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ORIGINAL ARTICLE

The Rich Palaeontological Heritage of SW Sardinia (Italy), a Possible Resource for a Geotourism Development

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Abstract
This paper overviews the rich and various palaeontological heritage of SW Sardinia (Italy). The most relevant fossiliferous localities were identified through accurate bibliographic research and evaluated based on their scientific and historical relevance and/or by means of field surveys. A hundred localities were selected and grouped into six areas where geotourism routes based on palaeontological heritage can be designed. Since the 1800s, Sardinia has been involved in scientific studies dedicated to the knowledge of its geology and palaeontology. One of the most studied areas is the Sulcis-Iglesiente, a territory with a long mining history. The revaluation of the former Serbariu coal mine of Carbonia as geo-palaeontological museum ("Sulcitan Palaeo-environment Museum—Edouard Alfred Martel") contributes to the promotion of the local geoheritage, and it is now considered one of the most important scientific museums of Sardinia. Finally, a series of geo-palaeontological routes starting from this museum are herein proposed to enhance cultural tourism and the socioeconomic growth in this territory.

Keywords Palaeontology · Geotourism · Museology · Sulcis-Iglesiente

Introduction

Sardinia is an Italian island located in the centre of the western Mediterranean Sea (Fig. 1). This region has enormous natural and environmental resources, but unfortunately, it is one of the most economically disadvantaged Italian regions. In fact, the progressive closure of factories and mines led to impoverishment and depopulation of several areas of the island, and the Sulcis-Iglesiente sub-region (SW Sardinia) is currently considered one of the poorest in Italy. However, its disadvantaged socioeconomic status is contrasted by a rich natural and geological heritage. This area has been exploited for a long time for its very rich mineral resources (e.g. lead, zinc, silver galena, coal). Indeed, local people have exploited these resources since prehistoric times. Following the economic sanctions against Italy during the fascist regime, the rich coal deposits of Sulcis were intensively exploited in the first part of the twentieth century, allowing the foundation of Carbonia, one of the largest inhabited centres in Sardinia. The end of the fascist regime autarky policy caused the gradual closure of coal mines which were replaced with the modern metallurgical industry in the following decades (Rollandi 1981). In recent years, also this sector was affected by the economic crisis leading to the closure of many factories (e.g. aluminium industry). On the other hand, the nature of the territory offers the concrete possibility of further cultural and natural tourism development (e.g. mining culture and industrial archaeology) (Fig. 2). The growing interest in these issues led to the establishment of the Historical and Environmental Geomining Park of Sardinia (Parco Geominerario Storico e Ambientale della Sardegna).

The most ancient rocks of the Italian territory emerge in the Sulcis-Iglesiente area, showing a very long geological history. Indeed, all geological periods of the Phanerozoic Eon are represented, from the lower Cambrian to the Holocene. This unique geodiversity is also related to a very rich palaeontological heritage, known since the beginning of the geological researches in Sardinia. In fact, numerous illustrious scientists have dedicated part of their lives to the study of the geology and palaeontology of this island. In particular, geologists and palaeontologists worked in the Sulcis-Iglesiente area and published papers on Palaeozoic or Cenozoic faunas and describing new taxa of great scientific

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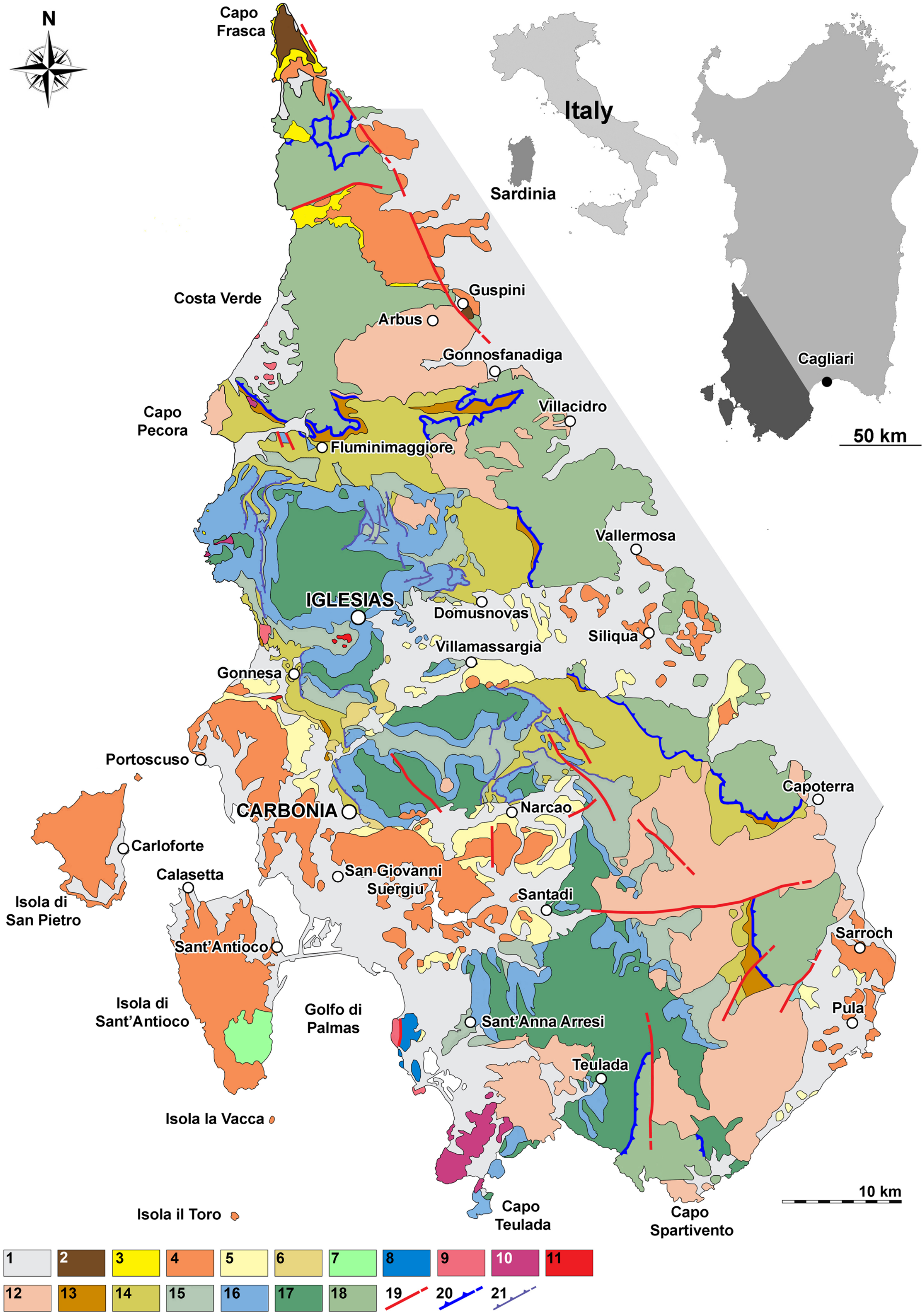
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Fluminimaggiore
Vallermosa
IGLESIAS
Domusnovas
Siliqua
Villamassargia
Gonnesa
Portoscuso
Capoterra
CARBONIA
Narcao
Carloforte
Calasetta
San Giovanni Suergiu
Santadi
Isola di San Pietro
Sant'Antioco
Sarroch
Isola di Sant'Antioco
Golfo di Palmas
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◂**Fig. 1** Location of Sardinia and simplified geological map of SW Sardinia, modified after Pillola et al. (1995), Carmignani et al. (2001), and Pavanetto et al. (2012). **1** Quaternary sedimentary covers (alluvial, colluvial, and aeolian deposits); **2** Pliocene–Quaternary volcanites; **3** Lower Miocene marine deposits; **4** Oligocene–Miocene volcanites; **5** middle Eocene–Oligocene continental deposits (Cixerri Fm.); **6** lower Eocene marine, transitional, and continental succession (Miliolitico and Lignitifero Fms.); **7** Cretaceous marine deposits; **8** Jurassic marine deposits; **9** Triassic marine and continental deposits; **10** Late Pennsylvanian–?Lower Triassic volcanites; **11** Middle Pennsylvanian (Moscovian)–lower Permian (Asselian) continental deposits (Rio San Giorgio and Guardia Pisano Fms.); **12** Carboniferous–Permian plutonic complex; **13** parautochthonous Silurian–Lower Devonian marine succession (Genna Muxerru, Fluminimaggiore, and Mason Porcus Fms.); **14** parautochthonous Upper Ordovician marine succession (M. Argentu, M. Orri, Portixeddu, Domusnovas, and Rio San Marco Fms.); **15** parautochthonous Cambrian (stage 4)–Lower Ordovician (?Floian) marine succession (Campo Pisano and Cabitza Fms.); **16** parautochthonous Lower Cambrian (stage 4) marine carbonatic succession (Santa Barbara and San Giovanni Fms.); **17** parautochthonous Lower Cambrian (stages 3 and 4) marine siliciclastic succession (Matoppa and Punta Manna Fms.); **18** allochthonous Cambrian–Ordovician marine deposits and volcanites (Bithia and Arburese tectonic units); **19** main post–Hercynian faults; **20** main Hercynian thrusts; **21** secondary Hercynian thrusts

relevance (Meneghini 1888; Bornemann 1891; Bosco 1902; Dal Piaz 1929).

Palaeontology is certainly one of the most easily suitable geoscience to be divulged to the general public and can provide the starting point for initiatives aimed at the protection and divulgation of the geological heritage of a determinate territory also through the geotourism. The latter is an innovative approach to classic natural tourism aiming at the safeguarding and promotion of natural heritage, with geosciences as its main elements, in association with knowledge of a given environment as a whole, including biosphere and environmental education, as well as aspects related to a sustainable increase in the local economy (Hose 2008; Del Lama et al. 2015; Berrocal-Casero et al. 2018). This touristic approach mainly aims to promote a territory history, culture, and traditions, contributing to the well-being of local communities. The interest in geotourism is highlighted by the numerous studies dealing with this important argument, especially to help in planning strategies for the development of economically disadvantaged areas (Dowling 2011; Cobos and Alcalá 2018; Columbu et al. 2019, 2021; Cobos et al. 2020; Franceschelli et al. 2021; Zoboli and Pillola 2021; Zoboli et al. 2021; Barroso-Barcenilla et al. 2022; Fancello et al. 2022).

The great variety of rocks and fossils of Sulcis-Iglesiente led to the design and implementation of the "Sulcitan Palaeo-environment Museum", currently located in the former coal mine of Serbariu (Carbonia). The creation of geo-palaeontological routes starting from the museum could be useful addition to the other environmental, natural, and cultural resources. To this purpose, an overview of the rich palaeontological heritage of the SW Sardinia is presented here providing an additional point of view in planning a geotouristic development of the territory.

Historical Background

The wealth of mineral resources of the SW of Sardinia has attracted a series of studies aimed mainly for purely economic reasons. However, since the middle 1800s, this area was involved in scientific studies dedicated to the knowledge of geology and other disciplines such as palaeontology. One of the first researchers who became interested in the geology of this area was General Alberto Ferrero La Marmora (or Lamarmora) (1789–1863), putative father of the geosciences in Sardinia (Fig. 3a). La Marmora was the first naturalist to collect abundant fossils from the lower Palaeozoic (from Cambrian to Silurian). These remains were partly illustrated in his important work "Voyage en Sardaigne", the part of which dedicated to geology, and palaeontology was published in 1857 (La Marmora 1857). Furthermore, La Marmora first described the Pleistocene aeolian succession of Funtana Morimenta (Gonnesa) and identified the Eocene coal deposit of Sulcis (La Marmora 1851). The samples collected by La Marmora were illustrated by Giuseppe Meneghini (1811–1889) who described several species of Cambrian and Ordovician trilobites (Meneghini 1857, 1880, 1881, 1882, 1888). Other studies on the geology and palaeontology of Sulcis-Iglesiente were carried out in the same period by Johann Georg Bornemann (1831–1896) (Fig. 3b), who mainly dealt with Cambrian faunas (trilobites and archaeocyathans) from different localities among which the famous Canalgrande fossil site, along the Iglesiente coast (Bornemann 1882, 1883, 1886, 1891). The Sulcis-Iglesiente area was visited several times by the famous Swiss palaeontologist Charles Immanuel Forsyth Major (1843–1923) (Fig. 3c), who collected several remains of Pleistocene vertebrates in the bone breccias of Monte San Giovanni (Iglesias–Gonnesa area) between the end of the 1800s and the beginning 1900s (Major 1882, 1901). Furthermore, Major erected the new species of dwarf proboscidean *Mammuthus lamarmorai* on remains found a few years earlier in the aeolian deposits of Funtana Morimenta, near Gonnesa (Acconci 1881; Major 1883). Finally, the remains of Quaternary birds found by him were studied by the English palaeontologist Richard Lydekker (1849–1915) (Fig. 3d) (Lydekker 1891). Different Cenozoic insular mammal faunas are known in Sardinia (e.g. Comaschi Caria 1953; Abbazzi et al. 2008; Mennecart et al. 2017, 2019; Zoboli and Pillola 2017a), and the oldest mammals of Italy were collected in the Eocene Sulcis basin (Major 1891; Bosco 1902; Monterin 1923; Dal Piaz 1929).

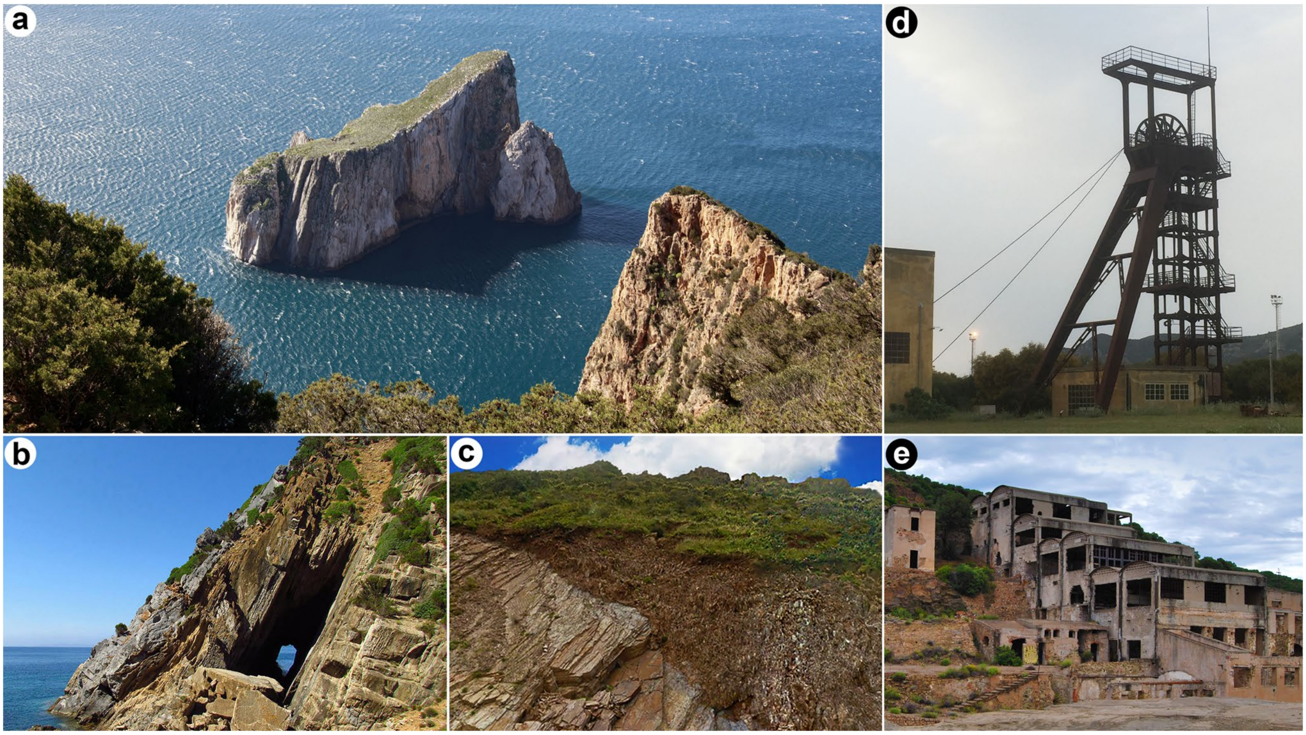

Fig. 2 **a** The Pan di Zucchero (or "Concali su Terràinu" in Sardinian language), Monte San Giovanni Fm., one of the most impressive and spectacular natural monuments of Sardinia and flagship of the coast of Masua (Iglesias) (photo by G. Frau); **b** the natural monument of Canalgrande (photo by G.L. Pillola); **c** The Sardic Unconformity ascribed to the Sardic Phase along the Strada Provinciale 83, between Funtanamare (Gonnesa) and Nebida (Iglesias), the middle Cambrian–Lower Ordovician Cabitza Fm. (bottom left) and the Upper Ordovician Monte Argentu Fm., Punta Sa Broccia Mb. (top right); **d** the coal mine of Serbariu (Carbonia); **e** the abandoned laveria of Seddas Moddizzis mine (Gonnesa)

In the second half of the 1900s, new studies were made by the Sardinian palaeontologist Ida Comaschi Caria (1911–1987) (Fig. 3e), who reported Miocene marine vertebrates and invertebrates in the Funtanazza area (Arbus) (Comaschi Caria 1963, 1973), Quaternary mammals in the aeolian deposits of Portovesme (Portoscuso) and Gonnesa (Comaschi Caria 1955a, 1965), and in the bone breccia of Is Oreris (Fluminimaggiore) (Comaschi Caria 1970). The studies on Palaeozoic faunas had a renewed interest in this period, making a better definition of the ages of the lower Palaeozoic formations. Among others, the Italian physicist, palaeontologist, and botanist Franco Rasetti (1901–2001) (Fig. 3f) established new species of lower Cambrian trilobites (Rasetti 1972), while the French palaeontologist Françoise Debrenne studied the archaeocyathans faunas of Iglesiente (Debrenne 1959, 1964, 1971, 1972). Finally, various works were published on the continental fauna and flora of the Carboniferous and Permian of Iglesiente during this time (Cocozza 1967; Del Rio 1973; Fondi 1980).

In recent decades, the knowledge of Palaeozoic marine faunas has considerably increased due to the contribution of specialists who studied different groups of marine invertebrates. Works of considerable importance were published on Cambrian (Elicki and Pillola 2004; Pillola 1991; Pillola et al. 1995), Ordovician (Havlicek et al. 1987; Hammann et al. 1990; Leone et al. 1991, 2002; Hammann and Leone 1997, 2007; Hammann and Serpagli 2003; Pillola et al. 2008), and Silurian–Devonian invertebrates (Gnoli 1982, 1992a, b; Olivieri and Serpagli 1990; Gnoli and Serpagli 1991; Gnoli and Serventi 2005, 2009; Gnoli et al. 1988, 1990, 2009; Kriz and Serpagli 1993; Storch and Serpagli 1993; Ferretti et al. 2009; Kriz 2009; Storch et al. 2002; Pillola et al. 2009; Storch and Piras 2009). New studies have also involved the continental taxa and ichnotaxa of the Pennsylvanian basin of San Giorgio (Iglesias) (Selden and Pillola 2009; Marchetti et al. 2018, 2020; Pillola and Zoboli 2021), the Permian lacustrine deposits of Guardia Pisano (Gonnesa) (Fischer et al. 2010; Pittau et al. 2002), reptiles from the Eocene of Carbonia and Gonnesa (Georgalis et al. 2020), and Pleistocene mammals from various cave deposits of Sulcis (Madurell-Malapeira et al. 2015; Zoboli and Caddeo 2016; Zoboli et al. 2019a).

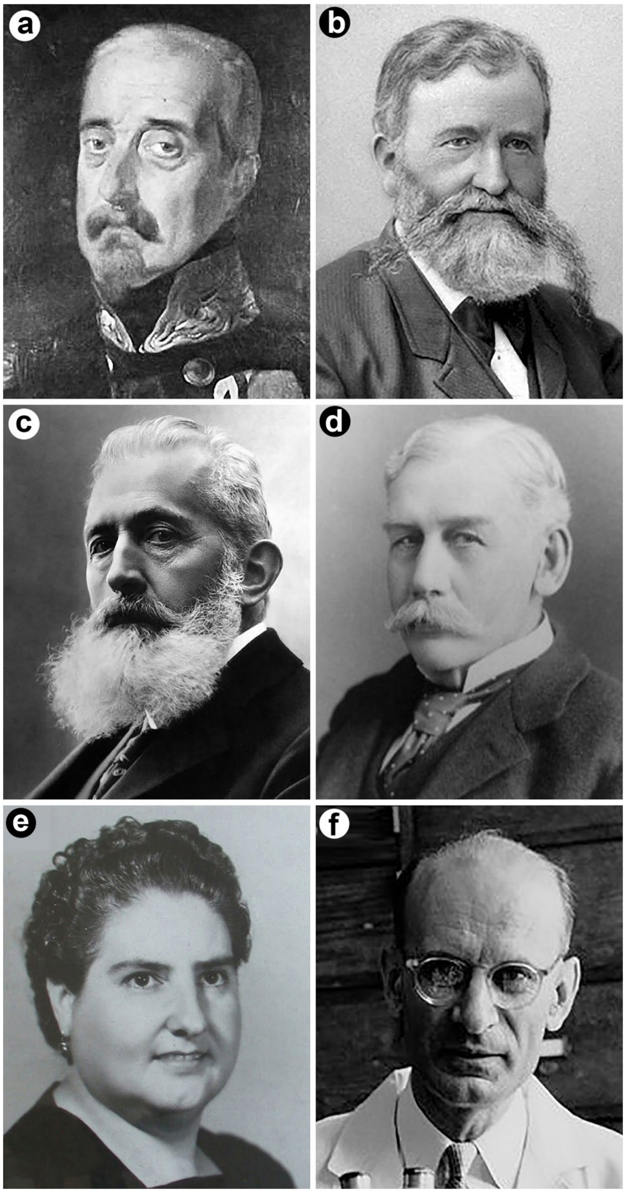

Fig. 3 Some of the most important geologists and palaeontologists who have worked on geology and palaeontology of SW Sardinia, **a** Alberto Ferrero La Marmora (1789–1863), **b** Johann Georg Bornemann (1831–1896), **c** Charles Immanuel Forsyth Major (1843–1923), **d** Richard Lydekker (1849–1915), **e** Ida Comaschi Caria (1911–1987), **f** Franco Rasetti (1901–2001)

Geological and Palaeontological Settings

The Sulcis-Iglesiente sub-region is located in the SW Sardinia and is principally characterised by narrow plains, hills, and mountains limited to the east by the Campidano graben, the largest plain of the island. The territory is generally divided into two main historical areas: the Iglesiente (to the north or north-east) and the Sulcis (to the south); however, the limits between these areas are not clear, or differ according to the authors, so they are usually grouped under the name of Sulcis-Iglesiente (Beretic and Plaisant 2019). Furthermore, some authors include the Arburese territory (Arbus, Guspini) into the Monreale sub-region. An archipelago extends along the Sulcis coast, the main islands of which are Sant'Antioco and San Pietro. Other small volcanic islets are located north-east of San Pietro (Isola Piana) and south of Sant'Antioco (Isola la Vacca and Isola il Toro). The southernmost tip of Sardinia is located in this sub-region (Capo Teulada) (Fig. 1).

Palaeozoic

A complete section of the Variscan chain is exposed in Sardinia, and the Sulcis-Iglesiente area is generally considered its "Foreland zone" or parautochthonous above which the nappes were thrusted on. On the parautochthonous, two main tectonic units were identified, the Bithia unit (in the Capo Spartivento area) and the Arburese unit (in the north and eastern areas), that potentially correlated to the units of the central-eastern Sardinia (Carmignani et al. 2001; Pavanetto et al. 2012; Cocco et al. 2018).

The parautochthonous is characterised by two mega-sequences separated by a regional angular unconformity named "Sardic Unconformity" (Teichmüller 1931). The lower mega-sequence is lower Cambrian to Lower Ordovician in age and is divided into three groups, each of them subdivided into two formations: the lower Cambrian (stages 3–4) Nebida Group (Matoppa and Punta Manna formations), the lower Cambrian (stage 4) Gonnesa Group (Santa Barbara and San Giovanni formations), and the lower Cambrian (stage 4) to Lower Ordovician (?Floian) Iglesias Group (Campo Pisano and Cabitza formations) (Pillola 1990a, b). The Nebida Group consists of a siliciclastic sequence characterised by alternating sandstones and siltstones at the base, still preserving sedimentary structures such as ripple marks, slumping, parallel and cross lamination, and a very rich fossil content (Fig. 4). The Matoppa Fm. is represented by calcimicrobial-archaeocyathan mounds, trilobites (e.g. *Dolerolenus courtessolei*, *Giordanella vincii*, *Iglesiella ichnusae*, *Hebediscina sardoa*), brachiopods, echinoderms, sponges, and other marine organisms including ichnofossils. The following Punta Manna Fm. is mostly a terrigenous deposit with episodic carbonate intercalations, characterised by an oolitic limestone level at the base. The palaeontological content is mainly represented by trilobites with species of the genera *Dolerolenus*, *Giordanella*, *Enantiaspis*, *Metadoxides*, and ichnofossils. Three different trilobite "informal biozones" (from the stages 3–4) are recognised in this formation on the basis of three species of *Dolerolenus*: *D. longioculatus*, *D. zoppii*, and *D. bifidus*. This group is continuous with the overlaying Gonnesa Group which consists of carbonate deposits. The Santa Barbara Fm. is characterised

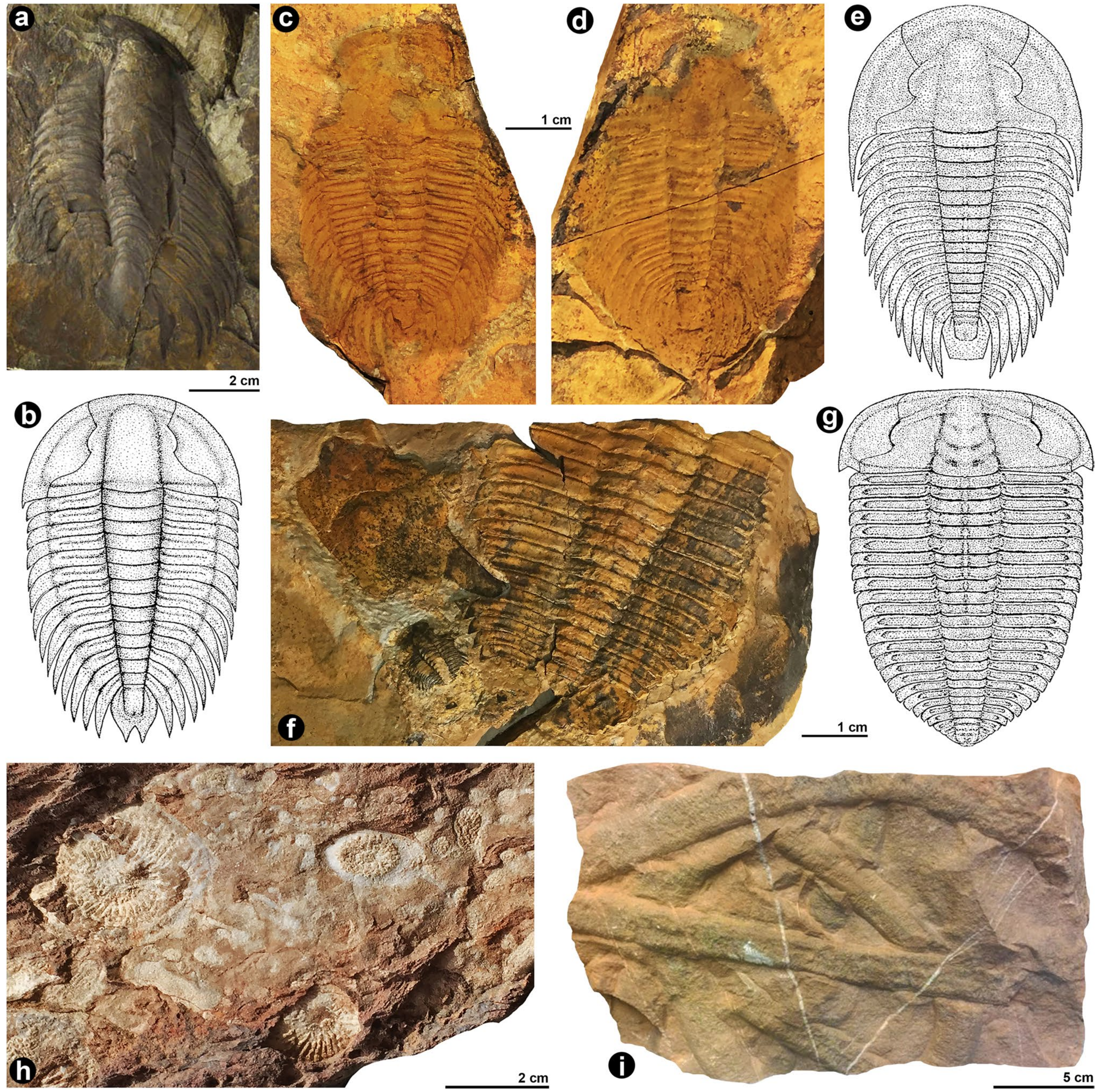

Fig. 4 Early Cambrian fossils of SW Sardinia (Nebida Group); **a** trilobite *Dolerolenus courtessolei* (Pillola 1991), from Seddas Moddizzis (Gonnesa), almost complete specimen (holotype), Matoppa Fm. (stage 3); **b** reconstruction of *D. courtessolei* (after Pillola 1991); **c–d** trilobite *Dolerolenus zoppii* (Meneghini 1882) from Canalgrande (Iglesias), almost complete specimen, Punta Manna Fm. (stage 4, *D. zoppii* biozone); **e** reconstruction of *D. zoppii* (after Pillola 1991); **f** trilobite *Metadoxides armatus* (Meneghini 1881) from Canalgrande, almost complete thorax and cranidium (in the lower left an incomplete specimen of *D. zoppii*), Punta Manna Fm. (stage 4, *D. zoppii* biozone); **g** reconstruction of *M. armatus* (after Pillola 1991); **h** archaeocyatha remains, Matoppa Fm. (stage 3); **i** invertebrate ichnofossils, Punta Manna Fm. (stage 3, *Dolerolenus longioculatus* biozone). Specimen **a** is stored at MDLCA, specimens **c**, **d**, **f**, **h**, and **i** are stored at PAS-Martel

by cyclic well-stratified carbonates (limestones and dolostones), which are covered by massive limestones of the San Giovanni Fm. The fossil content of these formations is relatively scarce. The Iglesias Group starts with alternating layers of claystones, nodular limestones, and marls of the Campo Pisano Fm. that lies above the San Giovanni Fm. (Elicki and Pillola 2004). The terrigenous (mainly claystone and siltstone) Cabitza Fm. closes the first mega-sequence that at the top is marked by the Sardic Unconformity. This last formation has a rich palaeontological content (trilobites, phyllocarids, hyolitids, echinoderms, brachiopods, and graptolites) that indicates a lower Cambrian (stage 4)–Lower Ordovician age (Gandin and Pillola 1985; Pillola and Gutierrez-Marco 1988; Pillola et al. 2008).

The second mega-sequence is represented by a thick Upper Ordovician siliciclastic succession, which lies unconformably over the above described lower Cambrian–Lower Ordovician succession (Leone et al. 1991). The succession starts with coarse conglomerates, sandstones, and siltstones of the Monte Argentu Fm., which is considered a syntectonic deposit settled in an alluvial fan to fan-delta environment still influenced by the Sardic phase (Laske et al. 1994). A clast abundance characterises the lower part of this formation (Punta Sa Broccia Member) and is derived from the erosion of the lithotypes of the first mega-sequence (mainly from the Cabitza Fm.). Scarce fossils were reported in this formation, but significant is the presence of the peculiar nektaspid arthropod *Tariccoia arrusensis* (Fig. 5a, b) reported in the Rio Is Arrus Member, in the Fluminimaggiore area (Hammann et al. 1990). A mainly siliciclastic succession made up of alternating siltstones, slates, silty sandstones, and coarse and medium grained sandstones lies above the Monte Argentu Fm. This succession is subdivided into different formations: Monte Orri, Portixeddu, Domusnovas, and Rio San Marco formations. The palaeontological content of these formations is very rich and consists of numerous trilobites (e.g. the genera *Dalmanitina*, *Zetillaenus*, *Deanaspis*, *Nobiliasaphus*, *Lichas*, *Dicranurus*, *Sardoites*), ostracods, brachiopods (e.g. *Svobodaina*, *Aegiromena*, *Iberomena*, *Drabovia*, *Nicolella*, *Longvillia*) (Fig. 5c), cystoids (e.g. *Corylocrinus*, *Caryocrinites*, *Heliocrinites*), crinoids, gastropods, cephalopods (*Lituites*), bivalves, tetracorals (*Palaeophyllum*), bryozoans, graptolites (*Normalograptus*), conodonts (e.g. *Amorphognathus*, *Panderodus*, *Walliserodus*), and ichnofossils (Maccagno 1965; Havlicek et al. 1987; Conti and Serpagli 1988; Hammann and Leone 1997, 2007; Storch and Leone 2003).

The Ordovician formations are followed by a Silurian–Devonian pelagic succession characterised at the base by fossiliferous black shales and lydites (Genna Muxerru Fm.) and, at the top, by massive limestones (Fluminimaggiore and Mason Porcus formations). The black shales of the Genna Muxerru Fm. (Llandovery) are very rich in graptolites (e.g. *Cystograptus*, *Neodiplograptus*, *Normalograptus*, *Monograptus*) (Fig. 6a, b) that allow to recognise several biozones (Storch and Serpagli 1993; Storch et al. 2002; Storch and Piras 2009). The other fossil content is represented by traces (e.g. the ichnogenera *Alcyonidiopsis*, *Cochlichnus*, *Planolites*) (Baucon et al. 2020). From the mainly siliciclastic lithotypes of the Genna Muxerru Fm., the succession progressively passes to the mainly carbonate lithotypes of

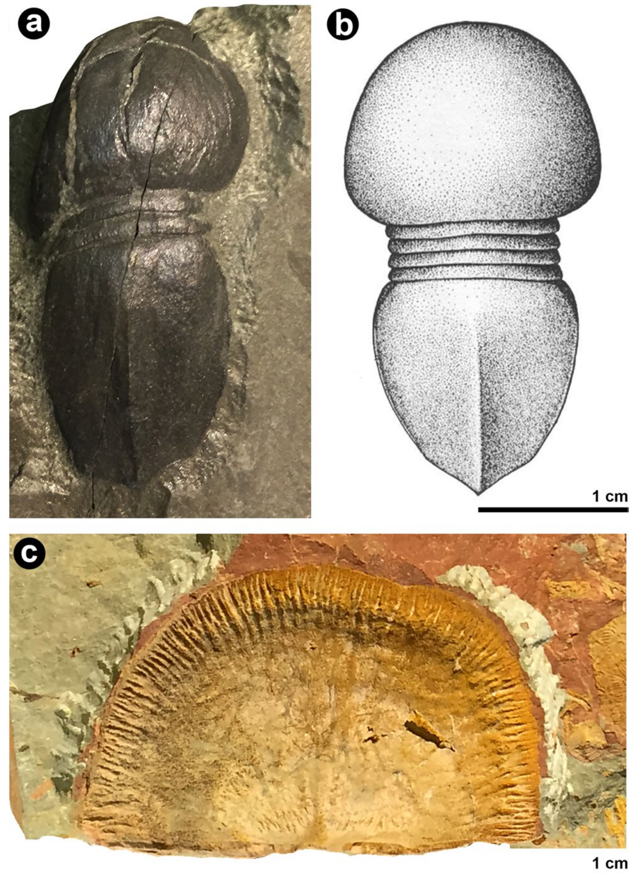

Fig. 5 Upper Ordovician fossils of SW Sardinia, **a** the peculiar nektaspid arthropod *Tariccoia arrusensis* Hammann et al. (1990) from Rio Is Arrus (Fluminimaggiore), Monte Argentu Fm. (Rio Is Arrus Mb.), **b** reconstruction of *T. arrusensis* (after Hammann et al. 1990), **c** the brachiopod *Longvillia mediterranea* Havlicek 1981, Punta Pedrona (Fluminimaggiore), Portixeddu Fm. All specimens are stored at PAS-Martel

the Fluminimaggiore Fm. (Silurian–Lower Devonian) and Mason Porcus Fm. (Lower Devonian). The first formation is characterised by very fossiliferous black limestones containing orthocone cephalopods (e.g. genera *Michelinoceras*, *Plagiostomoceras*, *Merocyclortoceras*), bivalves (e.g. *Cardiola*, *Maminka*, *Slava*, *Slavinka*) (Fig. 6c, d), conodonts (e.g. *Ozarkodina*, *Polygnathoides*, *Panderodus*), graptolites, problematic organisms (*Kolihaia sardiniensis*), and arthropods. This latter group is represented by rare trilobites (cf. *Balizoma* and *Raphiophorus*), phyllocarids (genera *Ceratiocaris*, *Dithyrocaris*, *Warneticaris*), and undetermined eurypterids (Gnoli et al. 1990; Gnoli 1992a, b; Kriz and Serpagli 1993; Gnoli and Serventi 2009; Kriz 2009; Pillola et al. 2009). The Mason Porcus Fm. is mainly represented by nodular limestones rich in conodonts, echinoderms, trilobites (e.g. families Phacopidae, Styginidae, and Aulacopleuridae), tentaculitids (*Styliolina* and *Nowakia*), tetracorals, problematic organisms (*Eurytholia bohemica*), and stromatactis-bearing

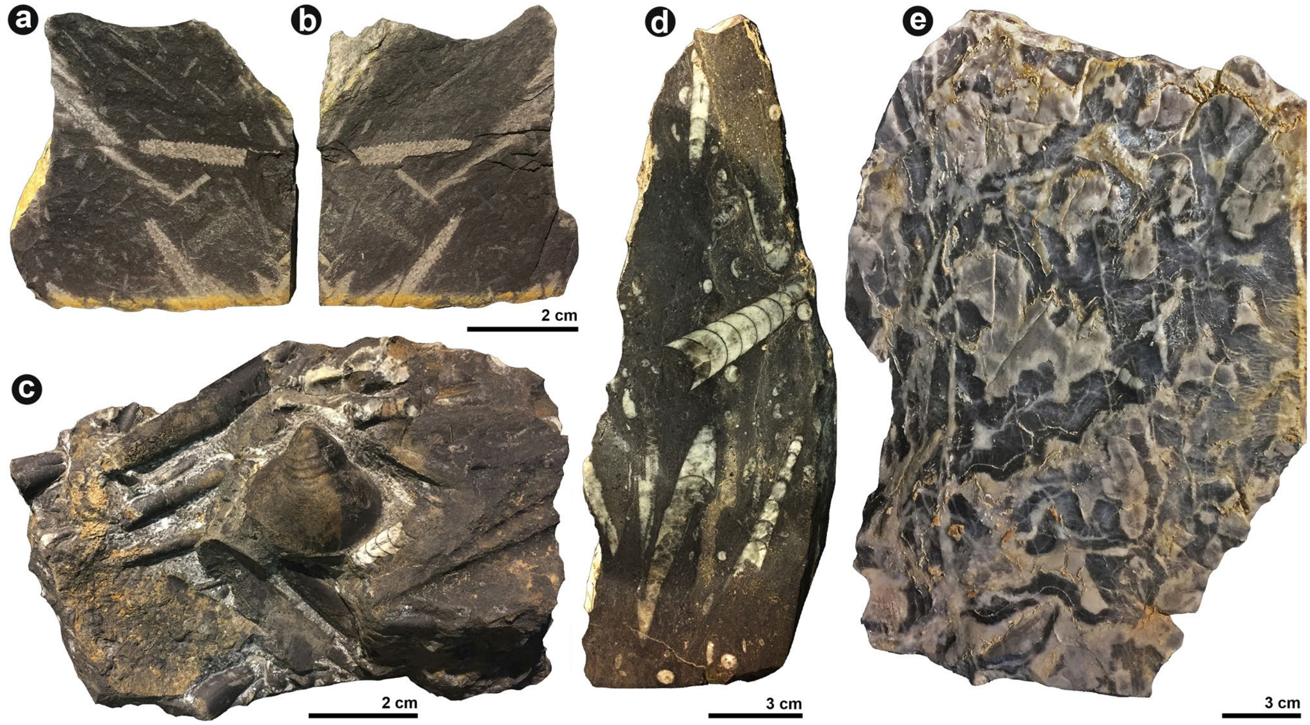

Fig. 6 Silurian–Devonian fossils of SW Sardinia, **a–b** graptolitic black shale (*Neodiplograptus* sp.), Monte Cortoghiana Becciu (Carbonia), Llandovery (Genna Muxerru Fm.), **c** orthoceratid cephalopods and bivalves (*Slava* sp.) association, Perd'e Fogu (Fluminimaggiore), Silurian (Fluminimaggiore Fm.), **d** polished section of black metalimestone rich in orthoceratid cephalopods, Perd'e Fogu (Fluminimaggiore), Silurian (Fluminimaggiore Fm.), **e** stromatactis metalimestone, Monte Padenteddu (Pula), Lower Devonian (Mason Porcus Fm.). All specimens are stored at PAS-Martel

mud-mounds (Fig. 6e) (Gnoli et al. 1988; Olivieri and Serpagli 1990; Corriga et al. 2022).

As reported above, different allochthonous tectonic units of the external "Nappe zone" of the Variscan chain are also present in the Sulcis-Iglesiente and Arburese areas. Simplifying, the Arburese Unit is represented by the siliciclastic succession of the Arenarie di San Vito Fm. (Cambrian–Lower Ordovician), unconformably caped by an Upper Ordovician volcano-sedimentary sequence. A rich fossil assemblage was reported in the latter sequence (Punta Serpeddì Fm.), from the Donigala locality (Sant'Antonio di Santadi, Arbus): gastropods, echinoderms, tetracorals, brachiopods (genera *Rafinesquina* and *Svobodaina*), and trilobites (e.g. genera *Calymenella*, *Dreyfussina*, *Prionocheilus*, *Sarrabesia*, *Lichas*) that allows a correlation with the Portixeddu Fm. and the lower part of the Domusnovas Fm. (Punta S'Argiola Member) of the Upper Ordovician succession of the "Foreland zone" (Hammann and Leone 1997).

The latest Palaeozoic rocks of SW Sardinia consist of post-Variscan continental fluvio-lacustrine sediments from the middle Pennsylvanian (Moscovian) to the Permian (Asselian) (Cocozza 1967; Barca and Costamagna 2003; Fischer et al. 2010). The main studied localities are the Moscovian San Giorgio basin (Iglesias) and the Asselian outcrop of Guardia Pisano (Gonnesa). The Carboniferous fluvio-lacustrine succession of San Giorgio (Fig. 7a) discordantly lies on the Variscan basement and currently is badly exposed and covered by deposits of the aborted Campo Pisano Pb–Zn mine. The most continuous succession crops out along the waterway drain cut, excavated near the mine dump that modifies the San Giorgio river path (Marchetti et al. 2020). The succession is very rich in micro- and macroflora (mainly arborescent horsetails and ferns), arthropods, and invertebrate and vertebrate ichnofossils (Fig. 7b). Three arthropod remains were collected in the succession: a wing of an undetermined blattoid (Fig. 7c), an almost complete fossil of a trigonotarbid arachnid (*Anthracomartus voelkelianus*) (Fig. 7d), and an exoskeleton fragment of the giant millipede-like arthropod *Arthropleura armata* (Fig. 7e, f) (Selden and Pillola 2009; Pillola and Zoboli 2021). Furthermore, a rich vertebrate and invertebrate ichnoassociation is reported: *Batrachichnus salamandroides*, undetermined tetrapod footprints, *Diplichnites* isp., *Cochlichnus anguineus*, *Treptichnus bifurcus*, and *Treptichnus* isp. The vertebrate tracks (trackmakers were probably small lepospondyl and temnospondyl anamniotes) of San Giorgio are the oldest of the Italian ichnofossil record (Fondi 1980; Marchetti et al. 2018, 2020). The fluvio-lacustrine sequence of Guardia

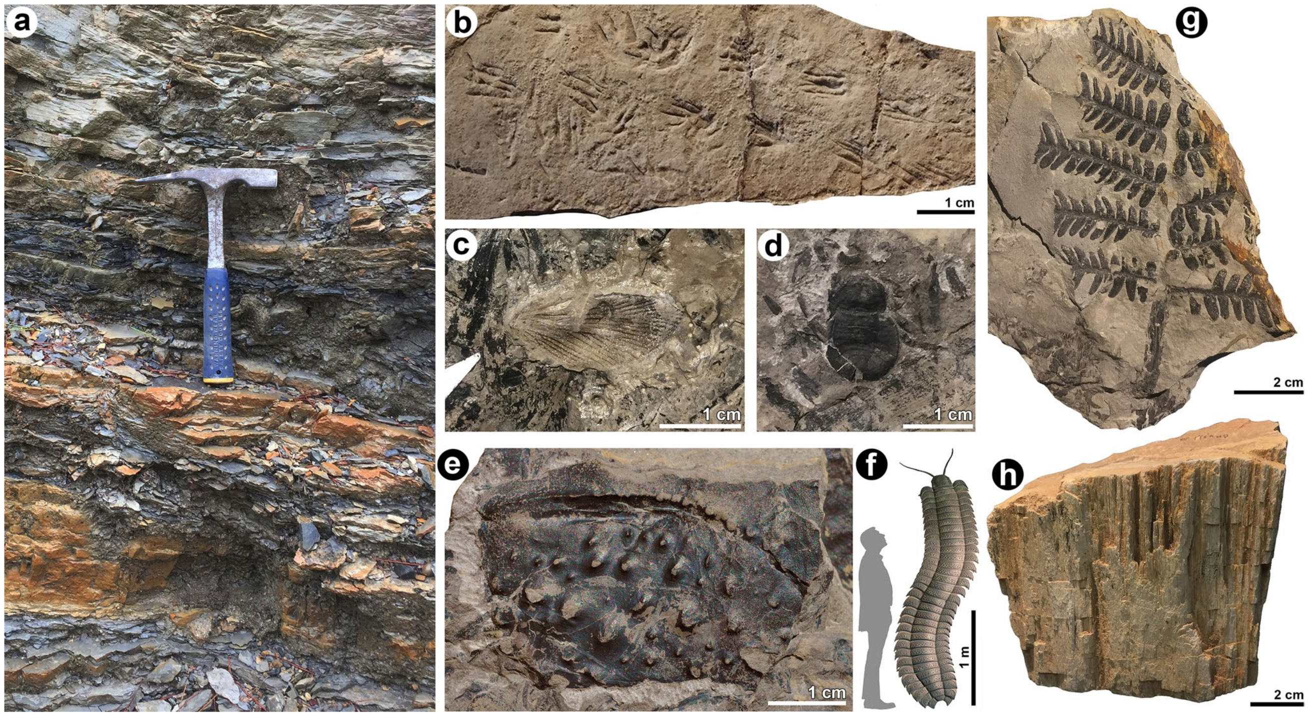

Fig. 7 Fossils from the Carboniferous-Permian of SW Sardinia. **a–f** Pennsylvanian (Moscovian) Rio San Giorgio Fm. (Rio San Giorgio basin, Iglesias), **a** siltitic dolostone and carbon-rich clays, **b** undetermined tetrapod footprints (concave epirelief), **c** undetermined blattoid wing, **d** trigonotarbid arachnid *Anthracomartus voelkelianus* Karsch 1882, **e** fragment of exoskeleton (right paratergite) of the giant millipede-like arthropod *Arthropleura armata* Jordan, 1854, **f** the impressive size of *Arthropleura armata* (modified after Schneider and Werneburg 2010). **g–h** Asselian Guardia Pisano Fm. (Guardia Pisano hill, Gonnesa), **g** fern *Pecopteris polymorpha* (Brongniart 1834), **h** silicified trunk (cf. *Agathoxylon* sp.). Specimens **c**, **d**, **e**, **g**, and **h** are stored at PAS-Martel, **b** is stored at MDLCA

Pisano has a very rich palaeontological content represented by micro- and macro-flora and microvertebrates. Plant remains consist in very well preserved ferns (e.g. *Pecopteris polymorpha*) (Fig. 7g), horsetails, and silicified trunks of pinales (cf. *Agathoxylon* sp.) (Fig. 7h). The dulcicolous fauna is represented by amphibians (undetermined *Brachiosaurus*), hybodontoid sharks (*Lissodus sardiniensis*, *Xenacanthus* sp., cf. *Orthacanthus* sp., ?*Bohemiacanthus* sp.), and acanthodians (*Acanthodes* sp.) (Fischer et al. 2010).

Mesozoic

The Mesozoic outcrops of SW Sardinia are not very extended. Triassic successions crop out in the Scivu–Is Arenas area (Arbus), Campumari (Gonnesa), Piolanas (Carbonia), and in the Porto Pino area (Sant'Anna Arresi). The stratigraphic and depositional patterns of the Triassic of SW Sardinia show analogies with the typical "Germanic facies" of Central Europe. Therefore, it is possible to recognise the three classical lithofacies: Buntsandstein, Muschelkalk, and Keuper (Costamagna and Barca 2002). The Middle Triassic palaeontological content of the Scivu–Is Arenas succession (Punta S'Arridelli and Punta Su Nuraxi formations) is represented by palynomorphs (*Cristianisporites triangulatus*), ostracods, bivalves (*Costatoria goldfussi*), and ichnofossils (*Planolites* and *Palaeophycus*). The Triassic succession of Campumari is represented by the Riu Is Corras Fm. (dubiously attributed to the Buntsandstein facies group) and the Campumari Fm. (Muschelkalk facies group, Middle Triassic). The palaeontological record of the first one is very scarce (ichnogenus *Palaeophycus*), but plant debris and palynomorphs (genera *Stellapollenites* and *Triadispora*) are reported in a marly-clayey horizon at the base of the latter formation (Pittau Demelia and Del Rio 1980). Furthermore, crinoids, bivalves, and ichnofossils are present in the overlying carbonates of the Campumari Fm. Finally, bivalves, gastropods, ostracods, foraminifers, echinoid spines, crinoids, ophiuroids, and cephalopods were signaled in the Middle–Late Triassic succession of Porto Pino.

Jurassic outcrops are present exclusively in the Porto Botte and Porto Pino areas, where a Lower–?Middle Jurassic marine succession is well exposed. In this area, two formations are present, the Guardia Sa Barracca Fm. (Lower Jurassic) and the Medau Mereu Fm. (Lower Jurassic–?Middle Jurassic). The first one is characterised by marls, limestones, and dolomitic limestones with a very rich palaeontological content: foraminifers (e.g. genera *Agerina*, *Orbitospella*, *Lenticulina*), bivalves (e.g. *Plicatula*, *Bositra*, *Pseudopecten*)

(Fig. 8a), ammonites (e.g. *Pleydellia*, *Tmetoceras*, *Dactylioceras*), brachiopods (e.g. *Lobothyris*, *Telothyris*, *Quadratirhynchia*, *Zeilleria*) (Fig. 8b), and coprolithes (*Favreina*). The Jurassic succession closes with the Medau Mereu Fm., which is mainly represented by calcarenites rich in foraminifers (e.g. *Praepatellina*, *Agerina*, *Nodosaria*), bivalves (*Bositra*), sponge spicules, and echinoderm remains (Taddei Ruggiero 1966; Martini et al. 1987; Barca and Costamagna 1997; Costamagna 2000).

The Cretaceous succession of SW Sardinia is present only in the Sant'Antioco Island, between the beaches of Maladroxia and Coequaddus (or Coaquaddus) (East coast of the island). The succession starts with Early Cretaceous (Berriasian–Valanginian) marls of the "Purbeckian facies" and continues with the limestones of the "Urgonian facies" (lower Valanginian–Aptian). The last facies has a very rich palaeontological content: foraminifers (e.g. *Glomospira*, *Cuneolina*, *Trocholina*, *Sabaudia*), dasycladacee (e.g. *Neomeris*, *Heteroporella*, *Salpingoporella*), rodoficee (*Lithocodium*), sponges, echinoderms, and bivalves (mainly rudists) (Fig. 8c). Finally, the Late Cretaceous is represented by few metres of Santonian limestones transgressive on the Lower Cretaceous succession and separated from the latter by a lateritised surface with bauxite residues (Maxia 1963; Chabrier et al. 1975).

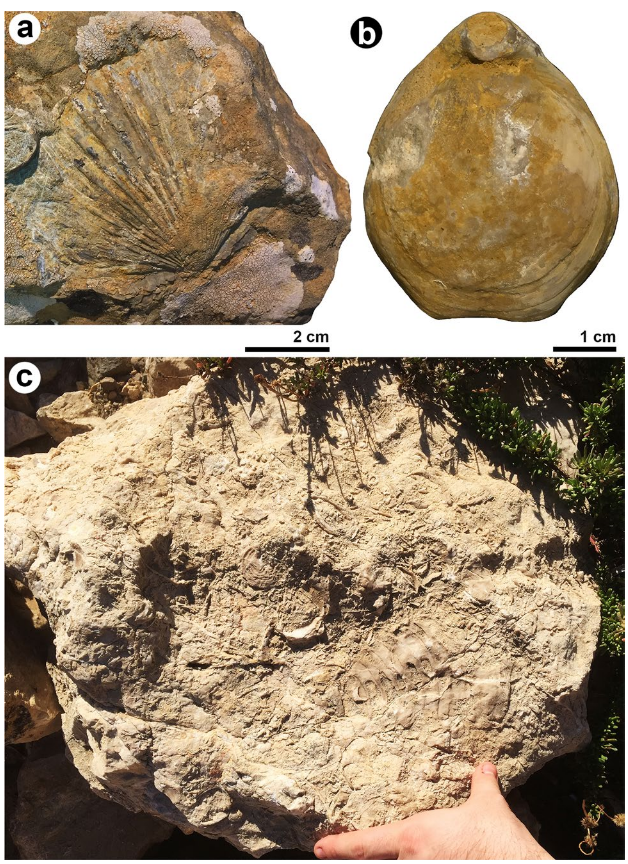

Fig. 8 Mesozoic fossils of Sulcis area, **a** incomplete bivalve shell (*Pseudopecten* sp.) from the Lower Jurassic Guardia Sa Barracca Fm. (Monte Zari, Sant'Anna Arresi), **b** terebratulid brachiopod (cf. *Lobothyris* sp.) from the Lower Jurassic Guardia Sa Barracca Fm. (Monte Zari, Sant'Anna Arresi), **c** limestone block rich in rudist and sponge remains, Lower Cretaceous of Coequaddus (eastern coast of Sant'Antioco Island). Specimens **a** and **b** are stored at PAS-Martel

Cenozoic

The Cenozoic succession of the Sulcis-Iglesiente area starts with Paleogene deposits (early Ypresian–Rupelian) that discordantly lie on the Variscan basement and which are generally covered by Oligocene–Miocene volcanites at the top. Three formations are distinguished from bottom to top: Miliolitico Fm. (early Ypresian), Lignitifero Fm. (late Ypresian–early Lutetian), and Cixerri Fm. (Lutetian–Rupelian). The Miliolitico Fm. is represented by limestones and marly limestones of lagoon environment. The fossil content is very rich: foraminifers (e.g. *Spirolina*, *Triloculina*, *Quinqueloculina*), bivalves (*Cyrena*), gastropods (*Potamides*), ostracods, and charophytes. An hemimandible of the perissodactyl *Atalonodon monterini* (Fig. 9a) was collected in this formation (in locality Terras de Collu, near Gonnesa) (Fig. 9b) and represents the oldest mammal of the Italian fossil record (Monterin 1923; Dal Piaz 1929). The Paleogene succession continues with the Lignitifero Fm., whose more representative outcrops are between Carbonia and Gonnesa. The formation is generally badly exposed; however, it is well known due to the numerous coal mining surveys. The succession consists of rhythmic alternations of layers of marls, bituminous limestones, clays, lignite layers, sandstones, and conglomerates (Agus and Pecorini 1978; Fanni et al. 1982; Cocozza et al. 1986). The palaeontological content is very rich and is represented by sporomorph (e.g. *Arecipites*, *Leiotriletes*), charophyte (*Nitellopsis*), macroflora (e.g. *Sabal*, *Palmacites*, *Flabellaria*, *Juglans*), bivalves, and gastropods (Fig. 9c, d) (Taricco 1924; Pittau 1974, 1977; Pittau Demelia 1979). Furthermore, fossil vertebrates such as bony fish (cf. *Alestes* sp.), turtles (Pan-Trionychidae indet.), perissodactyls ("*Lophiodon*" *sardus*), and marsupials (*Amphiperatherium* sp.) were reported by various authors (Bosco 1902; Taricco 1924; Cappetta and Thaler 1974; Kotsakis 1985). The Cixerri Fm. closes the Paleogene sedimentary succession. It is a terrigenous formation represented by siltites, sandstones, conglomerates, and lacustrine limestones (Pecorini and Pomesano Cherchi 1969; Costamagna and Schäfer 2013). The Cixerri Fm. rests conformably to unconformably over the Lignitifero Fm., or it is posed unconformably over the Variscan metamorphic basement; upwards, it passes sharply through an unconformity to Oligocene–Miocene volcanites. The palaeontological record is poor and consists of rare plant remains, freshwater gastropods (*Stagnicola* cf. *orelongo*), and large pleurodire turtles of the genus *Eocenochelus*

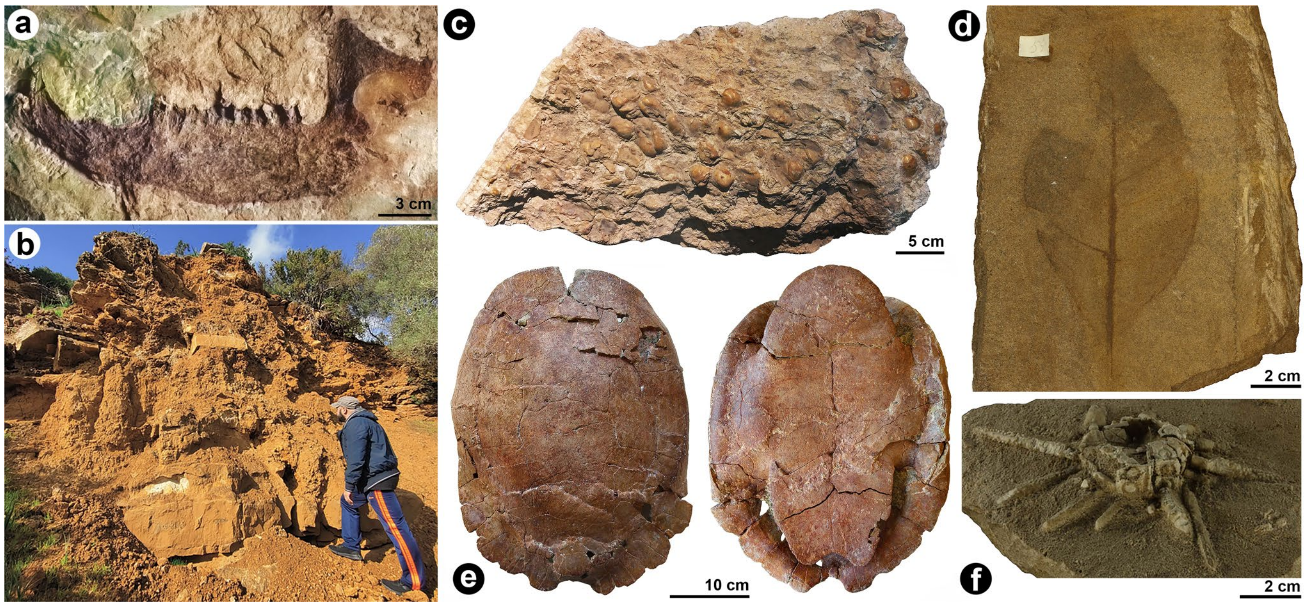

Fig. 9 Cenozoic fossils of SW Sardinia, **a** hemimandible of the perissodactyl *Atalonodon monterini* Dal Piaz 1929 from the early Ypresian Miliolitico Fm. (Terras de Collu, Gonnesa) (modified after Kotsakis et al. 2008), **b** the abandoned limestone quarry of Terras de Collu where the fossil of *A. monterini* was found, **c** brackish water bivalves and gastropods from the abandoned coal mine of Piolanas (Carbonia), late Ypresian–early Lutetian Lignitifero Fm., **d** leaf of Juglandaceae (*Juglans* sp.) from the Bacu Abis area (Carbonia), Lignitifero Fm., **e** almost complete shell of a large fresh water turtle (*Eocenochelus* cf. *eremberti*) in dorsal and ventral views, middle Eocene (Cixerri Fm.) of Medau is Fenus (Carbonia), **f** the echinoid *Tylocidaris* (*Sardocidaris*) *scarabellii* (Stefanini in Nelli 1907) from the Early Miocene (Aquitanian) of Funtanazza (Arbus). Specimen **a** is stored at MGPT-PU, specimen **c** is stored at PAS-Martel, and specimens **d**, **e**, and **f** are stored at MDLCA

(Fig. 9e) (Maxia 1959; Georgalis et al. 2020; Zoboli et al. 2022).

During the latest Paleogene and Neogene, the SW Sardinia was interested in a calc-alkaline volcanic cycle; therefore, sedimentary deposits are relatively underrepresented in this area. However, a very fossiliferous Miocene marine succession cropping out along the Arburese coast (Funtanazza, Sa Calada Bianca, Is Argiolas Manna, and Cala Campu Sali), where sponges (e.g. *Craticularia*), corals (e.g. *Balanophyllia*, *Ceratotrochus*), bryozoans (*Retepora*), echinoids (e.g. *Tylocidaris*, *Spatangus*) (Fig. 9f), bivalves (e.g. genera *Cardita*, *Cardium*, *Venus*, *Arca*, *Lucina*, *Glycimeris*), gastropods (e.g. *Pereiraia*, *Ormastralium*, *Turritella*, *Bolma*), cartilaginous fish (*Otodus megalodon*, *Isurus hastalis*), bony fish (*Sparus cinctus*), and reptiles (Crocodylia indet.) were reported (Comaschi Caria 1955b, 1973, 1974; Borghi and Stara 2016; Zoboli et al. 2019b).

Quaternary successions are represented by discontinuous alluvial deposits, aeolian and beach sandstones, and cave deposits. Middle–Late Pleistocene mammal remains were collected in aeolian sandstones of different localities in the territories of Gonnesa and Portoscuso (Fig. 10a–d). A skeleton of the dwarf Sardinian mammoth *Mammuthus lamarmorai* (Fig. 10e, f) and several proboscidean and cervid footprints (classified as *Proboscipeda panfamilia* and *Bifidipes* isp., respectively) were reported in the Funtana Morimenta site (Gonnesa), while fossils of the megacerine deer *Praemegaceros cazioti* were collected in the Porto Paglia (Gonnesa) and Portovesme (Portoscuso) areas (Comaschi Caria 1955a; Pillola and Zoboli 2017; Zoboli et al. 2018; Zoboli and Pillola 2018, 2021; Pillola et al. 2020). The Quaternary vertebrates of Sardinia are very well known due to the rich deposits and bone breccias localised in numerous caves and fissure fillings (among others: Abbazzi et al. 2004; Zoboli and Pillola 2016, 2017b). The great extension of Cambrian carbonate outcrops of the SW Sardinia allowed the development of numerous caves, which in some cases are exploited for tourism purposes (e.g. Santa Barbara, Su Mannau, Acquacadda, and Is Zuddas caves). Many of them are characterised by clayey deposits and bone breccias rich in vertebrate remains (mainly birds and mammals) which allowed the reconstruction of the Middle and Late Pleistocene fauna of this part of Sardinia (Fig. 11a–d). Fossils of endemic mammals such as primates (*Macaca majori*), canids (*Cynotherium malatestai* and *C. sardous*), mustelids (*Enhydrictis galictoides*), cervids (*Praemegaceros sardus* and *P. cazioti*), rodents (*Microtus* [*Thyrrhenicola*] *henseli* and *Rhagamys orthodon*), lagomorphs (*Prolagus sardus*), and eulipotiphlans (*Talpa tyrrhenica* and *Asoriculus similis*) were collected in numerous cave deposits of

Fig. 10 Pleistocene aeolian sites, **a**–**b** footprints of megacerine deer, Pleistocene of Porto Paglia (Gonnesa), **c** Pleistocene ripple marks along the coast of Porto Paglia, **d** students of the Sapienza University of Rome visiting the important late Middle Pleistocene ichnosite of Funtana Morimenta (Gonnesa), **e** left manus and left pes of the Sardinian dwarf mammoth *Mammuthus lamarmorai* (Major 1883) from the late Middle Pleistocene of Funtana Morimenta–Guardia Pisano hill (Gonnesa), NMB (Major's Collection), **f** size of the Sardinian mammoth (about 1.5 m in height at the shoulder)

Fluminimaggiore, Gonnesa, Nuxis, Santadi, Iglesias, and Carbonia areas (Major 1901; Comaschi Caria 1970; Gliozzi et al. 1984; Van der Made and Palombo 2006; Madurell-Malapeira et al. 2015; Zoboli et al. 2016). An interesting invertebrate interglacial malacofauna (e.g. the gastropods *Conus* [*Chelyconus*] *ermineus* and *Thetystrombus latus*) was collected in the Tyrrhenian (MIS 5e, Late Pleistocene) littoral sandstones of Porto Botte (Giba) (Fig. 11e–g). Other Tyrrhenian fossiliferous deposits are present in the Sant'Antioco Island (e.g. Maladroxia) and along the Arburese coast (Costa Verde).

Methodological Approach

An accurate bibliographic research aimed at identifying the fossiliferous sites with historical and scientific heritage (e.g. type localities of taxa) in the SW Sardinia. Other sites have been identified through field surveys. The acquired data allowed the selection of 100 fossil sites. Following spatial distribution parameters related to the physiographic and geological features of the territory, the sites were grouped into six areas to provide a planning framework for the design and development of different geotourist routes focused on the palaeontological heritage (Fig. 12).

The process for evaluating palaeontological heritage followed the methodology proposed by Endere and Prado (2015). It is based on six categories containing 21 criteria and a score range. Each value was coded as multistate, where a zero value represents absent or low value, and the subsequent numbers indicate the increasing heritage value. The sites were scored against the listed criteria, and the total score allowed the ranking of the sites. The sites that reached 25 points were considered of great strategic importance for the planning of future enhancement and protection projects of the palaeontological heritage.

The six categories and the criteria are:

1) Palaeontological, PC (nature of fossil, NF – 1 to 3 points, preservation, P – 0 to 2 points, diversity of fossils, DF – 0 to 2 points, type localities, TL – 0 to 2 points, taphonomic information, TI – 0 to 2 points)
2) Geological, GC (significance, GS – 1 to 3 points, integrity of the site, GI – 0 to 2 points, scientific potential, SP – 0 to 3 points)
3) Contextual, CC (context, C – 0 to 2 points, visual contribution to landscape, VL – 1 to 4 points, association with archaeological remains and mining archaeology, AA – 0 to 2 points)
4) Integrity, IC (geographic situation, GS – 0 to 2 points, vulnerability to damage related to fossil collecting, V – 0 to 1 points)

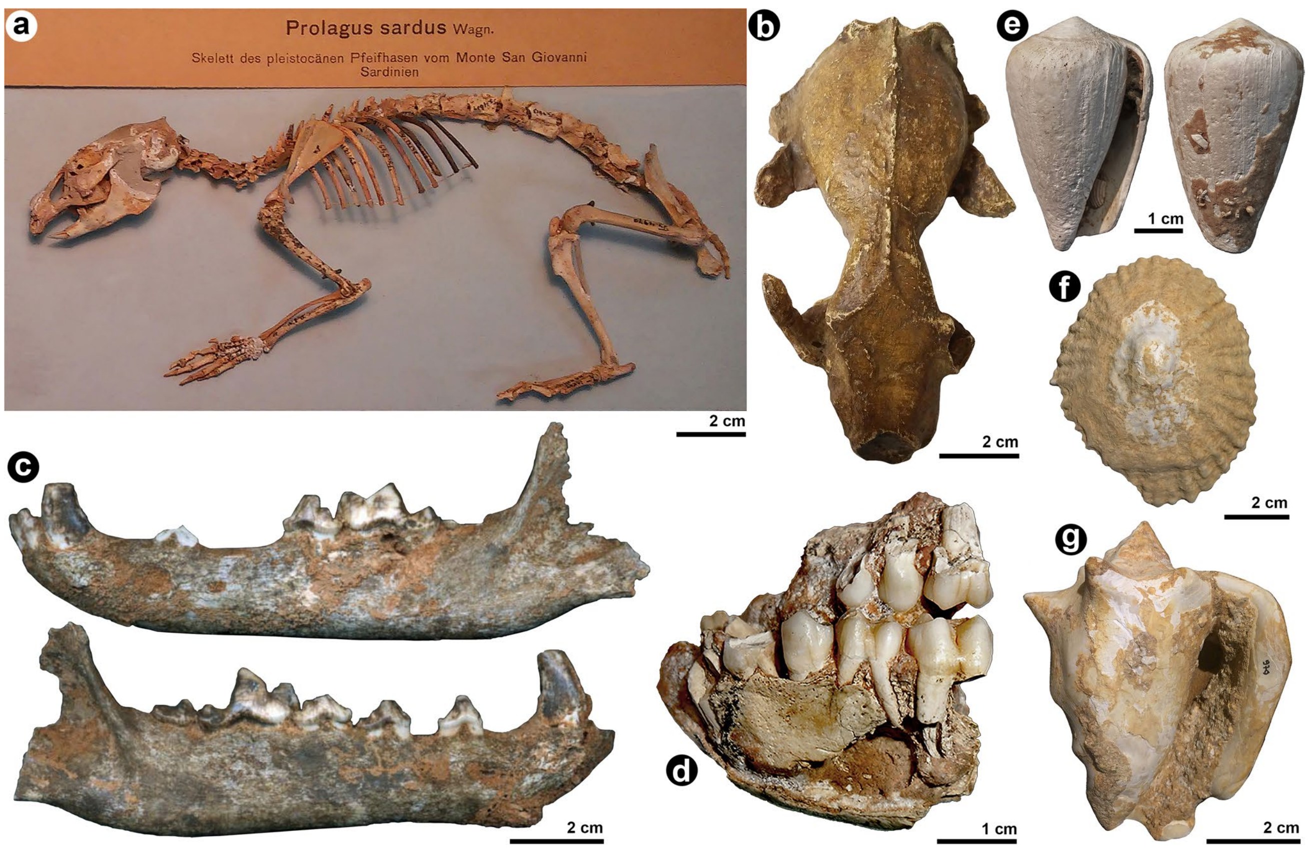

Fig. 11 Pleistocene continental and marine fossils of SW Sardinia, **a–d** mammals from Pleistocene fissure fillings and cave deposits, **a** *Prolagus sardus* (Wagner 1829), mounted composite skeleton, Monte San Giovanni (Gonnesa–Iglesias) (NMB), **b** *Enhydrictis galictoides* Major 1901, plaster cast of the skull in dorsal view, the original fossil was collected in the fissure fillings of Monte San Giovanni (NMB), **c** *Cynotherium malatestai* Madurell-Malapeira et al. 2015, left and right hemimandibles in labial view, Grotta dei Fiori (MPUR), **d** *Macaca majori* Azzaroli 1946, incomplete mandible in occlusion with its fragmentary maxilla, Cava Alabastro (Is Oreris, Fluminimaggiore), lateral left view (PAS-Martel); **e–g** gastropods from the Late Pleistocene (Tyrrhenian, MIS 5e) of Porto Botte (Giba), **e** *Conus* (*Chelyconus*) *ermineus* Born, 1778, **f** *Patella ferruginea* Gmelin, 1791, **g** *Thetystrombus latus* (Gmelin 1791), all gastropod specimens are stored at PAS-Martel

5) Sociocultural, SCC (historical value, HV – 0 to 4 points, educational and interpretation value, EI – 0 to 3 points, touristic interest, TI – 0 to 2 points, complementary value, CV – 0 to 2 points, community association with or public esteem, CA – 0 to 4 points)
6) Socioeconomic, SEC (urban value, UV – 0 to 2 points, mineral value, MV – 0 to 2 points, public works, PW – 0 to 2 points)

Institutional Abbreviations: MDLCA, Museo Sardo di Geologia e Paleontologia "Domenico Lovisato", University of Cagliari (Italy); PAS-Martel, Museo dei Paleoambienti Sulcitani – "Edouard Alfred Martel" (Carbonia, Italy); MPUR, Museo di Paleontologia, Sapienza University of Rome (Italy); MGPT-PU, Museo di Geologia e Paleontologia, University of Turin (Italy); NMB, Naturhistorisches Museum Basel (Switzerland).

Distribution and Evaluation of the Sites

One hundred palaeontological sites were analysed in this study and grouped into six areas: Capo Frasca – Costa Verde, Fluminimaggiore – Domusnovas, Carbonia – Iglesias, Isola di Sant'Antioco – Golfo di Palmas, Nuxis – Teulada, and Sarroch – Pula (Figs. 12, 13, and 16). The distribution of the sites is closely linked to the local geological context, but another factor could be the different concentration of mining activities that allowed more geological studies in specific areas. Most of the sites are in fact located in the Fluminimaggiore – Domusnovas and Carbonia – Iglesias areas that have a long mining history (Fig. 14a). Furthermore, the age of the sites is also closely linked to the geological context (Fig. 14b). For example, all of the Neogene sites are located in the Capo Frasca – Costa Verde area, while those of the Cambrian–Devonian age are mainly distributed in the Fluminimaggiore – Domusnovas and Carbonia – Iglesias areas. Quaternary sites are instead localised

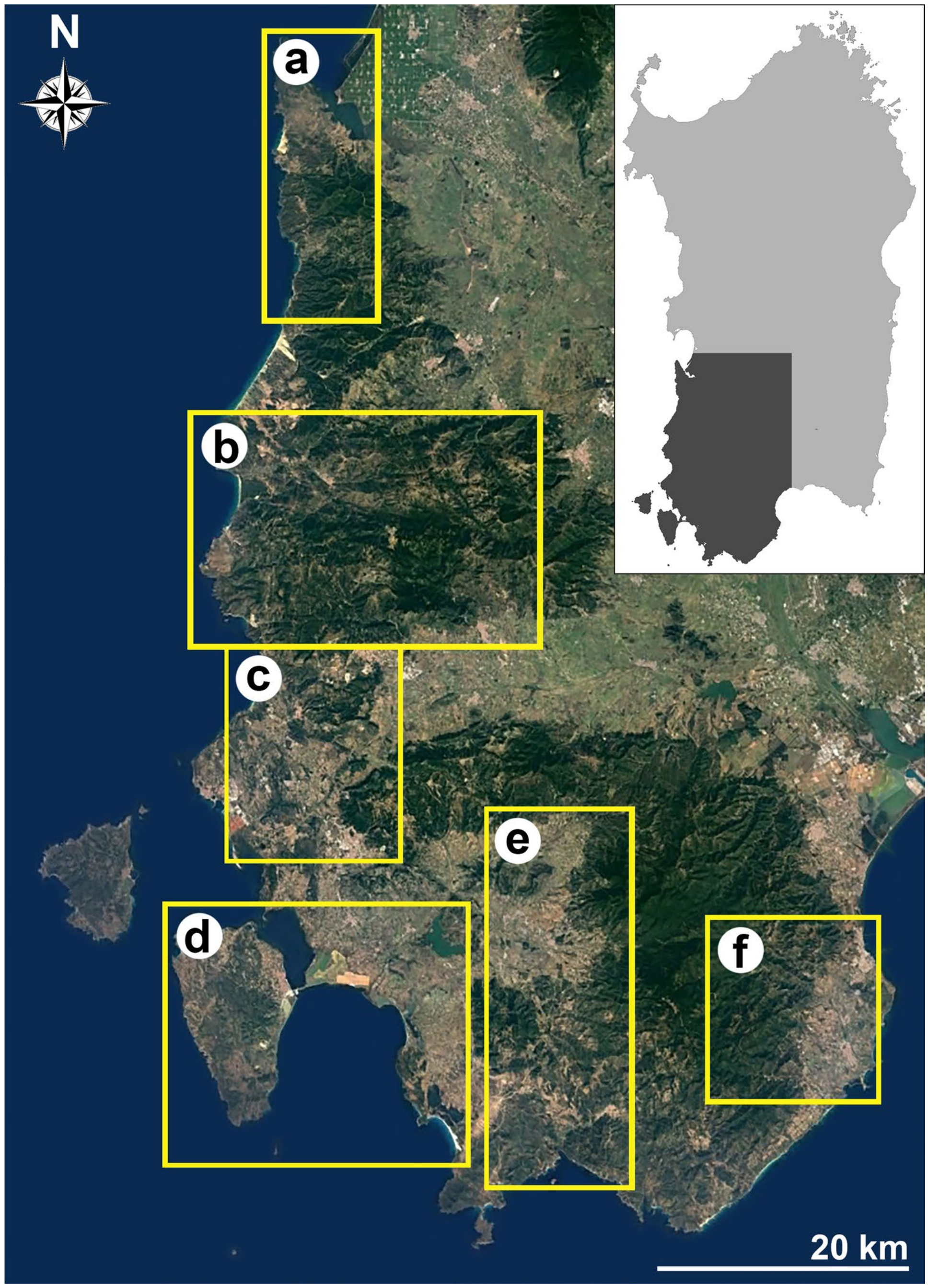

Fig. 12 The six studied areas of SW Sardinia, **a** Capo Frasca – Costa Verde area, **b** Fluminimaggiore – Domusnovas area, **c** Carbonia – Iglesias area, **d** Isola di Sant'Antioco – Golfo di Palmas area, **e** Nuxis – Teulada area, **f** Sarroch – Pula area

along the coasts (Tyrrhenian deposits, Late Pleistocene), in aeolian deposits (Middle to Late Pleistocene) or in karst areas (Middle-Late Pleistocene bone breccias), and have a relatively less constrained distribution by the geological nature of the Palaeozoic basement.

Twenty-four sites achieved a high score (score higher than 25), 6 of them are located in the Fluminimaggiore – Domusnovas area, 10 in the Carbonia – Iglesias area, 6 in the Capo Frasca – Costa Verde area, and 2 in the Nuxis – Teulada area (Supplementary Table). Unfortunately, the sites 2 and 3 of the Capo Frasca – Costa Verde area cannot be used for geotouristic purposes because these are located in a restricted military area (Fig. 13a).

The Geo-palaeontological Museum and the Possible Development of Geotourism

Sardinia has a lower population density than other Italian regions, but the Sulcis-Iglesiente sub-region is a relatively populated area due to the existence of Carbonia and Iglesias,

Fig. 13 Fossil localities; **a** Capo Frasca – Costa Verde area: 1) Donigala, 2) Sa Lisporra – Capo Frasca 3) Scogli Neri, 4) Funtanazza, 5) Sa Calada Bianca, 6) Is Argiolas Mannas, 7) Cala Campu Sali, 8) S'Archivoni, 9) Pistis, 10) Su Pistoccu (archaeological site); **b** Fluminimaggiore – Domusnovas area: 1) Monte Cuccurinu area, 2) Cuccu Aspu – Monte Azieddas area, 3) Punta Manna – Canale Matoppa area, 4) Canalgrande area, 5) Monte Sa Gloria – Schina Sa Grutta area, 6) Lago Corsi area, 7) Sa Rocca Bianca quarry, 8) Su Corovau – Cruccueu area, 9) Gutturu Pala, 10) Piscina Morta, 11) La Caletta, 12) Bunker, 13) Case Ubaldo, 14) Buggerru old road, 15) Nanni Frau mine, 16) Punta Pedrona, 17) Sa Grutta area, 18) Scruidda, 19) Su Sizzimurreddu, 20) A'Ongias, 21) Ovile Piras, 22) Monte Argentu area (Campu Cabras, Riu Sa Palma), 23) Su Delegau, 24) Fluminimaggiore southern area, 25) Billittu, 26) Medau Murtas – Roia Srappas area, 27) Galemmu – Perde Fogu Area, 28) Riu S'Acqua Frisca, 29) Perda Muzza area, 30) Cona Arrubiu, 31) Piasteddu, 32) Punta S'Argiola, 33) Genna Muxerru area, 34) Genna Quadroxiu, 35) Terra Murus – Mason Porcus area, 36) Perda S'altari, 37) Corti Baccas, 38) Cabina Enel, 39) Punta Su Nuraxi, 40) Is Oreris area (Cava Alabastro, Cava Santa Lucia, Cava Grande); **c** Isola di Sant'Antioco – Golfo di Palmas area: 1) Punta Tonnara, 2) Su Port 'e Su Trigu, 3) Monte Sarri, 4) Maladroxia South, 5) Serra Is Tres Portus, 6) Coequaddus, 7) Porto Botte, 8) Porto Pino, 9) Punta Saline, 10) Punta Maggiore, 11) Cala Lunga, 12) Cala Sapone, 13) Maladroxia northern area, 14) Cala Francese, 15) Cannisone; **d** Nuxis – Teulada area: 1) Grutta de Su Montixeddu (archaeological site), 2) Su Peppi Mereu quarry, 3) Grotta Cava Romana, 4) Grotta di Is Zuddas, 5) Grotta Campanaccio, 6) Grotta di Monte Meana, 7) Grotta Sa Cona; **e** Sarroch – Pula area: 1) Punta S'Omu de Is Abis, 2) Castello Carzola, 3) Monte Padenteddu, 4) Fradis Minoris

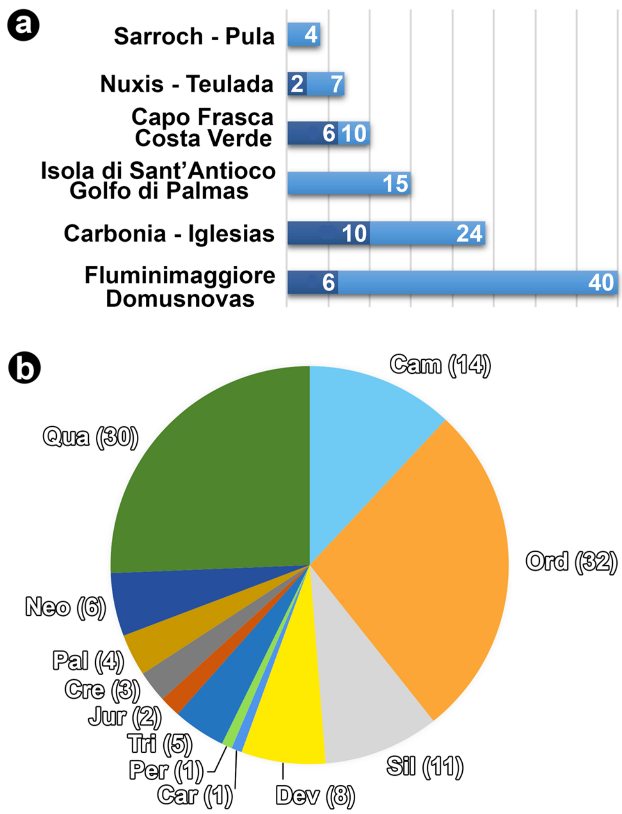

Fig. 14 Distribution of fossil sites considered in the study, **a** in light blue bars the total number of sites in the different areas, in dark blue bars the number of sites with high scores for each areas, **b** ages of the sites (N.B. some sites may present outcrops and fossils having different ages)

two of the larger cities of the island. The geo-palaeontological sites located near roads ad inhabited centres are easily accessible by the population and therefore can be more easily inserted into geotourist paths than others located in inaccessible and badly connected areas. One of the most important geo-palaeontological museums of Sardinia is located in the municipality of Carbonia and could become the starting point for planning geotouristic itineraries in SW Sardinia.

The PAS-Martel of Carbonia

The PAS-Martel is located in the area of the former coal mine of Serbariu (Grande Miniera di Serbariu, Carbonia) (Fig. 15). The museum was born due to the initial contribution of some members of the speleological group of Carbonia (Gruppo Speleologico E.A. Martel), who collected rocks, minerals, and fossils in the Sulcis-Iglesiente area since the 1970s. Over time, the museum expanded its collection, thanks to purchases, donations, and deposits. Between the end of the 1980s and the early 1990s, the fundamental contribution of the then Municipal Administration of Carbonia allowed the museum to make use of new furnishings that considerably improved the exhibition itinerary. Originally, the museum collection was housed in a small building near the centre of Carbonia, but in 2008, it has been moved to the large halls of the pavilion of the former mechanical workshops of the Serbariu mine.

The new museum consists of an area of approximately 1740 m^2, of which approximately 1050 m^2 are used for the exhibition and educational activities. The current exhibition has over 600 specimens (rocks and fossils) exposed in showcases and in tactile tables. The materials are divided into two distinct exhibition routes, the first one deals the geoevents and the bioevents recorded in the rocks of the SW Sardinia. Rocks and fossils are chronostratigraphically displayed from the lower Cambrian to the Holocene. Furthermore,

Fig. 15 The Museo dei Paleoambienti Sulcitani – E.A. Martel of Carbonia, **a** external view of the museum, **b** the large panel showing the planimetry of the museum, **c** the main hall, **d** the biodiversity path

panels with palaeogeographic maps and palaeoenvironmental reconstructions accompany the visitors through each geological period. The PAS-Martel is of great regional and national importance; in fact, the oldest fossil organisms of Italy such as archaeocyathan and trilobites dating back to the lower Cambrian are housed in the museum. Very interesting fossils are also those belonging to the Pleistocene insular mammals such as the Sardinian dwarf mammoth and the Sardinian pika (*Prolagus sardus*). The second exhibition route is dedicated to the palaeobiodiversity. The fossils of this section come from all over the world and are sorted on the basis of the systematic group. The new arrangement of the museum increased the educational offer for children through various activities aimed for every age group (Pillola 2000; Zoboli and Pillola 2020).

Geoitinerary

The PAS-Martel is liked to the main city of Cagliari, served by an airport, via private and public transport such as trains and buses. The museum is a walkable distance from the Carbonia train station, and it is also well connected to the nearby villages of SW Sardinia. These features allowed to design of a series of geotouristic routes extending in the Sulcis-Iglesiente area. Three of these with a starting point from the PAS-Martel are illustrated below (Fig. 16, Table 1):

Route 1—The first route link the museum to the eastern area of Carbonia dominated by the karst valley of Rio Cannas. Several caves and abandoned quarries with fissure fillings with Pleistocene bone breccias are present along the valley (e.g. Cannas, stop 1). Grotta dei Fiori is one of the most interesting caves in the area (stop 2). Bone breccias and deposits from the Middle–Late Pleistocene are present inside and outside this cave. Here, bird and mammal remains were collected, including the holotype of the endemic canid *Cynotherium malatestai* (Pavia and Bedetti 2003; Boldrini et al. 2010; Madurell-Malapeira et al. 2015) (Fig. 11c). Lower Cambrian rocks of the Nebida and Gonnesa groups (stages 3 and 4) outcrop along the Rio Cannas valley (stop 3), which palaeontological content consists of trilobites, archaeocyathans, and ichnofossils (Fig. 16c). The holotype of the trilobite *Giordanella vincii* was collected in this area (Pillola 1991). Finally, the Mesolithic site of Su Carroppu shelter (stop 4) is located after the small village of Sirri (stop 4). This site hosted human remains dated about 10,000 y BP (Modi et al. 2017).

Route 2—The second route is located in the northern area of Carbonia, between the villages of Barbusi, Caput Aquas, Medau Brau, and Medau de Is Perdas. A well-exposed portion of the Palaeozoic succession makes this area very interesting. In fact, several fossiliferous localities from the Cambrian (Monte Pertunto, stop 5), Ordovician (Cannamenda 1–2, stops 3 and 4) (Fig. 16e), Silurian (Medau Brau, stop 2), and Silurian–Lower Devonian (Medau de Is Perdas, stop 1) are present along this route. Various holotypes were collected in these localities such as Ordovician trilobites of the Portixeddu Fm. (*Deanaspis*? *novaresei*, *Thaleops* [*Amphoriops*] *zoppii*, *Actinopeltis iglesiana*, *Eccoptochile tumifrons*, *Lichas vinassai*, *Dicranopeltis ubaldoi*, *Diacanthaspis* [*Diacanthaspis*] *tariccoi*) and Silurian invertebrates (e.g. the bivalve *Joachymia barbusi* and the graptolite *Subduriagraptus cortoghianensis*) (Kriz and Serpagli 1993; Storch and Serpagli 1993; Hammann and Leone 1997, 2007). Furthermore, outcrops of the Lignitifero Fm. (Eocene) are well exposed in the abandoned coal mine of Piolanas (stop 6) in which coal layers alternating with fossiliferous limestones and marls rich in invertebrate and plant remains are present (Fig. 9c).

Route 3—The third route is the longest and extends in the area between Carbonia and Iglesias, but most sites are located in the territory of Gonnesa. This last area is characterised by palaeontological sites and abandoned mines such as the laveria of Seddas Moddizzis mine (stop 8, Fig. 2e). Various holotypes of lower Cambrian trilobites were found in this area (*Sardoredlichia frabouleti*, *Dolerolenus coutessolei*, and *Dolerolenus longioculatus*) (Pillola 1991). Great importance also have the mining area of Cabitza – Campo Pisano (stop 14, Fig. 16d), where the type material of the middle Cambrian trilobite *Eccaparadoxides mediterraneus* was collected (Pompeckj 1901; Dies Álvarez et al. 2010). Some fossil localities of the Lower Ordovician (stop 7) and Upper Ordovician (stops 9–12) are also present in the Gonnesa area. These latest sites have a very rich fossil content of the Portixeddu Fm. such as the Sa Siliqua site (stop 10), where the type material of the trilobite *Sardoites pillolai* was found (Hammann and Leone 2007). The Sardic Unconformity ascribed to the Sardic Phase is well visible along the Strada Provinciale 83 (stop 12, Fig. 2c). The lacustrine deposits of the Carboniferous of San Giorgio basin (stop 15) and the Permian of Guardia Pisano (stop 3) have great scientific importance. In the first site, several outcrops rich in plant remains sometimes preserved in life position are present (Fig. 16f), while in the latter, some plants (mainly ferns) and small fresh-water vertebrates were collected such as the holotype of the hybodontoid shark *Lissodus sardiniensis* (Fischer et al. 2010). The Cenozoic localities include Terras de Collu (stop 2) where the fossil of the oldest Italian mammal was found (Fig. 9a, b) and the outcrops of the fluvial Cixerri Fm. from which remains of fresh-water turtles were collected (stops 1 and 4, Fig. 9e) (Georgalis et al. 2020; Zoboli et al. 2022). Finally, the Pleistocene sites are represented by the ichnosites of Porto

Fig. 16 The proposed geoitinerary, **a** the routes and the main fossil localities of the Carbonia – Iglesias area, Route 1: M) PAS-Martel, 1) Cannas, 2) Grotta dei Fiori, 3) Rio Cannas valley, 4) Su Carroppu (archaeological site). Route 2: 1) Medau de Is Perdas, 2) Medau Brau, 3) Cannamenda 1, 4) Cannamenda 2, 5) Monte Pertunto, 6) Piolanas coal mine. Route 3: 1) Medau Is Fenus, 2) Terras de Collu, 3) Guardia Pisano, 4) Murecci, 5) Porto Paglia, 6) Funtana Morimenta, 7) Mont 'e Cani, 8) Seddas Moddizzis area, 9) Plage 'e Mesu road, 10) Monte Vincis – Sa Siliqua area, 11) Funtanamare area, 12) Sardic Unconformity (along road SP83), 13) Monte San Giovanni area and Grotta Santa Barbara, 14) Cabitza – Campo Pisano area, 15) San Giorgio. **b–g** Fossils in the routes: **b** PAS-Martel sign; **c** large invertebrate ichnofossil, Punta Manna Fm. (stage 3, *Dolerolenus longioculatus* biozone), Rio Cannas valley (route 1, stop 3); **d** cranidium of trilobite (*Eccaparadoxides mediterraneus*), Cabitza Fm. (Cab3, Guzhangian), Cabitza – Campo Pisano area (route 3, stop 14); **e** grey siltstone with brachiopod remains, Portixeddu Fm. (Upper Ordovician), Cannamenda 1 (route 2, stop 3); **f** trunk of arborescent horsetail (*Calamites* sp.) in life position, San Giorgio Fm. (Moscovian), San Giorgio basin (route 3, stop 15); **g** footprint of megacerine deer (*Bifidipes* isp.), Pleistocene of Porto Paglia (route 3, stop 5)

Paglia (stop 5, Fig. 10a–c) and Funtana Morimenta (stop 6, Fig. 10d) (Zoboli and Pillola 2021) and the bone breccias of Monte San Giovanni (stop 13) where the holotype of the Pleistocene mustelid *Enhydrictis galictoides* was found (Fig. 11b) (Major 1901). Furthermore, the Grotta di Santa Barbara is located in this area. This is a tourist cave discovered in 1952 during the mining activities of the San Giovanni lead–zinc mine (Bindua, Iglesias).

Final Considerations

Among the geosciences, palaeontology is probably one of the most relevant disciplines for divulgation to the general public, as shown by the numerous palaeontological museums or prehistoric theme parks. In addition, TV documentaries, films, video games, toys, and books, dedicated to prehistory have flooded pop culture for many years now. Such interest

Table 1 Stops of herein proposed routes starting from PAS-Martel (Carbonia). Cam. Cambrian, Ord. Ordovician, Sil. Silurian, Dev. Devonian, Car. Carboniferous, Per. Permian, Tri. Triassic, Pal. Paleogene, Qua. Quaternary. Main fossils: Inv. invertebrates, Ver. vertebrates, Pla. plants, Ich. ichnofossils

Route	Stop	Locality	Municipality	Age	Main fossils	Score
1	1	Cannas	Carbonia	Qua.	Ver.	19
1	2	Grotta dei Fiori	Carbonia	Qua.	Ver.	26
1	3	Rio Cannas valley	Carbonia	Cam.	Inv./Ich.	23
1	4	Su Carroppu	Carbonia	Qua.	Ver.	30
2	1	Medau de Is Perdas	Carbonia	Sil.-Dev.	Inv.	16
2	2	Medau Brau	Carbonia	Sil.	Inv.	15
2	3	Cannamenda 1	Carbonia	Ord.	Inv.	18
2	4	Cannamenda 2	Carbonia	Ord.	Inv.	18
2	5	Monte Pertunto	Carbonia	Cam.	Inv.	13
2	6	Piolanas mine	Carbonia	Pal.	Inv./Pla.	21
3	1	Medau Is Fenus	Carbonia	Pal.	Ver.	17
3	2	Terras de Collu	Gonnesa	Pal.	Inv./Ver.	26
3	3	Guardia Pisano	Gonnesa	Per./Qua.	Ver./Pla.	27
3	4	Murecci	Gonnesa	Pal.	Ver.	11
3	5	Porto Paglia	Gonnesa	Qua.	Ver./Ich.	27
3	6	Funtana Morimenta	Gonnesa	Qua.	Ich.	31
3	7	Mont ‘e Cani	Gonnesa	Ord.	Inv.	17
3	8	Seddas Moddizzis area	Gonnesa	Cam.	Inv./Ich.	25
3	9	Plage ‘e Mesu road	Gonnesa	Ord.	Inv.	16
3	10	Monte Vincis - Sa Siliqua area	Gonnesa	Ord.	Inv.	16
3	11	Funtanamare area	Gonnesa	Ord.-Dev./Tri.	Inv.	23
3	12	Sardic unconformity (SP83)	Gonnesa	Cam.-Ord.		
3	13	Monte San Giovanni area	Gonnesa/Iglesias	Cam./Qua.	Inv./Ver.	27
3	14	Cabitza - Campo Pisano area	Iglesias	Cam.-Ord.	Inv.	28
3	15	San Giorgio	Iglesias	Car.	Inv./Pla./Ich.	33

can be funneled to raise citizens' awareness and, above all, government commitment to perform protection and enhancement interventions of geo-palaeontological sites.

The great palaeontological heritage of the SW Sardinia has been underlined. The numerous geo-palaeontological sites scattered throughout the Sulcis-Iglesiente highlight the long and complex geological history of this sub-region of Sardinia, the geologically oldest area of Italy. This territory undoubtedly has a rich natural, archaeological, and historical heritage that attract tourists annually, especially during the summer. The abundance of abandoned mines also testifies a profound connection with the geological resources of the area. Different museums and cultural centres dedicated to geology, speleology, palaeontology, and mining activity are indeed present in the territory such as the "Ecomuseo Miniere di Rosas" (Narcao), the "Sa Marchesa—Sito Geo Speleo Archeologico" (Nuxis), the "Museo dell'Arte Mineraria" (Iglesias), and the "Museo del Carbone – Centro Italiano della Cultura del Carbone (CICC)" (Carbonia). Among these, the PAS-Martel of Carbonia represents a unicum and significant tourism resource for SW Sardinia. Despite its brief history, the museum curates a rich and diverse geological and palaeontological heritage that could represent a relevant source for educational and geotourism purposes.

Finally, the available data herein reported clearly indicate that the great number of palaeontological sites, their scientific and historical relevance, and their spatial distribution could easily fit into a series of geotourism routes. SW Sardinia is an economically poor area; therefore, the creation of new development opportunities through cultural tourism, such as geo-palaeontological routes linked to the local museums, could provide an additional useful contribution for its socioeconomic growth.

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Declarations

Conflict of Interest The author declares no competing interests.

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