

Testing the hypogenic hypothesis for the origin of granite multi-concave topography using electrical resistivity tomography: A case study from the Southern Albera Massif (Pyrenees, Spain)

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ABSTRACT

The pediment developed on the unweathered granite rocks of the South Albera Massif exhibits the characteristic morphology of an exhumed weathering front, where prominent residual landforms (tors and granite boulders) coexist with >240 weathering basins that shape a typical multi-concave topography. Active hydrothermalism is observed in the area, supporting the hypothesis that such weathering depressions may also be hypogenic in origin. Here we use Electrical Resistivity Tomography (ERT) to investigate the geo-electrical structure of the subsurface beneath four temporary ponds and associated depressions. The resistivity images reveal sub-vertical zones with resistivity low grades (150 and 450 Ohm-m) consistent with weathered granite, which spatially correlate with the shear zones identified at the surface. These weathered zones reach widths of approximately 100 m and extend vertically to depths beyond the effective ERT investigation depth (>170 m). The potential hypogenic origin of weathering depressions is supported by the following observations: (1) the occurrence of upwelling hydrothermal springs within one of the areas; (2) the widening of some weathered zones with depth; and (3) the preservation of unaltered rock masses overlaying altered zones. Spatial relationships between the studied depressions and the sub-vertical weathering structures are intricate. While some depressions entirely or partially overlap hypogenic alteration zones, in other cases, they fall outside the limits of these structures. This feature highlights the complexity of the weathering front evolution, where epigenic and hypogenic alteration processes coexist, driven by both structural factors and convergence of fluid flows of different nature.

1. Introduction

Multi-concave topography was defined by Thomas (1974) and Migon (2006) as a terrain where topographic basins assume the status of a characteristic landform. This typical granite landscape is modeled over unweathered bedrock, whose dimensions range from 1 km² to 100 km². Surface configuration includes both enclosed and interconnected weathering basins, forming complex spatial patterns. Multi-concave topography has been reported in tropical areas as well as in middle and high latitudes (Migon, 2006). Its genesis has been usually attributed to a selective and progressive epigene alteration of the bedrock driven by downward groundwater flow in subedaphic conditions. This results in weathering mantles that overlay unweathered rock massifs along

highly irregular surfaces known as weathering fronts (Ruxton and Berry, 1957; Mabbutt, 1961; Phillips et al., 2019). The uneven advance of the weathering mantle is purported to be the consequence of lithological (rocks with different composition or texture) and structural (rocks with different degree of fracturation) heterogeneity (e.g. Johansson et al., 2001; Worthington et al., 2016; Lebedeva and Brantley, 2017). Weathering basins are expected to form in these locations where the alteration progresses to greater depths. The erosion of the weathering mantle would lead to the exhumation the weathering front in the form of etched surfaces with polyphasic genesis (Twidale and Vidal-Romaní, 1994; Twidale, 2002). These surfaces expose the irregularities generated during the progression of weathering in depth, revealing both residual landforms (inselbergs, tors, granite boulders) and concave landforms

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(weathering basins) (e.g. Migon and Lidmar-Bergström, 2001; Twidale and Vidal-Romani, 2004, 2005). Once exhumed, these landforms keep on evolving but under surface conditions. Weathering basins can evolve into endorheic habitats hosting wetlands of high hydrological and ecological value.

Here, we investigate the origin of clustered weathering basins located on the granite pediment of the South Albera Massif (Eastern Pyrenees Range, NE Spain), an area declared as a Natural Wildlife Reserve in 1996 by the Catalan Government due to its floristic diversity and singularity. These basins form a multi-concave topography

developed mainly over unweathered granite rocks (Roqué et al., 2014). These authors identified 241 weathering basins spread over 52 km² of granitic pediment, occupying a total area of 1.9 km², 31 of which host temporary ponds. Little is known about the hydrological dynamics that control water inflows and outflows in these wetlands. Topographic features and torrential Mediterranean climate favor the temporary accumulation of surface runoff in these depressions during the wet seasons (spring and autumn, ca. 240 mm of precipitation in each season). Conversely, evapotranspiration largely exceeds precipitation during the dry seasons (summer and winter, ca 120 mm of precipitation),

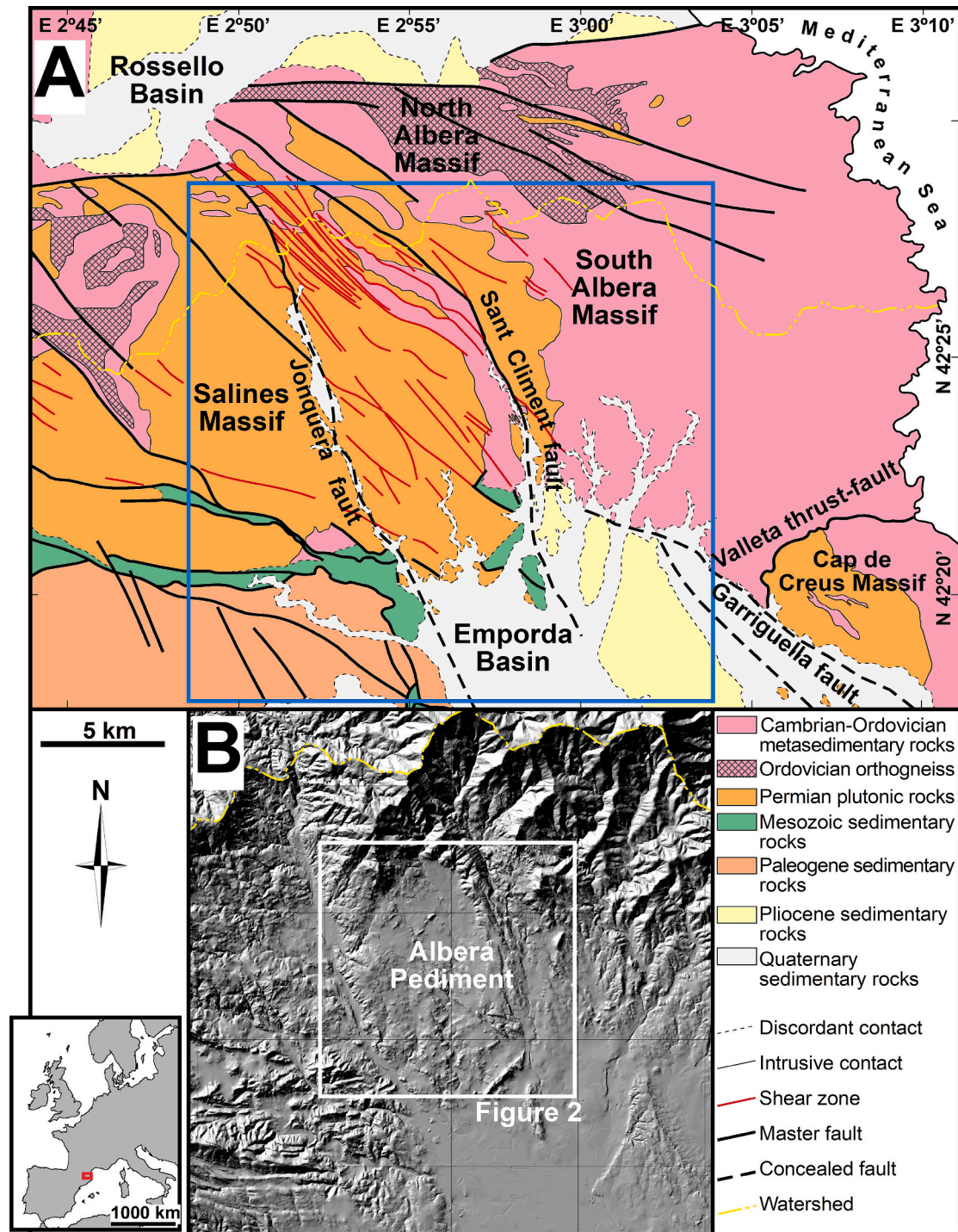


Fig. 1. A: Geological setting of the South Albera Massif (based on IGC, 2001, 2002, 2006). B: Hillshade elevation model of the study area (altitudinal data from Cartographic and Geological Institute of Catalonia, ICGC).

which causes ponds to partially or completely dry (Font and Vilar, 1998). Nevertheless, eight sulfurous perennial hot springs are present in this area, linked to a deep geothermal flow system developed within the granite rocks (Auqué et al., 2004). Recharge of some wetlands seems to be contributed by thermal waters rising through the main faults and shear zones (Linares et al., 2011). The occurrence of active hydrothermal fluids ascending through tectonic discontinuities in the granite suggests a possible hypogenic origin for the development of weathering basins at the weathering front, as well as for the multi-concave topography as a whole. The importance of hypogenic flows in the genesis and growth of karst landforms has been widely demonstrated in karst environments (carbonates and evaporites) (e.g., Dublyansky, 2014; Klimchouk et al., 2017; Gutiérrez et al., 2019), and, in particular, the key role of ascending hydrothermal flows as drivers of karstification has been broadly documented (Dublyansky, 2019). Furthermore, the role of hydrothermal fluids in the genesis of deep weathering mantles have been already reported in different parts of world (Migon, 2006 and references therein). However, the literature addressing the influence of hydrothermalism on the geometry of residual granite landforms and enclosed basins is very scarce (e.g. Coque-Delhuille, 1988). At smaller scale, Klimchouk (2018) suggested the hypogenic origin related to upward fluid flows for small landforms such as tafoni and honeycomb.

We stress the hypogenic hypothesis that relates hydrothermal circulation along tectonic discontinuities (faults and shear zones) with the genesis of major landforms on the studied weathering front (i.e. weathering basins). The occurrence of upwelling groundwater flows through main faults in granitic massifs analogous to the Southern Albera Massif (e.g. Folch and Mas-Pla, 2008; Roques et al., 2014) and other comparable areas nearby (i.e. Charpentier et al., 2024), together with the geomorphic signatures of the multi-concave landscape investigated here may support this working hypothesis. To test this hypothesis, a near surface geophysical survey using Electrical Resistivity Tomography (ERT), combined with detailed geomorphological field observations, is proposed. This approach is aimed at investigating the subsoil structure beneath the studied depressions, and at establishing the possible relationships between both surface and subsurface weathering features, supporting their hypogenic origin.

2. Geological setting

2.1. Lithology and structure

The study area is located on the southern side of the Albera Massif, at the convergence between the Pyrenees Range and the Empordà Basin. It is bounded by the La Jonquera to the west and Valleta faults to the east (Fig. 1A). The available geological maps (IGC, 2001, 2002) provide comprehensive information on the bedrock geology of this region. The bedrock of South Albera is formed by the Paleozoic basement of the Pyrenees Range. Three lithological units are distinguished: (1) a Cambrian-Ordovician metasedimentary sequence, including centimetric-banded schists with interbedded black slates, marbles, quartzites and rhyolitic tuffs; (2) an Ordovician orthogneiss mass linked to a large pre-Variscan sheet-shaped granitoid intrusion (Liesa et al., 2011); and (3) Permian plutonic bodies intruded into the metamorphic rock-mass, mainly composed of biotite and biotite-hornblende granodiorites and tonalites, as well as NE-SW trending decameter-wide and kilometer-long dikes of leucogranite (Vilà et al., 2005). The Paleozoic basement is unconformably covered by the Mesozoic sedimentary sequence at the southern edge of the Albera Massif. This sequence encompasses: (1) Lower and Middle Triassic conglomerates, sandstones and red lutites (Buntsandstein facies); (2) Middle Triassic limestones and marls (Muschelkalk facies); and (3) Upper Cretaceous siltstones, sandstones, marls, and limestones. Nevertheless, most of the southern boundary consists of an unconformity between the Paleozoic basement and Pliocene and Quaternary alluvial fans, which fill the Neogene Empordà Basin.

The Valleta thrust-fault is a SE-vergent pre-Neogene structure that outlines the boundary between the low-grade metamorphic rocks of the Albera Massif (hanging wall) and the medium to high-grade rocks of the Cap de Creus Massif (footwall) (Liesa et al., 2011). A number of NW-SE trending shear zones are in the Albera Massif western sector, (Figs. 1A and 2). These shear features range from 1 to 10 km-length and 1 to 5 m-width, exhibiting planes dipping 50° to 70° and NE dip. The age of these structures and their relationship with other fault systems remain unresolved, although they are generally attributed to the Late Paleozoic. The Jonquera, Sant Climent and Garriguella-Roses faults are the master structures related to the trending normal fault system that controls the development of the north Empordà Neogene Basin (Mas-Pla et al., 2023). All these faults are seismically active, although they present low-magnitude earthquakes (≤ 3 M) (ICC, 1999, 2001). The Jonquera Fault is formed by a set of two parallel NNW-SSE to NW-SE trending faults and shows a dextral strike-slip component along a 25 km strand. Their fault planes dip ca. 65° to the NE, with a maximum vertical net displacement ranging between 800 and 1200 m. Garriguella fault is a WNW-ESE normal displacement structure that is broadly concealed by Quaternary sediments. It is about 15 km long, with a fault plane dipping 65° to SW and a net displacement of ca. 500 m.

2.2. Geomorphology

The South Albera Massif comprises two main geomorphological units: (1) A prominent mountain ridge located to the N, which elevations reach up to 1257 m a.s.l. (Neulós Mont). This area is dominated by prominent granite landforms such as bornhardts, castle koppies and nubbins. Here, only a few remnants of an arenaceous weathering mantle (grus weathering mantle, according to the definition by Migon and Thomas, 2002) are preserved in sheltered locations. (2) A pediment located at the foot of the mountain ridge and gently sloping towards S (Fig. 1B). The studied weathering basins are located on the western half of the pediment, over dominant granite rocks (Fig. 2). The pediment initiates abruptly at 220 m a.s.l. and descends slightly over 9 km to a height of 85 m a.s.l., where it meets the Pliocene and Quaternary alluvial fan deposits that fill the Empordà Basin. Very locally, the pediment develops on metamorphic rocks; in this case, this paleosurface is located 25 m above the granite outcrops. Granite boulders and tors are dominant landforms on the pediment, as well as elongated low hills that arrange according to the strike of the leucogranite dikes. This landscape corresponds to a typical exposed polyphasic etchplain (e.g. Twidale and Vidal-Romaní, 1994, 2005). As a singularity, the pediment features 241 endorheic basins surrounded by residual landforms. These depressions have an ellipsoidal plan shape, with little morphological expression since at most their surface is located between 3 and 5 m below the surrounding relief (Fig. 3). The areas they occupy range between 531 m² and 56834 m² and the length of their major axes (L) varies between a minimum of 34 m and a maximum of 386.5 m. The average length ratio between their axes (L/W) is 2.7 (Roqué et al., 2014). These basins form a multi-concave topography whose architecture is controlled by structural factors. They are arranged according to preferred directions and depict a clear asymmetry, where the major axes elongate in agreement to the dominant tectonic discontinuity system (shear zones and faults strikes) (Fig. 3D). Grus weathering mantle remnants are only preserved in the lower part of the pediment. In NE Spain, grus weathering mantles have been reported and attributed to the Neogene (Roqué et al., 2013). Fluvial erosion dominated in the South Albera Massif during Pliocene and Pleistocene, and the redeposition of grus mantles sourced the Pliocene arkosic sediments that fill the north Neogene Empordà Basin (IGC, 2006). The existence of well-developed weathering mantles on the sediment-source area during the Neogene is supported by the petrology of the pediment-margin alluvial fans (arkosic sandstones and granitic gravels), as well as by the presence of large granite boulders interbedded within the proximal facies of the oldest deposits. The massive grus mantle wasting led to exhumation of the weathering front in the form of

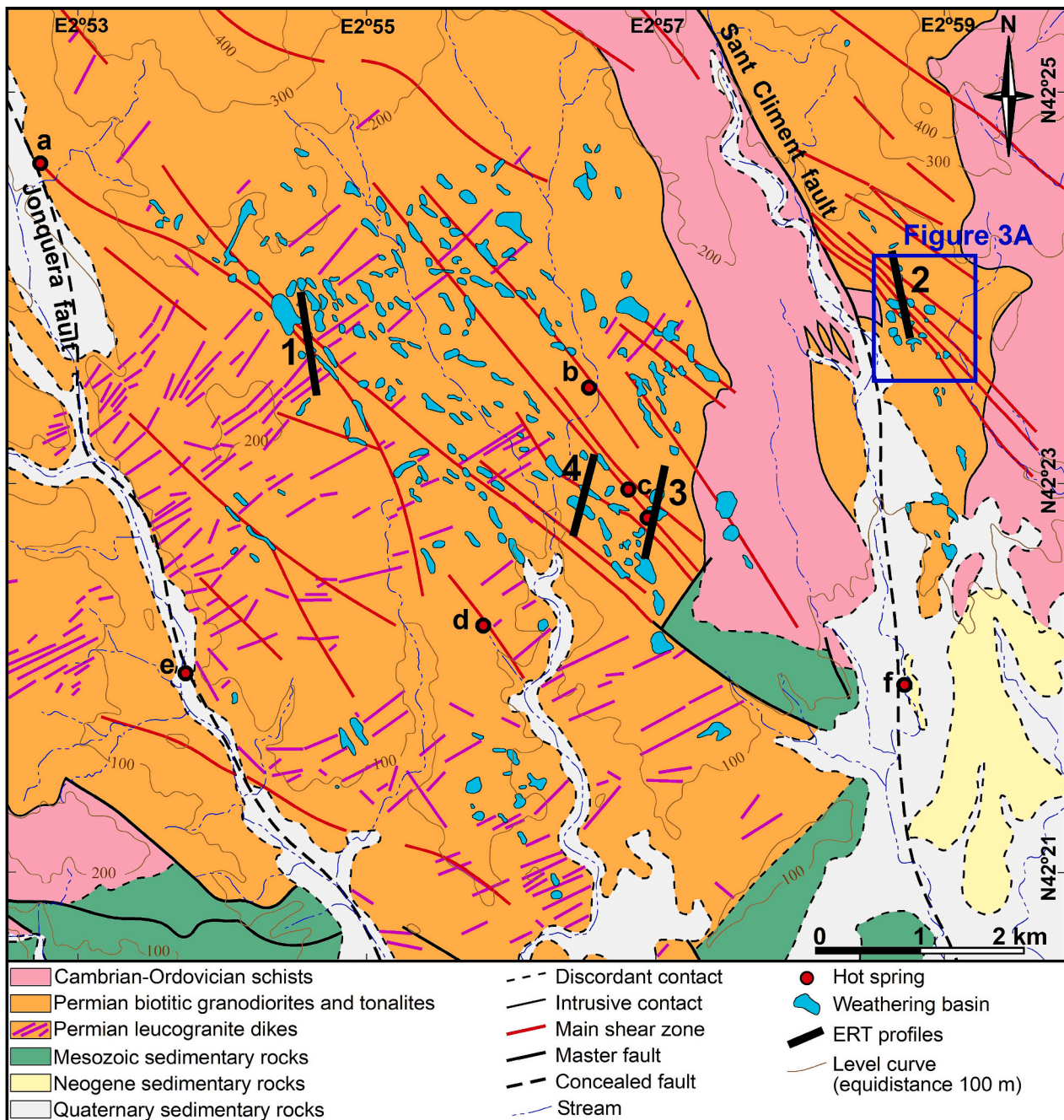


Fig. 2. Geological map of the study area (modified after IGC, 2001, 2002 and own data). Weathering basins are outlined in blue. Red circles indicate thermal springs (a: Jonquera, b: Bell-lloc, c: Pudent Pond system -three aligned springs-, d: Capmany, e: Banys Merce, f: Sant Climent). Thick black lines outline the ERT profiles carried out (1: Canadal Pond system, 2: Gutina Pond system, 3: Closa Pond, 4: Llompol Pond). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

an etchplain, on which several ephemeral wetlands have developed.

2.3. Hydrogeology

The South Albera Massif hydrogeological system encompasses the different groundwater flows characteristic of granitic massifs (Zarroca et al., 2015): (1) Local flows within unconfined detrital aquifers, characterized by well-connected intergranular porosity. These aquifers are hosted by Quaternary and Pliocene alluvial fans located in the southern part of the pediment, which is devoid of wetlands. (2) Local and intermediate flows within semiconfined aquifers, which are hosted in the fractures of the rock horizon underlying the weathering mantles

remnants, with which may be hydraulically connected to. Regarding hydrochemistry, calcium-bicarbonate is the dominant hydrofacies (Linares et al., 2011). (3) Intermediate and regional flows circulating across deep fault planes affecting the fresher rock basement. These fault planes acts as a confined or leaky aquifer fed by the overlain aquitards. And (4) Regional hydrothermal flows within the fresh granitic rocks of the Jonquera-Sant Llorenç de Cerdans plutonic complex (Soulé, 1990; Chevalier-Lemire et al., 1990; Eude et al., 2021), and which are linked to the major fault system. In addition to the hydraulic gradient, convective mechanism also drives the flow in this case (Albert et al., 1979). Up to 8 active thermal sulfurous springs associated with these systems are documented in the area (Auqué et al., 2004) (Fig. 2). These thermal

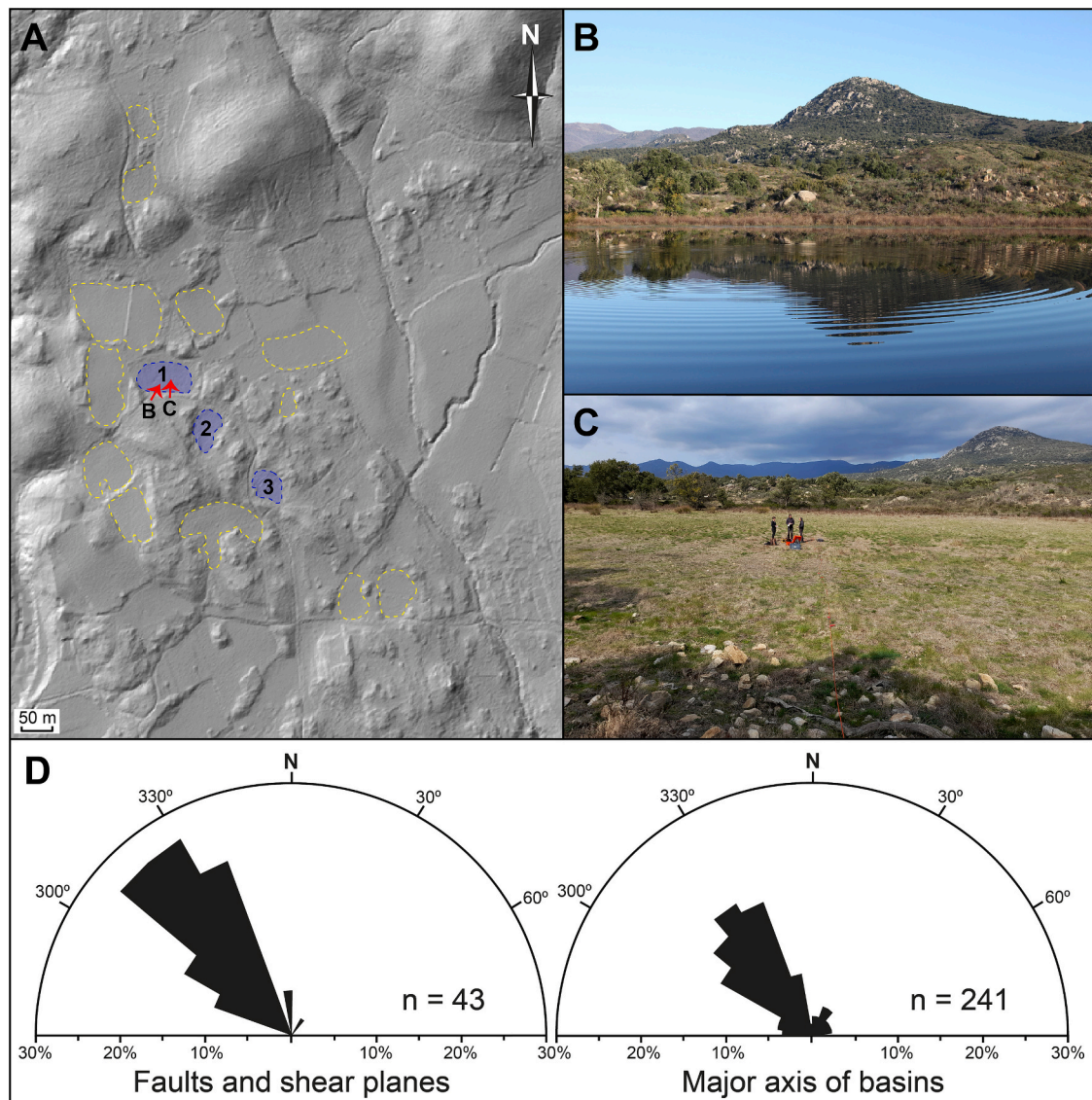


Fig. 3. A: Hillshade elevation model of the Gutina Pond system (see Fig. 2 for precise location) (1: Cardonera Pond, 2: Rajoleria Pond, 3: Prat Pond). B: Cardonera Pond with water, January 2012 (photograph taken from red arrow in A). C: Cardonera Pond completely dry during geophysical surveys, March 2022 (photograph taken from red arrow in A). D: Rose diagrams showing the orientation of the major axis of tectonic structures ($n = 43$) and the studied weathering basins ($n = 241$), modified from Roqué et al. (2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

waters are characterized by sodium-bicarbonate hydrofacies (Linares et al., 2011) and high pH values that scale up to pH ~ 9.6 to 9.7. Temperatures at the discharging points do not usually exceed 18 °C to 28 °C. However, estimated reservoir temperatures ranges 80 °C to 105 °C at the depth in which equilibrium is established with albite, K-feldspar, quartz and kaolinite (Auqué et al., 2004).

3. Methodology

A geophysical survey was conducted to explore the unexposed structure of the multi-concave topographic landform studied here. The geophysical investigation focused on 4 different sectors (Fig. 2), which were selected according to the outcomes from previous research (Linares et al., 2011; Roqué et al., 2014). Specifically, the location of the profiles was chosen based on the location of the hot springs, the dimensions of the ponds that were achievable with the equipment, and the arrangement of the shear bands. The surveying consisted of four 800-m-long Electrical Resistivity Tomography (ERT) profiles. Shorter profiles previously carried out (150 m to 250 m long) allowed an investigation

depth of about 40 m to be reached, insufficient to visualize the deep structure beneath the weathering basins. Given the length of the new profiles, the ability to run them in a straight line without obstacles (fences, buildings, livestock) was a significant limiting factor. The profiles were captured over weathering basins hosting temporary ponds, and the profiles midpoint were placed on pond centers. Profiles were taken when the ponds were dry (Fig. 3C). Additional 400-long profiles were also captured, in order to image some parts of the system in more detail.

ERT is a direct current technique aimed at imaging the resistivity distribution of the near-surface using multi-electrode systems (Griffiths and Barker, 1993). Bulk resistivity is chiefly controlled by intrinsic rock properties such as porosity, moisture, and fluid hydrochemistry. Since ERT is particularly sensitive to these parameters, it is a valuable tool for delineating weathered and highly fractured zones that affect the rock massif (Olona et al., 2010; Arias et al., 2016). These features can exhibit hydraulic conductivity well above of fresher rock mass, serving as preferential groundwater flow pathways. Consequently, weathered zones and open fracture structures circulated by low-resistivity fluids (i.

e., mineralized groundwater) should be easily identified in resistivity images (Zarroca et al., 2015; Sreeparvathy et al., 2019). On the other hand, there is limited literature on the investigation of aquifers and wetlands associated with granitic rock using ERT. Beauvais et al. (1999, 2003, 2004) successfully applied ERT to characterize hydro-geomorphic processes and documented the geometry and structure of granite bedrock beneath lateritic weathering horizons in Senegal. Chandra et al. (2010, 2012) investigated by means of ERT the hydrogeological behavior of geological discontinuities caused by intrusive quartz dikes and shear zones. Riddell et al. (2010) reported on the geophysical interpretation of wetland hydro-geomorphology in granitic areas of South Africa, using ERT.

Goelectrical data were collected using an ABEM Terrameter LS2 resistivitymeter of 64 electrodes and 4 multicore cable sections. Data acquisition was carried out using Gradient array configuration, with an inter-electrode spacing of 10 m and a total profile length of 800 m. Additional 400 m-length profiles were also captured on the same locations at electrode spacing reduced to 5 m. It should be noted that the smaller the inter-electrode space, the higher the spatial resolution. The maximum effective investigation depths achieved beneath the array midpoints of the 800 and 400 m-length profiles were of ca. 170 m or 85 m, respectively. The positions of the arrays midpoint were geolocated with a Garmin ETREX 22× GPS, with an accuracy of ± 3 m. A total of 1030 data points were captured for each profile, regardless of the interelectrode spacing. The measured apparent resistivity data were inverted into a best-fit goelectrical models in the form of resistivity images by means of the software Res2DInvx64 4.10. The inversion algorithm is based on smoothness-constrained least-squares inversion, implemented via a quasi-Newton method (Loke and Barker, 1996). As starting models, we used constant electrical resistivity distributions equivalent to the average apparent electrical resistivity values of the corresponding pseudo-sections. The optimization method then adjusts the 2D electrical resistivity model trying to iteratively reduce the difference between the calculated and measured apparent electrical resistivity values. The root-mean-square (RMS) error provides a measure of this difference and thus an indication of the reliability of the final model. A topographic correction was also applied to account for the model-distortion caused by the topographic curvature. The topographic elevation of each electrode position was obtained from the digital elevation model at a spatial resolution of 2 m (source: Cartographic and Geological Institute of Catalonia, ICGC).

4. Results

Goelectrical images were interpreted by an integrated approach: (1) geological and geomorphological information from direct observations; (2) hydrogeological data; and (3) comparisons with previous literature on goelectrical modeling in analogous granite geological contexts (e.g. Chandra et al., 2010; Olona et al., 2010; Roqué et al., 2013; Belle et al., 2018). Based on such data, a characteristic value of the different electrofacies present in the study area are established: Unweathered granite (600 to >2000 Ohm-m depending on fracture density); Weathered unsaturated granite (150 to 450 Ohm-m); Weathered saturated granite (25 to 150 Ohm-m); Pond sediments (50 to 100 Ohm-m). In the two last cases, the resistivity values vary depending on the degree of saturation and the hydrochemistry of the pore fluid, which is more than likely the most influential factor controlling the resistivity in this case. This explains why these materials show similar bulk resistivity. In the geophysical profiles carried out, these sedimentary fills can be distinguished from the weathering front because they form a horizontal and largely homogenous surface layer.

4.1. Profiles ERT-1, Canadal Pond system

S–N oriented profiles were collected on this area, with array centers on the temporary Palau Pond: One profile ERT-1a (400 m-long) and

ERT-1b (800 m-long) (Fig. 4). Both profiles capture an elongated weathering basin situated 25 m south of the Palau Pond edge. The rocks outcropping in this area are unweathered granodiorites and biotite-hornblende tonalities, intruded by leucogranite dikes. The profiles cross over two northwest-southeast-trending shear zones, both dipping ca. 70° to NE, the first near the profile midpoint and the second ca. 90 m towards S.

The ERT-1b resistivity image reveals a sub-vertical band of ca. 130 m-wide, of lower-resistivity (150 and 300 Ohm-m) than the surrounding high-resistivity materials (≥ 1000 Ohm-m) (LRA1 in Fig. 4). This band extends down to the maximum imaged depth (ca. 170 m). The resistivity values of this band are typical of weathered granites. In contrast, the high-resistivity of background materials are more consistent to the unweathered rocks that configure the typical weathering front exposed as residual granite landforms. The location of the low-resistivity band matches the surficial trace of the two shear zones. The temporary Palau Pond and the neighboring basin partially overlap this band, although part of the pond does not lie directly above it. The higher resolution ERT-1a image provides further details. A high-resistivity anomaly (600 to 2000 Ohm-m) is capping the shallowest part of the low-resistivity band (HRA). These high-resistivity materials correspond to unweathered granodiorites and tonalites outcropping at this point. An additional lower-resistivity anomaly is identified in both profiles (LRA2). This anomaly locates 20 m below the northern edge of the pond and it extends to another 20 m in depth. Its lateral continuity does not exceed 40 m beyond the northern pond edge.

4.2. Profiles ERT-2, Gutina Pond system

A 400 (ERT-2a) and 800 (ERT-2b) m-length profiles were collected in this area, oriented SSE–NNW. The profiles do not overlap in the central section but in the southern section in this case, were the temporary Cardonera Pond locates (Fig. 5). ERT-2a midpoint matches the pond center and reasonably matches the x-location 600 m of ERT-2b. The landscape is dominated by the exhumed tors and granite boulders of leucogranite that surround the weathering basins. ERT-2b crosses on 4 parallel N–S trending shear zones, which dip 70° to the NE, while ERT-2a only crosses the 2 southernmost.

The resistivity images are concordant with the direct observations performed in regard of the arrangement of weathered and unweathered zones in the area. A background high-resistivity (≥ 600 Ohm-m) is observed beneath the unweathered areas, where more prominent residual relief is a feature. This is at the southern sector of the longer ERT-2b profile (electrode position from $x = 800$ to 600 m), as well as in its central and northern sectors (Fig. 5). Beneath Cardonera Pond, the resistivity drops down to 75 to 350 Ohm-m, which are typical grades of weathered granites. Therefore, low-resistivity materials extending down to 15 m-depth do not relate to pond sediments but to granite alterites. Low-resistivity anomalies are also reported beyond the N edge of the pond. A 150 to 450 Ohm-m anomaly occupies a sub-vertical band between electrode positions $x = 470$ to 560 m (LRA1 in ERT-2b profile). This 90 m-wide feature matches its location with one of the shear zones identified in this area, and extends down to the maximum imaged depth. Profile ERT-2a provides more detail on this lower-resistivity band. Once the anomaly is projected on the surface, it partially matches a weathering basin, but also projects beneath an outcrop of unweathered granite boulders of high-resistivity (≥ 1000 Ohm-m). Similar pattern is also imaged by the longer ERT-2b profile. An analogous low-resistivity sub-vertical band (400 to 450 Ohm-m) is also imaged at the northern half of ERT-2b (LRA2). This position is also coincident with one of the previously identified shear zones. As a singularity, this band sharply narrows above 50 m-depth, up to just 20 m width at the topmost part. Capping this band are high-resistivity materials (≥ 1000 Ohm-m) and, thus, unweathered granite materials (HRA).

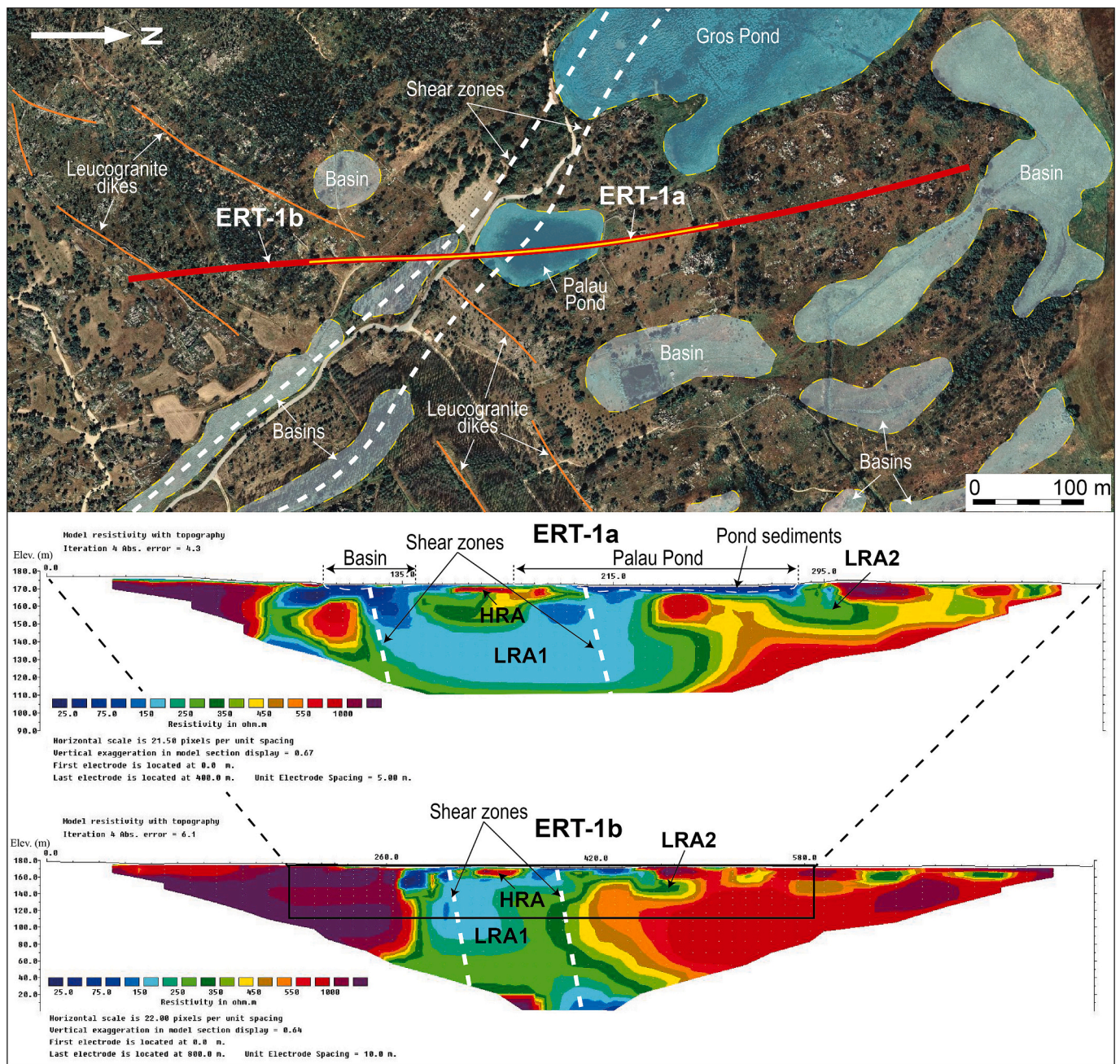


Fig. 4. ERT profiles in the Canadal Pond system. Surface geological data (shear zones and leucogranite dikes) have been obtained from direct observations during fieldwork. The two profiles are centered on the temporary Palau Pond, and were acquired while the pond bed was dry. ERT-1a is 400 m long (electrode spacing 5 m) and ERT-1b is 800 m (electrode spacing 10 m). The geoelectrical models use the same ranges of resistivity values (i.e. 0–25, 25–50, 50–75, 75–100, 100–150, 150–200, 200–250, 250–300, 300–350, 350–400, 400–450, 450–500, 500–550, 550–600, 600–1000, 1000–2000 and >2000 Ohm-m).

4.3. Profile ERT-3, Closa and Pudent ponds

An 800 m-length N-S trending profile was conducted in this area, centered on the temporary Closa Pond. It intersects an active thermal sulfurous spring (Pudent Pond), located 110 m away the array midpoint, towards S. The rocks outcropping in this area are unweathered biotite-hornblende granodiorites. The area is almost flat and devoid of boulders or other residual landforms. The ERT runs across up to 3 N-S trending shear zones, all dipping ca. 75° to NE. One of such is located near the center of the Closa Pond; the second coincides with the position where the sulfurous hot spring emerges (together with 2 additional hot springs somewhat away), and the third places 100 m S (Fig. 6).

High-resistivity unweathered granodiorites (resistivity ≥ 1000

Ohm-m) are also dominant in ERT-3 (Fig. 6). On this background, several low-resistivity anomalies attributable to weathering zones stand out. The most striking is a 90 m-wide band beneath the Closa Pond, whose resistivities ranges from 150 to 350 Ohm-m (LRA1). A second sub-vertical anomaly of 300 to 450 Ohm-m locates beneath the thermal spring that feeds the Pudent Pond (LRA2). An additional low-resistivity (from 25 to 200 Ohm-m) anomaly is also imaged underneath Closa Pond (LRA3). This anomalous zone does not extend beyond 40 m-depth. However, it connects both sub-vertical anomalous bands, configuring together the most prominent low-resistivity domain of the studied sections. The southernmost shear zone, located at electrode position ca. $x = 630$ m, does not depict associated any sub-vertical low-resistivity band but a shallower low-resistivity anomaly 300 to 450 Ohm-m (LRA4),

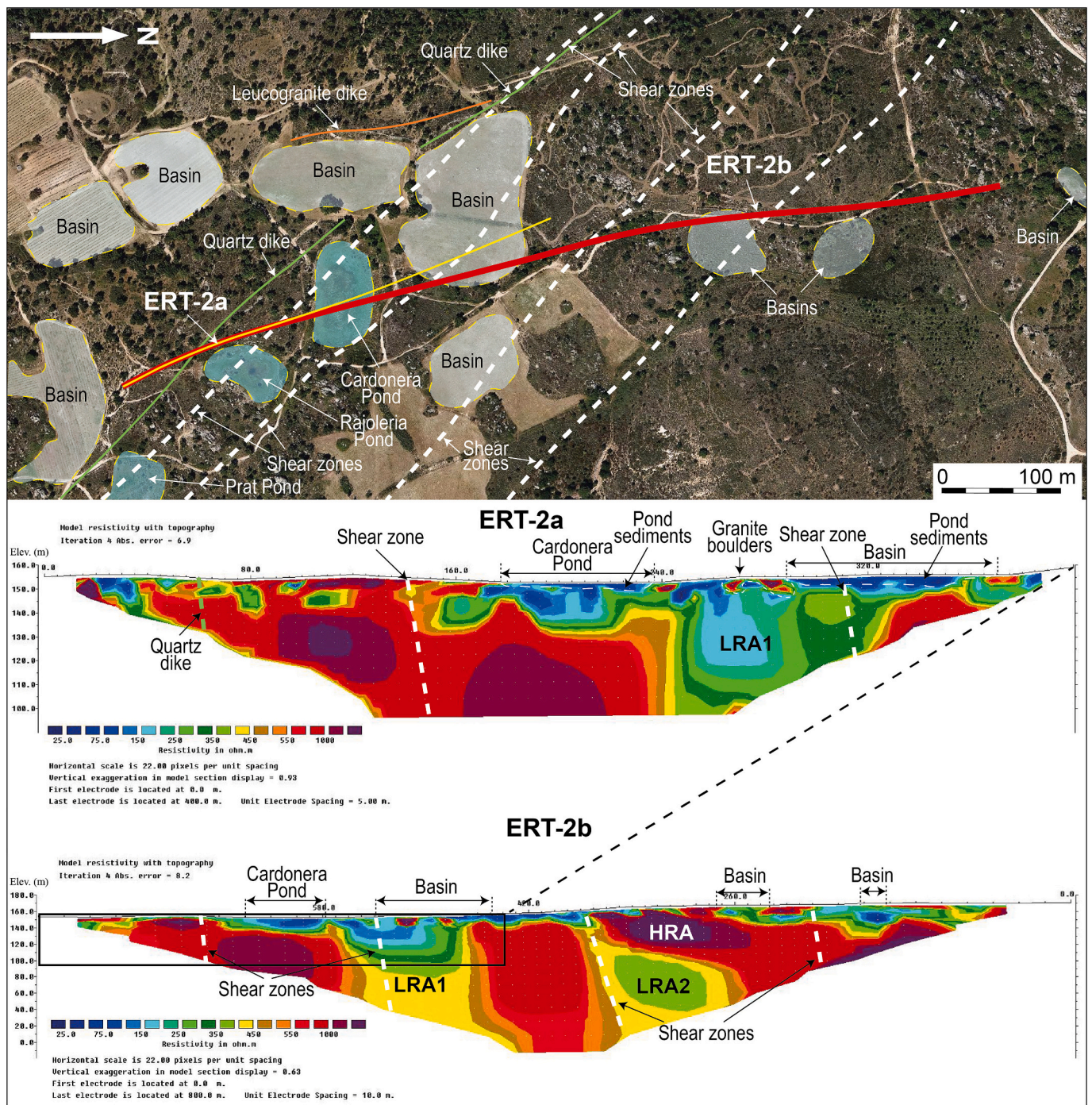


Fig. 5. ERT profiles in the Gutina Pond system. Surface geological data (shear zones and leucogranite and quartz dikes) have been obtained from direct observations during fieldwork. The two profiles cross the temporary Cardonera Pond, and were acquired when it was dry. ERT-2a is 400 m long (electrode spacing 5 m) and ERT-2b is 800 m (electrode spacing 10 m). The geoelectrical models use the same resistivity classification as in Fig. 4.

which does not extend down to 20 m-depth.

4.4. Profile ERT-4, Llampol Pond

ERT-4 is an 800 m profile conducted on the temporary Llampol Pond, and oriented S–N. The landscape is dominated here by low relief, only interrupted by some residual tors and granite boulders of unweathered biotite-hornblende granodiorite. 130 m northern wards the edge of the pond, the ERT profile crosses through a WNW-ESE shear zone dipping ca. 60° ENE. The shear zone is associated with an elongated weathering basin that is captured by an ephemeral creek (Fig. 7).

Unweathered granodiorites of high resistivity (resistivity ≥ 1000 Ohm-m) are the dominant materials in the central and southern sector of the ERT-4 image, while some lower-resistivity anomalies are depicted in the northern part. The major low-resistivity anomaly, the sub-vertical band of low-resistivity (75 to 400 Ohm-m) is linked to the shear zone and the associated elongated depression (LRA in Fig. 7). This feature seems to widen upwards, from 110 m-wide at the bottom of the image to 190 m-wide in the near-surface. The low-resistivity band is partially capped by higher-resistivity materials (600 to 2000 Ohm-m), attributable to unweathered granite (HRA).

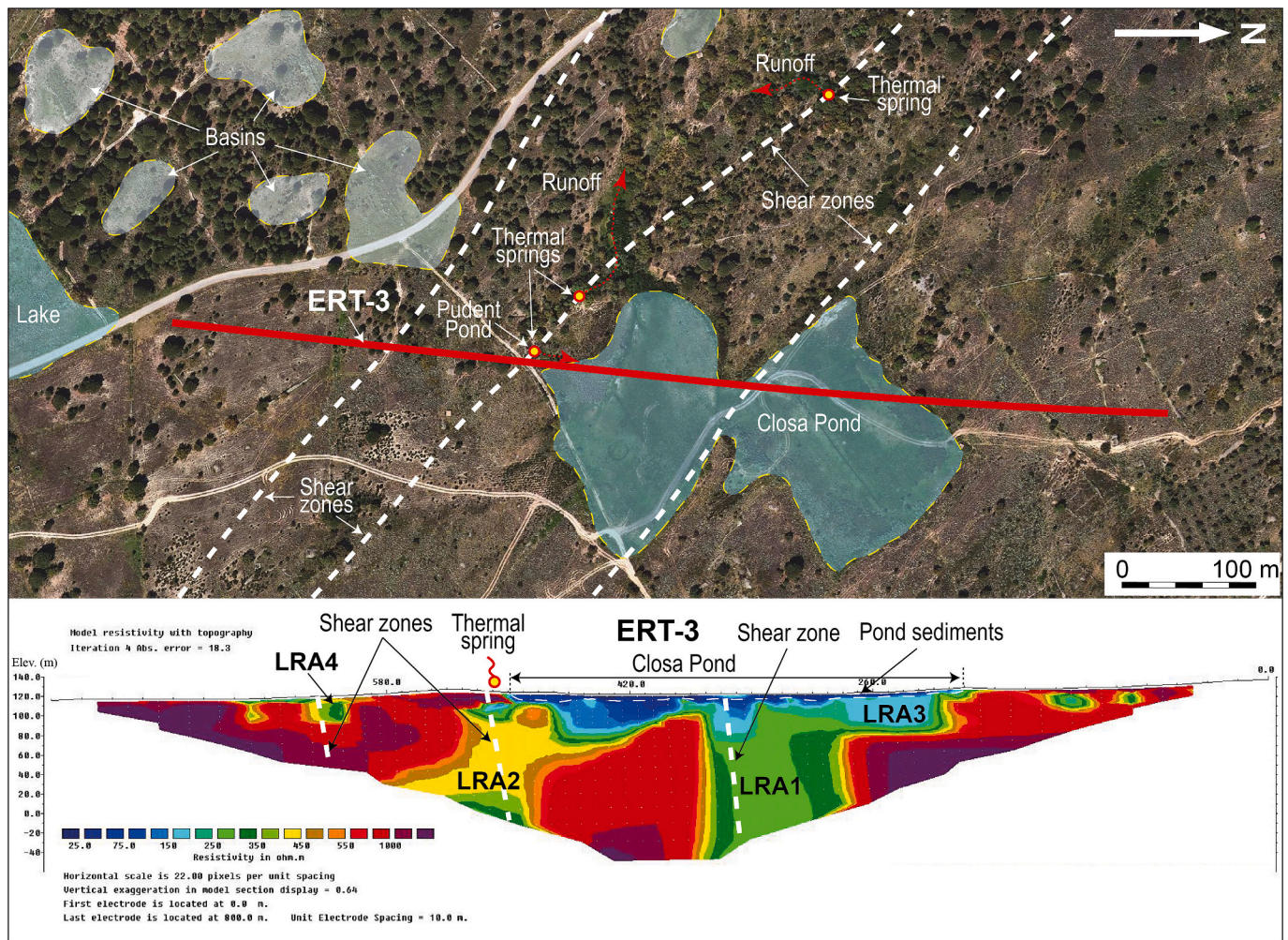


Fig. 6. ERT profile across the Closa and Pudent ponds. Surface geological data (shear zones) have been obtained from direct observations during fieldwork. The profile crosses the temporary Cardonera Pond and was acquired when the pond was dry. It is 800 m long (electrode spacing 10 m). The geoelectrical model displays the same resistivity ranges as in Fig. 4.

5. Discussion

ERT has shown effectiveness at identifying and distinguishing between weathered and unweathered granite domains in all the surveyed localities along the Albera Massif. Overall, the investigated subsurface is dominated by a (a) high-resistivity background (from 600 to >2000 Ohm-m), attributable to low-weathered granite rocks, and (b) several lower-resistivity anomalous zones (<600 Ohm-m). This general geoelectrical pattern is highly consistent with the observed landscape heterogeneity and can be interpreted in terms of weathering. The elongated depressions and temporary ponds are the geomorphic expression of highly weathered alterites, while residual tors, boulders and flat zones are the expression of less-weathered granites. This characteristic multi-concave landscape has its counterpart in the subsurface, where weathered lower-resistivity materials extend beneath the depressed areas, embayed by higher-resistivity unweathered zones of intact rocks that extend beneath the most prominent residual reliefs. Based on the observations carried out in the different localities, a conceptual model of the different weathering processes and landforms is proposed (Fig. 8).

The ERT survey also revealed further details on the geometry of weathering zones and weathering processes. The most prominent low-resistivity anomalies consist in sub-vertical alteration bands that are associated with shear zones. These bands reach widths between 40 and 130 m, and are composed of materials with resistivities ranging between 150 and 450 Ohm-m. These bands extend beyond the maximum

effective investigation depth for ERT, which is >170 m for the 800 m-long profiles. These structures are spatially discontinuous, and reasonably match the position of the shear zones mapped on the surface. However, their width largely exceeds the width of the associated shear zones, which in turn rarely exceed 5 m wide. Similar sub-vertical alteration features have been identified in previous ERT investigations of aquifers in analogous granitic scenarios (i.e. Belle et al., 2018). It should be noted that the hydraulic behavior of tectonic discontinuities is variable, and they can act as conduits, barriers, or both simultaneously (e.g. Bense and Person, 2006). It is the case of the investigated Albera Massif, in which shear zones constitute or control groundwater flow pathways through the granitic rock mass. This observation is supported by the heterogeneity shown by the weathering anomalies along the associated shear zones, as well as because the main groundwater discharges are discontinuous rather than continuous along the same shear zones. The resistivity of dry fractured rocks may be well above that of fresh rock, since air has an even of higher resistivity than rock matrix. Conversely, when the voids are filled with water, the bulk resistivity significantly decreases, and resistivity differences of several orders of magnitude can be observed, as is the case here. It should be noted that features observed in 2D resistivity images must be interpreted by caution, since the resistivity values they show are also influenced by those located in the surroundings of the profile ("3D effects") (Hung et al., 2019). However, some general patterns regarding lateral features may be established. Weathering bands show regular width along the

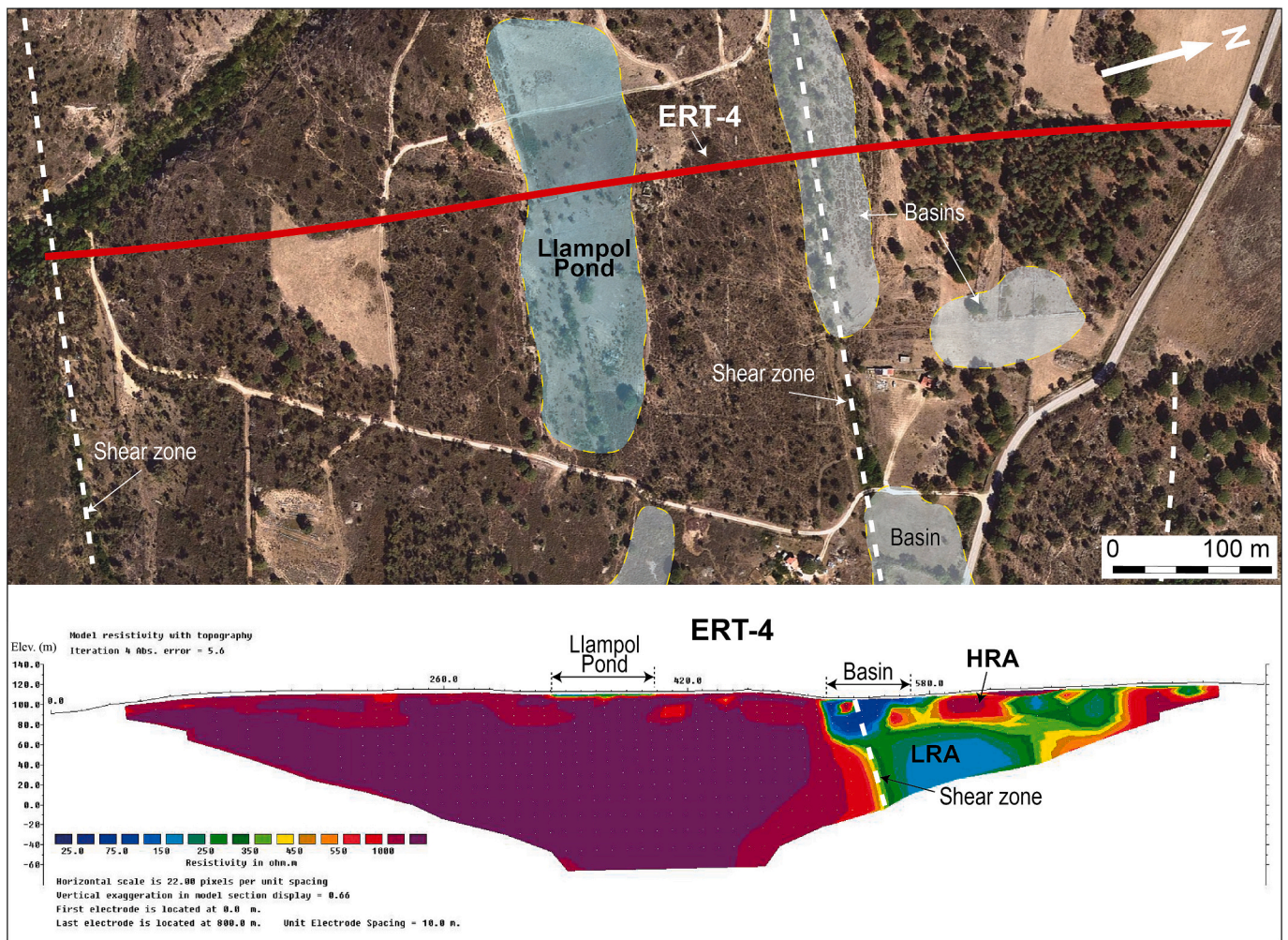


Fig. 7. ERT profiles across Llampol Pond. Surface geological data (shear zones) were collected from direct observations during fieldwork. The profile crosses the temporary Llampol Pond and was acquired when the pond was dry. It is 800 m long (electrode spacing 10 m). The geoelectrical model displays the same resistivity ranges as those shown in Fig. 4.

entire depth. They are alternatively connected to shallower and wider low-resistivity anomalies outlining an uppercase “T” shape (i.e. LRA1 in ERT-2a, Fig. 5; LRA1 in ERT-3, Fig. 6; LRA in ERT-4, Fig. 7), or undergo a progressive narrowing in an upward direction as is the case of Gutina Pond system (i.e. LRA2 in ERT-2b, Fig. 5). This pattern has been interpreted as the result of deep hypogenic alteration along major tectonic planes.

One of the alteration bands (ERT-3) is located just beneath one of the thermal springs in the Closa and Pudent ponds locality (LRA2 in Fig. 6). This suggests that the hypogenic circulation of fluids is currently active along the shear zones, and that rock alteration is at least partially driven by these ascending flows. The geometry of this alteration band observed in ERT-3 outlines an “hourglass” shape formed by the sum of two triangles. The progressive narrowing upwards depicted by the lower triangle (pointed upwards) is similar to what is observed in the northern half of ERT-2b image (LRA2 in Fig. 5), where the weathering band narrows upward beneath a surficial core of unweathered granite. This observed pattern is not consistent with an alteration driven by water infiltration from the surface along tectonic discontinuities (epigenic). The sandy saprolite (grus) that forms when granite weathers is more permeable than the unweathered rock, and this promotes the lateral spreading of chemical weathering by hydrolysis from fracture planes or shear zones to outwards. This process should result in an inverted triangle shape, wider towards the top, not the bottom. This is the case observed beneath the southern bottom of Closa Pond. There, the

resistivity reaches minimums (75 to 150 Ohm.m) down to 40 m-depth (Fig. 6). But the upward narrowing of the band observed from the bottom to 40 m-depth could not be explained by epigenic weathering but by the advance of upwards hypogenic weathering, linked to upwelling intermediate and regional groundwater flows. A clear example of this framework is the thermal spring emanating southern of Closa Pond.

Noticeable lateral expansion of the sub-vertical alteration bands is clearly observed in profiles ERT-2a and b (Fig. 5) and ERT-3 (Fig. 6). This near-surface sub-horizontal progression is consistent with the increased fracturing due to rock decompression, which configures an intensely fissured layer of high hydraulic conductivity that can reach ca. 45 m thick (i.e. Belle et al., 2018). These increased permeability zone allows for local lateral groundwater flows linked to direct infiltration or deconfining of upwelling flows (e.g. Phillips et al., 2019). These authors also emphasize the hydrogeological complexity of weathering fronts. A clear example is the Palau Pond locality. There, the profiles ERT-1a and b (Fig. 4) reveal that the weathered granite north of Palau Pond extends beneath the unweathered granite. Similar are the cases of ERT-2a (Fig. 5), where the weathering band is capped of unweathered granites that outcrop as prominent boulder cluster; and both ERT-1 (Fig. 4) and ERT-4 (Fig. 7), where analogous unweathered “caps” overlie the sub-vertical alteration bands. This pattern also points out that hydrothermal alteration plays a key role on the weathering mantle evolution, as previously proposed by Coque-Delhuille (1988) for the kaolin deposits SE England Island.

Hypogene and epigene weathering

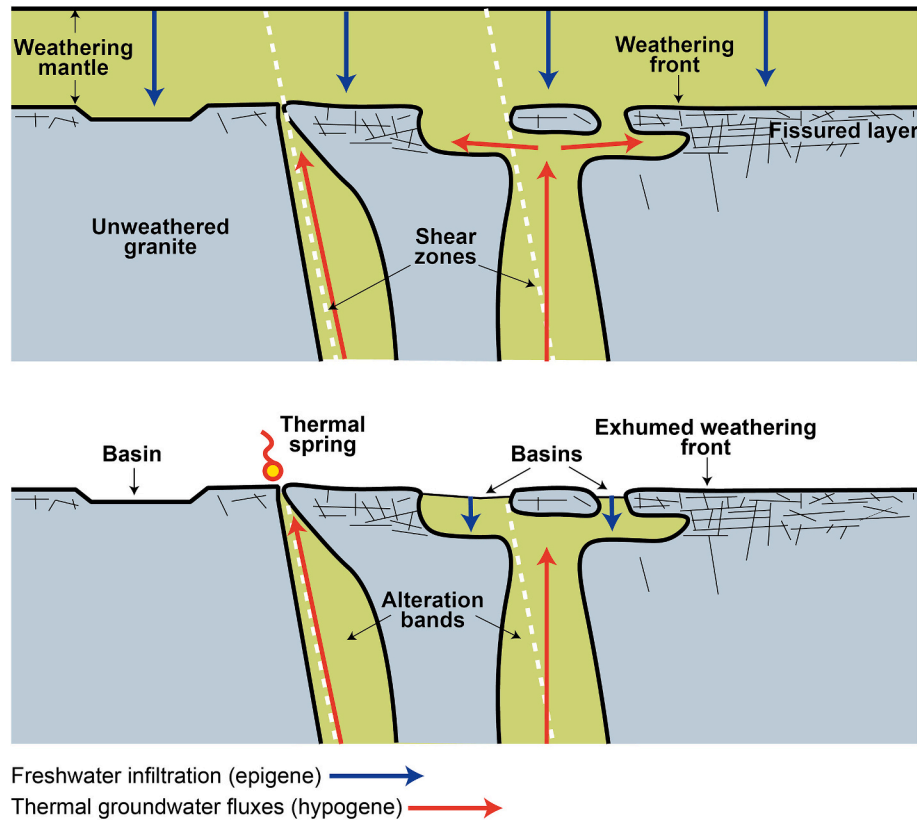


Fig. 8. Coupled epigenic-hypogenic hypotheses for the development of weathering basins within a weathering front. Image above, progression of weathering beneath the weathering mantle; below, the exhumed landscape relief.

The formation of closed and endorheic depressions with associated subsidence and volume reduction in the study area can be attributed to several geomorphological and geochemical processes unrelated to fluvial erosion. Intense hydrolysis of feldspar minerals (particularly plagioclase and K-feldspar) leads to the formation and mineralogical transformation of kaolinite, gibbsite, and other clay minerals (Pédro, 1997). This, accompanied by the removal (by leaching and eluviating) of soluble components such as silica, alkalis, and alkaline earth elements, by groundwater flow results in a net mass loss and volume reduction of the granitic rock (isovolumetric weathering transitioning to non-isovolumetric alteration), ultimately contributing to surface subsidence (e.g. MacLean, 1990). Furthermore, clays formed and accumulated within the depression may experience cycles of swelling and contraction due to changes in moisture, which can promote the formation of microcracks and the removal of sediments by aeolian ablation during dry cycles. The relationship between the depressions that define the multi-concave topography of the southern Albera Massif pediment and the detected sub-vertical alteration bands may not be always simple. ERT surveying confirms that these structures are associated with ponds and depressions developed within the weathering front, which are currently exposed to the surface. However, their spatial boundaries do not always coincide precisely. For example, Palau Pond (ERT-1, Fig. 4) is linked to a deep sub-vertical alteration structure, but the matching is only observed in the southern half of the pond. In the northern sector, the weathering progresses laterally but does not do the same downwards. The elongated depression intercepted S of Palau Pond in the same profile does align with the sub-vertical band, which retains a “cap” of unweathered rock that separates the two depressed zones (HRA in Fig. 4). Cardonera Pond (ERT-2, Fig. 5) and the adjacent depression at N show a similar spatial relationship: the sub-vertical alteration band is

not exactly overlapped by the two depressions, but instead falls between them, beneath a central promontory of unweathered rock. Thus, alteration responsible for the evolution of the two depressions appears to have been linked to lateral flows spreading from the vertical alteration band. The profile captured on Closa Pond (ERT-3, Fig. 6) shows that the sub-vertical alteration band locates nearly in a central position, but its lateral boundaries extend further away than those of the pond, coinciding reasonably well with the imaged sub-horizontal alteration zone. In the case of Llampol Pond (ERT-4, Fig. 7), there is no evident spatial relationship between alteration bands, and the pond bottom, ponded on fresh granite rocks. Nevertheless, this pond outlines an oval, with its major axis aligned in the same direction as the regional shear zones trending. Thus, although it depicts a strong structural control, the weathering signature points to be of epigenic origin in this case, probably because the weathering horizon is the thinnest in the area. In contrast, the elongated depression intercepted north of the pond by profile ERT-4 is clearly associated with a deep alteration structure, whose morphological features are patently hypogenic in origin. Therefore, the overall observations made in the Albera Massif reveal that its characteristic multi-concave landscape is the result of a complex weathering history, in which both epigenic and hypogenic processes converge, driven by several groundwater flows of different natures. These observations may largely transcend the study area and, since a number of granite massifs share many of the characteristics reported here (Fig. 8), our conceptual model of functioning and evolution of weathering mantles and fronts could be easily exported to many other regions worldwide.

6. Conclusions

The geoelectrical images obtained from the electrical resistivity tomography (ERT) reveal the presence of sub-vertical alteration zones associated with shear zones, which extend to depths greater than >170 m beneath the exhumed weathering front. These structures exhibit rectangular or triangular cross-sections, widening with depth, and reach widths up to approximately 100 m. These sub-vertical structures may serve as a conduits for ascending hot waters, which may feed thermal springs, establishing a direct link between hypogenic thermal flow and weathering features. The fact that the alteration zone is broader at depth -observed in some structures- supports the hypothesis that alteration progressed upwards, from depth towards the surface. Moreover, "caps" of unweathered rock have been observed atop some of the weathering bands. The presence of such features that are not compatible with epigenesis further reinforces the hypogenic interpretation. However, the spatial relationship between the depressions that define the multi-concave topography and these sub-vertical alteration structures is complex, which is attributed to that lateral flow processes also are playing a role. The geoelectrical images also indicate that, in specific cases, depressions formed exclusively through epigenic weathering processes. Overall, the data reveal a complex weathering front, shaped by the coexistence of hypogenic and epigenic alteration processes, along with lateral fluid flows. Regardless of their origin, erosion of the weathering mantle exposed the most deeply weathered zones, which subsequently evolved into topographic depressions. Some of these depressions host functional wetlands, sustained by hypogenic (sulfurous thermal waters) and/or surface (runoff) water inputs, which are a defining feature of the study area. Our observations lead to propose a conceptual model that illustrates the different key hydro-geomorphological processes driving the formation and evolution of weathering mantles, as well as the associated forms. Since many granite massifs share features with the Southern Albers Massif, the model proposed here will be easily scalable and exportable to other regions worldwide.

CRedit authorship contribution statement

Eduard Madaula: Writing – review & editing, Investigation, Conceptualization. **Carles Roqué:** Writing – review & editing, Investigation, Conceptualization. **Mario Zarroca:** Writing – review & editing, Investigation. **Gisela Gonzalvo-Henry:** Writing – review & editing, Investigation. **Anna Menció:** Writing – review & editing, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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We would like to dedicate this work to the memory of R. Linares, whose contributions, dedication and enthusiasm are deeply missed.

Data availability

Data will be made available on request.

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