

A multi-disciplinary study of deformation of the basaltic cover over fine-grained valley fills: a case study from Eastern Sardinia, Italy

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Abstract The Pliocene to Early Pleistocene volcanic activity which generated the basaltic plateau of the Orosei-Dorgali area in Eastern Sardinia led to the disruption of the local hydrographic network by damming some tracts of the fluvial valleys incised in the granite basement. This resulted in the formation of lacustrine basins, whose fine-grained fills were partly interfingered and eventually covered by younger lava flows. In the SW part of the plateau, close to the Galtelli village, a number of unknown depressions, locally named “Paules,” were formed. In order to reconstruct their subsurface structure, two electrical resistivity tomography surveys were carried out across these depressions. The geophysical results, which demonstrate the existence of a disrupted layered system, were used to build a numerical geomechanical model that suggest the depressions originated by local collapses of the basaltic cover due to the compaction of the underlying fine-grained valley fills.

Keywords Plio-Pleistocene basaltic plateau · Loading subsidence · Electrical resistivity tomography · Geomechanical modeling

Introduction

The extensive basaltic plateau surrounding the Mesozoic limestone of the Monte Tuttavista near Orosei (Eastern Sardinia) (Fig. 1) in the SW part, hosts a number of flat-bottomed, closed depressions, locally with stepped margins, with roundish and commonly elongated and irregularly lobate shapes (Fig. 3), known as “Paules.”

“Paule” is a term in Sardinian language meaning marsh, and it is related to the clayey marshy bottom of a closed depression, where water tends to accumulate because of limited drainage. In recent times, the marshy bottoms of the Sardinian Paules have generally been reclaimed for agricultural use. Most of these depressions occur in an area located close to Cantoniera Paules (“Cantoniera Paludi” in the more recent topographic IGM map: coordinates: 40° 21' 10. 23" N; 9° 33' 00.61" E, SW of Galtelli) (Fig. 1). Five Paules have been identified in an area of 5 km × 2 km, intersected by the road S.S. 129 Trasversale Sarda between the 18- and 22-km markers. From west to east, the Paules are named according to toponyms: Fruncudunue, Porcargios, Biriddo, Manolitto and Dorrisolo (Fig. 3). Elongated Paules, such as Dorrisolo and Biriddo, are closer to the Cedrino River valley, that runs to the east of them, and are oriented in a NNE–SSW direction, sub-parallel to the local trend of this valley (Figs. 1, 2, 3). The maximum depression to the bottom of the Paules is about 5 m.

The Paules (Fig. 3) have shapes ranging from subcircular (Paule in locality Porcargios: about 240 m × 290 m) to elongate–lobate (Paule in locality Dorrisolo: length of 670 m; Paule in locality Biriddo: length 1250 m) to irregularly lobate (Paule in locality Fruncudunue: about 1175 m × 825 m; Paule in locality Manolitto: about 175 m × 110 m).

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Fig. 1 Geologic sketch map of the eruptive district of Orosei-Dorgali (Dieni and Massari 1966, slightly modified). 1 Basaltic lava flows (late Middle/early Late Pliocene to Early Pleistocene) interfingering with clay, sand and gravel of the Nuraghe Casteddu Formation (NCF). Circles with a number refer to main eruptive centers (see Dieni and Massari 1966) 2 Tertiary formations and Quaternary deposits. 3 Jurassic and Cretaceous limestone and dolostone. 4 Pre-Mesozoic basement (granite and schists). 5 Main faults. 6 Bed attitude. P area of “Paules”. A–A' and B–B': geological sections shown in Fig. 2

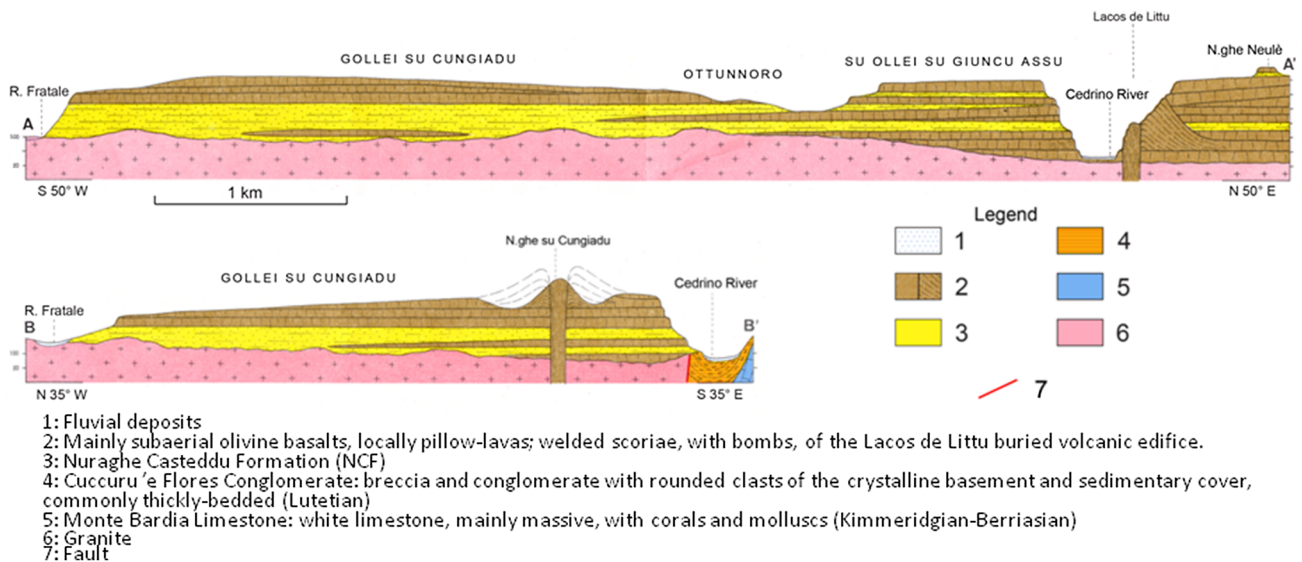
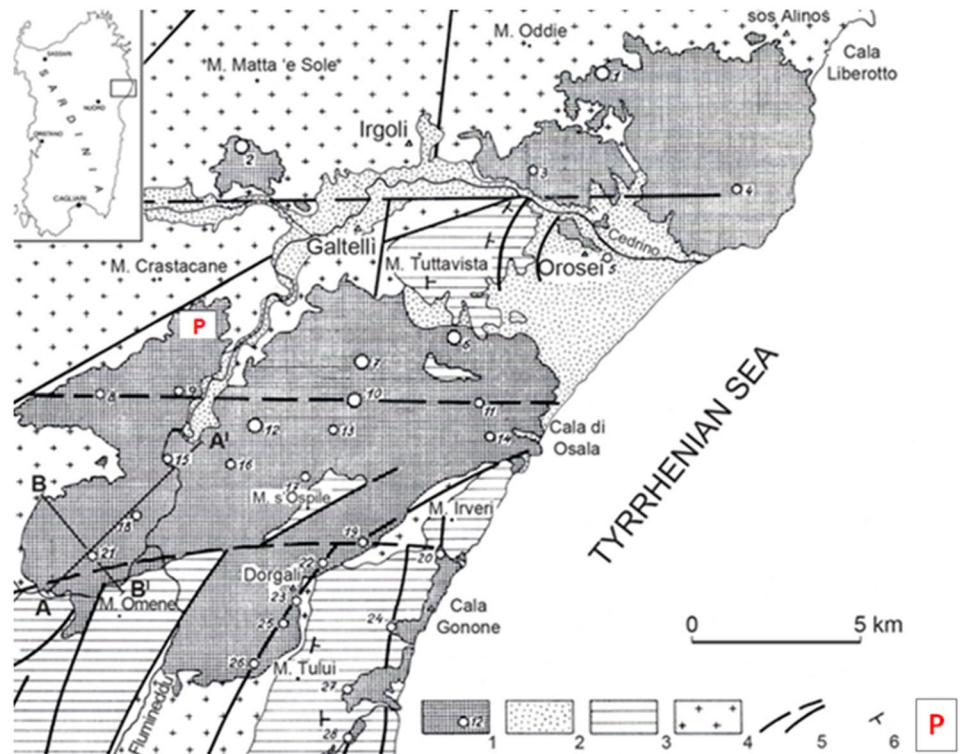


Fig. 2 Geological sections across the basaltic Orosei-Dorgali plateau (traces in Fig. 1). (Massari and Dieni 1973, slightly modified)

The origin of these depressions is unknown. Calvino et al. (1959) interpreted these depressions as distal areas not covered by the lava flows, i.e., far from the eruptive centers. Other genetic interpretations hypothesized a relationship with the processes/forms linked to the volcanic activity, such as the collapse of lava tube roofs (Greeley

1971; Greeley and Hyde 1972; Peterson and Swanson 1974) or craters, possibly turned into lava lakes (Jaupart and Vergnolle 1989).

Geological field surveys have ascertained that the basaltic lavas of the Orosei-Dorgali volcanic district overlie and interfinger with clayey sandy deposits

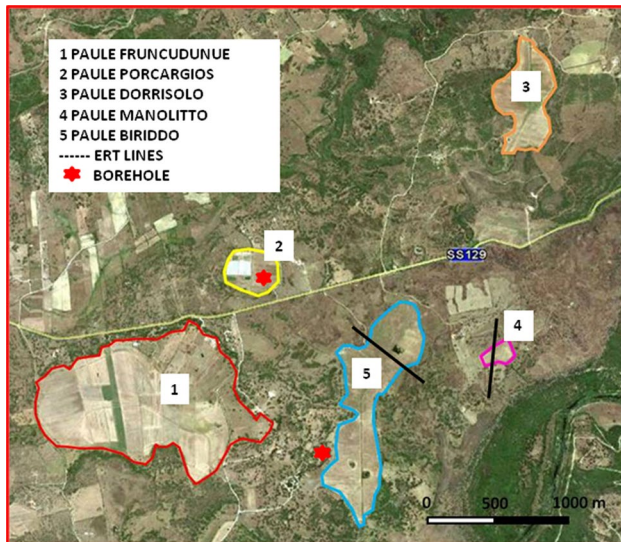


Fig. 3 Google Earth view of the Paules area, near Galtelli (Nuoro), eastern Sardinia, Italy, successively modified

of a fluvio-lacustrine formation, called the Nuraghe Casteddu Formation (NCF) (Massari and Dieni 1973). This formation could have been generated by the disruption of the local hydrographic network by damming some tracts of the fluvial valleys incised in the granite basement. In this view, another hypothesis about the origin of the Paules could contemplate the collapse of the layered system described above (granite, NCF, basalt), due to the gradual expulsion of the water trapped inside, given the additional load caused by the weight of the basaltic cover. Two boreholes drilled for water supply inside and outside two of these depressions locally confirm the existence of this geological sequence. The borehole inside the “Paule” showed: (1) a first thin layer of soil deposit to 2 m depth; (2) a second layer about 2 m thick of weathered basalt; and (3) a sequence of granitic soils down to the fractured granite basement about 100 m depth.

The borehole outside the “Paule” showed a geological sequence composed of: (1) an alternation of weathered and unweathered basalts and soils down to 23 m depth; (2) a 17-m-thick layer of weathered granite; and (3) unweathered granite down to 100 m depth. However, up to now no specific study has been conducted to ascertain the subsurface evidence supporting one or another of the above hypotheses.

Lamarmora (1857) and Lauro (1937) reported another type of shallow marshy depressions named “Pauli,” filled with slack water for the most part of the year, hosted in the basaltic plateau known as “Giara di Gesturi” in central Sardinia. These depressions are elongated with an

extent of some hundreds of square meters, and appear radially oriented relative to the eruptive cones of Monte Zeppara Manna and Monte Zeppareda. The radial-elongated orientation relative to the cones suggests an origin linked to the volcanic activity, such as depressions left in the intermediate areas between lava tongues. These Pauli in the Giara di Gesturi, given their shape and orientation with respect to the volcanic cones, thus appear to have a clear origin, which in turn is likely to be different from that of the depressions in Orosei-Dorgali area. In addition, the geology of the Giara di Gesturi also points toward a different genesis of the depressions, given that the Giara is a tabular basaltic upland overlying tertiary formations of the lower-medium Miocene, slightly inclined toward the north, with a contact surface fairly planar and uniform.

The main goal of this manuscript is to help define the subsurface structure of the depressions in the Orosei-Dorgali basaltic plateau, as this structure, in turn, can provide evidence that can discriminate between the different genetic hypotheses of these depressions, as formulated up to now. To this end, geophysical measurements were taken, and particularly electrical resistivity tomography (ERT) surveys, across two of these depressions (Fig. 3). In order to corroborate the key hypothesis resulting from the geophysical investigations, a numerical geomechanical model was built that simulates the most likely mechanism of generation of these depressions, using possible ranges for the geomechanical properties of the local geological formations.

Geological setting

The Orosei-Dorgali volcanic district covers an area of 150 km², and its eruptive centers are distributed along N–S to NE–SW tectonic lineaments, particularly concentrated at the intersection of these trends and the subsident E–W trending faults (Teichmüller 1931). The volcanic activity led to extensive successions of lava flows, infilling topographic lows and accumulating to form a plateau. This plateau is thought to have been of the fissural type in the initial stage, followed by a great number of central edifices, active almost simultaneously in a restricted area (Fig. 1). Considering only the recognizable volcanic edifices rising at present from the surface of the plateau and neglecting those which are buried below the younger lava flows, up to thirty edifices have been identified (Dieni and Massari 1966; Massari and Dieni 1973).

The basalts of the Orosei-Dorgali volcanic district were erupted during the Plio-Pleistocene volcanic cycle (Beccaluva et al. 1977) linked to the extensional tectonics of

Sardinia and Tyrrhenian Sea, leading to the modern configuration of the Orosei Gulf (Lauro 1939; Bonicelli Vardabasso 1968). According to Beccaluva et al. (1985), the Plio-Quaternary volcanic activity in Sardinia was characterized by two distinct acmes, the older between 3.0 and 2.4 Ma and the younger around 0.4 Ma. A number of petrographic and petrochemical studies show that the eruptive activity can be defined as intraplate volcanism, mainly represented by flood basalts of mantle provenance, ranging from alkaline to transitional alkaline and subalkaline, locally associated with more evolved products (Beccaluva et al. 1985; Lustrino et al. 2000, 2002). The lavas are mainly composed of uniform basalts, with olivine, titanite, or hypersthene–enstatite and labradoritic–bitownitic plagioclase, and are characterized by abundance of peridotitic nodules (e.g., in the Osala area, Fig. 1), locally making up an important fraction of the erupted products.

The fluidity of the flows is indicated by the tabular geometry and lateral extension and by the existence of small lava tunnels, tumuli, pressure ridges, fusiform volcanic bombs, and auto-intrusive squeeze-up dykes. The volcanic activity, particularly in the last phase, was predominantly of slow effusive type, with episodes characterized by Hawaiian and Strombolian activity (Beccaluva et al. 1985). Generally, the thickness of individual lava flows is around 1 m, lesser in the distal or lateral reaches of the flows (Fig. 4) and greater in preexisting infilled topographic depressions (Dieni and Massari 1966). Sections subsequently carved into the plateau, such as those observable along the canyon of the Cedrino River, are particularly thick (Massari and Dieni 1973) and show the stacking of lava flows, commonly jointed into prismatic columns. The lava flows are sometimes intercalated with sediments from the underlying NCF. The interlava units range in thickness from a few centimeters up to some tens of meters (Fig. 2).

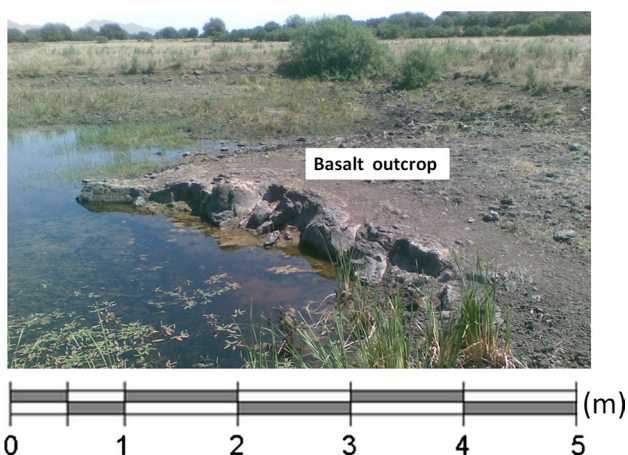


Fig. 4 Image of a basaltic outcrop in Paule Biriddo. Note the accumulation of water in the depression

The NCF sedimentary infill is mostly made of lacustrine clays in the lower part, with abundant leaf remains, and generally coarsens upwards, becoming dominated in the uppermost part by arkosic sands and granule-grade gravel, probably linked to braided river systems (Massari and Dieni 1973, Fig. 1). The deposits are predominantly derived from the granitic substrate and are still in an unconsolidated state. The NCF was assigned to the “early Villafranchian” by Marini and Murru (1981) on the basis of faunal (Esu 1978) and palynological content as well as paleomagnetic and radiometric data from the basaltic lavas. This attribution was shared by Esu and Kotsakis (1985) for the lowermost layers of the formation, which yielded mollusk and vertebrate faunas again indicating an “early Villafranchian” age, correlated by the authors with the Piacenzian stage. The same chronostratigraphic assignment has been maintained by Esu et al. (1993) in their more general study about paleobiogeographical observations on Villafranchian continental mollusks of Italy.

The lacustrine episodes identified in the NCF are related to the damming action exerted by the lava flows, leading to continuous instability of the hydrographic network, with rivers forced to change their courses many times (Massari and Dieni 1973). The influence of the volcanic activity on the hydrography and, therefore, on the distribution and stratigraphic architecture of the deposits, was likely to be pervasive, considering the large extension of the volcanic products in this area.

This volcano-sedimentary complex is considered as the record of a morphogenetic cycle characterized by the smoothing out of the topography by filling erosional depressions mainly carved into the granitic substrate (Pelletier 1960; Dieni and Massari 1966; Massari and Dieni 1973). In particular, the depressions result as a part of the former hydrographic network, incised during a major uplift-triggered erosive cycle generating deep incisions (as deep as 150 m) in the landscape. This erosion is thought to post-date a Pliocene phase of molding of the topography into wide pediments. The modern granite landscape topography, exhumed after the recent removal of the composite sedimentary-volcanic cover, clearly illustrates the deeply incised landscape existing at the time of flooding by fluvio-lacustrine deposits and lava flows.

In particular, the substrate of the volcano-sedimentary complex including sediments of the NCF and the lava flows is mainly represented by rocks of the crystalline basement, mostly granite, secondly Tertiary formations and, in the lower course of the Cedrino River between the villages of Onifai and Orosei, Lower Pliocene marine sands and clays (Fig. 2).

The age of the volcano-sedimentary complex of Eastern Sardinia is not well constrained. Chronologic tie points are the Lower Pliocene marine deposits locally

occurring in the substrate (Orosei) and the fact that the basalts of the Orosei-Dorgali district show inverse polarity (De Jong and Manzoni 1968; Massari and Dieni 1973), and should therefore be older than the Matuyama–Brunhes inversion (784 Ka). Selli and Fabbri (1971) described a conglomerate dredged from the bottom of the Orosei Canyon, off the Gulf of Orosei, at a depth of 2200 m, at a point where seismic sections highlight the cropping out of the boundary surface between a lower displaced succession and upper undisturbed units. Recently, Mariani et al. (2009) reviewed the literature on the recent volcanic deposits in Sardinia, as described by different authors (Beccaluva et al. 1977, 1985; Conti et al. 1996; Petteruti Lieberknecht et al. 2003; Lustrino et al. 2004, 2007), who highlighted the impact of lava flows on the coastline in the Western Sardinia.

Methods

Geophysical measurements

Electrical resistivity tomography measurements (e.g., Binley and Kemna 2005) provide, in general, the 2D or even 3D spatial distribution of the subsoil electrical resistivity, starting from electrical current and potential measurements at the ground surface or between two or more boreholes, according to Ohm's law. In surface acquisition, electrode spacing and total length of the electrode spread determine the spatial resolution and the investigation depth. In fact, given a fixed number of measurement channels/electrodes, a small spacing guarantees a good resolution, but is limited to a shallow investigation depth, while a larger electrode spacing reduces the resolution but increases the investigation depth. The investigation depth of ERT also depends in a nonlinear manner on the electrical resistivity distribution, where the electrical resistivity is closely related to the nature of the investigated bodies. In particular, large contrasts between the electrical properties of neighboring bodies make them easily visible from measurements taken at the ground surface. For example, in considering a porous system, pore fluids and clay content considerably reduce the sediment resistivity (Monego et al. 2010).

In the case presented here, a strong contrast of electrical properties was expected between the materials forming the subsurface of the Paules (granite and the fine-grained sediments of the NCF).

According to Reynolds (2011), the resistivity of granite, NCF (the NCF is considered as an alluvium and sand) and basalt is summarized in Table 1.

Based on these considerations, in June 2010 two ERT survey lines were carried out across the Paule Biriddo and

Table 1 Ranges of electrical resistivity values for the formations expected in the subsurface of the “Paules” (modified from Reynolds 2011)

Material	Nominal resistivity (Ωm)
Granite (weathered)	$3 \times 10\text{--}5 \times 10^2$
Basalt	$10\text{--}1.3 \times 10^7$
Clays	$1\text{--}10^2$
Alluvium and sand	$10\text{--}8 \times 10^2$
Sand clay/clayey sand	30–215
Sand and gravel	30–225

the Paule Manolitto using 48 electrodes with a 10-m spacing, for a total length of 470 m and roughly 100 m of investigation depth. In the Paule Biriddo the ERT line spanned a cross section of the northern part of the structure in NW–SE direction, while in the Paule Manolitto the ERT line was acquired in a S–N direction (Fig. 3), in order to cross the section along its minimal extent and produce as much as possible a representative 2D image of the structure.

The data acquisition was performed for both lines using an IRIS Syscal Pro instrument and a dipole–dipole acquisition scheme. To assess data quality, the acquisition comprised both direct and reciprocal data. The reciprocal data were obtained by swapping potential with current electrode measurements to have a good estimate of measurement errors (Daily et al. 2004; Cassiani et al. 2006). This procedure is fundamental in regularized least-squares inversions (e.g., Occam type inversion), while the model prediction directly depends on quantitative estimates of the error level. In this case, an error of 5 % of the average of two measurements has been used as a threshold above which data are to be rejected. The same percentage has been used as a target for the inversion performed using the ProfileR version 2.5 code (Binley 2008), based on the Occam inversion approach (LaBrecque et al. 1996).

Geomechanical modeling

As described in the introduction, a few alternative hypotheses have been proposed for the generation of the Paules. As the geophysical imaging results are compatible (see “Geophysical survey results” section) with a collapse of the layered system due to the gradual expulsion of water associated to the additional load of the basaltic cover, a numerical geomechanical model was developed, simulating the loading of the basalt lava flows on the granite-sediment system and the subsequent depletion of the pressurized water trapped in the sediments was performed. The simulations have been performed using the advanced finite element

code produced by ISAMGEO GmbH, Wiesbaden, Germany, commonly used for geomechanical simulations for the oil industry (e.g., Plischke and Cassiani 2005; Kristiansen and Plischke 2010). For all simulations, a soil constitutive model commonly adopted for clastic sediments, i.e., the well-established modified Cam Clay model (MCCM—Roscoe and Burland 1968) was used. For the granite a simpler linear elastic model was adopted, with Young's modulus equal to 500 MPa and Poisson's ratio equal to 0.3. The model reproduces the Paule Manolitto channel geometry (that can be easily approximated to two-dimensions), as obtained by the ERT results, about 80 m large and 75 m deep. The total 2D domain used for the simulations extends over 140 m width and 95 m depth. Fixed boundary conditions were considered on both lateral sides and at the bottom. The adopted finite element mesh is shown in Fig. 5. Note that the use of 2D plain strain simulations is justified by the geometry of the Paule, largely elongated in one direction.

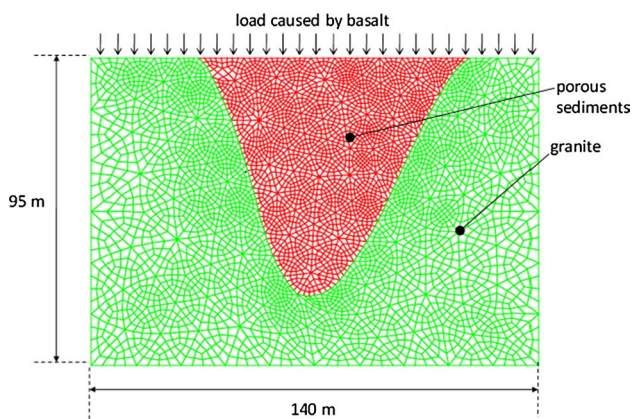
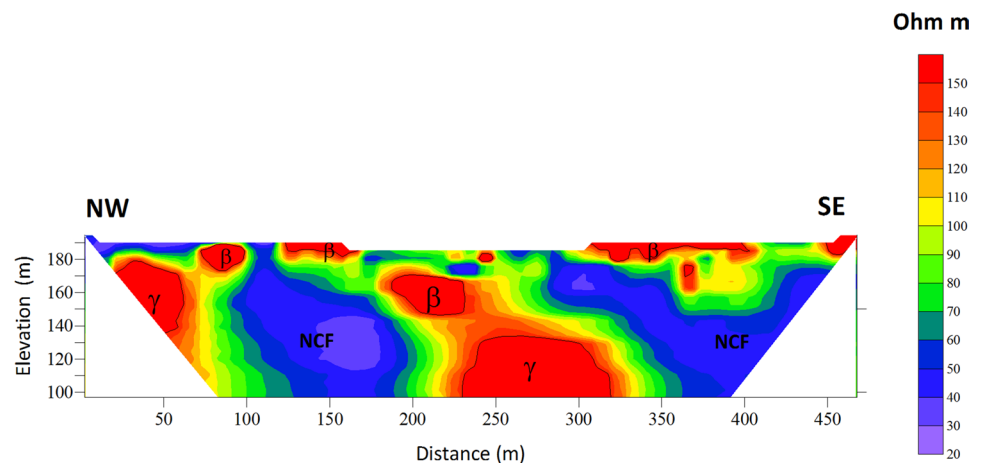


Fig. 5 Sketch of the domain considered in the geomechanical simulations. Red sediments (NCF). Green granite

Fig. 6 Result of ERT line collected in Paule Biriddo (γ = granite, β = basalt, NCF = Nuraghe Casteddu Formation): see Fig. 3 for location



Results

Geophysical survey results

The results of the ERT lines collected in Paules Biriddo and Manolitto (Figs. 6, 7) show medium to low resistivity values (20–150 Ω m) and confirm the existence of a complex, non uniform system.

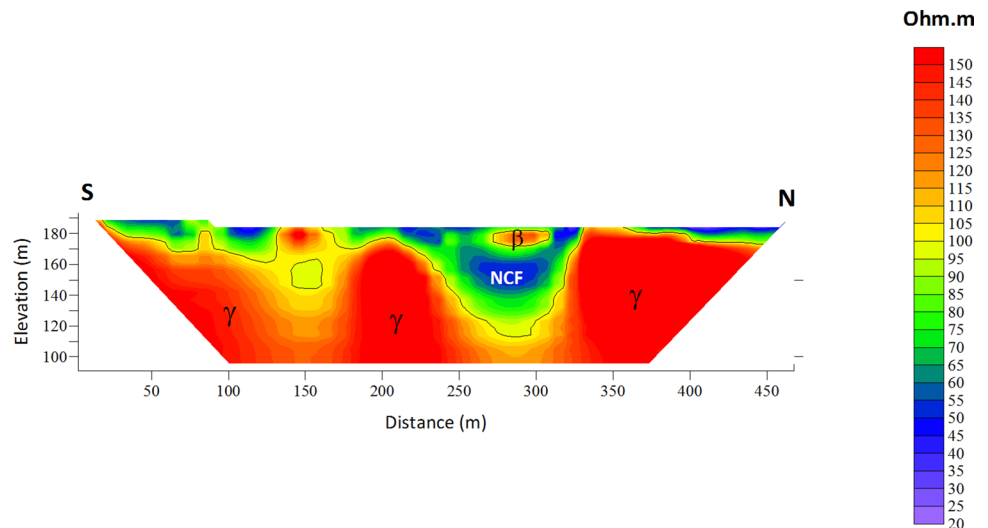
The geometry of both Paules, as investigated by ERT, clearly shows a channeled pattern. The smaller size of the Paule Manolitto allows the ERT survey to depict the full depth extent of a main conductive body, inside a channel about 80 m wide (Fig. 7).

On the other hand, the ERT section of Paule Biriddo (Fig. 6) shows two conductive bodies unconfined in the deeper part, probably evidence of large buried paleovalleys, separated by a granite central ridge, and incised for more than 100 m, thus reaching a depth larger than the maximum investigation depth possible with the given acquisition geometry.

In both sections the flanks and the bottom of the channels are interpreted as representing the partially fractured granitic bedrock. In fact, the resistivity values of this formation (150 Ω m) support this assumption (Reynolds 2011). Some resistive flat features, (130–150 Ω m) close to the ground surface are likely to correspond to partly collapsed basaltic slabs. Note that the resolution of ERT does not allow the detection of structures thinner than the electrode spacing (in this case 10 m) so that the more resistive basalt is only clearly visible where it is thick enough (about 3 to 5 m).

The low-resistivity zones (20–60 Ω m in Figs. 6, 7) may represent the NCF interposed between the basaltic cover (β) and the granite (γ). In this interpretation, the settlement of the basalt slabs in the central part of the Paules could be linked to differential subsidence effects. This mechanism

Fig. 7 Result of ERT line collected in Paule Manolitto (γ = granite, β = basalt, NCF = Nuraghe Casteddu Formation): see Fig. 3 for location



could be easier to understand for the Paule Manolitto, where the surface depression (about 5 m) appears to correspond to the central part of the channel, where the NCF thickness is maximum (Fig. 7). In the Paule Biriddo, the same depression value (about 5 m) is also localized in the central part of the structure, even though a granitic ridge seems to be located at the center of the ERT profile (Fig. 6).

Geomechanical modeling results

The basalt emplacement is simulated by adding a vertical load to the system equal to the weight of the basalt slab: For an assumed basalt thickness of 5 m (density about 2700 kg/m³), the resulting load is about 1.35 bar (Fig. 5). The assumption is that, at the time of basalt emplacement, the infilling sediments were saturated with water and were open to the atmosphere above, before lava arrival. In the simulations, initially, the pore pressure was hydrostatic (with a freshwater density of 1000 g/dm³) and the sediments were normally consolidated. The basalt load caused the water body to be suddenly confined, under undrained conditions, so the total basalt load is carried jointly by the sediment matrix and the water. As a result, the pore water pressure increases suddenly to 1 bar (above atmospheric pressure) and subsequently, over an undefined time period and depending on the sediment permeability, the resulting water overpressure was dissipated and the water in the saturated sediments returned to the original conditions, with the pressure of the top surface equal to atmospheric pressure. A linear pressure decline over time is assumed in the simulations.

The most critical aspect of the simulations is the choice of the governing parameters for the MCCM, that control the sediments’ geomechanical behavior. A

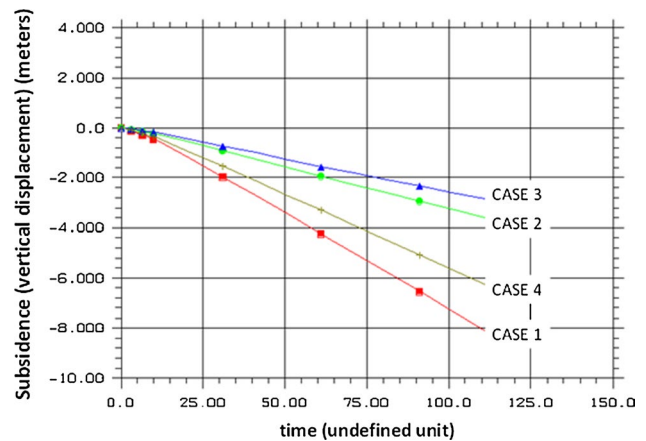


Fig. 8 Time-history plot showing the vertical displacement in the center of the simulated channel in the four cases studied with the observed ground subsidence, given the expected geometry and the geomechanical characteristics of the four cases studied

limited parametric study was performed, varying the two most important MCCM parameters, i.e., the compaction index λ and the reference void ratio e_0 , within the ranges usually considered for shallow soils according to Wood (1991). The following four cases were considered:

- Case 1: $\lambda = 0.6, e_0 = 0.3$
- Case 2: $\lambda = 0.3, e_0 = 0.3$
- Case 3: $\lambda = 0.3, e_0 = 0.6$
- Case 4: $\lambda = 0.6, e_0 = 0.6$

Figure 8 shows the vertical displacement (subsidence) of the central point of the channel, at the ground surface, as a function of the undefined time scale during which the initial overpressure is fully dissipated. As shown, the

corresponding surface subsidence varies in magnitude roughly between 3 and 8 m, encompassing the observed range of topographic lows at the centers of the observed Paules. Note that the simulations assume that the basalt slab has no mechanical resistance, as expected once the basalt is fractured due to thermal shrinking. This fracturing would also facilitate the water escape and the pressure progressive reduction. From this parametric study it can be concluded that the hypothesized mechanism of collapse is perfectly compatible with today's observed system, also with respect to the subsurface structure as imaged by geophysical surveys.

Discussion

The ERT surveys conducted on the Paules Biriddo and Manolitto have provided fundamental information for the imaging of the subsurface structure of the two depressions, in particular given a geoelectrical characterization of the different subsoil formations. In particular, this new evidence help discriminate between genetic hypotheses formerly put forward for the existence of the Paules. The range of measured electrical resistivity values leads to excluding the presence of large voids in the subsurface, thus making it very unlikely that the hypothesis suggesting the depressions may be caused by the collapse of cavities such as lava tubes. A second key result of the ERT surveys is the confirmed presence of deeply incised paleovalleys, with depths in the 150-m range, likely to be currently filled by fine-grained material (appearing thus as electrically conductive). The observed resistivity values are compatible with literature values for a sequence of granite, loose sediments, and basalt (Table 1), thus confirming the existence beneath the Paules of valleys deeply carved in the granite bedrock, filled with the NCF sediments and subsequently covered with the more recent basaltic flows. The information above has been used to develop a geomechanical model that produces results compatible with a subsidence mechanism driven by the expulsion of water from the loose sediments of the NCF trapped by the basalt lava above.

Note that some simplification has been necessarily introduced in the conceptual scheme and consequently, in the numerical model used. In particular the emplacement of lava on the riparian zone of the paleoriver must have occurred not directly onto water-filled sediments (with the exception of the river bed) but onto a thin layer of unsaturated sediments with a very shallow but not emerging water table. Therefore, the direct contact of lava and water probably occurred at only a few locations. This does not mean that a pressurization of the water in the sediments could not occur in a relatively short time after the lava emplacement,

as a consequence of compaction of the shallow unsaturated zone and the underlying sediments. This initial short-time transient phenomenon was not modeled, which would also be coupled with water flow upward within the sediments, as there is practically no information on the detailed parameters involved, but rather the model concentrated on the longer-term dissipation of the water pressure partly due to the fracturing of the basalt cover itself and the consequent water outflow.

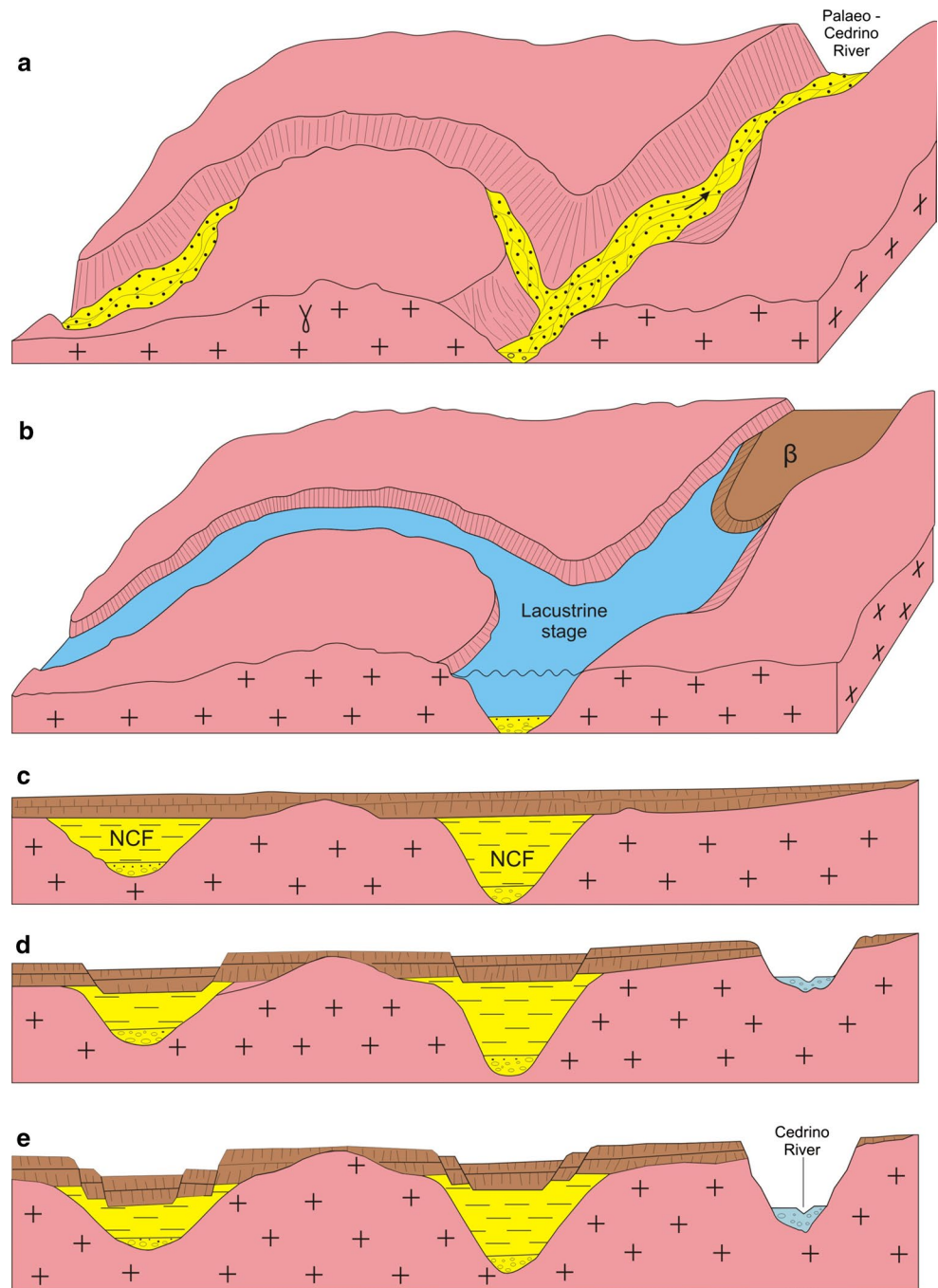
Peperites have also not been observed in the area, and if present may be supporting evidence for the contact of lava with water-filled sediments. This contact may not have been direct, as explained above, but only after a certain lapse of time during which lava may have solidified or anyway cooled down enough not to cause violent water vapor outbursts. Also, the genesis of peperites is often debated (White et al. 2000; Skilling et al. 2002), but in all cases it seems to require substantial energy to provide physical mixing of magma and loose sediments, often facilitated by a fully saturated conditions of the sediments themselves. This occurs, for example, in the Columbia River Basalt Group (CRBG) district case (Hooper 1987; Hooper and Conrey 1989), where very large masses of lava have been emplaced rapidly (Self et al. 1996). However, substantial differences exist with the CRBG case, where volumes and thus thicknesses of basalt cover are much larger than observed in the Orosei-Dorgali district. This implies, incidentally, that collapse structures such as the Paules are unlikely to take place, and in fact are not reported there. In the case of the Orosei-Dorgali district, the very fluid lava flow is testified by the small thicknesses and large extent of the basaltic cover, and consequently the energy associated to accumulation of mass during lava flow was certainly not very large, and the generation of peperites very unlikely.

Conclusions

The following conclusions can be drawn from the combination of the geophysical survey, the geomechanical modeling, and the analysis of geological and paleogeomorphological setting of the investigated area.

The geophysical survey highlights that the substrate of the Paules corresponds to sediment-infilled depressions with V-shaped sections suggestive of fluvial incised paleovalleys. Moreover, the Paules show a rough alignment in a NNE–SSW direction, which is subparallel to the local trend of the present-day Cedrino River valley (Fig. 1), suggesting that the depressions revealed by the geophysical survey are roughly aligned along a major paleodrainage axis corresponding to ancient, abandoned courses of the Cedrino River and linked tributaries, arguably active prior to the onset of eruptions (Fig. 9a).

Fig. 9 Three-dimensional sketch of the geomorphological evolution of the study area, before (a) and after (b) the volcanic event, and schematic sections (c–e) depicting the collapse of basaltic flows into the fine-grained valley fills: γ = granite, β = basalt, NCF = Nuraghe Casteddu Formation (not drawn to scale)



In the earlier stage of volcanic activity, basaltic lava flows invaded the topographic lows and caused a drastic change in the drainage network, with diversion of the fluvial courses. Due to the damming effect exerted by the lava flows, the residual segments of this abandoned paleovalley network, through which streams no longer ran, became the site of pools and small lakes (Fig. 9b), where fine-grained sediments could gradually accumulate up to the ultimate infill of the depressions. Eventually, lava flows related to the late stage of the eruptive activity levelled the topography, and

covered even these sediment “plugs” (Fig. 9c). Using the ERT results, that confirm the existence of a layered system in accordance with the geological setting reported by Masari and Dieni (1973), a numerical geomechanical model was performed to verify the hypothesis of collapse as a consequence of pressurized water outflow.

The geophysical survey and geomechanical modeling prove that basaltic cover in the area of Paulas has been affected by sinking. This sinking is interpreted to result from loading and compaction of the underlying

fine-grained sediments of the Nuraghe Casteddu Formation (NCF), and the particular location of the Paules is inferred to correspond to the areas where the infilling sedimentary succession of the NCF was remarkably thicker than elsewhere, thus allowing greater compactional subsidence after the loading by the basaltic lava flows (Fig. 9d). This progressively led to reduction and eventual loss of sediment porosity by expulsion of the interstitial water due to the effects of both self-weight loading, and loading exerted by the emplacement of lava flows. The porosity loss certainly led to a substantial volume reduction. It is suggested that the porosity decrease followed a slow exponential pattern in the stage of self-weight loading, but was affected by a rapid acceleration after the emplacement of lava flows.

The interstitial water may have easily flowed out of the sediments into the substrate, represented by the ubiquitous pedogenized upper part of the granite, generally several meters thick, consisting of arkosic, practically loose and permeable material, thus relieving pore pressure throughout the sedimentary column. Moreover, the drainage of the interstitial water has probably assisted by the, usually very dense, joint network crossing the granite.

In some instances the sinking of the basaltic cover resulted in the formation of a number of steps at the margins of these flat depressions (Fig. 9e). This may reflect both a progression in time of the sinking process, and a spatially varying amounts of compaction, due to the fact that the progression of compaction was controlled by the thickness of the underlying sedimentary sequence. The results of this multidisciplinary study definitely support the hypothesis that the “Paules” were generated by compaction and loading subsidence effects.

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References

- Beccaluva L, Deriu M, Macciotta G, Savelli G, Venturelli G (1977) Geochronology and magmatic character of the pliocene-pleistocene volcanism in Sardinia (Italy). *Bull Volcanol* 40(3):153–168
- Beccaluva L, Civetta L, Macciotta GP, Ricci CA (1985) Geochronology in Sardinia: results and problems. *Rend Soc Ital Min Petr* 40:57–72
- Binley AM (2008) ProfileR version 2.5. <http://www.es.lancs.ac.uk/people/amb/Freeware/ProfileR/profiler.zip>. Accessed 15 July 2010
- Binley AM, Kemna A (2005) DC resistivity and induced polarization methods. In: Rubin Y, Hubbard SS (eds) *Hydrogeophysics. Water science and technology library*, vol 50. Springer, New York, pp 129–156
- Bonicelli Vardabasso S (1968) Il Quaternario lungo la fascia costiera della Sardegna. *Atti X Congr Int St Sardi*, 33–54
- Calvino F, Dieni I, Ferasin F, Piccoli G (1959) Rilevamento geologico della parte meridionale del foglio n. 195 Orosei (Sardegna). *Boll Soc Geol It* 78:57–79
- Cassiani G, Bruno V, Villa A, Fusi N, Binley AM (2006) A saline tracer test monitored via time-lapse surface electrical resistivity tomography. *J Appl Geophys* 59:244–259. doi:10.1016/j.jappgeo.2005.10.007
- Conti P, Eltrudis A, Funedda A, Pasci S, Barca S, Carmignani L, Oggiano G, Pertusati PC, Salvatori I (1996) Carta geologica della Sardegna, scala 1: 200000, Servizio Geologico Nazionale e Regione Autonoma della Sardegna. A cura del comitato per il coordinamento della Cartografia Geologica e Geotermica della Sardegna
- Daily W, Ramirez A, Binley AM, LaBrecque D (2004) Electrical resistivity tomography. *Lead Edge* 23:438–442
- De Jong AK, Manzoni M (1968) Paleomagnetismo e cronologia delle colate basaltiche di Orosei (Sardegna). *Boll Soc Geol It* 87:713–717
- Dienni I, Massari F (1966) Il Neogene e il Quaternario dei dintorni di Orosei (Sardegna). *Mem Soc It Sci Nat Mus Civ St Nat Milano* 15:89–141
- Esu D (1978) La malacofauna continentale plio-pleistocenica della formazione fluvio-lacustre di Nuraghe Su Casteddu (Sardegna orientale) e sue implicazioni paleogeografiche. *Geol Rom* 17:1–33
- Esu D, Kotsakis T (1985) Les vertébrés et les mollusques continentaux du Tertiaire de la Sardaigne: paléobiogéographie et biostratigraphie. *Geol Rom* 22:177–206
- Esu D, Girotti O, Kotsakis T (1993) Palaeobiogeographical observations on Villafranchian continental molluscs of Italy. *Scr Geol Spec Issue* 2:101–119
- Greeley R (1971) Observations of actively forming lava tubes and associated structures, Hawaii. *Mod Geol* 2:207–223
- Greeley R, Hyde JH (1972) Lava tubes of the cave basalt, Mount St. Helens, Washington. *Geol Soc Am Bull* 83(8):2397–2418. doi:10.1130/0016-7606(1972)83[2397:LTOTCB]2.0.CO;2
- Hooper PR (1987) The Columbia River flood basalt province: current status. In: Mahoney JJ, Coffin MF (eds) *Large igneous provinces: continental, oceanic, and planetary flood volcanism*, vol 100. American Geophysical Union Monograph, Washington, pp 1–27
- Hooper PR, Conrey RM (1989) The tectonic setting of the Columbia River basalt eruption. In: Reidel SP, Hooper PR (eds) *Volcanism and tectonism of the Columbia River flood basalt province. Special paper 239*. Geological Society of America, Boulder, pp 293–306
- Jaupart C, Vergnolle S (1989) The generation and collapse of a foam layer at the roof of a basaltic magma chamber. *J Fluid Mech* 203:347–380. doi:10.1017/S0022112089001497
- Kristiansen TG, Plischke B (2010) History matched full field geomechanics model of the Valhall Field including water weakening and re-pressurisation. In: SPE EUROPEC/EAGE annual conference and exhibition held in Barcelona, Spain, 14–17 June 2010, paper SPE 131505
- LaBrecque DJ, Miletto M, Daily WD, Ramirez AL, Owen E (1996) The effects of noise on Occam’s inversion of resistivity tomography data. *Geophysics* 61:538–548
- Lamarmora De FA (1857) *Voyage en Sardaigne; troisième partie. Description géologique et paléontologique*. 2 vv.: XX+707+781, Bocca, Turin

- Lauro C (1937) Studio geologico-petrografico delle rocce vulcaniche post-mioceniche della Sardegna. II. La “giara” di Gesturi. *Period Miner* 8:125–143
- Lauro C (1939) Studio geologico-petrografico delle rocce vulcaniche post-mioceniche della Sardegna. III. I basalti di Orosei-Dorgali. *Period Miner* 10:33–81
- Lustrino M, Melluso L, Morra V (2000) The role of lower continental crust and lithospheric mantle in the genesis of Plio-Pleistocene volcanic rocks from Sardinia (Italy). *Earth Planet Sci Lett* 180:259–270
- Lustrino M, Melluso L, Morra V (2002) The transition from alkaline to tholeiitic magmas: a case study from Orosei-Dorgali Pliocene volcanic district (NE Sardinia, Italy). *Lithos* 63:83–113
- Lustrino M, Morra V, Melluso L, Brotzu P, D’Amelio F, Fedele L, Franciosi L, Lonis R, Liebercknecht AMP (2004) The Cenozoic igneous activity of Sardinia. In: Conticelli S, Melluso L (eds) A showcase of the Italian research in petrology: magmatism in Italy. *Per Mineral Spec Issue* 73:105–134
- Lustrino M, Melluso L, Morra V (2007) The geochemical peculiarity of “Plio-Quaternary” volcanic rocks of Sardinia in the circum-Mediterranean Cenozoic Igneous Province. In: Beccaluva L, Bianchini G, Wilson M (eds) Cenozoic volcanism in the Mediterranean area. *Geol Soc Am Spec Paper* 418:277–301
- Mariani P, Braitenberg C, Antonioli F (2009) Sardinia coastal uplift and volcanism. *Pure appl Geophys* 166(8):1369–1402
- Marini A, Murru M (1981) Sull’età della Formazione di Nuraghe Casteddu (Dorgali–Sardegna orientale). *Rend Soc Geol Ital* 4:11–12
- Massari F, Dieni I (1973) La formazione fluvio-lacustre di Nuraghe Casteddu ed i suoi rapporti con i basalti di Orosei-Dorgali (Sardegna). *Mem Soc Geol Ital* 12:377–410
- Monego M, Cassiani G, Deiana R, Putti M, Passadore G, Altissimo L (2010) Tracer test in a shallow heterogeneous aquifer monitored via time-lapse surface ERT. *Geophysics* 75(4):WA61–WA73. doi:10.1190/1.3474601
- Pelletier J (1960) Le relief de la Sardaigne. *Mém Doc Rev Géogr Lyon* 13:484
- Peterson DW, Swanson DA (1974) Observed formation of lava tubes. *Stud Speleol* 2:209–222
- Petteruti Lieberknecht AM, Fedele L, D’Amelio F, Lustrino M, Melluso L, Morra V (2003) Plio-Pleistocene igneous activity in Sardinia (Italy). *Geophysical research abstracts*, vol 5. European Geophysical Society, Munich, p 07260
- Plischke B, Cassiani G (2005) A finite element analysis of the local geomechanical behavior of rock close to a marker-equipped borehole: effects of drilling, completion and reservoir depletion. In: *Proceedings seventh international symposium on land subsidence (Sisols 2005)*, Shanghai, China
- Reynolds JM (2011) An introduction to applied and environmental geophysics, 2nd edn. Wiley, Chichester
- Roscoe KH, Burland JB (1968) *Engineering plasticity*. Cambridge University Press, Cambridge
- Self S, Thordarson T, Keszthelyi L, Walker GPL, Hon K, Murphy MT, Long P, Finnemo S (1996) A new model for the emplacement of Columbia River basalts as large, inflated pahoehoe lava flow fields. *Geophys Res Lett* 23(19):2689–2692
- Selli R, Fabbri A (1971) Tyrrhenian: a Pliocene deep sea. *Acc Naz Lincei Cl Sci fis mat nat* 8(50):580–592
- Skilling IP, White JDL, Mc Phie J (2002) Peperite: a review of magma-sediment mingling. *J Volcanol Geotherm Res* 114:1–17
- Teichmüller R (1931) Geologie des Tyrrhenisgebietes. I: Alte und junge Krustenbewegungen im südlichen Sardinien. *Abh Ges Wiss Göttingen math phys Kl* 3:857–950
- White JDL, Mc Phie J, Skilling I (2000) Peperite: a useful genetic term. *Bull Volcanol* 62:65–66
- Wood DM (1991) *Soil behaviour and critical state soil mechanics*. Cambridge University Press, Cambridge