia, and thus establishing the foundations of systematic pedagogy.

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Although it is true that the teaching of Physical Geography has been affected by a stage of profound transformations, these changes and the consideration of some fundamental questions in connection to geographic knowledge and its teaching affect several sciences and particularly question the teaching in secondary schools in Latin America. The teaching of Physical Geography involves extensive knowledge, know-how, strategies, resources, competencies and skills, typical of a geographer, characterized by the complexity, and the dynamism of the phenomena, which involves the ordinary man and its relationship with the surrounding environment.

Paraphrasing Mastache (1998:15) "… The construction of any special didactics must take into account the philosophical characteristics of the corresponding particular science… "

The positioning of didactics in Physical Geography, thus implies, an ethical decision, and a philosophical posture, by virtue of its essential features as part of Geography: a social science. Geographical knowledge is gained together with someone else, and the didactics of Physical Geography takes into account the other like the recipient of teaching. Working for "the other," who learns from their own frames of reference, positions us as teachers ethically. This "other" is a different social subject, who is subjected to vertiginous changes, manages a volume of information and has access to media and information technology which was unthinkable 20 or 30 years ago.

These lines, therefore, will attempt to develop some of the didactic tools, deployed and used for 4 years in teaching training in the field of Physical Geography at the Provincial Institute of Higher Education IPES "Florentino Ameghino," in the city of Ushuaia, Tierra del Fuego, and will also encourage an open reflection on this teaching practice. Constantly thinking and reflecting on this positioning of Physical Geography as science and the role that the didactics of geography plays.

"What is that big book?" said the little prince."What are you doing?"

"I am a geographer," the old gentleman said to him.

"What is a geographer?" asked the little prince.

"A geographer is a scholar who knows the location of all the seas, rivers, towns, mountains, and deserts."

"That is very interesting," said the little prince. "Here at last is a man who has a real profession!" And he cast a look around him at the planet of the geographer. It was the most magnificent and stately planet that he had ever seen.

"Your planet is very beautiful," he said. "Has it any oceans?"

"I couldn't tell you," said the geographer.

"Ah!" The little prince was disappointed. "Has it any mountains?"

"I couldn't tell you," said the geographer.

"And towns, and rivers, and deserts?"

"I couldn't tell you that, either."

"But you are a geographer!"

"Exactly," the geographer said. "But I am not an explorer. I haven't a single explorer on my planet. It is not the geographer who goes out to count the towns, the rivers, the mountains, the seas, the oceans, and the deserts. The geographer is much too important to go loafing

> about. He does not leave his desk. But he receives the explorers in his study. He asks them questions, and he notes down what they recall of their travels. And if the recollections of any one among them seem interesting to him, the geographer orders an inquiry into that explorer's moral character."
>
> "Why is that?" "Because an explorer who told lies would bring disaster on the books of the geographer."

By going over this quotation from "The Little Prince" by Antoine de Saint-Exupéry, we are exposed to the candid gaze of the little prince before the "wise geographer" and some certain but rigid paradigms of the past (not yet surpassed, though). It makes us reflect upon current Geography, which is expected to respond to a demand with strong social connotations such as climate change, poverty, overpopulation, inequality, sustainable development, access to safe water, use of agrochemical sand, genetically modified organisms, mega mining. All of these issues are directly linked to the didactic positioning adopted, which necessarily involves an ethical positioning as regard these issues not only before our students but also ourselves.

2 Ancient Dilemmas: Physical Geography Versus Human Geography

2.1 General Versus Specific Didactics

This old dilemma is presented to students as a duality. It is the first dilemma that the students of Geography face on an attempt to investigate: what is this confrontation about and who wins, in case there is a winner, what is more important: the mountains, the rivers, the conformation of landscape, the climate? or is it globalization, migration, exclusion of poverty, country blocs or neoliberal policies? It is still a much greater and more complex issue: it is the interaction of the social man with the environment that surrounds him, where the man and the society that conforms is the center. That is why Geography is in essence a social science. Should the mountain be considered as landscape, obstacle for communications, mining resource or housing? What use of the mountain will the man consider? What is the relationship that the man has with the mountain?

Furthermore, Pagés (2002) wonders what the nature of didactic knowledge is. Paraphrasing the response and applying it in the field of the didactics of Geography it can be said that "it is specific knowledge, which comes from a social practice (the teaching of Geography) where disciplinary, sociological, anthropological, epistemological, and psycho pedagogical knowledge takes place" (Insaurralde 2009 p. 95).

As regard the second dilemma, general versus specific didactics, it could be said that the great development registered in specific didactics in recent years has tensed its relationship as general didactics generated a "progressive alienation" between both of them.

Alicia Camilloni (2007:37) reconciles these differences by stating "…the relationship between general didactics and specific didactics is complex and that the reciprocal fertilizations are necessary for general didactics and for specific didactics of the disciplines, levels, ages and different types of subjects and educational institutions." The contributions are significant and the interrelationships are fertile, therefore for all. General didactics cannot replace specific didactics, or the other way about.

2.2 The Image as a Didactic Tool in Geography

As geographers and professors in Geography we have developed our professional field around the image and the practices linked to the complex lattice of the visual. It is important to consider that the landscape is the visible, perceivable aspect of the geographical space, and it constitutes the primordial scenic framework of Geography.

The selection, acquisition, production and management of the image become a primary competence to develop in the teachers of Geography, when it is necessary to select, prioritize and use didactic resources suitable for the construction of geographic knowledge classes. The enormous profusion of images and their availability is a typical trait of nowadays. It is attributed to an old Chinese proverb, the phrase "an image is worth more than a thousand words." The image works as a synthesis of information; it has a great explanatory power, in particular those schemes which, in addition to the location of the elements, indicate the direction of the movements, and the causes of the system of forces at stake. For example, this is the case of the movement of the tectonic plates or the subduction margin of the Pacific coast of South America (Fig. 1).

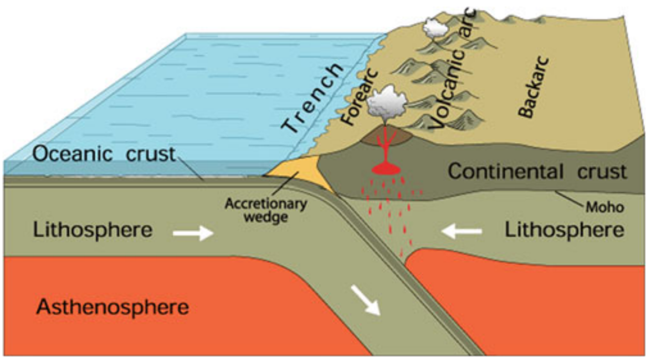

Fig. 1 Block diagram of the subduction margin of the Pacific coast of South America Credit: (USGS) United State Geological Service

3 Image Origin

The educational potential of a picture, together with the explanation provided by the teacher tend to be enough for a thorough understanding of the phenomenon. Otherwise the phenomenon would pass unnoticed and its transmission would be difficult.

Like other resources, it is important to know how the image was taken, (the source), in what circumstances and what was the intention or framework in which the author took it, the intention linked to his cosmography. We know that the impact it will cause may differ greatly from that originally and intentionally sought, (even opposed to the original), given that we are all different subjects faced with the object of knowledge. Different cultures will observe the same image from different referential frames, and thus different valuations will be made.

4 Field Outputs

The output of the field is conceived as a scientific activity assimilated methodologically to any type of investigation, as Delgado states it (1999). It is a pedagogical strategy, of experiential character, which enables us to signify the concrete space. Therefore, the systematic acquisition of new or gross data within a previously selected and delimited area is carried out. Direct contact with the landscape enables the educational process, it invites the local analysis of great richness in order to acquire the spatial awareness that the environment provides.

Fieldwork is presented within the organizational and dynamic formats of the curricular units suggested in the curricular design of Geography teaching. It conforms a systematic space of synthesis and integration of knowledge by means of field examination as well as interventions in narrow fields. Fieldwork encourages the ability to observe, interview, listen, document, relate, collect and systematize information, recognize and understand differences, exercise analysis, develop teamwork and develop reports, producing operational investigations in delimited cases (De Lasa et al. 2015:28).

As expressed in the design (De Lasa et al. 2015:26), the initial training seeks to encourage career development of future teachers in.

Planning and making field trips, as a didactic strategy of the teaching of Geography, favoring the recognition and appropriation of local resources and their social actors.

Producing field reports, to systematically document the experience and gather information at the field trip, as part of the student's process of production and appropriation of knowledge.

5 Fieldwork

It is considered a systematic space of synthesis and integration of knowledge through the accomplishment of work of investigation in the field and interventions in bounded fields with the support of a teacher/tutor (Fig. 2). It enables the contrast of conceptual frameworks and knowledge in real areas and the study of situations as well as the development of capacities for the production of knowledge in specific contexts. As such, these curricular units operate as confluence of assimilated learning in the subjects and its reconceptualization, in the light of the dimensions of concrete social and educational practice, as areas where problems are collected to work in seminars and as spaces where the productions of the workshops are tested and analyzed.

Fieldwork specially develops the ability to observe, interview, listen, document, relate, collect and systematize information, recognize and understand differences, exercise analysis, work in teams and develop reports, producing operational investigations in delimited cases. It is important during the curricular development, that the successive fieldwork recovers the reflections and knowledge produced in the previous periods, and it is possible to sequence it every 4 months.

These two lines of didactic action constitute a small sample of how rich and complex the analysis of current Geography (in general) and Physical Geography (in particular) teaching is. A critical position in the light of different problems is taken.

Fig. 2 IPESFA Professoriate Team at the top of Jeu Jepen Hill (Credit: Ignacio Magneres)

It is questioned not only the teaching but also teaching practice itself, the man and the environment and how it is used. We wonder inter and intragenerationally what legacy we leave behind for this and future generations.

The production and publication of their own images, obtained during a geographical field work, make these two strategies planned and executed with pedagogical intention converge. Thus an unparalleled didactic tool is obtained due to its experiential value, for all participants, for its innovative and genuine character, (it is not about images downloaded from the Web or some text) and inner elements of the construction of geographic knowledge are put into play. These elements evoke and relate theoretical–practical contexts of great value. In this respect, we try to highlight the true meaning of field trips, following the words expressed by specialists in neuro-linguistics like Joseph O'Connor and John Seymour (1992), "in every learning process we remember 10% of what we read, 20% of what we hear, 30% of what we see, and 90% of what we do."

Acknowledgements Here is my recognition to those teachers who planned trips coordinate, prepare field reports, register and overcome multiple drawbacks (bureaucratic, climatic, logistic, etc.) in order to generate instances of significant learning, marking indelible traces and generating experiences of geographic learning for our students.

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Teaching Earth Sciences in the Provincial Educational System of Tierra del Fuego

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Abstract Including a chapter in the study of Geological Resources in Tierra del Fuego and refers to its teaching, acquires a relevant importance, not only because it allows citizens to learn from their own assessment but also because it allows to go deeper on its methodological aspects when teaching Natural Sciences based on the natural environment's diversity in the province, it also enables students to build their knowledge from early ages in specific and adequate contexts. Using conceptual components based on the theorization and the use of models in teaching can be combined with more practical aspects that are available for its exploitation in the geological resources of the province. Knowledge cannot be achieved without information or interaction; we teach to observe, discover, describe and interpret the environment and the design of didactic itineraries is fundamental to attain contextualized teaching.

Keywords Teaching Earth Sciences · Provincial Educational System

1 Introduction

We generally associate the concept of geological resources with the concept of natural resources and we relate them to extractive activities that man carries out directly on Earth and whose purpose is to obtain energy o produce some goods. But there is another important view in the study of geological resources and it is related to the area of education and the teaching and learning processes carried out at secondary and tertiary educational institutions of the country and particularly in the Provincia de Tierra del Fuego, Antártida e Islas del Atlántico Sur.

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2 Project and Development

At the secondary level, there is a subject called "Earth Science" that has been included as such since the implementation of the National Education Law N 26206 of 2006. It belongs to the Natural Science modality of the Oriented Cycle and the conceptual contents developed in it are established in the Resolution M.E.D N 2800/20014 of the Ministry of Education of the Provincia de Tierra del Fuego.

The proposals established in the Curriculum Design of the subject that, they are focused to delve the knowledge of the planetary history. Their aim is the understanding of the Earth's evolution and the development of life on it. For this purpose, explanatory concepts and models of Earth Science are used to understand the terrestrial dynamics.

In the Curriculum of the Biology Teachers' Training of tertiary level at the Provincial Institute of Higher Education "Florentino Ameghino" in Ushuaia and "Paulo Freire" in Río Grande, Earth Science is an annual subject of 3 hours a week. Among its objectives, the following are the most important. They have been taken from the Teachers Training Resolution Plan M.E.D N 4333/12:

1. Provide students with concepts, strategies and procedures to access the knowledge of geology and geomorphology.
2. Identify the processes that have generated the different landscapes.
3. Prioritize, compare and validate the information around the world in order to contribute to the development of a critical thinking.
4. Provide conceptual and procedural elements that explain the natural processes which generated the different landscapes.
5. Promote the value of the landscape through local and regional protection and preservation strategies.

The contents are organized under three main thematic matters: "The Earth," "The Litosphere materials" and "Erosion and landscape modeling." Briefly they are the following:

The Earth: The Earth and its subsystems. The Earth layers: biosphere, atmosphere, hydrosphere, lithosphere. The structure from its chemical composition and its physical properties. The Continental Drift Theory. The Tectonic Plates Theory. The Stratigraphic Chart : Eras and Periods. Ground Motions. Structures: faults, and folds. Characteristics. Associated effects.

Lithosphere materials: Minerals, Igneous, sedimentary and metamorphic rocks. Intrusive processes. Volcanism. Types of volcanoes. Magma and lava. Metamorphism. Classification of metamorphic rocks. Sedimentary rocks. Types of sedimentary rocks. Soil formation and it structure. Edaphic classification. Mining sites in Argentina.

Erosion and modeling of the terrestrial landscape: Geological action of water on the continents. River erosion. Meanders and captures. River valleys. Groundwater. Hydrological cycle. Geological action of the wind. Wind erosion and its products. Forms produced by wind erosion. Types of landscapes. Geological action of ice.

Continental and valley glaciation. Fjords and coasts by glaciation. Isostasis. Geological action of the sea. Water movement: waves, currents and tides. Coast and shore. Sediments. Geological importance of organisms. Debris movement.

The teaching of this subject in the Biology Teachers Training is carried out by a methodology of classroom–workshop developing theoretical–practice classes. The aim is that students can build their knowledge based on the analysis of local and regional characteristics of the physical environment. It is worked on the study of the geological evolution of the region taking into account the different events that determine it, the different processes that generate rocks, and the predominant land modeling forms. Among them the ones corresponding to glacial modeling. This view about the object of teaching determines the way of teaching it and the didactic device used, has to be in accordance to the characteristics of the students who will be the future teachers within the National Educational System.

The chosen theoretical–methodological approach is similar to the constructivist one, where knowledge is built and moulded by experience and based on the work group of students. In education we always refer to the components of a pedagogical triangle whose vertices are the student, the teacher and the object of learning. In this case, the learning object or contents can be defined as a set of knowledge, mental processes, skills, attitudes and methods. When programming them or including them in an institutional planning, their usefulness, significance, functionality, level of difficulty and their adaptation to the psychological and cognitive development of students must be taken into account. The students' interest and their needs are also important to be considered. But doubtlessly the object of study of the "Earth Science" subject is available in all the geological units of the provincial territory, becoming a natural resource suitable for education.

In this context, the classroom, that is the main setting where teaching practices take place, should be complemented with curriculum activities based on procedural contents and experience. Didactic proposals like field trips improve the teaching quality of the discipline and set an adequate scaffolding for the teachings in situ. This didactic tour allows working on observation, description, elaboration of hypotheses, modeling, etc. simultaneously. But above all, it leads us to understand the magnitude of the geological phenomena that were developed and are currently developed in geographical spaces and time scales greater than the dimensions students use daily, resulting in characteristic and changing landscape configurations.

The eastern portion of the Main Island of Tierra del Fuego belongs to the Argentine Republic, specifically to the Provincia de Tierra del Fuego, Antártida e Islas del Atlántico Sur. The meridian of 68° 36' 3" W is the one that indicates its limit from the Republic of Chile. This meridian runs southward from Cabo Espíritu Santo (Espíritu Santo Cape) to bahía Lapataia (Lapataia Bay) and from there it runs eastwards along the coasts of Canal Beagle (Beagle Channel). The relief offers two particular aspects: The Andean mountain range and the plains in the Extra Andean portion. The rocky outcrops have a great areal distribution and belong to different types of rocks (sedimentary, igneous and metamorphic) and different ages that go from the Paleozoic?-Jurassic (Lapataia Formation) to the quaternary deposits constituted by glacial, glacifluvial deposits, soils and nonspecific deposits. Much of the Fuegian territory endured a great invasion of ice during the Quaternary and its effects are manifested in the different types of geoforms (major and minor) that dominate the landscape and are very suitable for observation and interpretation. This landscape provides a wide range of alternatives for the design of didactic itineraries along the provincial routes or the navigation along the Canal Beagle (Beagle Channel).

In this context, from the subject of Earth Science, it is proposed to the educational community, including students, alumni and other subjects teachers, to do a field trip beginning at the City of Ushuaia (Fig. 1), and traveling along the National Route 3 northward to the border landmark (Hito I) located at the Cabo Espíritu Santo, the northernmost point of Isla Grande de Tierra del Fuego, near of the Magellan Straits (Fig. 1).

Fig. 1 Map of the Isla Grande de Tierra del Fuego showing the locations of the teaching and study stops

The general aim is to recognize the main geoforms of the landscape and, based on them, make an adequate environmental interpretation by inferring the geological and biological climatic processes that determined the evolution of the region.

The working modality to be developed will be the traveling workshop, making stops at sites of geological and geomorphological interests, including representative examples of geological formations and modeling geoforms to be observed and analyzed by the attendees.

The following activities are carried out at each site:

(a) Geographical location with the use of maps, satellite charts, aerial photographs and GPS.
(b) Identification of the type of modeling with the respective erosion and accumulation geoforms in the landscape.
(c) Identification of minerals and structures to determine the different lithological types.
(d) Formulation of hypothesis about environmental evolution.
(e) Recognition of the temporal and spatial scale on which the analyzed geological processes occurred.

Site N°1: Glaciar Martial (Martial Glacier)

Located on the northwest of the City of Ushuaia. From here you have a panoramic view of the city and the Beagle Channel. In its valley, the geomorphological characteristics, derived from the last glaciation, are examined. In this way, we try the students to recognize the glacier accumulation geoforms (lateral moraine), the major geoforms (glacial valley, cirque glaciers, cols, ridges, spurs, etc.) and the minor geoforms of glacier erosion (drumlins, ridges, striae, etc); the dynamic of the glacier itself by identifying the areas of accumulation and ablation, mass balance, ice flow, glaciar advance and retreat, influence of solar radiation in the distribution and orientation of the slopes (sunny spot hillside and shady side) and finally the topographic relationship between the glaciar Martial (Martial Glacier) and the glacier that occupied the Beagle Channel.

Another important activity to be done is to determine the magnitude of the glaciation. So it is tried to calculate in situ the thickness of the glacier that occupied the Beagle Channel. To do this calculation, it should be taken into account the lithological composition of the erratic blocks that are located there, its current location (altitude above the sea level) and finally the depth of the Beagle Channel.

In this valley, there are also geoforms corresponding to the periglacial environment as the early development of stone polygons in some areas. Students are required to propose hypotheses about its origin taking into account the natural physical conditions that determine this environment.

Site 2: Olivia river mouth (Fig. 2)

In this environment, the activity is that students can observe, describe and analyze the quaternary sediments located near the mouth of the Olivia River. To do this activity, they will have to draw on to concepts related to the geological features produced by

Fig. 2 Olivia River meander

the rivers within a watershed (erosion, transportation and sedimentation) with the physical conditions for the formation of a delta, variations of the basement level and the gradient.

They are composed of sandy gravels, of steep inclination and height with respect to the current basement level, corresponding to a paleodelta of the Olivia River developed in an ancient environment very different from the present one.

The highlighted pedagogical activity is that students will be able to establish hypotheses about the environmental conditions that gave origin to this geoform and also to distinguish these deposits from other quaternary deposits of different origin located along the Beagle Channel.

Site 3: Valle Carbajal (Carbajal valley) (Fig. 3)

Located in a viewpoint of this site, we make a description of the geology of the area, taking as a reference the different outcrops present and the structures they determine, referring to the geological time and the dimensions of the space where these rock formers processes are developed.

Based on the local geomorphology, the features of the site are mainly of glacial origin and it is the result of the geological effect done by a valley glacier during the glaciated period in the area. As a result it can be observed extraordinary major and minor geoforms of glaciar erosion, glacial accumulation as well as the fluvial dynamic and the current mass removal processes.

Fig. 3 Valle Carbajal (Carbajal valley)

Referring to glacier modeling, the main goal is that students can dimension the magnitude of the glaciation. To do this, they are proposed to identify the major erosion geoforms in the landscape of the Carbajal valley, by estimating the thickness of the glacier, the direction of displacement of the main glacier and the topographic location of the affluent glaciers and its consequent hanging valleys.

With the retreat of the glaciers, the valleys are occupied by lakes (on which peat advances) and rivers, so the modeling action of the relief is the main consequence of this dynamic, developing flat bottom valleys on which the Olivia River basin extends. This environment is propitious for students to identify the main geoforms of river modeling and to relate them to the phases of the evolution of a river.

In this Andean region of Tierra del Fuego with steep slopes, great availability of water and the formation of ice, the mass removal processes acquire great importance and can be observed frequently in the landscape and in ground movements made when the National Route 3 was being built. The main activity for the students is to identify these processes, establish the factors that determine them and the appropriate actions to mitigate the effects in case they affect a public or a private good.

Site N°4: Paso Garibaldi

Continuing the itinerary along the National Route 3, the selected site is the Paso Garibaldi, which is located on the Alvear mountain range at approximately 450 m above the sea level. It is located between high altitude rocky walls and it connects the

Tierra Mayor valley (to the South) with the valley of Escondido Lake (to the North) and constitutes a panoramic viewpoint of geological as well as touristic interest.

With the support of satellite images and geological maps of Tierra del Fuego, it is carried out a spatial analysis and a comparison of the lithological units in the area. Its main objective is that students are able to recognize the structural characteristics of this place by identifying the Magellan fault, identifying the edges of the involved plates and their displacements.

Site N°5: Cerro Jeu-Jepén (Jeu Jepen hill) near Tolhuin

We move a few kilometers away from the National Route 3 and go up a side road to one of the few outcropping plutonic rocks area in the Argentine part of the main Island. On this site you can see due to a quarry mining the disposal of pluton, its relationship with the host rock and its weathering areas. Together with the students, we try to identify, although the fine texture of the rocks, the present minerals in order to determine in situ the estimated composition of the igneous rocks of the outcrop.

From the viewpoint, it can be seen a different perspective from that shown at Site 4. It is an extensive structural feature that represents the Magellan current fault. It separates the tectonic plates of Scotia, in the South, from the South American one in the North. Some running rivers, cut by beaver dams, meander among inextricable peats are flowing to a huge glacier lake: The Khami o Fagnano Lake, which is the second largest in Argentina.

Site N°6: Head of lago Fagnano (Fagnano Lake)

On the side of the route, the first sedimentary rocks emerge. They belong to the Paleocene-Eocene period (Rio Claro formation). Based on the identification of the fossils, the student´s activity consists in identifying sedimentary structures and textures in order to be able to determine roughly the characteristics of the sedimentary environment. The concept of sedimentary basin is analyzed and the geographical coordinates of the site are taken. These data will be compared with other sites of interests during the itinerary.

Site N°7: Río Ewan (Ewan River)

About 10 km from Tolhuin (a small town between Ushuaia and Río Grande), high and long river terraces shape the landscape. They do not match with the current Ewan river dynamic, with low flow and low slope. For this reason, students are asked to hypothesize about the origin of these geoforms by linking them with the regional environment.

Site N°8: Río Fuego—Cabo Domingo (Fuego river—Domingo cape)

In the area between the mouth of the Río Fuego and the Domingo cape, we can see plains of coastal cords from the Holocene period and an elevated gravel beach. The purpose of these observations is to show changes in the sea level in recent periods of time, working on the concepts of marine transgression and regression linked to the quaternary glaciations in both hemispheres. Students will read published papers about the topic.

Site N°9: Bridge over Grande river

From this site, there is a good panoramic view to the east and we can recognize the main features of the Grande river environment. The river geoforms are identified, the dynamic of the Grande river is analyzed and it is compared with other rivers of the province. It can be seen the interaction produced by the mouth of this river into the Atlantic Ocean.

Site N°10: Estancia Sara (Sara Farm)

The main glaciation axes in Tierra del Fuego were located on what we know today as the Magellan Straits, the "Inútil and San Sebastián" bays, the Fagnano Lake and the Beagle Channel that flowed eastward and came from the Darwin range.

To get to the area on which the second axe was located, we move 60 km northward from the City of Rio Grande where Estancia Sara is located. Through an internal rural road, we access to the coast from where we go to Sinai Point.

This rural road runs along a field of lateral morraines where there are many erratic rocks (Figs. 4 and 5) of granodioritic composition that remain as relicts along the Atlantic coast being some of them of colossal dimensions.

The activities on this site are directed toward the observation and description of the lithological characteristics of the erratic rocks. To do this, the students have to identify the main minerals in them to achieve an adequate classification of the

Fig. 4 Deposits of glacial origin nearby Estancia Sara (Sinai Point)

Fig. 5 Erratic boulders in Punta Sinai (Sinai Point)

glacial-origin deposits, which can be seen on the coast as well as the erosive action of the waves, the formation of cliffs and finally the ground-forming processes.

Site N°11: San Sebastián

Near the border crossing of San Sebastián, outcrops of Carmen Silva Formation of Late Oligocene can be seen (Fig. 6). The main activity of the students here is to analyze the environmental conditions in which these rocks were produced taking into account the structure of the rocks, their texture and the fossils content.

Site N°12: Cañadón Beta (Beta stream)

It is located at approximately 80 km northward from San Sebastián and its coasts are characterized by having marine placers that gave rise to the Gold Fever in Tierra del Fuego more than a century ago, when some explorers from the Oriental Europe ventured to these latitudes and discovered the precious metal. Today, using the same techniques some gold hunters the marine placers of the northern coasts of the island.

Recreating handmade washing is a practice that sparks the curiosity and interests of students. They analyze the physical characteristics of the minerals present in beach deposits in order to select the right place to collect the material and to do the washing process more efficient.

Site N°13: Hito I (boundary post) (Figs. 7 and 8)

Fig. 6 Carmen Silva Formation

The itinerary finishes at the north end of the island, at a geographical point of interest called Hito I, located next to Magellan Strait in the Espíritu Santo cape and determines the boundary between Argentina and Chile on the Isla Grande de Tierra del Fuego.

At this point, a sharing of information is carried out about the contents dealt in each of the sites visited, emphasizing the spatial and temporal dimension of the phenomena and processes in order to validate and to construct significant learnings because as future teachers they must take all these knowledge to the classroom. Another important aspect included is to think how we can make an appropriate didactic transposition when these contents are included in a school planning.

We must emphasize that the Provincia de Tierra del Fuego, Antártida e Islas del Atlántico Sur, unlike other Argentine provinces, holds invaluable geological resources in a territory with a great diversity of environments, reliefs, coasts and islands. These aspects are of undoubtedly political and economic interests but also pedagogical interests. So its assessment constitutes a significant platform for teaching at different levels of public education.

Fig. 7 Cliffed Coast near the landmark

Fig. 8 End of the itinerary at Hito I (Espíritu Santo cape)

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History of Gold in Tierra del Fuego

David Nelson Federico Guevara

Abstract The history of gold in Tierra del Fuego, developed late at the end of the nineteenth century; and extended for a long time in the insular geopolitical space of the Argentine Republic, does not bear any similarity with other regions. First, due to its insularity in a distant and inhospitable territory, well named *The End of the World*. Second, centrality of the main protagonist, almost exclusive in relation to others. Finally, the coinage in native gold of good law. It is a story linked to gold mining industrialization, in which historical figures move throughout, invisible to our sight, confined in a geography with unique and unrepeatable characteristics.

Keywords History · Gold · Coinage · Stamp · Sovereignty · Coins · Numismatics · Philately · Cooperatives

1 Introduction

The Argentine geopolitical insular space of Tierra del Fuego, where the central events of the history of gold took place, is the object of study of this present work of historical research. It began to take shape and presence with the marine activities held by the Argentine navigator and gentleman of the sea, commander Luis Piedra Buena (1833-1883), with the famous cutter "Luisito," from June 23, 1881 (Escudé and Cisneros 2000). In addition, the signature of a Treaty of Limits between Argentina and Chile completes the study. In that document, in his Article 3, is provided that: "In Tierra del Fuego a line will be drawn starting from the point called Cape of the Holy Spirit at latitude 52º 40', and it will extend southward, coinciding with the western meridian of Greenwich, 68th 34', until reaching the Beagle Channel. Tierra del Fuego, divided in this way, will be Chilean in the western part and Argentine in the eastern part…"

The signing of this treaty, gave frame, in December of 1881 to the departure of the Argentine Expedition to the seas and Austral Lands of the Republic. In charge of

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its Scientific Commission, impelled by the Argentine Geographical Institute (IGA), was placed the Lieutenant of the Italian Navy Giacomo Bove (1852-1887) and also designated to the corvette Cabo de Hornos as main ship, conductor of the scientific commission, accompanied by the cutter Patagones. It had authorization of acquiring a suitable steam, while the military chief, in charge of directing the flagship in these seas of the South, was the already well-known Argentine sailor, Commander Luis Piedrabuena (1833-1883). Among the expeditionary scientifics were: Domingo Lovisaio, geologist; Decio Vinciguerra, zoologist and botanist; Lieutenant J. Roncagli, of the Italian Navy was the painter, photographist artist, Carlos Spegazzini, naturalist, representative of the University of Buenos Aires; and the Captain of the Argentine Navy Edelmiro Correa, as representative of the Argentine Geographical Institute (Bove 1883).

The preliminary report of the mentioned scientific expedition contains different technical reports, among others. The one presented at a Conference given at the Argentine geographical Institute by Professor Domingo Lovisato. This man, who referred to the mining of Tierra del Fuego, in particular the gold that is of interest in this research, pointed out: "if the primitive biological forms of the southern regions are varied, we ought to regret that this variety is not the same as in minerals that those they are composed of. They are reduced in general to this: Gold, appears as the in the eastern part of the Island of the States, in the foothills of M. Richardson and phenolic araba in quartz in some auriferous points of the setentrion of the same island and of Tierra del Fuego in the Beagle Channel. Silver, mixed with sulphide (sukfato/sulforo), found in small pieces on the green rocks with quartz to the right of Cook Harbor. Lead, …".

In the continuity of the expedition, Giacome Bove, being in Ushuaia, on board the Gulet "San José" (former Golden West), became aware of the existence of coal in Sloggett Bay, known by the Yagans as "Hammacoia," and under that purpose, in addition to the exploratory, he went in that direction, accompanied on this occasion by Thomas Bridges and his two eldest sons, Despard and Lucas (Canclini 1951); unfortunately, after his arrival in Sloggett, the unexpected changes in the climatic conditions caused that the ship to be thrown to the coast and then tumble on his left flank, later destroyed by the storm, and only the expertise of the sailors allowed an early evacuation of crew, passengers and part of the collections, being rescued sometime later with the help of the cuter Allen Gardiner.

The preexisting sea activities of the Argentine navigator Commandant Piedrabuena, the signing of the Treaty of Limits 1881, and the results of the Bove Expedition; they inexorably led the national authorities to order the dispatch of the "South Atlantic Expeditionary Division," commanded by Commodore Augusto Lasserre (1826–1906), who arrived in the Bay of Ushuaia on September 28, 1884, to establish national sovereignty in those areas (Canclini 1989); Immediately afterward, by virtue of Law Nº 1532 on the organization of the National Territories, sanctioned and promulgated in October 1884, the creation of the Governorship of Tierra del Fuego (National Register 1882/84), was established, and for the same period Tenniente de navío Felix was designated as the first governor who hold the position from November 25 1884 to June 6 1890, Mario Cornero was his successor.

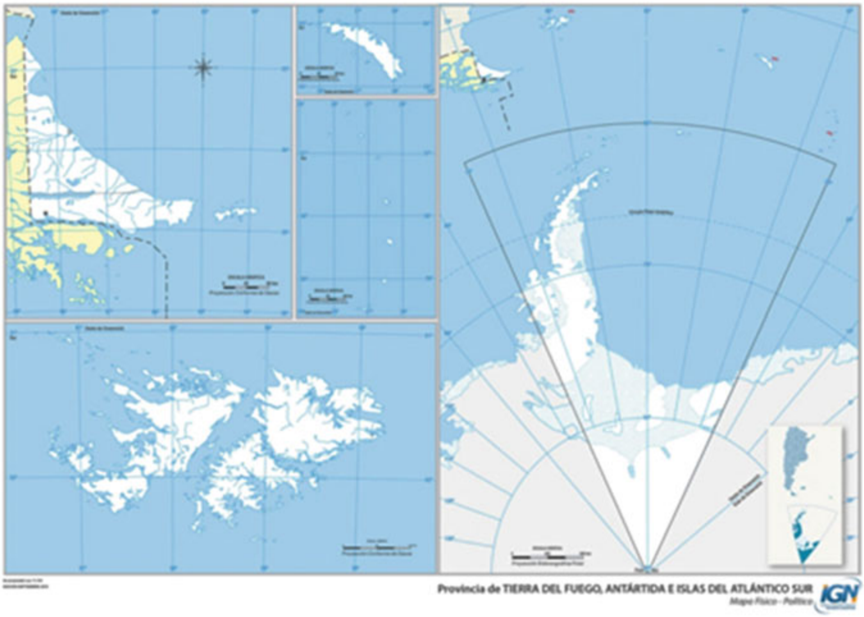

Fig. 1 Physical Political Map of the Isla Grande de Tierra del Fuego, Islas Malvinas, Islas Georgias del Sur, Islas Sandwich del Sur y Antártida Argentina. *Credit* IGN

The Argentine insular geographic space (Fig. 1), thus shaped, is where the fantastic History of gold in Tierra del Fuego took place, although late in relation to other territories; and as it may be appreciated throughout its development, the tasks of the miners who worked under gold regulations to participate cooperatively; the strategies deployed in terms of security before the looting of establishments, located in places as far away as inhospitable; the metallurgic extraction and coinage with native Fuegian gold, and the private issuance of a seal for mining use, with the geopolitical implications of the case, clearly marked the difference with other regional histories; and even, to the point of awakening today, the archaeological interest before the possibility of being in front of a model of organization and methods in the exploitation like the one of the mining Roman societies in Europe, since they could be analogous to the operation of the most legendary of the mining establishments of Tierra del Fuego.

2 First Gold Background, the Protagonists

The general interest of the population and the state bureaucracy in Ushuaia, in particular, was crescendo before the possibility of the existence of gold in Tierra del Fuego, Argentina, from the wreck in 1882, in Slogget Bay of the Schooner "San José" (former

Golden West), of the Bove expedition. When Lucas, one of the sons of the English missionary Thomas Bridges (1842–1898), collected “black sand” and mud from the beach, and later, in 1885, while residing in the Anglican mission of Ushuaia, he showed what was collected to Governor Felix Paz who was interested in the subject and sent a ship to look for more mud. He returned with a load and the surprise was the content of the precious metal. (Vairo 1999); in the same course of action the report of the Fuegian governor, to the Minister of Finance of the Nation Dr. W. Pacheco, dated in Ushuaia, March 11, 1888 (Guevara 1996). He cited the existence of gold in the mentioned Slogget Bay, adding that from the samples collected at the site, he observed that the type of gold present was thick and that the particles did not weigh less than 0,004 lb and advised the commercial exploitation of this deluge.

However, despite the important discovery and the quality of the various protagonists, some as pioneers and others representing the Argentine state. The true History of Gold in Tierra del Fuego, Argentina, territorial framework necessary to contextualize these historical episodes of mining order are linked to the Fuegian gold industry. Since the first existing antecedents in this matter, developed in the general geography of the Isla Grande de Tierra del Fuego, correspond to the Chilean sector, where gold manifestations were detected in a river of the Boquerón mountain range that Serrano Montaner in 1879 named it from “Gold,” similarly, other miners such as Pedro Ponce de León, Luis Wolf and Cosme Spiro operated shortly after (Martinic Beros 2003).

Consequently, the territorial exploratory action as the discovery of gold mines in the northern area of Tierra del Fuego, Argentina acquires geopolitical and mining relevance since the spring of 1886, by Romanian explorer and geographer Julius Popper (1857–1893) who thus became the main protagonist of the history of Fuegian Gold. For the purposes of a greater and better understanding of the historical reasons for his presence in these southern latitudes, this investigation develops briefly his biographical sketch.

3 Historical Notes of Julius Popper, from Bucharest, Romania to Buenos Aires, Argentina

Julius Popper (1857–1893) (Guevara 2016) was born on December 15, 1857, in the mysterious and orthodox Bucharest, Romania. He grew up in a modest and cultured family of Jewish origin from the Ashkenazi community, originally from Poland. His family set up a bookstore on the old 37 Vacaresti Street. When he reached his youth, in order to start studies, he traveled to France, where most of the renowned historians, biographers and novelists studied, mentioned that he began his studies at the Polytechnic School of Paris.

After his academic training in French schools, circumstance that was not possible to be corroborated in documents by this investigation, Popper, in his inexhaustible eagerness to acquire more and new knowledge, began traveling from the end of 1879 to 1881, heading to the Old Middle and Far East of the world.

Fig. 2 Julius Popper 1879, author: Hikoma Ueno (Uyeno) Nagasaki, Japón. *Credit* MFM Ushuaia, Tierra del Fuego, Argentina

First, he visited Constantinople, then capital of the Ottoman Empire (now Istanbul) and Turkey. Then he went to Egypt, India, China and Japan. His visit to the empire of the rising sun was photographically recorded by the famous pioneer of Japanese photography Hikoma Ueno (Uyeno) (1838–1904) (Belza 1975) (Fig. 2). About these trips, there is an accurate and useful reference to them in an extensive and descriptive letter, published in Romanian by the Monthly Magazine of the Metropolitan Library of Bucarest (Neguţ 2001). This letter was written originally in french by Popper's own hand to Professor and Academician Vasile Alexandrescu Urechia (1834–1901), President of the Romanian Geographical Society, dated in Buenos Aires, Argentina, on April 29, 1887.

Popper returned in 1881, to his endearing and beloved home country in times when the monarchy was proclaimed with the coronation of German Prince Karl Eitel Friedrich Zephyrinus Ludwig von Hohenzollern-Sigmaringen (1839–1814), as Charles I (Carol) of Romania and of the consort princess Elisabetta Paulina Otilia Luisa (1843–1914) of Wied as Queen Elizabeth (Fig. 3) famous Roman poet queen of Romania who in the literary world of the time was known under the pseudonym "Carmen Sylva." This woman awoke in the young explorer the spirit of loyalty and admiration he demonstrated in his exploratory campaigns to Tierra del Fuego. In particular, giving in the name of "Carmen Sylva" to an imposing mountain range that marks San Sebastian Bay, and to an extensive river (today río Chico) (Fig. 4) that flows near Domingo cape, located north of the City of Río Grande.

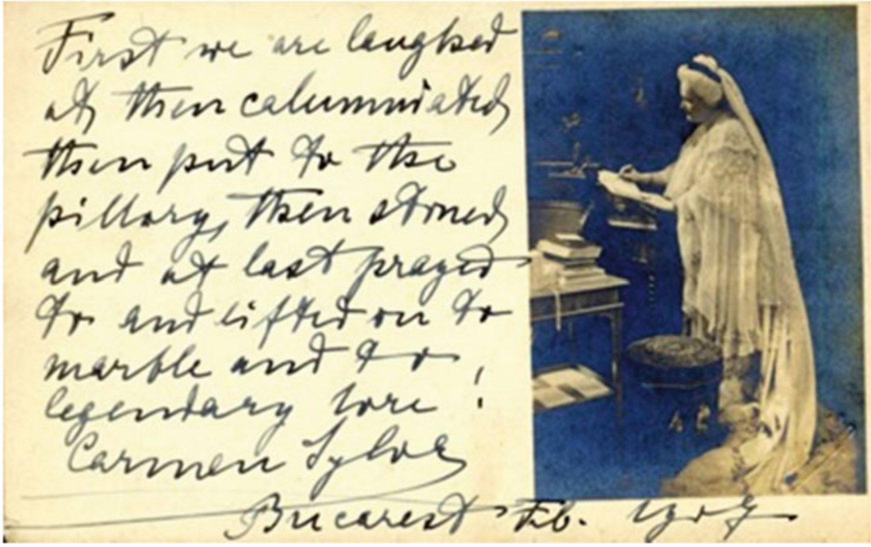

Fig. 3 Postcard of Queen Elizabeth of Romania signed with the pseudonym of Carmen Sylva Dispatched in Bucharest, Romania, February 1907. *Credit* Héctor Luis Pezzimenti

Fig. 4 Popper Expedition, Tierra del Fuego, 1886 Popper registering tagging theodolite Rio Carmen Sylva (Chico) Mouth in the Argentine Sea, South Atlantic Ocean. *Credit* Oscar Zanola

In relation to this historic and emblematic “Río Carmen Sylva” (today Río Chico) of Tierra del Fuego, Argentina, it is worth noting the beautiful oil painting named “Carmen Sylva.” Mrs. Delia del Carmen Velázquez was born in Paso de los Libres, Corrientes, but she is actually living in the City of Río Grande Tierra del Fuego, Argentina. She is known as “Cota.” She has an extensive knowledge about the activity of mining alluvial gold connoisseur of the geography of the island; and exquisite plastic artist, trained in the Tierra Canela Workshop, School of art and gallery of Professor Liliana del Valle. She represented the place in 2011, with a beautiful oil painting that she called: “Carmen Sylva” (Fig. 5); where you can see from the top the majestic and wide opening in meanders of the Carmen Sylva river (today río Chico, and the background a celestial sky that is confused with the waters of the South Atlantic Ocean, on the sea coast, named “Mar Argentino.”

Before leaving Bucharest for the last time, to the port of New Orleans, USA, in August 1881, he established cultural and scientific links with the distinguished historian, writer and liberal politician, academic professor Vasile Alexandrescu Urechia and with engineer George I. Lahovary of the Romanian Geographical Society, a venerable scientific and cultural institution that had in Popper one of its most prominent correspondent partners, for its invaluable contribution to science, particularly to geography as for its high patriotic spirit toward its native Romania. This is revealed

Fig. 5 Oil “CARMEN SYLVA” (2011). Author Ms. Delia del Carmen Velázquez (Cota). *Credit* David N. F. Guevara

by the epistolary correspondence, exchanged between them, the working history in the archives of the bulletin of the mentioned Romanian geographical institution.

He arrived in 1883 to the "queen of the south," the multiracial New Orleans, founded in 1718 by French settlers and constituted over the years in the main river seaport of the Mississippi river of the State of Louisiana in the USA, where actively participated in hydraulic construction works and built maps (Tulane 2000) in 1893 and 1884. Later, at the beginning of 1884, he decided to move to the Caribbean island of Cuba, where he contributed his experience and collaborated in the layout of the remodeling plan of Old Havana, when he averaged the year, he moved to the capital of the United Mexican States, and joined the Diario de los Forasteros (SER 2018). Finally, he decided to travel to distant Brazil, where he received news published by the Argentine Navy Transport "Villarino," which gave account of the fortunate discovery of gold to the south of the American continent, Cabo Vírgenes, Santa Cruz, Argentina, by the shipwrecked of the French ship "Arctique." This event trigged the late gold rush in the southern tip of the American continent, emulating his Californian couple in 1849, circumstances that led to the transfer of Popper to the City of Buenos Aires, Argentina, closing his intense American journey.

4 Julius Popper, Buenos Aires to Cabo Vírgenes, Santa Cruz, Argentina, and the Gold of the Patagonian Coasts 1885–1886

Julius Popper, in search of his golden destiny, arrived at the port and cosmopolitan Buenos Aires, Argentina, at the end of 1885. And, it is probable that his status as a correspondent partner of the Romanian Geographical Society, together with his membership in universal Freemasonry (Lewin 1974), as his exquisite Parisian formation, facilitated the rapid social acceptance of the Romanian engineer, in the most select circle of the aristocracy local n fact, the early friendship with the lawyer, Dr Joaquín María Cullen, with his own mining experience (Catalano 2004), allowed him to have the first resources for the necessary equipment, constitution and registration of an incipient mining company in his name, to Exercise gold activities in southern Argentina. Then he moved, at the beginning of the year 1886, as Technical Director of this novel mining company to the continental end of the Argentine Republic where he carried out an exploration and mining work in order to determine the feasibility of a gold exploitation in the sector.

He also carried out an "in situ" survey of the general situation of the different mining camps such as that of the La Fortuna Mining Company, located in the much-touted "ditch to pique" deep cleft between hills where gold floods were found a few hundred meters north of Vírgenes cape (Braun Menéndez 1971) in the then National Territory of Santa Cruz. The type of native gold found in the black sands of the place was chemically analyzed by the Mint Tester of Buenos Aires Professor Doctor Juan José Jolly Kyle (1830–1922) and its results were published in the Annuals of the

Argentine Scientific Society, Tomo, Second Half of 1886, namely The gold of the Vírgenes cape … Lately I have tested three samples of the black gold sand each from the washing of ten arrobas from the sands of Vírgenes cape. Having treated portions of these samples by scarification with lead and borax, the gold "sic" platizo buttons were (sic) incumbent and refined with nitric acid, giving the following results:

	I	II	III
Gold	873.3	873.3	882.3
Silver	126	117	117
JJJ Kyle"			

5 Popper Expedition to Tierra del Fuego. First Record Gold Mines, 1886–1887

Popper, on his way back to Buenos Aires, informed about the geological conditions of the prospecting sector, the economic expectations of gold exploitation as the characteristics of the gold washing site installed in the place and rightly recommended that all available efforts be destined to explore and consolidate Argentina's presence in the distant and enigmatic Isla Grande de Tierra del Fuego, which he observed repeatedly from the opposite shore of the Magellan Straits. Firm on his purposes, he presented the project of his expedition to Tierra del Fuego and achieved important support, he gathered a qualified group of expeditionaries and supervised the organization to the last detail and informed the Ministry of Interior Dr. Isaac J. Chavarría through a written presentation, dated August 22, 1886, that the purpose of the expedition was to explore Tierra del Fuego from a scientific point of view, and requested the respective authorization to carry armed personnel in anticipation of attacks by Indians, permission that he obtained without major difficulties, on September 6, 1886, processed by File N° 4083/1886. The fact of carrying armed personnel on the expedition was probably linked to the widespread caution that motivated the scientific and exploration fields. he revelation by the British naturalist Charles Darwin (1809–1882), regarding the position of H.M.S. Beagle and his Commander Robert Fitz Roy (1805–1865), in the navigation of the month of December of the year 1832 to Tierra del Fuego where they accused without hesitation the Fuegians of "cannibalism."

Finally, at the end of September 1886, the expedition commanded by Popper, landed on the Isla Grande de Tierra del Fuego, accompanied by the Mining and Metallurgy Engineer Don Julio Carlsson; who developed mining activities in the Province of Córdoba, some technical assistants and a group of elected laborers, including Mr. Castro and Grassano, who formed an expeditionary group of 18 armed men, all of them willing not to back down from any adversity. He camped on the bahía Porvenir, and during his March to the Santa María river, He found a gold washing site belonging to the Greek Cosme Spiro, where eight men were in charge of depositing sand shovels inside a gutter or sluice, crossed by a strong current from the same river and managed to extract 30–40 g of gold daily.

Always following the March of the mentioned river, he found another analogous washing site from an Englishman who sold this property to an Argentine company. Popper recalled that this exploitation system is identical to that used everywhere, where you can have a natural stream of water and the great American machines Hydraulic Mining, they are nothing more than hydraulic works to take the water where it is needed, which brought to his memory the remembering of the gold works carried out in the Iberian Peninsula, no less than 20 centuries ago and whose description Plinio has bequeathed us.

He continued on his way east of the beach of the Inútil Bay and after crossing some stream, he met Mr. Wolff, a well-known friend from Punta Arenas who established a gold washing site in the area; who gladly accepted the invitation to accompany him to the unknown region. They marched through a large, slightly wavy pampa; devoid of vegetation and desolate aspect, mined by tuco-tuco caves that hindered the March of horses toward the beaches of San Sebastián Bay, on the South Atlantic, Argentina, where they arrived in early October 1886.

Popper recalled that a few days before running a guanaco, they found themselves in front of some 80 Indians who painted their faces red and completely naked, distributed behind small bushes fired a rain of arrows that fell on the expeditionaries who nailed around to the horses without causing any damage. They quickly dismounted and answered with the Winchester the indigenous aggression, which he called as a strange combat, where while the fire was burning the Indians threw their mouths on the ground, stopping throwing arrows but barely ceased firing again the Indians launched their arrows. Gradually, the expeditionaries won the wind side, which forced the Indians to retire and two of them, because of this unequal confrontation, were killed on the ground. The unfortunate balance of the confrontation, where two aborigines of the Selknam or Ona race, killed on the ground, gave rise to the controversial photographic records (Guevara 2016), that this research repudiates, and that they integrate Popper's album. Their historical or circumstantial enemies, then, will use those records, unscrupulously, after the unexpected, premature and mysterious death of the Romanian explorer. In the continuity of his exploration (Figs. 6 and 7), Popper, together with Engineer Carlsson, made a geological description. The text of which is exposed below maintains the description and mineralogical individualization of the time. In that order, he said that the explored region must belong to the tertiary formation, being constituted by large stratified masses that are associated with sandstone, sometimes laminated and covered with a layer of 5–20 feet of gravels of angular forms. Recognizing, as the mineralogical species that most abound to granitic and felsitic porphyry, diorit, gneiss, granite, serpentine, cienita, trachita, quartz, amphibolite and Pedro Silex. In addition, he found extensive bands of bluish black sands generally composed of magnetites, rubies and tiny size granato; and concluded that the only metal capable of being exploited is an alluvial gold composed of 90% fine gold, 9.5% silver and 5 thousandths of other substances.

Popper on his return to Buenos Aires, after the expedition to Tierra del Fuego, made a presentation, dated February 7, 1887, perhaps it was the initial reason for

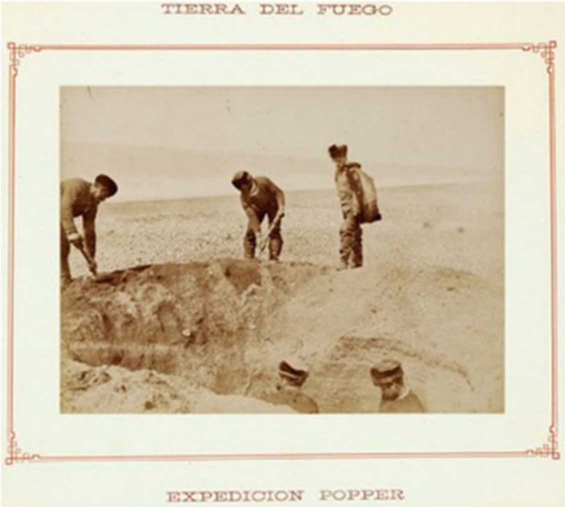

Fig. 6 Popper Expedition to Tierra del Fuego, September–December, 1886. Search, calicatas and discovery of gold in “El Páramo,” 1886. Album Popper, 1887. *Credit* Oscar Zanola

Fig. 7 Popper Expedition to Tierra del Fuego, September–December, 1886. Search, calicatas and discovery of gold in “El Páramo,” 1886. Álbúm Popper, 1887. *Credit* Oscar Zanola

disagreements with the qualified group of local investors, whose file, Popper Expte. P-1-1887, managed before the Minister of Finance on February 11, 1887. In his dual capacity as discoverer and representative of a mining company directed by Dr Joaquín María Cullen, he corresponded to the manifestation of discovery of deposits of gold alluvial sands in exploitable proportion and to the request of five mining belongings in fixed establishment, contiguous or separated, in the terms of the recent sanctioned Argentine Mining Code, located in the northern area of Tierra del Fuego, Argentina.

This registry constituted the first notarial seat in the Book of Mining Registries, year 1891 and in the Official Registry Book of Mining Belongings "Granted" of the National Territory of Tierra del Fuego, Year 1892. These historical books (Fig. 8), duly initialed and authorized by the National Department of Mines and Geology, were still deposited, on November 13, 1997, at the Museum of the End of the World, Ushuaia, and Tierra del Fuego, Argentina. In the same way, it is pointed out that, from the reading of the Official Registry of Mining Belongings "Granted," 1891; it appears that the number of mining belongings granted to Julius Popper—File P-1-887—amounted to a total of 18 mines, according to the following detail: "Cullen valley Nº1," "Cullen valley Nº2º," "Páramo 1º, 2º y 3º," "Páramo 4º," "Páramo 5º," "Carmen Sylva 1º y 2º," "Cullen," "San Sebastián," "Alfa," "Carmen Sylva 3º," "Beta," "Altar," "Talesia," "Austral" y "Auricosta."

Fig. 8 Books Official Registry of Mining Belongings "Granted" Territorio Nacional de Tierra del Fuego, Bueno Aires Year 1891 and 1892. *Credit* Oscar Zanola

6 Conference at the Argentine Geographic Institute (IGA), Popper 1887

The alternatives of this unique expeditionary activity of Popper in Tierra del Fuego were exposed magnificently upon his return by Romanian explorer in his conference (IGA 1887) of March 5, 1887. It was presented at the headquarters of the Argentine Geographic Institute, published in the Bulletin of the month of April 1887, Volume VIII, Notebook IV, accompanied by a careful and descriptive cartography that the explorer called "Tierra del Fuego—North Section—1887—Sketch of the Land of the Onas. Explored by the Popper Expedition—September–December 1886" (Fig. 9), containing the toponymics given to the sector, the paths of the transport and road of the technical personnel, the line traveled by people and ships of the expedition as the

Fig. 9 Popper Expedition to Tierra del Fuego, September–December, 1886. Sketch of the Land of the Onas. Popper Album, 1887. *Credit* Museo del Fin del Mundo

geographical situation of Indians villages and the great erratic rocks. In addition, the text of the mentioned conference is part of the album: “Tierra del Fuego. Expedition Popper,” along with 84 other tagged reproductions, whose original has its covers lined in fur seal and interior covered in a very fine red tapestry. This historic piece is part of the cultural heritage of the Museo del Fin del Mundo, Ushuaia; the historian Dr. Armando Braun Menéndez (1898–1986) donated it in the 1980s. At the discretion of the renowned Argentine photographic researcher and historian, Dn. Juan Gómez, is the oldest photographic testimony that exists in our national archives on Tierra del Fuego.

7 South Golden Washing Sites. “El Páramo” Mining Establishment. San Sebastián Police Station, Tierra del Fuego, Argentina, 1887–1890

After the successful conference of March 5, 1887 of the Romanian explorer Julius Popper at the Argentine Geographic Institute and the records of gold mines of February 7, 1887; he concluded by consolidating, on July 25, 1887, the constitution of the “Gold Washing Companies of the South.” This document included outstanding personalities of the Buenos Aires society namely: Doctor Bernardo de Irigoyen, Don Carlos P. Lumb, Don José María Ramos Mejía, Doctor Joaquín María Cullen, Don Rafael Ruiz de los Llanos, Don Alfonso Ayerza, Doctor Tomás A. Le Breton, Don Julio M. Rojas, Don Emilio Lamarca, among other important characters.

However, this mining company had an ephemeral existence, since it was terminated on February 28, 1890. The main reason for this ending was the transfer of the mining belongings and its physical assets to the Engineer Julius Popper. This land consisted of 2,500 ha corresponding to El Páramo, Alfa, Cullen, El Águila and the existing ones up to Cabo Espiritu Santo, in exchange for the commitment that he assumed to deliver in compensation and during the subsequent 3 years 15% gross of the total gold that is achieved in the laundries of Tierra del Fuego. The real reasons that led the members of the “Gold Washing Companies of the South,” to transfer the assets to Popper and the consequent dissolution of the mining company in 1890, drew attention of several members. For instance, the British Mining and Civil Engineer Henry Davis Hoskold, who in opportunity to work for the Mining Directorate of the Argentine Republic, prepared an official reporter (Hoskold 1904). When referring to Mining and Mining in the National Territory of Tierra del Fuego, he pointed out “for some unexplained reasons, this company ceased to exist, and Mr. Popper took over the mines and the establishment on his own and continued with exploitation until 1893, when he suddenly died in Buenos Aires.”

In the continuity of the history of the Fuegian Gold, it is pointed out that Popper named “El Páramo” with correct justice (Fig. 10). It is a desolate maritime site, located north of the San Sebastián bay, Tierra del Fuego, on a spike bathed by the waters of the Atlantic and blown down by the winds, where he installed the legendary

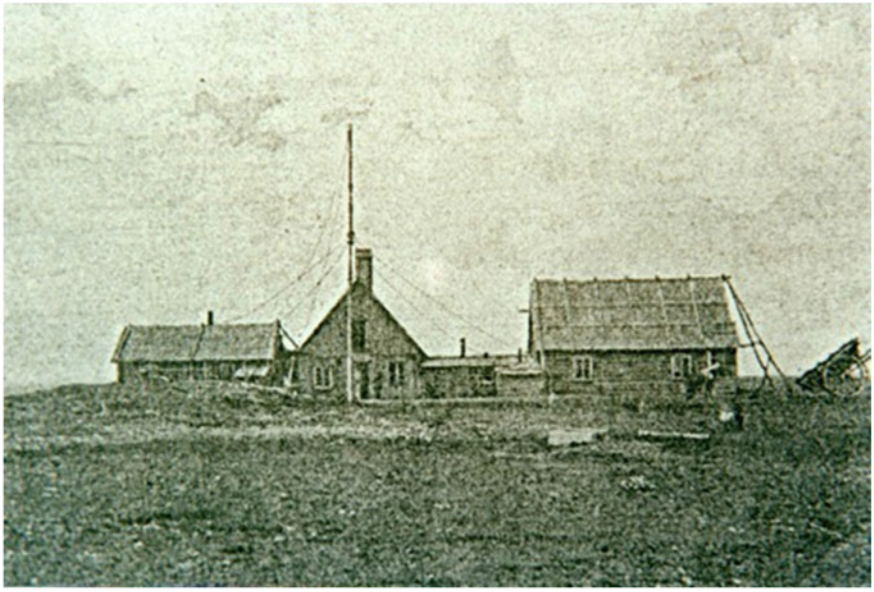

Fig. 10 General view of the mining establishment of El Páramo in 1895. Otto Nordenskjold Swedish Expedition Tierra del Fuego (1895–1897). *Credit* Argentine Embassy in Sweden (Poulsén 2001)

mining establishment in 1887. This construction was carried out with the materials arrived in two vessels chartered for that purpose, one was the Virgen del Carmen steam and the other was the María Luisa boat. Once the differences with the "Gold Washing Company of the South" were resolved, he took charge of the establishment and within 3 weeks recovered half a kilo of gold per day, gradually displacing, due to logistical problems. The initial system of large gutters (Fig. 11), pumps, mining hoppers and decauville tracks; such as the use of hundreds of kilos of mercury and tons of Cardiff coal, was changed by transportable electrical appliances. The famous gold harvester, with a minimum yield of gold that amounted to 10 g for the daily work of each man, minted in 1889 coins of 1 and 5 g of the same metal and in 1891 issued the first local mining seal of Tierra del Fuego, Argentina.

The primitive San Sebastian Police Station (Fig. 12) also known in Popper's time as "Filaret" or the "Páramo," was established about 12 km west of the mentioned mining establishment, on the Filaret ravines or Maximum, close to the international dividing line between Argentina and Chile. Arranged, strategically, in merit of the geopolitical situation of the sector, after the signing of the 1881 boundary treaty, showing the national symbols of the Republic of Argentina on the doorway of the police station. The author of this historical investigation found a spectacular panoramic view of the aforementioned police station. This sighting is thanks to the kindness of Kerstin Poulsén, Assistant of the Argentine Embassy in the Kingdom of Sweden, corresponding to Otto Nordenskjöld's book, "From the Land of Fire"; where

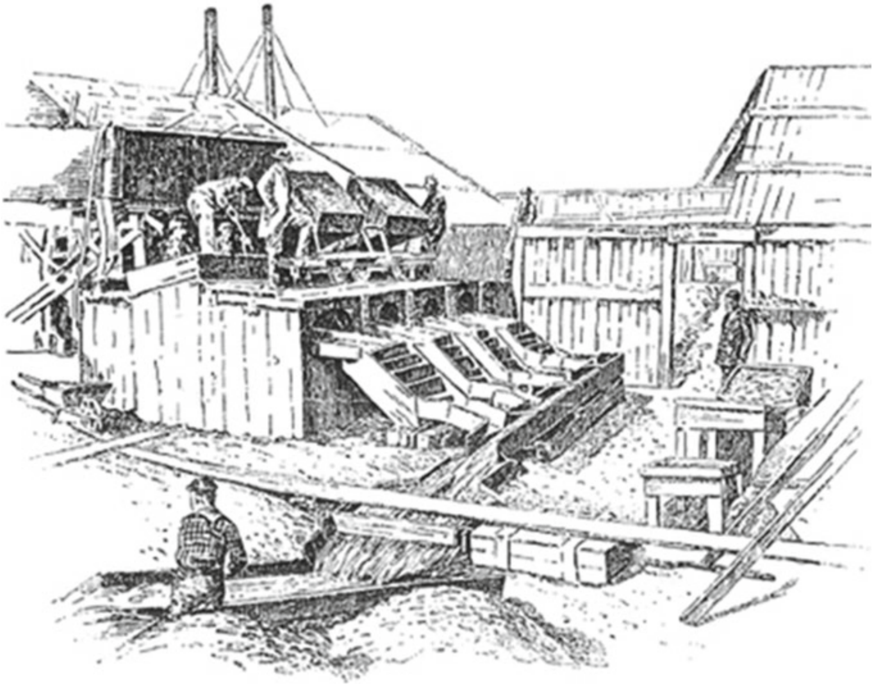

Fig. 11 Lavadero de Oro de El Páramo, 1894. *Credit* John Randolph Spears, 1895

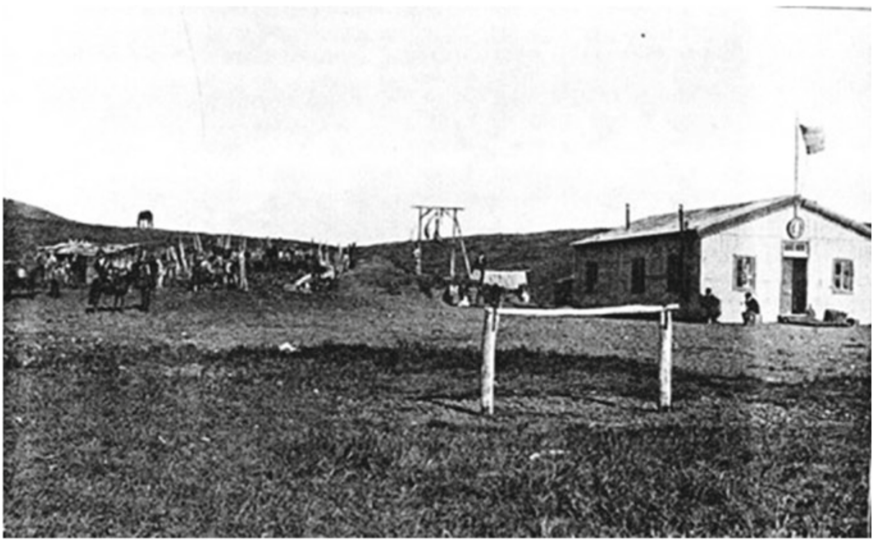

Fig. 12 General view of the first San Sebastián Police Station, "Filaret" or the "Páramo." Otto Nordenskjold 1895. Swedish expedition to Tierra del Fuego (1895–1897). *Credit* Argentine Embassy in Sweden (Poulsén 2001)

he narrates the alternatives (1895–1897) of the Swedish expedition, a photographic record (Nordenskjold 1895).

8 Tierra del Fuego, El Páramo, and the Production of Gold. Baker, US Consular Report 1888; and Popper's Gold Ingot, Presented at the Universal Exhibition in Paris, France 1889

Regarding the gold production of Tierra del Fuego, Argentina, in the corresponding period, 1887–1888, this investigation will be sent to the valuable report (Baker 1890), published in Washington in 1890, by the American Consul in Buenos Aires Edward Lewis Baker. The Consul, in relation to the mining industry of the Argentine Republic, pointed out that the best proof of what several gold mining companies are doing is the export table, since the product must be sent out of the country for refining. At the same time, Baker described in detail, the shipments of minerals abroad in 1887, where there is no gold outflow. However, for the first three quarters of 1888, as of September 30, revenues show a significant increase in shipments of minerals and gold for the first time appears in the list of exports with 325,524 kg of gold dust (gold dust). He also reported that gold was a product of mining operations in Tierra del Fuego, Argentina, near San Sebastián bay, by Mr Popper who has developed the existence of valuable gold deposits in that area, and had just to return to the area with a complete team of miners and mining devices for a more extensive study.

As in the Argentine southern (end of the South American continent), the former commissioner of San Sebastián, Dn. Máximo (Max) Popper, resisted the unjustifiable personal siege by exalted neighbors, who wanted to kill him during his passage through the Magellanic Punta Arenas, Chile, on his way to Buenos Aires. On the European continent, it was inaugurated, with the presence of high dignitaries, men of science and art, the International Exhibition of Paris, France, whose symbol stood, unequivocally, in the Field de Mars, the famous iron tower (Eiffel Tower), opened on May 31, 1889, designed by French engineer and architect Alexandre Gustave Eiffel (1832–1923). During this international exhibition, the Civil and Mining Engineer, Henry Davis Hoskold, appointed General Director of the National Department of Mines and Geology of the Argentine Republic, showed an 11 kg gold ingot, extracted from the Popper mines.

9 The Battle for the Fuegian Gold in the Beta Stream, and the Straw Scarecrows. The Moor, 01/08/1889

Popper, threatened to lose everything in the hands of bandits of different nationalities that ravaged their mining establishments, decided to make a final attempt. For the second time, he tries to repel the invaders and settle very close to headquarters located in the Beta arroyo, canyon of the same name, South Atlantic Ocean, on the northern tip of Tierra del Fuego, Argentina. About these events, which took place on January 8, 1889, historically known as the "Battle of the Beta stream," where soldiers, according to Popper's own accounts: "They were straw scarecrows, the dummies of the Páramo, the last resort of the establishment!…" In addition, the first Romanian explorer's biographer, the historian Armando Braun Menéndez (1898-1986), concluded: "… that since that memorable day of the battle of the Beta stream, Popper's dominance over the entire coastline of Earth del Fuego, from the end of the Holy Spirit to the end of Peñas, was continuous and undisputed".

10 Historical Gold Mining Labor Document, Tierra del Fuego, Argentina, April 1889

The author of this historical research paper, David N. F. Guevara, found in the work of the American explorer Charles Wellington Furlong (1874–1967), who visited El Páramo in 1908, a new reference about the labor regulations in force in El Páramo. This discovery led to a consultation with the Reading Room Supervisor Sarah Hartwell of the Dartmouth College Library, Hanover, New Hampshire, Rauner Special Collections Library, who with his usual kindness, located and sent the requested material. Once the aforementioned material was received, it was found that the copies corresponded with the form of a workbook from a miner in El Páramo and a regulation for the workers who received profit sharing for their job. The documents prove the importance that the Engineer Romanian Julius Popper gave to the mechanisms that regulated human relations, working and associative life.

This historical labor document, dated April 22, 1889 in El Páramo, individualized as "Tierra del Fuego. Golden washing sites in the south. Notebook. Regulations for workers who work for profit sharing" (Guevara 2016). It was printed in the form of a practical personal notebook, 9 cm format, $\times$ 14 cm. which was delivered to each mining worker, under a signature of conformity. It consisted of 30 pages, 65 regulatory articles, XII chapters, plus 3 particular annexes where the debt and credit of distilled and molten gold, fines and bonuses were recorded, finally closing the worker's account summary. By looking over this curious and interesting regulatory piece of labor order, we note that the same contained the worker's data, similar to a census file, advancing in practice to the population census that will take place only in 1895. It continued with the company's obligations. For instance, Article 7 establishes that from every one hundred (100) g of gold obtained, the company transfers to the miner 30 g free of all expenses. Furthermore, the duties of the miner's section organize the work in at least 6 h a day and 6 days a week; provided with a necessary coat, a waxed suit, water boots and food utensils. The regulation continues pointing out in Art. 13 Food and facilities, that the company (Lavaderos de Oro del Sud) provides to each worker. They will receive the following weekly maintenance consisting of: 1,330 g of fresh meat, cod 165 g, noodles 420 g, coffee 160 g, tea 18 g, sugar 630 g, onion 80 g, fat 200 g; Fresh bread at discretion, like the yerba mate, the carrot, potatoes, beans, rice, salt, pepper and farina (wheat cream made from soft wheat). The incorporation into the diet of the mining workers of El Páramo, of the "yerba mate" (Ilex paraguariensis) (Giberti 2011) brought the author's attention. He deduces that the incorporation of this remarkable American infusion of habitual and permanent consumption In Argentina, particularly in the provinces of Entre Ríos, Corrientes and Misiones, as in the bordering countries of Paraguay, Brazil and Uruguay, perhaps was linked to the previous knowledge acquired by the Romanian explorer about the benefits of this plant. Knowledge obtained from the works of Aimé Jacques Alexandre Goujaud, named Bonpland (1773–1858), physician, botanist and wise French naturalist, universally known as Aimé Bonpland, and in Argentina as "Amado Bonpland," the Arandú karaí, in Spanish "lord wise," from the Guaraní peoples of the missions.

It is also noted that the Romanian explorer and geographer Julius Popper (1857–1893), distinguished the French naturalist, Aimé Bonpland (1773–1858), for his scientific work, imposing his name on a Fuegian river, Río Bonpland (Belza 1978) located geographically in the Department of Ushuaia, S 54° 55', W 66° 00', south of the Isla Grande de Tierra del Fuego.

The river source is sierra Noguera and it runs into the northwestern sector of the Aguirre Bay, that is, Spanish Port, in some maps, unfortunately, this river appears as Cook (incorrect name). Finally, it is pointed out that Bonpland's mortal remains rest in a modest pantheon in the local cemetery of the City of Paso de los Libres, Province of Corrientes, Argentina, where in some of the plates, the universal Freemasonry recalls its belonging to the Star of Missions Lodge No. 41 (Fig. 13).

11 The "Gold Harvester," Popper 1889–1890

With the passage of time, as this research already mentioned when developing the installation of the Mining Establishment of "El Páramo" 1887, Popper, abandoned the process of recovering gold in large apparatus with plates and amalgamation rifles, which demanded significant water flows like mercury. He replaced that equipment, using devices of his invention that he patented on November 13, 1889 under the number 830. These devices functioned in a significant number in the Páramo, Cullen valley, Carmen Sylva and some others in Sloggett bay and simplified the process of washing gold sands. In addition, they allowed the recovery of gold directly over the beach when operating in the areas of greatest gold enrichment that are visually manifested with a high concentration of black sands rich in heavy minerals. At the

Fig. 13 Recognition of universal masonry to the French sage Beloved Bonpland Cemetery of Paso de los Libres, Corrientes, Argentina. *Credit* David N. F. Guevara

same time, the device invented by him, became ingrained in the Fuegian gold activity, since its patent in 1889, whose evolution and use by Argentine and Chilean miners were confirmed by chronicles of the time, in prospecting reports in beach deposits or in photographic records.

Among the most notorious and oldest photographic records (Fig. 14) displayed, by this historical investigation, it is the one corresponding to a group of miners operating in December 1895 the famous "gold harvester," in the El Páramo beaches. It represents the visit and permanence in the sector of the explorer Doctor Nils Otón (Otto) Gustavo Nordenskjold, on the Swedish expedition to Tierra del Fuego, developed between 1895 and 1897. Then, in order to own investigations, it was determined that this photo reproduces a typical scene of the daily work of a work cooperative. In this case, miners gathered in groups of six members, with their respective tools and equipment of the trade, constituting the first photographic record of the cooperative of Tierra del Fuego, Argentina. As a conclusion to this historical evolution, and the use of the Famous: "Gold Harvester", It is noted that during the 1990s, the mining activity developed in Cañadón Tortuga (Fig. 15) and the mythical Cañadón Beta streams, by the Fuegian Mr. Roberto Luis Sobral, to his premature death, that happened on the 18th of June in 2004; with own devices, re-designed, mechanically, electrically and chemically, whose working principle was similar to Pope's invention, place him into the first miner's group, who decided to do a great sacrifice, their gold mining operations, on the lonely beaches in Tierra del Fuego (Fig. 15).

Fig. 14 "Miners washing gold," El Páramo, 1895. Otto Nordenskjold. Courtesy of the Argentine Embassy in Sweden (Poulsén 2001). The famous gold harvester invented by Julius Popper 1889–1890 is observed. First photographic background of the cooperative of Tierra del Fuego, Argentina. *Credit* David N. F. Guevara

12 Coining Tierra del Fuego

12.1 Native Gold Coins from Tierra del Fuego

The minting in 1889 of the native gold coins of Tierra del Fuego, Argentina, constitutes in itself one of the most exciting and extensive chapters on mining, metallurgical and coining activity, initially developed by Julius Popper (1857–1893) in the mint of the distant and mythical Fuegian Páramo in the "End of the World."

According to Richard Hanscom, an American numismatist, under the characteristics of a private gold coin, as well as private gold coins in the USA, in the Carolinas and Georgia in the 1830s; and in California in the 1850s. Later, for operational and other reasons related to financial commitments, he moved the mint to Mint House in Buenos Aires, Argentina, giving rise to both the famous "gold poppers" of 1 and 5 g, which immortalized him in the world of numismatic collecting and that even today, is the subject of debate and study by historical and numismatic researchers.

The historic coinage took place during the Presidency of the Argentine Nation (1886–1890), practiced by Dr. Miguel Juárez Celman (1844–1909), Roca's brother in law and former Governor of Córdoba, and the Vice Presidency of Dr Carlos Pellegrini.

Fig. 15 Roberto Luis Sobral, Cañadón Tortugas, Tierra del Fuego, Argentina, 1989. Apparatus redesigned mechanically, electrically and chemically by R. L. Sobral. *Credit* David N. F. Guevara

Meanwhile, the Government of Tierra del Fuego, established in Ushuaia, was held by the Lieutenant of the Ship, Félix M. Paz, appointed since 1884, a position he held until his resignation on April 23, 1890, succeeding the Surgeon-Major of the Navy Dr Mario Cornero. At that time, 1889, the Argentine Republic was living a serious economic and financial crisis, product of the collapse of the Guaranteed National Banks, created following the North American model. In addition, the speculative euphoria stock market and the rising price of gold, which forced the suspension of the price of the precious metal in the spring of that year. In addition, the excess of money issuance, the cessation of debt payments, the closure of the Baring Brothers house in London and the corruption of the prevailing political regime, the result of the fraudulent elections of 1886, inexorably led to the events of July 26 of 1890. It was known as the Park Revolution or the Revolution of 90, led by the Radical Civic Union (UCR) of Leandro Nicéforo Alem (1841–1896) (Fig. 16).

In the first part of this investigation, when mentioning Popper Expedition to Tierra del Fuego 1886, a revealing fact about Popper's knowledge was incorporated, about the use of hydraulic mining techniques, applied by the Romans in the farms of gold in Dalmatia and Hispania, described in the compilation of the time by Plinio "the old man," in his monumental work "Naturalis Historia." Techniques that keep a certain similarity with the gold exploitation in pleasures, developed since the year 1887, in the establishment of El Páramo. It is even possible to infer this influence in the

Fig. 16 Oil on canvas by Leandro Nicéforo Alem (1841–1896). Centennial box 2.50 × 1.50 × .17 Paso de los Libres, Corrientes, Argentina. *Credit* David N. F. Guevara

management and selection of personnel, as in the 1889 reprimand in the Fuegian mint. Other circumstances that acquire particular importance are the tests and smelting of the native gold in El Páramo, the precariousness of the place, the severe climatic conditions and the elements used for this minting task, according to Popper's own accounts and the enhancement of the "in situ" checks carried out on this historical investigation.

12.2 Roman Organization and Methods in the Exploitation of Gold in El Páramo in Tierra del Fuego. Claude Domergue, Tolouse, France, 1996

Undoubtedly, from these field checks, the extensive knowledge that Julius Popper had about these mining, metallurgical and coining activities. An example of this is the interest shown by other researchers in knowing in detail about the operation of the mining establishment of "El Páramo." In fact, during 1996, Professor Emeritus of

Archeology at the University of Toulouse-Le Mirail and prestigious French archaeologist Claude Domergue (1932) (SEDPGYM 2011), who has conducted extensive and recognized research of the historical–archaeological type of mining Roman in the Iberian Peninsula, sent a letter on December 2, 1996, to the former Director of the Museo del Fin del Mundo in Ushuaia, Mr Pablo Oscar Zanola. In addition, they exchanged email with the author of this historical investigation, on October 19, 1999, both from Toulouse, France. On those emails, he pointed out that the organization and methods in the exploitation of Roman mining societies in Europe could be analogous to the operation of the mining establishment of Popper. For example, the mail service with private stamps, the currencies in his name, and the name of the society, since provisions of this type can be compared with archaeological documents concerning the organization of Roman mining societies.

12.3 Amalgamation, Furnace, Muffle and French Foundry Crucibles. El Páramo, 1889

The native gold, recovered by the miners of the gold sands of El Páramo, under the terms of the "Regulation and conditions of service for the exploitation of gold to participation" in the "Gold Washing in the South—Tierra del Fuego," it was cast in a typical reverberate furnace built in this case of Gartcraig brand Scottish bricks, which used as combustion Cardiff quality coal, acquired in Punta Arenas. In the labyrinth of this reverberating furnace a muffle of refractory material was placed, built by Mon. A. Goyard—Rue Alexandre Dumas, 42, Paris (Fig. 17). Today it is exhibited in the Museo del Fin del Mundo, donated several years ago by the former villager Don Carlos Rubinos as a contribution to the Fuegian historical cultural heritage. In this, muffle of French origin, foundry crucibles of the same brand were located, which also had the words Mr Girard stamped as the number corresponding to their size and engraved on the bottom of these the word Croix. Also, numerous cast iron crucibles of the Mon Sagot brand of Pinchart & Willocq Srs. Rue St Maur 119 were used in El Páramo (Fig. 18).

12.4 Gold and Platinum Title in El Páramo, Popper-Kyle 1889–1890

The gold product thus recovered by the Popper harvesters installed on the beaches of El Páramo, was heavy, sealed, registered and subsequently tested periodically, in order to control the title, in particular the metal destined for the 1 and 5 g coins. Coined first in the establishment and then in Mint House from Buenos Aires, with natural gold and without Tierra del Fuego league, whose law was: 864 thousandths of Gold (Au) and 132 thousandths of Silver (Ag). This historical investigation, regarding the

Fig. 17 French furnace used in El Páramo, 1889. Mark Mon. A. Goyard—Rue Alexandre Dumas, 42, Paris. Courtesy of MFM Ushuaia, Tierra del Fuego, Argentina. *Credit* David N. F. Guevara

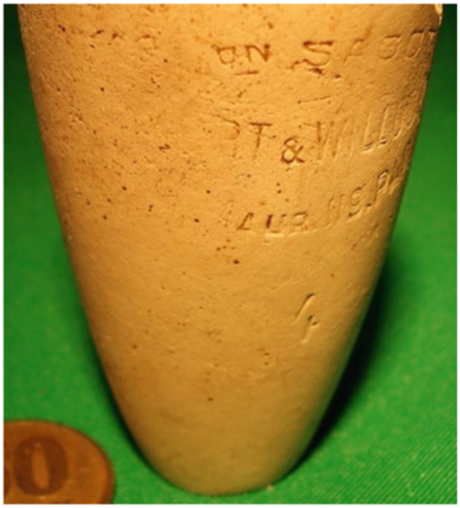

Fig. 18 French pots used to melt gold in El Páramo, 1889. *Credit* David N. F. Guevara

Fig. 19 El Páramo, native gold, 1998. Courtesy of El Páramo SRL Miner Company. *Credit* David N. F. Guevara

fueguine reprimand, corroborated the aforementioned gold law (SEGEMAR 2004), through the invaluable collaboration of El Páramo Miner Company S.R.L. (BOTDF 1992). This is a local mining company of family origin from the City of Río Grande, which performed the analysis of precious metals on samples (Fig. 19) from the sector mined by Engineer Julius Popper.

The aforementioned verification correlates with the results for the 1 g and 5 g series of Casa de Moneda Buenos Aires, 1889, determined by the Official Essayer Kyle (1890), chemist and professor, who was born in Stirling, Scotland and arrived in Argentina in 1862, providing important services to the Republic, in its technical functions in the Patent Office of Invention, in the Mint, in Health and Scientific Works—Academic. In addition, in the year 1890, the prestigious Kyle recorded the first antecedent on the existence of Platinum in the country, when he analyzed a mineral sample sent by Popper, noting that: "The gold sands of the Argentine coasts, whose exploitation during the last years has been practiced with some success, notably by the" Lavaderos del Sud Society," in the establishment" El Páramo "located near the Cabo de San Sebastián… they enclose in a small quantity the metals of the platinum group."

The presence of minerals from Platinum Group (PGM) in the El Páramo sector will be ratified in 2004, on samples studied (CONICET-CADIC) that come from the area of Nombre cape, located about 185 km north of the City of Río Grande, within the mining area of "Mina Agustina," owned by the Mining Company El Páramo SRL.

12.5 Letter from Popper to Bartolito Mitre 1892, Accompanying the Gold Coins of Tierra del Fuego

A good and practical reference on this coinage from Tierra del Fuego, Argentina, arises from Julius Popper himself, when he wrote a letter, which is then transcribed, dated in Buenos Aires, July 9, 1892, to his friend Don Bartolomé Mitre y Vedia (1845–1900), known as Bartolito. He was Director of the newspaper La Nación (1882–1893), sending to the father, General Bartolomé Mitre, the collection of his gold coins, which he called "specimens of the modest numismatic Fuegian". Both the gold pieces native to Tierra del Fuego and the letter (Mitre 2003) of the Romanian explorer are still preserved in the Mitre Museum:

> Buenos Aires July 9, 1892
>
> Mr. Bartolome Mitre and Vedia
>
> Distinguished sir and friend.
>
> The lack of regular communications between Tierra del Fuego and the capital of the republic and the constant fluctuations of paper money have been the reason for commercial transactions in that territory are made in "grams of gold." In addition, the need to avoid the inconveniences that arise from the handling of dust and nuggets of this metal resulted in the minting of one and five gram coins whose collection I am pleased to send you.
>
> Coins A and B are from the first mint already sold out. Its lack of careful execution is explained by the circumstance that from the wedge, the engraving, the lamination and coining to the same tools necessary for each one of the operations have been made in the Páramo, by which it subscribes, and in a period in which that lacked the most indispensable elements to 'such a class of works.
>
> The C and D leave the Mint House of this capital, minted as the precedents with the natural gold and without league of Tierra del Fuego.—Emission ten thousand grams. Law gold 864, silver 132.
>
> There have only been six copies of the coin E, since the wedge of the part that bears the emblem after the sixth edition was torn apart
>
> Hoping that these specimens of the modest Fuegian numismatics will be welcomed in the collection of his illustrious lord father, he greets you attentively.
>
> Your friend and S.S.
>
> Julius Popper"

12.6 *Description of the Popper Reprimand, Juan Ángel Faríní. 1953*

The work that provided the first description and complete enumeration of Popper's coins, corresponded to the then Director of the Mitre Museum, Buenos Aires, Argentina, in the period 1948–1956 and 1966–1973, Dn. Juan Ángel Faríní (1901–1973), with the numismatic study "The Currency of Tierra del Fuego", published in December 1953, in the magazine N° 6 of the mentioned museum. Likewise, Farini provides on page 59, 61 and 62, of the aforementioned work, a detailed description, according to the place of coining in 1889, delivered by Popper to Mitre in 1892, and which integrate the valuable monetary Mitre.

12.7 *Coinage of "El Páramo" 1889*

> "Type A. Obverse: Legend, in a circle and between two stars with five peaks: Tierra del Fuego. This legend closes the year of the minting: 1889. In the field within a circle and on grains or traces of ore, sign with the inscription: POPPER. Reverse Legend, in a circle: LAVADERO DE ORO DEL SUD. In the field, within the circle and on grains of mineral, interlaced poster with a 5, with the inscription: GRAMOS. Obverse and reverse: Graph. Corrugated singing Module: 17.5 mm Weight 5 grs." (Fig. 20).
>
> "Type B. Obverse: Caption in circle shape, between two five-peak star: Tierra del Fuego. This caption is closed whit the coinage year: 1889. In the field, within the circle on grains of mineral, there is a caption: POPPER. Reverse: Caption in circle shape between two five-peak stars: EL PÁRAMO. One word finishes this caption: UN GRAMO. In the field, within the

Fig. 20 Julius Popper, coinage El Páramo. Obverse and Reverse (676) 5 g gold coin, 1889 type A. Mitre Museum Monetary, Buenos Aires, 2006

Fig. 21 Julius Popper, coinage El Páramo. Obverse and Reverse (677) 1 g gold coin, 1889 type B. Mitre Museum Monetary, Buenos Aires, 2006

circle on grains of mineral. Pik and maze en sotuer. Head and back: graph. Corrugated edge. Module: 12,5 mm. Weight: 1 g" (Fig. 21).

12.8 Coinage Mint House Buenos Aires

"Type C. Obverse: Legend, in a circle: Tierra del Fuego 1889. Reverse: Legend in a circle and between two points: gold Washing site: Close this legend, the words: DEL SUD. In the field, within a circle and grains of ore, interlaced poster with a 5, with the inscription: GRAMOS. Closing the circle of the field: AU. 864—AG. 132. Obverse and reverse: Graph. Corrugated singing Module: 18.5 mm Weight 5 gr." (Fig. 22).

"Type D. Obverse: Caption in circle shape: Tierra del Fuego 1889. In the field, within the circle on grains of mineral, legend: POPPER. Reverse: Legend in circle shape. EL PÁRAMO, UN GRAMO. In the field, within the circle on grains of mineral, pick and mace in sotuer tied by a lace. Under these tools continue to the circle: AU. 864 AG. 132. Head and Back: Graph. smooth edge. Module: 13 mm. Weight: 1 g." (Fig. 23).

On the currency, which Popper classifies as "E," Fariní pointed out in the last part of page 62, the following:

"This copy that is in the Mitre Museum monetary is one of the rarest pieces of Argentine numismatics. It is a one-gram coin, of the minting made in the Mint of Buenos Aires.

Apparently, the same type D, already described, has notable peculiarities and differences, such as:

1st: The inscription relative to the Law of the metal: AU.864—AG.132, in type E, touches the circle of the field. 2nd: In that type E, the letters of the legends are smaller—3rd: The peak and the club are larger. 4th: The ribbon loop with which they are attached is also larger. 5th: The peak coincides with the letters: The one of EL PÁRAMO, and the mace with MO from PÁRAMO. In type D, the peak coincides with PA of PÁRAMO and the club with the second A of PÁRAMO" (Fig. 24).

Fig. 22 Julius Popper, coinage Casa de Moneda Buenos Aires. Obverse and Reverse (678) 5 g coin of gold, 1889 type C. Mitre Museum Monetary, Buenos Aires, 2006

Fig. 23 Julius Popper, coinage Casa de Moneda Buenos Aires. Obverse and Reverse (680) 1 g gold coin, 1889 type D. Mitre Museum Monetary, Buenos Aires, 2006

13 Gold Coins of Popper, Historical and Numismatic Museum "Héctor Carlos Janson," 2017

Opened on May 30, 1941, the Museum received, in 1968, the name of its driver, the first vice president of the Central Bank, Dr. José Evaristo Uriburu. In 2017, he takes the name of Héctor Carlos Janson, one of the greatest exponents of numismatic studies in the country, after the donation of his collection. Historical and Numismatic Museum "Héctor Carlos Janson," located on 216 San Martín Street in the City of Buenos Aires preserves and exhibits, among its valuable collection of numismatic, pieces, which are part of the Nation's heritage. For instance, the famous currencies

Fig. 24 Julius Popper, coinage Casa de Moneda Buenos Aires. Obverse and Reverse (679) 1 g gold coin, 1889 type E. Mitre Museum Monetary, Buenos Aires, 2006

minted in 1889, by the Romanian explorer and geographer, Engineer Julius Popper (1857–1893), with gold native to Tierra del Fuego.

At the time of numismatic cataloguing, a useful, necessary and outstanding tool for the world of national and international numismatic collecting are the works of the researcher, collector and numismatic editor Dn. Héctor Carlos Janson, whose name is now the 2017 BCRA Museum, for example his 2011 cataloging work, "The Currency in the Argentine Territory, 1574–2010." In the chapter, corresponding to the coining in Tierra del Fuego, Argentina in 1889, the 8 individualized specimens plus the essays recognized in this work is meticulously described on pages 503 through 506 and 514, with the author's interesting notes.

About the amount of Popper coins, which were minted of type "C" and "D," Mint House Buenos Aires, which Janson classifies as CJ # 5 and CJ # 7, respectively, deducts 1,000 for the first and 5,000 of the second. It is also expressed that the reference catalog is constantly updated by its author and as for Popper currencies they still maintain the same descriptions and classification number, if new developments arise they are incorporated and updated year by year.

14 Controversial Duplication of the Gram of Gold Popper, Ushuaia, 1994. Research Guevara

The HANIS Association (Decree TNTDF 1979) (History, Anthropology and Nature of the Islands of the South and Antarctic Argentina) as an intermediate entity of advice and cooperation with the Museum of the End of the World (Territorial Decree No. 621/79) at that time. In order to establish a genuine fund to meet the needs of the museum, resolved in 1994, the reproduction of the Popper Currency; which has printed: “LAVADERO DE ORO DEL SUD.” That is to say 5 g of type “C,” limiting the emission to 300 gold pieces, whose external module would be similar to the current 25 cents coins. While in charge of making the dies, a company from the area remained, “Auro Sur,” as can be seen from the report to the President of HANIS, Escribano Ignacio Jordá, made by the newspaper El Sureño (of Río Grande) in its edition of Sunday, December 11, 1994, page 16.

However, despite the foregoing, HANIS began selling gold pieces of 3,122 g (Fig. 25), corresponding to Series 1 of the doubling of the Popper grams of the “D” type Mint Buenos Aires, with numbered certificate of authenticity, whose outer module measures: 17 mm and the inner module of 13.3 mm. This model corresponded to the exact reproduction of Popper’s original gram, with a hoop envelope containing the following inscriptions in relief on the Obverse and Reverse: “USHUAIA” and “AU 900/000.” Respectively, added at the suggestion of the suitable personnel of the Central Bank of the Argentine Republic, to differentiate them from the original currencies and that do not resemble a counterfeit.

In addition to collecting in general, the dies used in this Series 1 are not yet able to be located by this historical investigation, despite the inquiries made, in order to obtain a photograph of them and their registration in the classification or cataloguing of Popper’s dies, developed since 2002 by the author. Later, from the controversies that aroused the exact reproduction to the original Popper’s gram, duplications began to be commercialized. They corresponded to Series 1 and subsequents (Fig. 26). Also, subsequent ones that have a lower weight and one more module large, similar to the original idea of 25 cents, since each piece of gold weighs 1.65 g, with an outer module of 21 mm and the inner module of 16 mm, whose complete dies are held by HANIS (Fig. 27).

Fig. 25 Duplications or reproductions Currency Popper, Series 1. HANIS Association. Museo del Fin del Mundo, Ushuaia. *Credit* David N. F. Guevara

Fig. 26 Popper Currency Duplications, Series 1 and Series 3 comparison. HANIS. Museo del Fin del Mundo, Ushuaia. *Credit* David N. F. Guevara

Fig. 27 Complete set of dies of duplication. Series 2 onwards. Ready-made Casa de la Moneda Buenos Aires/HANIS. Courtesy of Mr. Roberto Murcia *Credit* David N. F. Guevara

14.1 First Classification of the Dies of the Gold Coins of Popper. Guevara 2002

Some time ago, more precisely in 2002, as part of the research work on the Romanian explorer and geographer, the author conducted a careful study, where he first classified the existing dies in Argentina and abroad, with Popper's known coins. It also accompanies a synoptic table that had its correspondence by the method of comparison between the existing dies and the classified numismatic pieces. The method took into account

1. Julius Popper in his signed letter of the year to Bartolomé Mitre and Vedia
2. Juan Angel Farini in his work “La Moneda de Tierra del Fuego,” 1953/1979
3. Hector Carlos Janson in his catalogue “La Moneda circulante en el Territorio Argentino 1767–1998,” 1998 edition

The table was published in November 2004 by the Argentine Mining Geological Service (SEGEMAR 2004. Also in February 2006, an English version was known, updated for: NI Bulletin (NI 2006), both from a mining perspective and another from numismatic collecting.

When asked about this classification of dies, the notable numismatic and Argentine historian, Mr. Arnaldo José Cunietti-Ferrando (1936–2018), expressed himself conceptually on September 9, 2002, noting that it is the first time that the existing dies with the known coins and an analysis of the alloy thereof are made. Moreover, added a piece of information of great interest for the study, noting that: “The National Bank Museum bought two of these dies at a very low price. Mr. Jorge Enriquez, its owner, had exchanged them to Mr. Rubinos from Ushuaia, who is the donor of the dies that are in the Museum of the End of the World … Now, when Rubinos made the exchange, he separated especially the dies so that reproductions could not be made, that is to say, that I disaggregate the games …”

After that unprecedented classification of Popper’s dies in 2002, the author recorded news. For example, the presentation of a new piece of El Páramo in 2003, Buenos Aires, Argentina, incorporated into the catalogue by Héctor Carlos Janson, such as CJ # 3.2.1 1889 A2-R2—1 g (E. Paoletti); and the existence of a new set of dies located in Punta Arenas, Chile. Whose high-resolution images and data about the history of these dies were kindly sent by Mr. Carlos González Macaya of the Anglican Society of Punta Arenas pointing out that they are in private hands and want to keep their identity anonymously.

Consequently, a new general calculation of the existing dies, indicates that the museum of the Argentine Nation Bank has, in its possession, two mismatched dies; one of 1 g of the El Páramo and another of 5 g Casa de la Moneda in Buenos Aires (Fig. 28). The Museo del Fin del Mundo in Ushuaia, Argentina has two pairs of dies, a pair of 5 g of the Moor (Fig. 29) and another pair of 1 g Mint of Buenos Aires (Fig. 30), respectively and finally a Pair of 1-gram dies, Buenos Aires, Argentina, in private hands, in the city of Punta Arenas (Fig. 31).

15 Classification of the Dies of Gold Coins Popper 1891. Update of the Synoptic Chart, Guevara 2019

Attentive to the foregoing, the update 2019, of the synoptic table corresponding to this first classification 2002, of Popper’s dies, is then developed (Table 1). In this

Fig. 28 Disarranged dies 1 gr. EL Páramo and 5 gr. Casa de la Moneda Buenos Aires Museum of the Banco de la Nación. *Credit* David N. F. Guevara

Fig. 29 Pair of dies 5 gr. Coinage El Páramo, 1889. Courtesy MFM. *Credit* David N. F. Guevara

case, to represent the "dies" in the aforementioned classification, the author of this research used the following nomenclature: DG # 1.1 to DG # 7.2, the trials and duplications range from DG # 23.1 to DG # 26.2.

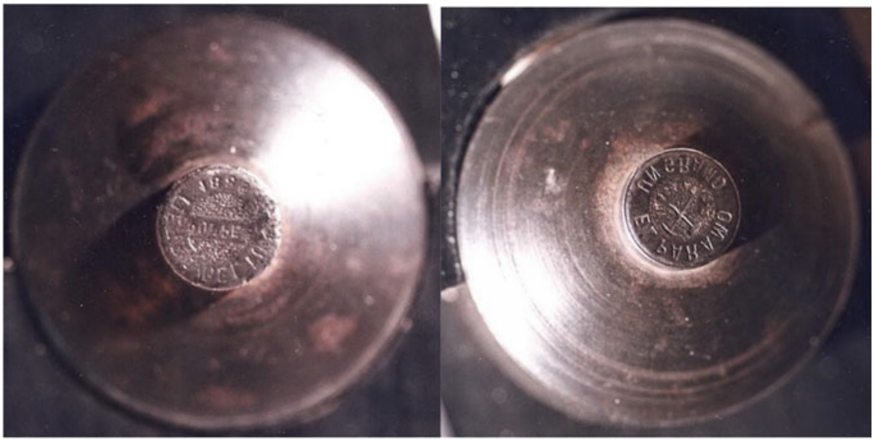

Fig. 30 Pair of dies 1 gr. Coinage Mint Buenos Aires, 1889. Courtesy MFM. *Credit* David N. F. Guevara

Fig. 31 Mint House coin Buenos Aires, Argentina, 1 g. Anglican Society Punta Arenas, Chile, 2007. Courtesy Carlos González Macaya

16 Numismatic Visit to the MFM, Ushuaia. Craft Dies First Token (Gold Token) Tierra del Fuego, Argentina, Hanscom/Guevara, 2004

Dick Hanscom, an American numismatic expert since 1976, a native of Newburyport, Massachusetts, graduated from the University of Maine in Orono, resident since 1974 in Fairbanks, Alaska, partner in Alaska Rare Coins. On arriving in Chile in 2004, with his wife Janice to visit his daughter, who was an exchange student, and being so south of the South American continent, they took advantage of these circumstances to visit the southernmost city in the world, Ushuaia.

Table 1 Synoptic table. Classification of the dies Popper. Update year 2019

Popper 1892 Coin	Janson 2011	Fariní 1953–1979	Grs.	Mint of 1889 striking	Dies YES/ NO	Guevara 2002–2019 Observe	Guevara 2002–2019 Reverse	Die in Museums
No Classif.	CJ# 1 TYPE I	No Classif.	5 GOLD	El Páramo TdF Arg.	YES	YES DG# 1.1	YES DG# 1.2	MFM Ush. Arg.
A	CJ# 2 TYPE II	A	5 GOLD	El Páramo TdF Arg.	NO	NO DG# 2.1	NO DG #2.2	NO
B	CJ# 3.1.1 3.1.2 3.2.1 TYPE I	B	1 GOLD	El Páramo TdF Arg.	YES	NO DG# 3.1	YES DG# 3.2	B.N.A MUSEUM Arg.
No ClaSsif.	CJ# 4 TYPE II	No Classif.	1 GOLD	El Páramo TdF Arg.	NO	NO DG# 4.1	NO DG# 4.2	NO
C	CJ# 5	C	5 GOLD	Casa de Moneda B. Aires	YES	NO DG# 5.1	YES DG# 5.2	Museo B.N.A Arg
E	CJ# 6	E	1 GOLD	Casa de Moneda B. Aires	NO	NO DG# 6.1	NO DG# 6.2	NO
D	CJ# 7	D	1 GOLD	Casa de Moneda B. Aires	YES	YES DG# 7.1	YES DG# 7.2	MFM Ush. Arg.
D	CJ# 7	D	1 GOLD	Casa de Moneda B. Aires	YES	YES DG# 7.1	YES DG# 7.2	Punta Arenas Chile

(continued)

Table 1 (continued)

Popper 1892 Coin	Janson 2011	Fariní 1953–1979	Grs.	Mint of 1889 striking	Dies YES/ NO	Guevara 2002–2019 Observe	Guevara 2002–2019 Reverse	Die in Museums
No Classif.	Trial Strikes CJ# 23.1 CJ# 23.2	Trial strikes	1 gr. GOLD 0,5 gr. BRONZE	Casa de Moneda B. Aires	NO NO	NO DG#23.1 DG#23.2	NO DG#23.1.2 DG#23.2.2	NO
NO Classif.	NO Classif.	No Classif.	1 gr. GOLD Anom. 2,5 gr. Trial Museo BCRA	Casa de Moneda B. Aires	NO	NO DG#24.1	NO DG#24.2	NO
No Classif.	Copy CJ#s/n°.1 CJ#s/n°.2 CJ#s/n°.3 CJ#s/n°.4	No Classif.	GOLD 3,122gr. 1,65 gr. 1,65 gr. 1,65 gr.	Aurosur Gra-Med Buenos Aires	NO YES YES YES	NO DG#25.1 DG#26.1 Ídem idem	NO DG#25.2 DG#26.2 Ídem Ídem	HANIS MFM Ushuaia Arg.

Also, in that remembered visit of 2004 to the Museo del Fin del Mundo (MFM), Dick Hanscom was kind enough to deliver to the authorities of the mentioned cultural institution, in the person of the then Director Dn. Santiago Reyes, a valuable collection piece that was exhibited in the showcases of the museum. Consisting of an old piggy bank that represents the first European iron house, known as “iron house” in Tierra del Fuego, it has the form of a house with a gable roof, destined to collect funds for the South Anglican missions (South American Missionary Society). In addition, at that time he received the promise of that MFM address, which would receive a doubling of the Popper Series 1 g, unfortunately, to date, that institutional promise remains unfulfilled.

Continuing in this order of numismatic themes linked to the historical activity of Julius Popper (1857–1893) in Tierra del Fuego. It should be noted that one of the direct consequences of that exchange, during the visit to Ushuaia at the end of 2004 was the renewed inspiration of Dick Hascom to restart the process of minting token or token with Alaskan native gold that extends positively to this day. These circumstances are cited by the American numismatic expert himself, on pages 9 and 10 of the book (Dick 2013) “Striking Gold in Alaska. Making token from placer gold” (Coining gold in Alaska. Making chips with pleasure gold) (Fig. 32).

Also, that valuable exchange between the American numismatic expert Dick Hanscom (extensive professional experience in the minting of tokens with Alaska native gold) and the author of this historical research work (experienced in the field

Fig. 32 Dick Hanscom, 4th. Edition, 2013. “Striking Gold in Alaska. Making token from placer gold”. (Coining gold in Alaska. Making chips with pleasure gold). Published by Alaska Rare Coins, Fairbanks, USA

Fig. 33 Craft test dies, Hanscom/Guevara. Essays first file (token) of El Páramo, 2009. *Credit* David N.F. Guevara

of gold mining fueguina) gave origin to the artisan preparation, for the purpose of studying, in 2009, a pair of test dies (Fig. 33) to rehearse the first token of El Páramo.

17 Origin and Production of Fuegian Gold in the 2nd. Popper Conference, 1891

In his second conference, held on July 27, 1891, Julius Popper will address the mining aspects that have relation to the gold industry of Tierra del Fuego. As request of the Romanian explorer, in the crowded halls of the Argentine Geographic Institute (IGA), under the successful title: Geographical, Ethnological, Statistical and Industrial Notes on Earth del Fuego (IGA 1891). Also, the author of this investigation, on the Centenary of the Argentine Mining Geological Service, in the institutional book under the title: "History of Argentine Mining" (2004), rescues passages of the conference related to the Origin and production of gold in El Páramo. It is pointed out that gold does not appear as in the rest of the gold floods in other regions, but on the contrary, gold goes in the opposite direction, and the waves are the ones that push them out from the depths, and the great storms push them towards the beach. Furthermore, when examining the black sands, gold particles appear more or less abundant, the size of corn grain to an imperceptible, microscopic scale, whose law is 850–900 fine, this gold is what gave rise to the mining establishment from San Sebastián Bay.

Regarding Fuegian gold production, Popper added that the amount of gold that was extracted from Fuegian gold beaches reaches more than 600,000 g. First, 175,000 g appear in the books of the Mint of Buenos Aires, as melted in their workshops. Second, 90,000 g in the Werhhahn House of Punta Arenas, as sent directly to Hamburg, all coming from the El Páramo establishment in the San Sebastián bay. It is a total of 265,000 g, more than a quarter of a ton of gold. Regarding the estimated value of exports affirmed as industries, only the gold, which resulted in an export of approximately 400,000 pesos gold bullion, nuggets and gold dust in the last 4 years.

The Romanian explorer and geographer Julius Popper (1857–1893), during his second conference at the Argentine Geographic Institute (IGA) in 1891, published the map of Tierra del Fuego on the Bulletin (IGA 1891) (Fig. 34). It contained international limits: "Tierra del Fuego according to the explorations and studies carried out by the Engineer Julius Popper 1886–1891 and the hydrographic compilations of the British Almirantazgo," incorporated as "Supplements to notebook VII and VII Volume XII of the Argentine Geographical Institute Bulletin."

Fig. 34 Historical map Tierra del Fuego, Julius Popper 1886–1891. Argentine Geographic Institute Bulletin (IGA) 1891. Courtesy IGN 2017, Buenos Aires. *Credit* David N. F. Guevara

18 Interconfesional Mining Cemetery of the Establishment of El Páramo

When Julius Popper's brother Máximo (Max) died (1868–1891), on August 27, 1891; his remains were buried along with other unfortunate Croatian miners, in the forgotten "Interconfessional Cemetery of El Páramo" (Fig. 35). Place described as a small square of Fuegian land of about 30 m, located 2,000 m southbound from the central location of the establishment and about 300 m west of the coastline, which receives both the intense winds of the Fuegian-Patagonian steppe and the strong swell of the impetuous waters of the Argentine Sea. The author, for some years now, visits those places where these historical events occurred. today practically inhalable, as with the remains of the cemetery of El Páramo, which led him to decide to publish in bilingual form, in the link of the official website of the author (Guevara 2001), the information necessary to call the attention to visitors about these circumstances. Also, he made a historical–geographical contribution carrying out GPS and marking (etrex Garmin): Latitude: 53° 0'6.86" S; Longitude: 68° 15'59.58" W (Fig. 36), which will allow it to be located, when someone decides to recover as value for Fuegian historical heritage.

Fig. 35 Interconfessional cemetery of "El Páramo." Perimeter built with Decauville rails and main cross *Credit* Roberto Brizuela

Fig. 36 Remains of the Interconfessional Cemetery of "El Páramo.". *Credit* David N. F. Guevara

19 The Stamp of Tierra del Fuego, First and Only Local, Private and Mining Seal of 10 Gold Cents of the Argentine Republic, 1891

Julius Popper (1857–1893) at the beginning of 1891 surprised his close and strangers one more time. Following the personal mark that always characterized him until the end of his days, he decided, according to the philatelic knowledge inherited from his father, the creation of First and only local, private and mining seal of the Argentine Republic, which he aptly called: "stamp-shaped mark." It corresponded to the demands of mining work and the creation of the new colonies, to the north and south of Tierra del Fuego, individualized as "Colonia El Páramo" and "Colonia Popper" (Río Grande). Likewise, he sustained before the national authorities that it lacks any postal value, and insisted that it was a checkmark as a "voucher," which delivered to each messenger to avoid the loss of the correspondence posed by the miners in their own establishments. According to the inscription, he represented 10 cents or centigrams of Fuegian gold, printed on sheets of 100 stamps, 10 × 10 squares, pink carmine, whose engraving was in charge of the Austrian Rodolfo Soucup and lithographed in the printing house of the house Juan H. Kidd and Co. on 151 San Martín street in Buenos Aires.

In addition, these stamps resolved the inconvenience that involved the handling of fractions smaller than the gram of gold, whose unit by weight and law of gold, was represented by the currency of 1 g of gold native to Tierra del Fuego, coined by the explorer in 1889. These situations occurred in such remote places and often isolated from the extensive geography of Fuegina. The stamps were made, first in an artisanal way in El Páramo and then in the Mint of Buenos Aires. In addition, the use of this ingenious and subtle "private" postal instrument (Fig. 37), of a mining nature in the form of a stamp, served as a stimulus to the messengers themselves. Considering that, in addition to the salary that Popper paid them, they received for each letter that led a stamp or mark of ten centigrams gold, which when returned received gold in cash. A practice that aimed to prevent the loss of correspondence posed by mining workers, in the different establishments located in inhospitable places in the northern area of Tierra del Fuego. Likewise, it is observed that the "private" local postal service for mining use, created by Popper, responded to a growing demand among the workers of the different own establishments and of the new colonies.

The instrumentation and administration of the aforementioned local seal from Fuegino between April and August of 1891 worked in "El Páramo" by the explorer's younger brother, Máximo Popper (1868–1891), as Director General and Francisco Eigl, as Deputy Administrator. These circumstances are possible to infer from both letters to the stamp merchants in London: Stanley Gibbons & Co. and Whitfield King & Co., dated April 25, 1891 and July 18, 1891, respectively, cited on pages 44 and 49 of the English publication on the stamp of Tierra del Fuego 1891 by Brian Moorhouse and John C. West.

Fig. 37 Local postage stamp. Tierra del Fuego. 1891. *Credit* David N. F. Guevara

Continuing with the theme on the Popper stamp, Ramón L. Cortés, deputy superintendent in San Sebastián who was in charge of the post office of that Fuegian jurisdiction, although he lived in Buenos Aires, on August 10, 1891, with unusual vehemence was stuck with unusual vehemence against Maximum Popper (1868–1891). Cortés did not hesitate to describe Maximum Popper as "criminal and accomplice in charge" of the violation of the Post Office Law in the extension of his complaint to the national authorities. Curiously, it happened on the eve of the premature and mysterious death of the young Romanian, occurred in El Páramo, in the absence of his brother Julius Popper, on August 27, 1891. Despite the attempts of Cortés and the Fuegian state bureaucracy with a seat in Ushuaia, to bring the Popper brothers to criminal justice, the proceedings worked on the occasion of this investigation were finally filed by the then General Director of Posts and Telegraphs, Dr. Carlos Carlés, dated November 5, 1892. This decision was probably destined to favor the development of the regional geopolitical scope project, promoted by Julius Popper (1857–1893) and Dr Francisco Ayerza (1860–1901), consisting of the laying of a telegraphic network and installation of lighthouses and maritime traffic lights in southern Argentina, from Viedma to Tierra del Fuego.

20 Mysterious Death of Julius Popper, Buenos Aires 06/06/1893

20.1 Did He Die as a Victim of a Conspiracy? the 25 Gold Mines and the Testamentary

The unique Fuegian historiography of Julius Popper (1857–1893) displayed throughout this work begins its closure. Based on unexpected as mysterious events, such as the death of the Romanian explorer and geographer, occurred at midnight on June 6, 1893, in the port of Buenos Aires, in the comfortable rental house on 373 Tucumán street. His subsequent burial in the family pantheon of the Ayerza-Cullen (Fig. 38) located in the Masonic Cemetery of La Recoleta as the enigmatic final destination of his mortal remains. The author on the occasion of his talk "Popper and his Gold Coins" affirmed that, as it arises from its inquiries and the documentary evidence established in the old Inhumations Registry of the Recoleta Cemetery, Book H-1892–1901 (Fig. 39), corresponding to the vault in question, individualized as: Section: 19 Plank: 23 Burial: ¼., the remains of Julius Popper are still deposited in the imposing and luxurious sarcophagus of the Decker house, located in the basement of the family pantheon of the Ayerza. In this way, he dismissed, among other speculations, that the remains of the Romanian explorer were exhumed and transferred for reduction, to a common ossuary in the Chacarita Cemetery, Buenos Aires, Argentina.

For the author, the facts and circumstances surrounding Julius Popper's premature and mysterious death, set forth above, suggest that the legitimate concern reasonable

Fig. 38 Place where the remains of Julius Popper rest Pantheon of the Ayerza, La Recoleta Cemetery, Buenos Aires. *Credit* David N. F. Guevara

Fig. 39 Record of Inhumations of the Recoleta Cemetery 1892–1901. *Credit* David N. F. Guevara

the willing for knowing the true causes of his death. On the other hand, the Romanian explorer and geographer were in very good health conditions as many witnesses stated, throwing away those versions that indicated him as a victim of an evil, frequent among the knights of the time, who led a dissipated or licentious life that by the way, it was not the case of Popper. In addition, it was widely known that he confronted the powerful sectors that considered him an insurmountable obstacle to the "corporate" development of his own wool interests. Those estates found themselves at that time in frank expansion in the Chilean sector of the island large, struggling to advance on the coveted Argentine island territory, as it finally happened, in mid-1893, after the death of the young Romanian explorer and geographer. The author of this investigation draws his attention to the suspicious presence in the aforementioned capital, of the administrator and proxy, German Julio Belfort, in office since April 1, 1892, who was absent from El Páramo, destined for Buenos Aires, via Punta Arenas, embarking in the month of May 1893, in the steam "Britannia." This occurred prior day's r to the death of Popper, being in charge of the Fuegian gold establishment, the other German Bruno Ansorge. Curiously, the aforementioned Belfort, who found the lifeless body of Julius Popper, began peremptorily to the inheritance trial, and then the owner, after judicial auction, of the explorer's gold mines.

Unfortunately, those certainties demanded by friends, the autopsies performed and certificates issued by the intervening medical professionals were never fully accredited. On the contrary, it seems that they precipitated the closure "in aeternum" of any criminal suspicion of his death. Allowing the expeditious burial of their remains that were deposited, with the prior honor of their lodge brothers, in the family crypt of the Ayerza, in the patrician and Masonic Cemetery of La Recoleta, Buenos Aires. Campo Santo that was removed in 1863, the blessing of the Church as a Catholic cemetery, for controversy with the local masonry of Buenos Aires.

In conclusion, multiple circumstances, whether they are of a geopolitical nature, according to the geographical framework of the controversies, which took place mostly in the area of the Argentine island sector, granted to Julius Popper. Those others that took place in the hostile Punta Arenas, and even the most contemporary to his death, such as the judicial litigation promoted by the Fuegian governor, aired in the high courts of crime justice in Buenos Aires. They contributed to deepen, over these more than 126 years, the suspicions of a conspiracy in the premature death of the same, perhaps victim of a refined and lethal poisoning.

The voluminous testamentary of Julius Popper is a valuable piece of historical documentary, whose succession trial started in 1893. It is contained in the files: No. 7644 (Fig. 40) and 7645 of the General Archive of the Nation (AGN), processed in the Civil Court of 1st. Instance with Nº. 537, folio 68, file 207; before the judge doctor Alberto Centeno, the secretary doctor Ríos and the fiscal agent Barrenechea. It consists of a main body of 319 folios, to which 19 incidents must be added for the collection of unpaid wages, fees, demands, mortgages, etc., among other concepts. As an illustrative example, it is noted that since the presentation of Julio Belfort, partner, and agent of the Romanian explorer, on June 21, 1893, before Dr. Alberto Centeno, Judge of the Civil First Instance, it was opened on the 25 of July 1893, the succession trial of Engineer Julius Popper, dated July 25, 1893. It was almost

Fig. 40 Probate record Julius Popper, 1893. Files [main body]: N° 7644—AGN. *Credit* David N. F. Guevara

coincidentally with the daily appearance of the Official Gazette of the Argentine Republic.

The gold mines of Popper, according to the succession itself, were 18 acquired in a judicial auction by the enigmatic Julio Belfort. However, the author, according to a new documentary record examined, on November 19, 1896 points out that the actual calculation of the gold mines that in their own right and by transfer corresponded to Julius Popper, amounted to 25 mining belongings.

The new documentary is found on "Report on the number and detail of the belongings in Tierra del Fuego of Mr Julius Popper," presented by the Director of the National Department of Mines and Geology of the Argentine Republic, the Civil and Mining Engineer, Henry Davis Hoskold.

21 The Final Destination of the 1893 Popper Gold Mines— "in Aeternum"

21.1 The Germans in El Páramo 1891–1904

The legendary mining establishment of "El Páramo", after the mysterious death of Julius Popper, which occurred on June 6, 1893 in Buenos Aires, remained in operations under the control of an Argentine-German corporation, known as The Paramo Mining Company. So the author of this research, published in 2004 (Guevara 2004), a comprehensive and thorough work on Fuegian mining, which included the treatment of this unique and little known topic, which now rescues and expands with unpublished data and of great historical value, oriented to know about the final destination of the gold mines of the Romanian explorer and geographer. Thus, the enigmatic German, Engineer Julio Belfort, who acquired the gold mines of the late Popper, in judicial auction ordered in the corresponding succession trial, for the sum of $ 2,850. Sum of money probably reunited with the economic contributions of the de facto society that He integrated with the other Germans: Ansorge, Glade, and Backhausen. Belford decided that the administration of El Páramo, remain operatively in the hands of the appointed deputy administrator Bruno Ansorge, that naturalist hired in 1891 to carry out botanical, geological and agricultural studies as the basis of the colonization proposed by the Romanian explorer, in the current location of the City of Rio Grande.

Within the framework of the aforementioned historical background update, this investigation has, among other documents, the results of the National Census of 1895 made in San Sebastián bay, Tierra del Fuego. This file card allowed the identification of at least four members of the group of Germans who were in charge of the aforementioned administration and management of El Páramo, such as other mines under their jurisdiction, namely: 1—Ansorge Bruno, 40, Germany, Chemist, 2—Belfort Julio, 32, Germany, employee, 3—Glade Carlos Teodoro, 34, Germany, Surveyor, and 4—Carlos Backhausen, 48, Germany, Military.

21.2 El Páramo, First Antecedent of the Cooperative Mining Associativism of Tierra del Fuego, Argentina, 1893–1904. Guevara Research

So far, a look about the administration and operational management of the mining establishment, in the hands of the Germans at the time of the death of Popper. However, it is important for the author of this work, to reflect in some way, how the mystique and the foundational tools of his project for Tierra del Fuego. For example, the labor regulations of May 1888, April 1889 and the mining book transcended to his figure and laid the foundations that propitiated and stimulated the healthy purpose of cooperative associative among organized mining workers, from 1893 to 1904. This was the first antecedent of the Feign cooperatives, corroborated in the photographic antecedent: “Miners washing gold,” El Páramo, 1895, by the renowned Swedish explorer, Rd. Nils Orton Gustavo Nordenskjold (Otto Nordenskjold) (1869–1928), who arrived in December 1895 to El Páramo, in the Argentine corvette “Uruguay.”

21.3 North American Ransom Expedition to Slogged Bay, Tierra del Fuego, Argentina. First Historical Antecedent of Gold Mechanization, 1896–1897

On October 14, 1896, a group of nine American expeditionary, “Clevelanders” residents of the State of Ohio, USA led by Moses Young love Ransom (1838–1906), departed after the golden passages of Popper and Spears. The departed from Sullivan' s Basin in Gowns Bay, New York, USA, embarked on the famous pilot boat No. 16, “Joseph Ferdinand Lou bat,” registration of Sandy Hook, commanded by Captain JH Connors and five crew. Carrying on board an innovative heavy mining equipment, destined for gold dredging whose invention patent was pending, the expeditionary arrived at Slogged Bay, Tierra del Fuego, Argentina, on February 1, 1897, prior stopover in Buenos Aires. The dragging operations held by the “Cleveland Group” began for a very short time, in the middle of March 1897, transforming this mining event of Bahía Slogged, into the first historical antecedent of gold mechanization in Tierra del Fuego, Argentina. Even before any other type of similar mining operation throughout the region, it will be repeated only with full intensity from 1902 to 1907.

The North American expeditionary in recognition, to the 25th President of the USA, William McKinley (1843–1901), gave the name of “Mackinley Mine,” to a mining property of the group, located 2000 meters east of the mouth of the López river, in Sloggett bay. The author published the results of this historical investigation about the North American Ransom expedition (1896–1897) to Sloggett Bay, in the institutional book. “Historyi de la Minería Argentina” Volume 2 Chapter 33, Tierra del Fuego, of the Argentine Geological Mining Service (SEGEMAR) 2004 and on the internet in bilingual form, in the corresponding link of the Web site: www.historiatdf.com.ar. The author thanked the collaborations received by Paul Tucker, Daniel Buck, David Sinclair, Arnoldo Canclini, and Inés Billard, who selflessly contributed background and useful translations.

21.4 Transfers of the Gold Mines of Popper, Belfort, Glade, Unwir and Cullen 1902–1953

To continue with the chronologic development of this research, there is a relevant fact, linked to Engineer Julio Belfort, former partner and agent of the Romanian explorer and geographer, when he transferred in July 2 of 1902, to his agent, Surveyor Carlos Teodoro Glade, the gold mines that belonged to Julius Popper (Expte. P-1-1887). This fact, due to its legal nature, motivated a decree of the President of the General Nation Julio Argentino Roca (1843–1914), published in the Official Gazette of the Argentine Republic, Year X, Nº. 2633, July 3, 1902, approving the Measures of various mining belongings of Tierra del Fuego. In addition, considering the aforementioned presidential decree, a concise historical review is made about the successive transfers of the gold mines of Popper, from its origins, a joint-stock company information "Laundries of Gold of the South" until the day of registration of the respective measurements in the name of Glade in 1904.

Subsequently, Carlos Teodoro Glade, on September 21, 1904, made a new transfer of Popper's belongings, in favor of Roberto Unwir, who was a renowned Mason, who actively participated in the development of Magallanes, Chile (Soto Bradasich 2009). He was also an unknown mining concessionaire that operated in the San Sebastián Department, Cullen Mining District, Tierra del Fuego, Argentina. Later he is found associated with people mostly of British origin and with livestock interests on both sides of the Argentine–Chilean border, for example, N.G. Wood, C. Wood, G.C. Rigly, M. Brown and A. Mac Donald, probably from their visit to the British Club of Punta Arenas, February 2, 1905, to one of the aforementioned members.

To continue with the study of the historical registration and final destination of the gold mines of the Romanian explorer and geographer, the author verified a record (dated July 31, 1925) of the then Notary of Mines, Natalio Abel Vadell. Found at Folio 1 of the Book of the Official Registry of Mining Belongings Granted from the National Territory of Tierra del Fuego. The mentioned book was authorized in 1891, where it is a fact that the Corporation "Station Cullen Limited" (Estancia Cullen) was the owner of the mining belongings of Popper, Expte. P-1-1887, until October 1953 as provided in the resolution of the General Directorate, dated April 30, 1925, Note 3232/925.

Also, incorporated as part of the historical inventory, the operation between 1922 and 1959, the "trencito de El Páramo" (Fig. 41), which belonged to the stay Cullen, built with parts of ferrous material establishing Popper; narrow gauge and motorized with a small two-stroke diesel locomotive with head injection, probably of German origin (Deutz), which is currently deposited in the Salesian Mission of Río Grande. This formation transported bundles of wool and merchandise in the interior sector of the El Páramo peninsula and San Sebastián bay, for later shipping in vapors, usually from the commercial firm Braun & Blanchard.

21.5 Famatina Gold Dredger, Sloggett Bay 1905–1908

When contextualizing the aforementioned transfer of the Popper mines, all of them located in Tierra del Fuego Argentina, the author found that by 1904, "Mechanized Gold Mining in Tierra del Fuego" (Martinic and Mimica 2003), was underway during the "gold rush of 900" in the Chilean sector of the Isla Grande, making axis in El

Fig. 41 Iron reminder from El Páramo train. It worked in El Páramo peninsula and in San Sebastián bay. *Credit* David N. F. Guevara

Porvenir, Cordón Baquedano. It was initially driven by the New Zealander Archival Cameron and Musgrave, and partly by several Americans, such as Roberts, Brickers and Sutphen, connoisseurs of mining work in California, allowing the introduction of the famous gold dredgers, whose mechanized tasks extended, approximately, until 1909.

Similarly, in the Sloggett bay, Tierra del Fuego Argentina, it operated a similar gold dredge, between 1905 and 1908, baptized with the name of "Famatina" (Guevara 2004) (Fig. 42). The firm Cutten Bros of Dunedin, New Zealand designed it and A. Brown of London built it. This would explain some of the reasons for the existence of a steam powered plant of English origin intended to move the rigging and other mechanisms of the dredge. It was a horizontal stationary compound, probably 150 psi (10.2 bar) of steam, manufactured from 1890 in nine available sizes, by the firm Ransomes, Sims & Jefferies Engineer, of Ipswich, England. This gold dredger belonged to a foreign company: "The Argentine Tierra del Fuego Exploration Company Ltd." (Karu Kinka 1977), with statutes approved by Decree of the National Executive Power, Expte. T. 66 October 24, 1905. Finally, the company was dissolved on January 13, 1908 and the belongings that were granted on October 19, 1906 went into common use. Finally, it is pointed out that the author during his field studies made several expeditions to the area of the legendary Sloggett bay (Fig. 43).

Fig. 42 Dredger "Famatina" 1905. Postcard, Editor José López TP # 19. Sloggett bay. Courtesy Mr. Héctor Luis Pezzimenti. *Credit* David N. F. Guevara

Fig. 43 Gold dredge "Famatina," Sloggett bay. *Credit* David N. F. Guevara

21.6 The Return of the Croatians to Popper'S Páramo. Tadic Tadic, Mina María, and the Gold Production of the Sector, Recorded in the Official Records, 1935–1945

This historical investigation, found in the Argentine mining records, from 1935 to 1945, an interesting and unprecedented background, which corroborates the full return of the mining spirit of the Croatians, those famous "Austrian Popper," who were mostly immigrants from the lands of Dalmatia and Itria. This region was part of the Austro-Hungarian Empire; it was the most famous mining establishments of the end of the world, a model of organization and exploitation, as "El Páramo" was. The fact happened after a long absence and the decline of the Balkan alliance, indicated by the author in this same work, from 1891, with the mysterious death in the place of Máximo Popper, brother of the Romanian explorer, probably victim of an intramural conspiracy.

In this case, the return of the alliance was personalized in the Croatian mining activity, Esteban Tadic Tadic, who began a new and intense decade of gold exploitation in El Páramo. This man was a Yugoslavian 60-year-old and single man who appears in the national registries as a landowner. Besides, he requested search permits for substances included, in paragraph 1 of article 4 of the Mining Code, in the National Territory of Tierra del Fuego, San Sebastián Department, which processed under File N° 92.811/1935 and No. 92.812/1935, respectively. Also, this investigation highlights an important background about the operation of Mina María (File 140.928-38), which had registered since the Dirección de Minas y Geología granted Esteban Tadic Tadic the easement for the facilities and constructions of the exploitation of the said mine . Thus obtained a land area of 4 ha, which were located according to the general plan of measurement.

From the gold production point of view, the mining activity at that time, 1935–1945, confirmed the potential and the gold law of these Fuegian deposits. As historically stated, the Romanian explorer and geographer himself, in his second conference of July 27, 1891, before the Argentine Geographic Institute. In this sense, the Expert of the Directorate of Mines and Geology of the Nation, Aníbal Bertagui, transferred to the site in 1941, provided a new piece of information on these aureus yields. Meanwhile, Mining Statistics of the Argentine Nation, recorded for the sector, from 1940 to 1945, a total production of 17,112 kg of gold.

21.7 Popper's Gold Mines, Bureaucratic End October 1953

In short, Julius Popper started these mining activities initially accompanied by Croatian workers, known as the "Austrian Popper," which had their operational continuity after his death in 1893. First, in the hands of the Germans; then under British interests, for example, the mechanization of the gold exploitation of Sloggett Bay, or even owned ownership of their mining belongings. Later, from 1935 to 1945, in a firm establishment, next to the historic “El Páramo N° 1,” the aforementioned Balkan alliance was reissued, with interesting and outstanding gold production. Finally, the gold mines registered by Julius Popper (1857–1893), on February 11, 1887 reached its bureaucratic end, being officially declared expired, on October 27, 1953, by Disposition of the S.E.M. No. 629/53. The registers were, specifically, individualized in the notarial entry as Registry No. 1, corresponding to Book of Mining Records of the National Territory of Tierra del Fuego, Argentina, Folio 1, the Year 1891, that was since 1925, held by Estancia Cullen (Limited Company Station Cullen Limited).

21.8 The Golden Destiny “in Aeternum” of Tierra del Fuego

Historical continuity, in terms of the exploitation of the gold deposits, involved in those old Popper possessions, in practice, had as protagonists, from the 1980s, in the northern area of Tierra del Fuego, in the sectors of the Cañadón Beta and Cañadón Tortuga, mainly Roberto Luis Sobral, until his sudden death on June 16, 2004. After his death, his son kept the mining activity rights in the mentioned canyons. In the beginnings of the 90 s, appears a register of a local mining company, “Compañía Minera El Páramo SRL” (Fig. 44), which takes the Romanian explorer and geographer’s favorite place. This place finds its location in the Cullen area, Cabo Nombre,

Fig. 44 Equipment of the El Páramo Mining Company. *Credit* David N. F. Guevara

El Páramo, Carmen Sylva and Bahía Sloggett, among other mining companies, geologists and engineers.

However, after this extensive and thorough historical tour, which included among other studies that corresponding to Popper's mining belongings, is known that the mining activity in Tierra del Fuego had to endure prolonged and unjustified interregnum. It is known that, the Fuegian miners, beyond the branch of the activity to which they belong, even today as in the old days, except for honorable exceptions, continue to experience great contradictions, linked to bureaucratic, corporate and geopolitical interests, which limited sensibly the normal development of their mining work.

22 Conclusions

In conclusion, as a corollary about the final destination of the mythical Popper gold mines, this present research works on the brilliant and extraordinary History of Gold in Tierra del Fuego, Argentina. The author points out that after more than 128 years, since the first registration of gold mines and subsequent bureaucratic closure of them, both the mines located in the northern zone and the southernmost insular end of Argentina, retain the validity of the historical place they occupied. Their validity symbolic that they transcend, as I point out in my book with a golden destiny "in aeternum" (Guevara 2016) and are part of the first antecedent of the Fuegian cooperative associative, build the national identity and exalt the rich history of the region.

As a corollary to the final destination of the mythical Popper gold mines, the author points out that after more than 128 years since the first registration of gold mines and subsequent bureaucratic closure of them, both the mines located in the northern zone and the southernmost insular end of Argentina, retain the validity of the historical place they occupied, their symbolic validity that transcends.

Thus this transcendence is expressed in Guevara (2016) with a golden destiny "in aeternum" and it is part of the first antecedent of the Fuegian cooperative associative, build the national identity and exalt the rich history of the Provincia de Tierra del Fuego, Antártida e Islas del Atlántico Sur.

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Isla Grande de Tierra del Fuego and Isla de los Estados Peatlands

Adolfina Savoretti, Juan Federico Ponce, Claudio Roig, and Andrea Coronato

Abstract This chapter highlights different aspects of origin, vegetation development and uses of Tierra del Fuego and Isla de los Estados peatlands. Most peatlands in the region were formed when the Last Glaciation was ending, during the Late Glacial period (between 19,000 and 11,500 years BP), while the active glaciers were receding. In peatlands, plant communities vary their composition along the time related to climatic and hydrological changes taking place during its formation. These changes are recorded in the succession of plant macro-remains preserved *in situ.* According to the dominant species, peatlands of Tierra del Fuego may be classified into three main types: *Sphagnum* or raised bogs, *Astelia* or cushion bogs and *Carex* or sedge fens. Uses of peat deposits are made principally on *Sphagnum magellanicum* bogs base on its particular properties. Different uses of the peat material can be mentioned: fuel, solid base for leguminosae inoculants, industrial absorbents for oil and hydrocarbons, orchid intensive culture, mushroom casing, aquariums and biofertilizers.

Keywords Peatbog · *Sphagnum* · Mining

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1 Introduction

Peatlands are wetlands in which the organic matter production is higher than its decomposition (Clymo 1984). As a result, considerable amounts of organic matter accumulate along thousands of years (Vitt and Wieder 2009). This organic matter is mainly formed by remaining fragments of partial decomposition of those plants which once lived on the peatland surface (Vitt and Wieder 2009). Several factors have an influence on its origin and preservation, such as a positive humidity balance (lower evaporation than precipitation), high relative humidity, geological and topographic conditions that favor water retention, low substrate pH and nutrients availability (Clymo 1984). Water saturation leads to a low oxygen content which added to low temperatures along the year inhibit microorganism's activity (fungi and bacteria), which produce the decomposition of dead vegetal matter. This is the way in which vegetal matter is decomposed at a lower rate than it is produced, allowing the accumulation of peat (Rydin and Jeglum 2006).

Peatlands are formed by two main layers: the upper one, aerobic, called acrotelm and a lower one, anaerobic, the catotelm (Vitt and Wieder 2009). The vascular plants (herbs, shrubs and trees) produce less biomass and decompose faster than the bryophytes (mosses and liverworts), which are dominant at the soil layer (Vitt and Wieder 2009). The surfaces of peatlands are covered by a continuous moss surface and most of the biomass occurring in this layer is represented by the material of the cell walls, which decompose more slowly. According to studies carried out in Canada, accumulated peat is material from bryophytes in a high percentage (Janssens 1990; Vitt and Wieder 2009).

As mentioned above, geological and geomorphologic conditions have an influence in the development of these ecosystems (Coronato et al. 2006). A peatland formation is favored by the occurrence of basins or closed depressions where small lakes or ponds are formed. This type of landscape is mainly associated to areas, which have been previously exposed to erosive glacial action, such as the basin of glacial valleys (Ponce et al. 2014). The glacier erosive task over the rock or sediment along which it flowed originated this kind of basins or depressions. Other types of depressions may be formed between glacial or glaciofluvial sediment accumulation landforms under or near the front of the glacier. Later, when the glacier retreated and left such depressions free, the small basins were flooded, either due to surface water runoff from the side slopes or to the occurrence of high phreatic water, giving birth to Lakes and ponds (Fig. 1a, b). Later, the lowering of the depth of these freshwater bodies, together with the growth of vegetation associated with waterlogging areas, produced a gradual advance and colonization by the vegetation over the water body, thus forming the peatlands (Ponce et al. 2014) (Fig. 1c, d).

Changes given to its drainage conditions may arise variations in the type of vegetation, leading to forming more than one type of peat material within the same peatland (Fig. 1e). Peatlands may also occur near streams and rivers, on the flooding plains and abandoned meanders. In the first three cases, which are flat, inefficient drainage conditions favor the waterlogging of large areas, thus allowing the growth of typical

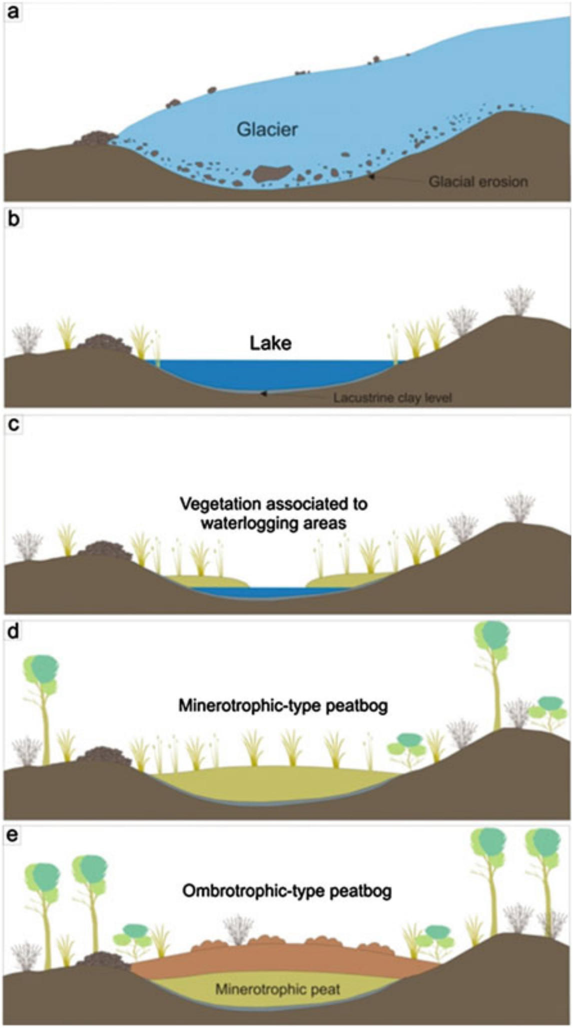

Fig. 1 Peatbog formation and evolution in the southern section of Isla Grande de Tierra del Fuego (modified from Ponce et al. 2014)

peatland vegetation; whereas in the latter, aquatic plant species start living within the residual waterlogging areas, starting the process of colonization and plant succession (Ponce et al. 2014).

2 Previous Works About Peatlands Classification in Tierra del Fuego

Among the several authors who produced valuable information about the peatlands of Tierra del Fuego Bonarelli's work (1917) must be highlighted. He carried out several classifications of peatlands in Tierra del Fuego, mainly based on different environments of origin, flora, peculiarities of the subsoil, chemical composition and climatic factors.

Some decades later, Roivainen (1954) made an important contribution when defining precisely the plant communities typical of the different types and subtypes of peatlands in Tierra del Fuego. He summarizes the spatial distribution according to three regional types: 1. Sedge mires, 2. *Sphagnum*-bushy peatbogs and 3. Rain peatbogs.

Auer (1965) interpreted the regional distribution of peatlands in Tierra del Fuego separately from the rest of Patagonia, pointing out the transition of the "Fuegian" peatlands from the mountain environment in the southwest to the seashore to the northeast. He made out profiles in several peatbogs, which show the variations on their thickness. Based on types of vegetation, latitude, altitude and environmental conditions, he defined six categories according to a latitude distribution, from north to south: steppe, transitional, *Sphagnum*, transitional and rainy area regional peatlands.

Pisano (1977) classified peatlands in three categories with several subtypes:

(a) Raised peatlands: including communities from the Magellanic tundra dominated by up-raised cushion bryophytes, over the general surface and over the secondary water table.
(b) Pulvinated peatlands: including not-raised peatlands over the "mineralized" phreatic water, which overlays the landscape. They are found in areas with higher rainfall than the raised peatlands.
(c) Graminoid peatlands: are those dominated by graminoid types, where these plants represent over 50%.

In his detailed floristic work, Moore (1983) described the peatlands developed in each vegetation unit of Isla Grande de Tierra del Fuego:

1. Deciduous Forest
    - *Sphagnum* bog: communities dominated by *Sphagnum magellanicum*, codominanted by *Empetrum rubrum*, with different species of *Carex*, *Gunnera magellanica*, *Marsippospermum grandiflorum*, *Perezia lactucoides*, *Gaultheria pumila*, *Tetroncium magellanicum.*
    - *Marsippospermum* bog: *Marsippospermum grandiflorum* is the dominant species, and cushion mosses, principally *Sphagnum* and liverworts are important components.

2. Evergreen Forest

   - *Sphagnum* bog: *Sphagnum* associations are similar to those described above, but there are also present *Donatia fascicularis*, *Oreobolus obtusangulus*, *Schoenus andinus*, *Senecio trifurcatus* and *Pilgerodendron uviferum.*

3. Magellanic Moorland

   - Cushion bog: *Astelia pumila*, *Bolax caespitosa Caltha dioneifolia*, *Donatia fascicularis*, *Drapetes muscosus*, *Gaimardia australis*, *Phyllachne uliginosa* are the most important cushion species.
   - Graminoid bog: *Schoenus antarticus*, *Tetroncium magellanicum* and *Carex kingii* are the dominant components, commonly associated with the cushion bog species listed above.

Roig (2000) presented a classification of the peat-producing vegetation communities of Tierra del Fuego aiming at defining those plant communities which are peat deposits producers. They may be summarized in the following: "*praderas turbosas*" (peaty grasslands), "*vegas* or *mallines*" and peatlands.

Finally, Amigo et al. (2017) reviewed and clarified the nomenclature of peatlands from Valdivian-Magellanian area based on plant-sociology data, defining four groups: (a) cushion bogs, (b) *Sphagnum* bogs, (c) "montane tundra" bogs and (d) sedge-grass bogs.

3 Peatlands at Isla de Los Estados

There are extensive peatlands in Isla de los Estados. There are mainly three types to be included in Zone 5 within Auer (1965) classification:

1. Sedge fens, with Cyperaceae, Juncaceae and other associated species such as *Astelia pumila*, *Drosera uniflora*, *Empetrum rubrum*, lichens and ferns (Niekisch and Schiavini 1998, unpublished).
2. *Sphagnum*-dominated bogs, where the peatmoss forms cushions accompanied by Cyperaceae, Juncaceae and Droseraceae (*Drosera uniflora*). It presents similar features to those of the peat deposits prevailing in the Isla Grande de Tierra del Fuego (Kühnemann 1976).
3. *Astelia pumila*-dominated bogs, where *Caltha appendiculata*, *C. dioneifolia*, *Marsippospermum grandiflorum* and *Empetrum rubrum* occur as secondary elements. This type of bog is found in the eastern section of the Isla Grande de Tierra del Fuego (Roig 1998).

4 Origin and Main Features of Tierra del Fuego Peatlands

Tierra del Fuego concentrates over 95% of the total area of peatlands within Argentina (Rabassa et al. 1996), spread basically along the bottom of valleys in the southern region of Isla Grande (Fig. 2). The average thickness of peatlands in Tierra del Fuego is around 4 m, but some are over 11 m deep fully containing deposits of organic matter (Ponce et al. 2014).

Most peatlands in the region were formed when the Last Glaciation was ending, during the Late Glacial period (between 19,000 and 11,500 years BP), while the active glaciers were receding. All along this last cold event, the Archipelago of Tierra del Fuego was covered by glaciers to a large extent (Rabassa et al. 2000). In the Main Island almost 50% of the area (about 22,500 sq.km) was covered by ice during the last Ice Age. In Isla de los Estados, the ice cover would have been almost complete (Ponce and Rabassa 2012). All along the Beagle Channel, Fagnano lake and Lasifashaj valley were taken up by some of the most extensive of the archipelago (Rabassa et al. 2000). When the last Ice Age was finishing the valleys formerly occupied by glaciers were partly taken up by lakes and large rivers. Later on, changes in the drainage of the basins and a milder climate allowed the vegetation to colonize shallow-pond basins as well as peatlands to occur at the bottom of the former glacial valleys (Ponce et al. 2014).

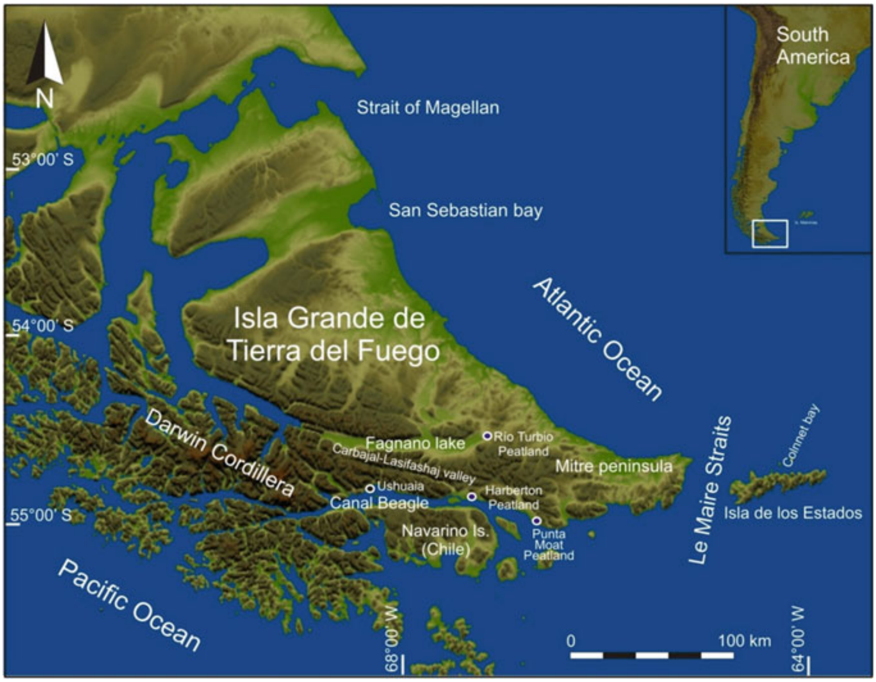

Fig. 2 Isla Grande de Tierra del Fuego and Isla de los Estados location map

The oldest record of a peatland in the argentine section of Isla Grande is found in Estancia Harberton, 55 km east of Ushuaia city, on the northern coast of the Beagle Channel. This bog threw an age of around 20,000 years and a depth of 11 m (Savoretti 2018). The oldest peatland found so far in Isla de los Estados is in Bahía Colnnet, on the northern coast, which is 16,000 years old and about 8 m deep.

5 Plant Composition

As seen in the different classifications of peatlands of Tierra del Fuego, the plants occurring depend on each type. Besides, these plant communities vary their composition along the time related to climatic and hydrological changes taking place during the Quaternary. These changes are recorded in the succession of plant macro-remains preserved within peatlands (e.g., Mauquoy et al. 2004; Mauquoy and van Geel 2007; Van der Putten et al. 2012; Echeverría 2016; Savoretti 2018). Macro-remains are those plant fragments, which are recognizable at first sight and are 0.5–2 mm in average (Dickson 1986; Birks 2017; Mauquoy et al. 2010). The study of these remains in peat-cores allows to find out changes in the plant composition that forms peatlands along the time, and make paleoenvironmental reconstructions and paleoclimate inferences.

The vegetation of the most abundant three types of Tierra del Fuego peatlands (*Carex*, *Sphagnum* and *Astelia*) is here presented as examples. Raised *Sphagnum magellanicum* bogs are widely distributed in the southern section of Isla Grande, *Astelia pumila* cushion bogs are common along the coast of Mitre Peninsula and in a wide range in Isla de los Estados, and *Carex* or sedge fens growing mainly in the northern section of Isla Grande.

Then the past plant composition is described qualitatively through the macro-remains that make the *Sphagnum* bog.

5.1 Harberton Bog

It is located on the northern coast of the Beagle Channel, surrounded by *Nothofagus betuloides—N. pumilio* forest. It is an ombrotrophic-raised bog dominated by *Sphagnum magellanicum* (Figs. 2 and 3). This peatland is within an inter-drumlin depression, in a drumlin field (Rabassa et al. 1990). It has an area of about 0.5 km^2 (Loisel and Yu 2013).

The vegetation is represented by:

Vascular plants: *Empetrum rubrum*, *Nothofagus antarctica*, *Carex magellanica*, *Rostkovia magellanica*, *Gaultheria pumila*, *Marsippospermum grandiflorum*, *Caltha appendiculata*, *Drapetes muscosus*, *Nanodea muscosa*, *Tetroncium magellanicum*, *Avenella flexuosa*, *Carex* sp., *Deyeuxia poaeoides*, *Luzula alopecurus*, *Juncus scheuchzerioides* (Roig et al. 2004).

Fig. 3 Aerial view of Harberton bog located on the northern coast of the Beagle Channel. It is an ombrotrophic-raised bog dominated by *Sphagnum magellanicum*

Bryophytes (mosses and liverworts): *Sphagnum magellanicum*, Metzgeriales, *Polytrichum juniperinum*, *Sphagnum fimbriatum*, *Racomitrium geronticum*, *Bryum pallens*, *Orthodontium linneare*, *Pohlia nutans*, *Campylopus* sp., *Dicranoloma imponens*, *Dicranoloma robustum*, Amblystegiaceae, *Noteroclada confluens* (Roig et al. 2004; Savoretti 2018).

Lichens: *Cladina* sp., *Cornicularia aculeata*, *Cladonia cornuta*, *Sticta* sp., *Parmelia* sp. (Roig et al. 2004).

5.2 Moat Bog

It is a cushion bog dominated by *Donatia fascicularis* cushions and *Astelia pumila* grasses, showing an irregular micro-topography with abundant freshwater ponds (Pisano 1977). The peatland covers an area of 1.7 sq. km and it is located east of Moat river, less than 1 km away from the coast of the Beagle Channel. It is surrounded by the Magellanic evergreen forest represented by *Nothofagus betuloides* and *Drimys winteri* (Heusser 1995; Borromei et al. 2014) (Figs. 2 and 4).

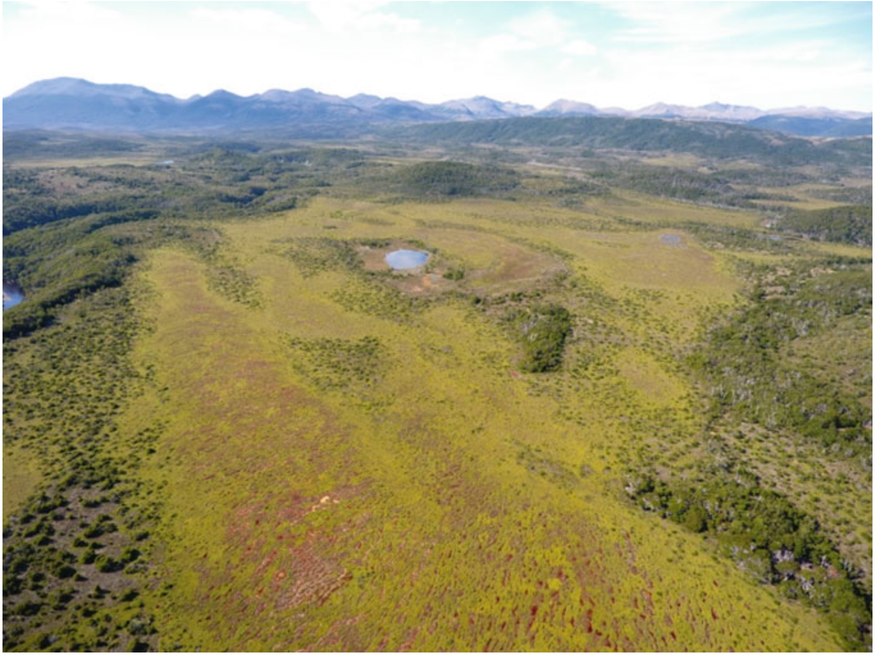

Fig. 4 Aerial view of Moat bog located in easternmost Beagle Channel. It is a cushion bog mostly made of *Donatia fascicularis* cushions and *Astelia pumila* grasses

The vegetation is exemplified by:

Vascular plants: *Caltha dioneifolia*, *Drapetes muscosus*, *Tetroncium magellanicum*, *Schoenus antarcticus*, *Gaimardia australis*, *Uncinia kingii*, *Acaena pumila*, *Drosera uniflora*, *Gaultheria antarctica*, *Gunnera lobata*, *Marsippospermum grandiflorum*, *Myrteola nummularia*, *Nanodea muscosa*, *Perezia magellanica*, *Gaultheria pumila*, *Tapeinia pumila*, *Tribeles australis*, *Berberis ilicifolia*, *Chiliotrichium diffusum*, *Embotrhium coccineum*, *Empetrum rubrum*, *Escallonia serrata*, *Philesia magellanica* (Moore 1983; Borromei et al. 2014).

Bryophytes (mosses and liverworts): *Sphagnum falcatulum*, *S. magellanicum*, *Dicranoloma billiardieri*, *D. chilense*, *D. imponens*, *D. robustum*, *Campylopus* sp., *Bryum pallens*, *Pohlia nutans*, *Lejeunea* sp. and Metzgeriales (Savoretti 2018).

5.3 Río Turbio Fen

It is a minerotrophic-type peatland (fen) dominated by the family Cyperaceae and different mosses species mainly of the family Amblystegiaceae (called *Carex curta* flooded peatbog by Roig et al. 2004). It is located east of Lake Fagnano, in the central area of the Isla Grande, surrounded by *Nothofagus antarctica* forest (Figs. 2 and 5).

The vegetation is represented by:

Vascular plants: *Carex canescens*, *Alopecurus magellanicus*, *Agrostis meyenii*, *Festuca contracta*, *Carex magellanica* and *Nothofagus antarctica* (Roig et al. 2004).

Bryophytes (mosses and liverworts): *Scorpidium revolvens*, *Sanionia uncinata*, *Sphagnum frimbriatum*, *S. magellanicum*, *Breutelia integrifolia*, *Brachythecium* sp., *Bryum laevigatum*, *Bryum pallens*, *Dicranella* sp., *Distichium* sp., *Syntrichia robusta*, *Marchantia* sp. (Savoretti 2018).

Fig. 5 Aerial view of Río Turbio fen located at east of Fagnano Lake. Minerotrophic-type peatland dominated by the family Cyperaceae and bryophytes

6 Changes in Composition of Peat-Forming Vegetation over Time: The Case of Harberton Bog

A general characterization of plant composition in depth of a *Sphagnum magellanicum* bog is presented and a paleoenvironmental reconstruction for the last 19000 years Cal. BP it is also mentioned (Fig. 6). This is the most mined type of peatland in Tierra del Fuego. The description of plant macro-remains composition was made out of a 1035 cm long peat core taken from Harberton bog. Vegetation zones and subzones were defined base on the exhaustive examination of macro-remains. Each delimitated zone represents a particular plant association, allowing a local paleoenvironmental reconstruction (modified from Savoretti (2018), see methodology therein).

- Zone HB-A (1035–550 cm)

The sedimentary features in the tract 1035–550 cm vary from gytjja to dark brown peat very humified to humified, quite compacted. The content of plant macro-remains is dominated by herbaceous and Bryopsida (non sphagnaceous mosses). *Sphagnum magellanicum* is found in low concentrations compared to Zone B.

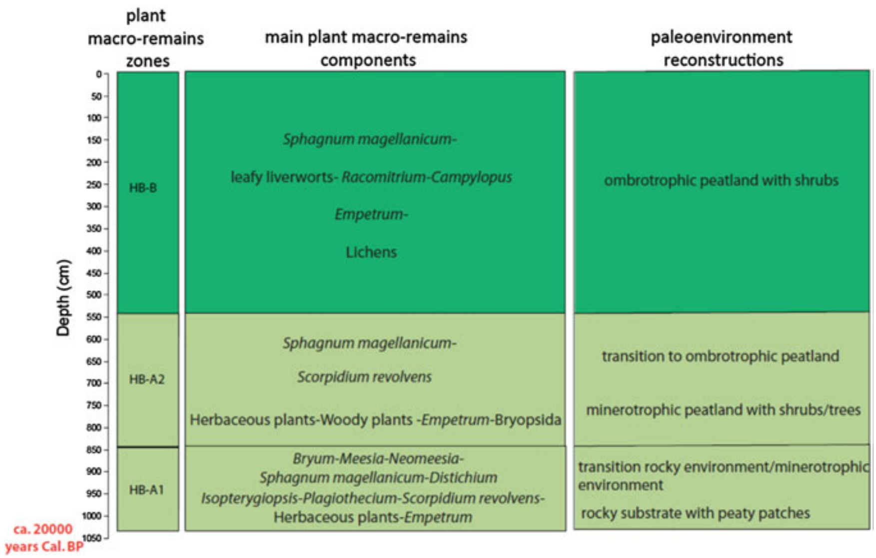

Fig. 6 Changes in plant macro-remains composition of 1035 cm Harberton peat-core, Tierra del Fuego. It is also detailed the paleoenvironmental reconstructions principally inferred from plant macro-remains content (modified from Savoretti 2018)

- Zone HB-A1 (1035–850 cm)

In this subzone 8 bryophyte taxons are recognized. It is the most diverse subzone of the group. Among the best-represented taxons are the mosses *Isopterygiopsis* sp., *Plagiothecium* sp. and *Scorpidium revolvens*. Vascular plants are found in high concentrations, the herbaceous plants being the most abundant; another important component are the Ericaceae seeds.

- Subzone HB-A2 (850–550 cm)

Vascular plants are dominant in this subzone, mostly represented by the herbaceous. Besides, *Sphagnum magellanicum* macro-remains were found at a similar rate as Bryopsida. *Scorpidium revolvens* is represented at a lower rate.

- Zone HB-B (550–0 cm)

The sedimentary features in the tract 550–0 cm vary from reddish humified to little humified peat with brown peat material alternatively. The content of plant macro-remains is dominated by *Sphagnum magellanicum*, while the concentration of vascular plants, as well as the concentration of Bryopsida, are very low compared with Zone HB-A. Remains of leafy liverworts and lichens (*Cladonia* sp.) were recognized only in the upper part of this zone. From 25 to 0 cm, there is a strong decrease of *Sphagnum magellanicum* with lichens and an increase in the concentration of liverworts.

7 Peat Mining and Commercial Value

Peat deposits from inner part of peatlands have been used since the twelfth century, as a low-calory fuel. From 1930 onward, first attempts for using peat with horticultural purposes, due to a set of physical and chemical properties which allow to develop a wide spectrum of growing media for intensive indoor cultures. The moss *Sphagnum* (with over 300 species at a global scale, according to Anderson et al. 2009) is at present one of the most appreciated for horticulture.

In the last two decades, new peat-based applications have been developed, based on different types of mosses and including the live moss on the peatland surface. Some of them are solid base for leguminosae inoculants, industrial absorbents for oil and hydrocarbons, orchid intensive culture, mushroom casing, aquariums, biofertilizers, etc.

Peat production in Tierra del Fuego started in 1970 and is regulated by the Minery Code (Código Minero) of Argentina. Local production is not enough to cover the national demand, this is why Argentina imports peatmoss from the North Hemisphere countries as Canada, Germany, Finland, Lituany, Estony, among others.

Before starting mining, peatlands must be drained to decrease the water level and allow low-weight machinery to enter the mine. Handy-scale mining peat is cut with

Fig. 7 Peat mining in a *Sphagnum magellanicum* bog from Tierra del Fuego. Peat is cut with shovels and is stored on "secaderos" in order to reduce its water content

shovels and is stored on outdoor "secaderos" (drying structures) in order to reduce its water content to ± 30%. Then the blocks are transported out of the peatland where it is milled and packed (Fig. 7). Most of Tierra del Fuego production is used within Argentina, which implies a high transportation cost to the main demand areas, at least 3,000 km.

Peat production and import statistics, from 1999 to nowadays, show a progressing increase; it has been higher than 10,000 tons/year since 2004, with a peak of 18,000 tons in 2017, out of which 12,000 tons were produced in Tierra del Fuego (Fig. 8). In trade terms and considering the period 2007–2017, Argentina imported a total of peat for US$ 16 million and purchases in the inner market for US$ 20 million (Fig. 9).

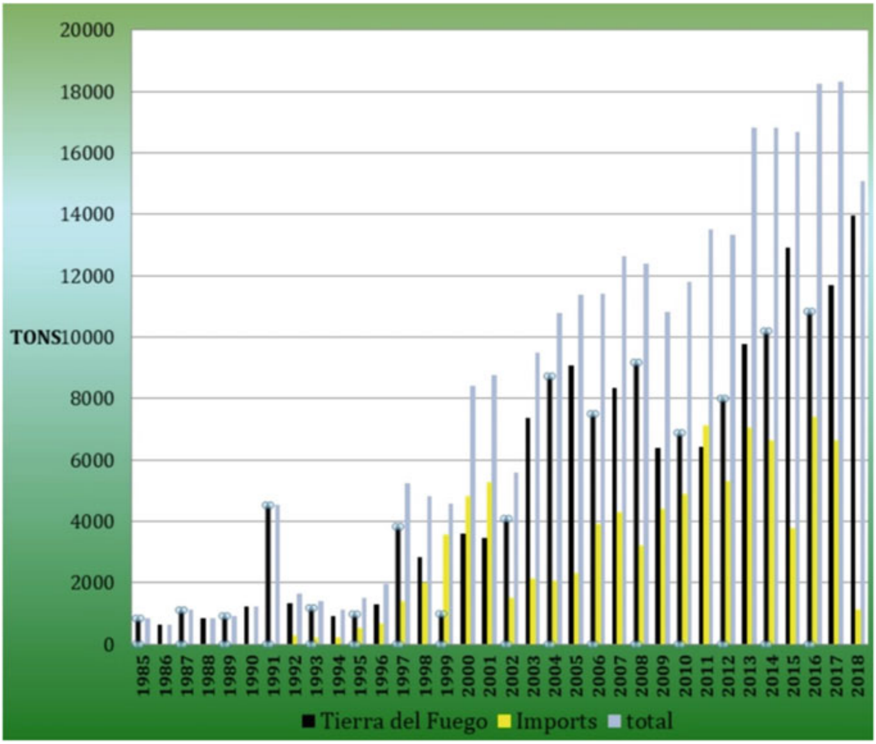

Fig. 8 Peat production in Tierra del Fuego and Argentine imports (tons)

Despite since 2011 Tierra del Fuego has implemented a strategy for the correct use of peatlands (Iturraspe 2016), it is necessary to elaborate conservation policies. This will be possible if studies on peatland restoration rate are carried out. By this reason, the continuity of studies on the biodiversity of Tierra del Fuego peatlands is essential.

8 Final Remarks

Tierra del Fuego peatlands are unique environments because of their geographical location, floristic and hydrological features and ecosystem significance (Rabassa et al. 2006). Another important aspect refers to their continuous growth and accumulation pattern making possible paleoclimatic and paleoenvironmental reconstructions at regional and local scales base on different proxy records (e.g. palynolomorphs, plant macro-remains, diatoms, atmospheric dust (Rabassa et al. 2006; Ponce et al. 2014)). Peatlands also have essential roles in the Carbone Cycle as natural methane sources

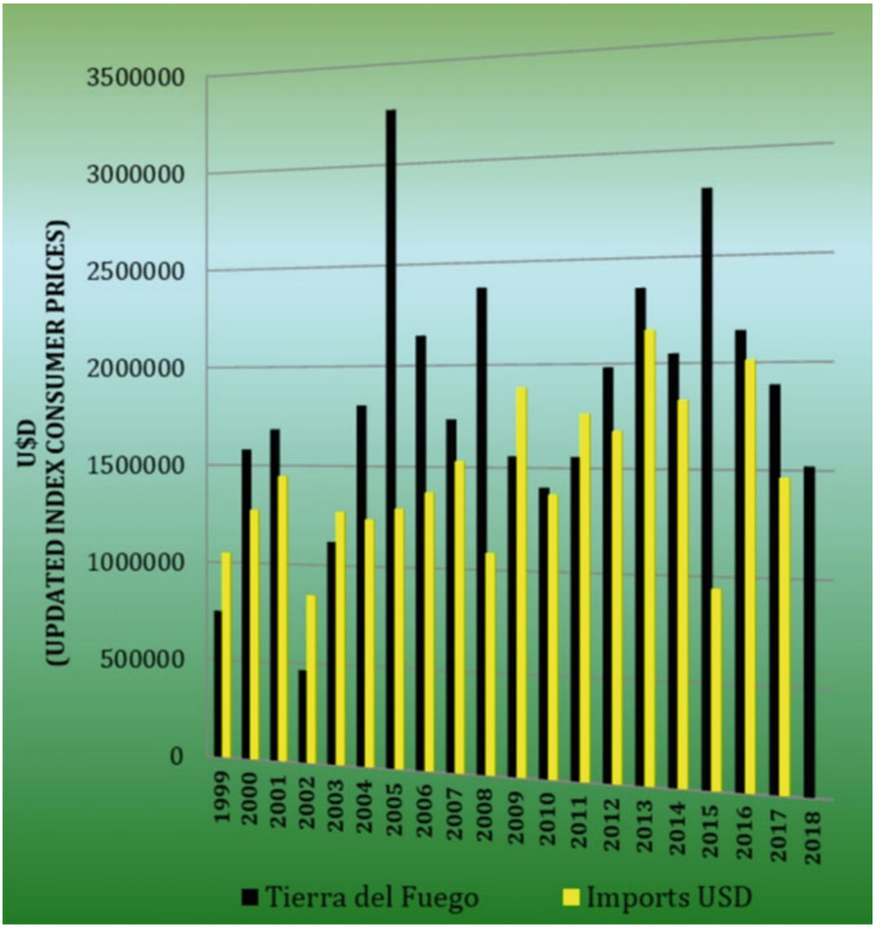

Fig. 9 Peat production in Tierra del Fuego and Argentine imports (US$)

(Münchberger et al. 2019) and as providers of freshwater, enhancers flood regulation capacity, improvers of water quality, and diminish soil erosion (Iturraspe 2016).

Great peatland extensions and their unique physiognomy between all the other ecosystems make them an important tourism attractive; winter sports plus recreational activities on them produce economic profit in Tierra del Fuego (Iturraspe 2016). Environmental and hydrological peatland conditions provided by the dominant vegetation (e.g. *Sphagnum magellanicum*, *Astelia pumila-Donatia fascicularis*) allow the development of a notable diversity of organisms such as mosses, liverworts and lichens, and they, for example, play a key role in bird nesting. Despite most of the Tierra del Fuego peatlands are in pristine conditions, the environmental problems of them generally increase as the regional population increases (Iturraspe 2016).

Giving people information about peatland origin, age of formation, types, biodiversity they hosted and their landscape values and functions is essential to make possible conservation actions in these particular environments.

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Lakes and Glaciers from Fuegian Andes. Morphology, Distribution and Origin

Cristina N. San Martín, Juan Federico Ponce, and Andrea Coronato

Abstract The intense glacial activity produced in the Fuegian Andes during the Quaternary period generated numerous erosive glacial landforms with abundant depressions, many of which presently are occupied by glaciers and freshwater lakes. A characterization of these glaciers and lakes is presented based on their geomorphological distribution, morphology and origin. The glaciers in the argentinian sector of the Fuegian Andes occupy cirques placed between 880 and 1380 m a.s.l. and are less than 1 km^2 in area. The lakes are distributed in cirques, glacial valleys, transfluence glacial surfaces (cols), interdrumlin areas, and on slopes and areas of scouring. Lakes are located between 17 and 1057 m a.s.l. and most of them have an area of less than 0.1 km^2. The origin of lakes located in lower elevations goes back to glacial retreat after the Last Glacial Maximum. The lakes in hanging valleys would have developed after 11,700 yr cal. BP, when the glaciers retreated from moraines corresponding to the Younger Dryas. Cirque lakes would have been the last to develop. The presence of Little Ice Age moraines allows us to assign a relative age to some of these lakes. At present, new lakes continue to develop and appear in cirques as the glaciers retreat. These glaciers and lakes of the Fuegian Andes constitute geological resources of tourist and scientific interest, and serve as freshwater reservoirs, lending importance to their preservation and study.

Keywords Lakes and glaciers · Glacial geomorphology · Glacial retreat · Freshwater reservoirs

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1 Introduction

Glaciers and lakes constitute freshwater reservoirs. Both are part of the annual hydrologic cycle being many of them connected into the same basins where they act as hydric regulators. Glaciers are considered as excellent past and present climatic change indicators. The global warming has produced a glacier retreat which is reflected in the growth and emergence of new lakes. Historically lakes have had importance for the societies, specially as freshwater resource, but also they provide food, transportation and energy.

This chapter presents a geomorphological and morphometric characterization of glaciers and lakes in the argentine sector of the Fuegian Andes in the Isla Grande de Tierra del Fuego and Isla de los Estados (Fig. 1). In addition, a simplified chronology is proposed for the different lakes based on their geomorphological location.

The Fuegian Andes are located in the southern sector of Isla Grande de Tierra del Fuego, to the east of Patagonian orocline (Cunningham 1993), and extend as far as Isla de los Estados. It is the only portion of the Andean mountain range with WNW-ESE orientation. This mountainous system is controlled by W-E and WNW-ESE trending fault systems (Cunningham 1993; Klepeis 1994), and their height decreases from W to E and from S to N. They constitute the lowest Andean peaks of Patagonia. Like much of the Isla Grande de Tierra del Fuego, they were repeatedly glaciated during the different Pleistocene glaciations (Coronato et al. 2004a, b). This intense glacial activity has generated a series of erosive glacial landforms in the landscape;

Fig. 1 Location of the Fuegian Andes and mentioned places

among these cirques and U-valleys are distinguished by their abundance. Glaciers, tarns, lakes and peat bogs currently occupy the floor of these cirques and U-valleys (Coronato 1995a; Rabassa et al. 2000).

The study area has a temperate-humid climate influenced by the Antarctic and Subantarctic air fronts of the South Pacific anticyclone (Tuhkanen 1992). The average annual sea level temperature is 5.9 °C; at the treeline (elevation of 600 ±100 m) average annual temperature is 2.4 °C (Puigdefábregas et al. 1988). The dominant winds come from the W–SW and the average annual precipitation at sea level is 546 mm/year. Precipitation presents a W–E gradient along the Beagle Channel, from Darwin Cordillera (2000 mm) to Punta Moat (600 mm) (Fig. 1). Between Lapataia and Punta Moat, annual precipitation values at sea level vary between 500 and 600 mm. To the east of Punta Moat, there is a steeply increasing gradient to reach annual values of 1000 mm in the eastern end of Isla Grande de Tierra del Fuego and Isla de los Estados, as a result of the direct entry of sea air masses from the south, free of orographic obstacles. In higher elevation areas, there are no instrumental records, but statistical calculations suggest that at an elevation of 535 m a.s.l., precipitation is three times higher than at sea level (Iturraspe et al. 1989).

The rocks in the Fuegian Andes correspond to Lapataia, Lemaire, Yahgán and Beauvoir formations (Upper Paleozoic-Lower Cretaceous). These are extensively deformed metamorphic rocks with many folds and faults. The Lemaire Fm. has the largest outcrop area and consists mainly of schists and slates. The Yahgán and Beauvoir formations comprise mostly slates resulting from the metamorphism of marine sediments. The valley floors and depressions are covered by glaciofluvial deposits and till from Pleistocene and Holocene glacial activity (Olivero et al. 2006).

The Beagle Channel and the Fuegian Andes were occupied by an extensive network of glaciers during the Last Glacial Maximum (LGM, ca. 25 ka cal BP, Rabassa 2008). Large outlet glaciers of the Darwin Cordillera (2000 m a.s.l., 55˚S 69˚W) ice cap flowed north and eastward to reach the present Atlantic submarine platform. These followed large, deep valleys known today as the Magellan Straits, Inútil Bay-San Sebastián Bay, Lake Fagnano, Carbajal-Lasifashaj valley and the Beagle Channel (Rabassa et al. 2000; Rabassa 2008). Cirques and high valleys of the Fuegian Andes were occupied by alpine glaciers which converged with the outlet glaciers and generated a glaciated regional network (Coronato 1995a, b).

Geomorphological evidences in tributary valleys of the Fuegian Andes made it possible to identify frontal moraines that indicate glacial advances after the LGM, during the Antarctic Cold Reversal (14,500–12,900 cal. yr BP) and the Younger Dryas (12,900–11,700 cal. yr BP) (Menounos et al. 2013). In cirques and hanging valleys of the Fuegian Andes, several moraines related to glacial advances during the Holocene have been identified (Rabassa et al. 1990; Strelin et al. 2001; Planas et al. 2002; Menounos et al. 2013; Ponce et al. 2015).

The latest episode of global advance in alpine glaciers is attributed to the Little Ice Age (LIA). The LIA was a cold climatic event that occurred between the 15th and mid-nineteenth centuries, with colder pulses in 1650 AD, 1771 AD and 1850 AD (Compagnucci 2011), which caused the advance of mountain glaciers, the freezing of large low-elevation rivers and the occurrence of stormy periods with anomalous precipitation (Wanner et al. 2008). The low temperatures were caused by a combination of large volcanic eruptions, diminished solar activity and inherent climate variability (Crowley and North 1999; Jansen et al. 2007). In Tierra del Fuego, there are no numerical ages for this event. Moraines located in cirques have been assigned a LIA age based on their position close to the current glacial fronts, fresh and uneroded forms and the absence of vegetation on their surface (Strelin and Iturraspe 2007; Strelin et al. 2008; Maurer et al. 2012; Menounos et al. 2013). These frontal moraines are located at an average height of 680 ± 131 m a.s.l. (Ponce et al. 2015).

Strelin and Iturraspe (2007) studied the evolution and mass balance of glaciers located in the Martial Range, providing data about glacial fluctuations during the Holocene and interpreting their future behavior based on climate models proposed for the next decades. Recently, in the framework of the National Glacier Inventory, the distribution, surface area and orientation of glaciers in the basins of the Rio Grande, Lake Fagnano and Beagle Channel were described (IANIGLA 2017).

2 The Glaciers of the Argentine Sector of the Fuegian Andes

The distribution of glacial coverage in the Fuegian Andes can be separated into two large zones. To the west of the international boundary, in chilean territory, is the Darwin Cordillera. It has altitudes of over 2000 m a.s.l. where the Darwin Cordillera ice field is located, from which outlet glaciers flow that in many cases reach the sea through fjords; to the east cirque and valley glaciers occur. In argentinean territory, the glacial coverage decreases notably due to the lower height of its peaks (less than 1500 m a.s.l.) and a decrease in precipitation. Glacier distribution is restricted to the area between the Beauvoir Range to the north, the mountains located along the north coast of Beagle Channel to the south and the Lucio López Range to the east; there are no glaciers in the Peninsula Mitre and the Isla de los Estados (Figs. 2, 3, 4 and 6). To a lesser extent, partially debris-covered glaciers and active and inactive rock glaciers occur. The last ones are located in the Martial, Beauvoir, Alvear, Vinciguerra, Valdivieso, Sorondo, Lucas Bridges and Lucio López ranges (Figs. 2 and 3). The Beauvoir Range has the highest density of these bodies.

In the area comprising the Alvear, Vinciguerra, Valdivieso, Martial, Sorondo ranges and the western part of the Lucas Bridges Range, 90 cirque glaciers have been identified. They have a total area of approximately 9.2 km^2, and an average area of 0.10 km^2, with a minimum of 0.01 and a maximum of 0.73 km^2. They are located at an average elevation of 1069 m a.s.l., between the elevations of 880 m a.s.l. and 1380 m a.s.l. The equilibrium line altitude (ELA) lies between 1050 and 1150 m a.s.l., about 100 m above the 0 °C isotherm (Iturraspe 2011). Nine percent of glaciers extend above the ELA, 47% are within the limits of the ELA, and 44% are below the ELA. The main glacier orientation is toward the SE quadrant, protected from sunshine and leeward from the predominant SW winds. These conditions allow

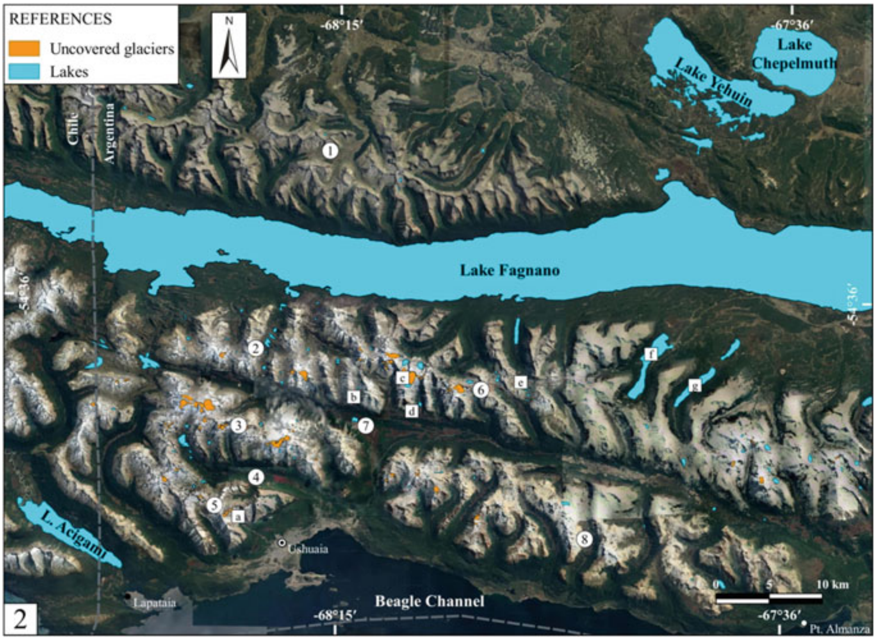

Fig. 2 Lakes and glaciers distribution on the western sector of the Fuegian Andes. (1) Beauvoir Range; (2) Valdivieso Range; (3) Vinciguerra Range; (4) Andorra Valley; (5) Martial Range; (6) Alvear Range; (7) Carbajal-Lasifashaj Valley, (8) Sorondo Range. **a** Martial Glacier; **b** Lake Ceniza; **c** Ojo del Albino Glacier; **d** Lake Esmeralda; **e** Paso Tristen col; **f** Lake Escondido, **g** Lake San Ricardo

lower ablation rates in the ice bodies due to lower insolation and greater conservation of the snow accumulating from precipitation and wind remobilization on windward slopes.

All the glaciers of the argentine territory of the Isla Grande de Tierra del Fuego are in retreat. Many of these were cirque glaciers until a few decades ago but have retreated to form glaciarets with an evident extinction in the coming years if current climatic conditions persist. Studies carried out by Strelin and Iturraspe (2007) indicate stability for the glaciers of Martial Range after the LIA until 1943. Then they recorded a slow decline until 1957, and a new stabilization until 1970. Since that time the authors indicate a continuous and accelerated recession to the present day. In addition, they show that these fluctuations coincide with the temperature and precipitation curves of the twentieth century in Ushuaia. The specific net balance measures are similar to those obtained for 11 mountain glaciers in the world, providing regional Fuegian confirmation of the global retreat trend.

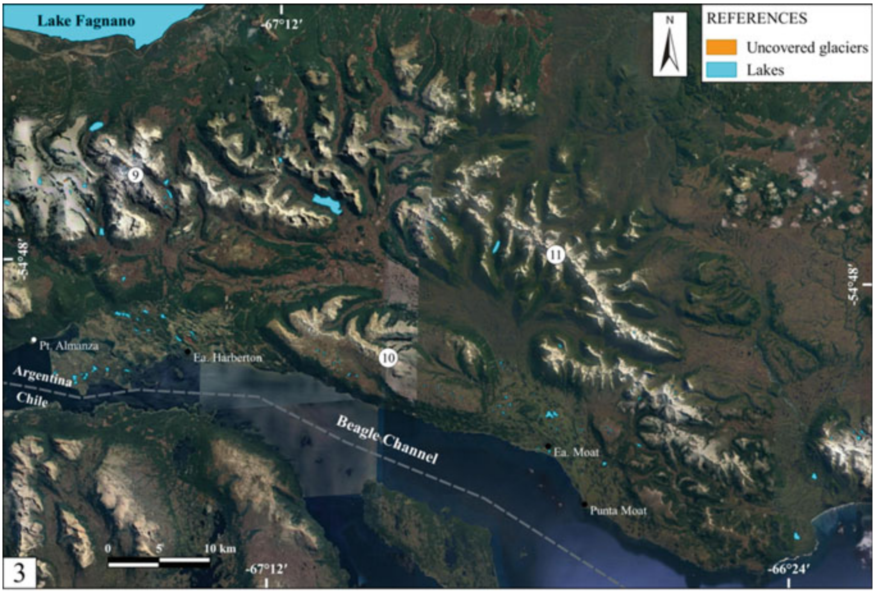

Fig. 3 Lakes and glaciers distribution on the central sector of the Fuegian Andes with the identified lakes and glaciers. (9) Lucas Bridges Range; (10) No-top Range; (11) Lucio López Range

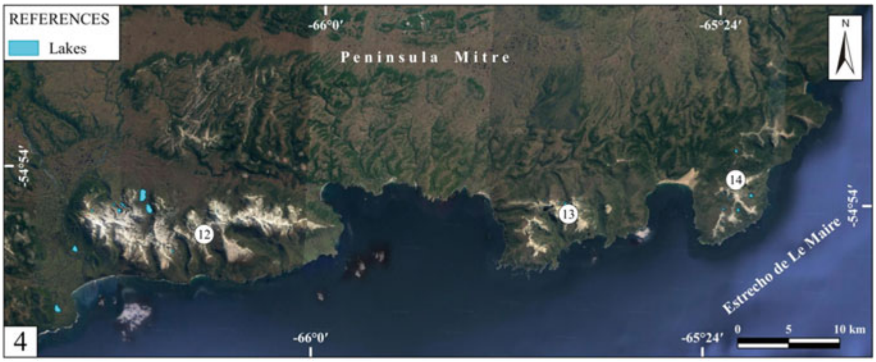

Fig. 4 Lakes distribution on the estern sector of the Fuegian Andes. (12) Lucio López Mts; (13) Atocha Mts; (14) Negros Mts

3 Lakes in the Isla Grande de Tierra del Fuego

A total of 412 freshwater lakes geomorphologically distributed between cirques, valley bottoms of glacial origin, cols, slopes, scoured areas and drumlin fields have been registered in the Fuegian Andes in Isla Grande de Tierra del Fuego. 67% of these water bodies are found inside cirques and glacial valleys. The landforms in which they are located have widely varying orientations, with the most frequent toward the SE. They are located between 17 and 1057 m a.s.l. and the largest proportion (28%) are between 600 and 800 m a.s.l. 83% of these bodies have an area of less than 0.1 km^2. The largest lakes have surface areas of 44.4 km^2 (Lake Yehuin) and 553.5 km^2 (Lake Fagnano or Kami). The water bodies are mainly circular or elliptical in shape, although some irregular shapes also develop. This is due to the underlying rock structures exerting control over glacial erosion, facilitating deepening in areas of weakness and thus controlling basin morphology.

LIA moraines have been identified in the vicinity of 60 lakes. Some lakes develop upstream and others downstream of these moraines. This allows for the establishment of a relative pre- and post-LIA chronology for these water bodies.

3.1 Geomorphological Distribution of Lakes

3.1.1 Cirque Lakes

Cirques are half-open, semicircular-shaped niches or hollows located on mountainsides or in the upper part of valleys. 37% (154) of the total lakes are emplaced on the floor of cirques, however, the area represents only 2.9% (4.23 km^2) of the total lake surface. The predominant orientation of the cirques containing these lakes is toward the SE (29%) and secondly toward the NE (26%). They are located at altitudes between 211 and 1057 m a.s.l. with a major mode (26%) located between 700 and 800 m a.s.l. Their average surface is 0.03 km^2. The shape of these water bodies is mainly circular. This is due to lake emplacement in glacial overdeepenings caused by enhanced glacial erosion within the cirques where sliding velocities were highest, in the old zone of the glacier equilibrium line. The depths obtained in a sampling of these water bodies indicate maximum values between 9 and 18 m.

In the cirques that contain these lakes there are 30 glaciers that provide meltwater to these water bodies (Fig. 5a). At the places where LIA moraines have been identified, 33 lakes are downstream, 7 are upstream and 2 are among moraines.

3.1.2 Lakes of Glacial Valleys

Glacial valleys are erosional landforms. The glaciers flow down into formerly V-shaped river valleys. Glacier erosion greatly modifies the shape of the pre-existing river valleys. The glaciers erode the side slopes and bottom of the valleys through preferential erosion and sediment transport driven by ice movement. The glacial valleys are deepened and flattened and side slopes are steepened, changing their cross-section from V-shaped to U-shaped. 30% (124) of the lakes occur in valley bottoms of glacial origin. The development of many of these valleys, mainly those with W-E orientation, coincides with the presence of geological structures associated with the Fuegian Andes evolution. These structurally controlled valleys contain the

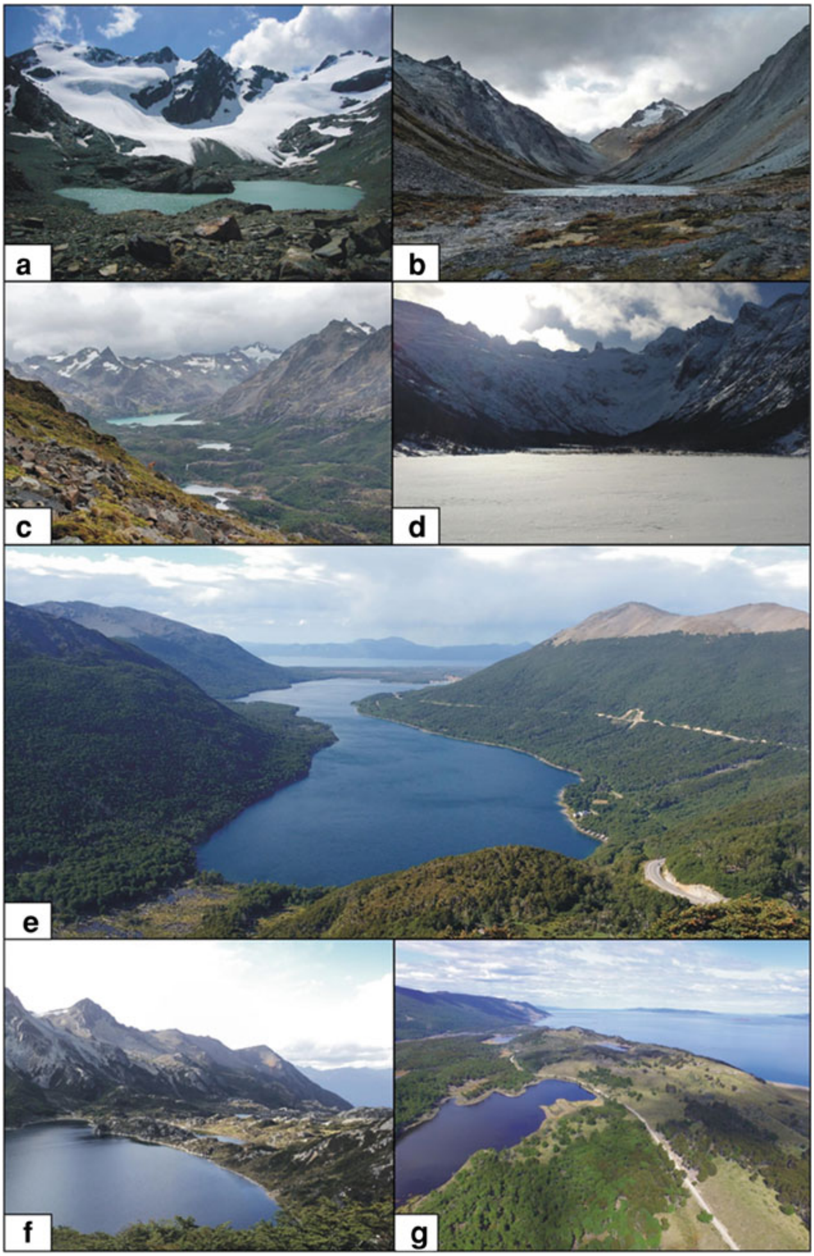

Fig. 5 **a** The Vinciguerra glacier and its proglacial lake. **b** Lake Ceniza located in a U-shaped hanging valley. At the headwater, there is a cirque glacier. **c** Paternoster lakes located in Andorra Valley. **d** The Lake Esmeralda freezes every winter, as do the other lakes of hanging valleys and cirques. **e** Lake Escondido, one of the biggest lakes emplaced in one of the main valleys. **f** Paternoster lakes located in a col (transfluence glacial surface). **g** Lakes in interdrumlins areas at Estancia Harberton

largest water bodies. Areally, they represent 93.5% of the total surface of lakes (Lake Fagnano is not included in this percentage due to its dimensions). The predominant orientation of the valleys containing these water bodies is toward the SE (48%). They occur at altitudes between 17 and 820 m a.s.l. with 23% between 600 and 700 m a.s.l. Their shape is mainly elliptical, extending along the floor of steep-walled valleys, which limits their lateral development and conditions their elliptical morphology. The development of these water bodies can be differentiated between hanging valleys and deep valleys.

Hanging valleys: Hanging valleys are typically formed when the main valley has been widened and deepened by glacial erosion, leaving the side valley abruptly cut off from the main valley below. There is a steep drop from the hanging valley to the main valley floor. The hanging valleys contain a total of 85 lakes (Fig. 5b). Some water bodies are arranged in series, forming paternoster lakes (for example, the paternoster lakes of the Andorra Valley) (Figs. 2 and 5c). The main orientation is toward SE (42%). They have a total surface of 6.78 km^2, representing 4.6% of the total lakes, with an average surface area of 0.08 km^2. The average elevation is 514 m a.s.l. The depths obtained in a sampling of these water bodies indicate values between 7.5 and 11 m. The surface of these lakes freezes in winter; ice thicknesses between 0.30 and 0.48 m has been measured in Lake Esmeralda and Lake Ceniza (Fig. 5d). At the headwaters of these valleys, glaciers occur whose meltwater drains into 31 of these lakes. In addition, there are 16 lakes located downstream of LIA moraines.

Deep glacial valleys: These valleys were generated by the largest and most erosive collecting glaciers, which received the contribution of tributary glaciers that flowed through the current hanging valleys. In these, there are 38 water bodies, among which are those with the largest surface area and longitudinal extent (Fig. 5e). The main orientation is toward the SE (23). The average elevation is 151 m a.s.l. Maximum depth data have been obtained for some of these water bodies such as Lake Acigami (80 m in the argentine sector), Lake San Ricardo (24 m), Lake Escondido (67 m) (Iturraspe et al. 1989) and Lake Fagnano (210 m). They represent 89.4% of the total area of water bodies, some of the larger being Lake San Ricardo (3 km^2), Lake Escondido (6.2 km^2) and Lake Acigami (17.7 km^2). The largest are Lake Chepelmuth (38.2 km^2), Lake Yehuin (44.4 km^2) and Lake Fagnano (590.3 km^2). Lakes Acigami and Fagnano basins extend into the territories of Argentina and Chile.

Lake Fagnano or Kami located in the center of Tierra del Fuego Island (54°S, ~68°W; 26 m a.s.l.) in both the Argentinean and Chilean territories, 94 and 6%, respectively. The lake is 105 km E-W long, 2.8 to 9.8 km wide and covers an area of 590.3 km^2. The lake basin has evolved along a portion of the Magellan-Fagnano Fault System developed along the transform boundary between the South American and Scotia plates (Fuenzalida 1972; Dalziel 1989) and was deepened by glacial activity during the Pleistocene. The lake comprises two subbasins: a smaller, deeper basin in the east reaching a maximum depth of 210 m, and an elongated, shallower basin in the west exhibiting ~110 m maximum water (Waldmann, et al. 2008). This is one of the most important glacial areas of southernmost South America, due to the extensive glaciated surfaces and the large volume of the glacier network that covered the region during the LGM (Coronato et al. 2009).

3.1.3 Lakes in Cols (Transfluence Glacial Surfaces)

These are almost horizontal, topographically elevated surfaces that connect the head and/or walls of two opposite or contiguous valleys. They originate due to the erosion of two adjacent and opposite glaciers. At times of maximum glaciation, the glaciers passed from one valley to another through these areas. 7% (29) of lakes are developed on these surfaces. Some water bodies are arranged in series, forming paternoster lakes (for example, the paternoster lakes of the Paso Tristen col) (Figs. 2 and 5.f). The orientation of these water bodies is highly varied, with N, SE and NW being the main orientations (7 Lakes oriented in each direction). The average elevation is 647 m a.s.l. The minimum elevation is 404 and the maximum is 996 m a.s.l. They have an average area of 0.036 km^2 and the total area represents 0.7% (1.02 km^2) of the total lakes. They have mainly circular shapes.

3.1.4 Lakes on Slopes

Slopes are inclined surfaces of rock, soil or even loose sediments of various inclinations, higher than 5°. Slopes may occur by processes of tectonic movements, weathering and erosion, or rarely by deposition, and generally by a succession of these processes. The slopes where water bodies develop are rocky slopes that have been eroded by glaciers, generating overdeepening in areas with preexisting zones of weakness such as faults and fractures. They present slopes between 14° and 27°, containing 2% (6) of lakes with orientations to the N, NE, E, SE and W. The average altitude is 616 m a.s.l., ranging between 383 and 867 m a.s.l. The average area is 0.004 km^2 and comprises much less than 1% (0.03 km^2) of the total area of lakes. Lakes shapes are circular and elliptical.

3.1.5 Lakes in Landscapes of Areal Scouring

Landscapes of areal scouring are extensive tracts of subglacially eroded bedrock, consisting of rock knobs, roches moutonnées and overdeepened rock basins. In the study area, there are two well-differentiated zones of such glacial erosion surfaces. To the south of Lake Fagnano and close to the international boundary, there is a large irregular surface with elongated elevations and depressions (Fig. 2). There are emplaced paternoster lakes at an average elevation of 414 m a.s.l. that drain their water toward Lake Fagnano. They have elliptical and irregular shapes. The elongated landforms on this surface are produced by the lithological and structural control over glacial erosion. On the other, at the top of the No-top Range, there are two extensive areas of low slope that present depressions occupied by several water bodies (Fig. 3). These lakes are oriented toward SE (30) and NE (13) and are at an average elevation of 463 m a.s.l. They present an average area of 0.02 km^2 and have circular and elliptical shape, with some irregular lake forms due to the later development of peat bogs in the depressions.

3.1.6 Lakes in Interdrumlins Areas

A drumlin is a hill or hillock of glacial drift with elliptic morphology resembling a whales's back shape. They are developed under glaciers and may have a rocky core. Drumlin dimensions may vary from 10 to 100 of meters long, with their width being smaller than their length, and their height ranging from 5 to 40 meters. The composition is extremely varied. Some are composed by bedrock and till, others mainly by till, others by part till and part sorted sediments and also there are drumlins composed mainly by sorted sediments. Drumlins usually appear in groups called drumlin fields, with a longitudinal arrangement parallel to the direction of the glacier movement. These fields are characterized by shallow depressions which separate the oviform hills. They are formed beneath glaciers that are rich in sediment due to the relatively high erodibility of the glacier valley. There are two fields of drumlins on the north coast of the Beagle Channel, one at Estancia Harberton (54˚52'S 67˚22'W) and the other at Estancia Moat (54˚56'S 66˚45'W) (Rabassa et al. 1990) (Fig. 3). In the depressions between drumlins, there are at least 54 lakes (Fig. 5.g). These present NW–SE and E–W orientations, similar to those of drumlins. They have an average area of 0.07 km^2 and are located at an average altitude of 93 m a.s.l. Their shape is typically circular but there are also irregular water bodies that mirror the shape of the depressions between drumlins. These depressions are sometimes occupied by peat bogs or marine inlets.

4 Lakes in Isla de los Estados

Isla de los Estados is located at the southernmost end of South America, forming part of the argentinean province of Tierra del Fuego, Antarctica and South Atlantic Islands (Fig. 1). It is located at a distance of 30 km southeast from Peninsula Mitre (eastern Isla Grande de Tierra del Fuego), both separated by the Estrecho de Lemaire, and has a surface area of 496 km^2. It is the southeastern end of the Andes Range above the present sea level. The topography is characteristic of terrain repeatedly glaciated during the Quaternary, with many cirques and glacial valleys like the rest of Fuegian Andes. In the eastern area of the island, the topography is less rugged than in its central and western areas (Ponce and Fernández 2013). This island has neither glaciers nor rock glaciers. It has 118 lakes located in overdeepenings in cirques (45%), in valley bottoms (42%), and on slopes (9%) and cols (6%) (Figs. 6 and 7). The lakes located in cirques have circular shapes, an average area of 0.09 km^2 and are at an average elevation of 310 m a.s.l. In the valley bottoms, lake shapes are elliptical, with an average area of 0.2 km^2 and an average elevation of 121 m a.s.l. On the cols, circular lakes develop, with an average area of 0.04 km^2 and an average elevation of 248 m a.s.l. The lakes that develop on slopes have circular shapes, an average area of 0.02 km^2 and an average elevation of 246 m a.s.l. The main orientations of the lake basins are toward NE (20%), SW (19%), N (14%) and NW (14%). The average elevation is 222 m a.s.l., with a minimum elevation of 16 and a maximum of 597 m

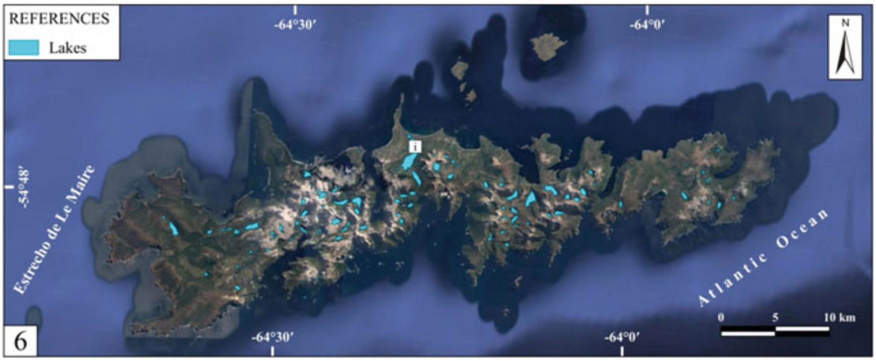

Fig. 6 Isla de Los Estados lake's distribution. (i) Lake Lovisato

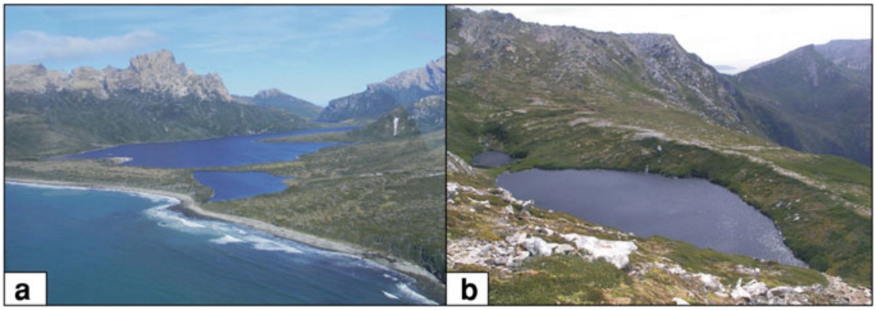

Fig. 7 **a** View to Lake Lovisato from the north coast of Isla de los Estados. **b** Lake located in a glacial overdeepening originated by the structural control over glacial erosion

a.s.l. They have an average area of 0.13 km^2, with the smallest lake having an area of 0.002 km^2 and the largest 2.3 km^2. Among the largest lakes is Lake Lovisato, 2.34 km^2 in surface area. The shape of these water bodies is mainly circular (73).

5 Time Windows of Lakes Formation

After the maximum development reached by the glaciers during the LGM, the natural global warming that marked the end of the Last Glaciation began. The time interval between the beginning of the glacier retreat from its maximum extent reached in the LGM to the beginning of the Holocene (11,500 yr BP) is known as Tardiglacial. The retreat of the glaciers in the south of Tierra del Fuego left numerous basins and closed depressions of erosive origin in the bottom of the valleys. As the ice retreated, meltwater accumulated in these depressions. There is geologic evidence to indicate that the central portion of the Beagle Channel was completely ice free 15,000 cal. yr

BP (Hall et al. 2013). Possibly, the lakes that today occupy the bottom of the main valleys and the interdumlin areas of Moat and Harberton were the first to be formed during the first part of the Tardiglacial (between 19,000 and 15,000 cal. yr BP).

Many of the peat bogs of southern Tierra del Fuego began to form around 19,000–14,000 cal. yr BP, when climatic conditions were benign for the growth of peat-forming vegetation. These peat bog colonized ancient lakes located in glacial overdeepenings in the main glacial valleys, which nowadays contain extensive areas of peatlands with ephimeral ponds on their surfaces.

In the hanging valleys, the presence of moraines assigned to the glacial advances corresponding to the Antarctic Cold Reversal (ACR, 14,500–12,900 cal. yr BP) and the Younger Dryas (YD, 12,900–11,700 cal. yr BP) (Menounos et al. 2013) allows us to infer that the tributary glaciers were disconnected from the main glaciers before 15,000 cal. yr BP. Many of these lakes with that geomorphological position would have formed no earlier than 11,700 cal. yr BP, when glaciers receded from the moraines corresponding to the YD.

Possibly the lakes located in cirques have been the last to develop, many of them during the early Holocene, when the glaciers of the Fuegian Andes reached a configuration similar to the present one, that is, retreating to the interior of the cirques.

The presence of LIA moraines in many cirques and hanging valleys in the Fuegian Andes allows us to assign relative pre- and post- LIA ages for 60 lakes. Of these, 25 are located immediately downstream of the LIA moraines so they could have formed prior to LIA, at some point during the Holocene. Two lakes are found between LIA moraines, so they would have formed during or after LIA. Finally, the geomorphological position of 33 cirque lakes indicates that they have formed during the last century, being upstream of the LIA moraines. Of these, 17 are in direct contact with current glaciers, therefore it is estimated that they have been formed during the last decades, associated with the recent retreat of the fuegian glaciers. These are located in the Martial, Alvear, Valdivieso, Vinciguerra, Sorondo and Lucas Bridges ranges.

6 Final Considerations

The great development of freshwater bodies in the Fuegian Andes is associated with intense glacial activity and water availability during the Quaternary. Most of the depressions currently occupied by lakes are the result of erosion by ice during different glaciations. The largest proportion of freshwater bodies are located inside cirques and glacial valleys, which are the most distinctive and abundant geomorphological features of the southern landscape of Tierra del Fuego. The abundant rainfall throughout the year and the contribution of winter snowfalls and glacial meltwater are the main sources of supply for these water bodies.

The glaciers and lakes present in the Fuegian Andes can be considered geological resources of tourism, trekking, scientific interest and as freshwater reservoirs. Although the populated areas to the south of the Isla Grande de Tierra del Fuego do not currently experience water supply problems, the accelerated growth of the population may demand new sources of supply in the near future. The Ushuaia city is supplied with water from the basins of the rivers Buena Esperanza, Arroyo Grande and Pipo. The first has 4 cirque glaciers in its basin, the second has 26 cirque glaciers and 22 lakes, and the third one has a cirque glacier and one lake. This demonstrates the current importance of these reservoirs in the provision of water to a large percentage of the population of Tierra del Fuego province. Increase batimetric studies would be important to obtain volumetric data and quantifying the water volume available in these lakes. Their characteristics description would allow us evaluate the behavior and water resource potential, which finally could contribute with strategies and sustainable usage politics of these water resources and risk prevent.

On the other hand, the growing interest of the local population and tourists in activities such as trekking and camping make these lakes and glaciers a tourist resource of great importance. At present, access through marked roads and trails is limited and restricted to a small number of glaciers and lakes while a large percentage remains little visited and are potential tourist attractions. There are some locations, such as Lake Esmeralda and Ojo del Albino Glacier and its proglacial lake, that receive a large flow of visitors throughout the year, even in winter, due to their accessibility (Fig. 2). The development and popularization of new access routes to other lakes and glaciers would provide more options for local people and visitors. Furthermore, these could improve the earnings for regional economy.

Finally, the lakes of the south of Tierra del Fuego can be considered as a source of information for scientific studies on the climatic and environmental changes that have occurred during the last thousands of years in the region. These studies are performed by analyzing sediments and microfossils contained in sediment cores obtained from the bottoms of the lakes. In addition, they make it possible to determine the behavior of the fuegian glaciers during the last millennium, and gauge their response to the global climatic changes that occurred during this period of time. As a complement, glacier monitoring (like the measure of the mass balance) is important for to know the glacial behavior in response to the current global warming. The small glacier area in argentinean sector of Fuegian Andes is reducing, so the increment of these studies would allow to make projections about the glaciers life and in consequence to constitute an important tool for decision making about water resources.

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Geophysical Methods Applied to the Study of Lakes and PaleoLakes in Tierra del Fuego

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Abstract During the last years, geophysical surveys have been carried out in order to study the possible tectonic origin of Udaeta Lake and the extension and thickness of glacio-lacustrine deposits cropping out in the Río Valdez mouth. In both cases, geophysical methods proved to be a powerful tool for the investigation of Quaternary tectonic and glacial activity in a zone of Tierra del Fuego, which is covered by a very dense forest that hinders the identification of rocky outcrops and natural exposures. The geometry of Udaeta Lake, located in the central section of the Magellan-Fagnano Fault System (MFFS), previously envisaged by other authors as a possible pull-apart basin, was investigated. Magnetic, gravimetric and detailed topographic profiles and vertical electrical soundings were surveyed. Geophysical results were integrated with fieldwork data allowing the identification of a transtensional zone with two E–W main sinistral strike-slip faults with a normal component that control the North and South coasts of the Lake. The central depression occupied by the Lake was also affected by inferred NE subparallel faults. The obtained results support a genesis of Udaeta Lake consistent with a pull-apart basin model and highlight the influence of MFFS on the formation of some water bodies located along the fault zone. Moreover, the constructed models contribute to a better understanding of earthquake

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rupture parameters and pattern of surface and in-depth deformation, improving the knowledge of the seismological behavior of the MFFS. In the Río Valdez mouth, located in the southeastern coast of Fagnano Lake, an outcrop of 7 m thick rhythmic glacio-lacustrine sediments was identified. It was interpreted that such outcrop was formed in a frontal morainic complex during the Pleistocene. Ground magnetic and resistivity surveys were carried out, in order to determine the thickness and areal extension of these lacustrine sediments. A maximum E-W extension of ~220 m, a minimum NNW-SSE one of ~180 m, and a minimum thickness of ~20 m were estimated. Considering this thickness and an assumed average sedimentation rate, the natural dam that promoted the paleoLake and their related lacustrine deposits could have existed prior to MIS 2, when the Last Glacial Maximum took place in the region.

Keywords Gravity · Magnetic and resistivity surveys · Lakes · Palaeo-Lakes · Glacial environment · Quaternary tectonic activity

1 Introduction

Recently, geophysical surveys have been carried out in Tierra del Fuego in order to study the possible tectonic origin of Udaeta Lake and the areal extension and thickness of glacio-lacustrine deposits cropping out in the Río Valdez mouth (Onorato et al. 2019; Prezzi et al. 2019). In both cases, geophysical methods proved to be a powerful tool for the investigation of Quaternary tectonic and glacial activity in a zone of Tierra del Fuego, which is covered by a very dense forest that hinders the identification of rocky outcrops and natural exposures.

Magallanes-Fagnano Fault System (MFFS) is a sinistral E-W striking transform fault system that cuts across the Isla Grande de Tierra del Fuego (Fig. 1), from the western end of the Magellan Straits to the limit of the Argentine Continental Shelf (Winslow 1982).

Models of pull-apart basin geometry have been described along the MFFS by many previous studies (e.g. Lodolo et al. 2003; Yagupsky et al. 2004; Tassone et al. 2005; Esteban et al. 2014; Alcacer et al. 2018; Lozano et al. 2018; Esteban et al. 2018). Costa et al. (2006) documented morphotectonic features near Fagnano Lake that were associated with the ruptures of two Ms 7.8 earthquakes that struck Tierra del Fuego on December 17, 1949. These authors also described the existence of evidence of the occurrence of two and possibly three paleo-earthquakes during Quaternary.

Udaeta Lake is located in the center-east of the Isla Grande de Tierra del Fuego, near the central sector of the MFFS (Fig. 1). On the basis of the analysis of satellite images, Perucca et al. (2015) suggested that Udaeta Lake could correspond to a pull-apart basin. Onorato et al. (2017, 2018) carried out a geomorphic and a bathymetric survey, characterizing the Lake as a sub-circular basin with steep slopes. They suggested that its northern and southern coasts would be structurally controlled by

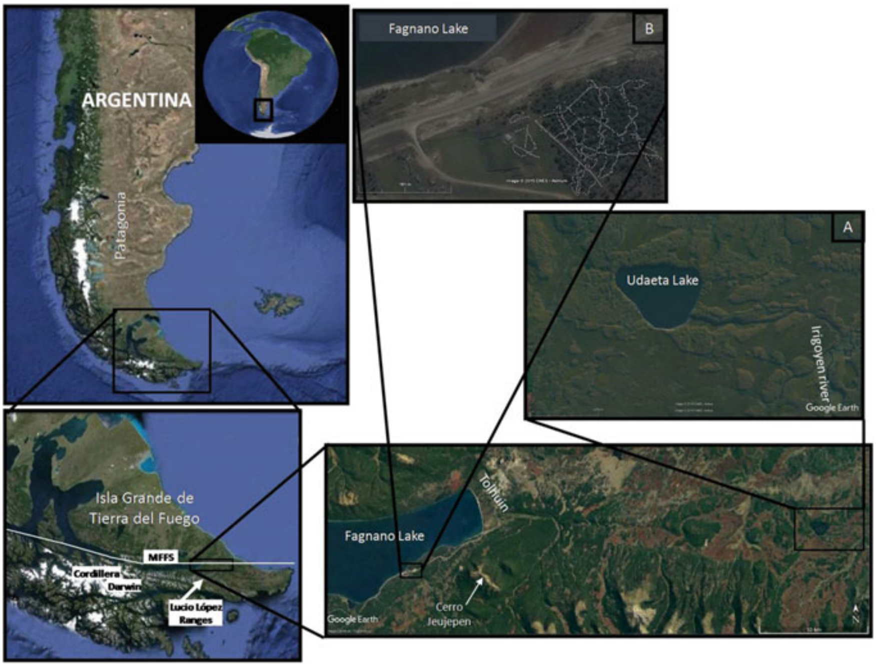

Fig. 1 Satellite images showing the location of the studied zones. White dots: magnetic stations measured in Río Valdez area. **a** Labeled black rectangle: geophysically surveyed area in Udaeta Lake. **b** Labeled black rectangle: geophysically surveyed area in Río Valdez. MFFS: Magellan-Fagnano Fault System

E-W trending fault scarps. Onorato et al. (2017, 2018) described several morphotectonic features along the MFFS typical of transcurrent faults: fault scarps, linear fault ridges, aligned vegetation, river diversions, changes in river gradient, tectonic gutters, displaced and parallel pattern river and ponds, among other features. Moreover, some fault sections cut through Late Pleistocene glacial morain deposits, confirming the occurrence of tectonic activity during Quaternary.

Geophysical and geological surveys have been carried out in order to investigate the possible pull-apart basin origin proposed for Udaeta Lake (Onorato et al. 2019). In addition, these surveys contributed to a better understanding of the MFFS as a potential seismogenic source, pointing out some geometrical complexities that could control future earthquake ruptures.

Esteban et al. (2014) determined that Fagnano Lake occupies a structural depression originated along a segment of the MFFS (Fig. 1). Fagnano Lake valley is one of the most important glacial landform zones in southernmost South America. Extensive glaciated surfaces and a large ice volume contained by a glaciers network that originates from the Cordillera Darwin (Fig. 1) covered the area during the Last Glacial Maximum (LGM), ca. 25 ka (Coronato et al. 2009; Waldman et al. 2010; Esteban et al. 2014). This landscape preserves paleoclimatic information of fundamental importance to gain deeper insight into the paleogeographic and paleoenvironmental evolution of the southern extreme of the continent.

Particularly, nearby the mouth of Río Valdez, at the southern coast of Fagnano Lake (Fig. 1), crops out a 7–8 m thick deposit of glacio-lacustrine rhythmites. Being located at 62 m a.s.l. and 25 m above the Lake shore, this deposit forms a plain between a morainic complex. The presence of dropstones indicates that it would correspond to an ice-contact Lake. This paleo-Lake would have been originated in a zone of contact among paleo-Fagnano and tributary paleoglaciers flowing from the Lucio López Ranges (Fig. 1) (Coronato et al. 2009).

Geophysical surveys were carried out (Prezzi et al. 2019) in order to reveal the volume and thickness of the sedimentary deposits that conform the glacio-lacustrine plain located close to Río Valdez mouth, which was described in an alongside road outcrop. The reconstruction of the size and shape of this paleo-Lake contributes to the interpretation of glacial paleogeography in central Tierra del Fuego.

2 Geologic Setting

2.1 Udaeta Lake

The Isla Grande de Tierra del Fuego is divided by the MFFS, involving two structural domains: a thin-skinned domain to the north of the fault and a thick-skinned one to the south (Winslow 1982). This zone corresponds to a continental transform margin with an in echelon geometry. Torres-Carbonell et al. (2008) documented a maximum age of ~7 Ma for the beginning of the strike-slip regime. These authors also determined that this age coincides with the creation of the divergent plate boundary between Sandwich and Scotia plates, which was proposed as the mechanism controlling the commencement of the strike-slip activity between South America and Scotia Plates.

MFFS has been mainly identified on the basis of the analyses of morphological features such as scarps, truncated vegetation, deflected drainages, broom-shaped river patterns, aligned sag ponds (Perucca and Bastias 2008; Onorato et al. 2017, 2018), truncated glaciofluvial fans (Coronato et al. 2002, 2009) and postdepositional structures in glacial sediments (Bujalesky et al. 1997).

The oldest rocks of the surveyed zone outcrop to the southeast of Udaeta Lake and would correspond to the Policarpo Formation (Maastrichtian-Danian age) (Fig. 2). This formation is composed by dark shales with scarce intercalations of fine grained sandstones (Olivero et al. 2002). To the east, the presence of Upper Paleocene marine sediments of La Barca and Tres Amigos Formations has been determined (Torres-Carbonell et al. 2008) (Fig. 2). Estuarine marine deposits of the Irigoyen Formation, possibly of Upper Miocene—Pliocene age (Malumián and Olivero 2005), crop out in the northwestern and southeastern sectors of the zone (Fig. 2). Finally, Quaternary glacial and glacifluvial sediments are widespread in the entire region. Udaeta Lake is located on a sedimentary substrate composed by sands, gravels, silts and clays from

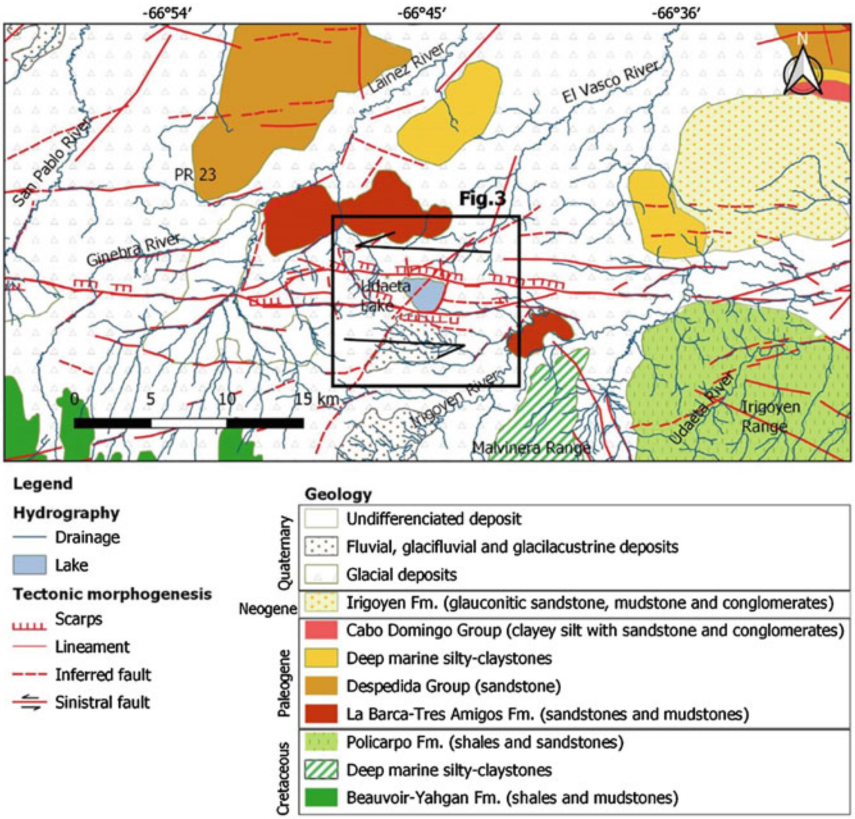

Fig. 2 Geological sketch of Udaeta Lake surroundings; (modified from Onorato et al. 2019)

glacial, glacifluvial and glacilacustrine origin of Pleistocene age (Coronato et al. 2009; Onorato et al. 2017), being the rocky basement still unknown (Fig. 2).

Morphotectonic evidences of MFFS, typical of strike slip faults, are found in the study area and along the Irigoyen river valley (Fig. 2). Fault scarps are the most remarkable geomorphological features, being identified along 34 km, from the eastern edge of Fagnano Lake up to 3.19 km to the east of the Udaeta Lake. Aligned moraines with an en echelon arrangement were also observed along the northern margin of Udaeta Lake.

Onorato et al. (2016) studied soft sedimentary deformation structures exposed in the southwestern shore of Udaeta Lake. They were interpreted as sismites associated to earthquake-related shocks (Onorato et al. 2016) and could suggest the occurrence of a nearby event of moderate magnitude (>5), or of a great magnitude earthquake with a more distant epicenter. In this same site, dendrochronological studies (Pedrera et al. 2014) suggested that ruptures took place on the MFFS in 1883 ± 5 and 1941 ± 10, in coincidence with February 1, 1879 (Modified Mercalli Scale, VI) and the December 17, 1949 (Ms 7.8) earthquakes that struck Tierra del Fuego.

2.2 Río Valdez

In spite of the absence of bare rock outcrops in the studied area, the presence of metasedimentary rocks of Beauvoir Formation is inferred. These metasedimentary rocks would surround the widely spread Quaternary glacial deposits (Olivero et al. 2007). Beauvoir formation is mainly composed by marine meta-sedimentary rocks as black slates, marls and tuffs (Capaccioni et al. 2013) of Early Cretaceous age. Most of the beds are massive, but there are some rhythmites intercalations given by very fine to fine sandstones and mudstones (Olivero and Martinioni 2001).

During the late Pleistocene, a glacier originating from the Cordillera Darwin extended eastwards through the Magallanes-Fagnano depression now occupied by Fagnano Lake. This outlet glacier was fed by at least fifty tributary glaciers. An alpine-type landscape, including erosional landforms, developed in the western sector of the actual Fagnano Lake. On the contrary, a piedmont-type landscape, including lateral moraines, glacio-fluvial and glacio-lacustrine terraces, developed in the eastern sector. This paleoglacier front reached a maximum advance of 35–40 km to the northeast of its actual easternmost head (Caldenius 1932). Such maximum advance is difficult to recognize, except by the remnants of eroded moraines (Coronato et al. 2009). On the other hand, lateral and basal moraines, kames, knobs and kettles and glaciofluvial plains are quite well distributed and preserved, making it possible to interpret glacier recessional phases (Coronato et al. 2002, 2009). This glacial landscape corresponds to the Last Glacial Maximum (LGM) event and its first recessional phase, ca. 25 ka and 18 ka BP, respectively, during the Marine Isotope Stage (MIS) 2 (Coronato et al. 2002, 2009; Rabassa et al. 2011; Rutter et al. 2012). To the south, Cerro Jeujepen (Fig. 1) blocked the flow from the Lucio López Range of tributary glaciers, forcing the junction with the Fagnano paleo-glacier at Río Valdez area. There, basal moraines extend up to 2.5 km from the Lake shore with elevations of 120 m a.s.l. and continue alongside the Lake coast, till to its eastern head. Such moraines are composed by till underlain by glacio-deltaic deposits of Middle Pleistocene age (Bujalesky et al. 1997). Fossil peat found in the lower units of till yielded 14C dates of 31,000 $\pm$ 510–48,200 $\pm$ 3300 years BP (Coronato et al. 2009), suggesting this region was covered by ice before the LGM. A terminal morainic complex constituted by arched hills was identified close to the Fagnano Lake shore, surrounding the Río Valdez mouth and the studied glacio-lacustrine deposit. Considering that this part of the Lake presents shallow depths, it was interpreted that the moraine ridges continue under the Lake, suggesting the occurrence of a frontal position during a recessional stage (Waldmann et al. 2010). Basal moraines separate the Lake coast from the interior kames, glacio-fluvial and glacio-lacustrine plains that were generated by the smaller, recessional, tributary glaciers. Coronato et al. (2002) interpreted sandy beds found at the base of Cerro Jeujepen as meltwater stream deposits coming from the tributary paleoglaciers during its recession. Taking into account radiocarbon dates obtained from basal peats located in the surroundings, it was concluded that most of the region was free of ice by 12,300 years BP. This area was one of the most extensively glaciated zones of Isla Grande de Tierra del Fuego, at the southernmost extreme of South America (Rabassa et al. 2011).

The geophysically investigated deposit is composed by 7 m of laminated silty-clay sediments with scarce laminated sands, overlaid in erosive contact by 4.25 m of chaotic gravels in a silty matrix corresponding to till. Each pair of rhythmites shows sets of 2 cm thick dark clay and 0.5 cm thick light silts. Convolute laminations are only observed at 2.75–3 m from the base.

3 Methodology

Total magnetic field was measured at 1902 magnetic stations, with a Geometrics 856 proton magnetometer. Three or more observations were taken at each station, and the corresponding values were averaged. The position of each station was determined by GPS. At regular time intervals (every hour), a base station located in the surveyed area was revisited to obtain control on the diurnal variation in the Earth's magnetic field. Afterward, the corresponding IGRF (International Geomagnetic Reference Field) value was subtracted.

Euler deconvolution was applied to magnetic anomalies trying to provide preliminary information of the depth distribution of the punctual sources. Such method is based on Euler's homogeneity equation (Reid et al. 1990, 2003; Salem and Smith 2005). Euler source points were calculated with SI = 1 and window sizes of 35 and 70 m through the software Oasis Montaj (Geosoft Inc.). Magnetic anomalies were also analyzed to determine the depth to the top of the magnetic source layer by power density spectra methods developed by Spector and Grant (1970) and improved by Blakely (1996), Okubo et al. (1985) and Tanaka et al. (1999). A semiautomatic, self-developed, software to perform the analysis was used (Núñez Demarco et al. 2017).

Tilt derivatives of the upward continued to 10 m reduced to the pole magnetic anomalies were also calculated with the aim of facilitating the location of contacts between distinct geological units.

Samples of Holocene sediments and sedimentary rocks cropping out nearby Udaeta Lake shore and of La Barca Formation were collected, and the corresponding magnetic susceptibilities were measured in the laboratory using a Bartington susceptibility meter.

3D susceptibility models were constructed in order to explore the nature of the bodies responsible for the detected magnetic anomalies in Río Valdez. The magnetic susceptibility of Río Valdez lacustrine sediments was measured by De Bernardi et al. (2013), it varies between 10 and 28 $\times 10^{-5}$ SI, showing an average value of ~14.1 $\times 10^{-5}$ SI. 368 oriented paleomagnetic samples from Río Valdez glacio-lacustrine outcrop were collected. Natural remanent magnetization (NRM) intensities, declinations and inclinations were measured with a Minispin (Molspin Ltd.) rotative magnetometer. Average intensity, declination and inclination of NRM were calculated, estimating values of 5.97 mA/m, 11° and −56.5°, respectively, which were

Table 1 Declination and inclination of the natural remnant magnetization, magnetic susceptibility and Köenisberger ratio of the different geologic units considered in the 3D forward magnetic model of Río Valdez zone; (modified from Prezzi et al. 2019)

Bodies	Natural remanent magnetization		Susceptibility	Köenisberger
	Declination (°)	Inclination (°)	SI	Ratio
Till sheet	0	0	0.004	0
Glacio-lacustrine deposits	11	−56.5	0.000141	3.13
Beauvoir Formation east	183	71	0.0003	20
Beauvoir Formation west	183	71	0.0003	1
Beauvoir Formation beneath	183	71	0.0003	20

used in the 3D model. The corresponding Köenisberger ratio was calculated (Table 1). An average magnetic susceptibility of 400×10^{-5} SI was considered to model the till layer covering the rhythmites. To achieve a good fit between measured and modeled anomalies, rock bodies to the east, west and beneath the glacial deposits were included in the model, with magnetizations dominated by reverse NRMs (Table 1). These bodies would correspond to the lower Cretaceous Beauvoir Formation (Martinioni et al. 2013), that crops out to the east of the studied zone in Cerro Jeujepen. Peroni et al. (2011) and Peroni (2012) measured the magnetic susceptibility of Beauvoir Formation obtaining values ranging between 9.1×10^{-5} and 45×10^{-5} SI, with an average value of 30×10^{-5} SI, which was the value utilized in the model. There are not paleomagnetic data available for Beauvoir Formation. Therefore, the reverse NRM direction assigned to Beauvoir Formation (Table 1) was calculated from the lower Cretaceous Ponta Grossa Dike Swarm paleomagnetic pole (Solano et al. 2015). The modeling software IGMAS was employed (Götze 1978; Götze and Lahmeyer 1988). IGMAS uses triangulated polyhedrons to approximate areas of constant density and/or susceptibility within the Earth's crust and mantle. The numerical algorithms were developed by Götze (1984). The initial geometries of the 3D modeled bodies are predefined by the user on a series of parallel vertical cross-sections. The automated triangulation of model surfaces between the parallel vertical cross-sections allows the construction of complicated model geometries. The optimal fit between observed and calculated anomalies is achieved during forward modeling by iterative geometry changes introduced by the user.

Vertical electrical soundings (VES) were carried out using a digital resistivity meter GEOMETER MPX-400 (Ponti Electronics) and a Schlumberger electrode array. The position of each one of the VES points was determined using GPS. The obtained VES were projected along profiles. Inverse 2D models of resistivity distribution along the profiles were numerically obtained in the form of a simple rectangular cell model using the software RES2DINV of Geotomo (Loke 1996–2002, 2001). This program allows an estimation of the cells resistivity that fits the values measured at surface, within certain discrepancy. During the inversion process, the initial model parameters are modified and improved by solving a least-squares equation (Lines and Treitel 1984). The difference between the calculated values of apparent resistivity and those inferred from field data are expressed through the root mean square (RMS). Finally, a contour plot showing the resistivity distribution of the modeled profile is obtained.

Relative gravity measurements were carried out using a ZLS Burris Standard gravity meter, 47 stations were surveyed along three profiles with a precision of 0.01 mGal. The survey was related to absolute gravity point 16 along line 383 of the IGN (Instituto Geográfico Nacional) located near Tolhuin (54.51425°S, 67.19025°W), with a value of 981405.61 mGal. The position of each one of the measured gravity stations was determined with the GNSS (Global Navigation Satellite System) Mobile Mapper, Magellan Thales model equipment. Current standards for reduction of observed gravity to Bouguer anomaly defined by the U.S. Geological Survey (USGS) and the North American Gravity Database Committee (Hinze et al. 2005) were applied through the utilization of the spreadsheet for reduction of raw data to the Bouguer anomaly developed by Holom and Oldow (2007). The observations taken at each station showed mean deviations ≤0.004 mGal. Average instrument drift correction in each station was of ~0.01 mGal. To calculate height and Bouguer spherical cap corrections, the height above the WGS84 reference ellipsoid of each station was measured with the above-mentioned GNSS equipment with a precision of 0.05 m. A density of 2.67 g/cm^3 and a reference height of 0 m were used. With the additional calculation of solid earth tide and terrain corrections, the complete Bouguer anomaly was obtained. Earth tide and terrain corrections were calculated using the software Oasis Montaj (Geosoft Inc.) and entered in the spreadsheet of Holom and Oldow (2007). The maximum value of terrain correction was 0.288 mGal, with an average of 0.184 mGal. An average error in complete Bouguer anomaly for each station of ~0.01 mGal was estimated.

2.5D density models were developed along the profiles trying to explore the nature of the bodies causative of the detected gravity anomalies. The modeling software IGMAS was utilized (Götze 1978; Götze and Lahmeyer 1988).

4 Results

4.1 Udaeta Lake

The location of the 10 vertical electrical soundings (VES) carried out in the study area is shown in Fig. 3. Seven of these VES were combined to produce a NW–SE 2-D cross-section along the western coast of Udaeta Lake (Fig. 4). Figure 4 presents measured and calculated apparent resistivity pseudo-sections and the resulting resistivity inverse model with a vertical exaggeration of 4.57 (with and without considering topography). In the resistivity inverse model, a high resistivity layer (~90–1200 Ω m) followed by a deeper conductive layer (~2–90 Ω m) was detected. The high resistivity layer shows variable thickness, with minimum values of approximately

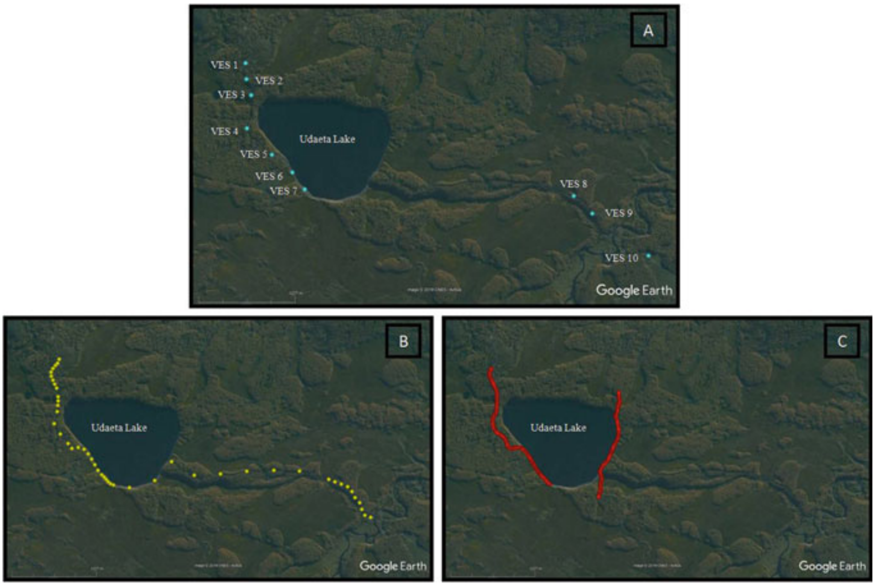

Fig. 3 **a** VES surveyed in Udaeta Lake area. **b** location of gravity stations. **c** location of magnetic stations

10 m in the northwestern and the northeastern extremes of the model (Fig. 4). On the other hand, in the central part of the model a depth to the top of the more conductive layer of ~40 m is observed (Fig. 4). It was interpreted that the more resistive layer would represent the surficial glacifluvial sediments, while the more conductive layer would correspond to the shales of La Barca Formation. The existence of two faults with different vergence was proposed from the resistivity pattern. Such faults would be responsible for the modeled thicknesses variations and would correspond to the northern and southern scarps of Udaeta Lake (Fig. 4). In addition, the central block located between these two scarps would be the downthrown block, with a minimum downthrown of ~30 m (Fig. 4). The other three VES were integrated along a NW-SE profile, located to the SE of Udaeta Lake. Figure 5 shows measured and calculated apparent resistivity pseudo-sections and the resulting resistivity inverse model with a vertical exaggeration of 3.63 (with and without considering topography). The existence of a high resistivity layer (~85–1000 Ω m) followed by a deeper conductive layer (~1–85 Ω m) was determined from the model. The high resistivity layer has a constant thickness of ~10–15 m, similar to what was observed in the southeastern extreme of the previous inverse model presented above (Fig. 4). This fact would indicate that VESs number 8, 9 and 10 (Fig. 3) were surveyed in the southern upthrown block.

The constructed 2.5D density model and the measured and modeled Complete Bouguer anomalies along the profile bordering the western coast of Udaeta Lake (Fig. 3) are shown in Fig. 6a. To achieve a good fit between measured and modeled

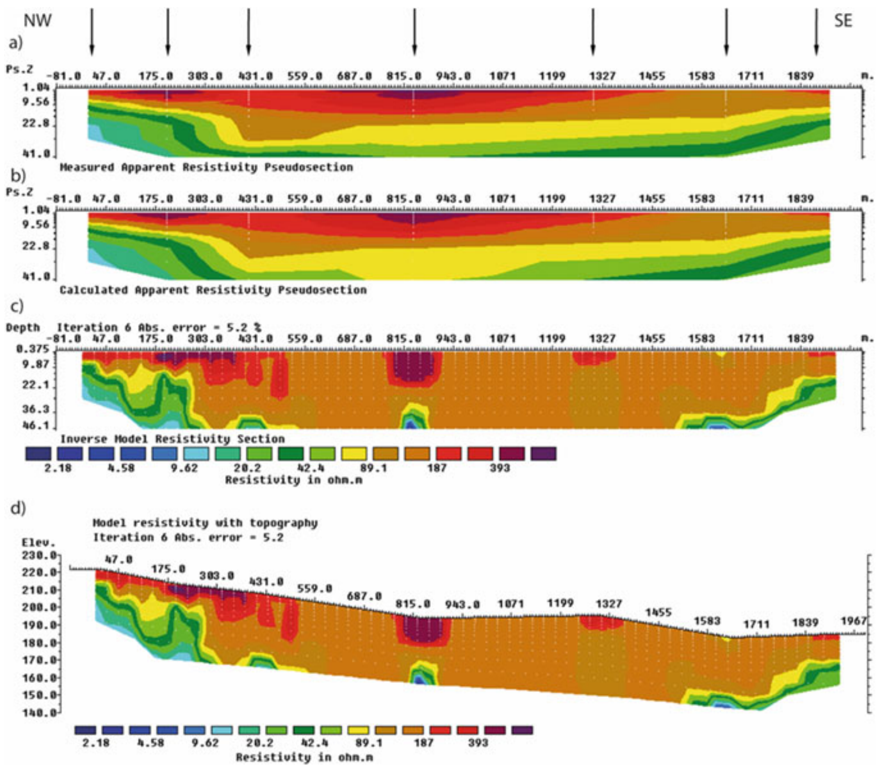

Fig. 4 **a** Measured and **b** modeled pseudosections, **c** 2D inverted resistivity section without considering topography, **d** 2D inverted resistivity section considering topography along the western coast of Udaeta Lake; (modified from Onorato et al. 2019). Black arrows indicate each surveyed VES

anomalies, a denser body (2.77 g/cm^3) in the northwestern extreme of the profile was included in the model. This body could represent different rocks, such as limestones, quartzites or granites. Unfortunately, rocky outcrops in the surveyed zone are covered by glacial and glacifluvial deposits with unknown thickness. To the south of the 2.77 g/cm^3 density body, two other bodies constitute the model: (1) an upper one with a density of 2.0 g/cm^3, which would correspond to the Holocene sediments; and (2) a lower one with a density of 2.64 g/cm^3, which would indicate the presence of consolidated sedimentary rocks. These sedimentary rocks could represent the fine-grained sandstones and shales of La Barca Formation (Upper Paleocene), identified by Torres-Carbonell et al. (2008) in Cerro Malvinera, 7 km to the SE of Udaeta Lake. This 2.64 g/cm^3 density body could also include conglomerates, coarse to fine-grained sandstones and siltstones of the Tres Amigos (Paleocene) and shales of Policarpo (Upper Cretaceous) formations. It was interpreted that the contact between the 2.77 g/cm^3 and 2.64 g/cm^3 density bodies would correspond to a fault that defines the northern scarp of Udaeta Lake. The modeled Holocene sediments reach a maximum thickness of ~100 m in the southeastern extreme of the profile. Figure 6b displays

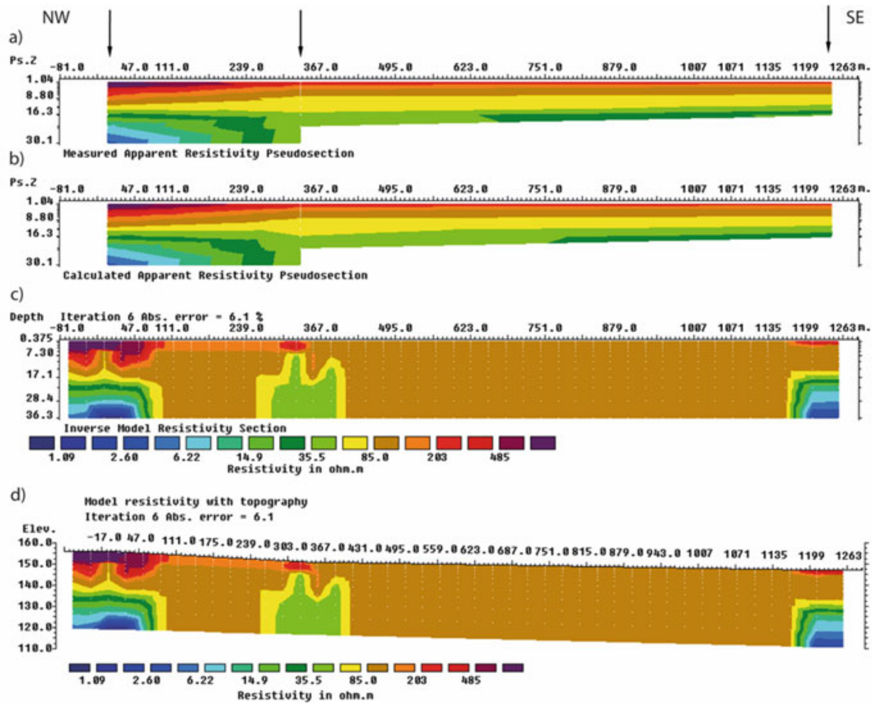

Fig. 5 **a** Measured and **b** modeled pseudosections, **c** 2D inverted resistivity section without considering topography, **d** 2D inverted resistivity section considering topography to the southeast of Udaeta Lake; (modified from Onorato et al. 2019). Black arrows indicaate each surveyed VES

the 2.5D density model and the measured and modeled Complete Bouguer anomaly along the W–E profile (Fig. 3) (which extends along the southern coast of Udaeta Lake). It can be observed that the thickness of the modeled Holocene sediments decreases progressively, presenting its minimum value (~0 m) beneath the eastern coast of the Lake (Fig. 6b). This minimum thickness coincides with the location of an inferred NE trending structure, which would control the eastern shore of the Lake. In accordance, Onorato et al. (2017) documented that Udaeta Lake bathymetry shows a strong slope in its eastern border. Moreover, several faults affecting till deposits were detected to the northeast of the Lake, pointing to a strong structural control for its eastern shore. Measured and modeled Complete Bouguer Anomalies along a NW–SE trending profile, surveyed to the southeast of Udaeta Lake (see Fig. 3 for location) are depicted in Fig. 6c. A good fit between measured and modeled anomalies is attained if the existence of a fault is considered. Such fault would correspond to the southern scarp, juxtaposing rocks with slightly different densities (2.64 g/cm^3 vs. 2.67 g/cm^3). The 2.67 g/cm^3 density rocks would represent Policarpo Formation (Upper Cretaceous age), suggesting the absence of younger rocks in that sector of the profile. This fact would indicate that the southeastern part of the profile was surveyed in an upthrown block. Furthermore, Holocene sediments (2.0 g/cm^3 density body)

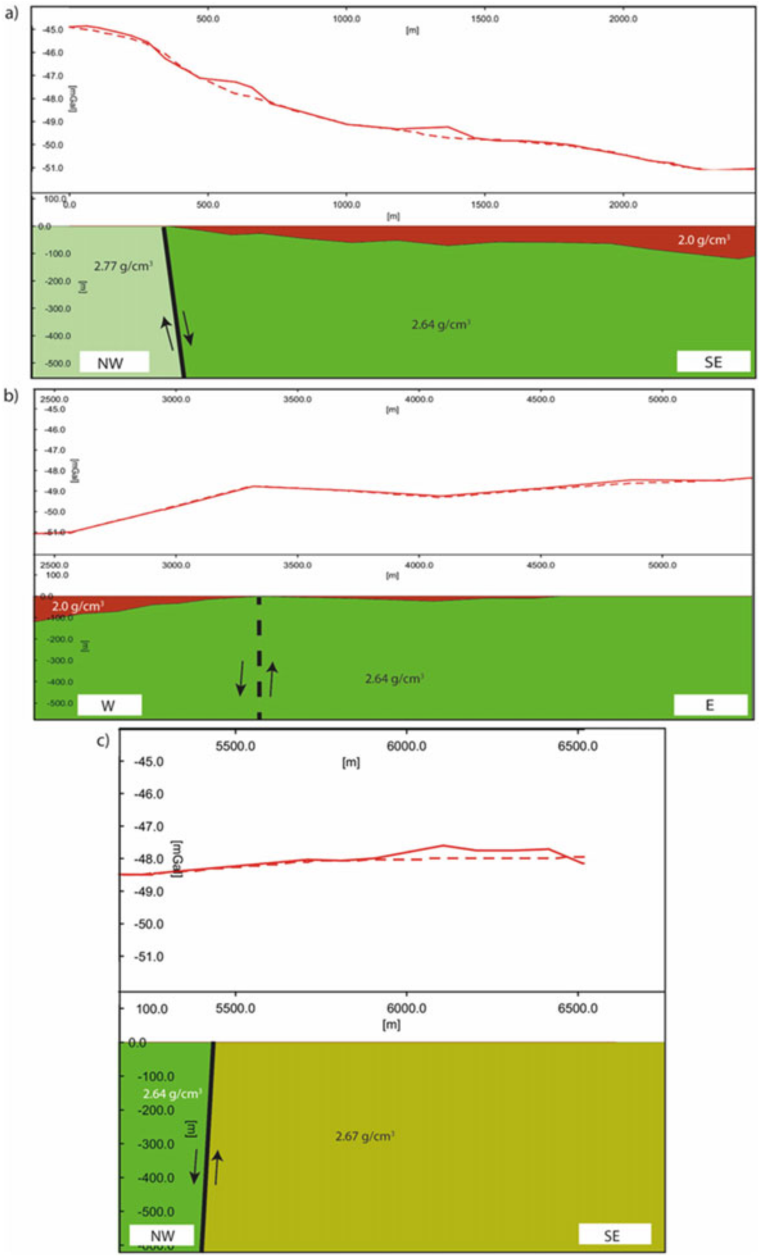

Fig. 6 Measured (red continuous line) and modeled (red dashed line) Complete Bouguer anomalies and 2.5D density models: **a** profile along the western coast of Udaeta Lake, **b** W–E profile along the southern coast of Udaeta Lake, **c** NW–SE trending profile located to the southeast of Udaeta Lake. See Fig. 3 for gravity stations location; (modified from Onorato et al. 2019)

are absent in the subsurface in the northern (2.77 g/cm^3 density body) and southern blocks (2.67 g/cm^3 density body) that constitute the 2.5D density models (Fig. 6a, c) but is present in the central block, supporting the interpretation that the central block is the downthrown block between the northern and southern scarps.

Figure 7 shows the magnetic profiles surveyed along the western and eastern shores of Udaeta Lake (see Fig. 3 for profiles location). Magnetic anomalies along both profiles have maximum amplitudes of ~20 nT (Fig. 7). These amplitudes are in agreement with the measured low susceptibility contrast between Holocene sediments and sedimentary rocks (0.81×10^{-7} m^3/kg) and La Barca Formation shales (0.55×10^{-7} m^3/kg). The northern and southern escarpments identified in the 2.5 D density models and in the inverse resistivity model, which define the northern and southern shores of Udaeta Lake, coincide with peaks and high gradients in the magnetic anomalies (Fig. 7, pale blue and pink bars). In addition, the probable existence of other structures between the northern and southern escarpments was inferred from the magnetic profiles (Fig. 7, green bars). A comparison of the magnetic anomalies detected along the western coast of the Lake and the 2.5D density model is presented in Fig. 8. A conspicuous magnetic peak coincident with the location of the forward gravity modeled fault correspondent to the northern scarp can be clearly observed. Such correspondence further supports the obtained results and proposed interpretations.

4.2 *Río Valdez*

Magnetic anomalies (Fig. 9) present maximum values (of ~ − 88 to −120 nT) at the center of the surveyed area. These maximum values define an elongated zone with NNE-SSW trend, flanked by minimum values (of ~ – 138 to −200 nT) to the E and W (Fig. 9).

Figure 10 displays magnetic anomalies and the Euler solutions obtained considering a SI of 1 and window sizes of 35 and 70 m. Most of the solutions are located along the elongated magnetic maxima, at average depths of ~3–7 m (Fig. 10). To the E and W of the magnetic maxima, Euler solutions are concentrated beneath the high gradient transition zones to the magnetic minima, at average depths of ~11–20 m (Fig. 10). The depth to the top of the magnetic layer (for 35×35 m square windows with an overlap of 33.25 m (95%)) applying 2D power density spectra methods was calculated, obtaining values ranging between 11 and 22 m (Fig. 11).

The tilt derivative and the horizontal derivative of the tilt derivative of the upward continued reduced to the pole magnetic anomalies delineate the contacts of the glacial deposits (Fig. 12a, b). In the case of the tilt derivative, the contacts are defined by the cero contour line (Fig. 12a) (Verduzco et al. 2004). On the contrary, the maximum values of the horizontal derivative of the tilt derivative delineate the contacts (Fig. 12b) (Verduzco et al. 2004).

The five vertical electrical soundings (VES) carried out in the study area were integrated to produce a NE-SW 2D cross-section (Fig. 13). Figure 14 displays measured

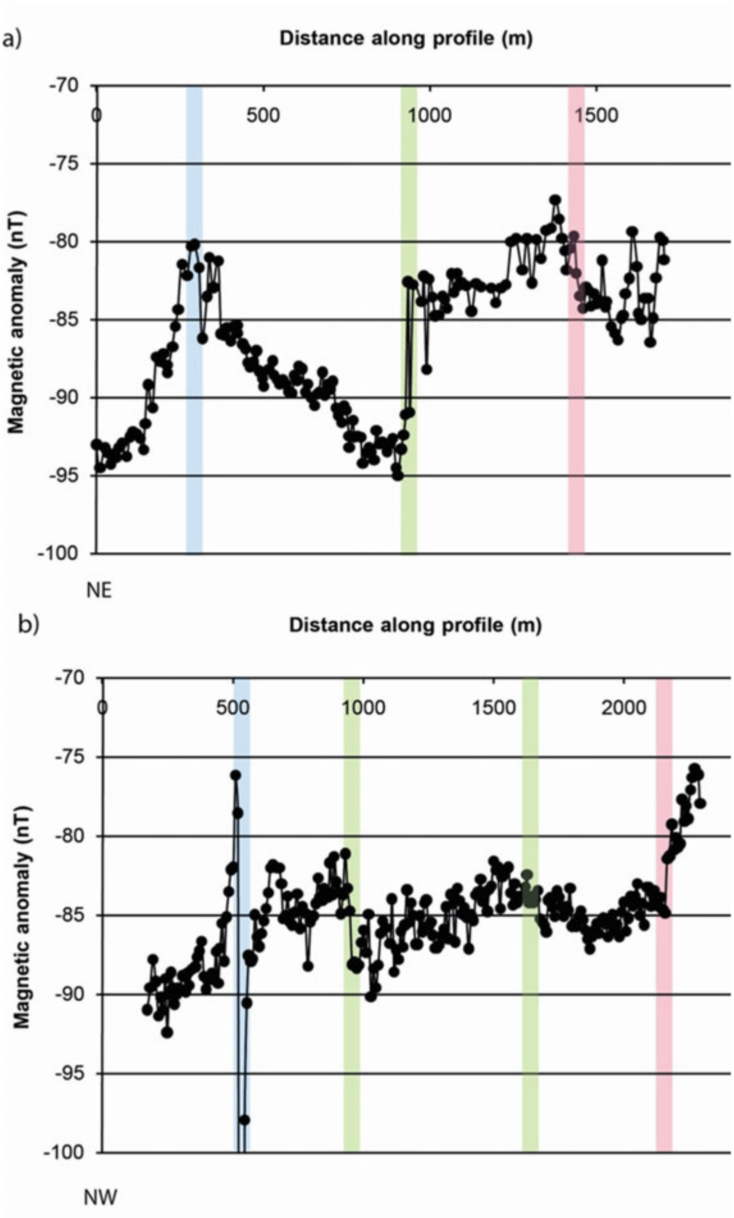

Fig. 7 Magnetic profiles surveyed around Udaeta Lake, peaks and/or high gradients interpreted as indicative of the northern scarp are indicated with pale blue bars, peaks and/or high gradients interpreted as indicative of the southern scarp are indicated with pink bars, peaks and/or high gradients interpreted as indicative of inferred faults are indicated with green bars, **a** along the eastern coast, **b** along the western coast

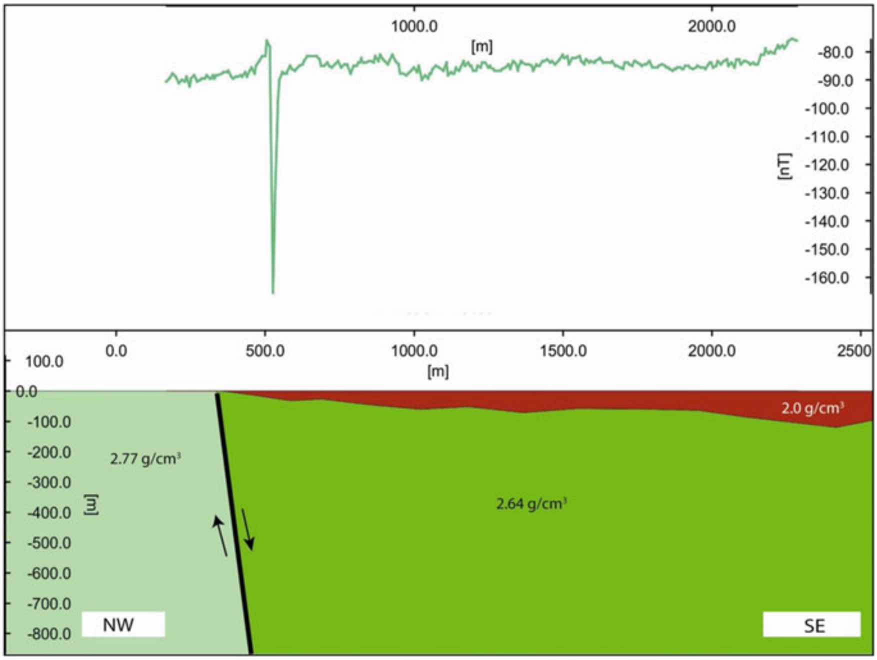

Fig. 8 Magnetic profile (green continuous line) along the western coast of Udaeta Lake compared with the corresponding 2.5 D forward gravity model; (modified from Onorato et al. 2019)

and calculated apparent resistivity pseudosections and the corresponding inverse model. To the top of the inverse model a layer with very high resistivities, ranging between ~300 and 3000 Ω .m, with a thickness of ~5–9 m is observed. Below this layer, a very low resistivity zone, with values ranging between ~50 and 200 Ω .m and extending down to at least 20 m depth, is identified (Fig. 14).

An initial thickness of ~5 m and an average magnetic susceptibility of 4×10^{-3} SI were used to model the till layer covering the rhythmites in the 3D forward magnetic model (Table 1). This initial thickness is in accordance with the thickness of the till outcrop. The body representing the glacio-lacustrine deposits underlying the till was assigned the susceptibility and measured NRM parameters shown in Table 1. In order to reduce the ambiguity inherent to the magnetic method, the minimum thickness, magnetic susceptibility and NRM parameters assigned to the till and rhythmites bodies were not changed during forward modeling. To achieve a good fit between measured and modeled anomalies, rock bodies to the east, west and beneath the glacial deposits were introduced in the model, with magnetizations dominated by reverse NRMs (Table 1). Figure 15 depicts 5 of the 10 parallel E–W sections that compose the model. The forward modeled 3D susceptibility structure thoroughly reproduces the measured magnetic anomalies. Only less than ~5% of the surveyed area shows residual anomalies larger than ± 5 nT (Fig. 16). They are of very short wavelength and are not systematically distributed. Residual values are tightly

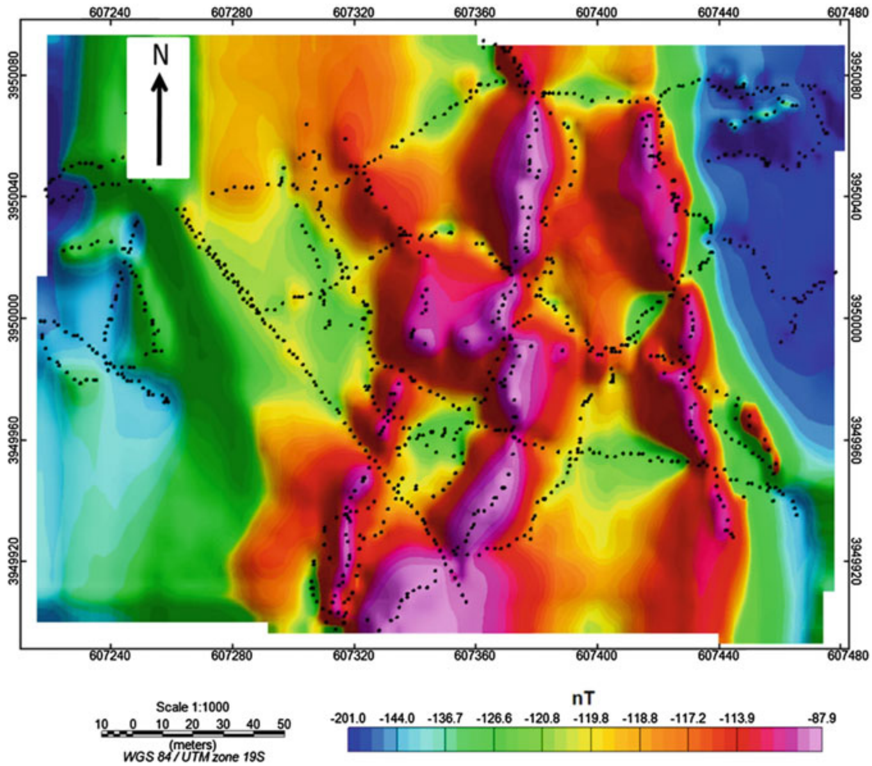

Fig. 9 Magnetic anomaly detected in Río Valdez area. Black dots: magnetic stations. Location of surveyed area is shown in Fig. 1 (B labeled black rectangle) (modified from Prezzi et al. 2019)

concentrated around 0 nT, with a standard deviation of 3.84 nT and a correlation coefficient of 0.97. These values indicate that the constructed model satisfactorily represents the magnetic susceptibility and NRM distribution in the surveyed area. Figure 17 presents a 3D view of the measured magnetic anomaly and the modeled 3D structure.

5 Discussion and Conclusions

5.1 Udaeta Lake

Based on geomorphological evidence, Onorato et al. (2017) suggested that Udaeta Lake would correspond to a pull-apart basin. The presence and location of two faults defining the northern and southern scarps of Udaeta Lake were inferred from the geophysical results, models and interpretations presented above (Figs. 4, 5, 6, 7 and

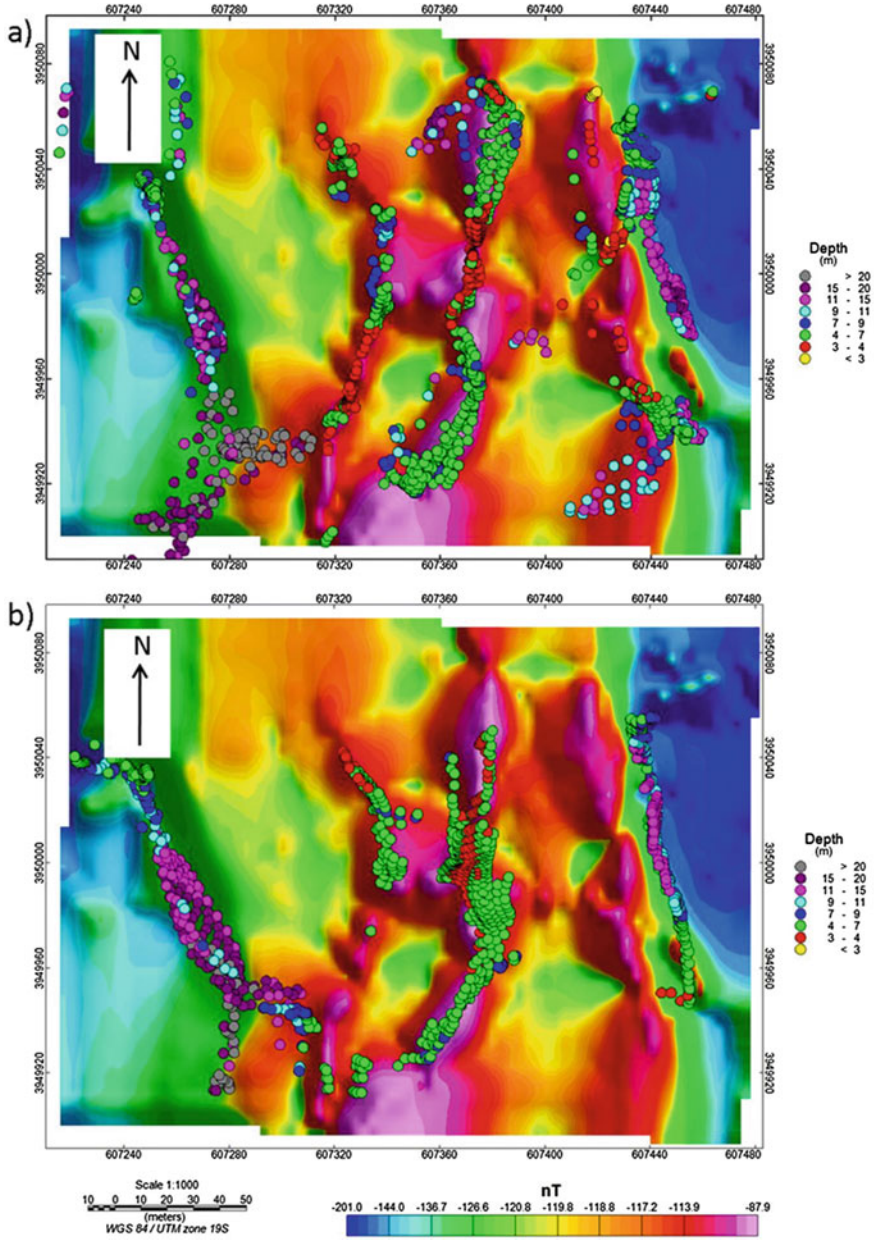

Fig. 10 **a** Euler solutions laid over the magnetic anomaly, calculated using a SI = 1 and a window size of 35 m.; **b** Euler solutions laid over the magnetic anomaly, calculated using a SI = 1 and a window size of 70 m; (modified from Prezzi et al. 2019)

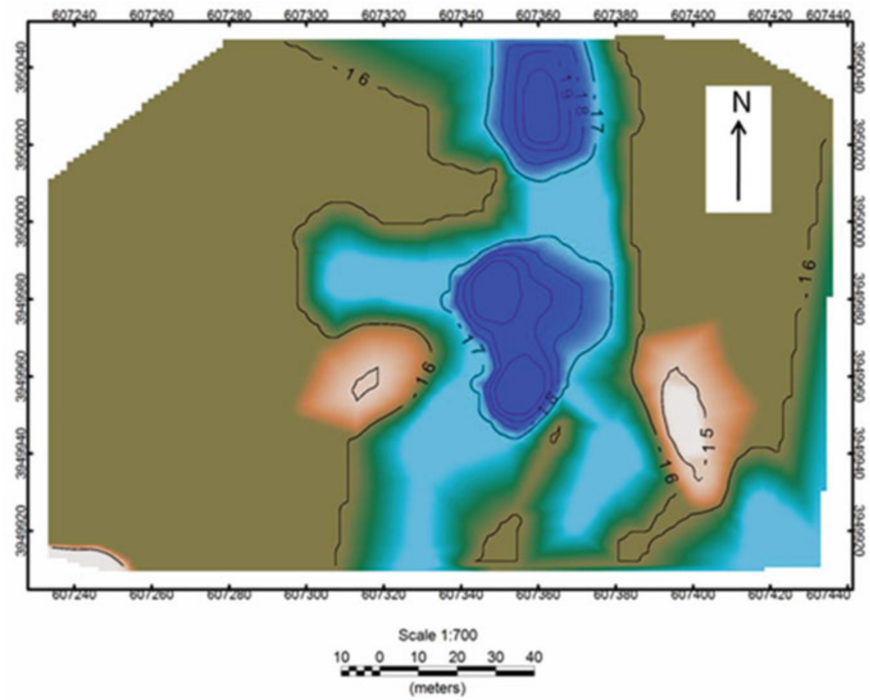

Fig. 11 Depth to the top of the magnetic layer (i.e., depth to the base of the glacio-lacustrine deposits outcropping in Río Valdez) obtained through power density spectra methods, using 35 × 35 m square windows with an overlap of 95% (modified from Prezzi et al. 2019)

8). It is proposed that such scarps would have been generated by a strike slip fault in a transtensive regime (Fig. 18b), registering strike-slip (sinistral) movements with a component of dip-slip (normal) displacement. The northern and southern scarps would present opposite vergences, configurating a releasing bend or a stepover with parallel fault segments. A minimum throw of ~30 m for both structures was estimated, occupying Udaeta Lake the central depression generated by these structures.

In spite of being smaller than the structural depressions described along MFFS and than Fagnano Lake pull-aparts, Udaeta Lake presents a distinctive characteristic: it is formed between two faults separated by just 1.30 km and have a depth of 25 m. Consequently Udaeta Lake constitutes a unique example, as no record of pull-apart basins with these characteristics has been previously described. It is proposed that Udaeta Lake corresponds to a pull-apart basin developed between two adjacent sinistral faults, located in the center east portion of the MFFS.

The ages of the deformed lacustrine deposits described in the southern coast of Udaeta Lake point to the occurrence of Late Pleistocene to Holocene tectonic activity (Onorato et al. 2016). The dense forest and the scarcity of appropriate outcrops seriously hinder field observations, being difficult to detect kinematic markers that would contribute to a more accurate knowledge of the fault system geometry and

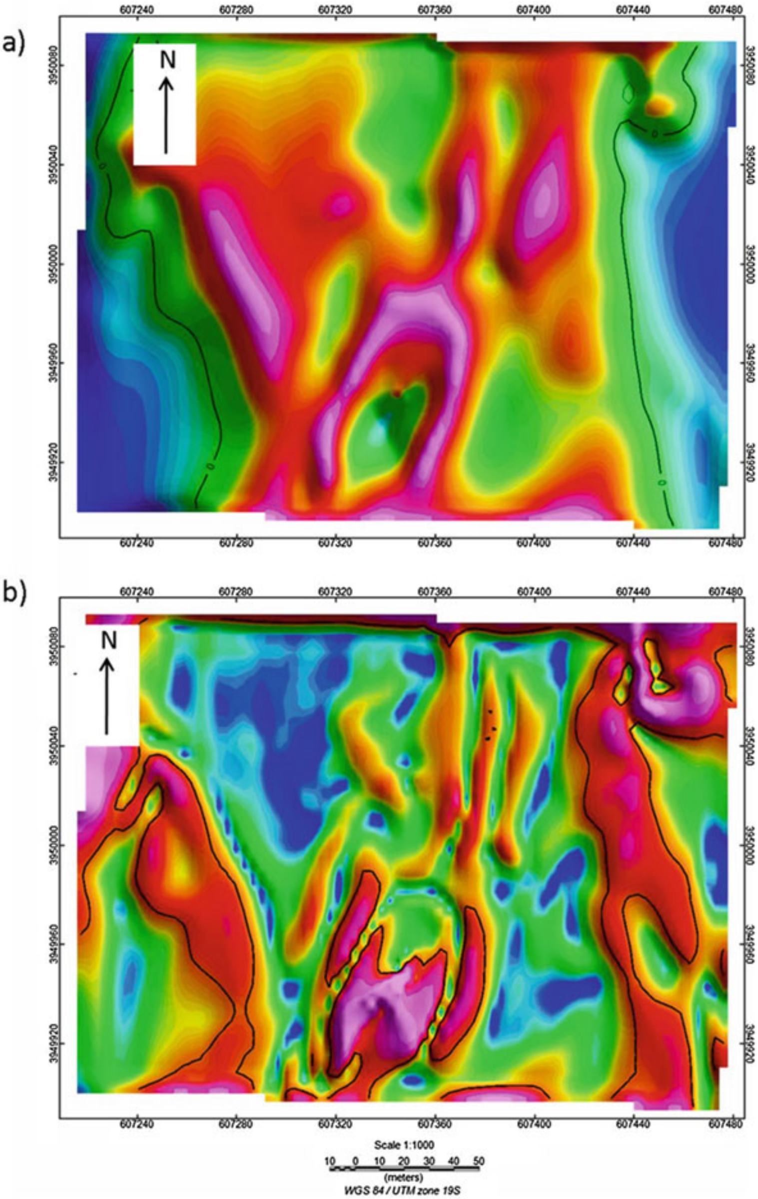

Fig. 12 **a** Tilt derivative of the upward continued reduced to the pole magnetic anomalies, showing the location of the contacts of the glacial deposits through the 0 contour lines. Black lines: 0 contour lines; **b** Horizontal derivative of the tilt derivative of the upward continued reduced to the pole magnetic anomalies, showing the location of the contacts of the glacial deposits through its maximum values. Black lines: maximum values contour lines; (modified from Prezzi et al. 2019)

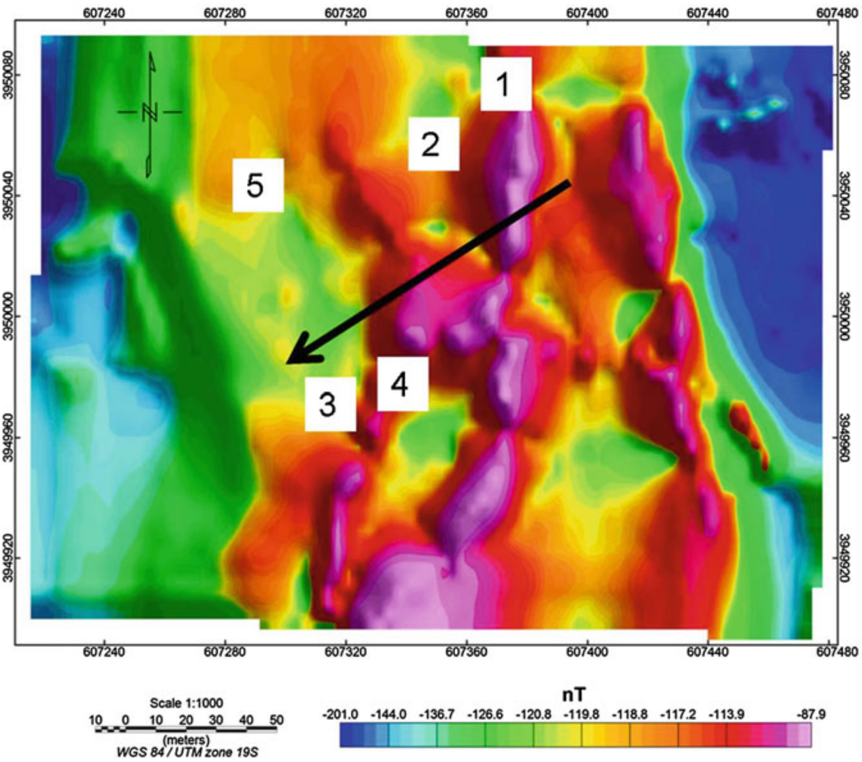

Fig. 13 Magnetic anomalies detected in the study area showing the location of the five VES carried out. Black numbers: location of each VES. Black arrow: cross-section along which the VESs were integrated; (modified from Prezzi et al. 2019)

timing of activity. However, drainage anomalies and the persistence and regularity of linear features (including the present forest) suggest an active tectonic control during the Upper Pleistocene-Holocene over the landscape.

Future quantitative geomorphology investigations of scarps evolution and river profiles together with kinematic and structural detailed data are necessary in order to further constrain the origin and evolution of Udaeta Lake. Still, the obtained results contribute to a better understanding of the MFFS geometrical complexities, enriching this continental transform fault database.

5.2 *Río Valdez*

From the applied geophysical methods, it was interpreted that the magnetic maxima would coincide with the presence of the glacio-lacustrine deposits. On the other hand, the high gradient transition zones to the magnetic minima to the E and W would indicate the location of the glacio-lacustrine sediments contacts, thereby depicting

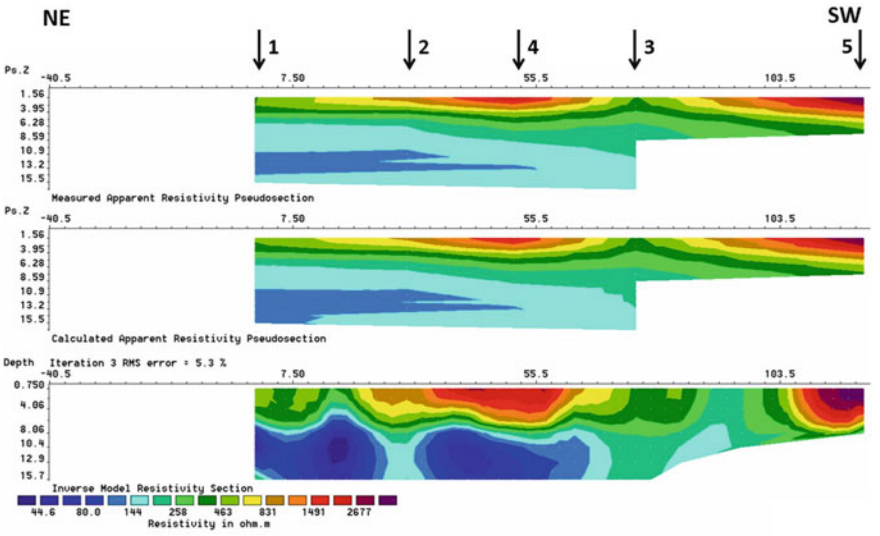

Fig. 14 Top: measured apparent resistivity pseudosection. Middle: calculated apparent resistivity pseudosection. Bottom: inverse resistivity model section. Black arrows: location of each VES in Río Valdez area; (modified from Prezzi et al. 2019)

the extension of such deposits. Most of Euler solutions coincide with the elongated magnetic maxima, at average depths of ~3–7 m (Fig. 10). Such depths would be in accordance with the average thickness (~4 m) of the till layer covering the glacio-lacustrine deposits in Río Valdez outcrop. Euler solutions are also concentrated beneath the high gradient transition zones at average depths of ~11–20 m (Fig. 10). Moreover, spectral method results coincide notably well with Euler depths estimations.

To achieve a good fit between measured and modeled anomalies, bodies to the east, west and beneath the glacial sediments were included in the model, with magnetizations dominated by reverse NRMs (Table 1). Such bodies would represent the lower Cretaceous Beauvoir Formation (Martinioni et al. 2013), which outcrops to the east of the surveyed area in Cerro Jeujepen. Taking into account the magnetic parameters used to model the glacio-lacustrine sediments and Beauvoir Formation (Table 1), the depth to the top of the magnetic layer calculated through spectral methods (Fig. 11) would correspond to the base of the glacio-lacustrine deposits and the top of Beauvoir Formation. Isopach maps of the till and rhythmites and an isochoric map of the base of the rhythmites were derived from the 3D model. A good coincidence between thicknesses less than 2–5 m and the 0 and maximum values of the tilt derivative and the horizontal derivative of the tilt derivative, respectively, was observed (Figs. 12b, 19a, b). Moreover, the till isopach map (Fig. 19a) and the isochoric map of the base of the rhythmites (Fig. 19c) show a very good agreement with Euler depths (4–7 m for till, 9–20 m for rhythmites) and with the depth to the base of the rhythmites obtained through power density spectra methods (maximum depth of 21–22 m) (Fig. 11). These coincidences support the 3D magnetic model as a robust

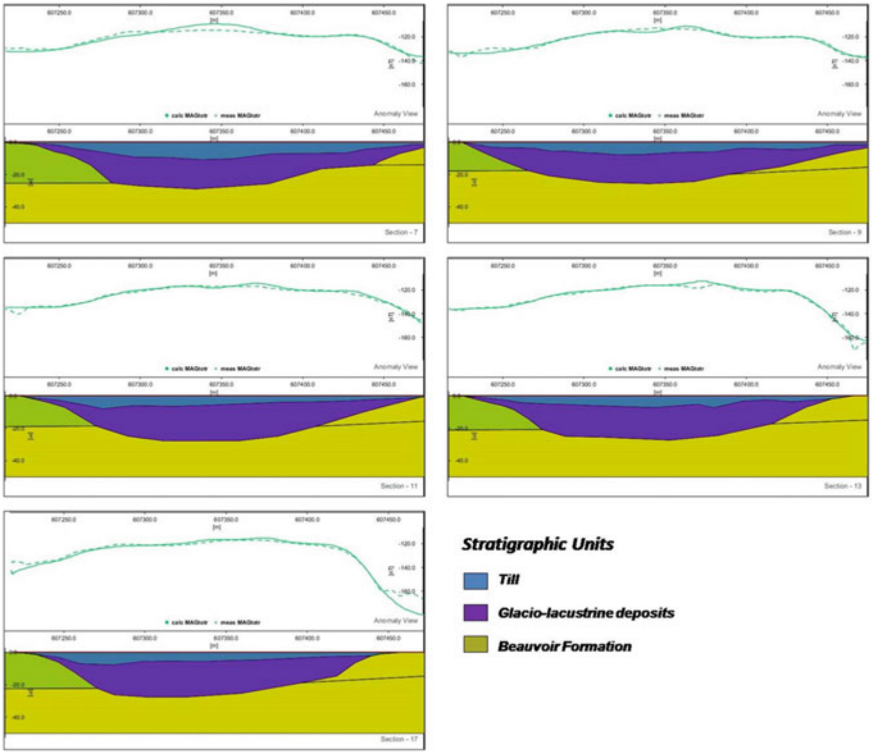

Fig. 15 Parallel E–W vertical sections composing the 3D forward magnetic model of Río Valdez area. Continuous green line: measured magnetic anomaly, Dashed green line: modeled magnetic anomaly; (modified from Prezzi et al. 2019)

characterization of the subsurface extension of the glacial deposits. Such deposits would have a maximum E–W extension of approximately 220 m and a minimum NNW-SSE extension of 180 m. The maximum NNW-SSE extension could not be defined because to the south of the studied zone there are houses, fences, pipes, etc., which would generate considerable magnetic noise.

Regarding the resistivity survey, the high resistivity layer would represent the till deposit, while the glacio-lacustrine sediments would correspond to the low resistivity zone identified in the inverse model. The till thickness deduced from the geoelectrical survey is in agreement with the depths estimated through Euler deconvolution and power density spectra methods of the magnetic anomalies. A minimum thickness of approximately 11–15 m was determined for the glacio-lacustrine deposits. It was not possible to reach the required investigation depths to estimate the total thickness of the rhythmites due to the dense forest that covers the studied area, hindering the usage of larger separation between current electrodes. Nevertheless, thicknesses of the glacio-lacustrine deposits estimated by Euler and spectral methods and through 3D modeling of the magnetic anomalies were coincident, with average values of

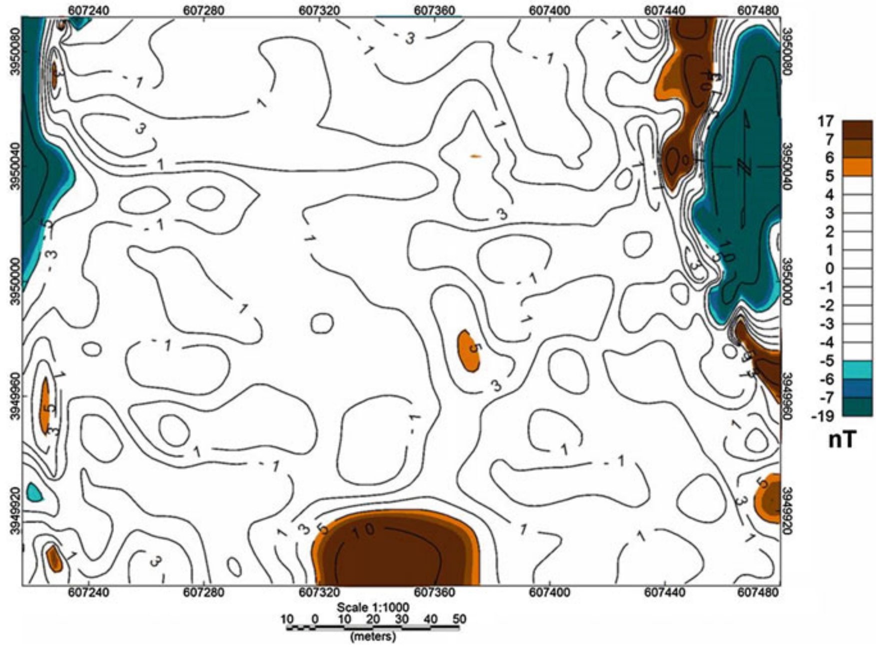

Fig. 16 Residual magnetic anomaly of Río Valdez area. Black lines: contour lines; (modified from Prezzi et al. 2019)

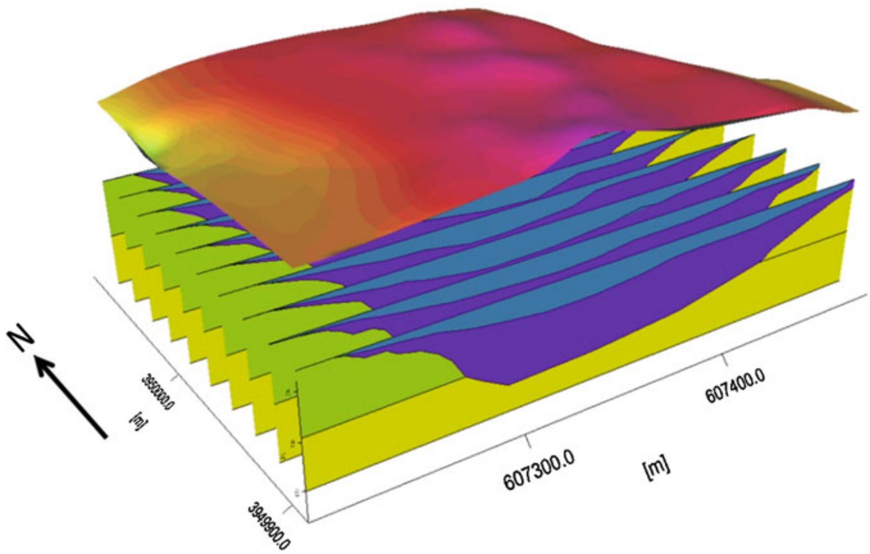

Fig. 17 3D view of the magnetic model of Río Valdez zone, showing measured magnetic anomaly; (modified from Prezzi et al. 2019)

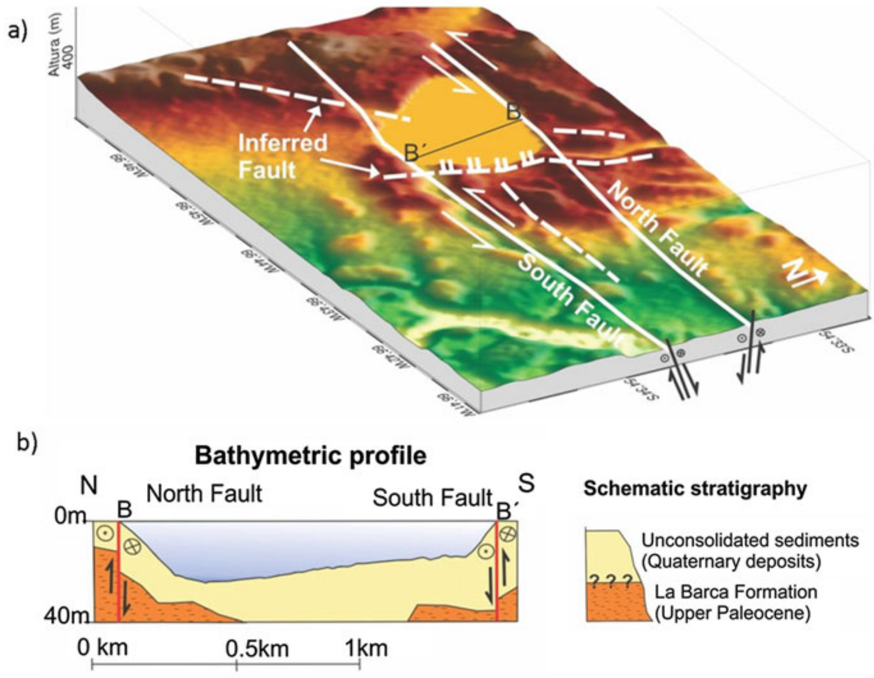

Fig. 18 **a** Dem of Udaeta Lake with main Quaternary structures, **b** Schematic geological and bathymetric profiles and stratigraphy; (modified from Onorato et al. 2019)

approximately 20 m and maximum ones of 22–23 m in the center of the surveyed zone.

Unfortunately, data about glacial sedimentation rates in Tierra del Fuego during the Pleistocene are not available, being difficult to constrain the age of the studied deposit. To carry out a rough estimation of the time interval during which Río Valdez Lake system was active, sedimentation rates of Potrok Aike Lake (51°58’ S–70°22’ O) were utilized, considering a continuous sedimentation process of rhythmites. However, it is important to mention that Potrok Aike was not an ice-marginal Lake during Pleistocene. The minimum sedimentation rate determined for Potrok Aike Lake of 0.37 mm/year (Kliem et al. 2013) was used, taking into account that Río Valdez deposits are rhythmites. From that rate, it was estimated that the investigated glacio-lacustrine sediments could correspond to a maximum deposition lapse of 54,054 years. This time lapse coincides with the 14C fossil peat ages obtained in the surrounding tills by Bujalesky et al. (1997) and Coronato et al. (2009) of 31,000 ± 510–48,200 ± 3300 years BP. These ages indicate that a glacial advance occurred in the region prior to the Last Glacial Maximum (ca. 25,000–23,000 cal. years BP). Consequently, the proposed hypothesis is in agreement with previous findings in the region, which suggest that glaciers were present before MIS 2. It is proposed that the natural dam that promoted the paleoLake, and the corresponding lacustrine

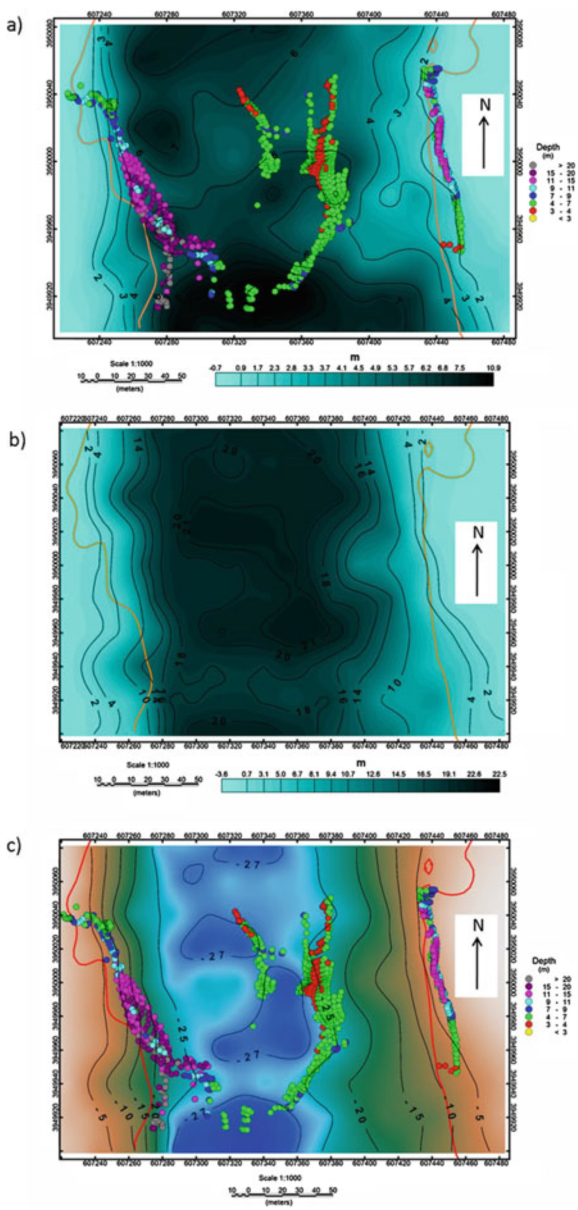

Fig. 19 **a** Isopach map of the till deposits overlaid by the Euler solutions calculated using a SI = 1 and a window size of 70 m. Orange line: 0 contour line of the tilt derivative of the upward continued reduced to the pole magnetic anomalies; **b** Isopach map of the glacio-lacustrine rhythmic deposits. Orange line: 0 contour line of the tilt derivative of the upward continued reduced to the pole magnetic anomalies; **c** Isochoric map of the base of the glacio-lacustrine rhythmic deposits overlaid by the Euler solutions calculated using a SI = 1 and a window size of 70 m. Orange line: 0 contour line of the tilt derivative of the upward continued reduced to the pole magnetic anomalies; (modified from Prezzi et al. 2019)

sediments, would have been operative probably ca. 57,000 yrs BP, near the boundary between MIS 3 and 4 (sensu Lisiecki and Raymo 2005). To better constrain this hypothesis, absolute dates for Río Valdez deposits are necessary.

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Geological and Geographic Resources Among Hunter-Gatherers of Tierra del Fuego: A View from Archaeological and Ethnographic Data

Karen Borrazzo and Martín Vázquez

Abstract This chapter deals with geological resources in a distinctive manner: it explores their use as raw materials and geographic markers within hunter-gatherer societies that occupied the Fuegian Archipelago since the end of the Pleistocene until historical times. Here we summarize archaeological and ethnographic data that allow us to identify past human decision-making, particularly some of the specific reasons for the choices that Fuegian people made about rocks and landscape features, as well as the ideas related to them. The trends observed in both archaeological and ethnographic data emphasize the deep knowledge that these populations had on the spatial distribution, physical properties and the potential use of minerals and rocks in the Fuegian landscape. Ethnographic mythological narratives underscore the central role of geology in building *Selk'nam* maps of the islandscape.

Keywords Lithic technology · Raw material · Landscape · Mythology · Fuegian achipelago

1 Introduction

The role of landscape and its resources in the past organization of human groups have been a central topic in archaeological research. Studies showed that each society dealt with the possibilities and limitations set by the environment in different and original ways (e.g., Binford 1978; Lee 1979; Bettinger 1987; Veth 1993; Orquera and Piana 1999; Borrero 2012; Brievik et al. 2016; Speth 2018). Among hunter-gatherers, landscape is the natural and material as well as the social and symbolic scenario in

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which origin myths and daily life take place. Thus, societies make sense of places and build senses of place (Hodder 1978; Ingold 1993; Taçon 1999). Rocks and minerals, in turn, while representing geological elements of the landscape, are among the earliest natural resources used by humans and their ancestors to manufacture tools worldwide (Harmand et al. 2015; Hayden 2015). In addition, they are both technological (i.e., toolstone, pigment) and geographic (i.e., refers to places of provenience) assets. Hence, while developing out of their local natural landscapes, people also shape and create cultural landscapes.

Isla Grande of Tierra del Fuego and the surrounding archipelago (southernmost South America) allow the exploration of the people— landscape relationship among terrestrial and maritime hunter-gatherers (Borrero 1985, 1998; Orquera and Piana 2005, 2009; Zangrando et al. 2011; Morello et al. 2012, among others). Furthermore, regional archaeological and ethnographic records showed that rocks and minerals were raw materials used by Fuegians since the peopling of the archipelago until the beginning of twentieth century (Chapman 1986; Massone 1987, 2009).

Therefore, this essay explores some aspects of the relationship Fuegians (especially pedestrian hunter-gatherers from Isla Grande of Tierra del Fuego) established with the regional geography and the geological resources by examining archaeological and ethnographic data. We focus our revision on the identification of past human decision-making and assess some of the reasons that may have guided human selection and use of geological and geographic resources.

2 Archaeological and Ethnographic Perspectives on Fuegian People

The peopling of Tierra del Fuego took place during the Pleistocene-Holocene Transition (Morello et al. 2012). The Tres Arroyos 1 rockshelter, located on the northern steppes of Isla Grande, provided the earliest date for the presence of humans in the Archipelago (ca. 10,500 BP). Faunal remains, lithic technology and hearths suggest that the earliest archaeological record resulted from ephemeral but reiterated occupations of the rockshelter (Massone 1987, 2009; Massone et al. 1998). By that time, retreating ice caps still covered larger areas of the Andean Ranges and the sea was 20 m below its current level (Clapperton 1992; Rabassa et al. 2000; Ponce et al. 2011). Climate was drier and colder than today and the Fuegian steppe was occupied by now extinct fauna (Martin et al. 2009). Early Fuegians were pedestrian hunter-gatherers with a diet centered on the consumption of guanaco (*Lama guanicoe*), the native wild camelid, and probably opportunistic use of extinct fauna (Massone 1987, 2004; Borrero 2003). Indeed, hunting, gathering and fishing was the dominant way of life in the whole Fuegian Archipelago until historical times (Borrero 1985, 1997; Legoupil and Fontugne 1997; Orquera and Piana 1999, 2005, 2009; Legoupil 2003; Zangrando et al. 2011).

Since the initial occupations and until ca. 8,000 BP, Isla Grande was connected to Patagonia mainland by a land bridge. After that date, the elevation of sea level due to the Holocenic deglaciation produced the flooding of the land corridor and the formation of the Magellan Strait, a marine channel of 3.5 to 30 km width nowadays (Clapperton 1992; McCulloch et al. 1997, 2005). Thus, a geomorphological event split and isolated from each other those pedestrian populations inhabiting southern South America (Borrero 1989–1990).

The Beagle Channel (southern coast of Isla Grande) provided the current earliest human record on the island after the formation of Magellan Strait. There, pedestrian hunter-gatherer occupations are recorded at Imiwaia I and Tunel I sites (7,840 ± 50 and 6,680 ± 210 BP, respectively; Orquera and Piana 1999, 2009). Between 6,400 and 5,000 BP, the populations inhabiting Beagle and the Western Channels developed a maritime way of life (Legoupil 2003; Orquera and Piana 1999, 2005, 2009; Orquera et al. 2011; San Román et al. 2016). Littoral and marine resources (e.g., pinnipeds, molluscs, fishes) are the staples for this new subsistence model that included navigation technology and specialized weaponry, such as bone harpoons (Orquera and Piana 1999; Scheinsohn 2010). Furthermore, navigation and maritime hunting technologies were in use among populations inhabiting southern Isla Grande and the Western Channels until historical times (Gusinde [1937] 1986; Bridges 1948; Borrero 1997; Orquera 2002; Orquera and Piana 1999, 2005, 2009).

On the northern steppe, several archaeological sites located on the Atlantic and Western coasts of Isla Grande exhibited hunter-gatherer occupations oriented toward the exploitation of terrestrial and littoral resources since 6,000 BP (Favier Dubois and Borrero 2005; Salemme et al. 2004, 2014; Santiago and Salemme 2017). Despite evidences for extra-regional contacts, there is no archaeological or ethnographic record for the incorporation of navigation technology among northern Isla Grande populations (e.g., Gusinde [1937] 1986; Morello et al. 2012). However, archaeological and historical records suggested that terrestrial and maritime hunter-gatherers alternatively inhabited Inútil Bay and the western coast of Isla Grande (Morello et al. 2012; Fig. 1). Furthermore, the local development of a mixed cultural unit was proposed (Gusinde [1974] 1991: 130–131; Martinic 1999; Morello et al. 2012).

By the late Holocene (4000 BP– nineteenth century) the regional archaeological signal increased; the frequency of sites especially raised since 1,500 BP. This trend probably is related to conservation (i.e., the better preservation of more recent archaeological record) as well as demographic (i.e., population growth due to the accomplishment of the effective occupation of the land, sensu Borrero 1994–1995) issues (Borrero et al. 2008; Oría et al. 2017; Ozán and Pallo 2019).

The Magallanes—El Cano expedition offered the earliest European record of Fuegian people: it was the sighting of large fires on the southern coast of the Magellan Strait (northern coast of Isla Grande) that would give the island its Spanish name (*Tierra del Fuego* = land of fire). Six decades later, Sarmiento de Gamboa participated in the first direct contact between European and *Selk'nam* people (native groups living in the Fuegian steppe) in Gente Grande Bay, on the northwestern coast of Isla Grande. Between seventeenth and nineteenth century, contacts with natives became more frequent as maritime explorations proliferated. These contacts had

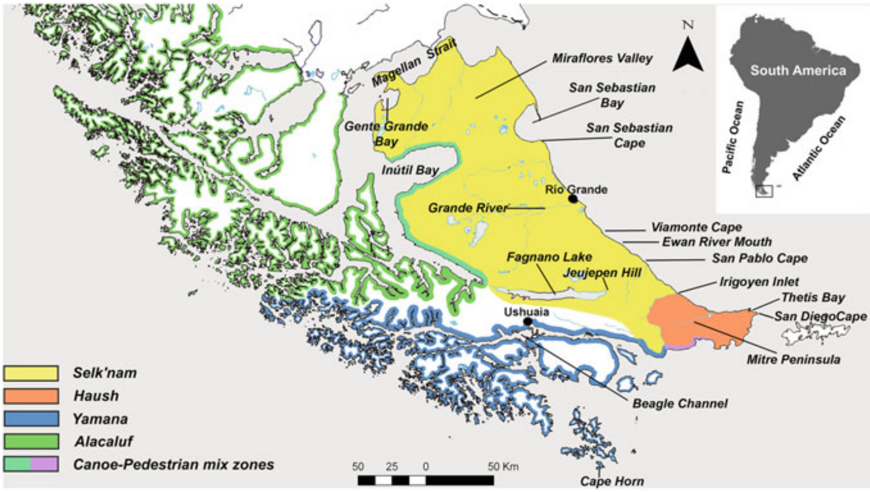

Fig. 1 Distribution of ethnographic groups in the Fuegian Archipelago until early twentieth century

terrible consequences for aboriginal societies (e.g., Martinic 1990; Borrero 1994, 2001; Mayorga 2018).

The mention of hunter-gatherers usually recalls the concept of Stone Age (Hayden 2015). Although technology among Fuegian groups was not limited to stone tools, rocks and minerals played a central role as raw materials in hunter-gatherer life style. For example, lithic projectile points, side- and end scrapers were regular elements in the Fuegian technological repertoire, as archaeological artifact assemblages showed (e.g., Orquera and Piana 1999; Borrazzo 2010; Morello et al. 2012; Oría 2012; Santiago 2013; Zangrando et al. 2011; De Ángelis 2015). In addition, the percussion method of firemaking, body painting, and several polishing tools involved the use of rocks and minerals as well (Lothrop [1928] 2002; Fiore 2004, 2016; Gallardo et al. 2018).

Ethnographic data describes two basic life styles in the Archipelago: canoe and pedestrian hunter-gatherers (Hyades and Deniker [1891] 2008; Gallardo [1910] 2002; Beauvoir 1915; Gusinde [1931] 1982, [1937]1986; Chapman 1986). The former inhabited the Magellan Strait and the Western Channels reaching the open sea in the Pacific Ocean; to the south of Isla Grande, maritime people occupied the Beagle Channel and the Cape Horn (Fig. 1). Western groups were known as *Alacalufes* (also *Hallakalup*) or *Kawésqar* while southern groups name was *Yamana* or *Yaghan*. The subsistence of these fisher-hunter-gatherer societies centered on the consumption of littoral resources (pinnipeds, fishes, mollusks, birds, and whales). Both developed specialized technologies for the exploitation of those resources and used regularly canoes for acquiring food and moving from one place to another (Legoupil and Fontugne 1997; Orquera and Piana 1999, 2005, 2009; Legoupil 2003; Orquera et al. 2011; San Román et al. 2016).

Fig. 2 *Selk'nam* people portrayed by Europeans in the early twentieth century. **a**, **b** pictures took by Furlong (1907–1908) (after Furlong 1910: 226 and Furlong 1933: 219); **c** picture took by De Agostini (1910–1920) (after De Agostini 1929: 251); **d** picture took by Gusinde (1923) (after Chapman 2002: 187–188)

Pedestrian hunter-gatherers known as *Ona* or *Selk'nam* (also *Shelknam*) occupied the steppes and the northern and central forests of Isla Grande of Tierra del Fuego (Gusinde [1931] 1982; Chapman 1986; Borrero 1991; Fig. 2). Guanaco was the main resource on their diet, which was complemented with the consumption of other terrestrial (birds and small rodents) and littoral (fishes, mollusks, pinnipeds, and occasional stranded whales) fauna. Although some differences were noted within this ethnic group (e.g., *Selk'nam* inhabiting the northern steppe and those living in the ecotone and forest environment to the south of Grande River), the largest differences were pointed out between *Selk'nam* and *Haush* (i.e., pedestrian groups that occupied the Mitre Peninsula, southeastern region of Isla Grande, Fig. 1). In spite of similarities held by these societies (life style, technology), several authors indicated the existence of linguistic variations and a larger dependence upon littoral resources by the *Haush* (e.g., Gusinde [1931] 1982; Chapman 1986; Vidal 2011).

3 Materials and Methods

This chapter presents archaeological and ethnographic data. The former provides a large corpus of information that resulted from more than 50 years of systematic archaeological investigation conducted by several research teams in the region (c.f. Vázquez and Prieto 2014). Here we focus on the lithic component of the Fuegian archaeological assemblages and consider the lithic artifacts recovered from excavation and surface surveys. Museum collections are incorporated qualitatively in this review. Fuegian archaeology provided the earliest artifact evidences for the human presence in the region since Pleistocene–Holocene Transition as well as the material record of historical hunter-gatherers and European contact. Therefore, archaeology offers access to the entire human occupational history of Tierra del Fuego through the study of assemblages of cultural remains deposited along thousand years. Here we build on archaeological data of lithic technology to explore the relationship of Fuegian people with the geological resources and employ the distributional information of lithic artifacts to approach past cultural geography.

Ethnographic data on Fuegian people—especially for those inhabiting the Isla Grande—come from a prolific documentary record produced from sixteenth to twentieth century. It resulted primarily from explorers of terrestrial or maritime expeditions (sixteenth to nineteenth century) and missionaries and ethnologists (second half of nineteenth to twentieth century) (for a review refer to Saletta 2013). As we stated above in reference to the archaeological record, ethnographic and historical documents also present a large corpus of information on Fuegians but they comprise a different type of record of human activity. Firstly, documents inform on a smaller temporal scale (in this case, temporal segments within the last 400 years). Secondly, historical sources include the direct observation of Fuegian people, their daily practices, including even some of their ritual ceremonies, and document some of their beliefs at that time. Thirdly, as historical archaeologists dealing with documentary records have emphasized, the narratives of each document are products of the subjectivity of the narrator and the context of production (Pitt 1972; Galloway 2006). In this chapter, we explore the way several *Selk'nam* myths explained the origin and position of geological features within the Fuegian islandscape.

4 The Study of Lithic Raw Materials in Archaeological Research

Since rocks and minerals were the raw materials employed for the manufacture of everyday tools, it is the key for archaeological research to know their spatial (and temporal) natural availability. In addition, raw material sourcing is critical for the study of past human mobility (e.g., Navazo et al. 2008; Durán et al. 2018). The regional survey of lithic sources to build a raw material database is a regular component in archaeological research of northern Isla Grande since the 1990s (Franco 1998; Franco and Borrero 1999; Ratto and García 1996; Borrazzo 2010, 2012, 2013; Borrazzo and Etchichury 2013; Borrazzo et al. 2010, 2015, 2019). In order to explore human choices on the use of geological resources as raw materials, here we depart from the data obtained through the regional research conducted by one of us (KB) in northern Isla Grande de Tierra del Fuego as well as the archaeological literature available for neighbor areas (e.g., Prieto et al. 2004; Santiago et al. 2007; Oría 2009, 2012; Oría and Pal 2010; Turnes et al. 2016).

The study of lithic raw materials in northern Isla Grande included systematic surveys aimed at locating potential raw material sources (after Franco and Borrero, 1999). The first stage of sourcing research was the use of regional geological data (e.g., Codignotto and Malumian 1981; Codignotto 1990; Bujalesky 1998, 2007; Vilas et al. 1999; Acevedo et al. 2002, 2011; Santamaría et al. 2019). Geological background data guided potential source sampling and provided some indication on what minerals and rocks may be locally available. The subsequent field survey allowed the identification and sampling of twenty-one sources of lithic raw materials within the Argentine portion of the island located to the north of San Sebastian Cape (Fig. 1). Each source was characterized archaeologically (type of source; accessibility, flaking quality, etc.; Nami 1992; Aragón and Franco 1997), morphometrically (size and shape of the nodules available, Franco and Borrero 1999) and petrologically (118 thin sections studied). Each rock sample with a described thin section was incorporated to the Fuegian Reference Collection used for the macroscopic classification of raw materials in archaeological lithic assemblages. In order to avoid misclassification due to the application of the macroscopic methodology[1], petrographic types determined microscopically were subsequently grouped into more general lithological categories that gathered those diagnostic attributes observable to the naked eye or through low magnification that made classification reliable. Macroscopic categories thus generated were rhyolitic and basaltic rocks (for fine-grained volcanic rocks); melanocratic and leucocratic rocks (for coarse-grained intrusive rocks); siliceous rocks (e.g., chert, chalcedony, opal); pelites (massive fine-grained sedimentary rock), shales (stratified fine-grained sedimentary rock) and silicified rocks (Borrazzo 2010, 2013).

For the study of the two raw materials available at the primary lithic source (i.e., outcrop) of Chorrillo Miraflores Valley, Chile (Prieto et al. 2004, Fig. 3a–d), we used macroscopic description, optical petrology, energy dispersive spectrometry via scanning electron microscopy (SEM-EDS) and inductively coupled plasma mass spectrometry (ICP-MS) (Borrazzo et al. 2010, 2015; Borrazzo 2012). The differential methodological treatment employed in the study of Fuegian lithic raw materials and sources responded to the distinct levels of precision required to establish lithic raw material provenance within the regional lithological background (Borrazzo 2010; Borrazzo and Ditchfield 2019).

[1] It is worth noting that lithic raw material classification of archeological artifacts is performed by macroscopic observation (naked eye or low-magnification). Only few archaeological specimens usually undergo thin section procedure since this technique requires the damage or complete destruction of the artefact for its study.

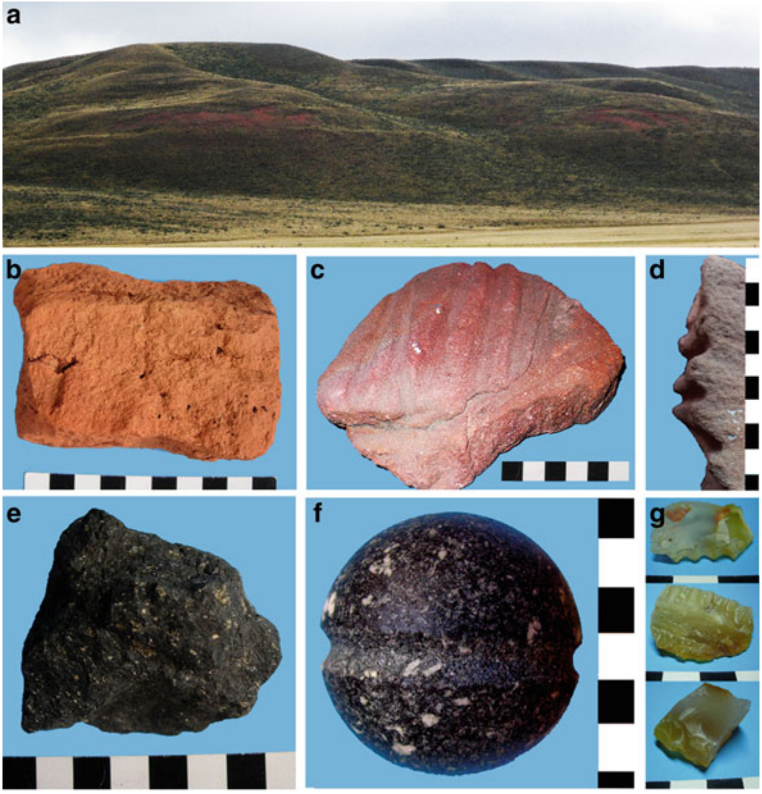

Fig. 3 Primary lithic source and several lithic raw materials from northern Tierra del Fuego. **a** Tuff outcrops in Miraflores Valley; **b** Tuff nodule collected at Miraflores Valley source; **c**, **d** Miraflores tuff polishers; **e**, **f** nodule and stone bola of diabase; **g** chalcedony flaked artifacts

5 A History Written on the Landscape

The notion of landscape we use in this essay is not restricted to the natural environment but includes the cultural dimension of place. Thus, landscape is conceived as the result of a dialectic relationship between societies and their habitat; it is a social construct that is culturally and historically situated (Thomas 1993; Morphy 1995; Criado Boado 1991; Taçon 1999; Santos-Granero 2004; Walker 2012). This historic definition of landscape poses the need for the notion of change to incorporate the mutability of culture, and it introduces the problem of addressing the study of "fossil or archaeological landscapes". Paleoecological, archaeological, and ethnographic data such as myths and toponymy provide the way of accessing past landscapes. Especifically toponymy transmitted by oral tradition and mythological narratives represents one of the means by which human groups affixed their memory to the landscape (Nacuzzi 1991; Vázquez et al. 2012; Mazzia 2013). Hence, space unfolds symbols and information related to territorial hierarchy, control, and demarcation. For this contribution, we focus our selection on mythological accounts with references to the Fuegian geography. Finally, ethnographic and archaeological time frames required specific approaches: while we used ethnography and archaeology to address the former, only archaeological studies were implemented to tackle the latter.

6 Results

6.1 Behavior Written in Stone: Geological Resources and Hunter-Gatherer Decision-Making

Archaeological research conducted on lithic resources availability and their human use showed that Fuegians primarily obtained raw materials from secondary deposits of glacial, fluvial, and/or marine origin since the end of the Pleistocene. Several of these sources offer igneous, sedimentary, and metamorphic rocks of adequate size and quality for flint-knapping (Franco 1998; Santiago et al. 2007; Borrazzo 2010, 2013; Oría and Pal 2010; Turnes et al. 2016). Among them, rhyolitic and silicified rocks are frequent, each of them accounting for ~25% of the nodules sampled at the sources (Borrazzo 2013). In addition, these rocks are the most represented lithic raw materials in Fuegian archaeological assemblages of pedestrian hunter-gatherers (Borrazzo 2010; Oría 2012; Oría and Salemme 2016; Turnes et al. 2016), accounting for 40 to 95% of the artifacts recovered to the north of San Sebastian Cape (Borrazzo 2013). Other less common raw materials displaying very good to excellent flaking quality are siliceous rocks (e.g., chalcedony, opal and silicified wood) which were intensively used for tool manufacturing throughout the island (e.g., Borrazzo 2010, 2013, 2014; Oría 2012; De Ángelis 2015). The regional availability of chalcedony is scarce, with only a few known potential sources, which comprise scattered small rounded nodules (c. 4 cm) (Borrazzo 2012). Their frequency in archaeological assemblages is 4 to 9%, being higher in areas naturally devoid of rocks (i.e., muddy tidal flat on northern of San Sebastian Bay, Borrazzo 2013).

The survey of lithic sources to the north of San Sebastian Cape showed that most of the lithologies exploited in the past are readily available at the regional scale and suitable nodules can be obtained within a radius of 10 km from any of the loci studied. However, lithic sources recorded differences in the frequency, lithologies, and size of the nodules available (Franco 1998; Franco and Borrero 1999; Borrazzo 2010, 2013; Borrazzo and Etchichury 2013). On the other hand, the technological study showed that variations recorded in raw material availability (i.e., size, frequency, type, and flint-knapping quality) influenced the composition of archaeological assemblages (Franco and Borrero 1999; Borrazzo 2012, 2013). Indeed, the comparison of technological data against regional lithic resource availability highlighted several trends. Firstly, it showed that flakes and debris were more frequent where it is plentiful of raw materials. Secondly, rocks exhibiting better flaking quality were more represented among archaeological assemblages recovered from landscapes devoid of raw materials. Thirdly, tool discard rate was higher in areas with scarce or no lithic raw material available. Fourthly, morphological variability of lithic artifacts stepped up as raw material availability increased. Fifthly, the frequency of cortex on stone tools decreased as raw material availability diminished. Finally, cores were more abundant and showed higher exploitation intensity in areas where lithic resources were scarce or not available at all (Borrazzo 2010, 2013). The patterns described showed that Fuegian hunter-gatherers actively incorporated the regional structure of lithic resources into the technological strategies selected for raw material provisioning and stone tool use. A similar trend was recorded to the south of San Sebastian Cape, where Turnes and colleagues (2016) identified raw material selection strategies in archaeological sites located within Grande and Avilés rivers basins.

Geomorphology represents another source of variation in the Isla Grande since it changed the landscape and the regional structure of lithic resources through time. For instance, coastal evolution destroyed and created new spaces and lithic sources (Borrazzo 2009, 2010, 2012). From the Mid-Holocene to present day, the coastal cliff north of San Sebastian Bay has been eroding while the coast of the bay prograded seawards (Bujalesky 1998; Vilas et al. 1999; Santamaría et al. 2019). These processes annexed isles to the land (e.g., San Sebastian Bay, Ferrero 1996; Favier Dubois and Borrero 2005; Borrazzo 2009), created new lithic sources (e.g., El Paramo spit, Bujalesky 1998, 2007; Vilas et al. 1999) and inhibited the access to preexisting quarries (e.g., burial of previously exposed gravel deposits, Franco 1998).

Research focused on the lithic raw materials used by hunter-gatherers for the manufacture of stone *bolas* in northern Isla Grande showed that the selection of rocks was not primarily influenced by availability (Borrazzo and Etchichury 2013). It was proposed that the regional preference for diabase derived from its better performance during manufacture and use of stone *bolas*, due to its higher resistance to impacts (Fig. 3e, f). The comparison of the frequency of this stone tool in the regional archaeological record and the natural distribution of the lithologies used for their production (diabase, diorite) in the lithic sources (i.e., gravel deposits) indicated that tool manufacture and discard took place in different segments of the northern Fuegian landscape. While production occurred in lithic-rich environments, finished stone *bolas* were mainly deposited in areas exhibiting low raw material availability (Borrazzo and Etchichury 2013).

In Chile, the outcrops at Miraflores Valley (Fig. 1 and 3a) represent the only primary lithic source area effectively used and therefore they are an exception in the macroregional big picture in which secondary lithic sources prevail (Franco 1998; Prieto et al. 2004; Santiago et al. 2007; Oría 2009; Borrazzo 2012). The two raw materials available at Miraflores outcrops (a tuff and silicified tuff) have unique macroscopic, petrological, and geochemical features that differentiate them from the rest of the rocks available in Fuegia (Borrazzo et al. 2010). Hence, while exhibiting a naturally confined distribution to a specific point of northern Fuegian geography, Miraflores raw materials were transported by hunter-gatherers covering ca. 28,000 km^2 within Isla Grande and even moved outside the island (Borrazzo 2012;

Borrazzo et al. 2015, 2019; Pallo and Borrazzo 2016). Miraflores tuff was exclusively used for the manufacture of polishers (i.e., abraders or sharpeners, a ground stone tool made of a block of coarse rock with grooves in which wood shafts or bone tools were polished or sharpened, Lothrop [1928] 2002). Indeed, this raw material is dominant among the polishers recovered in the Fuegian Archipelago (Borrazzo et al. 2019; Fig. 3b–d). As for silicified tuff, the most frequent tool made on this rock was a small end scraper (Borrazzo 2012; Borrazzo et al. 2015). Use wear experimental studies showed that Miraflores end scrapers performed scraping tasks efficiently and tool edges remain acute and useful longer than edges shaped on chalcedony and rhyolite end scrapers (De Ángelis 2014).

The lithic technology of Isla Grande of Tierra del Fuego also records the presence of exotic rocks (i.e., extra-Fuegian provenience), such as the green and black obsidians from Otway-Skyring and Pampa del Asador (Morello et al. 2004, 2015; Oría et al. 2010; Orquera and Piana 1999). The arrival of these non-local raw materials to the northern Fuegian steppe involved the interaction between canoe and pedestrian groups (Morello et al. 2012).

6.2 A Land Built with Stories: Exploring Narratives on Ancient Landscapes of Tierra del Fuego

There is a prolific record of Fuegian mythological narratives. They address the origin of men and women, animal and plants, celestial bodies as well as topographic features, always emphasizing the perceived symbolic dimension of the landscape (Gusinde [1931] 1982; Chapman 1986; Staller 2008). The antiquity of these ethnographic narratives remains unknown (Crowell and Howell 2013). The examples summarized in the following paragraphs illustrate the relationship of *Selk'nam* people with the geography and geological features of the Fuegian islandscape.

6.2.1 *Kenós*, the Demiurge, and the Origin of the Fuegian Landscape

According to *Selk'nam* mythology, the actions, struggles and adventures of several characters that lived in ancient times established the order and principles that ruled the contemporary world. *Kenós* was instructed by *Temáukel*—the ultimate spirit—to organize the world and distribute the winds and clouds. *Kénos* created human ancestors using clay. People was immortal at that time so they could choose to become an animal, wind, a rock or a mountain when they got tired from living. For instance, *Oixála*, *Téxnol*, *Euwan,* and *Síla* turned into mountains and stayed in their territory forever. Thereby, every living creature or feature of the landscape was once a human ancestor.

6.2.2 *Haruwens*, Hunting Territories

Territoriality was a strong factor among *Selk'nam* societies. Land was structured through the kin access to hunting territories known as *haruwen* (Fig. 4). Relatives of the family group had granted access to the land and its resources. Mythological explanation for the origin of this land division emphasizes that chaos reigned before *haruwen* were created. The story includes three main characters: *Taíta*, an evil and powerful woman, a wise old man named *Kaux* and his grandson, *Taiyín*. *Taíta* lived in Thetis Bay (*Laswàix*), in Mitre Peninsula. She overmastered *Selk'nam* nation and controlled its access to water and hunting territories; adult and children died of starvation and thirst. Therefore, the elders decided to kill the wicked woman to release their people. *Kaux* (the old owl) asked for help to his grandson living on the north of the island. *Taiyín* traveled and killed *Taíta* with a stone. When people heard that *Taíta* was dead, they tried to drink but lakes and ponds were covered with the blood of the evil woman. Then, *Tayin* collected the dirty water and several large rocks, and he threw them all far away in different directions. Anywhere one of those rocks fell, new springs and lakes appeared. That provided water sources for every region of the island. He hurled a few huge rocks to the north, thus separating the Isla Grande of Tierra del Fuego from the mainland; then *Tayin* threw a large rock toward

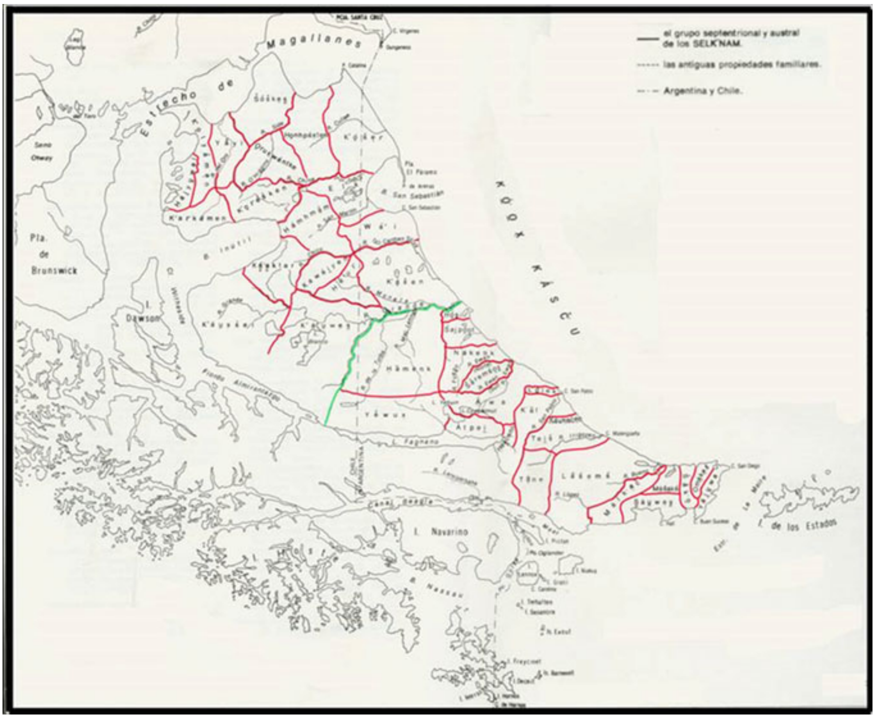

Fig. 4 The distribution of *Selk'nam haruwen* (after Gusinde 1937, 1982)

the south and formed the Beagle Channel. Finally, he took several rocks and threw them to the west thus creating the small islands and the complex Western Channels. By the time this mythological event ended, *Selk'nam* geography was already in place. To avoid that anyone could control the access to all of the resources at once again, *Kaux* divided the islandscape into *haruwen* and distributed those territories among the *Selk'nam* families. Thus, each family group would have its own territory where its members could drink and hunt freely.

6.2.3 *Kwányip*'s Saga and His Nemesis, *Cemuke*

Kwányip is another *Selk'nam* ancient hero that came from the north. *Háis*, *Kwányip*'s father, was from the north too and therefore people from the south was suspicious about him. People from the south built the first big hut for the *hain* (male initiation ceremony, Gusinde [1937] 1986) near San Pablo Cape; according to the myth, the hut was a mountain range called *Máustas*. While people stayed at San Pablo area, *Háis* did not get close to their settlements but one day he kidnapped a single woman, *Sáter*, and forced her to work for him. Lately, she was transformed into a shrub (*Ribes magellanicum*) and *Háis* himself became a cliff located to the north of San Pablo Cape. His wife, *Kásmen*, turned into a mountain and *Síla -Háis*' brother- and his sons -*Téxnol* and *Euwan*- became cliffs near San Diego Cape.

In the ancient time, *Kwányip* was the adversary of *Cénuke*, a powerful and evil shaman that scared and murdered *Selk'nam*. *Kwányip*'s older brother, *Aukménk*, died because *Kwányip* prevented him from waking up from *Aukménk*'s rejuvenation dream. To revive his brother, *Kwányip* should ask *Cénuke* to wash *Aukménk*. *Cénuke* inherited the power of resuscitation from *Kenós*. When *Cénuke* heard that *Aukménk* died because of *Kwányip*, he got angry and left. He went up in the sky followed by his family. People then blamed *Kwányip* for the departure of *Cénuke*. As *Kwányip* was in mourning, he painted in red and wore the painting the whole day. However, before leaving, *Cénuke* made *Akelkwóin* (sister and mother of *Kuányip*) to get sick and died. Since *Cénuke* was not in the country to wash *Akelkwóin*, she could not revive. *Kwányip* was grieving and he painted himself in red again. Finally, *Kwányip* gathered his family together and went up in the sky. For generations *Selk'nam* could see *Kwányip* and his family shining together in the red star on the sky. *Akelkwóin* was a tall person; she became a mountain soon after she died. She grew prominently among the ranges located on the northwest of Fagnano Lake (*Kami*). *Aukménk* became a mountain too. He stands near his sister *Akelkwóin*.

6.2.4 *Caskels* and the Stone Fire Starter

Cáskels was a giant that hunted and ate humans. He had a stone that produced sparks and lighted fire quickly. The source for this special rock were the ranges, known as *Cáskels* by the *Selk'nam*, located near the Irigoyen Inlet. One day, *Cáskels* kidnapped *Kwányip*'s nephews to make them work at cleaning human remains in his hut. Therefore, *Kwányip* decided to kill the giant. After a long and useless struggle to escape from a river, *Cáskels* laid down exhausted in the stream. Then, *Kwányip* broke the giant's spine with his own foot and *Cáskels*, after making a terrible sound, died. *Kwánip* rescued his nephews and they shot stones to *Cáskels*' eyes using their slings; the fragments of *Cáskels*' eyes fell into the water. According to *Selk'nam* narratives, grey and green dots in the bottom of the lakes were the fragments of *Cáskels*' eyes. The body of the giant became a large rock, which is located in *Cácis*, a narrow area near Río Grande, close to Primera Argentina Ranch.

6.2.5 *Shaiwaal* and *Jeujepen*: Examples of *Selk'nam* Toponymy in Geological Features of Isla Grande

The study of the origin and meaning of toponymy is a field scarcely explored in Tierra del Fuego but research is even scarcer for native toponymy (Belza 1974). Nonetheless, indigenous toponymy is present in modern cartography: official maps of the Argentine portion of Tierra del Fuego include names such as Ewan, Chaipot, and Ushuaia. Indeed, Shaiwaal and Jeujepen are two features of the Fuegian geography labeled with native words.

Shaiwaal is a 7 km long gravel and coarse sand deposit outcropping parallel to the current maritime coast between Viamonte Cape and Ewan river mouth. It is a marine paleobeach dated to Middle Pleistocene (Bujalesky and Isla 2006). Although Shaiwaal is located within a forest area, trees did not colonize it and thus it stands as a long deforested corridor near the woods. Shaiwaal is the *Haush* word for 'the *Shai* road'. Ethnographic data indicate it functioned as the scenario of competition and racing activities that involved members of different *haruwen* during historical times. Local archaeological signal is low and it is represented by a few small sites and isolated findings. The available radiocarbon date is ca. 1700 year BP (Oría et al. 2017). Shaiwaal's myth of origin refers to *Shai*, an experienced hunter well known for his extraordinary strength, who was disregarded by his neighbors because he was very fat. In order to put an end to that situation, *Shai* dared them to compete in a race with him. The members of both groups (*Shai*'s and the neighbors) made fun of *Shai* when they heard about the duel. The day before the competition, *Shai* cleared a long corridor from trees until the finish line. *Shai* ran through the clean path and won the race easily (Bridges [1948] 2000).

Jeujepen is a 704 m a.s.l. hill located in the headwaters of Kami (Fagnano) Lake, in the center of Isla Grande. From a geological perspective, it is an isolated granitoid hill formed by a domed intrusion of the Andean Batholith dated to the Early-Late Cretaceous boundary (Acevedo et al. 2000; Peroni 2012). From an ethnographic perspective, Jeujepen was a major asset in the landscape since it was a highly visible topographic feature and it stood as the crossroad of indigenous trails connecting central and southern areas of Isla Grande (Fig. 5). Lucas Bridges' detailed account allows us to approach the meaning of Jeujepen Hill for local native groups: "*Many of the mountains in Ona-land, especially those separated from the main range, were human beings long ago and should be treated with respect. That was the Ona legend… One*

Fig. 5 View of Jeujepen Hill from the headwaters of Fagnano (Kami) Lake

of this was Heuhupen, the table-land that had once been a witch… Her two daughters, less conspicuous than she, stood out of either side of their mother" (Bridges 1948: 302). Little is known about this mythological character; she was a powerful magician that, annoyed at being rudely pointed at, might wrap herself in clouds and bring on bad weather.

7 Discussion

Geological resources are an integral part of the Fuegian landscape. In the past, lithic sources provided hunter-gatherers with raw material and information as well. Differences in optical, physical, mechanical, and geographical properties of the available lithologies prompted their selection for distinct uses combining social and functional requirements. In this section, we illustrate this point with several examples integrating archaeological and ethnographic data.

Chalcedony is one of the more frequent raw materials used for end-scraper manufacture in northern Tierra del Fuego. Artifacts made on this raw material were recovered in almost every archaeological site of northern Isla Grande, but always in low frequencies (Borrazzo 2010). The regional availability of chalcedony is scarce and widely distributed; they occur as small rounded gravels and were exploited by the bipolar flaking technique. The low predictability of encountering chalcedony in Fuegian landscape may have promoted an embedded (or opportunistic) provisioning strategy for its procurement. The dominant use of chalcedony for end-scraper manufacture may respond to the search of durable edges (Greiser and Sheets 1979; Ratto and Nestiero 1998). Nevertheless, a *Selk'nam* woman mentioned the translucency of chalcedony—an attribute lacking on other good flaking quality minerals and rocks of

Tierra del Fuego—as the main characteristic of this raw material (Chapman 1986: 64; Fig. 3g). She called it "*hain*" (also name for the *Selk'nam* male initiation ceremony).

As we mentioned above, Miraflores tuff was the preferred lithic raw material for polisher manufacture in the Fuegian Archipelago. Furthermore, it was proposed that this raw material may have been the driving factor in the exploitation of the Miraflores Valley source area. Indeed, two of Anne Chapman's *Selk'nam* informants (Angela Loij and Federico Echeuline) mentioned that inhabitants from northern Isla Grande usually brought *hamker*, "the famous stone used to polish arrow shafts," for exchange (Chapman 1986: 63). Several other ethnographic references stressed the prominence of "northern *hamker*" for polishers thus suggesting that the Miraflores tuff was a highly valuable resource among Fuegian groups (Chapman 1986:64; Hyades and Deniker [1891] 2008: 103). Its conspicuity in the landscape due to the presence of the reddish regolith on the top of the hills (Fig. 3a) may have reinforced the role of Miraflores source as a geographic marker (Borrazzo 2012). It is worth noting that although tuff is an inland resource, its earliest archeological occurrence (~4000 yr BP, Legoupil et al. 2011; Morello et al. 2012; Borrazzo et al. 2015) was recorded on small islands of the western Magellan Strait. In addition, the primary coastal distribution of Miraflores polishers suggests that its use was related to the exploitation of sea resources. Since canoe people seem to have a central role in the regional spread of Miraflores tuff, it was interpreted that its use was probably associated with cultural mixed configurations (not strictly terrestrial nor maritime). Nevertheless, the provisioning of Miraflores rocks within Isla Grande probably operated without recourse to maritime mobility (Pallo and Borrazzo 2016; Borrazzo et al 2019).

Regarding Miraflores silicified tuff, although its source was available since the times of the initial peopling of Isla Grande, its earliest use was dated to 4000 BP and it only had a quantitatively marginal contribution to the Fuegian lithic assemblages ever since (Borrazzo 2012). In addition, there is no correlation between frequency of silicified tuff artifacts and the distance to Miraflores Valley. Alternative models for the anthropic deposition of silicified tuff artifacts within Isla Grande may consider redistribution mechanisms from specific sites or the existence of additional natural sources not yet identified (Borrazzo et al. 2019). As we mentioned earlier in the text, end scrapers are the dominant tool-type made on this raw material. Since the sizes of these stone tools display no correlation with the distance to Miraflores source, it was proposed that the deposition of silicified tuff artifacts took place within the home ranges of the same human group. The similarities in projectile points shape across most of the Isla Grande (Charlin et al. 2014) and the ethnographic information on Fuegian hunter-gatherer mobility since 1880 onwards (Bridges [1948] 2000; Gusinde [1937] 1986; Chapman 1986) agree with the argument of large scale of human circulation during the Late Holocene.

The brief selection of *Selk'nam* mythological accounts for the origin and meaning of some of the main landscape features we presented here also underscored the role of cosmological narratives as a cultural archive of indigenous geographical knowledge. The mythical representations of Fuegian societies are of anthropological interest since they can shed light on several aspects of social organization, cognitive structures, etc. (Levi-Strauss 1978). In this chapter, we focused on the value of these narratives as reservoirs of past geographical information and their adaptive role for human groups with a subsistence based on high mobility and the exploitation of the land at large scale. In hunter-gatherer societies such as *Selk'nam*, the regional geographical knowledge and the circulation of information are key to minimize risk and achieve an adequate exploitation of resources (Binford 1983; Whallon 2006; Borrero et al. 2011). The *Selk'nam* notion of space entailed dealing with complex information and large geographic scales that allowed accounting for multiple landscape dimensions.

The location of lithic raw material sources and outstanding geological features in the landscape were among the transmitted information. Mythological narratives may have been a primary transmission device of this type of data and thus crucial for decision-making about fundamental aspects of hunter-gatherer societies such as mobility and resource exploitation (Whallon and Lovis 2016).

The examples reviewed here show that geographical information is coded in cosmology, myths, and toponymy recorded in narratives. Thus, the organization of geographic data at different scales hinged on engaging and reproducing cosmological narratives that guaranteed the preservation and transmission of knowledge between family groups through space and time.

Since Middle Holocene times, the development of navigation technology built new bridges ("water bridges," Fiore 2006) that did not only reconnect Isla Grande to the mainland but also to the smaller islands of the Fuegian Archipelago. In this manner, social connectedness (i.e., "proximity" resulting from social interaction) underway by the Late Holocene undermined geographical insularity of the southern tip of South America. Fuegian lithic technology recorded the macro regional circulation of material and ideas and thus allows to explore the insular land–seascape relationships and history (e.g., Legoupil et al. 2011; Morello et al. 2012; Charlin et al. 2014; San Román et al. 2016; Stern 2018; Borrazzo et al. 2019; Borrero et al. 2019). The human behavior recorded in stone revised here showed that while integrated within off-islander macroregional networks, Fuegians inhabiting the north of Isla Grande may have retained their identity by reinvesting their landscape with the memory of a mythical past tied to the island's geography and its ancestral dwellers (Hoelscher and Alderman 2004; Frieman 2008), as historical *Selk'nam* cosmology suggests. Some of the technological traits in the archaeological and ethnographic record can also be interpreted as effects of social representations of different Fuegian groups on technical behavior (c.f. Lemonier 1986). Indeed, the spatial trends in morphological variations recorded on Late Holocene archaeological projectile points and ethnographic arrows recovered from the Fuegian Archipelago agreed with the general distribution of ethnic groups portrayed by chronicles in historical times (Charlin et al. 2014, 2016).

8 Conclusions

This chapter reviewed archaeological and ethnographic information on the role of geological resources as raw materials and geographic markers among hunter-gatherer societies that inhabited Tierra del Fuego since the Pleistocene-Holocene Transition. We focused our study on northern Isla Grande archaeology and the mythological accounts of ethnographic *Selk'nam*. On the one hand, we assessed lithic raw material choices and explored their causes by integrating archaeological and ethnographic data. The selection of rocks and their cultural circulation in the islandscape highlighted Fuegians' deep knowledge on the regional geology and evidenced the active role of human decision-making in the use of geological resources. On the other hand, we reviewed *Selk'nam* mythological narratives related to Fuegian landscape features. *Selk'nam* myths were effective cultural devices that preserved and transmitted geographic knowledge through space and time. After our revision, geological resources emerge as *leit motifs* of Fuegian human history. Performances like rituals and ceremonies may have reinforced that society remembered traditional knowledge. Fuegians made sense of places and built senses of place.

In sum, nature and culture had both actives roles in the history of Tierra del Fuego landscape. Hence, the conservation of the latter is also a chief way of preserving social memory as well as the material remains deposited within the Fuegian scenario during millennia of human occupations.

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Geotourism—Interpretation—Ethnogeology: Extraordinary Geological Resources in Tierra del Fuego

Gabriel Chicote

Abstract Geological tourism is a clearly growing field and its future is very promising. This is easy to deduce knowing that it is a type of sustainable tourism. The Interpretation of Geological Heritage—in its widest sense—is the ideal way to connect the general public with geological resources (georesources), motivating them to appreciate it and all this in the most enjoyable way possible. Ethnogeology is one of the specialities that allows the geological interpreter to establish this geological/emotional connection in the quickest, simplest, and ultimately most practical way. Applying these disciplines to the exceptional Geological Heritage on show in Tierra del Fuego is the best way to create a way of respectful development of the environment that takes advantage of the varied geological resources present in this region of Argentina.

Keywords Geotourism · Ethnogeology · Interpretation of geological heritage · Georesource

1 Introduction

Geology is one of the main elements of the landscape, its knowledge allows us to develop tourism exploitation, dissemination, and awareness projects in line with the trends of protection and enjoyment of the environment in force today. A clear example can be seen in the Spanish Pyrenees, more specifically in the Sobrarbe-Pyrenees Geopark in the province of Huesca (Fig. 1).

Despite the obvious growth of new tourism trends in Argentina, unfortunately, geology remains an unknown player in this sector. In any case, this general ignorance of geology can be considered, in some way, as an advantage for professionals who

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Fig. 1 Peña Montañesa seen from Aínsa, in the heart of the Sobrarbe-Pyrenees Geopark. *Credit* Luis Granadino

having, acquired the necessary skills, know how to create a niche in a market which has the potential to play a key role in the national economy.

Tourism associated with geology has been practiced for a long time, although the general public is not fully aware of it. Thus, in Argentina, there are countless places that stand out from the geological aspect that are presented under another aspect, as can be shown if we analyze the catalog of the best-known tourist destinations in the country or display almost any tourist map (Fig. 2).

2 But What Is Geological Tourism or Geotourism?

It should be noted that currently there is no formal agreed definition of geotourism. Until the World Tourism Organization gives an official one, it seems that anyone can establish their own definition by establishing similarities and comparisons with other types of tourism already existing.

Following a logical and pragmatic criterion, "geotourism" can be defined as tourism whose main attraction and driving force is geology or rather the geological landscape

The term Geotourism has its "nuances" as we will see in some of the following definitions given by different authors and publications.

For some, it is a type of tourism that supports or contributes to improving the geographical characteristics of a zone, be it the environment, historical heritage, aesthetic, cultural aspects, or the general welfare of the local inhabitants (Tourtellot 2009).

This definition clashes with other definitions, more in a geological line, both before and after its publication:

Fig. 2 Map of the tourist book "Tierra del Fuego" by the biologist Natalie Goodall

(1) "The provision of interpretive resources and services to promote the social value and benefit of geological and geomorphological sites of interest, and ensure their preservation and use by students, tourists or other visitors" (Hose 1995).

(2) "A segment of the tourism industry that has geological heritage as its main attraction and seeks to ensure the conservation of its resources whilst promoting visitors' awareness and, using interpretation to make this heritage accessible to the lay public and promote dissemination and development of Earth Sciences"(Rushkys 2007).

(3) "From the etymological point of view, geotourism is composed of two words: geo and tourism. The first comes from the Greek term Gaia, the mother earth from which all living and non-living creatures are born (according to Greek mythology). The etymology of the word itself centers its meaning on the geological characteristics of a zone." (Carcavilla et al. 2011).

It is clear which is the main differentiating element of this type of tourism.

The best solution to this conflict of definitions is to join forces so that Geotourism develops in the best possible way, respecting the competence of each group. Of course, all people interested in geology have a place in this field, but they must be scientifically and professionally skilled.

If we are seeking to provide visitor facilities for the largest number of suitable clients, in keeping with the latest trends of "alternative" tourism—different from the usual beach and umbrella packages—and if we also want it to serve for something more than simply generating financial movements, then we will be talking about a type of tourism that we can include in what was called Ecotourism and that, nowadays, is better known as Sustainable Tourism for Development (Fig. 3).

It is important to stress that a very positive consequence of trying to achieve the objectives that Geotourism pursues and that it is possible to make the geological heritage better known, by raising awareness among a wider public and ultimately favoring the conservation of said Heritage.

3 All that Blitters is not Gold!

A tourist destination, just became it is geological, does not necessarily mean that it is of special quality or value. Thus, a visit to a cave, for example, is clearly Geological Tourism, but it may be limited to being an activity lasting a couple of hours and not go beyond mere observation, without any scientific basis, pointing out that a particular shape resembles some member of the family or it may be transformed into a quite different experience that allows the "participant" to enjoy something unique, knowing how and why this "geospace" has been formed while including references to economic impact, local history, and culture, etc. The "family member" aspect can also be included, of course!

It is for this reason that professionals specializing in geotourism should take adequate training in tourism, education, and geoconservation (Chicote et al. 2018). Therefore, these professionals should be a kind of super professional, a blend of geologist, tour guide, scientific disseminator, environmental educator, group promoter, heritage interpreter and scientific researcher, etc. Ah! without forgetting magician, visionary and, in these times, superhero.

To sum up, I would propose a figure of a professional capable of performing all these tasks: the Geological Interpreter Guide.

That Geological Interpreter Guide has to be the element capable of transforming a rock-hard georesource into something accessible and interesting in the eyes of the beholder; that a dinosaur fossil bone is transformed into a whole pack of Triceratops fleeing in terror after a T-Rex attack; that a mountain of more than 3000 meters high becomes a coral reef, similar to the present day Australian Great Reef, or that the Beagle Channel evokes a scientific journey (Fig. 4) that forever changed the vision of human, animal, and planet evolution in general, that mankind had had until that moment.

Geological Interpreter Guide knows the georesource and its physical, social, and cultural attributes, appreciates it, wants to share it and proposes to do so in a pleasant, attractive, suggestive, responsible and rigorous fashion while being sensitive to the needs and concerns of the receiving public and with a purpose: to promote knowledge, respect and therefore the conservation of that georesource, without forgetting that it is essential that the "listeners" enjoy a rewarding and enriching experience.

Fig. 3 Utopia or future reality? (UNWTO United Nations World Tourism Organization). *Credit* Gabriel Chicote

Fig. 4 Some of the "corners" of the Beagle Channel speak clearly of the epic-geological character of past scientific journeys. *Credit* Rodrigo Soldon. https://creativecommons.org/licenses/by-nd/2.0/

Without any doubt, the best tool to achieve such ambitious goals is the Interpretation of Heritage but what exactly is Heritage Interpretation?

Heritage Interpretation is the group of communicative methods and techniques that are used to reveal the significance of a heritage resource. The aim of this action is to ensure that, with the understanding of the meanings by the public, he adopts an attitude of respect and appreciation for the place he visits (Morales et al. 2009).

In the Dictionary of the Royal Spanish Academy of Language (Twenty-Second Edition), we find seven definitions for the verb "to interpret" where some keywords appear: Explain, Translate, Express, Personal, Execute, Represent, Artistic, to which should be added "in measure."

In the definitions given by the "fathers" of interpretation and current references, certain terms, concepts or arguments stand out, such as

(a) Experiences.
(b) Interchanges.
(c) "Feel something that the interpreter feels."
(d) "Delivered in the presence of the inspirational object." For us that is the Georesource.
(e) "Translate from a scientific language into a language understandable by the receiving public, taking into account that it can presented at very varied levels of education."

Bearing in mind that Geology is a very little known scientific discipline among the general public, we must avoid, at all costs, using cryptic language and concepts,

Fig. 5 Pinacle calcareous in the Cañón del Mascún. *Credit* Gabriel Chicote

which can lead to the general public perceiving it as a remote topic and the guide to feel misunderstood.

> Hey! Don´t you find this pleinsbachian synclinorio wonderful?" Or isn´t that crenulation rinconelido mold compound stunning?

These are some of the questions that the frustrated geological "disseminator" might find themselves saying when they finish giving a master class to an audience that begins very interested and gradually becomes "unhooked" from the georesource.

Therefore, to present these scientific concepts to the public, the best approach will be to include a degree of Entertainment, even humour, which does not prevent the message from being scientifically rigorous.

La Tita de Bellosta in the Cañón del Mascún, Cordillera de los Pirineos, Spain (Fig. 5), always brings a grin when it is well interpreted by the Geological Interpreter Guide.

> Legend has it that Bellosta was a local fellow famous for his Tita, for the large size of his Tita …

The humorous aspect can be understood if we imagine a group of Argentine tourists listening to the geological interpretative discourse of how the Playa de la Concha was formed and evolved into San Sebastián, Basque Country (Spain). As long as the Geological Interpreter Guide has been able to use the "intrinsic" characteristics of his audience for "their" benefit."

4 Some Important Notes About Interpretation

4.1 Visitors' Interests

It should not be forgotten that the geological interpreter guide has to be very aware of them. When designing our message, we must know our visitors' interests well, in order to connect better with them. Depending on their concerns, we will modify the presentation to be more effective.

4.2 Interpretation as a User-Friendly Management and Geoconservation Tool

It is recommended that the manager of a natural area, through interpretive actions, facilitates access to certain places and encourages attractive activities in them. In this way, human "traffic" can be directed to where it is most convenient at any time of the year, so as to be managed effectively without having to prohibit acces or impose limits. It will be in the medium or long term, but it is more assimilable by the public than strict prohibitions. Management, dissemination and raised awareness is achieved all in one go!

4.3 Either the Interpreter Believes It, or It Almost Certainly Will not Work

From my experience, there is nothing more motivating and that makes it easier for you to connect with the public than if they see you are enthusiastic, convinced, and motivated. If, at the end of an activity, they tell you that "it shows that you are keen" it is a very good sign. Furthermore, unfortunately, the world of interpretation, with rare exceptions, presently requires many sacrifices and is often only rewarded with the satisfaction of having transmitted your enthusiasm, passion, and respect for what you interpret.

(a) Thrills: get to emotions, otherwise you can never arouse admiration and respect and with it, the desire to conserve. Exciting experiences are much more enjoyable than cold and aseptic ones. Horror and tragic movies are clear examples. Sometimes the name of the place is already exciting (Fig. 6).
(b) Establish bridges of union: Between the georesource and the visitors that allow them to touch the emotions.

Fig. 6 Lago Escondido ("Hidden" lake). *Credit* Rogelio D. Acevedo

5 What About Ethnogeology?

Another term of interest is that of Ethnogeology which has recently been defined as a discipline that lies between popular ethnography and geology, and refers precisely to the traditional use and culture of rocks and landscapes; In short, the relationship between human beings and stones (Sacristán et al. 2016).

In order to establish the bridges of union, or connections, indispensable between the interests of the recipient and the georesource, ethnogeology is the branch of knowledge that will more directly provide us with that information with which "to reach the heart" in our interpretive message. It is the most direct, fastest, and easiest way to establish the union between the tangible and intangible, between the physical characteristics of the geological resource to be interpreted, the values that it has and/or that it represents and the interests and/or concerns of the recipient. Once this first point of attachment is established that holds the attention of the receiver, it will be easier to deliver the rest of the message.

(a) Traditional stonework. Effort, perseverance, achievements.
(b) Traditional materials and construction methods. Resource optimization, durability, pragmatism.
(c) Scientific exploratory trips. Epic, the search for knowledge, effort, sacrifice for others, etc.

There are boths tangible and intangible aspects (values, beliefs, emotions) that allow us to bring geology closer to the visitor or tourist.

As can be inferred from all of the above, the geological heritage that can be used for geotourism can be very variable or present many different characteristics, and all of them can be used for recreational economic purposes.

Although all the characteristics are profitable, we must start with “something” and that something must be, undoubtedly, geological and, if possible, with a clearly defined intrinsic value.

The places to start looking will be the “Geosites.” Those locations are already established by UNESCO, where geology prevails over all the other elements that make up the landscape and that also have remarkable qualities, at least at the national level, for any visitor who approaches these out-of-the-way places, often off the beaten track.

6 Examples of Geotouristic Resources in Tierra del Fuego

If we limit ourselves to the inescapable characteristics that a geological resource must have in order to be a viable geotouristic resource, these are

(a) Contrasted geological value.
(b) Spectacular in location: Outstanding scenic value.
(c) Usable teaching value.
(d) Cited scientific value. It is not the same as teaching material, but it is sometimes very closely related.
(e) Important economic value is not essential but recommended for its effect of attracting people.

If those who are familiar with of Tierra del Fuego do not visualize twenty possible georesources, it is that I have not yet explained myself well; or that they do not know the spectacular Tierra del Fuego so well (even name meets all the requirement to be geotouristic). One thinks of Volcanoes of “Game of Thrones” or apocalyptic lands that would be perfect scenarios for the next installment of Mad Max.

We will start with the most famous worldwide, which is no mean feat.

The Beagle Channel, near the Darwin Range (Bujalesky et al. 2008).

Everything previously written about links between history, values, material and intangible heritage or epic science falls short when we talk about Darwin and his journey in the Beagle (Fig. 7).

There is another particularly magical place which, undoubtedly looks like a painting by Dalí, in Punta Sinaí, located in the North of the Isla Grande (Figs. 8 and 9): a field of granodiorite erratic boulders, which have been carried 150 Km by the glacier from the batholith of the Darwin Range and deposited in a small area on the present day coast (Coronato et al. 1999, 2004; Bujalesky 2007).

If you had to choose a Geopark at the End of the World, I would choose the latter. Although to include something ethnographic, it would be necessary to expand the

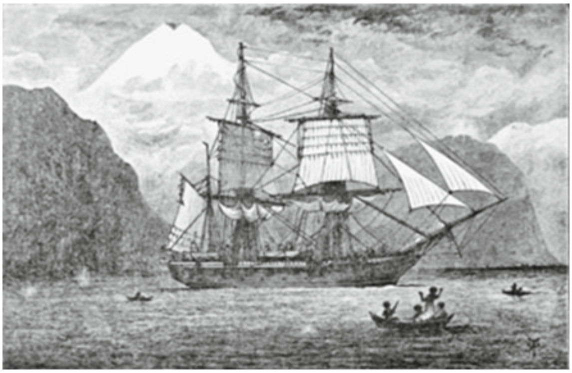

Fig. 7 The passage of the Beagle through the Magellan Straits, a historical landmark of science. *Credit* R. T. Pritchett (https://en.wikipedia.org/wiki/HMS_Beagle#/media/File:PSM_V57_D097_Hms_beagle_in_the_straits_of_magellan.png)

Fig. 8 Uneven blocks of Punta Sinaí. *Credit* Rogelio D. Acevedo

area to Beta canyon, the gold deposits exploited tirelessly by Julius Popper, a gold digger whose legendary figure oscillates between reality and myth.

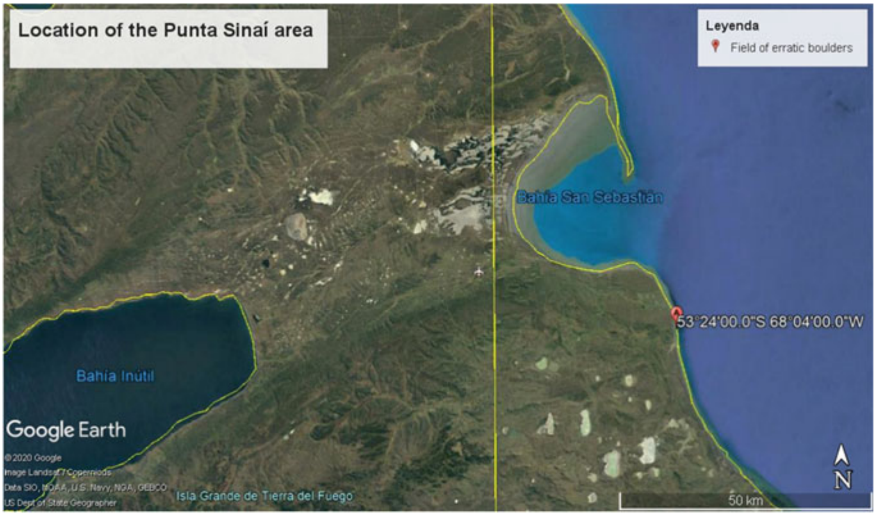

Fig. 9 An aerial photo, how is it, makes you want to explore and discover. Can the wind have so much influence on the landscape? *Credit Google Earth*

7 Geotouristic Heritage that Cannot Be Touched

So far we have focused almost exclusively on the physical, present, tangible Geotourism Heritage. There is another component that, although from the scientific-geological point of view it is not usually taken into account, many times it should not be at the risk of losing the scientific rigor sensu stricto. It should be taken into consideration when we talk about geotourism, of interpretation of the geological heritage, of ethnogeology, which we have previously corroborated that, in addition to being a very useful tool in this professional field, it is also a branch of knowledge that will allow us to establish bridges of union and connections between the observer and the georesource that we are going to exploit, or rather take advantage of Geotouristically speaking: Intangible Geological Heritage.

8 Julius Popper or the Romanian Engineer Who Cured His "Ailment" in Tierra del Fuego. Intangible Fueguine Geological Heritage. Sickness? Gold Rush

He was born in Bucharest on December 15, 1857 and from 1886 he traveled the northern part of the Main Island of Tierra del Fuego, developing gold extraction in "El Páramo."

On the map of Tierra del Fuego based on the explorations and studies carried out by Popper in 1886–1891 and the hydrographic compilations of the British Admiralty, dated in 1892, you can see the toponymy that Popper gave to several geoforms, among them, the canyon which he called Arroyo Alfa or the Cañadón Beta.

Julius Popper, who arrived in Buenos Aires in 1885 and in 1886 reached Tierra del Fuego, is therefore responsible for the denomination of many rivers and streams, and it was he who gave the name of Alpha to the stream that he mistakenly understood to be the most northern. To the south, according to the story, the next canyon was called Beta, with a strange place name of Hellenic reference. Curiously, the alphabetical order does not follow the path he traveled, since he accessed this sector of Tierra del Fuego from the south when he landed in October 1886. The streams are nominated from North to South. Moreover, it is notable that he did not use reference names in Castilian neither did he try to know the names given by the Selk'nam to those water courses, and opted for names that would denote a classical formation without any connection with the nominated place except words that took his fancy,

> The non-scientific information that does not seem to contribute anything but links, softens or makes the message go deeper into the visitors, leaving an impression.

9 Differentiating Between Geodidactic and Geotouristic Is Important

Before closing this publication, it is necessary to clarify two terms that are sometimes used interchangeably but that although in one sense they can be almost synonymous, on the contrary do not work as equals.

An element with geotouristic potential almost always, if not always, will have geodidactic potential since, if only for that geotouristic value, it is noteworthy when it comes to facilitating the understanding of the importance of geology in our lives or in the history of the evolution of the planet or a particular settlement. On the other hand, a georesource with a high geodidactic value does not necessarily have to have geotouristic value when some of the other parameters that would qualify it as such can be practically nil.

An example can be a small fold in a cutting of a main road that allows you to easily understand what its different parts are and why as it has formed in that way. Its geo-educational value for High School and even University students can be high although its geotouristic potential may be practically null, since it is not an interesting feature, its spectacularity is low, its accessibility and potential observation is poor and its value is practically nil.

The need for rigorous studies of the geotouristic potential of locations such as Tierra del Fuego to be developed is paramount for sustainable development of these places while minimizing environment of impact. These studies should be carried out by multidisciplinary groups led by geologists specialized in the field, who will coordinate the studies and field work of other professionals such as tourism technicians, paleontologists, geographers, economists, sociologists, historians, naturalists, and specialists in the Heritage of Mankind, etc. All this supported by the residents and the Local Authorities who must be incorporated into the project in order to have the necessary future support when it comes to addressing the undertaking, so commendable and important as Geological Parks or even UNESCO Geoparks.

10 Conclusions

In short, some of the existing georesources in Tierra del Fuego are already so well-known worldwide, historically and culturally speaking that they are easily exploited as geotouristic resources, and may only require minimum training of those intermediaries in the field, who are the tour guides and naturally at a higher decision-making level, the technicians working in the Local or National Administrations involved.

If we use these outstanding elements—the georesources, not the guides—as an attraction and we offer facilities for tourists from all walks of life, we will be able to apply that old, well-established successful formula, namely previously--known elements plus the surprise of new discoveries equals an unforgettable, rewarding experience.

The Interpretation of Natural Heritage as a communicative discipline adding ethnogeology as a connecting tool, is essential for good management and correct development of Geotourism, with "collateral damage" being perfect preservation of the georesource—Geoconservation—and, in the end, of the surrounding environment—Geoconservation. The Interpretation of Geological Heritage becomes indispensable to manage correctly all those emotional components "Effort, sacrifice, legacy, reward, development, promise of improvement, etc." In short, seeking a better future. Is there anything more emoyional? What appeals more to the feelings than HOPE of a better life for our children.

Acknowledgements Personally, Rogelio Daniel Acevedo for reminding me to write this chapter of such a wonderful book, for the patience he has had at all times and his confidence in this project. In it, I have tried to reflect what Geotourism has taught me in my years of guidance in the field; although this has sometimes caused me to deviate a little from the main issue that I had to address. My sincerest apologies for that.

In general, to each and every person, rocks or sediments, that struggled so that Geotourism or Geological Tourism could develop as a type of sustainable tourism for the development of those less favored places of our beloved and often mistreated GEA.

My most sincere considerations to the Official College of Geologist of Spain for its support. I cannot finish without mentioning David Malcolm Edwards, my private English reviewer, his wisdom and patience have made this chapter possible, and Marisa, my partner, for always being there.

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A Geological Heritage Itinerary Across the Andes in the Isla Grande de Tierra del Fuego

Joan Reche, Joan Poch, Mercè Corbella, David Gómez-Gras, and Francisco J. Martínez

Abstract This chapter presents a strategy for disseminating some of the most important characteristics of the geological heritage of the Isla Grande de Tierra del Fuego. First, the geodiversity elements are related to the major morpho-structural episodes during the geological history of the Isla Grande, from the Jurassic—lower Cretaceous back-arc extension, through Andean compression that progressed diachronically from the SW Andean cordilleran belt (late Cretaceous) toward the NE Magallanes fold-and-thrust belt and Magallanes foreland basin (early Cenozoic) to final Cenozoic-to-recent sinistral transcurrent fault tectonic regime. Next, the didactic and geotouristic potential of a selection of localities is evaluated using different geoheritage criteria. We discuss the geological heritage potential of localities along the Canal Beagle as the low-grade metamorphic rocks at bahía Lapataia (W of Ushuaia), the older rock outcrops of the Isla Grande. To the NE, going from Ushuaia though Paso Garibaldi we found the meta-volcanoclastic rocks of Lemaire and Yahgán Fms., temoins of the volcano-sedimentary processes in the Jurassic-lower Cretaceous back-arc Rocas Verdes basin. The Yahgán Fm. rocks are seen deformed in Mount Olivia slope, a magnificent example of the Andean compressional episode. As examples of the Andean plutonic intrusives we discuss the geopotential of the diorite-syenite plutonic complex of Cerro Jeu-Jepén, near Tolhuin at eastern tip of Lago Fagnano and the ultramafics outcrops at Estancia Túnel, intruded in Yahgán rocks, with its contact metamorphic aureole and located in the N shore of Canal Beagle. Some examples of recent processes as the glaciofluvial and the seismically related deposits are analyzed near the E end of Lago Fagnano. Also, of recent glacial origin are the large erratic blocks of Punta Sinai and the placer type heavy mineral (including gold) deposits on the N coast of San Sebastián Bay, at the NE tip of Isla Grande.

Keywords Geological heritage · Geoconservation · Geotourism

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1 Introduction

The chapter is based on the conclusions reached by a team of Spanish and Argentinian geologists during the 2007 project named: "Establishment of key aspects for research and dissemination of geology in Argentinian Fuegian Andes". The project was funded by the Spanish Agency of International cooperation to development (AECID) of the Spanish Foreign affairs and cooperation Ministry (MAEC), in the framework of the complementary Action C/012815/07 between the Universitat Autònoma de Barcelona—UAB (Spain), the Universidad Nacional de Salta—UNSA (Argentina) and the Centro Austral de Investigaciones Científicas—CADIC (Argentina). The conclusions of this project constitute a proposal of Itinerary of Geotopes in Isla Grande de Tierra del Fuego. This itinerary aims to synthesize the main events in the Geologic history of Tierra del Fuego, using examples with high potential for geotourism.

In this context, the main purpose of this chapter is to show the methodology used to propose a set of elements of geodiversity that allows explanation of the geological history of Isla Grande de Tierra del Fuego to a non-specialized public. This disclosure proposal is made with the will to contribute to the sustainable development of the region through geotourism.

2 Geographic and Geological Context

The Fuegian Andes orogenic belt comprises at least five arcuate structural units. Following (Menichetti et al. 2008) we distinguish from SW to NE: (a) an accretionary wedge, facing toward the Pacific ocean, active from the late Miocene and located between the Chilean oceanic trench and a fore-arc basin to the E; (b) the late Cretaceous calc-alkaline Patagonian batholitic intrusive; (c) the Fuegian Andes Cordillera running from the exhumed basement rocks of Cordillera Darwin metamorphic core complex (Hervé et al. 1981; Khon et al. 1993) located in Chile through the area located S of Seno Almirantazgo (Magallanes strait)—Lago Fagnano lineament, the Navarino and Hoste island, sierras Sorondo and Lucas Bridges, Península Mitre and Isla de los Estados; (d) the Magallanes fold and thrust belt with thin-skinned tectonics and (e) the Magallanes foreland basin at the NE part of Isla Grande de Tierra del Fuego. All these units testify several tectono-stratigraphic episodes, from a general extensional regime prevailing in the Jurassic-lower Cretaceous, trough late Cretaceous compression during the Andean orogeny which involved thick-skinned thrusting and three-phase folding in the basement units plus late thin-skinned tectonism in the foreland upper units to Tertiary-recent left-lateral wrench tectonism along E-W sinistral transform fault systems (as the Magallanes—Fagnano system) associated to exhumation of older rocks and also to contemporaneous neotectonics (Fig. 1).

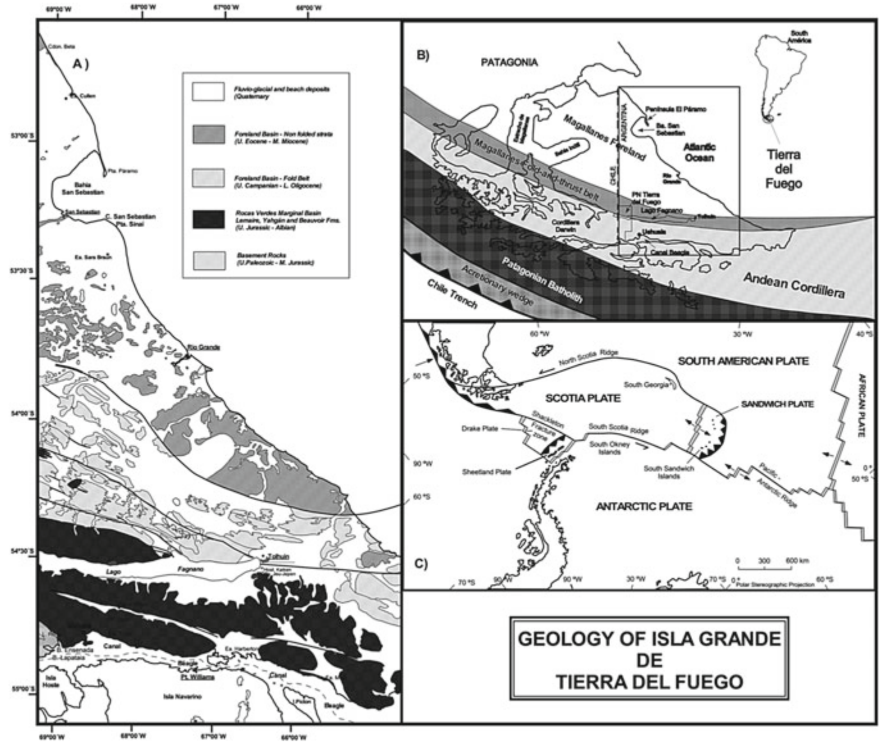


Fig. 1 Geological features of Isla Grande de Tierra del Fuego and related areas. A) Main Stratigraphic domains (based on Olivero and Malumián, 2008). B) Main physiograpic and structural provinces in the S. Patagonia - Tierra del Fuego (based on Menichetti et. al., 2008). C) Geotectonic scenario showing main tectonic plates and plate boundary types. Note that the Isla Grande is traversed by a main transform lineament fault (the Magallanes - Fagnano fault zone - N. Scotia Ridge) separatin two main plates: the South American Plate to the N. and the Scotia Plate to the S

3 Geotourism and Sustainable Development

The term "geotourism" has at least two meanings: in one the term is restricted to the geological aspects of territory. In other words, it refers to the field of culture and nature, in which geology is included.

The first meaning is a specific version of the so-called "ecotourism". In this case, "geotourism" is defined as "the set of actions aimed at promoting the tourist and recreational use of geological resources with the aim of socially and economically promoting a place or region". The person who does geotourism is "the one who travels with the objective of experiencing, learning and enjoying the heritage of the Earth" (Hose 2008).

In the second meaning, the term refers to "tourism that enjoys natural and cultural heritage, and that contributes to the conservation and promotion of its distinctive values" (Tourtellot 2000). This definition, which is adopted in this chapter, offers the opportunity to improve the attraction of non-specialist visitors because geological values are thus perceived as part of the local heritage. It is easier for the visitor to be interested in geology when he realizes that the culture, the abiotic environment and the biotic are intertwined to configure the landscape he is admiring.

This meaning is also used by the UNESCO World Geoparks for their sustainable development strategy, in which they combine the conservation of geological heritage, education and geotourism as part of the holistic management of geodiversity (UNESCO 2015).

4 Geoconservation and Geotourism in Tierra Del Fuego

The geographical location and scenic beauty of Tierra del Fuego has attracted visitors from all over the world for decades, including scholars of Earth sciences (Schwarz et al. 2013). The Sixth Argentine Congress of Quaternary and Geomorphology, which took place in 2015, is an example of the interest of the international scientific community.

Thanks to these studies, dozens of elements of geodiversity with potential for the development of geotourism have been identified in the province of Tierra del Fuego (Schwarz 2017; Schwarz and Coronato 2017; Schwarz and Coronato 2018; Schwarz 2019). Even geological itineraries have been proposed, such as the Ushuaia-Estancia Harberton transect (Schwarz and Migoń 2017). This itinerary is based on the field trip experience of the aforementioned congress and includes, among others, Mount Olivia, Lasifashaj river, Cornu Hill, Brown Bay and Harberton Bay, among others. These geosites are already being used by the tourism industry, but according to Manosso (2012) "the scientific contents offered to tourists should be more extensively explored so that these localities are not only appreciated for their aesthetic value". This objective could be achieved through thematic panels (Miranda et al. 2011).

Given the challenge of ensuring the conservation of the values of the geological spaces of interest, as a previous step to their use for geotourism (Martínez-Fernández 2013), it should be noted that Argentina does not have a specific legislation for the protection of the geological heritage. However, it has some laws and legal figures that give it indirect protection. Thus, for example, since 1992 Provincial Law N° 55 on the Environment establishes guidelines for the conservation of ecosystem functionality, which includes the abiotic environment. On the other hand, Provincial Law N° 272 of 1995 deals with the conservation of biogeographic units by establishing different types of Protected Natural Areas (Provincial System of Protected Areas). Among the figures for the protection of the natural environment, the "Multiple Use Reserve" stands out, characterized by a management model that integrates the protection and sustainable use of natural resources, in line with the UNESCO Global Geoparks.

This approach, already studied by Bruschi (2007), is consistent with the need to preserve certain elements of geodiversity through holistic management, which integrates the relationships of residents and visitors with the geological, biological and cultural values of the territory.

5 Dissemination Strategy Based on Geodiversity

Within the framework of the social, economic and environmental sustainability of the 2030 Agenda (UNESCO 2015), the dissemination strategy presented here is aimed at the conservation and use of certain elements of geodiversity for the benefit of local communities. In order to support this sustainability, the exploitation of geological materials (minerals, rocks, fossils, etc.) has not been considered for commercial purposes that may result in the reduction of the territory's geodiversity.

The proposed strategy is compatible with the management model of the UNESCO World Geoparks (Poch 2019), and may be useful for the World Geoparks Network of the UNESCO for Latin America and the Caribbean (http://www.redgeolac.org/).

It is, in short, a strategy for the dissemination of geological heritage mainly through geotourism. In addition to sustainability, the proposed strategy is based on the concepts of geodiversity, geological heritage and geotourism.

A strategy consisting of three phases is proposed:

(a) Identification of the scientific value of the local geodiversity: the record of the geological history of the Fuegian Andes.
(b) Selection of the elements of geodiversity suitable for geotourism. These elements become part of the geological heritage of the region.
(c) Communication of geological history.

6 Work Methodology: Selection of Geodiversity Elements Suitable for Geotourism

The completeness of the record of the geological history of the Andes on the Isla Grande of Tierra del Fuego has been verified through the compilation of scientific publications cited in the bibliography. According to Brilha (2016), the most objective value that characterizes the geological heritage is its scientific value.

During two 2008 field campaigns, the Argentine-Spanish team visited various areas of geological interest, which frequently combined scientific, didactic and informative values. Next, the geozones with potential geotopes were selected. The term "geotope" refers to outcrops with an important geological meaning, but not exceeding 100 ha, while the term "geozone" refers to areas that group several nearby geotopes or directly areas of geological interest that exceed 100 ha (Druguet et al. 2007).

The final selection of geotopes with potential for geotourism was carried out in accordance with the criteria specified in the previous section. Selected representative features in these geotopes are shown in pictures in Figs. 3 and 4. With the selected spaces an itinerary has been proposed that allows telling the geological history.

Based on Brilha (2016), the following selection criteria (qualitative assessment) has been used for the identification of potential geotopes:

Table 1 Scientific interest

Value	Minimum score	Highest score
Scientific relevance	The geotope is not relevant	The geotope is relevant nationally or internationally
Representativeness: utility as a reference mode	Very poor example as a geological model	Exceptional example as a geological model

- Scientific use: representativeness (contribution to understanding the regional geological history), integrity (present conservation status), and scientific knowledge (existence of scientific data already published).
- Geotourism use: interpretative potential (geological feature to be easily understood by lay people), accessibility (conditions of access for the general public) and safety (minimum risk for visitors).

To complete the characterization of the selected geosites, Tables 1, 2 and 3 presents the quantitative assessment of the scientific interest, potential for geotourism and their risk of degradation based on Fuertes-Gutiérrez and Fernández-Martínez (2010, 2012). See the map in Fig. 2 for the location of the selected geotopes.

Table 2 Potential for geotourism

Value	Minimum score	Highest score
Ease of understanding	It requires a high level of specialization (geologists)	It is suitable for all audiences of any educational level
Aesthetic value	It has no appeal	It attracts attention because of its beauty and aesthetic quality, so it is considered the perception of the local population
Observation conditions	It is not observed in its entirety and some essential features cannot be observed	Exceptional observing conditions: easily observed in its entirety
Accessibility	It is a place with difficult access that involves some risk	It can be reached by car or on foot from a good road
Association with other elements of natural or cultural interest	It is not possible to include elements of natural or cultural interest in the tourism discourse	In the same space, there are other elements of natural or cultural interest that can be included in the tourism discourse

Table 3 Risk of degradation

Value	Minimum score	Highest score
Conservation state	Very deteriorated, with significant loss of relevant features	Well preserved. No signs of deterioration
Intrinsic vulnerability	Low vulnerability. Elements that are only sensitive to large-scale change or total transformation of land use	High vulnerability. Simple contact can cause variations in the conditions of the assets
Current and potential threats	Space in an environment without development perspectives	A space that can be affected by urban expansion
Pillage Risk	Low risk. There is no geological material to plunder	High risk. It is very easy to find and collect geological material

7 Scientific Value of Local Geodiversity

The selected geological outcrops described in this chapter are all located in Argentina, in an area between the parallels 53º S (N side of San Sebastián Bay) and 55º S (N side of Canal Beagle) in the Isla Grande de Tierra del Fuego. Together, they represent the essentials of geological history events of the area. The basement units are represented in Argentina by the greenschist facies, low grade, quartz-rich folded metapelites of the Lapataia Fm. located WSW of Ushuaia (areas near Roca Lake (or Acigami), Lapataia and Ensenada Zariategui bays). These rocks testify the development of an accretionary prism upon the Gondwana margin (Hervé et al. 1981) since pre-Jurassic times. Above this basal unit rest the volcanoclastic Lemaire Fm. also named the porphyritic series (upper Jurassic), the volcanoclastic to turbiditic Yahgán (Kranck 1932; upper Jurassic—lower Cretaceous) and the more distal and pelagic Beauvoir Fm. (Camacho 1967; Olivero and Martinioni 1996 (Upper Cretaceous), that represent the extensional disruption of Gondwana and the generation of a marginal basin during Mesozoic times. The old pre-Jurassic basement materials as well as those deposited in the Mesozoic extensional basins were compressed and uplifted during the Andean orogeny, since the middle Cretaceous. They also were intruded by a suite of calc-alkaline plutonic rocks that are represented in localities along the N shore of the Canal Beagle (río Pipo valley or the area near Hito XXVI, on the S slope of Mt. Mesa Real), near Estancia Túnel and along National Route N° 3, at Cerro Jeu-Jepén, near Tolhuin, among others. Selected localities on E shore of the Fagnano lake and some localities on San Sebastián Bay are good representatives of the Cenozoic and for the most recent geological processes.

8 Geozones with Potential Use for Geoturism

With the fieldwork data, and using the above referred general criteria, seven geozones have been proposed for the tourism itinerary (Figs. 2, 3 and 4):

1. Lapataia Fm. at Lapataia and Ensenada Zaratiegui bays
2. Ushuaia - Río Grande through Paso Garibaldi
3. Cerro Jeu-Jepén

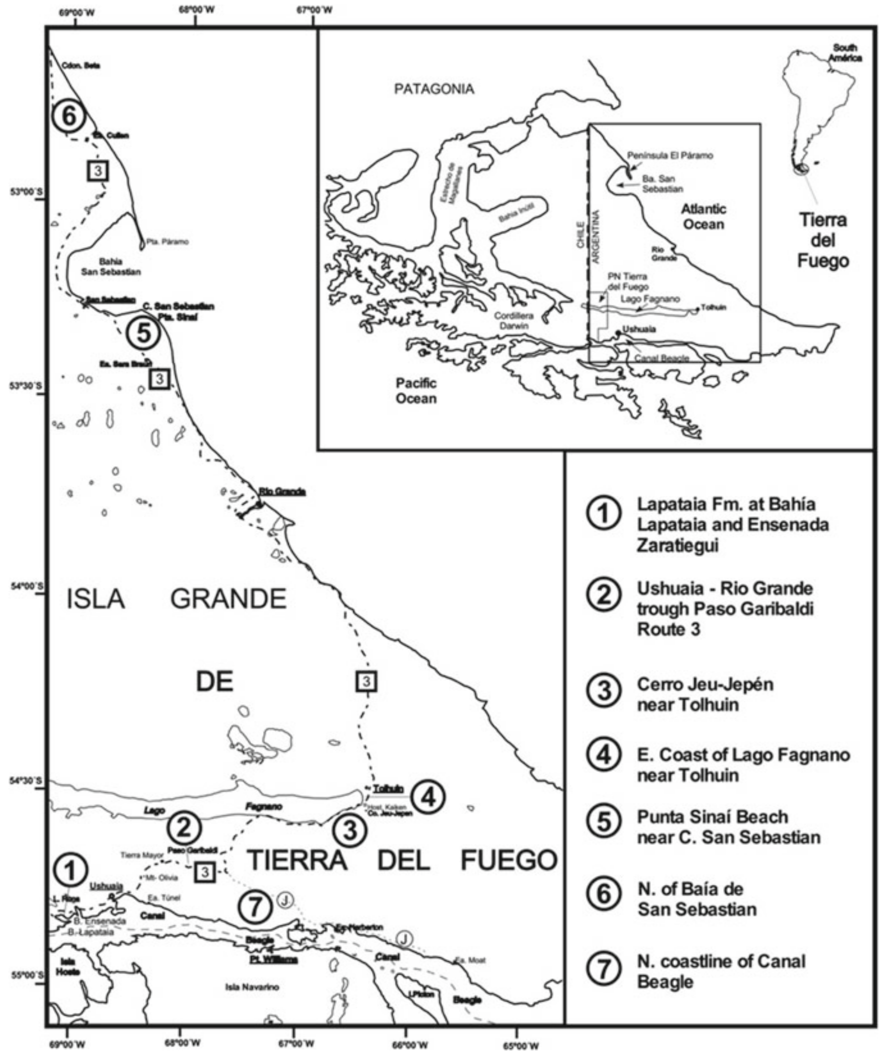
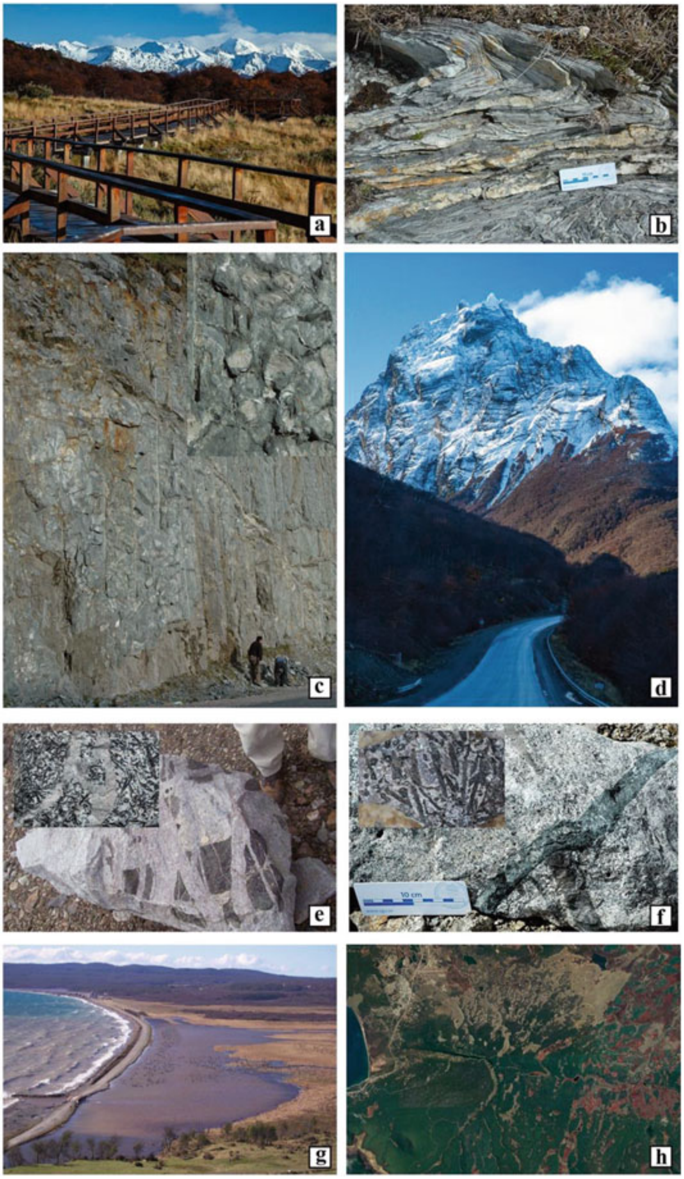


Fig. 2 Proposed itinerary of Geosites along the main Route N° 3 from Ushuaia and Route J toward the N side of Canal Beagle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◀**Fig. 3** Representative features of the proposed geosites. **a** Cordillera Darwin (in the foreground), seen from Bahia Lapataia. **b** Aspect of Lapataia Fm. basement metamorphic rocks on bahía Lapataia. **c** Outcrop of Lemaire Fm. (basic metavulcanites with pillow structures), representative of Rocas Verdes basin, along with National Route N° 3 (see Fig. 2), between Ushuaia and Paso Garibaldi. **d** Folded Yaghán Fm. **e** strata seen on the S. face of Mt. Olivia, also along from Route N° 3. **f** and **g** Different igneous intrusive relations seen at Cerro Jeu-Jepén. Amphibole bearing (see insets at upper left on each figure) gabbro-diorites are intruded by leucocratic syenite veins (**g**) and spessartine lamprophyre veins (**f**). **g** View of the E tip of Lago Fagnano, where a new sand barrel formed due to seismic waves during the 1949 earthquake and originated a natural breakwater that isolates a temporal shallow pond. **h** Satellite view of E tip of Lago Fagnano, where the nearly E–W trending scarp corresponding to the Magallanes –Fagnano sinistral transform can be seen to influence the course of small rivers *Credits*: J. Reche (a, b, c, d, f); R. D. Acevedo (e, g); Google Maps, 2020 (h)

4. E coast of lago Fagnano
5. Punta Sinaí beach
6. N of San Sebastián Bay
7. N coastline of Beagle Channel

1. The Oldest rocks in Isla Grande de Tierra del Fuego

Lapataia and Ensenada Zaratiegui bays include some basement outcrops recording the compressive phases of Andean orogeny and showing folded and cleaved metamorphic rocs (green slates, phyllites, schists) and quartz veins (Fig. 3b). Some features of these materials are suggestive of a volcanoclastic origin. From the bay, one can see spectacular views of Cordillera Darwin that are constituted also of basement rocks (Fig. 3a).

Lapataia Bay is a fjord located on the N side of Beagle Canal at the SW tip of the Argentinian sector of the Isla Grande de Tierra del Fuego, 18 km from the City of Ushuaia. This bay was formerly occupied by a glacier tongue tributary of a much bigger Canal Beagle glacier body, as testify the U-shaped valley and the presence of moraine deposits. The Redonda island, located near the Canal Beagle is interpreted as a former Nunataq, a rock island that was once surrounded by the ice mass. The bay is surrounded by Magellanic type forest and its bottom is inhabited by submarine formations of a giant algae (*Macrocystis pyrifera*). The bay is rich in the fauna of birds as austral seagulls and cormorants, marine mammals as seals, invertebrates as the Patagonian spider crab (*Lithoides santolla*) and fishes. Anthropologically it has the interest that an ethnic group of sea-hunters-gatherers, the Yahgans occupied these coasts c. 1700 bp. as some accumulations of ashes, bones and mussel shells (named “Conchales”) found in the area testify. Although in the project, this bay is still not compressed in the Parque Nacional Tierra del Fuego protected area, although it is administered by the Administración de Parques Nacionales and its N and SW shorelines are accessible through national Park tracks as the “Senda Costera”. The main access to Lapataia Bay is through a segment of National Route N° 3 coming from Buenos Aires. It constitutes an unofficial section of the so-named Ruta Panamericana, running officially from Alaska to Buenos Aires, but featuring an extension to Tierra

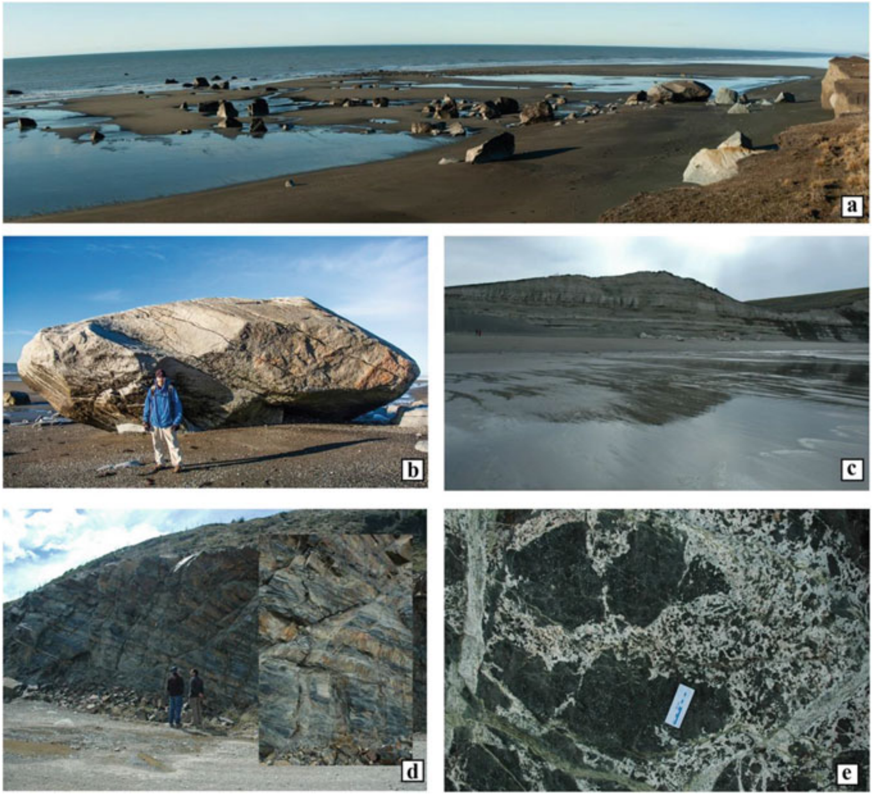

Fig. 4 Representative features of the proposed geosites (cont.). **a** Panoramic view of an erratic boulder field at Punta Sinaí beach. **b** detail of one of the biggest erratic boulders, using a person as scale. The boulders are embedded in glacial sediments (see right side of photo a) and finally deposited onto the beach due to sea erosion of the sedimentary formation front. **c** Neogene sedimentary beds from the unfolded foreland basin strata, N of bahía San Sebastián. Placer-like deposits of garnet and opaque minerals are found in areas on this beach and nearer zones (cañadones Beta and Tortuga). **d** Deep basin, turbiditic-like sediments of the Yaghán Fm., near Estancia Túnel, along the N coastline of Canal Beagle (Isla Grande de Tierra del Fuego). e: Aspect of the Estancia Túnel ultramafic intrusives. The ultramafic rocks are cut by leucocratic syenitic veins *Credits*: J. Reche (a, c, d, e); R. D. Acevedo (b)

del Fuego. National Route N° 3 ends in a famous location named "Word End" in Lapataia Bay.

Ensenada Zaratiegui is also located on the N shoreline of Beagle channel. The access is through a detour from National Route N° 3, 15 km W of Ushuaia. An attraction of bahía Ensenada is the touristic quay named "Puerto Guaraní" with boats going to the Redonda island. Also interesting are the tracks along the Senda Costera toward the N shore of Lapataia Bay with views toward Isla Hoste and Murray channel and having good places to practice birth sighting. Also, of interest is diving to see the submarine giant algae forests. There is also a free camping area.

The Roca Lake is a NW–SE trending Chilean–Argentinian lake generated by the embayment of Lapataia river due to glacial moraine deposit. The lake is inside the Parque Nacional Tierra del Fuego.

2. National Route N° 3: from Ushuaia to Río Grande through Paso Garibaldi

Along National Route N° 3, (between km 3042 to 3044) and departing from the City of Ushuaia, we can visit some outcrops of Jurassic—lower Cretaceous formations. The outcrops located between Mt. Olivia (1326 m.), the highest Andean peak near Ushuaia, and the Lago Escondido, near Paso Garibaldi, were described in detail by Quartino et al. (1989).

The outcrops constitute a thick submarine volcano-clastic ensemble (Olivero and Malumián 2008; Guillot et al. 2016) with sedimentary rocks (conglomerates, cherts or radiolarites) and volcanic materials featuring tuffs, breccias, rhyolitic flows and pillow-lava structures (Fig. 3c). The rocks, that are strongly deformed and cleaved, record the back-arc extensional phase in Tierra del Fuego (Pankhurst and Rapela 1995; Pankhurst et al. 2000). On these outcrops, besides the nice pillow lava structures, spectacular views of the NW slope of Mt. Olivia can be seen (Fig. 3d).

From the Mirador of Paso Garibaldi, a major plate tectonic boundary can be seen on the foreground of Lago Escondido, following Lago Fagnano long axis, in a line parallel to the horizon. This boundary is constituted by the Magallanes–Fagnano transform fault system (Cunningham 1993). As a consequence of the sinistral movement of this tectonic accident, the Paleogene terrains in Sierra de las Pinturas, belonging to the South American Plate to the N and the upper Jurassic terrains belonging to the Scotia Plate, where the Mirador is settled in, are being juxtaposed upon one another (Klepeis 1994; Lodolo et al. 2003). The recent activity of the transform fault strongly influences surficial features like course of small rivers, as shown in the area E of Lago Fagnano (Fig. 3h).

Also, from these outcrops on the National Route N° 3 we have a nice view over big peatlands (Coronato and Roig 2000; Roig 2001), as the Oyarzún peatland, developed on Tierra Mayor and Carbajal valleys. Those valleys, forests and peatlands constitute a Natural Reservation (Reserva Natural Tierra Mayor). Those are also privileged localities to observe the beaver dam constructions, so abundant in Tierra del Fuego. The Fuegian forest is dominated by three types of beech trees: Magellanic coihues, ñires and lengas. This area also constitutes a major center for winter activities (dog sledding, hiking, skiing in nearby Cerro Castor Resort).

3. Andean igneous intrusives at Cerro Jeu-Jepén

Cerro Jeu–Jepén is located near the E tip of Lago Fagnano, S of the locality of Tolhuin. These outcrops constitute a quarry front excavated on an igneous dome-shaped composite stock intrusive (middle Cretaceous) related to the main Patagonian batholith (Guillot 2016). The top of the dome stock is composed mainly of gabbro-diorite rock varieties containing ultramafic hornblendite enclaves. After the mafic magma differentiation, a residuum rich in alcalis intruded later and formed a sienitic central body from which sienite veins emanate and intrude in the upper diorites-gabbros. Discontinuous small monzonitic bodies are located on the contact between the gabbros-diorites and the sienites and probably originated through metasomatic processes. A swarm of spessartine lamprophyre veins and leucocratic quartz-feldspathic and calcite-rich veins crosscut the whole complex. The intrusion induced a contact metamorphism in the country rocks, mainly slates. Acevedo et al. (2000) dated the age of the intrusive as circa 93 million years (My). Some intrusive rock relations can be seen in Fig. 3e, f.

Cerro Jeu-Jepén is easily accessible both from Ushuaia and from the nearest locality of Tolhuin along National Route N° 3. There are some trekking routes already established from Tolhuin. It has a splendid and spectacular vantage viewpoint over the Lago Fagnano and the City of Tolhuin.

Tolhuin, near the E tip of Lago Fagnano, is the only big populated nucleus between Ushuaia (111 km to the S) and Río Grande (105 km to the N). Among its touristic attractions are the Lago Fagnano itself (see later section), the viewpoint of Cerro Jeu-Jepén, the río Valdez and Laguna Negra natural reservations, the Khami historical Museum and El Torito Bay in Lago Fagnano.

4. Recent glacial and glaciofluvial processes at the E coast of Lago Fagnano

Near the E tip of Lago Fagnano (Fig. 3g, h) and the City of Tolhuin there are some localities with nice examples of Quaternary glacial and glaciofluvial deposits developed over the Cenozoic-upper Cretaceous basement. These are related to the front of the Fagnano glacier mass that flowed from the uplifted western area of Cordillera Darwin during the Quaternary.

To the N of Tolhuin, we can see big peatlands (Coronato and Roig 2000; Rabassa et al. 1996) developed on former glacial lakes as the Río Turbio peatland, of exceptional thickness, related to neo-tectonism along the Magallanes–Fagnano transcurrent sinistral fault system. Along the cliffs facing the S margin of the lake, sedimentary sequences of glacial origin are exposed (Bujalesky et al. 1997).

On the path to the near Estancia La Correntina several glacio-fluvial forms (Coronato et al. 2002) can be observed (draining channels, basal moraines, kame terraces, glaciofluvial planes and glaciofluvial cones) as well as more evidences of the active neotectonics. Of particular importance are the barrier gravels generated by seismic waves or oscillations in the surface of Lago Fagnano waters ("seiches" of Kvale 1955) during the earthquake of December 17, 1949 (Fig. 3g).

Lago Fagnano is a c. 104 km Chilean–Argentinian long lake located between the city of Tolhuin at its E tip (Argentina) and the Azopardo river that connects its waters to the Seno Almirantazgo (Magellan strait) in Chile at its W tip. Its long morphology is intimately related morphostructurally to a big neo-tectonic accident, the Magallanes–Fagnano fault (Fig. 3h). Quaternary glaciers also modeled this area as formerly occupied the full length of the present lake. Apart from the city of Tolhuin touristic infrastructure, there are good hosting places near the lake, as the Hosteria Kaikén and Khami cottages.

5. Recent glaciofluvial processes (erratic boulders) at the Punta Sinaí beach

In this area, some blocks (Fig. 4a, b) transported by the former lateral moraine of a Magellan strait glacier lobe that occupied the area between the western bahía Inútil (Chile) and the eastern bahía San Sebastián (Argentina) where deposited and remain still on the beaches, after most of the finer sediments, where the blocks are embedded, have been eroded away (Coronato et al. 1999).

The former glacier extended from the N side of Cordillera Darwin in Chile to a frontal moraine now submerged 70 m depth and 26 km E from the Atlantic Argentinian coastline (Isla and Schack 1995). The erratic blocks form an ensemble of more than a hundred dispersed fragments of crystalline rocks originated in Cordillera Darwin probably due to debris avalanches over the surface of the glacier. On the coastal cliffs, one can observe the lateral moraine deposits that still contain some embedded blocks, as well as other glacial and fluvioglacial sediment types.

Punta Sinaí is located at the S. promontory of San Sebastián Bay. The locality is situated c. 80 km N of the City of Río Grande, the second most important city of the Isla Grande de Tierra del Fuego, after Ushuaia. It is accessible through National Route N° 3.

At c. 25 km from Punta Sinaí there is Estancia Sara, one of the biggest farm in the Island, with 64,000 Ha. dedicated to the breeding of ovine and bovine cattle. It is important for its production of wool of great quality. In order to visit the area on the coast where the erratic blocks are exposed, a permission from the Mines and hydrocarbons Argentinian state organism is compulsory. Also needed are notifications to the foreman of Estancia Sara and managers of the hydrocarbon enterprises exploiting the zone. This need for permission can be critical for the establishment of Punta Sinaí as a geotope with easy access to the general public.

In addition to the glacial erratic block field, the site can be attractive for its archaeologic sites featuring "concheros" and other lithic and bone remains (Borrero 1985; Massone 1997). Near Estancia Sara, a good example of marine terraces from the last interglacial period can be observed as well (Codignotto and Malumián 1981). South of Punta Sinaí, in the area of río Chico various Pleistocene littoral deposits can be also observed (Bujalesky 1998).

Río Grande has interesting museistic offer, like the Regional natural and anthopological Museum Monseñor Fagnano, located at the La Candelaria Salesian Mission.

6. Placer type deposits of Cañadón Beta–Cañadón Tortuga (N of San Sebastián Bay)

Cañadones (Canyons) Beta and Tortuga are located near the Chilean–Argentinian Atlantic border, at the N tip of the Isla Grande de Tierra del Fuego, on the linear coast N of San Sebastián Bay (Fig. 4a) and near the eastern opening of Magellan Straits to the Atlantic Ocean. The sands of these coasts are rich in a great variety of heavy minerals including gold (mined during the gold fever at the end of XIX century), magnetite, ilmenite, rutile, corundum, zircon, titanite, garnet, staurolite, pyroxene, tourmaline and others (Santamaría et al. 2016).

The highest concentrations of these minerals are found near coastal cliffs ("Backshores") were they form discontinuous lenticular bodies with metric extension and thickness of only a few cms (see Fig. 4c). Their original provenance can be located in emerged and submarine quaternary glacial sediments forming the coastal cliffs or the submarine terraces in the area (Acevedo et al. 2007; Ponce et al. 2011) with some fluvial and marine reworking (Gómez and Martínez 1997).

The accessibility of this location is also through National Route N° 3. The importance of this locality is geologic, mainly as an example of placer mineral deposits, but also as a historic and cultural site. Settlements of European colonists during the nineteenth century gold fever was the result of the intention to exploit the detrital gold-rich placers.

Of particular interest is the figure of Julius Popper, a Romanian mining engineer, colonist, adventurer and founder of "Compañía Anónima Lavaderos de Oro del Sur" that extracted c. 265 kg of gold from placers at Punta Páramo, a long sand promontory in the San Sebastian Bay, now declared an historical national location. Julius Popper was a prominent figure and one of the main responsibles of the named Selknam (or Ona) genocide (second half of nineteenth century and first decades of twentieth century) of the autochthonous aboriginal peoples of Tierra del Fuego due to interests from the big cattle companies and colonist in search for new settlements or mineral resources as the gold.

7a. Recent glacial processes along the N. coastline of Canal Beagle

Between the bahía Brown and punta Moat at the easternmost end of the N. coast of Beagle channel, several localities feature nice examples of glacial forms and deposits (Rabassa et al. 1990). For example, at bahía Brown, a marine flat erosion surface developed over glacial sediments can be seen at Isla Gable. The structure of these sediments includes a basal tillite, glaciolacustrine clays and silts, glaciofluvial sands and some "drumlin" forms on the top A drumlin field can be visited near the Estancia Harberton and at Cambaceres Bay. A small peat-bog can be seen near Estancia Harberton. Just before entering the Estancia Moat, located near the Atlantic mouth of the Beagle Channel, we can have a good view of some arcuate terminal moraine formations developed during the four glacial retreat episodes, near the punta Moat.

Estancia Harberton was the first Estancia founded in Tierra del Fuego. It was founded by the missioner and pioneer Thomas Bridges (1842–1898) and author of the book the Uttermost Part of the Earth (Bridges 1948). This Estancia was declared National Monument in 1999. It has a touristic guesthouse and cafeteria. Among the tourist attractions, there is the Acatushun museum of birds and austral mammals, some Yagan indigenous settlements and the trip to near Martillo Island where one can see colonies of Magellan and Papúa penguins and cormorants. The habitats of the indigenous Yahgan sea nomads can be visited along the Beagle Channel.

7b. Andean igneous intrusives and contact metamorphism on Estancia Túnel

The Estancia Túnel constitute an intrusive body in the black to grey folded pelites and psammites of the Yahgan Fm (Fig. 4d) (Acevedo et al. 2002). Apart from ultramafics, although in lesser amounts, it has some more felsic varieties as gabbros, diorites, quartz-diorites, monzonites and tonalites (Fig. 4e). The intrusion shows few evidences of deformation concentrated near the intrusive borders where it is also affected by intense alteration to epidote. Some leucocratic syenitic veins crosscut the ultramafic–mafic complex. It constitutes an example of the "Andean diorites", as described by Kranck, (1932).

Estancia Túnel is easily accessible from Ushuaia (at 10.6 km) through National Route N° 3 and later through a non-paved coastal road path leading to Baliza Escarpados and from there through a narrow transitable rural path. There are also established along-the-coast trekking–biking paths from Ushuaia.

Along some of these paths, the visitors can access the Playa Larga, declared natural and cultural reserve that forms part of the Provincial System of Natural Protected Areas, from where there is an impressive panoramic view of the city of Ushuaia. Characteristics of Playa Larga are also the famous "árboles bandera" (flag trees) with its incredible forms due to the influence of the dominant and strong winds of the area.

9 Conclusions

The proposed itinerary (Fig. 2) allows combining geological and non-geological values of local heritage. Hence its high geotourism potential. The tourist who travels it has the opportunity to visit the four main geologic provinces that characterize Isla Grande de Tierra del Fuego. From south to north: Southern Andean Cordillera, Magallanes Fold and Thrust Belt and Magallanes Foreland Basin (see Fig. 1). The characteristics of the rocks allow the visitor to discover the main elements of geological history as well as to observe the biodiversity and culture that have shaped the impressive landscape of Isla Grande.

However, it is necessary to continue developing infrastructure to facilitate accommodation and travel of tourists over long distances, in addition to elements that facilitate the interpretation of geological heritage (panels, brochures, geological guides) and its connection with other values of the territory.

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Differential Uplifting Rates Across the Magellan Fault: Interactions Between South American and Scotia Plates

Gustavo Gabriel Bujalesky, Federico Ignacio Isla, and Alejandro Montes

Abstract The Isla Grande of the Fueguian Archipielago is located on two plates, the South American Plate to the north, and the Scotia Plate to the south. Both plates are separated by the Magellan Fault, assumed a transform fault. Dealing with the sea-level evidences, significant differences between north and south have been estimated. The trailing-edge coast has been uplifting during the Pleistocene at a rate of 0.02 mm/yr between 3 and 1.4 Myers and at a higher rate of 0.05 mm/year for the last 1,4 Myers. As the Mid-Holocene sea-level fluctuation was recorded at both sides of the fault, it was possible to discern an uplifting trend of 0.3 mm/yr to the north (San Sebastián and Rio Chico coastal plains), and to a higher uplifting trend of 1.3 mm/yr to the south of the fault, at the Beagle Channel area. Along the northern side of the plate boundary, the uplifting rates also vary from west to east: 3.3 mm/yr at the western side and 0.2 mm/yr for the eastern side. These increasing uplifting trends were achieved managing different methods, and are explaining an increase in the modern tectonic activity.

Keywords Uplifting trends · Plate interactions · Sea-level indicators

1 Introduction

The Argentine sector of the Isla Grande de Tierra del Fuego is located between 52°40′ and 55°7′ S, and 65°05′ and 68°40′ W (Fig. 1). This region splits into two plates: the South American Plate to the north and the Scotia Plate to the south,

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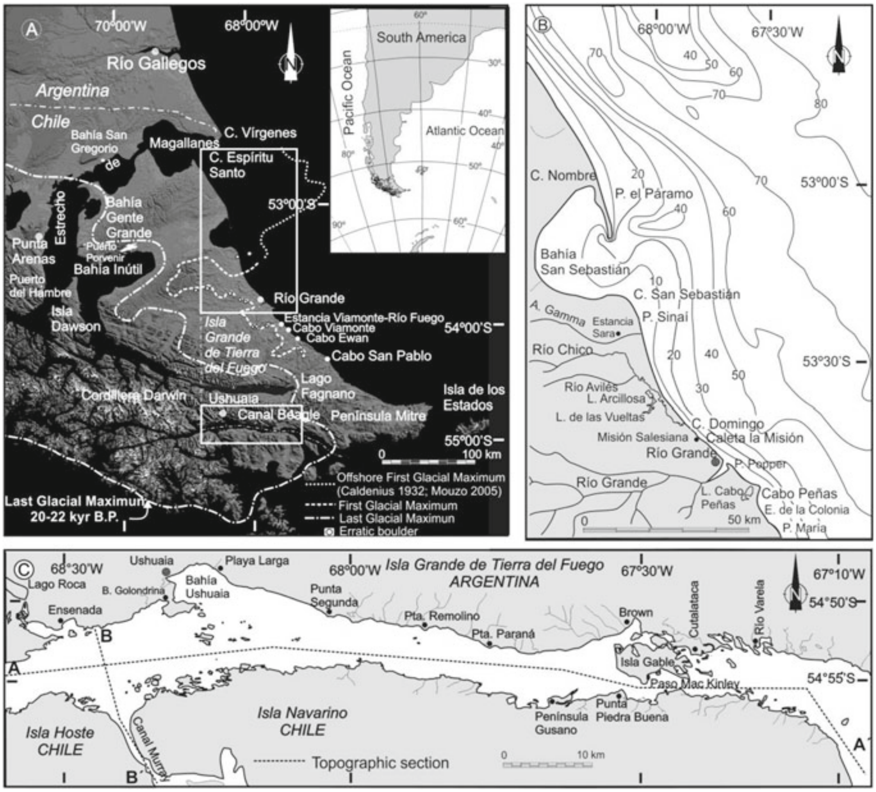

Fig. 1 **a** Location map of Isla Grande de Tierra del Fuego, with the extension of Last Glacial Maximum; **b** Northern Atlantic coast of Tierra del Fuego, depths in meters referred to the spring low tide level (SLTL) according to nautical chart from Geomarine (1989); **c** Beagle Channel

both related to the assumed Magellan transformed fault. The eastern Atlantic coast extends along 330 km, with a NW–SE trend. It undergoes a macrotidal range (up to 10 m) and is exposed to high-energy Atlantic waves and strong and intense westerly winds. Extensive beaches and littoral forms are composed of gravel and coarse sand. Pleistocene glaciogenic deposits are hanged to high cliffs at its northern section. These and other submerged glacial deposits have supplied the sediments for beach generation.

The southernmost coast of Tierra del Fuego (northern Beagle Channel and southern Atlantic coasts) extend for 220 km along a W–E trend. It presents a rocky shoreline, where pocket gravel beaches develop within embayments. The Beagle Channel occupies a drowned glacial valley connecting the Atlantic and Pacific oceans. This channel is 5 km wide, averaging depths between 100 and 450 m with microtidal range conditions. Holocene raised beaches occur in many places along this southern coast and their elevations vary considerably.

Glaciation has conditioned coastal development in Northern Hemisphere beyond the limits of the last major ice advances, including much of the coasts of northwestern Europe, and the Atlantic and Pacific coasts of North America. The term "paraglacial" has been applied to postglacial processes significantly influenced by the effects of former glaciations and to intervals during which these processes operated (Carter et al. 1987). The coastal paraglacial cycle exhibits a marked spatial and temporal variability influenced by the local geometry of the source deposits and the rate of change of the sea level. Paraglacial landscapes are recognized by irregular coast morphology, over-deepening of preglacial basins and valleys, and a variable sediment deposition. The more frequent sources of paraglacial sediments include glacial or periglacial diamicts or alternating beds of sand, gravel or cobble deposited in proglacial environments. These deposits could be reworked into coastal barriers by sub-aerial or sub-aqueous processes, culminating into wave or aeolian deposits. Depositional forms include solitary gravel ridges, spits, bay-head barriers, beach-ridge plains and transverse bars (Carter et al. 1987).

Gravel beaches and other littoral forms of the Atlantic coast of Tierra del Fuego represent the Southern Hemisphere counterparts of the paraglacial coastal sedimentary environments of high and middle latitudes of Canada and Northwestern Europe. It must be taken into account the great difference in terms of extensions and thickness of the Last Quaternary glaciation expressed as huge continental ice sheets in the Northern Hemisphere and restricted to glacial valleys and ice sheets in Tierra del Fuego and Southern Patagonia. Isostatic postglacial rebound was significant in the Northern Hemisphere but negligible in Tierra del Fuego (Mörner 1991), considering the significant seismotectonic uplift of this archipelago, at least during the Holocene.

Tierra del Fuego has been subject to episodic supply of ash from active volcanoes from the Andes (Kilian et al. 2003; Stern 2008; Fontjin et al. 2014).

The study of the geomorphology and evolution of the Fuegian coast must consider the dissimilar characteristics between the northern and southern parts of Tierra del Fuego, regarding tectonic behavior, extensions of the Pleistocene glaciations, wave and tide climate, availability of sediments and the slope of the coastal plains local hydrodynamic conditions. This paper analyses the differential tectonic evolution across and along the Magellan Fault System considering morphologic and sedimentological characteristics of both sides.

2 Geology, Tectonics and Seismicity

The southern part of the Isla Grande is located within the Andean Cordillera tectonic domain. The W-E orientation of the Fuegian Andes is the result of the transform motion between the South American, Antarctic and Scotia plates. The alignment formed by the western end of the Magellan Straits, Seno Almirantazgo and Lago Fagnano marks the boundary between South America and Scotia plates and the northern limit of the left lateral transpressional transform motion (Fig. 2). Recent fault scarps, sag ponds, sediment deformation structures and landslides along this fault system indicate a significant tectonic activity during the Quaternary (Dalziel

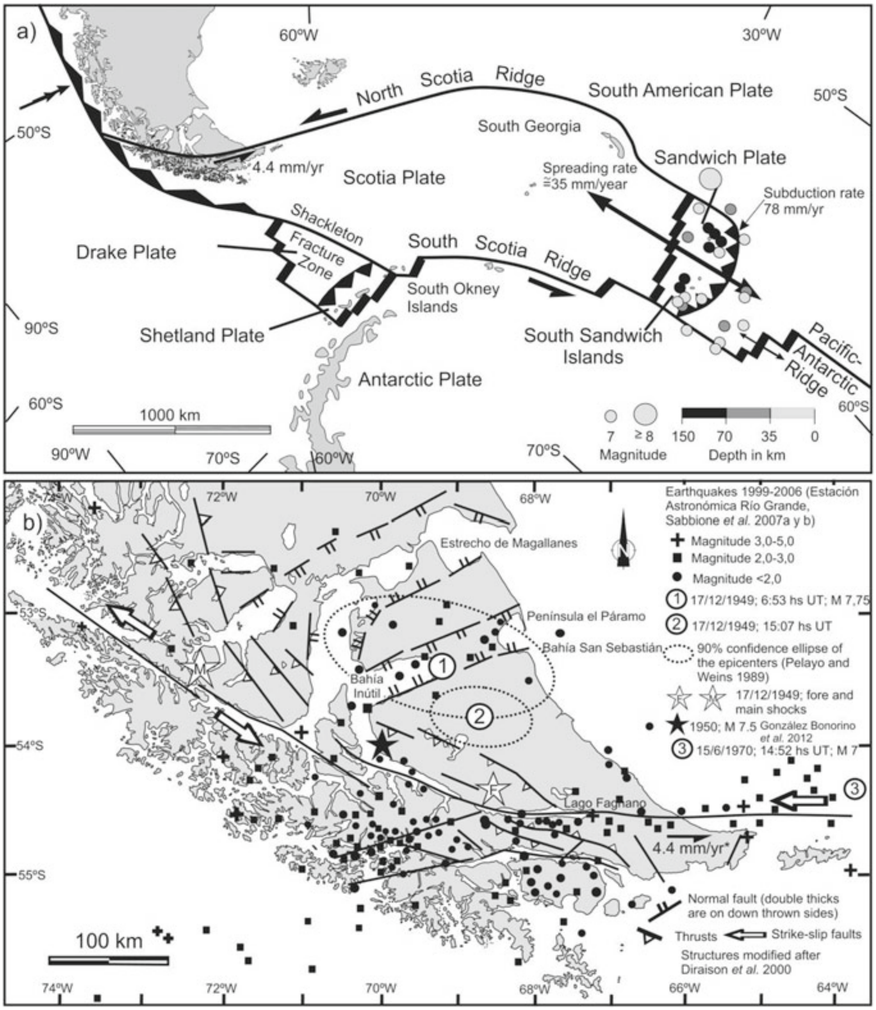

Fig. 2 **a** Plate tectonic setting of the Scotia Arc (Dalziel 1989) and earthquakes of magnitudes greater than 7 since 1900 at the South Sandwich Islands subduction zone; **b** Plate tectonic setting with major fault lineaments at Tierra del Fuego (after Pelayo and Wiens 1989; Diraisson et al. 2000; González Bonorino et al. 2012)

1989; Costa et al. 2006; Pedrera et al. 2014; Onorato et al. 2016). The basement is composed of pre-Jurassic highly deformed metamorphic rocks, covered by late Jurassic to Early Cretaceous volcanoclastic rocks and by Early Cretaceous metamorphic rocks of marine origin (Borrello 1969; Kranck 1932). These Mesozoic rocks are overlain by Palaeocene marine beds and continental deposits (Caminos et al. 1981; Buatois and Camacho 1993; Olivero and Martinioni 1999; Olivero and Malumian 1999). Several tectonic deformation stages (Late Palaeozoic-Early Mesozoic, Cretaceous and Eocene-Miocene) affected the sedimentary sequence (Caminos et al. 1981; Torres Carbonell et al. 2014).

The northern Atlantic lowlands developed on a stable platform, composed of non-deformed Jurassic-Cretaceous marine sandstones. The oldest exposed sediments are Tertiary rocks of continental and marine origin (Ghiglione et al. 2002). Plio-Pleistocene glacial deposits overlie the Tertiary rocks (Bujalesky and Isla 2005).

The southernmost Andes have a history of Paleozoic compression, a rifting between Triassic and Early Cretaceous, and another compression since Late Cretaceous to Quaternary (Diraisson et al. 2000). In the Fueguian cordillera and foothills, folds and thrusts trending ESE, are slightly oblique to the orogen, whereas strike-slip faults are parallel to it and left-lateral. On the foreland and northeastern side is the Magellan Basin, folds and thrusts are parallel and rifts are sub-perpendicular to the orogen. A kinematic analysis of fault–slip data indicates mostly sub-horizontal shortening and stretching directions. The tectonic history of Austral (Magallanes), Malvinas and South Malvinas sedimentary basins involves Triassic to Jurassic crustal stretching, an ensuing Early Cretaceous thermal subsidence in the retroarc, followed by a Late Cretaceous–Paleogene compressional phase, and a Neogene to present-day deactivation of the fold-thrust belt dominated by wrench deformation (Ghiglione et al. 2012). At present, the South Malvinas basin is dominated by a transpressive uplift of its active margin with minor sediment supply, while the western basins experience localized development of pull-apart depocenters and transpressional uplift of previous structures (Ghiglione et al. 2012). The Fuegian Andes underwent at least three cycles between subcritical, critical and supercritical stages of behavior in terms of deformation, erosion, and sedimentation. A succession of syntectonic angular and progressive unconformities occur at the Atlantic coast: (1) an angular unconformity between the Danian and Late Paleocene sequences, (2) a series of progressive and syntectonic angular unconformities developed from the Late Early Eocene to the Late Eocene, and (3) a Lower Miocene syntectonic unconformity. Faulting occurred in three episodes: thrusting, ca. 61–55 Ma, thrusting, ca. 49–34, and strike-slip event, ca. 24–16 Ma (Ghiglione and Ramos 2005), with an estimated maximum age of 7 Ma (late Miocene) for the strike-slip movement (Torres Carbonell et al. 2008, 2014). The interaction between the fault systems and the tectonic regimes that have affected the island north of the South America-Scotia boundary led to the existence of a Neogene-Quaternary rift system responsible for the opening of the eastern Magellan Straits (Ghiglione et al. 2012). The relationship between a Jurassic extensional fault arrangement and the main stress directions related to the strike-slip plate boundary suggest that Jurassic transfer faults reactivated extensionally generating the Magellan rift system (Ghiglione et al. 2012).

GPS measurements, collected north and south (between 1993 and 1999) of the Magallanes–Fagnano fault system showed that the Scotia plate is moving eastwards at a rate of 5 mm/year related to the South America plate (Del Cogliano et al. 2000). A relative movement of 4.4 ± 1.1 mm/year was estimated (Mendoza et al. 2011). On the other hand, they observed a relative uplift of 3.1 ± 0.4 mm/year for the area westward of 67°50′W with respect to the eastern locations. This result follows from the mean absolute vertical velocities of western and eastern positions: 3.3 ± 0.3 and 0.2 ± 0.2 mm/year, respectively.

The Scotia plate bounds eastwards to the small South Sandwich Islands Plate (2300 km from Tierra del Fuego). A subduction zone develops at the eastern flank of this plate with strong and intense seismicity (Pelayo and Wiens 1989). Twenty seismic episodes of magnitude 7 were recorded since 1990, plus one earthquake of magnitude 8. A subduction rate of 78 mm/yr was estimated (United States Geological Survey 2009). This is the nearest region that combines the conditions for a potential seismic source of tsunamis that could affect the Atlantic coast of Tierra del Fuego (Fig. 2a). A tsunami impact stroke in the northwestern Malvinas Archipielago about 1500 14C years B.P., considered originated at the middle Atlantic ridge, south of Saint Helena Island (Regnaud et al. 2008).

3 Glaciations

Several Plio-Pleistocene glaciations were recognized in northern Tierra del Fuego (Caldenius 1932; Meglioli 1992). Piedmont glaciers dominantly radiated northwards and eastwards from the Cordillera Darwin along deep valleys or corridors (Magellan Straits, bahía Inútil-bahía San Sebastián, Almirantazgo-Lago Fagnano and Beagle Channel; Fig. 2b) toward the Atlantic Ocean. These facts are supported by erratic-boulder fields located to the west and north of City of Río Grande. The area northwards of Bahía San Sebastián was located in a higher interlobated position, almost undissected by rivers (Meglioli 1992). Considering that there are no-till deposits between Río Chico and Cabo San Pablo, it was assumed that this area was never glaciated (Meglioli 1992). Drift deposits are scattered in Serranías del Norte, a hilly area close to Río Grande and extending toward the Argentina–Chile boundary. The Río Grande Drift was assumed as the oldest glaciation, composed of scattered erratic boulders resting on top of dissected Tertiary bedrock hills (Meglioli 1992; Fig. 1a). These erratic boulders were also identified offshore bahía San Sebastián (Isla and Schnack 1995; Mouzo 2005a, b). The largest concentrations of these boulders are in the inner continental shelf but extend to depths of 90 m (100 km offshore). The horizontal maximum size of the boulders can reach 15 × 10 m with heights up to 6.5 m. Sub-bottom seismic survey records showed Pleistocene glaciogenic deposits (till and cross-bedded glaciofluvial units) thinning eastward from the coast to the middle continental shelf (60 km offshore from Cabo Nombre). The glacial flow descending from Darwin Cordillera was blocked by sierra de Beauvoir and other hill NW–SE lineaments bending toward the tectonic basins of Magellan Straits and bahía Inútil-bahía San Sebastián (Meglioli 1992). The last glaciation (older than 16 kyrs and younger than 47 kyr BP, Late Wisconsinan) in northern Tierra del Fuego was restricted to the western Magellan Straits and bahía Inútil, Chilean territory (Porter 1989, Meglioli 1992). The evolution of these two piedmont tongues (Magellan and bahía Inútil-San Sebastián bay) has been sketched in detail (Darvill et al. 2016).

Along the Beagle Channel, the last two Quaternary glaciations were recognized reaching approximately 1400 m thick during Late Wisconsin (Rabassa et al. 1990; Rabassa and Clapperton 1993; Rabassa et al. 2000). The Last Glacial Maximum was attained around 20–22 kyr BP when terminal moraines were deposited at the area of punta Moat (100 km eastwards Ushuaia; Fig. 1a). The first event of deglaciation was found in Harberton peat bog basal layers radiocarbon dated at 14,680 ± 100 years B.P. Basal peat bog layers from Bahía Lapataia (20 km westwards Ushuaia) reported 14C ages of 10,080 years B.P. indicating the vanishing of the glacial system. It was considered that the valley was occupied by a glacial Lake about 9400 14C yr B.P., and that Lake was replaced by seawater before 8200 14C yr B.P (Rabassa et al. 1986). The paleontological evidence of raised littoral deposits, positioned about the present sea level, indicates that the marine environment was fully established along the channel at least by 7900 14C yr BP, reaching a maximum sea level between 6,000 and 5,000 yr B.P. (Rabassa et al. 1986, Gordillo et al. 1992, Bujalesky 1998, 2007). The extrapolation to the past of mean tectonic uplift trend of the Beagle Channel forms the present depth of the Murray Channel, Paso Mackinlay, northwestern and southeastern branches topographic sills intersect the eustatic sea-level curves (Fleming et al. 1998) about 11,500 to 11,000 years B.P. immediately after the Younger Dryas period. This fact let infer that from that moment, the seawater overpassed the topographic sills and the valley became flooded very rapidly. Submerged fluvial sequences and peat bogs transgressed by marine deposits indicate that after the deglaciation, glaciofluvial and glaciolacustrine environments developed in the Beagle basin followed by a rapid flood (Bujalesky et al. 2004). The shallow depths of the four channels that connect this deep basin with the Atlantic and the Pacific oceans and the balance between eustatic sea-level trend and the tectonic uplift during the Holocene suggests that the valley was rapidly flooded by the sea over-passing Mackinlay and Murray sills. The non-erosive contact observed between the marine facies and the well-preserved peat bog developed southwards of Peninsula Ushuaia is indicating this rapid transgression.

These evidences from the Beagle Channel Glacier were also recorded along the Fagnano Lake Paleoglacier (Coronato et al. 2009). At this glacial valley, the oceanic flood was originated from the west (Seno Almirantazgo, Chile) and Holocene lacustrine deposits were studied spanning between 7184 ± 47 and 5124 ± 47 years B.P and disturbed by earthquakes (Onorato et al. 2016).

Glacier advances from the Chilean side were reported during the Early Holocene (8 kyrs) and the "Neoglacial" advances dated between 5400 and 4900 yrs BP (Wenzens 2005; Kilian and Lamy 2012).

4 Climate, Tides and Waves

The climate of Tierra del Fuego Archipelago is determined by its upper mid-latitude location within the belt of prevailing westerlies (latitude 40° to 60°S) in the path of eastward-moving cyclones and not far from the Antarctic ice (Tuhkanen 1992). The Andean Cordillera causes a steep climatic gradient from west to east and from south to north. The most frequent winds strike from the west in the Magellan region and Río Grande city (annual frequency 39.3%, average velocity 33 km/h). In Ushuaia, the relief causes deviations and southwest is the prevailing direction of winds (23.6%, 31 km/h, Servicio Meteorológico Nacional 1986).

The Atlantic coast of Tierra del Fuego undergoes a macrotidal range with a semi-diurnal regime. The mean tidal range at the Atlantic coast increases from south to north (bahía Thetis: 2.5 m; Cabo San Pablo: 4.6 m; Río Grande: 5.2 m; bahía San Sebastián: 6.6 m; Fig. 1). The flood and ebb currents reach velocities of 2 knots. On the other hand, the Beagle Channel has a microtidal range and a semi-diurnal regime with diurnal inequalities. Mean tidal range is 1.1 m at Ushuaia and the tidal wave moves from west to east (Servicio de Hidrografía Naval 2011).

The wave climate approaching from the Atlantic Ocean is not so strong due to the dominance of the persistent winds from the west. IMCOS Marine Limited (1978) reports data from ship's observations collected by the British Meteorological Office, covering the sea area from the coast to 65°W and between 50°S and 55°S (1949–1968). This data reports that: (a) there is a very low frequency of wave heights higher than 3.5 m; (b) 20% of the waves were less than 1 m in height on average throughout the year; (c) there is a low frequency of long-period waves, and wave periods higher than 10 s come from the E–NE; (d) gales of 41–47 knots come from any direction between N and ESE (with a return period of 50 years) and were estimated to generate extreme waves of height of 12 m height and a period 11.5 s in a depth of 50 m (referred to spring tide level); and (e) these extreme waves are breaking in a water depth of 15 m (chart depth + tidal height above datum + storm surge). A one year record at the Cullen (52°49′19″S–68°13′52″W, 110 km north of Río Grande) gave the following results: (a) a maximum wave height of 5.86 m (Compagnie de Recherches et d'Etudes Oceanographiques and Geomatter 1985); (b) a maximum significant wave height of 3.43 m; (c) an average significant wave height of 1.02 m; (d) a maximum period of 17.5 s; (d) a maximum significant period of 12.9 s; (e) an average significant period of 5.5 s; (f) the waves higher than 3 m corresponded to periods of 7 to 9 s; (g) the longer periods were associated to wave heights of 1.25 m; (h) the stronger swell were associate with north-northeastern winds; (i) the estimated extreme wave height is 5.8 m for NE to E winds and of 7 m for N winds with a return period of 50 years.

The Beagle Channel presents a fjord dynamics controlled by significant and seasonal pluvial sources, and by tidal flow from both the east (Atlantic) and the west (Pacific; Isla et al. 1999). Two layers of different salinity and temperature develop in the water column during summer eastwards of Gable Island. Lower salinities and temperatures without water stratification up to a depth of 22 m were measured westwards of Gable Island during summer due to the increment of freshwater input to the channel. The bathymetric sills of Isla Gable, Murray Channel and northwestern and southwestern Beagle Channel branches the fjord dynamics, but also limit the relative effects of the tidal currents and the gravity waves originated from the west (D´Onofrio et al. 1989). The Beagle Channel has a short fetch and therefore waves are choppy with periods of 1 to 3 s.

5 Seismicity

Tierra del Fuego became colonized during the middle of the XX century. However, an earthquake was recorded in 1879 (February 2, about Mw = 7; Cisternas and Vera 2008). The well-known 1949 (December 17th) earthquake was also estimated about Mw = 7.5 − 7.8 (Lomnitz 1970; González Bonorino et al. 2012). Two ruptures were reported for that earthquake: a fault was surveyed at several places close to the Fagnano Lake while a trench across a secondary fault was excavated at the Rio San Pablo surroundings (Onorato et al. 2016). At this precise site, three events of the Holocene age were recorded as previous to the 1949-year event (Costa et al. 2006). Considering a simple two-dimensional vertical strike-slip fault, a relative plate motion of 6.6 ± 1.3 mm/yr was estimated. Assuming a locking depth of 15 km, the recurrence time is about 750 years (Smalley et al. 2003). The asymmetry at the tree rings collected close to the Fagnano–Magallanes Fault System approximated to those two major earthquakes of 1879 and 1949 earthquakes (Pedrera et al. 2014). Turbiditic deposits recorded from cores from the Lago Fagnano are indicating earthquakes that occurred during the Holocene (Moy et al. 2011). However, a different tectonic scenario was established for the region of the Yehuin and Chepelnut Lakes, north of the Magallanes Fault System (Lozano et al. 2018). A compressive scenario dominated during the interval 56–16 Myers, and was replaced by a strike-slip regime about 11–7 Myers known as the Deseado Fault system.

6 Methods

Detailed leveling surveys of the Holocene gravel beach ridges were carried out using a Total Station Pentax R-326 and differential GPS equipment (ProMark 7). Leveling sections were performed using the stop and go method, with 30 s of permanence at each point. Data processing was carried through Ashtech Solution 2.70 software. The altitudes were referred to as present storm berm. The classic equation for calculating vertical motion rate to obtain the Pleistocene uplift rates was applied (Pedoja et al. 2011).

Ground-penetrating radar (GPR) surveys were performed normally to the coastal landforms to visualize the inner structure of the extensive gravel beach ridge plain of Río Chico and the architecture of a unique and prominent overtopping fan located in the middle section of Ensenada de la Colonia. Changes in sediment composition, water content/type and grain shape, orientation and packing can cause significant changes in electrical properties. Therefore, subsurface features such as sedimentary structures, lithological changes and the water table can produce primary reflections. The SIR 3000 GPR equipment (Geophysical Survey Systems Inc., GSSI), operating with shielded antennas of 200 and 400 MHz at different distances were combined, configured with a 100 ns range, 1024 scan samples, 64 scans/seconds and stacking equal to 12. A common midpoint (CMP) survey was carried out using two connected

100 MHz antennas on the overtopping fan to deal with the dielectric constant. The profile is 960 m long, and subdivided into 3 sections for details, as will be seen later. The processing of the GPR records was carried out with the software Radan 6.0 (Geophysical Survey Systems, Inc., 2004) adjusting vertical positions, the gain and performing the migration analysis of the sections. The reflection profiles were interpreted using standard principles of radar stratigraphy to identify different radar facies. These are sets of reflections with distinctive configurations, continuity, frequency, amplitude, velocity characteristics and external bedforms. The uppermost part of the profiles cannot be interpreted in this way because of the noise associated to the air and ground waves. Radar surfaces can be interpreted as representing non-depositional or erosion hiatuses in a sedimentary sequence. In deposits composed entirely of sand and gravel, they also effectively mark the positions of bounding surfaces.

7 Results

7.1 Long-Term Uplifting Trend of Northern Tierra Del Fuego

Pleistocene beaches crop out in the northeastern coast of Isla Grande de Tierra del Fuego, along 100 km between punta Sinaí (53º24′S-68º04′W) and Cabo Ewan (54º07′ S; 67º09′ W; Fig. 1). The oldest raised beaches, composed of gravel and sand, are located on top of the hills surrounding La Arcillosa and Las Vueltas ponds, Domingo cape and Miranda hill (Fig. 3). The altitude of these gravel beaches, on the top of Cerro Miranda (53º41′52″ S; 68º02′55″ W, 10 km westward the present coast), is around 130 m a.p.s.b. This deposit is a 2 m thick bed of medium gravel with a gray cemented matrix of medium to coarse sand. Pebble imbrications are dipping seawards. A red-brown oxidation paint covers partially most of the well-rounded pebbles. This bed is considered an ancient gravel beach deposit overlaying a Miocene sandy silt formation. These raised gravelly beaches are assumed to correspond to the Middle Pliocene, between the transition of oxygen isotope stages M2/M1 and G19/G18 (3.29 Ma to 2.97 Ma B.P.; Shackleton 1995). During this period of a relatively warm and stable climate, the reduction of the ice volume caused a sea level rise of 25 m above the present with an increase in the sea surface temperature at high latitudes (Dowsett et al. 1999). These gravel deposits of the Cerro Miranda Formation would correlate with the 131-138 m a. s.l. marine terrace at Cabo Buen Tiempo at the northern margin of Río Gallegos inlet (Hatcher 1897; Feruglio 1950). Yellowish ferruginous sand layers contain a variety of molluscs, oysters, *Pecten sp.*, *Trophon sp.*, *Terebratella sp.* (brachiopod). Another gravel beach deposit develops on top of the La Arcillosa hill (53º35′ S; 68º02′ W, 1.5 km westward the present coast) and Domingo cape 53°41′ S; 67°51′ W). The sedimentary texture of this fossil gravel beach overlying Miocene sandy silts is very similar to the deposit of Cerro Miranda crest, and contents abundant fragments of the bivalve *Cyclocardia velutina* (Smith 1881).

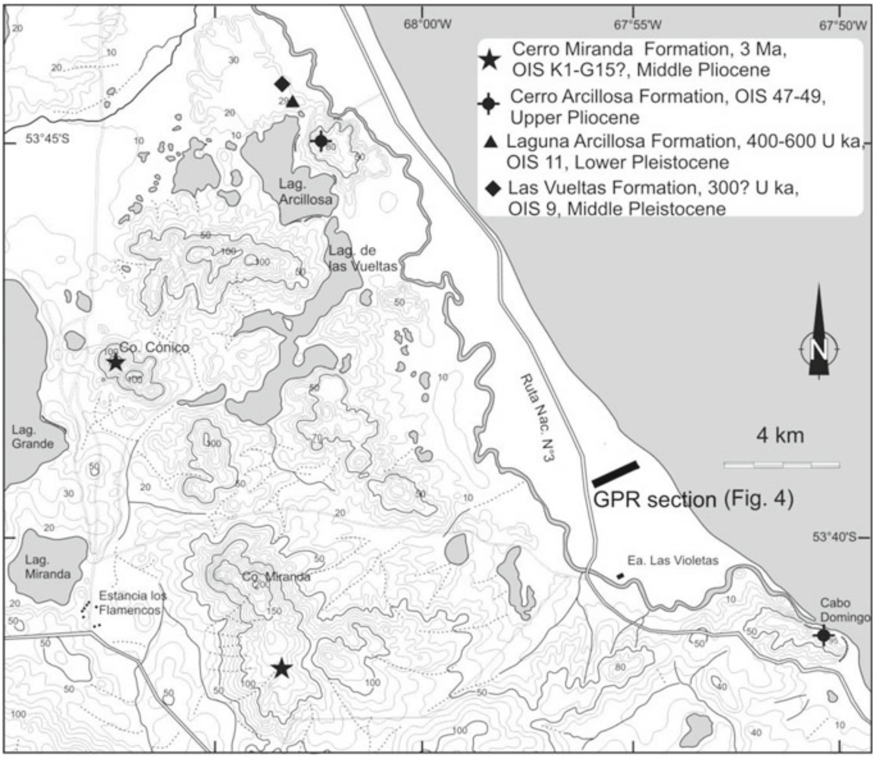

Fig. 3 Topography and Pleistocene sedimentary deposits in the Río Chico area (modified from Montes et al. 2018)

Six levels of Pleistocene, mixed sand and gravel beaches, were recognized in this northern region of Grande Island. Taking into account their relative altitudes, the diverse absolute dating carried out on mollusc valves (Uranium series and aminoacid racemization; Rutter et al. 1989) and the comparison with their counterparts from the Patagonian coast (Feruglio 1950; Schellmann 1998; Schellmann and Radtke 2003), these gravel beaches have been assigned to different 18O isotope stages (Bujalesky et al. 2001, Bujalesky and Isla 2005). The fossil mollusc faunas in these ancient beaches are relatively poor and they do not allow inferring environmental conditions different from the present highstand (Gordillo and Isla 2011).

An Upper Pleistocene gravel beach ridge plain (2.6 km wide) develops at the central part of Ensenada de la Colonia (Fig. 4). This deposit corresponds to the last interglacial stage (Oxygen Isotope Substage 5e, La Sara Formation; Bujalesky et al. 2001; Bujalesky and Isla 2005). Its storm berm facies reach a difference of level of 6.5–7 m above the present storm berm. This littoral landform is covered with a vegetated thin layer of aeolian sediments and shows a smooth surface. The inner structure is composed of planar cross-bedding coarse to medium gravel layers, with imbricated disc pebbles, dipping seawards. The eastern margin around the bay

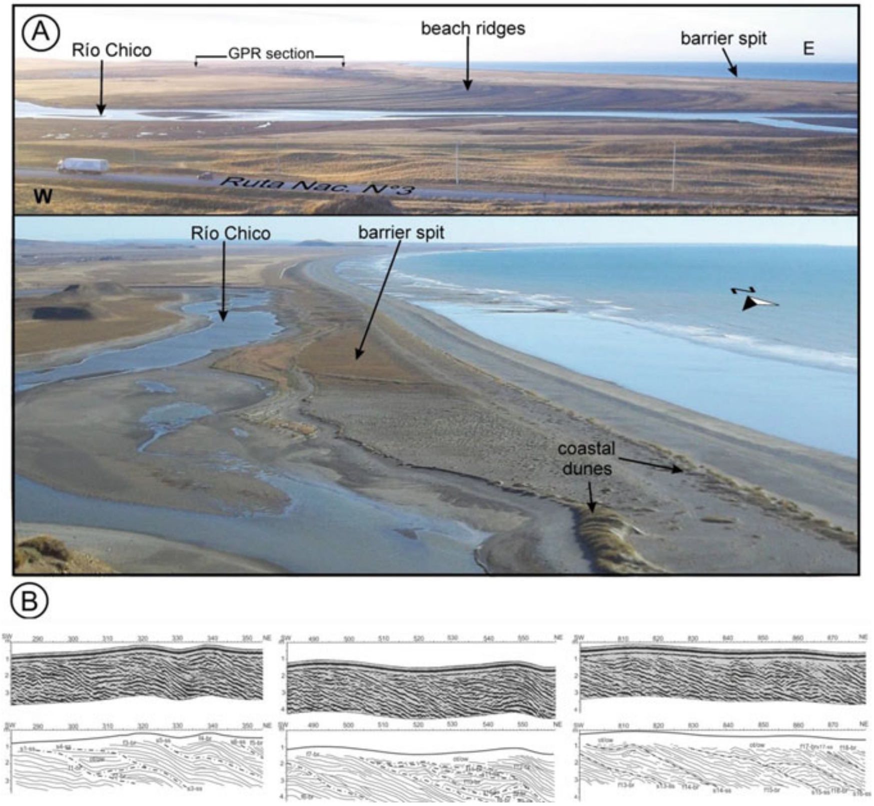

Fig. 4 **a** Aerial view of the Rio Chico coastal plain where the GPR surveys were performed; **b** GPS sequences of gravel berm ridge facies, corresponding to high energy storm waves. Overtopping and overwashing facies cover the tops of the beach ridge plain. The profile is 960 m long and subdivided into 3 sections for details

develops a former erosive scarp carved during the Holocene transgression. This fossil erosive scarp 5.5 m altitude shows a semicircular shape, along 150 m in a north-south direction, at the middle axis of the embayment.

The relative altitudes, the available absolute dating and the ages inferred from height relationships of the Pleistocene beaches of the Atlantic coast were plotted (Fig. 5). The estimated average tectonic uplift for the last 1.4 Ma is of 0.05 mm/yr, and lower (0.02 mm/year) for the interval between 1.4 and 3.0 Ma. The 130 m altitude oldest raised beach, located on the top of Cerro Miranda, assigned to the Middle Pliocene (3.29 to 2.97 Ma B.P) was corrected (−25 m), according to the Dowsett et al. (1999) estimation of a 25 m over present mean sea-level, during that warm period. This eustatic correction lowers its altitude referred to the present sea level to 105 m (Fig. 5).

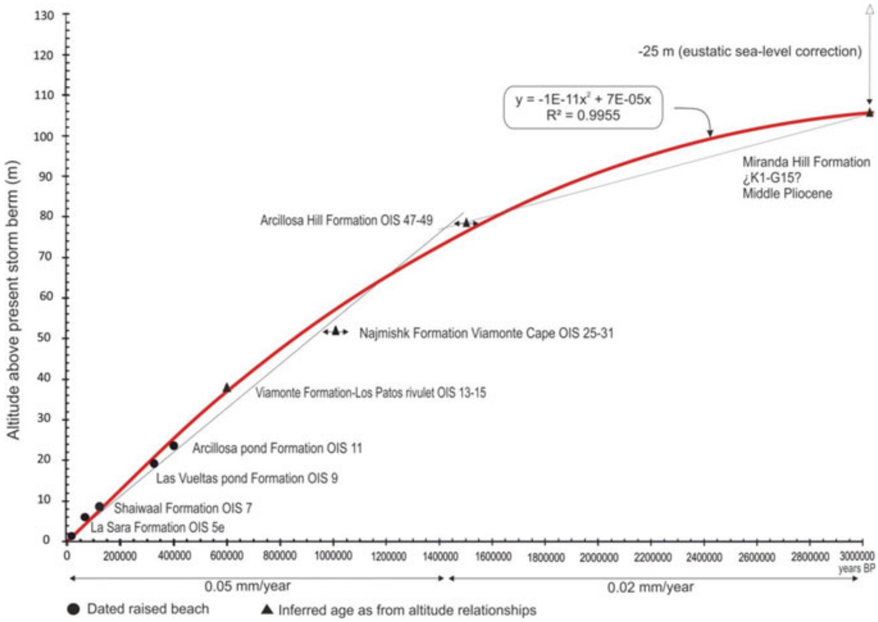

Fig. 5 Altitude of Pleistocene gravel beaches of the northern Atlantic coast of Tierra del Fuego referred to the present storm berm versus age. An average tectonic uplift of 0.05 mm/year was estimated for the last 1 M years

7.2 Holocene Sequences from Northern Tierra del Fuego

The set of beach ridges from the southern Bahía San Sebastián shows great dispersion according to the position and type of these coastal deposits (cheniers and gravel beach ridges). The growth of El Páramo spit (Fig. 1) took place in the past 6000 years. The Holocene sedimentation took place after the sea-level stillstand. The initiation of the regressive sequence is not precisely dated but a radiocarbon date indicates a minimum age of 5270 ± 190 yr B.P. (Vilas et al. 1987, Ferrero et al.1989, Isla et al. 1991, Vilas et al. 1999). The 3.3 km wide sequence of cheniers developed between 4070 and 975 14C yr B.P., suggesting a relative sea level fall of 1.6 m. Each of these chenier alignments originated every 300–400 yr (Ferrero et al. 1989). The inner littoral deposits were located in a more protected position in the bay. The San Sebastián bay is partly closed by the El Páramo gravel spit (22 km long). Sediment supply was provided from coastal or submerged glacial deposits. Initially, a cuspate foreland grew attached to the northern coast of the embayment. Gradually, a spit grew with the supply of detritus to form beach ridges facing toward the bay in the northern part of the spit. As the spit grew alongshore, sediment feeding to the northern shore of the bay diminished. The Atlantic shore was progressively eroded and gravels from the fossil ridges were recycled (González Bonorino and Bujalesky 1990). The leveling across the older beach ridges originated at the bay flank of the spit suggests that the sea level fell slightly. The approximately 1 m altitude decrease from the oldest beach ridge to the youngest can be explained by a fetch shortening and a decrease in wave energy within the bay as consequence of the tidal flat progradation (Isla et al. 1991). At San Sebastián tidal flat, the seaward gradient of the supratidal deposits would be partially the result of the diminution in wave height within the bay in response to spit growth and progressive protection from Atlantic swells (Bujalesky 1990; Bujalesky and González Bonorino 1990).

Río Chico gravel beaches are located outside the San Sebastián bay-Inútil bay glacial corridor determined by a graben structure and deposited on a relative shallow embayment. The estimated average tectonic uplift for the last 6000 years in northern Tierra del Fuego is of 0.3 mm/year. This amount is ten times higher than the rate estimate for the last 1 Ma (Fig. 5). Part of this gradient could be attributed to wave dynamics processes, such as a higher storm wave set-up (Montes et al. 2018). The geomorphology and evolutionary trend differences between Bahía San Sebastián Bay and the Río Chico paleo-embayment essentially arise from the underlying palaeorelief carved during Pleistocene glaciations into Tertiary rocks. The río Chico embayment developed in an interlobate position while the former into a deep piedmont valley. The río Chico embayment was relatively little disturbed by fluvial or glaciofluvial discharge during the Middle Pleistocene, receiving only the glaciofluvial overflow from the northern margin of the basin. The low gradient palaeorelief of the extensive, relative smooth and shallow subtidal platform allowed the formation of regressive gravel beaches and marsh environments in wave protected areas. These facts also favored the preservation of fossil beach relicts. During the Pleistocene transgressions, the area located at the present confluence of Chico and Avilés rivers (Fig. 1a), was a tidal inlet, allowing the development of estuarine facies extending up to 16 km landward, reaching the proximity of Grande, de la Suerte and O'Connor ponds. During the Holocene and at the Atlantic flank, an extended beach ridge plain grew from the northern margin of the embayment diminishing the wave attack. Its backbarrier side was stabilized by an estuarine facies (Fig. 3b). Growth of this beach ridge plain took place under limited sediment input conditions compared to the Península El Páramo. The progressive elongation was maintained by erosion and sediment recycling (cannibalization), resulting in a modern landward retreat (Isla and Bujalesky 2000). The downdrift extreme of the beach ridge plain evidences a pulse of sediment scarcity where an elongated lagoon developed between a beach ridge plain and the outer beach ridge (Fig. 3c).

Dealing also with the Holocene record, the alluvial plain of arroyo La Misión was occupied by a lake (at a present level of 5.7 m below high tide level) that was flooded by the marine transgression about 9000 14C yr B.P. (Auer 1959, 1974). A tidal flat developed at an altitude of 0.9 m a.h.t.l. between 4000 and 2000 14C yr B.P. (Mörner 1991).

7.3 Long-Term Uplifting Trend of Southern Tierra Del Fuego

Rabassa et al. (2008) recognized an Upper Pleistocene (OIS 5e) marine shell deposit at 10 m a.s.l. at Corrales Viejos (55º S–67º15′W), southern coast of the Beagle Channel, Navarino Island, Chile. This deposit was interpreted as a fossil beach, 0.9 m thick and composed entirely of broken and rounded marine shell fragments. It was dated at a minimum age of 41,700 14C years B.P., therefore suggesting a Last Interglacial age.

7.4 Holocene Sequences of Southern Tierra Del Fuego

Holocene raised beaches recognized along the northern coast of the Beagle Channel reached maximum elevations of nearly 10 m above storm berms. The altitude of these fossil storm berms was correlated to their ages in 14C years before present (Gordillo et al. 1992; Bujalesky 2007). An average tectonic uplift of 1.3 mm/year was estimated for the last 6,000 years. However, a polynomial trend line fits better to the raised beaches data than the lineal. It is inferred that the tectonic uplift was not homogeneous along time but evidenced at least three different stages. For the interval 6000-2600 BP an uplift of 1.3 mm/yr was calculated, an uplift of 0.2 mm/yr for the interval 2600-1000 years BP and a higher uplifting trend of 2.1 mm/yr for the last 1000 years. The youngest terraces (Playa Larga 405 ± 55 14C yr B.P. at 1.7 m and Bahía Brown 985 ± 135 14C yr B.P. at 1.8 m, above the present counterpart) suggest that the last coseismic uplift movements could have been quite recent, in relation to its average return period and it would have been probably followed by a long quiescent time to allow the stress accumulation according to the prevailing long-term tectonic trend (Gordillo et al. 1992).

8 Discussion

Feruglio first reported the uplifting trend of the Atlantic coast of Patagonia in regard to the marine terrace succession (1950). Porter et al. (1984) considered that the Holocene relative sea level along the Magellan Straits and the Beagle Channel reached a maximum altitude of at least 3.5 m above the present sea level about 5000–6000 14C yr B.P. These authors proposed a glacioisostatic and hydrostatic warping as the cause of this sea level behavior. However, the records of Puerto Hambre are located more than 100 km behind the outer limit of the last glaciation (Porter et al. 1984). They considered these data as "apparently anomalous", and interpreted that this area may reflect an isostatic response to deglaciation. They disregarded that Puerto Hambre is located north of the Magellan Fault alignment while the Beagle Channel to the south of this fault area. Mörner (1991) pointed out that the

Estrecho de Magallanes and the Beagle Channel coasts underwent different uplifting trends, and that the area has not undergone significant glacioisostatic warping during the Holocene. He considered, for the regional Holocene eustatic changes, a sea level rise from 9000 to 4000 14C yr B.P. to a level only slightly above present, but he argued that these higher levels seem to content the effects of storm waves rather than tidal flat levels. The layout of the GPR-defined coastal facies from the río Chico Holocene beach plain have been controlled by the interactions of storm-wave activity and sediment supply (Montes et al. 2018) without significant uplifting effects in the internal structures.

The tectonic uplift rate for the last 1000 yr BP inferred from the raised beaches of Beagle Channel is relative consistent with the GPS survey estimation of 3.3 mm/year for the area positioned westward of 67°50′W (Mendoza et al. 2011). While the observed GPS relative uplift velocity of 0.2 mm/year for the area positioned eastward of 67°50′W is approximate the average tectonic uplift estimated for the fossil gravel beaches of the northern Atlantic coast of Tierra del Fuego (0.4 mm/yr). The comparison of the Holocene tectonic uplift rates between the northern Atlantic coast (0.4 mm/yr) and the northwestern coast of the Beagle Channel (1.3 mm/yr) indicates a differential raise about three times greater for the last 6000 yr B.P. (Fig. 5). In turn, the altitudes of 5 m a.p.s.b for the mid-Holocene raised beaches measured in Cambaceres bay (Zangrando et al. 2016), are showing the complexity of the tectonic activity along the Beagle Channel.

On the other hand, at the Chilean territory tectonic processes were conditioned by the interaction between plates. Until 14 Myers the Nazca Plate subducted below the South American Plate at a rate of 7–8 cm/yr (Kilian et al. 2018). Since the collision of the Chilean Ridge, the Antarctic Plate is obliquely subducted to rates of 2–3 cm/yr. However, at Western Isla Grande (Bahia Brookes, Seno Almirantazgo) a subsidence of 2 m was reported based on some trees remaining drowned on the bay (Fuenzalida and Harambour 1984). Unfortunately, there is no more precise data about these subsidence conditions.

Tierra del Fuego was subject to episodic fallouts of ash supplied from different volcanoes. Hudson Volcano provided ash deposits dated on 7180 ± 160 radiocarbon yrs BP at Fagnano Lake (Moy et al. 2011). Other volcanoes that affected the region were the Aguilera (3100 yrs BP) and Mount Burney activated at 8800 yrs BP, 4150 yrs BP and 2040 yrs BP (Kilian et al. 2003; Stern 2008; Breuer et al. 2013a, b).

9 Conclusions

The analysis of the differential tectonic behavior of the northern and southern coasts of the Grande island of Tierra del Fuego permits to resume some conclusive remarks:

1. Quaternary glaciations, expressed as glacial valleys in Tierra del Fuego, have conditioned the development of the coastal and fjord sedimentary environments.

The northern Atlantic coast is a paraglacial landscape where the abrasion platforms developed on an inherited glaciofluvial relief. Reworked coarse-grained deposits and Pleistocene gravel beaches provided the main sediment supply for the growth of the Holocene gravel beach ridge plains and spits.

2. The southernmost Pliocene and Pleistocene beaches recorded in the World crop out in Tierra del Fuego islands. Pleistocene littoral deposits were recognized at levels of 53, 38, 23, 19, 12 and 8 m above present storm berms, corresponding to the Oxygen Isotope Stages 25–31, 13–15, 11, 9, 7 and 5, respectively. They are specially preserved at the interlobate positions located between San Sebastián bay and Lago Fagnano glacial valleys. The semiarid climate conditions prevented the fluvial erosion during the interglacials.
3. The isostatic postglacial rebound is negligible in Tierra del Fuego compared to the seismotectonic effects. The altitudes of Pleistocene gravel beaches at the northern Atlantic coast indicate an average tectonic uplift of 0.02 mm/yr between 3 and 1.4 Myers increasing to a rate of 0.05 mm/year for the last 1,4 Myers. Holocene gravel beaches and cheniers of San Sebastian bay and río Chico at this coast show a higher average tectonic uplift of 0.3 mm/year for the last 6,000 years.
4. The average tectonic uplift rate at the Northwestern Scotia Plate is significantly higher, about 1.3 mm/yr during the last 6,000 yr. Along the Beagle Channel, a maximum rate is estimated at the west diminishing eastward. A detailed analysis for this area indicates that the seismotectonic uplift was not homogeneous through time: 1.3 mm/yr between 6000 and 2000 years BP, 0.2 mm/yr for the interval 2600–1000 yrs BP, and 2.1 mm/yrs for the last thousand years.
5. The comparison of these Holocene uplifting rates between the southern South American Plate (0.3 mm/yr) and the northwestern Scotia Plate (1.3 mm/yr) confirms that the differential movement between both plates is not only horizontal as it was assumed.

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Paleomagnetic and Magnetic Studies of Quaternary Units in Tierra del Fuego, the South Atlantic Islands and Southern Patagonia

María Julia Orgeira, Guillermo Ré, Claudia Gogorza, and Ana María Sinito

Abstract This chapter summarizes the results obtained applying paleomagnetic and rock magnetic techniques to late Cenozoic rocks and sediments from Patagonia and Isla Grande Tierra del Fuego. A large number of studies were carried out in upper Cenozoic basaltic lava flows, glaciolacustrine sediments, Lake sediments and sediments from archaeological locations. Many paleomagnetic and chronostratigraphic studies have contributed to the determination of the ages of different glaciations, as well as to the correlation between the different localities. Moreover, during the last decades, several paleomagnetic projects in lake sediments allowed reconstructing the behavior of the Holocene geomagnetic field from southwestern Argentina. These results are decisive for determining regional and global patterns of longer period secular variations, and for having a better understanding of the physics of the Earth's core. More recently, several environmental magnetism studies have been carried out on eolian sediments and lake sediments. Some results from these studies are presented in this chapter.

Keywords Paleomagnetism · Paleosecular variation · Environmental magnetism · Late Cenozoic

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1 Introduction

This contribution is a review of the scientific contributions carried out in southern Patagonia and Isla Grande de Tierra del Fuego, Argentina, using paleomagnetic methods and techniques of magnetic properties. General topics developed are listed below.

Paleomagnetic studies have been applied in paleogeographic studies, providing evidence of rotation of tectonic blocks. Also, it has been used in stratigraphic correlation and geochronological calibration of paleontological zonation. These areas represent classical research uses of paleomagnetism.

Geomagnetic field directional changes due to paleosecular variation have been successfully used to time correlation Late Cenozoic deposits. Studies of the behavior of the geomagnetic field (GF) have received much interest over the last few decades. Since direct observations only go back a few centuries at best (Merrill et al. 1996; McElhinny and MacFadden 1997), reconstructions of the field direction and intensity in earlier times must rely on paleomagnetic studies, both in archaeological and geological materials. The analysis of these different kinds of records allows a better understanding of both the time-averaged field and its paleosecular variation.

Global warming is at present a clear and evident phenomenon from direct observations of average air and ocean temperatures, as well as of the widespread melting of snow and ice. Vulnerability to climate change in certain areas of the planet in terms of ecological, economic and social concerns is an area attracting urgent study. Currently, due to the low number of studies that have focused on the late Cenozoic geological record, there is no consensus about the past climate changes and exactly when they took place in the high–middle latitudes of Argentina. Addressing this gap in knowledge, multidisciplinary studies have begun in the south of South America, including environmental magnetism studies.

2 Paleomagnetic Studies of Lava Flows

One of the pioneering works was the paleomagnetic study of the Miocene Barda Negra basalts and Uppermost Pliocene basalt of Pampa de Zapala, Neuquén province (Valencio 1965a, b). A stable primary remanent magnetization and a secondary viscous component, removable by 20–30 mT of AF were carried in the samples collected from these sites. The primary magnetization from Pampa de Zapala has reverse polarity.

Mejia et al. (2004) reported results on the basaltic lava areas of southern Patagonia. Paleomagnetic directions were obtained from alternating-field or thermal demagnetization of 53 lava flows from the Pali-Aike volcanic field and the Meseta Vizcachas plateau lavas (Fig. 1). K–Ar and 40Ar/39Ar radio isotopic ages of these flows (Mercer 1976; Meglioli 1992; Singer et al. 2004a) have been obtained to depict the glacial history of Patagonia; a Pliocene–Pleistocene age was suggested. Mejia et al. (2004)

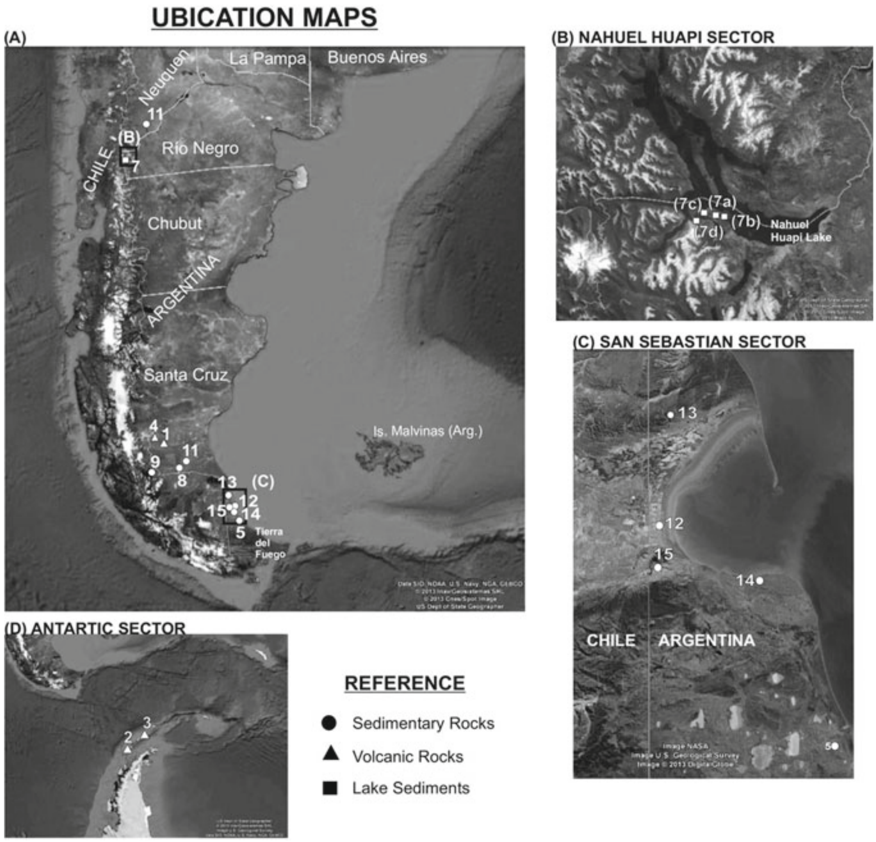


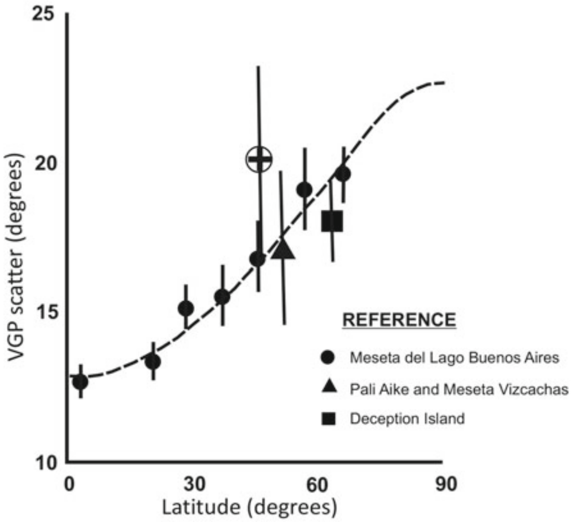
Fig. 1 Location of the sites. 1: Meseta Vizcachas; 2: Decepción Is.; 3: 25 de Mayo, Is.; 4: Cerro del Fraile; 5: La Misión; 6: Santo Domingo cape; 7: Lago Nahuel Huapi (7a: Lago El Trébol, 7b: Brazo Campanario, 7c: Lago Moreno and 7d: Lago Escondido); 8 Potrok Aike Lake; 9: Mylodon Cave; 10: Piedra del Aguila; 11: Las Buitreras Cave; 12: San Sebastian Bay; 13 Las Mandíbulas 1; 14: San Genaro 2; 15: Cabeza de León 4

obtained radiometric ages spanning from 0.1 to 15.4 Ma. Magnetic polarities obtained from lava flows are in agreement with the expected polarities of the magnetic polarity timescale for these ages (Cande and Kent 1995).

The mean direction from sites with ages younger than 4 Ma is Dec = 358.7°, Inc = 68.2°, a95 = 3.5°, a value that is coincident within the statistical uncertainty of the direction of the geocentric axial dipole (GAD) for that area (Inc = −68.1°). The secular variation described by virtual geomagnetic pole positions (VGPs) angular standard deviation for these sites is 17.1° (Fig. 2), in agreement with the value expected for that latitude according to Model G of paleosecular variation (McFadden et al. 1988).

Additionally, Mejia et al. (2004) reported a significant discrepancy between the International Geomagnetic Reference Field (IGRF year 2000) and the GAD obtained

Fig. 2 Least squares fit of Model G to both normal and reversed polarity scatter of VGP from lavas for the past 5 Ma (after McFadden et al. 1991) and Secular variation described by the VGP angular standard deviation. Meseta del Lago Buenos Aires (modified from Brown et al. 2004); Pali Aike and Meseta Vizcachas (Mejía et al. 2004); Deception Island (Baraldo et al. 2003)



for the same area. The anomaly in the detected inclination for the area is 20°. This anomaly seems to reflect the pronounced non-dipolar structure of the present geomagnetic field in South America.

Valencio and Fourcade (1969) originally studied the Cenozoic volcanic rocks from Deception Island. Later on, Baraldo et al. (2003) continued with the research in the area, performing paleomagnetic studies on lavas, pyroclastic flows and several recent dykes. The volcanic Deception Island is located at 62°57´ S, 60°37´ W (Fig. 1), within the Bransfield marginal basin that separates the South Shetland Islands from the Antarctic Peninsula. The sampling included all the stratigraphic units exposed on Deception Island consisting of basaltic, andesitic and trachytic lavas, basaltic dykes and pyroclastic flows. High-quality paleomagnetic data were obtained. Following stepwise thermal and alternating field demagnetization, consistent characteristic remanent magnetizations were determined at 21 sites. The presented paleomagnetic and petrographic studies of the lavas also include late Miocene andesites and basalts from 25 de Mayo Island (Ardley Peninsula). Lavas from Deception Island carried normal remanent magnetism, which led the authors to suggest an age of less than 0.78 Ma (Brunhes Chron). Lavas from 25 de Mayo Island show normal and reversed polarities of their remanence. In both localities, the magnetic directions suggest that the geomagnetic field was dipolar, axial and geocentric during the eruption of the lavas. With the directions of remanent magnetization, two paleomagnetic poles (pp) were calculated for the Late Pleistocene (84° S, 170° E) and the Late Miocene (86° S, 126° W) (Valencio and Fourcade 1969).

The overall mean direction of the remanent magnetization is D = 348.8°, I = −73.7°, a95 = 4.4°, N = 21, and is consistent within error with the geocentric axial dipole direction at the study locality. The available radiometric date of 153 ± 46 ka agrees with this and suggests a minimum chronostratigraphic span of 100 kyr for the sampled rocks. All of the studied rocks show normal polarity, indicating a Brunhes Chron age. The mean directions show a Fisherian distribution and dispersion values compatible with current paleosecular variation models (Fig. 2). The calculated mean paleomagnetic direction is 2° away from the expected GAD direction, well within its a95 (4.4°). The inclination of the calculated mean direction is lower than the expected one, in opposition to the expected higher inclinations in the Southern Hemisphere owing to the far-sided effect.

Studies of some magnetic properties have been done on this volcanic island. A good correlation between bulk magnetic susceptibility and lithology was found in each stratigraphic unit (Baraldo and Rinaldi 2000). Hysteresis cycles and forward backfield isothermal remanent magnetization curves were made using one sample per site. A large majority of the domain size of the analyzed samples fall in the pseudo-single domain field, suggesting that most of the rocks are potentially good recorders of the geomagnetic field direction.

Singer et al. (2004a, b) presented a new stratigraphy and, 39Ar/40Ar and paleomagnetic results of a sequence located in Cerro del Fraile, southern Patagonia (Fig. 3). The sequence comprises 10 lava flows interbedded by seven tills. The isotopic data indicate the eruption took place between 2,18 and 1,07 Ma. Reunion and Olduvai subchrons have been recorded in the studied rocks. According to the mentioned authors, the deposition of till on the piedmont surface prior 2,18 Ma and six subsequent tills between 2,18 and 1,07 Ma mark frequent glaciations of southern South Patagonia during marine isotope stages 82–48.

3 Paleomagnetic Studies from Glaciolacustrine Sediments

A 10 m oriented core of Holocene sediments provided the first paleomagnetic record obtained in Tierra del Fuego. La Misión (53°40´ S, 67°50′ W) is situated 10 km north of City of Río Grande, on the northeastern coast of the Isla Grande de Tierra del Fuego (Fig. 1). This area was chosen for coring and detailed paleomagnetic analyses due to the remarkable sea level history and paleoclimatic evolution claimed by Auer (1965, 1970, 1974). The surface of the studied deposit lies a few meters above the current sea level in a paludified valley running SW–NE, south of Domingo cape cliff (Fig. 1).

The tephrochronology established by Auer (1950) became a standard reference for Fuego-Patagonia at a time when the radiocarbon dating method still was in its initial phase. The tephrochronology established by Auer was confusing for the later researchers (Heusser 1987). Markgraf (1980a, 1980b) found it necessary to re-core La Misión. The new core provided data for a substantial revision of the old chronology. Markgraf (1980a, 1980b) dated the organic material from the bottom layers in La Misión (late-glacial according to Auer; 1965), obtaining ages of 9,300 ± 180 and 8,490 ± 400 radiocarbon years B.P. for the transition steppe to forest. These radiocarbon datings agree reasonably well with that obtained by Deevey et al. (1959) of 7,850 ± 110 years B.P, which was rejected by Auer (1965). The age at the base of the core recovered by Markgraf, (1980b) is a little younger than 8,000 years B.P. and

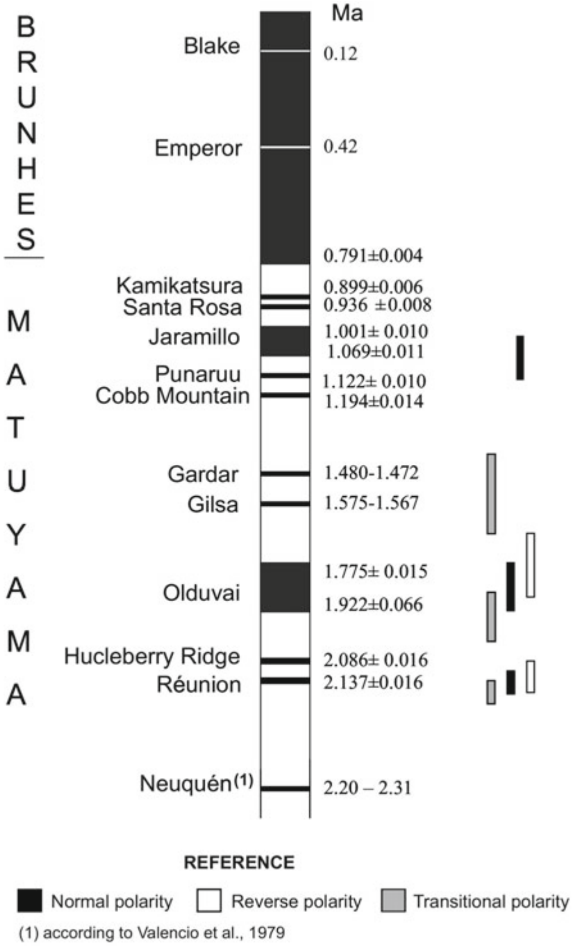


Fig. 3 Temporal extension of the transitional (grey), reverse (white) and normal (black) polarities of the Cerro del Fraile flows in relation with GMPS (modified from Singer et al. 2004a; Chanell et al. 2002) [(1) according to Valencio et al. 1979)

at the depth of 2.1 m (where a regression begins) about 3,000 years B.P. A special report on the sea level changes and sedimentological changes were later published (Morner 1989a, b).

Moreover, paleomagnetic results show a very scattered record (Sylwan 1989). Figure 4 shows the curves of declination and inclination after 20 mT demagnetization. Both declination and inclination curves show significant scatter. The curve of paleointensity versus depth (Fig. 5) reveals two different zones; the top (1–2.1 m) with intensities in the range 1–3 emu/cm3 and below 2.1 m, with higher intensities generally ranging between values of 10 and 60 uemu/cm3. The susceptibility shows a similar pattern. Q-factor values (ratio intensity/susceptibility, Fig. 5) are in general about 4; in the uppermost 2.1 m a marked decrease is observed, however, and around 4.2 and 8.2 m low values of intensity also occur.

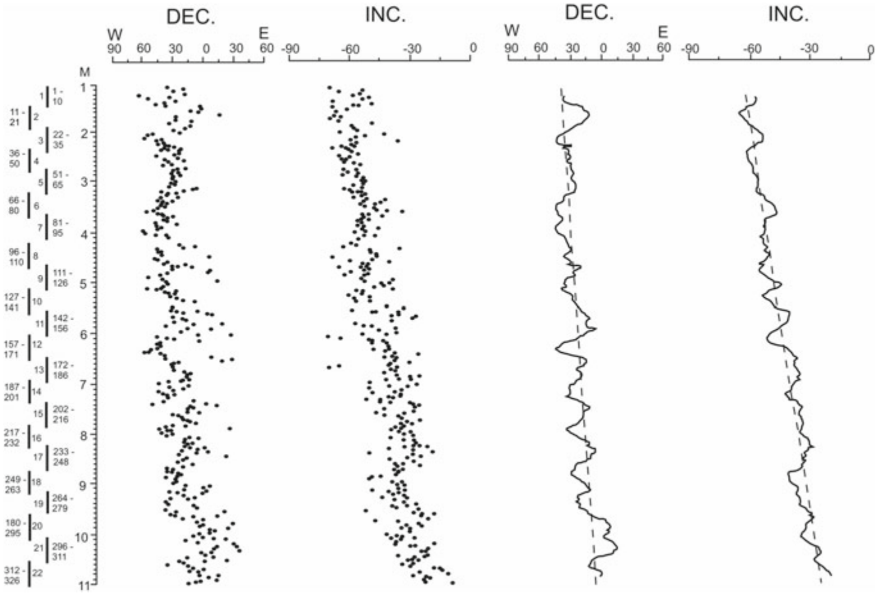


Fig. 4 Data of declination and inclination obtained from La Misión. To the left the true data, to the right 9-points running mean and best line-slope versus depth in meters. Beside the depth, there is a detail of the core segments with their number and the samples contained in them (from Sylwan 1989)

Changes of magnetic properties may provide information about environmental changes. In this case, a sharp decrease of magnetic susceptibility and intensity was interpreted as corresponding to the regression of the sea at about 3,000 yr BP for this area (Fig. 5) (Sylwan 1989).

4 Paleomagnetism of Lake Sediments in Argentina

4.1 First Stage

During the last decades, many efforts were done in order to reconstruct the behavior of the Holocene geomagnetic field by studying sediment records of lakes from south-western Argentina (Fig. 6). The first paleomagnetic studies were carried out on cores obtained from three lakes located near 41°S, 71.5°W in Río Negro Province, namely (Brazo Campanario, a narrow arm extending from Lake Nahuel Huapi, Lago Moreno and Lake El Trébol, a small almost circular lake of about 600 m diameter (Valencio et al. 1982, Mazzoni and Sinito 1982; Sinito et al. 1983; Creer et al. 1983a, b; Sinito et al. 1984; Valencio et al. 1985; Sinito 1990).

The results of these works can be summarized as follows:

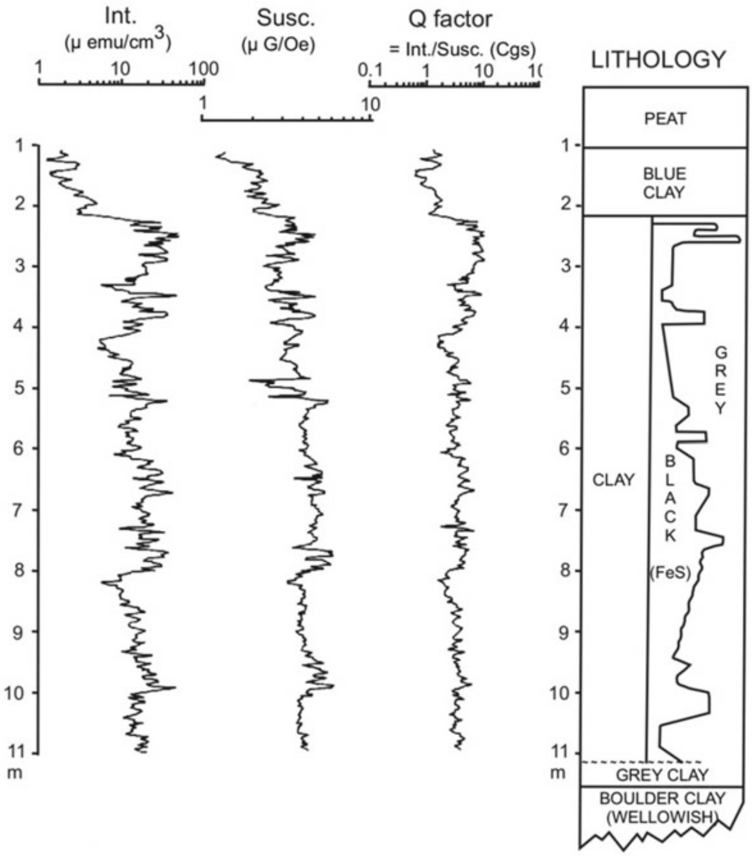


Fig. 5 Intensity, susceptibility and Q-factor curves of La Misión site, Northern Tierra del Fuego, plotted parallelly to a schematic sedimentological profile (from Sylwan 1989)

At the within-lake level, five lithological units could be broadly defined and were useful as a general guide in defining detailed correlations based on the magnetic susceptibility (k) and intensity of remanent magnetization (NRM). In one of the three lakes, el Trébol, it was possible to derive a closer, lithologically based, correlation and this was consistent with that based on the magnetic parameters. Inter-lake correlation was derived from the inclination and declination patterns considered as a pair, also taking account of a set of radiocarbon age determinations to remove any ambiguities. All the individual measurements were transformed to a time-scale prior to stacking to produce type-curves. The records for El Trébol and Brazo Campanario Lake extended back to about 6000 radiocarbon years before present while Lake Moreno provided a record extending back to about 14,000 radiocarbon years before present. The records exhibited variations with similar overall characteristics to those previously obtained for Europe and North America, but there appears to be no correlation with the northern hemisphere patterns on a swing to swing basis. Both clockwise and anticlockwise precession of the geomagnetic vector were evident, both from spectral analysis of declination/inclination pairs and Virtual Geomagnetic Poles (VGP paths).

Sinito (1990) compared PSV of the geomagnetic field obtained from the previously cited papers with results from different theoretical models, which suggested the possible sources of the field. Attempts were then made to simulate long period secular variations using modified Alldredge and Hurwitz's models. The modified models comprised eight radial dipoles, which oscillate sinusoidally and/or drift.

The different parameters of the models were fitted to the paleomagnetic data from southwestern Argentina. The best fit was obtained with a mixed model; between 6000 and 3000 years BP all radial dipoles oscillate and some of them drift as well. Later the drift rates become lower and, finally, between 1700 years BP and present times, all radial dipoles only oscillate.

Sinito and Nuñez (1997) carried out paleomagnetic studies on bottom sediments from Lake El Trébol, South Argentina. The pairs of k and NRM profiles showed a good correlation with the sedimentological macroscopic descriptions, and also with those of shorter cores previously studied. Declination and inclination logs were consistent with the correlations. Radiocarbon dating from earlier studies has enabled to construct a secular variation record from South Argentina for the past 17,000 years. The declination and inclination logs showed a significant anomaly at about 15,500 years B.P., which was accompanied by a decrease in both intensity of magnetization and modified Koenigsberger ratio, but without any change in susceptibility. These results suggested the possibility that a geomagnetic excursion or very short reversal of the geomagnetic field was recorded. Excursions at about this time have been recorded in several other parts of the world.

4.2 Second Stage

After the first studies, the researchers could realize that one of the most important problems to take into account in these lakes is the presence of abundant tephra layers along the sequence. The tephra layers have a different chronological meaning because they were deposited instantaneously. For this reason, to carry out a chronological correlation these layers cannot be considered comparable to the rest of the sediments. In general, the values of Declination and Inclination corresponding to the tephra layers of these sediments are very different from the mean values of these parameters and they are not consistent among cores. This event shows that in this case, tephra is not a very good magnetic recorder of directions. This behavior of volcanic ashes was also reported by Peng and King (1992). After the identification of the tephra layers from the lithological profiles and also from the susceptibility logs, they were removed from the sequence and the gaps that were produced along the profiles by the removal were closed, obtaining a shortened depth.

This renewed methodology was applied in the study of new data: Escondido (Gogorza et al. 1999, 2002, 2004), Moreno (Gogorza et al 2000; Irurzun et al. 2008, 2009), El Trébol (Gogorza et al. 2006, 2008, 2011; Irurzun et al. 2006) and Potrok Aike (Gogorza et al. 2011, 2012).

4.2.1 Magnetic Studies

Magnetic measurements were made to characterize sediments and to investigate their response to a variety of applied magnetic fields. The response is mainly driven by the mineralogy as well as concentration and grain-size distribution of magnetic carriers.

Magnetic susceptibility was measured at low (0.47 kHz, klow) and high frequencies (4.7 kHz, khigh), respectively. The frequency dependence factor (Ffactor, (%)) was calculated from the difference between measurements at high and low frequencies, i.e., Ffactor (%) = 100*(klow-khigh)/klow.

All samples were measured for the determination of intensity and directions of the natural remanent magnetization (NRM, D and I). Alternating Field (AF) demagnetization and principal component analysis (Kirschvink 1980) have been applied to determine the characteristic stable inclinations and declinations of the NRM. In general, about 20% of the samples were completely demagnetized as pilot samples in steps of 5–10 mT (11 steps to a maximum alternating field of 100 mT). These results were used to determine the best procedure for demagnetizing the rest of the samples, which were demagnetized in five steps (5–40 mT).

The following measurements were performed for all samples: the Anhysteretic Remanent Magnetization (ARM) was acquired in a peak alternating field of 100 mT with a steady bias field of 0.1 mT. The Isothermal Remanent Magnetization (IRM) was acquired at room temperature in increasing steps of up to 1.2 T reaching saturation (SIRM), and in increasing steps back until canceling the magnetic remanence was achieved using a IM-10-30 Pulse Magnetizer (ASC Scientific). Subsequently, AF demagnetization of the ARM and SIRM, respectively, were measured using the same steps as for the NRM demagnetization. Sub-samples were taken for hysteresis measurements and then calculated the ratios of saturation remanence to saturation magnetization (MRS/MS) and coercivity of remanence to coercive force (HCR/HC). Finally, a group of pilot samples was subjected to thermal demagnetization after applying a direct field of 1.2 T, followed by thermal demagnetization in 15 steps from 75 to 700 °C. After each step, remanent magnetization and k were measured for cooled samples. Stepwise thermal demagnetization curves and magnetic susceptibility measurements were determined and unblocking temperatures (TU) were estimated. Associated parameters were calculated: S (IRM300mT/SIRM), remanent coercive field (BCR), SIRM/k; ARM/k; SIRM/ARM, anhysteretic susceptibility (kAnh).

4.2.2 Results

At the within-lake level, lithological units could be broadly defined and were useful as a general guide in defining detailed correlations based on the magnetic susceptibility and intensity of remanent magnetization. Inter-lake correlation was derived from the inclination and declination patterns considered as a pair, also taking account of a set of radiocarbon age determinations to remove any ambiguities. All the individual measurements were transformed to a time-scale prior to stacking to produce type-curves.

Lake Escondido

Paleomagnetic and sedimentological studies were carried out on two short cores (40 cm) and nine long cores (up to 4 m) (Gogorza et al. 1999) and on four longer cores, about 11 m long (Gogorza et al. (2002) from the bottom sediments of Escondido Lake (41°S 71° 30′W) (Fig. 6).

The predominance of pseudo-single/single domain magnetite as main carrier, as well as an increase of concentration and grain size with depth was determined. Within-lake correlation was based on lithology, magnetic susceptibility and intensity of remanent magnetization, because the patterns of these parameters showed similarity for every core. Radiocarbon dating suggests higher deposition rates during the early stage of the lacustrine basin (Late Pleistocene). The transfer functions depth–age also allowed constructing a secular variation record from south Argentina for the past 8,000 years BP (Gogorza et al. 1999) and it extends back to 19,000 years BP (Gogorza et al. 2002).

Relative changes in geomagnetic field intensity (RPI) over the last 16,000 years BP were recovered from the study of the four long cores (Gogorza et al. 2004). The remanent magnetization at 20mT (NRM20mT) was normalized using ARM, SIRM) and k. Coherence function analysis indicates that the records are not significantly affected by local environmental conditions. This suggests that the variations in normalized remanence are mostly likely due to geomagnetic paleointensity fluctuations. ARM is the best normalizer for the Lake Escondido sediments.

Lake El Trébol

Paleomagnetic studies carried out on four long cores about 11 m long and two short cores about 3 m long collected from the bottom sediments from Lake El Trébol (41°04′S 71°29′W) (Fig. 1) are described (Gogorza et al. 2006).

Rock magnetic studies suggest that the dominant remanence carrier is magnetite and titano-magnetite within the pseudo-single domain (PSD) grain size and the concentration of these minerals change in a factor of ten. Radiocarbon age estimates from these cores and earlier studies allow us to construct a paleosecular variation record for the past 24,000 years. The spectrum obtained from spectral analysis shows major peaks at periodicities of about 1150, 1500, 2490, 3630, 5240 and 11,810 years. Both clockwise and counter-clockwise precession of the geomagnetic vector is evident from the analysis of the Bauer plots (Bauer 1985), with a preponderance of clockwise movement. The general agreement between the presented declination and inclination records is good, also confirming that the signals recorded in the investigated sediments are of geomagnetic origin.

The comparison with the previous work (Sinito and Nuñez 1997) shows that the anomalous direction registered at about 18,400 calibrated ages in this core is not registered in these new records. This possible excursion was registered in only one core, for this reason further work was necessary to validate it; these results do not allow confirming the existence of that excursion.

The composite NRM20mT/ARM20mT curve represents an estimate of geomagnetic paleointensity variations (Gogorza et al. 2006; 2008). The obtained records meet the strictest criteria for RPI records: the most commonly applied mineral magnetic criteria, paleomagnetic stability, agreement between results of different paleomagnetic normalization and agreement with records obtained from other geographical areas.

Lake Moreno

Data from paleomagnetic and sedimentological studies carried out on four cores (Gogorza et al. 2000) and three cores (Irurzun et al. 2008) from the bottom sediments of Lake Moreno (41°0′S, 71°30′W) (Fig. 6) were integrated with data obtained by Creer et al. (1983a, 1983b) in order to obtain a continuous record of SV for the last 20,000 years,

Rock magnetic results suggest a high proportion of magnetite and (titano)magnetite with a predominance of PSD domain. The individual measurements were stacked and transformed to a time-scale to produce type-curves. The secular variation of the geomagnetic field was studied using spectral analysis and precession analysis of the magnetic vector. The spectrum obtained from spectral analysis shows major peaks at periodicities of about 1500, 2400, 3300, and 6200 yr. for inclination data and major peaks at periodicities of about 1200, 2300, and 3500 yr. for declination data. In order to test the stability of the obtained periodicities, spectral analysis was applied to every 6000 yr. time span at intervals of 500 yr. for both records. Both clockwise and counter-clockwise precession of the geomagnetic vector is evident from the analysis of the VGP path plots, with a preponderance of clockwise.

The composite curve of NRM20mT/ARM20mT represents an estimate of geomagnetic paleointensity variations for the period 13,000–24,000 years BP calibrated. The paleointensity records determined by conventional normalizing methods and by the pseudo-Thellier method (Tauxe et al. 1995) are almost consistent.

Laguna Potrok Aike

High-resolution secular variation curves of geomagnetic inclination and declination recorded in the lacustrine sediment from Laguna Potrok Aike (51°58′S, 70°23′W) (Fig. 6) for the period AD 1880 to 1480 (Gogorza et al. 2011) and for the last

16,000 cal. BP (Gogorza et al. 2012) was obtained. These records were recovered within the SALSA (South Argentinean Lake Sediment Archives and modeling) project.

Mineral magnetic measurements indicate that PSD domain magnetite is the major carrier of the remanence allowing the reliable determination of stable natural remanent magnetization inclinations and declinations from alternating field demagnetization and principal component analysis. Paleomagnetic secular variation records reveal most of the familiar features of declination and inclination that have previously been reported in other records from South Argentina but conspicuous centennial-scale differences are also observed.

The most likely carrier of the remanence is PSD magnetite and titano(magnetite). We normalized NRM at 20 mT with the intensity of SIRM at 20 mT in order to construct an RPI record. The Holocene/Late-Pleistocene PSV records from other Southern Argentinean sites show similarities with Laguna Potrok Aike although some discrepancies in the amplitude and age of the features are obvious. These differences are probably caused by smoothing effects due to different sedimentation rates, different sediment grain sizes, inaccuracies in the various chronologies, as well as different measuring techniques (u-channel versus discrete samples) and/or local non-dipole features.

4.2.3 Comparison with Regional Records of SW Argentina

In order to improve the understanding of Holocene to Late Pleistocene PSV in Southern Argentina, a regional comparison of directional records was performed with the inclination and declination records from laguna Potrok Aike (Gogorza et al. 2012) with lakes Escondido (Gogorza et al. 2004), El Trébol (Irurzun et al. 2006) and Moreno (Gogorza et al. 2000), all of which are located more than 1000 km north of laguna Potrok Aike. Synchronous features of PSV are better observed in sites located nearby, but dominant swings in direction can be coeval up to a distance of 4000 km (Lund 1996; Barletta et al. 2010).

In general, several highs and lows are displayed in the inclination and declination curves (Fig. 6). Some characteristic inclination and declination features are shown using in and dn, respectively. Significant inclination lows “i2”, “i4”, “i6”, “i8”, “i9”, “i11” and highs “i1”, “i3”, “i5”, “i7”, “i12” and “i13” are identified. The absence of several of these features and the different amplitudes observed in the data of Lake Moreno are due to the fact that they were subjected to a smoothing process after they were stacked (Gogorza et al. 2000). The steepest inclinations are observed at about 2600, 5900, 7000 and 13,200 cal. BP at laguna Potrok Aike and lakes El Trébol and Escondido, although the last feature is less prominent in Lake Escondido. The shallowest inclinations are observed at 11,100 and 3500 cal. BP; the last is identified in laguna Potrok Aike and Lake Escondido. In general, the declination records are least consistent. There are some distinct declination minima at around 2600 and 5000 cal. BP in all the records and the most pronounced one is observed at about 13,700 (14,100) cal. BP in laguna Potrok Aike (in Lake El Trébol and Lake

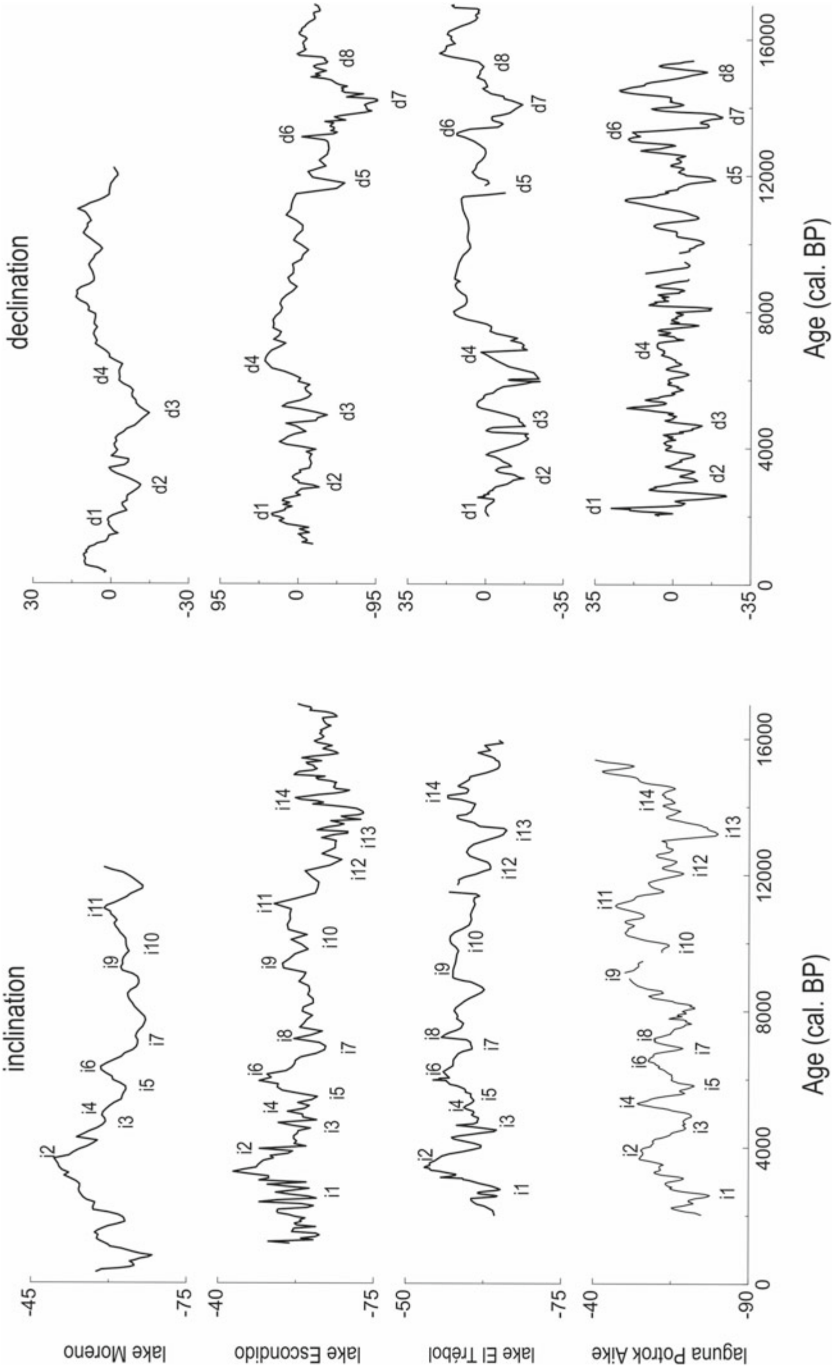


Fig. 6 A regional comparison of directional records (performed with the inclination and declination records) from laguna Potrok Aike (Gogorza et al. 2012), and lakes Escondido (Gogorza et al. 2004), El Trébol (Irurzun et al. 2006) and Moreno (Gogorza et al. 2000)

Escondido). Higher frequency variations are observed in the declination records of laguna Potrok Aike between 7500 and 9500 cal. BP.

The apparent lower resolution observed in the other Argentinean lakes could simply be explained by the lower sedimentation rates recorded in Lake Escondido (0.3 mm/year) and Lake El Trébol (0.4 mm/year) compared to laguna Potrok Aike (5–8 mm/year) in most of this period. Finally, the age models of the records and/or inaccuracies in dating methods could explain the small discrepancies in timing observed between laguna Potrok Aike and the other records. Nonetheless, the overall consistency of PSV patterns among these records suggests that these features are common for Southern Argentina. These coeval features also suggest that PSV can provide a useful tool for stratigraphic correlation on a regional scale in Southern South America.

In Fig. 7, the RPI record of laguna Potrok Aike is compared for the last 10,000 years with the records of lakes Escondido (Gogorza et al. 2004) and El Trébol (Gogorza et al. 2006) and the geomagnetic model CALS7K.2 (Korte and Constable 2005). Similar features are observed which are labeled p1-p6. However, because of the different sedimentation rate, short-term centennial features, such as observed at laguna Potrok Aike, are not resolved in low-resolution composite records, such as lakes Escondido and El Trébol. In particular, a similar long-term trend of increasing intensity from 6700 cal. BP until 3800 cal. BP (3000 cal. BP) is observed in laguna Potrok Aike (in Lakes Escondido and El Trébol). It is interesting to mention that the RPI high around 9300 cal. BP is also observed in North America (Barletta et al. 2010; St-Onge et al. 2003) and Greenland (Snowball et al. 2010). Moreover, the paleointensity lows observed around 3000 and 7500 cal. BP can be correlated with features seen in the sediment cores collected from Hole 1202B in the West Pacific (Richter et al. 2006), Fish Lake (Verosub et al. 1986), the synthetic record OH93 (Ohno and Hamano 1993), and RPI estimates obtained from ByaP2 and ByaP1, the Holocene lake sediment sequence collected in central southern Sweden (Snowball and Sandgren 2004). The global occurrence of these features suggests that they might be related to dipolar sources.

Such reproducibility between lakes validates the quality of the paleomagnetic records and suggests that the PSV and RPI profiles from these high resolution and well-dated records could be used as a robust regional correlation tool in Southern South America.

5 Paleomagnetic Studies from Sedimentary Sequences

Paleomagnetic results from a section at Mylodon cave (Seno de Última Esperanza, Chile) (Fig. 1) are reported by Nami (1995). According to previous 14C data, the sediments have ages between 13,500 and 5,360 ka BP. The unblocking temperature ranging from 450 to 550 °C suggested that the magnetic mineral belonged to the titanomagnetite series. The changes in declination and inclination of the ChRM for the section show directions with little deviation from the present axial dipole in the

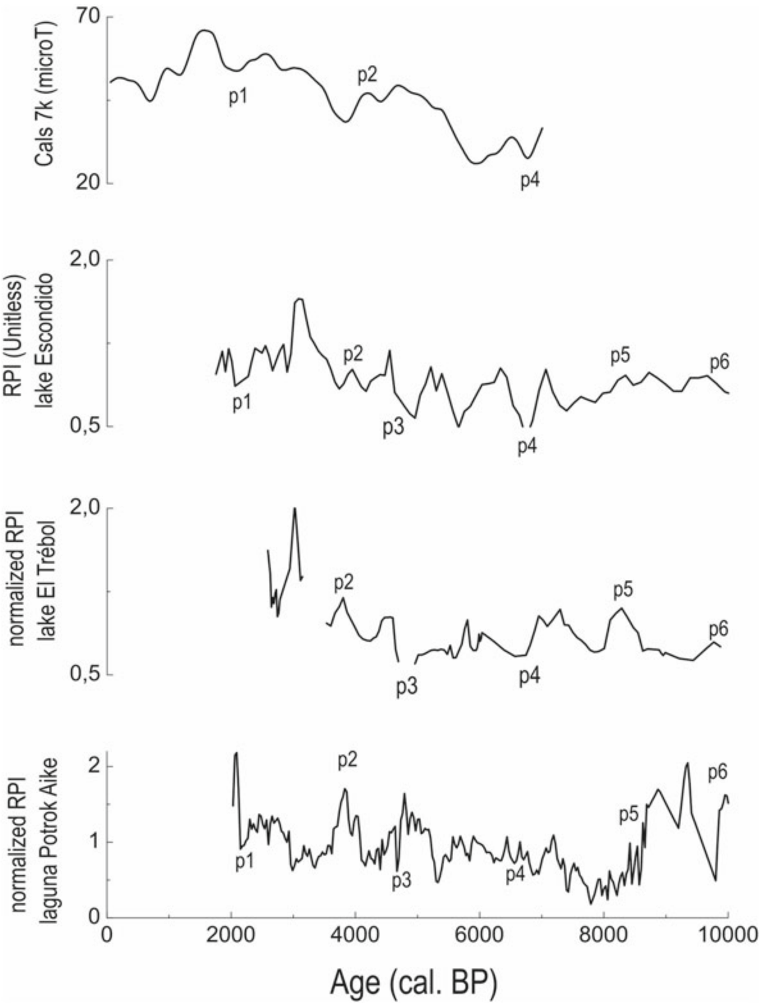


Fig. 7 RPI record of laguna Potrok Aike, compared with lakes Escondido (Gogorza et al. 2004) and El Trébol (Gogorza et al. 2006) records and the geomagnetic model CALS7K.2 (Korte and Constable 2005)

lower section, whereas samples from the top section show directions corresponding to an obliquely normal and obliquely reversed field. The corresponding VGPs are plotted in Fig. 8a. According to the authors, these positions suggest the existence of an excursion of the earth magnetic field found in southern South America during the Early to Middle Holocene, the "Mylodon excursion", younger than 10 ka BP taking into account the available radiocarbon ages. The inclination and declination found from the top part of Mylodon Cave agree with the data from Angostura Blanca

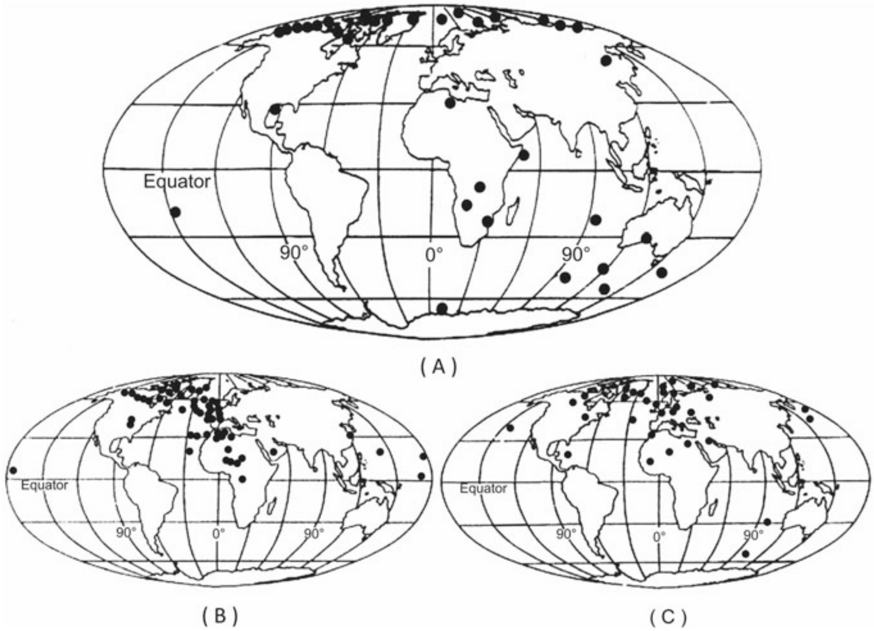


Fig. 8 VGPs positions for the excursion recorded in: **a** Mylodon Cave; **b** Piedra del Aguila; and **c** Las Buitreras (after Nami 1995 and 1999a)

(Nami and Sinito 1993) which probably correspond to the last phase of the "Mylodon excursion" (Nami 1995).

Paleomagnetic data from two sedimentary sequences corresponding to the Late Pleistocene to Holocene ($\approx 11 \pm 0.5$ ka BP), located in Piedra del Aguila (Neuquén Province) and Las Buitreras Cave (Santa Cruz Province) are presented by Nami (1999a) (Fig. 8). The author found that a gentle but significant eastward shift in the declination (over 40°) and a less conspicuous shallowing of the inclination can be observed in the upper part of the section, between $\approx$ 2.5 and 1.9 ka BP. The declination (D) and inclination (I) from Las Buitreras cave show long pulses that suggest a possible excursion of the geomagnetic field during the Late Pleistocene to Early Holocene, similar to the one found in Mylodon Cave (Nami 1999a). The positions of the corresponding VGPs are plotted in Fig. 8b and c.

Nami (1999a) suggested that other archaeological and paleontological sites in southern South America include records of a probable excursion of the Earth's magnetic field (EMF) sometime in the Late Pleistocene and Early Holocene. This fact suggests that the "Mylodon excursion" may have had a regional extent. All the available data was included in an analysis of VGPs distribution (Mena and Nami 2002), using the bases of spherical density grams (Love 2000). The distribution suggests that it is not only the transitional VGPs that have a peculiar distribution but also those of stable polarity or possible excursion fields are displayed in a geographic pattern where the longitudes have a non-uniform distribution (Mena and Nami 2002) (Fig. 9a–c).

VGPs from the Mylodon excursion coincide remarkably with those from the Red Rock archaeological site, in California USA (Mena and Nami 2002), where paleomagnetic studies from three sedimentary sections attributed to Middle and Late Holocene, have normal, intermediate and reversed directions (Nami 1999b). This suggests that the GF probably underwent an excursion in southwestern North America during the Middle Holocene.

Recently, Walther et al. (2007) have begun a paleomagnetic study on the glaciogenic sedimentary record of northern Tierra del Fuego Island with the aim of obtaining accurate age data for these deposits. Research was initiated on the Middle Pleistocene río Cullen and sierra San Sebastián drifts—bahía San Sebastián—which show outcrops with lateral continuity (Fig. 9). The paleomagnetic analysis reveals that the studied cores bear more than one magnetic component. Two blocking temperature ranges have been recognized in the río Cullen drift; a low (300–400 °C) and a high (500–580 °C) Curie temperature rank. According to the authors, the mineral carriers of magnetic remanence with low blocking temperatures are Ti-rich titanomagnetites and those with high Curie temperatures are magnetite and Ti-poor titanomagnetite. The studied samples of the San Sebastián drift, in turn, show a low stability secondary magnetic component and a high-stability unidirectional magnetic component. Two blocking temperature ranges have been also observed in the San Sebastián drift: a low (200–350 °C) and a high (450–580 °C) Curie temperature range. The magnetic carrier in both drifts is a titanomagnetite.

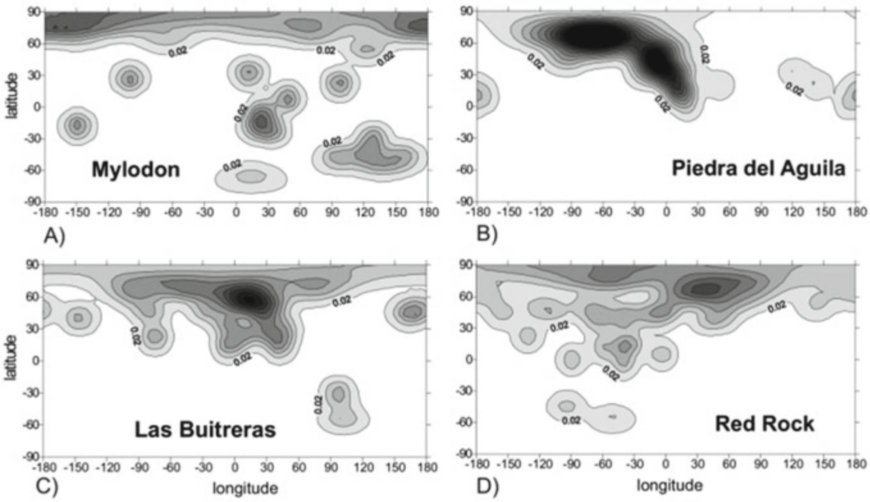


Fig. 9 Contour plot map of densities of VGP (units are probability/steradian) for the records from: **a** Mylodon cave; **b** Piedra del Aguila; **c** Las Buitreras; and **d** Red Rock (modified from Mena and Nami 2002)

VGP were computed with stable remanent magnetization. These data allowed the determination of magnetic polarity which is normal for all the studied samples. The age of these glaciogenic deposits has been considered as < 1.01 Ma. This is the age of Pampa de Beta Drift or the "Large Patagonic Glaciation" (LPG) which is older than the glaciogenic events resulting in the deposits sampled for this work. Therefore, the only possible correlation of the obtained data with the table of reversions of the GF is with the Brunhes chron (<0.78 Ma).

6 Environmental Magnetism Study of Holocene Sediments and Paleosol Sequence in Tierra del Fuego

The influence of climate is a major factor in the formation of a soil. Both chemical and biological activity increases with increasing temperature and humidity. Although the magnetic carriers are a minority within the rocks and sediments, their sensitivity to chemical changes, make them excellent detectors of environmental change (Verusob and Roberts 1995, among others).

For these reasons, environmental magnetism studies have seen a surge in interest in the last two decades.

Orgeira et al (2000) present an environmental magnetism study in the coastal area of bahía San Sebastián (Tierra del Fuego, 53° a 53° 20′ S; 68° 20′ a 68° 40′ W, Fig. 10). In this area the presence of a buried soil assigned to the Late Holocene was detected; it had developed in deposits of clay to fine eolian sand and colluvial sand with some gravels. This buried soil was associated with archaeological and paleontological material. Numerous absolute dates indicate that it has a chronological correspondence with an environmental fluctuation detected in other areas of Southern Patagonia (Stine 1994), which may be ascribed to the Medieval Climatic Optimum in Europe (approximately from the tenth to thirteenth centuries AD (Lamb 1965, 1977).

In two of the localities studied, Sitio San Genaro and Sitio Cabeza de Léon, the presence of a buried soil can be seen that is attributed to the effects of the aforementioned climatic event.

The main objectives of the study of Orgeira et al. (2000) were to determine if a magnetic imprint of the medieval climatic fluctuation exists in the studied sequences and to determine if a magnetic signal of human activity exists in the levels in which archaeological material is obtained.

In Fig. 10, the values of the obtained magnetic properties in each of the studied localities are presented. The curves of thermoremanence obtained indicate that the ferromagnetic mineral present is magnetite, which according to the parameters of the hysteresis loop is mainly MD.

In the three profiles studied the magnetic fraction detected is homogeneous from the mineralogical point of view (exclusively magnetite); likewise, the sizes of the determined magnetic particles (MD and PSD) clearly indicate a detritic origin for this magnetic fraction. This implies that during the physical-chemical processes that

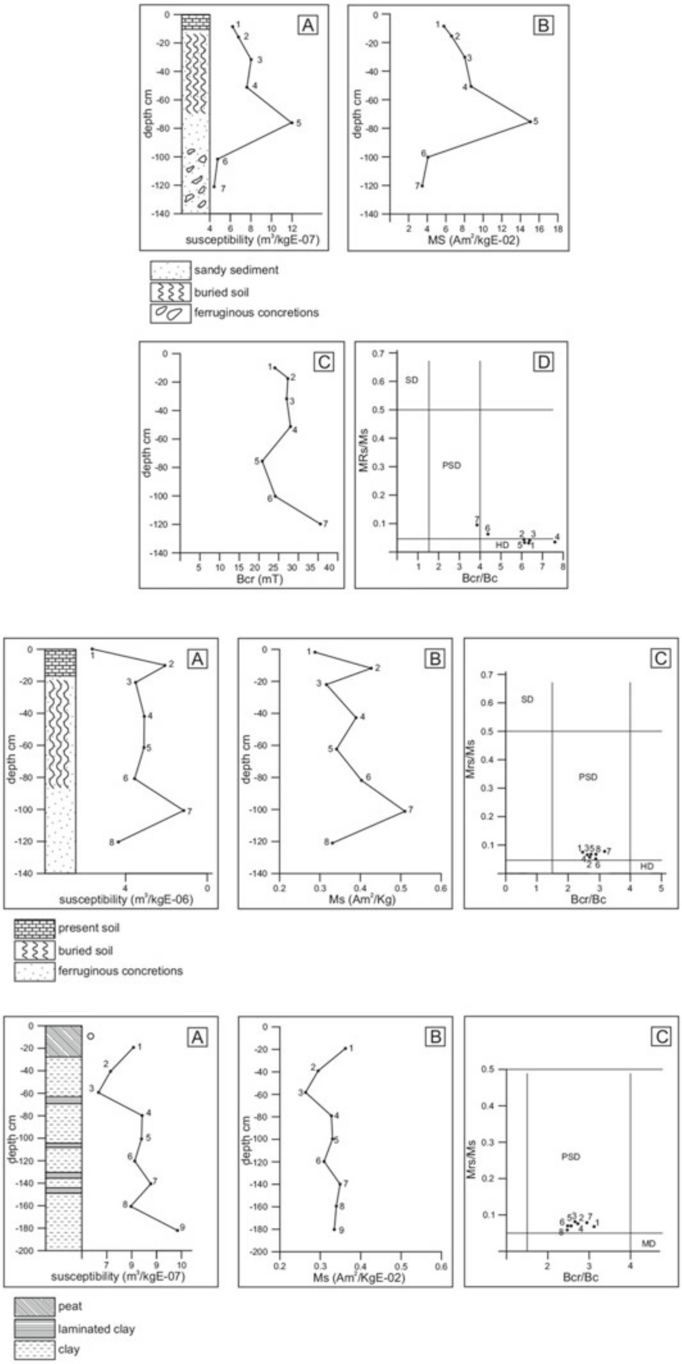


Fig. 10 Results of the environmental magnetism study in the coastal area of Bahia San Sebastian (Tierra del Fuego). San Genaro site (A, B,C and D top of figure), Cabeza de León site (A,B,C center of figure), and Las Mandíbulas site (A, B and C, bottom of figure)

occurred in the sediments as a result of the climatic changes there was no neoformation of magnetic minerals. Another interesting point is that in the cases studied a single magnetic signal is found, characterized by a drop in the concentration of magnetic minerals coeval with the edaphization process in different parent materials. This magnetic signal does not, however, have the same amplitude. This difference is attributed to the contribution of different organic material in different sedimentary environments. The study concludes that the magnetic behavior of the studied material due to the change of climate was analogous although with different magnitudes. A reduction in the concentration of detritic magnetite is observed, this is interpreted as a consequence of the partial dissolution of this mineral during actions linked to the edaphization process. Likewise, a definite magnetic signal is observed generated by the fluctuations of the phreatic layer. Finally, with the methodology employed, no magnetic evidence of anthropic activity was recorded in the studied profiles.

Orgeira et al. (2012) present preliminary environmental magnetism results from 80 samples collected along an eolian sedimentary sequence with 8 interbedded paleosols in Laguna Arturo sequence (Tierra del Fuego). 14C data indicates that the studied record represents the Holocene (Fig. 11).

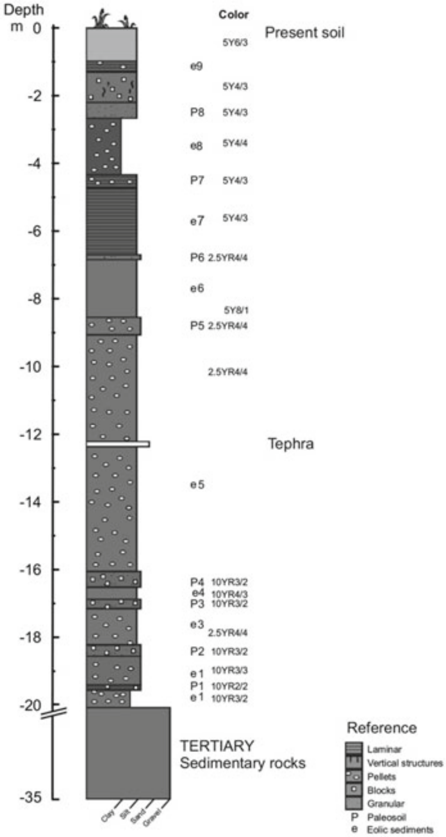
The sedimentary sequence of laguna Arturo provides evidence that in the north of Tierra del Fuego the environmental conditions were variable throughout the Holocene. Arid conditions promoted deflation and eolic accumulation of sediments that were later affected by pedogenesis during wetter periods. These cycles were repeated from ca. 11ky BP until the present reaching a maximum rate of accumulation during the middle Holocene (Coronato et al. 2011a and b). Given the latitudinal position of the sequence, the occurrence of strong thermal changes in the atmosphere capable of triggering physical-biological-type pedogenetic processes would not be expected. Rather, the spatial variability that the pressure centers of southern South America had and the dynamics of their interaction could have caused notable differences in the supply of atmospheric humidity in the region and consequently a change in the values of precipitation. An increase of 100 mm with respect to the present precipitation value (350 mm per year) would put the region in a category close to subhumid, and consequently, the action of the wind would have been restricted.

The magnetic results principally include hysteresis data at room temperature, variation of magnetic susceptibility at two frequencies (470 and 4700 Hz), and measurements of susceptibility at high and low temperatures in selected samples. Figure 12 shows hysteresis parameters measured in all the samples collected in the profile (Ms saturation magnetization, Mrs saturation remanent magnetization and Hc coercivity).

The variations in extensive parameters, such as magnetic susceptibility, Ms and Mrs along the studied profile suggest that the concentration of ferrimagnetic minerals differs from one paleosol to another.

Taking into account the hypothesis proposed by Orgeira et al (2011) the obtained magnetic results suggest that the moisture in the different studied paleosols was different during their formation.

The magnetic parameters seem to suggest periods of higher water storage, related with more humid climatic conditions than at present in the paleosols represented by P7, P5, P4 and P2 from the studied profile. In these levels loss of magnetic



Sedimentary units	Laboratory code	Material	^{14}C ages (yrs BP)	Average calibrated BP ages (SHCal04)	Sediment accumula-tion (m)
Surface					2.622
Palaeosol 7	AA89591	*Lama guanicoe* bone	434 ± 43	471	4.245
Palaeosol 5	AA89590	*Lama guanicoe* bone	4,871 ± 59	5552	6.494
Palaeosol 4	AA85452	*Lama guanicoe* bone	5,800 ± 64	6538	0.844
Palaeosol 3	AA89592	Canidae bone	6,333 ± 67	7163	2.582
Palaeosol 1	AA89589	Organic carbon	9,941 ± 59	11304	0.722

Fig. 11 Sedimentary profile from Laguna Arturo, Tierra del Fuego. 14C data obtained from samples collected in the profile

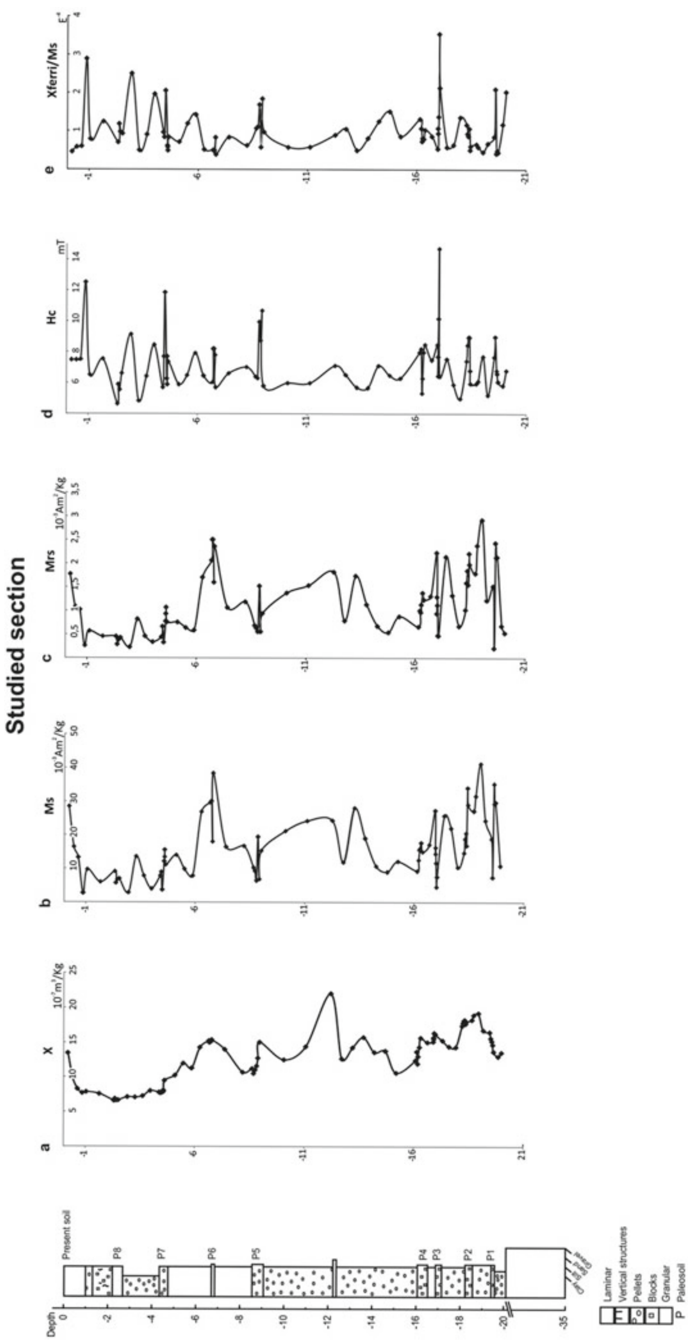


Fig. 12 Hysteresis parameters measured in all the samples collected in the profile of Laguna Arturo, Tierra del Fuego (Ms saturation magnetization, Mrs saturation remanent magnetization and Hc coercivity)

minerals, mainly by reductive processes, could have occurred during the pedogenesis. This implies necessarily higher precipitation in the area during the formation of these soils. In contrast, in the present soil, P1 and P6, not only is the preservation of detritic magnetic particles recorded but also an increase in these particles is seen. Consequently, the water storage was similar in all of these paleosols and the precipitation would be similar in the time periods they represent.

Greater values of precipitation would have offered a greater availability of water in the region, assured the permanence of water in the lagoons and reduced the availability of source areas of eolian material. The similarity between the physical conditions of the present soil with the paleosols developed since the mid-Holocene to present allows us to establish alternating wet and dry periods throughout the entire Holocene, with different climate characterizations. The present conditions were established progressively since the mid-Holocene, following the period in which the thickest sediments were deposited, between 6.5ky and 5.5ky BP.

7 Final Remarks

Paleomagnetic studies of Late Cenozoic rocks and sediments in Patagonia and Isla Grande de Tierra del Fuego have been made from the earliest times of the discipline. A large number of studies were carried out in upper Cenozoic basaltic lava flows, glaciolacustrine sediments, lake sediments and sediments from archaeological and paleontological locations. Many paleomagnetic and chronostratigraphic studies have contributed to the determination of the ages of different glaciations, as well as to the correlation between the different localities. Morover, during the last decades, several paleomagnetic project in lake sediments allowed to reconstruct the behavior of the Holocene geomagnetic field from southwestern Argentina. These results are decisive for determining regional and global patterns of longer period secular variations, and for having a better understanding of the physics of the Earth's core.

More recently, several environmental magnetism studies have begun to be carried out on eolian sediments and lake sediments. Some results from these studies have been presented in this chapter.

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Provenance of the Coastal Sands of the Western Scotia Plate: Tierra del Fuego and Antarctic Peninsula

Federico Ignacio Isla, Ximena Contardo, Jorge Spagnuolo, and Gustavo Gabriel Bujalesky

Abstract The Scotia Plate is interacting between the South American and the Antarctic plates. The original plate has been subdivided in relation to new studies that recognized an active oceanic ridge that separate it from the Sandwich Plate. At the same time, the Shackleton Fracture Zone separates it into two other small plates: the Drake and the South Shetland plates. All these plates are mostly of oceanic composition with a small portion of continental crust emerging at the northwestern corner, at the south of the Fuegian Archipelago. Most of the emergent areas of these plates have been repeatedly glaciated during the Quaternary, although the last glaciation was not so extended as in the Northern Hemisphere. In order to get light about rock provenance, beach and coastal sands were collected and analyzed in their mineral composition, assuming that they are indicating the geotectonic setting. Quartz, lithic fragments and plagioclases are dominant at the Atlantic coast of the Isla Grande de Tierra del Fuego. These sediments have been transported by piedmont glaciers from the Darwin Cordillera. On the other hand, and due to their volcanic origin, opaque minerals are dominant at the beaches of the South Shetland Islands, and less common at the Antarctic Peninsula. To the north and south of the Scotia Plate, there is an important contribution of metamorphic minerals (garnets). These contributions are related to the Patagonian Batholith at Beagle Channel, and to those rocks outcropping at the South Orkney Islands and the Antarctic Peninsula.

Keywords Sand provenance · Western scotia plate

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1 Introduction

The Scotia Plate is located between South America and Antarctic plates (Fig. 1). Two transform faults separate these plates: The North Scotia Ridge and the South Scotia Ridge (Ruano et al. 2014). In detail, four plates have been discriminated: Scotia, South Sandwich, South Shetland and Drake plates (Groeneweg and Beunk 1992; Agusto et al. 2007). Most of them are composed of oceanic crust with continental crust limited to the northwestern (South America) and southwestern portions (Subantarctic islands). This special configuration makes it difficult to reconstruct the geologic evolution, with different plausible interpretations derived from their complex interactions (Eagles et al. 2005). Structural models were conceived departing from outcrops from different islands and sea-bottom seismic surveys. For the last 40 Myers there was an east-migrating subduction zone at the boundary of South American and Antarctic plates, a key modulator has been the collision of ridge crests at this boundary (Barker et al. 2001). As most of these islands are still covered by ice during most of the year, their composition had been inferred according to sediments collected from beaches and shallow banks (Isla et al. 2000; Gelós et al. 2000). Glacier irradiation based on Geomorphology, and detailed bathymetric charts from the Sub Antarctic islands were handled in order to analyze the sediment provenance to the narrow continental shelves (Sugden and Clapperton 1977), however there is not much information about the submerged moraines.

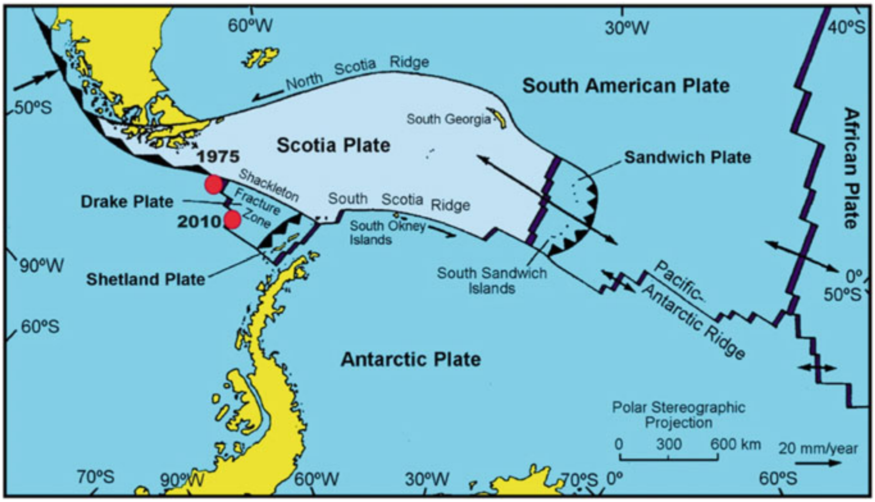

Fig. 1 Spatial relationships between the Scotia and the other minor plates. Red dots are the locations and year of occurrence of the most recent earthquakes (modified after Isla and Bujalesky 2008)

The sediments of these modern oceanic plates originated from the oceanic floor during the Neogene, and can only be sampled in small portions of their borders: at the north (southern Fuego Archipelago, and South Georgia Islands), at the east (South Sandwich Islands) and the southwest (South Shetland Islands). Provenance was analyzed at the Argentinian side of the Grande Island of Tierra del Fuego from rocks of Late Cretaceous to Miocene ages (Zahid and Barbeau 2010). At this island coastal deposits accumulated during the Quaternary highstands. Those of the Antarctic Peninsula and surrounding islands were dominated by ice processes.

In the present paper, the composition of the beach and coastal sediments from the western portion of these plates were analyzed and interpreted in their relationships. It is an update of analyses performed on samples collected from Argentina and Antarctic territories (Isla et al. 2000; Gelós et al. 2000) adding results not published (Contardo 2001) from the Chilean Tierra del Fuego. This new data is interpreted in terms of mineral provenance considering new information (geologic maps, seismic legs, geomagnetic surveys) about the composition and evolution of the interacting plates.

2 Geological Setting

The Scotia Plate is the largest, with outcrops of metamorphic and sedimentary rocks at the south of the Isla Grande de Tierra del Fuego (Klepeis 1994). At this northwestern corner, granites, siliceous schists and gneisses were mapped either at the Chilean and Argentinean territories (Winn 1978; Cunningham 1995; Olivero et al. 1999). Toward the north, at the limit with the South American Plate (Fig. 2a), volcaniclastic rocks were surveyed. The Lemaire Formation of Jurassic age is overlain by the low-grade metamorphic rocks, tuffs, and turbidites of the Yahgan Formation, comprising a marginal basin called "Rocas Verdes" of Lower Cretaceous age (Olivero et al. 1999; Olivero and Martinioni 2001).

To the northeast, most of the South Georgia Island (Fig. 1) is composed of two formations: Cumberland Bay and Larsen Harbour (Mair 1987). Cumberland Bay

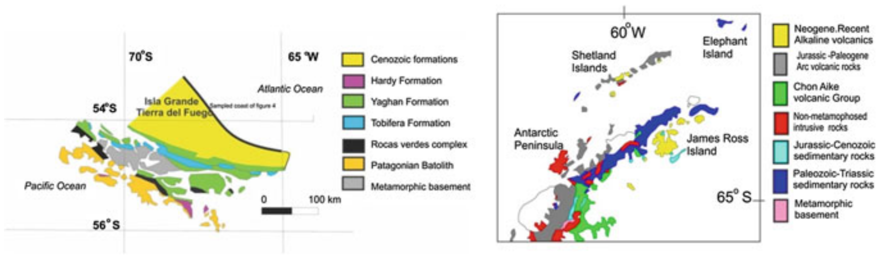

Fig. 2 **a** Geologic sketch of the Grande Island of Tierra del Fuego (modified from Calderón et al., 2016). **b** Geologic sketch of the Antarctic Peninsula (Modified after Burton-Johnson and Riley 2018)

Formation consists of 8 km thick of deformed volcaniclastic turbidites of Mesozoic age, correlated to the Yahgan Formation of the Fueguian Archipelago (Winn 1978). The ophiolitic sequence of Larsen Harbour Formation outcrops at the southeast of this island, where mafic volcanic and intrusive rocks were affected by oceanic hydrothermal metamorphism (Mair 1987).

The South Sandwich Plate (Fig. 1) is of limited extension and only emerging as a very modern volcanic arc. The arc is composed either of tholeiitic and calc-alkali basalts, although dacites are also sampled (Baker 1975). Rhyolitic pumicites were extruded during an eruption of 1962. At Freezland Rock pyroclastic units were intruded by andesitic dykes. Calcic plagioclases, olivine, clinopyroxenes, orthopyroxenes and magnetite were reported (Baker 1975).

The Phoenix Plate subducted below the Antarctic Plate during late Mesozoic and Cenozoic. Its spreading ceased about 3.6–2.6 Myrs. It is limited from the Scotia Plate by the Shackleton Fracture Zone (Martos et al. 2013). The Drake Plate is also small and limited between the Scotia, Antarctic and South Shetland plates; a triple junction has been subducting below the Antarctic Plate (Martos et al 2013). It is submerging and composed of a volcanic oceanic bottom.

The South Orkney Islands compose a microcontinent with a compressive relation to the Scotia Plate with a significant seismic activity (Ruano et al. 2014). They are considered belonging to the northernmost border of the Antarctic Plate (Fig. 1).

The Geology of the South Shetland Plate (Fig. 2b) is difficult to discern as much their rocks are covered by ice most of the year. However, volcanic and plutonic rocks of calc-alkaline affinity have been reported (Smellie et al. 1984; Trouw and Gamboa 1992). Sedimentary sequences initiate with turbidity-current deposits of Permian-Triassic age, known as Miers Bluff Formation from Livingston Island (Trouw and Gamboa 1992; Arche et al. 1992; Pallás et al. 1992). Overlying, sedimentary rocks are associated to the Cretaceous-Mid Tertiary magmatic arc (Trouw and Gamboa 1992). Low-grade metamorphic rocks, mostly blue schists and phyllites, are restricted to Elephant, Clarence, Livingston (False Bay schists) and Smith islands, although there is a high grade metamorphic belt (Smellie et al. 1984). Pliocene rocks were mapped in detail at King George Island (Birkenmajer 1982). Mid-Holocene raised beaches have been reported at some these islands (Del Valle et al. 2002). The very-modern volcanic activity is explained by the recurrence of eruptions of the volcano of Deception Island (Roobol 1973).

At the Antarctic Peninsula, rocks of several ages and compositions have been recognized. Basement metamorphic rocks were covered by sediments of Permian, Triassic and Jurassic ages (Burton-Johnson and Riley 2018). Volcanic activity is present since the Mesozoic (Fig. 2b).

3 Methods

Sediments were collected from beaches, shallow banks and bays, by the mean of grab samplers. At lab they were dried and sieved according to grain-size intervals of 0.5

phi units. As sediments spanned from gravel to sand, the 88-125 microns interval was chosen to separate the heavy and light fractions. Each fraction was analyzed using a binocular microscope (Isla et al. 2000; Gelós et al. 2000); percentages were referred as the interval between 88 and 125 microns. Total percentages were recalculated into a triangle distribution in regard to their proportions of monocrystalline and polycrystalline quartz (Q), feldspar (F), and lithic fragments of volcanic origin and volcanic ash (L). The QFL triangle is handled in order to relate sand composition to tectonics of the supplying rocks (Dickinson and Suczek 1979). Mineral-content percentages were gathered in a database related to their location in a GIS system (Arc View).

4 Results

Very different mineralogical suites were recognized from sediments collected from different coastal deposits of Western Scotia Region (Fig. 3). Compositions were analyzed in terms of each tectonic setting.

4.1 Tierra Del Fuego (South American-Scotia Plates Transition)

Samples collected at the Atlantic coast of Isla Grande, north of the Magallanes transform fault, are dominated by lithic fragments, altered minerals, plagioclase and quartz (Isla et al. 2005). Opaque minerals were sampled in significant proportions in Río Grande and Estancia Pirinaica. Between San Sebastian Bay and the río Irigoyen outlet there was no significant change in quartz, lithic fragments or feldspar grains that could indicate any longshore transport (Fig. 4). South of the Magallanes transform fault, garnets increase significantly toward Peninsula Mitre (puesto Donata sample; Fig. 3). Samples collected around Navarino Island (Beagle, Murray and Ballenero channels) are dominated by sand and silts (Contardo et al. 2000).

Along the Beagle Channel, significant changes were also detected. The sample collected at the Olivia river delta was composed dominantly of lithic fragments and quartz (Fig. 5). Instead, the sample from the bottom of the channel close to Puerto Williams was composed mainly by quartz and amphibole, with less portions of lithic fragments (Contardo 2001). Close to Lennox Island (Richmond channel), lithic fragments and quartz were dominant. Toward Peninsula Mitre, the southern coast of the Grande Island was dominated by altered minerals, potassium feldspar and quartz. South of Navarino Island, at Nassau Bay, drag samples were composed basically of lithic fragments and quartz (Fig. 2). Toward Ponsonby Sound, lithic fragments were almost exclusive (Contardo 2001) in a similar way to the Ushuaia sample (Olivia river delta).

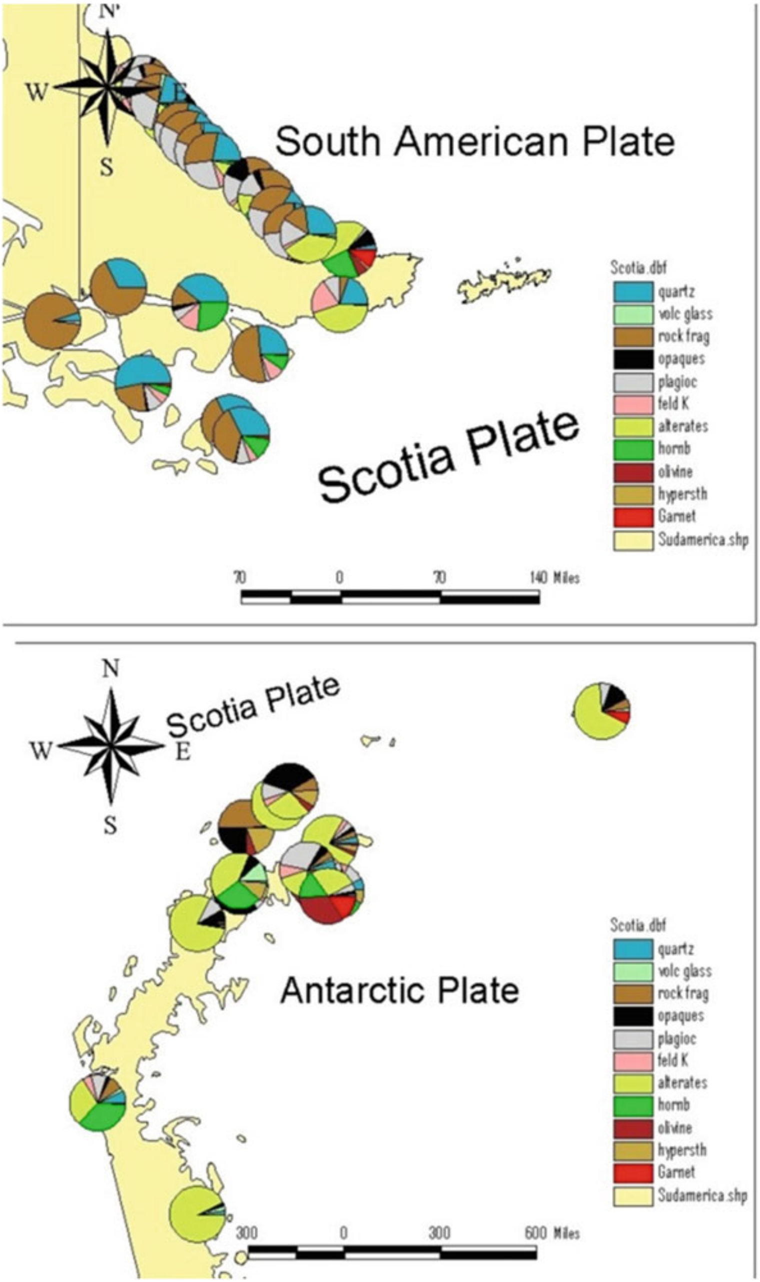

Fig. 3 Mineral composition of coastal deposits. **a** Transition between the Scotia and South American plates at Tierra del Fuego; **b** Transition between the Scotia and Antarctic plates at the Antarctic Peninsula

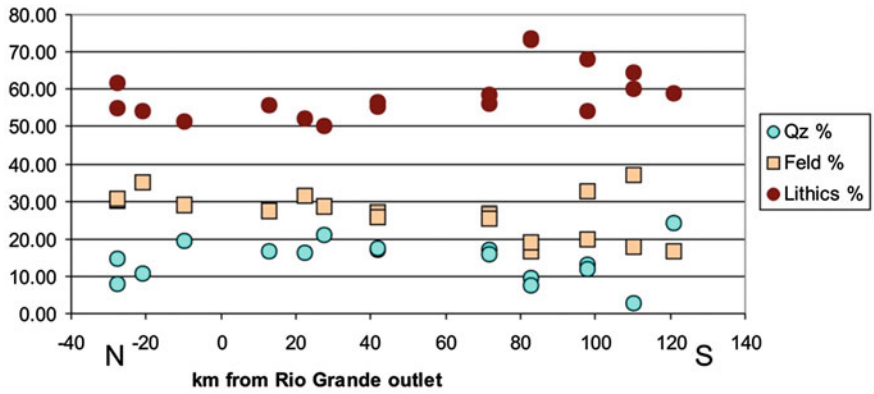

Fig. 4 Percentages of quartz, feldspar and lithic fragments content in sand samples from the beach foreshores of the Atlantic coast of Tierra del Fuego. Distances in km measured from the outlet of the Grande river

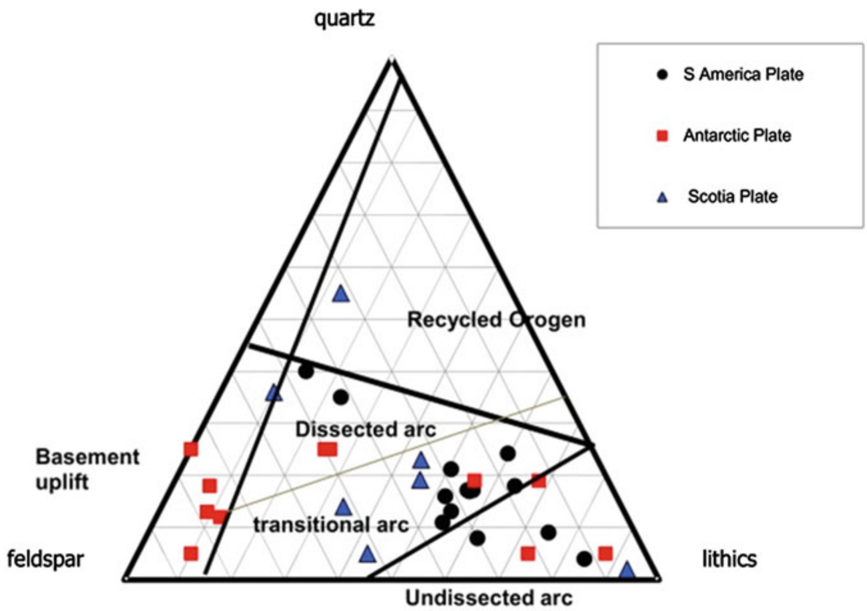

Fig. 5 Distribution of the samples collected on the three plates on a QFL triangle (modified from Dickinson et al. 1983)

4.2 South Orkney and South Shetland Islands

South Orkney Islands were reported as a microcontinent with frequent earthquakes that triggered mass-transport deposits toward the northern basins, Dove and Scan (Ruano et al. 2014). The only sand sample collected from Laurie Island was composed of altered lithic fragments with less proportion of opaque minerals, plagioclase and garnets; the latter are assumed as originated from metamorphic rocks.

The northernmost samples collected from the South Shetland Islands were composed dominantly by lithic fragments and opaque minerals (Fig. 5). Close to the volcano of Deception Island, the sediments collected are volcanic rock fragments, opaque minerals, orthopiroxene and olivine (Gelós et al. 2000; Isla et al. 2000).

4.3 Antarctic Plate

The northernmost samples at the Antarctic Peninsula (Esperanza Bay) were composed dominantly by altered minerals and opaque minerals (Fig. 3).

There are very small outcrops from the Antarctic Plate close to the Scotia Plate. At San Ildefonso Islands, a turbiditic sequence of 100 m is composed of proximal fan sandstones, a distal fan with alternating sandstones and lutites, and on top a conglomerate with lens of sandstones. It is assumed that it represents a basin called Cabo de Hornos (Mpodozis 1980). The petrography of these rocks indicates a dominant andesitic composition with scarce elements of plutonic rocks (granitoids and potassium feldspar).

Samples collected around the James Ross Island are composed dominantly by altered minerals and olivine (close to volcanic areas: bahía Delirio and Cerro Nevado) and hornblende grains (Fig. 3). At some beaches, plagioclase dominate over potassium feldspar.

5 Discussion

Beach sands have been proposed to give light about the tectonic setting of their supply watersheds (Potter 1986) and about the rock composition beneath the glaciers (Isla et al. 2000).

Mesozoic fan turbidites and conglomerates from the Fuegian and South Georgia islands were sampled and compositionally analyzed (Winn and Dott 1978). Quartzose sandstones and volcaniclastic rocks were already reported as dominated by quartz and lithic fragments. Other levels of the Yahgan Formation and Tekenika Beds are composed of lithic fragments with small proportions of total feldspar (calc-alkaline and potassic). Significant shifts in the provenance of Tierra del Fuego

Archipielago have been reported since ca. 39 Myers (Barbeau et al. 2009; Zahid and Barbeau 2013). On the other hand, information from La Meseta Formation (Eocene) from the Marambio (Seymour) Island indicates deltaic to shallow-marine sediments (Marenssi et al. 1998). Their heavy-minerals content is dominated by green-brown hornblende, pyroxenes, garnets, opaques and epidotes, with less proportion of hypersthene, zircon, apatite, kyanite, staurolite, zoisite, sphene and tourmaline. Considering the proportions of quartz and feldspar a QFL triangle indicates a deposition in a convergent active margin. However, along this coastal-marine formation there are variations in the provenance that are suggesting variations in the supply by volcanoes (Marenssi et al. 1998). New analyses of the composition of Tertiary formations compared to modern suites could give light about tectonics or plate interactions.

Modern samples collected from the South American Plate correspond to a volcanic arc, either dissected, undissected and transitional (Fig. 5). These sediments are assumed to be transported by piedmont glaciers from the Darwin Cordillera to the Atlantic coast. The only sample collected along the Atlantic coast of Tierra del Fuego south of the Magellan Fault (Puesto Donata; Fig. 2) belongs to a recycled orogenic, due to a 55% of quartz. The remaining samples correspond to undissected and to a transitional arc.

Samples collected close to the James Ross Island have a high percentage of feldspar and therefore placed in the uplifted basement region. Those samples collected close to the South Shetland Islands are considered from a volcanic arc (Fig. 5).

Many authors attempted to discern the evolution of the “Scotia plates” considering their interactions during the Neogene (Eagles et al. 2005; Loddolo et al. 2006; Eagles and Jokat 2014); some of these plates have been subducted in high proportions during this interval. South America and Antarctic plates have been moving between each other since Jurassic times, splitting from the Gondwana mega continent (Eagles and Jokat 2014). It is estimated that 50% of that Mesozoic plates have disappeared beneath the South Sandwich Islands and the South Orkney microcontinent. During the Cretaceous, the South American Plate subducted beneath the South Orkney microcontinent until a change in the direction of this plate in relation to the Antarctic Plate (Eagles and Jokat 2014).

Quaternary glaciations signified the transport of minerals specimens from some plates to others. In this sense, the Patagonian Batholith of the Darwin Cordillera delivered sediments to the Atlantic and Pacific coasts of Tierra del Fuego. At the Atlantic coast, the provenance signal is smoothed during the Quaternary highstands in embayments with a significant effect of longshore transport (Gordillo e Isla 2011).

On the other hand, high-grade metamorphic and igneous rocks from the Antarctic Peninsula supplied sediments to beaches and coastal areas related to islands located on the “Scotia plates”.

6 Conclusions

1. Quartz, lithic fragments and plagioclase are dominant along the Atlantic coast of the Isla Grande de Tierra del Fuego.
2. Due to their volcanic origin, opaque minerals are dominant at the beaches of the South Shetland Islands; they are less common at the Antarctic Peninsula.
3. To the South of the Scotia Plate, there is an important contribution of metamorphic material supplied from the South Orkney Islands and the Antarctic Peninsula.
4. The presence of volcanic glass is related to volcanic eruptions; the presence of garnets (South of Tierra del Fuego and North of Antarctic Peninsula) is linked to metamorphic rocks.

Acknowledgements Several colleagues contribute to the sampling of beach and marine sands, either during Argentinian and Chilean cruises.

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An Overview on the Mineral Resources of the Argentine Antarctic Sector

Claudio A. Parica and Marcela B. Remesal

Abstract Acknowledge of Antarctic mineral resources is not an easy task, at first, because the hard regulations about any possible interest on mining, oil production. Most of the information has some years or it depends of the observations of researches at the time of any other project about Geology mainly. Anyway, this knowledge means a reservoir of information when the Antarctic Treaty would start a process of discussion. Metallic minerals, Cu Zn and Mo are located at many localities in the South Shetland Islands and Antarctic Peninsula, related to Andean magmatism, also at Wilkes Basin. Ni, Cr and Co, at the northernmost of the Antarctic Peninsula, meanwhile at the south, Au and Ag. Fe at Queen Fabiola Land and some small outcrops at many areas represented with pyrite. Mn nodules in Aurora Basin and Wilkes Land, U in Amery Basin and oil in two basins, Weddell Sea Basin and Ross Sea Basin. Some coal was reported and exploited many years ago, at Mary Bird Land. Rare earth elements are also considered in the Transantarctic Mountains.

Keywords Mineral resources · Antarctica

1 Introduction

We can start with a question, why are scientists interested in Antarctica? Many answers could be expressed. The motives to acquiring knowledge of Antarctic have been included in personal, scientific, economic, strategic, sovereignty, political, and

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some others we can imagine. Such motives have led explorers, scientists and governments to be interested in Antarctica for the study of Earth, and the atmosphere, biological, physical and oceanic sciences.

Since the early nineteenth century, several expeditions reached Antarctica looking for resources, mainly for economic reasons, for example, seals and whales, at the very beginning there are no certain data about where and when sealers and whalers got their resources.

During 1871 at the First International Geographical Congress by Georg von Neumayer, who brought the idea to successive Geographical Congress until, in 1895, the Sixth Congress recorded its opinion "that the exploration of Antarctic Regions is the greatest piece of geographical exploration still to be undertaken…" and recommended scientific societies to urge that scientific exploration be undertaken before the end of the century (Fifield 1987).

When the end of the nineteenth century many expeditions arrived in Antarctica with scientific purposes, expeditions from France, UK, Russia, Belgium, Sweden, Norway started the "official" knowledge of the Antarctic seas and frozen lands. On 1901, the geologist Otto Nordenksjöld on board the Antarctic Norwegian boat arrived in Buenos Aires with the purpose to ask for help to his scientific expedition, in this way the argentine government accepted and asked to join a navy officer, Lieutenant José María Sobral. This navy officer was accepted by Dr. Otto Nordenksjöld—leader of the Swedish expedition—immediately with the purpose to know about Antarctica and the research in these lands. Later, José María Sobral was the first argentine geologist; he studied geology at the University of Uppsala, Sweden.

When it was time to get back the expedition, the Antarctic was sunk in Antarctica trapped by the ice, in this way the argentine President Julio Argentino Roca ordered to send an argentine boat to rescue the expedition. This was successful; all the scientific expedition was rescued on November 8, 1903 arriving to Buenos Aires on December 3rd with all the people safe, scientists and crew on board the Corvette Uruguay (today a museum anchored at Buenos Aires Port).

After the heroic rescue, President Roca decided to buy the buildings at the Orkney Islands made by the Scottish expedition of Dr. William S. Bruce. Since February 22, 1904, Argentine is the largest time country with permanent presence in Antarctica. Meteorology, glaciology, magnetism and seismic, were the main researches carried out since those times.

When talking about resources we must understand the special regime on Antarctica, the Antarctic Treaty signed on December 1, 1959, established conditions about any pretension for different resources included in different protocols of protection the environment, these are the reasons because studies on economic resources are not carried out. Most of the information is old and sometimes very poor, this is the main problem to find information, and nobody agree to publish about this sensitive theme for Antarctica.

2 Argentine and the Sovereignty

The Argentine Republic, member of the Antarctic Treaty System, is claiming the sector between 25º to 74º W and 60º to 90º S (South Pole). Other countries also are claiming territories, like Chile, UK, France, New Zealand, Australia and Norway. Argentina, Chile and UK have an overlap in claims (see Figs. 1 and 2).

After sign the Antarctic Treaty no other countries can ask for any territory, anyway, any country can sign the Antarctic Treaty and perform research programs.

The reader may wonder why economic resources are presented beyond the Argentine Antarctic sector. The answer is simple, although the Antarctic Treaty is in force, it has no effect on eternity, sooner or later the countries will meet to discuss not only issues related to claims of sovereignty but also the exploitation of their resources, therefore it is important to know, to know what can be claimed.

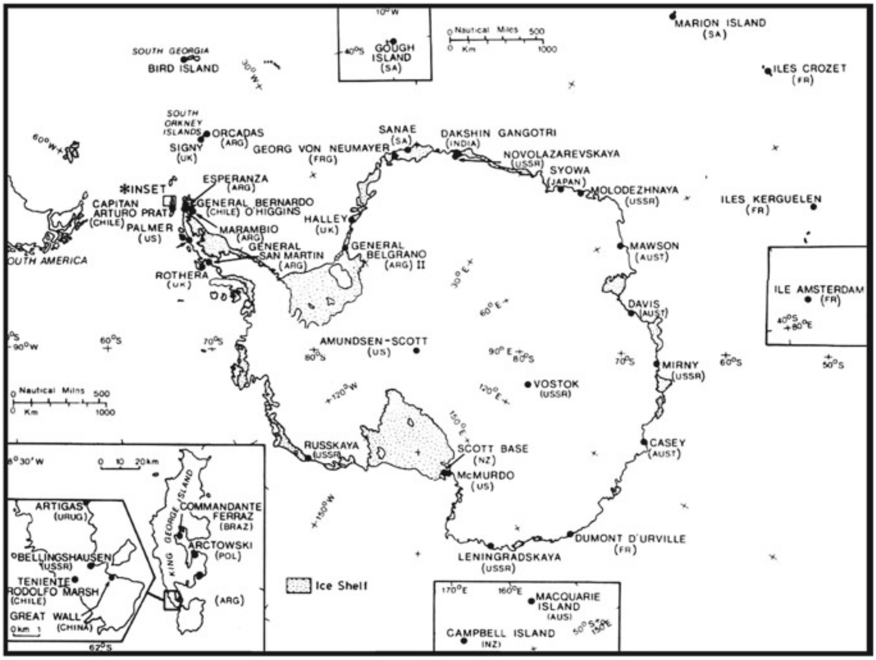

Fig. 1 The Antarctic Continent and distribution of stations

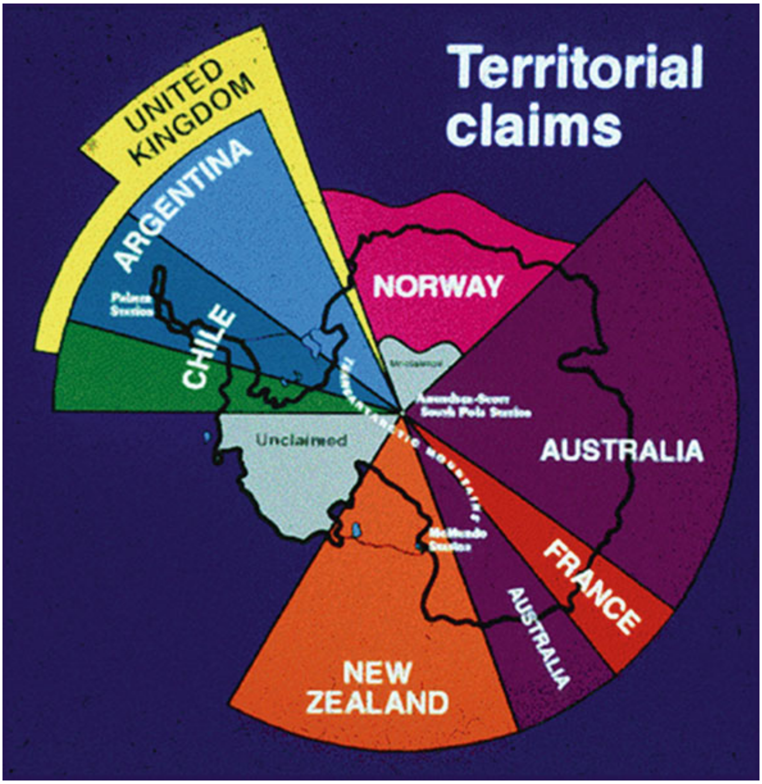

Fig. 2 Antarctic territorial claims

3 Ice as a Water Resource

Most of the times, we can read or hear that Antarctica is the greatest resource of freshwater for the world, in fact, this is true. Ice on land and in the ocean is the single distinctive feature of Antarctica. The Antarctic ice sheet is in part as much as 4.75 km thick and contains some 90% of the world's ice and 70% of the water store of freshwater.

Time to time start plans to move floating icebergs to northern latitudes, in fact this is possible to do, anyway for sailing icebergs is necessary to know how deep the bottom is during the journey and how much these icebergs could be reduced because higher temperatures.

Ice, from many technical points of view, is of course, a mineral. There is no question that freshwater in the form of ice would be welcome in most arid countries. The estimated annual yield of three icebergs in Antarctica is of the order of 1000 km at least (Fig. 3).

The problem would be how to get the resource from where it is to where it could be put to use. The SCAR report Possible Environmental Effects of Mineral

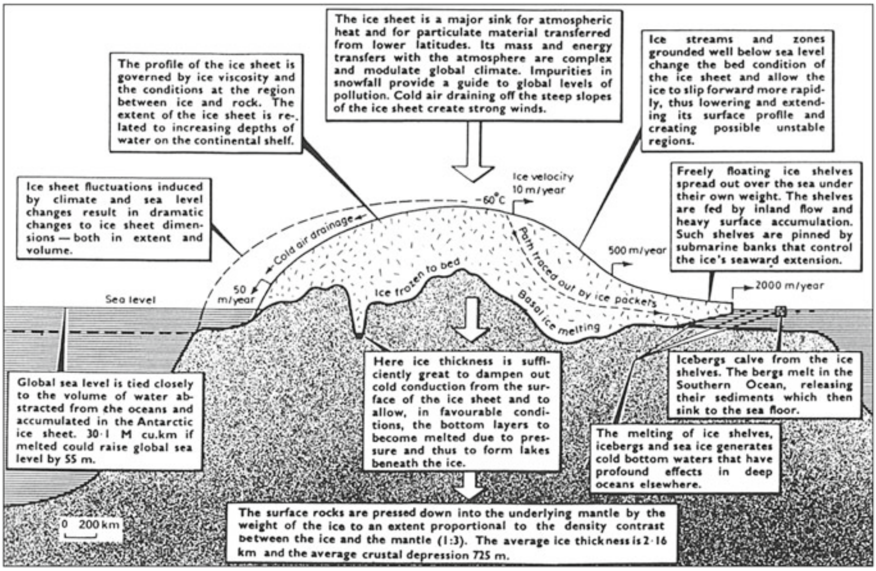

Fig. 3 Continental ice in Antarctica (Fifield 1987)

Exploitation in Antarctica states: The idea of using Antarctic icebergs has been carefully investigated and even tried in a small way. Theoretically, icebergs could be floated to any point accessible by water route with minimum depths of 200 m. All the feasibility studies of the past few years have concluded that the operation of towing the icebergs was not beyond reason though no unprotected iceberg would survive the journey from the Antarctic to low latitudes yet to do so to southern Australia would be not beyond reason.

4 Mineral Resources of Antarctica

Research into the earth sciences in Antarctica is primarily aimed at scientific problems, and this is the main reason why scientists undertake their work often under difficult and sometimes dangerous conditions. However, one by-product of the research is information that must be taken into account when the Antarctic´s potential of resources is considered. For a meaningful appraisal of the continent´s petroleum and mineral potentials, it is vital that information resulting from Antarctic geological and geophysical research be assessed (Fifield 1987).

The development of Antarctica, especially its relationship to the formerly juxtaposed continents, makes it possible to speculate about the likelihood of resources existing there. The location of zones of economic resources on the one adjacent continent can be used in attempting to predict where similar zones might occur

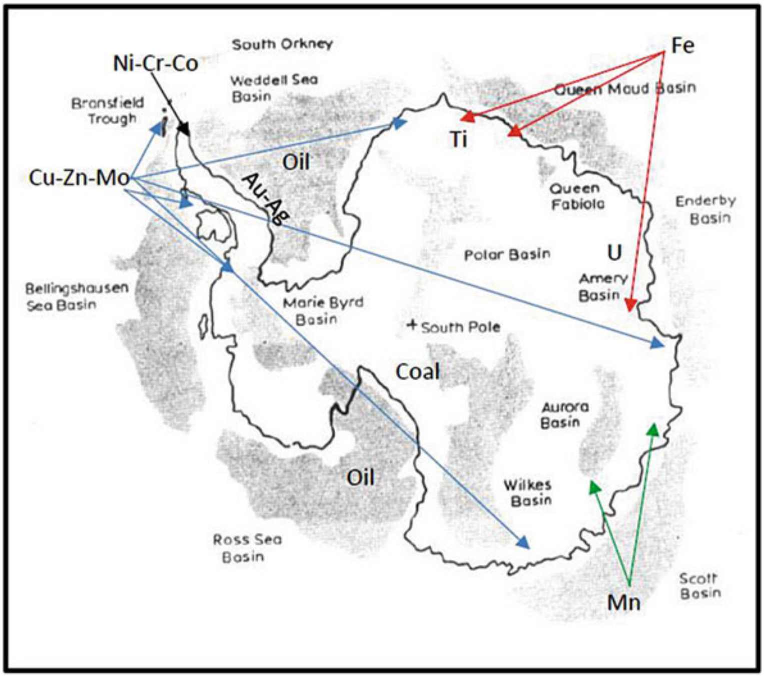

Fig. 4 Oil and mineral resources in Antarctica

in Antarctica; also, the rocks associations and evolution can be a suitable feature to predict possible or probable mineralizations (Fig. 4). Furthermore, the history of breakup of Gondwana will provide information on the geological development of the continental margin during and after breakup of Gondwana, and thus on the potential for mineral and petroleum resources.

During the 70s and early 80s, Argentina carried out a program to analyze potential mining resources at the Antarctic Peninsula and the South Shetland Islands.

When we consider the Antarctic Argentine Sector, this covers territories of East Antarctica and Trans-Antarctic Mountains/Ross System.

5 What Does the Antarctic Treaty Say About Mining?

There has never been any commercial mining in Antarctica thanks to the Antarctic Treaty, which has completely banned mining under the Environmental Protocol. When the original treaty was signed in 1959, mining was not incorporated let alone formally discussed. The mining issue was first raised in 1970 by the UK and New Zealand who had been approached by mineral companies who were interested in exploration in the Southern Ocean.

Between 1982 and 1988 a set of tough environmental protection, measures were set out under the Convention on the Regulation of Antarctic Mineral Resource Activities (CRAMRA). Under the convention, mining could take place if all parties agreed that there was no risk to the environment. The aim of the convention was to have a framework in place in the advance of any future mining. In 1989, France and Australia refused to sign the convention, saying that no mining should be allowed to take place in Antarctica-period. CRAMRA never entered into force but helped to provide the framework for the Environmental Protection Protocol. This entered into force in 1998.

Petroleum occurs in sedimentary rock sequences. On the Antarctic continent, most of the few sedimentary rocks which are exposed are mostly unsuitable with preservation of oil, because deformation and metamorphism. There were recognized some basins, some are sea basins, and some others located mostly in the greater Antarctica. In the seas: Weddell Sea Basin, Bellingshausen Sea Basin, both in the Argentine claimed sector, and some others out, like the Ross Sea Basin, Scott Basin, Enderby Basin, Queen Maud Basin. Located in the continent, Mary Byrd Basin, Polar Basin, Wilkes Basin, Aurora Basin, Amery Basin and Queen Fabiola Basin. All these last basins were recognized as the result of multichannel seismic studies.

Methane hydrates were also searched in the Weddell Sea Basin just during two summer campaigns, but these studies were not continued instead to find serious evidences or its presence.

Sedimentary rocks in the Weddell Sea and Ross Sea Basin maybe reach thickness more than 10 km. Some notorious pack ice in the Antarctic, however, characterizes the former area. Now nobody is thinking about any economic exploitation of these basins, at first because Antarctic Treaty regulations, and if second, not less important the economic matters to start a too difficult enterprise in Antarctica.

6 Some Other Mineral Resources

One of the main problems to know the Antarctic resources is the Antarctic Treaty and SCAR recommendations because of the impact of any exploitation. Another problem is Antarctica by itself, weather, ice, extreme climatic conditions, etc. Because SCAR recommendations, there are no economic information available, nobody wants to publish about resources, especially minerals or oil.

Most of the information reported here about some minerals came from (BAS Web page, Australian Antarctic Institute, Lurgo et al. 1981, Fifield 1987 and filed exploration by the authors during several Antarctic campaigns).

6.1 Coal

Coal of Permian age (about 250 million years old) occurs throughout much of the length of the Transantarctic Mountains. The coal is generally characterized by being thin, lenticular, and discontinuous, with a high content of ash and moisture. The grade is higher where the coal has been backed by later intrusion of dolerite. Much energy would be required to recover any Antarctic coal, which therefore must be viewed at present as an uneconomic resource, from the standpoint of both money and energy. Permian coal of higher (though still low) quality occurs in the Beaver Lake area of the Prince Charles Mountains.

6.2 Iron

Iron deposits occur in Antarctica, and especially in East Antarctica, where traces of banded iron formation are known from Enderby Land through to Wilkes Land, the largest occurrence being in the Prince Charles Mountains in Mac. Robertson Land. Here, at Mount Ruker, banded iron formations up to 70 m thick are interbedded with metamorphosed rock types. Geophysical surveys indicate that the iron formation extends for several tens of kilometers under the nearby ice sheet.

There are also minor occurrences of iron-rich rock in Dronning Maud Land, in the Dufek Intrusion and in the Transantarctic Mountains. The iron content of these formations is, however, not high.

If one bears in mind their remote location and the hazards and expense of exploration, mining and transport it appears that economic exploitation is extremely unlikely.

Ravich et al. (1982) report that in 1956 Soviet Geologists recorded large subrounded boulders of ferruginous quartzites resting on high-grade metamorphic rocks of crystalline basement exposed in the NE Vestfold Hills. In 1966, jaspilites and ferruginous quartzites were found at Mount Ruker (lat. 73º 38′ S, long. 68º 40′ E, out of the Argentine Antarctic sector claimed).

At South Shetland Islands, related to andesitic volcanism (Jurassic to Tertiary) some quartz veins with pyrite associated are present in Admiralty Bay, 25 de Mayo Island (King George Island), Fildes Peninsula, Keller Peninsula. Ferguson (1921) has mapped a large pyrite-quartz replacement deposit in folded Upper Jurassic volcanic rocks (Jurassic Volcanic Group Antarctic Peninsula) on the NE of 25 de Mayo Island on nearby offshore islands. He has reported that the deposit is as much as 30 m wide and 1.5 km long and estimated that it contains many thousands of tons of pyrite. Hawkes (1961) has mapped a quartz diorite pluton, having a diameter of 3 km at least near this locality.

Grykurov and Polyakov (1971) reported close to Bellingshausen Station (Russian station today) at Fildes Peninsula, hydrothermal mineralizations of pyrite, limonite and hematite.

Iron oxides are present at Robert Island in Coppermine Cove, magnetite at Greenwich Island. At Livingston Island, Hurd Peninsula, (Caminos et al. 1973) has disclosed hydrothermally altered rocks (albite, sericite, epidote and prehnite) and quartz and calcite veins containing chalcopyrite, covellite, galena, pyrite, sphalerite, malachite, azurite, hematite and limonite. These deposits are localized along a fault zone of Late Cretaceous or early Tertiary age in folded sedimentary folded rocks of the Miers Bluff Formation, 10 m wide and 1.5 km along the fault zone. del Valle et al. (1974) studied this deposit and identified in addition to the minerals listed above, tetrahedrite, tennantite, chalcocite, bornite, linarite, antlerite, cerussite and witerite (not all of iron minerals of course).

Trinity Peninsula consists of folded sedimentary rocks of the Trinity Peninsula Series intruded by Andean Plutons. Adie (1957, 1964) has reported masses and numerous small veins of pyrite, chalcopyrite and tourmaline in the Trinity Peninsula Series at the contacts of Andean quartz diorite and diorite plutons that are 1–4 km diameter (Adie 1969) in northeastern Trinity Peninsula.

At Alexander Island minor pyrite, hematite, magnetite and cassiterite occur in fractures near Andean Plutons and dikes on the south of the island (Bell 1973).

According to Fleet (1968), spare metallic minerals are an adjacent to Upper Cretaceous granitic Andean plutons along the Oscar II Coast. These plutons intrude folded sedimentary rocks of the Trinity Peninsula Series and folded sedimentary and silicic to intermediate volcanic rocks of late Jurassic age. Fleet (1968) found pyrite and fluorite in a pegmatite dike near a granite pluton about 9 km diameter in the southern Oscar II Coast.

6.3 Copper and Lead

Copper, although only in minor mineralization, has been found during geological studies in the Antarctic Peninsula and links with mineralization in South America have been suggested. There are, however, important differences, including the observation that copper mineralization of the Andes does not continue to the southern Andes. Within the very remote, inland Pensacola Mountains there are exposures of the Dufek Intrusion—a large, layered, basic igneous complex. These exposures are only a small part of the intrusion, however, and airborne magnetic and radio-echo sounding surveys indicate that it extends over an enormous area, maybe as much as 50000 km^2.

Copper deposits, associated to lead were described by Caminos et al (1973) and del Valle et al (1974) at Hurd Peninsula, Livingston Island, with mineralizations of chalcopyrite, bornite and galena, in a disseminated outcrop, 1500 m large and 500 m wide.

Aitkenhead (1975) has mapped at Trinity Peninsula small veins containing Quartz and Green Copper stains.

A fragment from copper bearing vein that contains chalcopyrite, bornite malachite, fluorite, epidote, quartz was observed in scree near Oscar II Coast (Fleet 1968).

Hydrothermal copper vein mineralization, represented by minor scattered disseminations and veins of pyrite, chalcopyrite and pyrrhotite and by low-grade hydrothermal alteration took place in the Lemaire Channel area, northern Graham Coast (Vieira et al. 1982).

6.4 Chromium

This has fuelled speculation on East Antarctica for deposits of metals of the platinum group and chromium. However, the difference in age between the two intrusions casts considerable doubt on such speculation, as do available geochemical data. More research is required before a reasonable assessment can be made. Present indications, however, are not encouraging.

6.5 Zinc

Zinc minerals are associated to copper minerals, one of the areas where this element was found in the South Shetland Islands, all of them in volcanic Tertiary rocks.

6.6 Manganese Nodules

Manganese nodules and encrustations are known from widely scattered locations in the Pacific sector of the southern oceans. Generally, manganese nodules occur far from land, on the deep seafloor. Some reports suggest that the copper, cobalt, and nickel contents of the nodules from the Pacific Ocean are dependent on latitude. Those in equatorial regions contain more associated metals than those in higher latitude.

6.7 Titanium

Some anomalies were described in the Argentine Antarctic Territory at Danco Coast (Lurgo et al. 1981). Also, Filfield (1987) describes small anomalies of titanium at East Antarctica.

6.8 Uranium

Uranium occurs in many geologic settings. Among the more important categories are quartz-pebble conglomerate deposits, deposits related to erosional surfaces in Precambrian rocks, disseminated and contact deposits in igneous and metamorphic rocks, vein deposits, and sandstone deposits of various ages. Again, some insight can be gained by comparing Antarctica with the surrounding Gondwana continents. South Africa contains an abundance of uranium and is a major uranium producer. However, most of the uranium produced in South Africa is a by-product of gold mining, principally from the Precambrian quartz-pebble gold conglomerates of the Witwatersrand region. Australia is also a major uranium producer. In Australia, most of the known uranium resources are contained in deposits spatially related to erosional surfaces in Precambrian rocks. The South African and Australian deposits suggest that uranium might be present in the Precambrian rocks of East Antarctica. Uranium minerals, or anomalous levels of radioactivity, have been found in some locations in Antarctica, particularly in Enderby Land, the Adelie Coast, outside the Argentine Antarctic Territory, meanwhile in the claimed sector just in the Transantarctic Mountains close to the South Pole. No known occurrences of radioactive minerals in Antarctica contain commercial quantities. However, larger deposits might be present in sedimentary basins that existed prior to the break-up of Gondwana (Office of Technology Assessment 1989).

6.9 Rare-Earth Elements

Prospects for Antarctica the rare-earth elements, sometimes called the lanthanides, are a group of 15 chemically similar elements with atomic numbers 57 through 71, inclusive. Although not a lanthanide, yttrium, atomic number 39, is often included with the rare-earth metals because it commonly occurs with them in nature, having similar chemical properties. Some members of the rare-earth group of metals are relatively abundant in the Earth's crust, such as cerium, neodymium, lanthanum, and yttrium, whereas others are considered rare. The rare-earth elements and yttrium are minor constituents in over 100 minerals, but in only a few are they sufficiently concentrated to be considered ore minerals. The two minerals that are the primary sources of rare-earth elements are bastnäsite ($(Ce,La,Y)CO_3F$) and monazite ((Ce, La, Pr, Nd, Th,Y)PO4) of which bastnäsite is the major source. These minerals generally occur in granitic rocks more commonly than in basic rocks, monazite is generally recovered from beach sand deposits as a by-product of other heavy minerals recovery, such as ilmenite, rutile, zircon and gold. Xenotime is a yttrium phosphate mineral found in the same environment as monazite and is a major source of yttrium.

In Antarctica, airborne radiometric surveys have found radioactivity anomalies that have been shown, on-field inspection, to be related to thorium- and uranium-bearing minerals as well as to rare-earth and tin-bearing minerals within sandstone of the basal (Devonian) parts of the Beacon Supergroup in the Transantarctic Mountains (see description in Parica 1999). Some descriptions at East Antarctica outcrops containing zirconium and the rare-earth elements, lanthanum and cerium can be found (Office of Technology Assessment 1989).

7 Final Considerations

Although metallic minerals are widespread in Antarctica, nearly all occur as isolated outcrops, crystals or small masses, and, as far as preliminary reports reveal, they have no economic significance at present times. Regulations around the Antarctic Treaty define a frame for the development of economic research of minerals, which introduce hard restrictions to any exploitation. As a single proposal, it should be of interest to deepen the subject of these resources, in the future, close or far, several matters of the Antarctic Treaty will be discussed, and it is important the knowledge the what and where. In fact, this chapter seems a historic compilation because of the hard regulations to economic research in Antarctica.

About ice, this is the other important resource considered to solve many problems in different areas of the world with insufficient water for life but now persists the logistic problem to move blocks of ice without significant losses to destination.

For the Antarctic Peninsula and islands related, we can consider that all the mineralizations are associated with subduction generated Andean plutonism, or perhaps with post subduction rifting. Anyway, most of the cited localities need closer investigation.

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Meteorites Found in the Argentine Antarctic Sector

Víctor Manuel García

Abstract This catalogue offers a list of basic data of meteorites finding in the Argentine Antarctic Sector extracted from the Database of Meteoritical Bulletin. References for all meteorites reported up to October 22, 2019 are included. The sites where the meteorites recorded here were found are: La Paz Icefield, Pecora Escarpment and Patuxent Range.

Keywords Meteorites · La Paz Icefield · Pecora Escarpment · Patuxent Range

1 Synthesis

In Fig. 1, is observable the locations of three sites of meteorite finds in the Argentine Antarctic Sector. In La Paz Icefield, 1,675 meteorites have been found and classified as of December 16, 2019. Also, 633 recorded in Pecora Escarpment and 184 in Patuxent Range. Two thousand, four hundred and ninety-two findings have been cataloged in total.

Because of space reasons, I must limit this inventory in a synthetic way and the rest can be consulted in the following link:

https://drive.google.com/drive/folders/1XJ78XSsCV-u-3PbH6yG76U0SUjy19_nN

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Fig. 1 Locations of meteorite finds in the Argentine Antarctic Sector

Acidity and Alkalinity as Foundational Parameters in the Ordering of Eruptive Rocks and Some Fuegian Examples

Rogelio Daniel Acevedo

Abstract It is feasible to obtain a comprehensive ordering of eruptive rocks based on two fundamental criteria: acidity and alkalinity. These concepts are eminently chemical, but it must be kept in mind that the chemistry of the main elements can be deduced starting from the mineralogical proportions refining the study of each rock forming mineral. Both of Johannsen and Streckeisen classifications, and IUGS or International Union of Geological Sciences recommendations also, are quantitative-mineralogical, which provide a strict nomenclatural reference but demonstrate difficulty in establishing the proportions of minerals. This natural difficulty, extreme in vulcanites, is not present in chemicals and normative classifications, but in this last case the rock loses its true petrographic spirit, established by the real minerals, after which the crystallization history and the rock understanding are. This preference for mineralogical classifications does not invalidate the importance of other based on chemical compositions. This simple chart contains eleven boxes from the combination of four columns (UB or ultrabasic, B or basic, M or mesosilicic, and A or acid) with three groups (I or calc-alkaline, II or subalkaline, and III or alkaline). All eruptive rocks fit there. AIII field doesn't exist due to foids are incompatible with quartz. At last, an addendum about potassic and sodic trends as alkali elements in common minerals is included. The conclusion is that the difference between sodic albite and the rest of plagioclases is as important as the difference between sodic albite and potassic feldspar. Mineralogical changes of great petrogenetic significance only could represent subtle chemical changes and don't reflect variances in the classificatory charts.

Keywords Eruptive rocks · Acidity · Alkalinity

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1 Introduction

The classifications in referential tables of the eruptive rocks are varied from the chemical point of view, but especially mineralogical. Professor Bernabé J. Quartino, taught us, his students, since his memorable cathedra of Petrography, at the Facultad de Ciencias Exactas of the Buenos Aires University, that the old but unfairly forgotten system of Professor Albert Johannsen (1931, 1932, 1937, 1938) was the finest effort toward quantitative mineralogical categorization of rocks in classes, orders, and families. Synthetically, the system adopted a simple tetrahedron with vertices of ferromagnesian minerals in the case of ultramafic rocks. In the other three classes the complex, and at the same time a clear system, is represented by a double tetrahedron that relies on four minerals only, which can be considered key or main minerals for classification, and these are plagioclase, K-feldspar, quartz, and feldspathoids. With the clarification that the double tetrahedron allows the plagioclase to be subdivided into the different orders by the relative content of anortite and albite, which once again highlights the concepts of Professor Karl Heinrich Ferdinand Rosenbusch in this regard (1896, 1907, 1908), giving rise to the distinction of the differential character of the so-called Order 1 (albite), which characterizes the rocks with an alkalinity tendency, without the need to resort to the name of alkaline feldspar of Streckeisen, which unites without distinction the potassium feldspar and the sodic albite, minerals of different petrological role. It is true that sodic albite differs from plagioclase in its most anorthite terms, but it is also true that potassium feldspar diverges from sodic albite until they are mutually exclusive, being the case of the presence of sodium and potassium in true alkali feldspars of high temperature or volcanogenic and to a lesser extent in orthoclase and microcline not exsolved. It is not the case of repeating the contents of the system here, but it is only worth highlighting some values, since Johannsen's work is known not only for its orderly content but for the precise lithological description (for which it is worthy of the concept of treaty fundamental) which quantitatively follows the classic Rosenbusch guidelines.

According to the above, the known incompatibility between minerals is present, such as quartz and feldspathoids, which are never seen together, as with certain people.

The symmetric nature of the subdivision in the families of the rocks with quartz is not a deficiency, as the modification of the Johannsen System seems to suggest by the point made by Professor Albert L. Streckeisen (1973), and recommended by the IUGS (1989), which takes the granite–granodiorite limit to 35–65% plagioclase content. Precisely Johannsen's symmetric division makes independent the nomenclatural picture of geological appreciations such as frequency, establishing a petrographic system in itself. The case of the distinction between granodiorite and granite is characteristic. Even in the field it is possible to discern whether plagioclase or K-feldspar is more abundant to decide the preliminary nomenclature. According to Streckeisen's values, this is more difficult. It is a point of view.

From the list of Johannsen, mineral classes arise for the nomenclatural and appreciative meaning; main minerals for classification consisting of those located at the vertices of the triangles of the graphic system; main minerals but not for nomenclature in families, such as biotite, amphibole, and pyroxene in non-ultramafic classes; and accessory minerals such as zircon, ilmenite, apatite, magnetite, and others.

There may be rocks characterized by minerals from the second group, such as the case of amphibole in granodiorite in contrast to the most common granites, or the presence of orthopyroxene for rocks with charnockitic character, or the abundance of muscovite in certain granites, or the content of amphibole and sodic pyroxenes, among many cases.

Both the Johannsen System and the Streckeisen System are quantitative-mineralogical, which although establishes a strict nomenclatural reference at the same time highlights the difficulty in establishing mineral proportions. This natural difficulty (extreme in very fine grained rocks and in many vulcanites) does not occur in what could arise from purely chemical or regulatory classifications, but in the latter case the rock loses its true petrographic essence established by the actual minerals present, after which is the history of crystallization and consequently the understanding of the rock.

This preference for mineralogical classifications does not invalidate the importance of those based on chemical composition and even less affects the valorization of pure chemistry. Moreover, this one, historically prior to the microstructural mineralogical approach, has given to petrography, and its transition to the petrological or genetic, a skillful basis for lithological interrelation, that is, for comparison by tabulation of chemical determinations, more difficult to achieve with mineral proportions. The concepts of alkalinity and acidity/basicity, so fundamental, are of chemical origin. But it should be remembered that the chemistry of the main elements can be deduced, although not very precisely, from the mineralogical proportions refining the study of each rock mineral. This applies as much as the inverse procedure consisting of deducing the theoretical mineralogical composition on the basis of chemical analysis, as is the case of the widely used CIPW norms. This results in the importance of the double chemical *versus* mineralogical contest in all consideration of rocks. It should also be noted that chemistry, and in this the petrological literature is generous, is especially applied in the characterization of magmas. Thus, chemistry does not focus only on petrology, but wide geology in its search for the clarification of the great unknowns of the planet, without thereby detaching itself from the mineralogical reality. It should also be noted that the development of instrumental analytical chemistry, with the ease it entails, has led to an excess in common uses to the detriment of the essential mineralogical and structural principal work, despite the fact that microscopic chemical-instrumental determinations contribute to the best knowledge of minerals, especially small ones, of rocks.

It should be remembered that the chemistry of rocks is part of the field of geochemistry which is broader than that of petrology in the natural world, although petrology, as part of geology, exhibits as its own the study of structures in varied scales. For authors like Professor Kalervo Rankama (1950), petrology is part of geochemistry, while it is valid that metamorphic and effusive rocks geochemistry are an approach as part of petrology.

Anyway, it is worth insisting, both disciplines are concurrent. In the case of the study of volcanic rocks of very fine grain, there is no doubt that this is so. In addition to the above, the work of Professor Samuel James Shand (1922) stands out emphatically for the petrological concepts that can accompany any merely descriptive task or even classifying.

2 A Simple Framework of Eruptive Rocks

Having presented the above as a starter to the main course, our master shared with us, his students, a table of eruptive rocks prepared by him and based on two fundamental lines: the degree of alkalinity and the degree of acidity/basicity or, in the same way, of differentiation. These are considered to be the two essential slopes in the characterization of eruptive rocks and their relationships. This according to the information arising from the mineralogical composition; in a word the chemical valuation is adopted through mineralogy, understanding of course the chemistry of the main elements and composition.

This is a simplified and qualitative appreciative and didactic chart. For this reason, it is called a sorting or ordering chart and not a classification chart, which can also be used as a basis for other tables or tabulations exhibiting refinement or detail.

The ordering chart is shown in Table 1. There are eleven cells that can include all types of rocks in an arrangement and coordination between them.

The letters U, B, M, and A that designate the four columns mean the simple presentation, respectively, of the terms ultrabasic, basic, mesosilicic, and acid, according to the classical division, in this appreciative case, adopted by petrography or elementary petrology according to the silica content of the rocks and other accompanying characteristics. The fact that the table uses this deduced chemical assessment does not invalidate the mineralogical characteristic of the system, since according to the minerals present and their approximate proportion, the character U, B, M, or A will be deductible, which is a measure of differentiation. Without prejudice that the direction can be adjusted from left to right by means of the simple file of chemically determining the percentage of silica.

Therefore, U are ultrabasic rocks (ultra-ferromagnesic or not); B are basic rocks (represented by normal basalt and gabbro); M are intermediate rocks (whose

Table 1 Where U–B–M–A represent magmatic differentiation, acidity/basicity, and I–II–III express the degree of alkalinity

	U	B	M	A
I	UI	BI	MI	AI
II	UII	BII	MII	AII
III	UIII	BIII	MIII	–

paradigms are andesite and diorite and in potassium terms syenite and trachyte); A are acidic rocks (strict examples are rhyolite and granite).

With respect to the denomination of the horizontal rows, the Roman numerals I, II, and III have been adopted, which successively imply calc-alkalinity, subalkalinity, and alkalinity.

In summary, I are "normal" rocks that do not have the distinctive characters of both sides II and III. They are called calc-alkaline rocks; II are subalkaline rocks (or if you want rocks with alkalinity elements without the presence of feldspathoids, particularly absence of nepheline); III are alkaline rocks (rocks essentially with feldspathoids, notably nepheline and secondary leucite).

It is understood that the AIII cell does not exist in normal processes due to the chemical incompatibility between quartz and feldspathoids, or rather, the non-formation of quartz in a liquid consistent with the crystallization of feldspathoids, or vice versa.

But how to enter the sequences U–B–M–A and I–II–III?

Well, from left to right you can see the following, in the main:

(1) Increase the possibility and quantity of quartz. Maximum in A, absent in U, rare in B.
(2) Consistent increase in the proportion of SiO_2.
(3) Decrease in the percentage of ferromagnesic minerals (decrease in color index).
(4) Density decrease.
(5) Evolution of the discontinuous olivine-pyroxene-amphibole-biotite series.
(6) Reduction of the possibility of presence of olivine.
(7) Evolution of the continuous series anorthite-albite. That is, a decrease in the percentage of Ca and Na increase. When plagioclase is absent or is albite, group II is entered.
(8) Increase in the possible content of hydroxylated minerals (biotite with exceptions in group II, amphibole, muscovite, and late-magmatic minerals).
(9) Possible increase in ferric-ferrous ratio.

As can be seen, most of the characters are observable or deductible microscopically or even magnifying glass, to be able to move in the sequence. In plutonic rocks, this responds to the known and elementary sequence of normal major rocks of group I: ultrabasic rock–gabbro–diorite–tonalite–granodiorite–granite or syenite. Syenite escapes linear succession by approaching characters of potassic subalkalinity.

In volcanic rocks, the sequence is ultrabasic vulcanite–basalt–andesite–dacite–rhyodacite–rhyolite or trachyte.

Sequence II and III (horizontal rows).

The entries in the horizontal rows are made as follows:

Group I: (in general chalcoalkaline rocks)

(1) Those rocks that do not show characters that allow placement in groups II and III.

Group II: (subalkaline rocks)

(1) The existing plagioclase is albite.
(2) Plagioclase is absent in differentiated rocks, for example, in syenites.
(3) Presence of biotite in basic or ultrabasic rocks.
(4) Presence of potassium feldspar in basic or ultrabasic rocks (e.g., trachybasalt).
(5) Presence of analcime and more rarely other feldspathoids with volatiles.
(6) Pyroxenes and amphiboles with subalkaline tendency, with titanium.
(7) Pyroxenes and subalkaline amphiboles with sodium, titanium, or ferric iron.
(8) Deductible high ferric-ferrous relationship.
(9) Leucite in minimum proportion.
(10) Characterization of peralcalinity.

Group III: (alkaline rocks)

(1) Occurrence of feldspathoids (alkaline rocks *stricto* sensu). Also, nepheline or clear appearance of leucite (approximately greater than 5 percent) could be present. It is understood that in group III rocks the characters of group II can be additively shown.

It is noted that in group II nepheline is not considered to define subalkalinity, and in turn in group III feldspathoids with volatile are not considered mainly the analcime to define alkalinity, nor very low presence of leucite.

Nepheline is the critical mineral of alkalinity and silica subsaturation because it is less siliceous than leucite and it is also respect to analcime. The latter also loses its near-magmatic significance due to its water content that presumes a possible particular enrichment of this mineral. It should also be remembered that the leucite is a high temperature pair of the K-feldspar with an incongruous melting point, so it may be present when the somewhat supersaturated rock composition indicates otherwise, which will be seen later when referring to the phase balancing systems.

The descending order of such subalcalinity/alkalinity indicator minerals is as follows: nepheline–leucite–analcime.

As already indicated, the cells are rock clusters, that is, without quantification, which is why the cells are the same size. This responds to an unquestionable truth, since *Natura non facit saltum*, particularly when nomenclature is applied. It will be possible to locate rocks estimately higher or lower (depending on the degree of alkalinity or subalkalinity) or more to the left or right as an appreciation of the degree of basicity/acidity.

Such is the case of the olivine basalt located on the left and below the tholeiitic basalt. The trachybasalt will be below the latter, as well as the labradorite andesite on its right.

The sorting chart allows to make lines of variation, as an indirect indication of magmatic evolution (Table 2).

A rhyolitic gait (1) from tholeiitic basalt (basalt–andesite–dacite–rhyolite) and a phonolitic gait (2) from basalt–olivine (olivine basalt–trachybasalt–trachyandesite, phonolite) appear here.

Table 2 The chart shows the classic evolutionary sequences from, respectively, tholeiitic and olivine basalt are shown in the scheme

	U	B	M	A
I		↗ → →→ → →	→ → 1→ → →	→ → →
II		↘ → →→ → →	→2 → →↘	
III			↘	

It can be seen that the initial difference is small but that the marches differ markedly and that the determining factor is that initial difference (more alkaline and olivine basalt more alkaline). It is noted how curve 2 descends in succession I-II which does not happen with curve 1, which passes through andesite (MI). Rows II and III, and this is especially true for II, are, so to speak, "genetic" lines where "gens" such as albite and titanium in pyroxenes and amphiboles are characteristic throughout the differential evolution. The case of granite (AI) and its neighbors exemplifies this particular or "genetic" characterization or imprint. Thus a common AI granite, with its so common oligoclase, will be easier to be associated with AI granodiorite and somewhat further with tonalite or diorite already in column M, which, instead, is associated with subalkaline granite (AII) because the albite is indicating the presence of a characteristic of row II, to a certain extent incompatible with row I. In one word, it is consanguinity and the AI cell is consanguineous with AI further to the left and even with MI and something less close with MI potassium, that is, the common syenite. The granite AII will be more related to the syenite MII.

Examples of some cells and their neighborhoods and the location of rocks:

(a) BI cell (basalt and its next area).

The common or tholeiitic basalt is taken as the center of the location. This is appreciative or conventional. In the neighborhoods appear olivine basalt, troctolytic basalt, trachybasalt, leucobasalt, spilite, analcime basalt, labradorite andesite, tefrite, and basanite. Some location examples can be seen (Fig. 1).

(b) Cell BI and its neighborhoods (gabbro and its neighbors) (Fig. 2).

Starting from the normal rock type gabbro, it is found in the neighborhoods troctolite, olivine gabbro, leucogabbro, meladiorite, teschenite, theralite, and diorite.

(c) Cell UIII and column U (Fig. 3).

This sector of the eruptive rock table has the interest of containing ultramafic rocks with feldspathoids and leucocratic foids-bearing rocks lacking feldspar or being the same in low proportion.

In other words, ultrabasicity (column U) is reached in two ways. One the concentration of ferromagnesic minerals, and another way the ultrabasicity by alkalinity accentuated with abundance of feldspathoids. In the first way, the common peridotites or perknites (IU), subalkaline rocks, for example, kimberlite (UII) or foids-bearing ultramafic rock (UIII) are reached. The concentration of the "dark" minerals

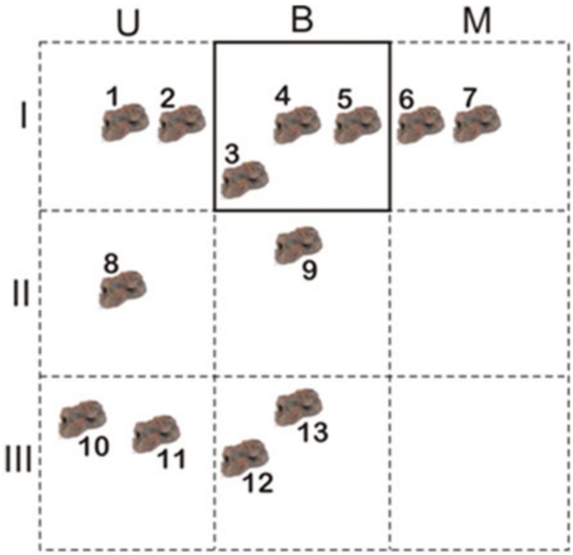

Fig. 1 1 picrite, ankaramite; 2 troctolitic basalt; 3 olivine basalt; 4 basalt or tholeiitic basalt; 5 leucobasalt; 6 labradorite andesite; 7 andesite; 8 limburgite; 9 trachybasalt, spilite, analcime basalt; 10 katungite; 11 ugandite; 12 basanite; 13 tefrite

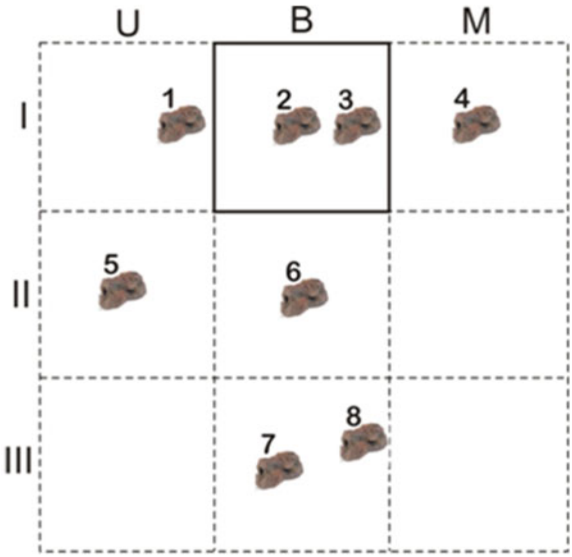

Fig. 2 1 troctolite; 2 normal gabbro, norite; 3 meladiorite, leucogabbro; 4 diorite; 5 kimberlite, biotitic pyroxenite; 6 analcime gabbro (teschenite); 7 nepheline gabbro (theralite); 8 foid syenite (shonkinite)

may have been mechanical, for example, by gravitational concentration of basaltic liquids. As a result, the ultramafic UIII enclosure escapes strict chemical–magmatic consideration. The same does not happen with the feldspathoids-bearing ultramafic rocks of UIII.

(d) Cell MIII (phonolithic field) (Fig. 4).
(e) Cell AI and surroundings (Fig. 5).

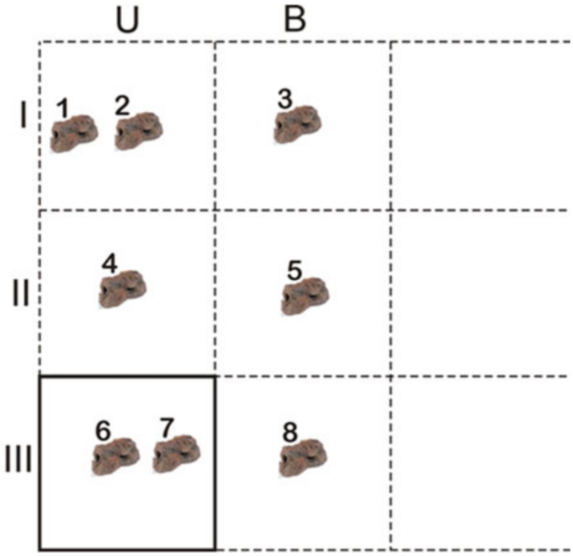

Fig. 3 1 dunite; 2 perknite; 3 gabbro; 4 kimberlite; 5 analcime gabbro (teschenite); 6 foids-bearing ultramafic rock; 7 foidite; 8 essexite-theralite

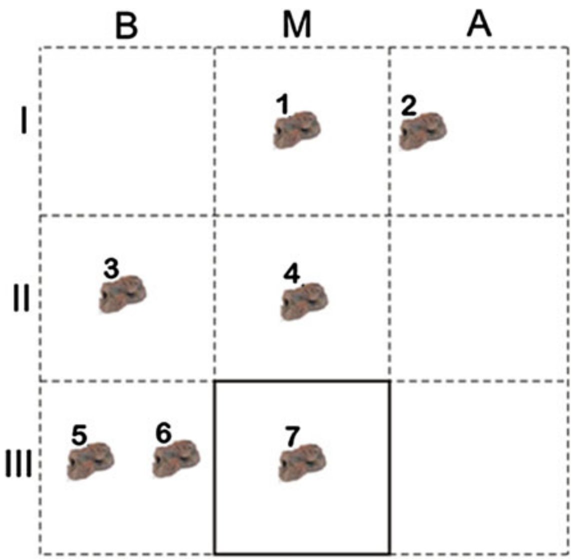

Fig. 4 1 trachite; 2 quartz-bearing trachite; 3 trachibasalt, spilite, analcime-bearing basalt; 4 subalcaline trachite-quartz albitophire; 5 basanite; 6 tefrite; 7 fonolite-tinguaite

Finally, the table shows a generalized distribution of the location of common rocks in a simplified chart of eruptive rock management (Fig. 6).

With respect to pegmatites, they are practically placed in column A if an evolution or differentiation leading to the pegmatitic state can be accepted which can be referred to, for example, in the case of granitic pegmatites, attenuated granitic magma state,

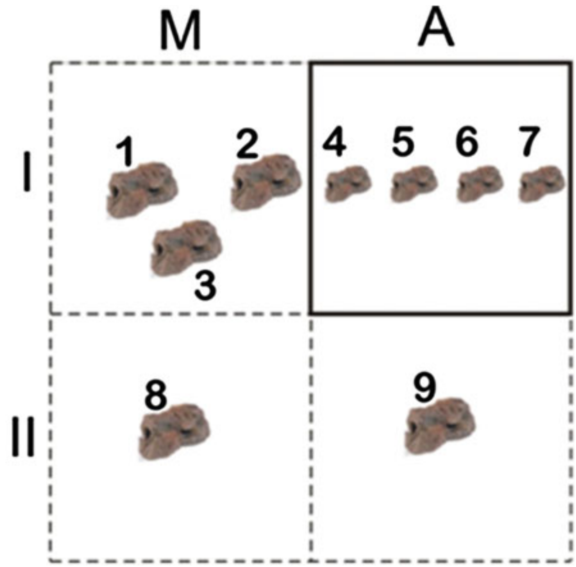

Fig. 5 1 diorite; 2 tonalite; 3 calk-alkali syenite; 4 granodiorite; 5 oligoclase-bearing granite; 6 quartz-rich granitoid; 7 silexite or quartzolite; 8 subalkaline syenite; 9 alkali-granite (Note: In boxes UII-UIII carbonatite must be located)

	U	B	M	A
I	Peridotite Perknite *Picrite* *Ankaramite*	Troctolite Olivine-bearing Gabbro Gabbro Anortosite *Troctolitic Basalt* *Olivine-bearing Basalt* *Basalt*	Diorite Calc-alkali Syenite *Andesite* *Trachyte*	Granodiorite Tonalite Granite Quartzolite *Dacite* *Rhyodacite* *Rhyolite*
II	Subalkali ultramafic rocks *Kimberlite* *Subalkali ultramafic Vulcanite*	Teschenite *Analcime-bearing Basalt* *Spilite* *Trachybasalt*	Subalkali Syenite *Subalkali Trachyte* *Albitophyre* *Queratophyre*	Albite-bearing Tonalite Subalkali Granite *Subalkali acidic Vulcanite* *Albitophyre and quartziferous Queratophyres*
III	Foidite Alkali ultramafic rocks Carbonatite *Nefelinite* *Leucitite*	Theralite Essexite *Basanite* *Tefrite*	Alkali Syenite Shonkinite *Phonolite* *Tinguaite*	X

Fig. 6 Generalized distribution in a simplified chart of the location of common eruptive rocks

	U	B	M	A
I	Ultramafic and mafic plutonic bodies of Estancia Túnel and Ushuaia peninsula		Andean Diorites	Erratic boulders of Punta Sinaí *Porphyritic Serie (Lemaire Fm)*
II	*Ushuaia Camptonite*	*Leucobasalts of Alvear and Sorondo ranges (spilites)*		
III				X

Fig. 7 Position of some Fuegian eruptive rocks in the U–B–M–A vs I–II–III sequences

for abundance of water. In the case of more basic rocks, the thick pegmatoid mineral aggregation will not reach column A.

With regard to the lamprophyres is possible to appreciate that they are rocks that carry in themselves their history of magmatic enigma, or are a special group within the set of eruptive rocks. Only the homologous characterization with that used in the table should be noted.

So vogesita is MIBI; kersantite, MBI, and spessartita, MB; odinite, BI; camptonite, UII. The sodium variety of vogesite is already MBII.

As a final point, examples of the igneous rocks previously mentioned can be found in Tierra del Fuego and some of them have been located in the acidity vs alkalinity chart of the Fig. 7.

3 Addendum About the Potassic and Sodic Trends as Alkaline Elements in Common Minerals

The topic has been widely investigated particularly in regard to feldspars. But a reference is of interest since in column M the duality of the syenite is presented on the one hand and the diorite on the other, that is, the concretion of the potassium line in the first case, and of the sodium line in the second.

Already at this level then sodium appears on the one hand and potassium on the other on account of the respective elements location in the minerals.

Summarizing, in terms of feldspars, K is placed on sanidine, orthoclase, and microcline, while Na is located in the plagioclase in tandem with Ca, in significant quantity from the middle plagioclase to the albite, and in the anorthoclase.

This scheme is not strict because it is well known that feldspars called potassic contain Na in solid solution.

The hydatogenic tendency, typical of certain minerals, to sodium and potassium cations can be tested, resulting at first impression that sodium is more hydatogenic than potassium, which is exemplified by nepheline and analcime on the one hand and leucite and sanidine for another. In common ferromagnesian minerals, sodium or potassium selectivity is also recorded, as well as potassium in biotite and sodium in amphibole and subalkaline clinopyroxenes.

Two contrasting situations. It should be noted that they refer, respectively, to the mineralogical structural disorder in rhyolites and the order reached in granitic and syenite rocks. A unique situation is usually found in rhyolites or trachytes when sodium and potassium become involved in several feldspathic phenocrysts that differ from each other. Such is the case of albite sometimes with minimal antiperthites, sanidine, or orthoclase, eventually very fine microperthitic, anorthoclase, and *sui generis* alkaline feldspar, the latter difficult to interpret, with albitic microexsolution, microperthitic albitic replacements, pressure twins, and very fine and imperfect twinning on a chessboard whereby the qualification of very particular alkaline feldspar is justified. An incomplete disorder system is noticed where potassium and sodium in feldspars have played reciprocally during a time when deformation has been added, perhaps the latter by contractive cooling. The opposite case is presented in plutonites, with interest for the relations between sodium and potassium feldspar and is manifested in mineral rims, perthitization, replacements, and myrmekitization that signify the posthumous phenomena of the crystallization of plutons, referred to feldspars. The common albitic rim in plagioclase indicates the late or final activity of sodic feldspar, as do the replacement disturbances in this case, more importantly since albite replaces potassic feldspar. As for antiperthites, less frequent than replacement perthites, they indicate the phenomenon of potassium activity in the late-magmatic advanced stage. The exsolutive perthites, favored by deformation, already in the post-magmatic stage, separate the two alkali feldspars reaching the highest mineralogical structural order and achieve the maximum point of differentiation with the sodium-potassium or potassium-sodium alkali feldspars of vulcanites.

A special case in the field of sodium feldspar versus potassium feldspar is that of the myrmekites. The most typical are those after the microcline, since they replace it by strengthening the idea of the greater sodium activity in the final crystallization of syenite or granitic series. Other myrmekites have been studied and described as pre-microcline, inversely to the previous ones, always within the feldspathic balance Na-K.

A conclusion that is added about all these aspects is that the difference between sodium albite and the rest of the plagioclase is as important as the difference between sodium albite and potassium feldspar and hence the interest of this being reflected in the classification tables as in Johannsen's system.

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Correction to: Geotourism—Interpretation—Ethnogeology: Extraordinary Geological Resources in Tierra del Fuego

Gabriel Chicote

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