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SCIENCE

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ABSTRACT
A geological, geomorphological and geo-touristic map, at 1:5000 scale, has been produced for the most representative area of the regional 'Special Nature Reserve of *Montalbano Jonico Badlands*', with the aim to represent the scientific and landscape features which allowed the establishment of the Reserve. The area is located in the Province of *Matera* (*Basilicata*), on the southwestern sector of the Apennines Quaternary foredeep, in Southern Italy. The map highlights stratigraphic signatures of international interest and badland landscapes, imprinted on a clayey marine succession straddling the Early-Middle Pleistocene boundary. This stratigraphic interval can be considered as an international reference section for global paleoclimatic signatures during Marine Oxygen Isotopic Stages 20–18 and for the base of the Middle Pleistocene Subseries/Subepoch. With the goal to disseminate these knowledges, to improve future research and to promote sustainable geo-tourism, the map allows visitors to enjoy the scientific features and scenery of the Reserve.

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1. Introduction

A map is a visual and symbolic representation of an area that highlights the relationships between elements. A geological and geomorphological large-scale map represents and illustrates in detail the geometry and spatial relationships between stratigraphical, structural and landscape abiotic features of an area; their interpretation and use allow understanding of the processes of landscape evolution and empower a sustainable management of geoheritage (e.g. Bernknopf et al., 1993; Boenzi et al., 2014; Ferrando et al., 2022).

With the progress of technology, geological and geomorphological maps benefit from the combination of accurate satellite imagery, aerial photographs, high-tech field equipment (e.g. GPS, tablet and dedicated applications) and Geographic Information Systems (e.g. Whitmeyer et al., 2010).

New data recently collected with large-scale geological field surveys, complemented with unpublished data collected by the Ciaranfi research group in the last thirty years (e.g. Ciaranfi et al., 1996; Marino et al., 2020) allowed us to produce an original 1:5000 scale geological and geomorphological map of the most representative area of the Special Nature Reserve of *Montalbano Jonico* Badlands, established with L.R. N° 3 of 27 January 2011 in the Province of *Matera* (*Basilicata* Region, Southern Italy). In the mapped area, the marine sedimentary succession, informally named *argille subappennine* (Azzaroli et al.,1968), was candidate to represent the Global Boundary Stratotype Section and Point (GSSP) of the base of the Middle Pleistocene Subseries/Subepoch.

The main goal of this work is to emphasize the role of geological and geomorphological mapping as a tool to summarize, represent and disseminate scientific features thus promoting new research and for educational and touristic purposes.

2. Literature review

2.1. Regional geological context

The Special Nature Reserve of *Montalbano Jonico* Badlands is located along the southwestern portion of the Plio-Pleistocene Southern Apennines Foredeep (Bradanic Trough, e.g. Migliorini, 1937; Casnedi, 1988) in the vicinity of the Ionian Coast, in the Basilicata Region, Southern Italy (Figure 1). This part of the foredeep is characterized by the presence (at about 700 m depth) of the buried frontal accretionary wedge of the Metaponto Nappe Auctt (e.g. SGI, 1965, 2012; Casnedi et al., 1982; Mostardini & Merlini, 1986; Carbone et al., 2013). These terrains, that represented the eastern margin of the Late Miocene –

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Supplemental map for this article can be accessed at https://doi.org/10.1080/17445647.2023.2179435.

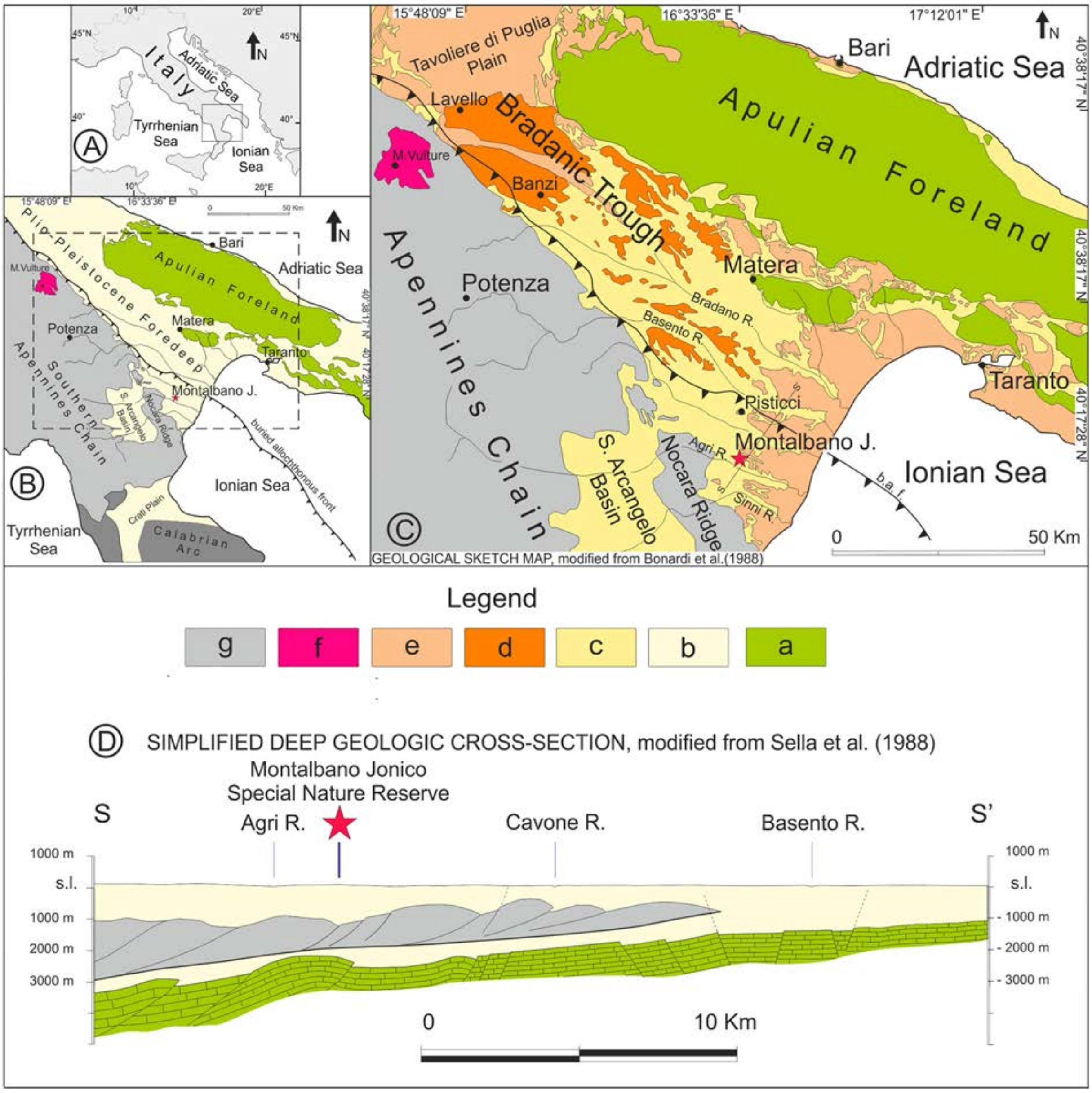

Figure 1. A: Regional geographic framework of Southern Italy; B and C: Simplified regional geological setting of Southern Italy and location of the Special Nature Reserve of *Montalbano Jonico* Badlands (red star). D: simplified geologic cross-section of the Southern Apennines front in the Ionian area. Legend of the simplified geological maps and cross-section in B, C and D: (a) Cretaceous units of the Apulian Foreland; (b) Pliocene-Holocene Southern Apennines Foredeep units in B and D; (c) Pliocene – middle Pleistocene Bradanic Trough units in C; (d) Early Pleistocene regressive coarse grained units of the Bradanic Trough; (e) Middle – late Pleistocene marine terrace deposits of the Bradanic Trough; (f) Quaternary volcanic units; (g) Triassic – Neogene units of the Apennines Chain. b. a. f. in C: buried allochthonous front. Modified from Marino et al. (2020).

Early Pliocene Apennines accretionary wedge, overthrust the axial portion of the submerged Quaternary foredeep, reaching its present position, roughly in the Late Pliocene – Early Pleistocene (e.g. Ciaranfi et al., 1979; Patacca & Scandone, 2007; SGI, 2012, 2014b; Carbone et al., 2013; Carbone & Lentini, 2015). This sector of the Bradanic Trough experienced a high rate of subsidence until the Calabrian; afterwards, it underwent regional uplift of about 0.2–0.8 mm/year that proceeded gradually from the hinterland to the present-day Ionian coastline (e.g. Ciaranfi et al., 1996; Doglioni et al., 1996; Westaway & Bridgland, 2009). However, some studies proposed for the same area higher uplift rates, ranging from 1.2 to 1.6 mm/year (Amato et al., 1997; Caputo et al., 2010). This geodynamic evolution was recorded by the Plio-Quaternary sedimentary succession outcropping in the area of *Montalbano Jonico* Reserve, represented from bottom to top by the following informal lithostratigraphic units: (i) wedge top deposits, referable to two depositional cycles known as *argille e sabbie di Craco* and *gruppo del Caliandro*, Pliocene; (ii) the *argille subappennine*, Early-Middle Pleistocene and (iii) marine and alluvial terrace deposits, Middle-Late Pleistocene (SGI, 2014b; Carbone & Lentini, 2015). This sedimentary succession unconformably overlies the Metaponto Nappe and represents the first post-Messinian deposits of the western margin of the Southern Apennines Foredeep (e.g. Pieri et al., 1996; Tropeano et al., 2002). The *argille subappennine* represents the post turbidite deposits of the Bradanic Trough *sensu* Casnedi et al. (1982) and corresponds to the *argille and sabbie sommitali* of Balduzzi et al. (1982); the age ranges from the Gelasian to the middle Pleistocene, from the hinterland to coastal areas (both the Adriatic towards the NE and the Ionian towards the SE) (e.g. SGI, 2011a, 2011b, 2012, 2014a, 2014b). The stratigraphic interval of this unit outcropping in the *Montalbano Jonico* area includes the Lower-Middle Pleistocene boundary (e.g. Ciaranfi et al., 2010; Marino et al., 2020) and has its coeval continental stratigraphic homologous in a lacustrine clay succession of the close *Sant'Arcangelo* Basin (e.g. Sabato et al., 2005; Onofrio et al., 2009;), see Figure 1(b,c) for location. The marine and alluvial terrace deposits, represented by distinctive regressive coastal wedges and alluvial plains at decreasing heights and ages from the hinterland (maximum height at 450 m a.s.l.) towards the actual shore line (minimum height at about 12 m a.s.l.), testify the gradual emersion of the Bradanic Trough and its interaction with Quaternary glacio-eustatic sea-level changes (e.g. Westaway & Bridgland, 2007; Cilumbriello et al., 2008; Moretti et al., 2010; Gallicchio et al., 2014).

2.2. The argille subappennine in the Special Nature Reserve of Montalbano Jonico Badlands

The *argille subappennine*, the key informal lithostratigraphic unit of the Reserve, is shown in a composite stratigraphic section of about 450 m, representing the middle and upper portion of its sedimentary succession (*Montalbano Jonico* Section – MJS, Figure 2) (e.g. Ciaranfi et al., 1996; Ciaranfi et al., 2010; Marino et al., 2020). This section has a shoaling upward depositional trend, passing gradually from alternating silty clays and clayey silts at the bottom, to alternating silty-clays and sandy layers at the top. The succession shows several intervals containing invertebrate macrofossils consisting of molluscs and subordinately burrowing echinoids, decapods, macroforaminifers, octocorals and remains of bony fishes (otoliths). On the basis of micro and macro invertebrate benthic assemblages, several deepening – shallowing cycles from epibathyal to sublittoral environments have been recognized; in particular, in the lower portion of the section a maximum water depth of ca. 500 m was inferred, while in the upper part of the section, an inner shelf setting was reconstructed (Stefanelli, 2003; Ciaranfi & D'Alessandro, 2005; Girone, 2005).

Tephra marker beds (V1-V6-9, in the Main Map), well distinguishable both in chemical and mineralogical composition, and in macrofossil assemblages of close stratigraphic intervals (Figure 3), were used as stratigraphical markers and allowed to propose a sedimentary succession with chronostratigraphic constraints (Ciaranfi et al., 2010). Radiometric dating with $^{40}Ar/^{39}Ar$ isotopes assigns V3 to 801.2±19.5 ka, V4 to 774.1 ± 0.9 ka and V5 to 719.5 ± 12.6 ka which falls within the Lower-Middle Pleistocene Mediterranean tephrostratigraphic frame. V3 and V4 were referred to the Monte Vulture volcanic activity, while V5 to the Campanian Volcanic zone (Maiorano et al., 2010; Marino et al., 2015; Petrosino et al., 2015; Nomade et al., 2019).

Some dark horizons characterizing the clayey succession correspond to sapropel layers correlated to insolation cycles 112, 104, 102, 90, 86 and 74, Figure 2 (Stefanelli, 2004; Maiorano et al., 2008; Girone et al., 2013; Nomade et al., 2019), according to the Mediterranean sapropel stratigraphy of Lourens (2004) and Lourens et al. (2004).

The calcareous nannofossil biostratigraphy indicates that the entire succession belongs to the Early-Middle Pleistocene according to the small *Gephyrocapsa* and *Pseudoemiliania lacunosa* biozones of Rio et al. (1990) (e.g. Maiorano et al., 2004; Maiorano et al., 2010). The analysis of the $\delta^{18}O$ curve, together with other stratigraphic constraints, allowed to calibrate the entire *Montalbano Jonico* section on an astronomical scale, thus obtaining a precise chronology in a stratigraphic interval through MIS (Marine Oxygen Isotope Stage) 37–16, from 1.24 to 0.645 Ma (Ciaranfi et al., 2010; Maiorano et al., 2010; Marino et al., 2015).

In the *Montalbano Jonico* Section, the stratigraphic interval represented by the Ideale Section (Figure 4), has been extensively studied, in order to reconstruct in detail the paleoclimate and paleoenvironmental evolution through the key interval of the Lower-Middle Pleistocene transition (e.g. Bertini et al., 2015; Nomade et al., 2019; Marino et al., 2020; Maiorano et al., 2021). The Ideale Section, including V3 and V4 tephra layers and spanning MIS 20–18, contains the expression of the Early-Middle Pleistocene boundary, at about 0.774 Ma, with the V4 tephra layer at the transition of substage MIS 19c to MIS 19b, and with the $^{10}Be/^{9}Be$ peak, which represents the geomagnetic dipole anomaly associated with the Matuyama/Brunhes polarity reversal (Simon et al., 2017).

3. Methods

In addition to traditional tools of the geological survey, for field work, we used an Apple tablet, with the FieldMove App (by Petroleum Experts Limited), in order to obtain georeferenced data and collect information as photo, sketches and notes in a simple and organized way. The topographic base map used for

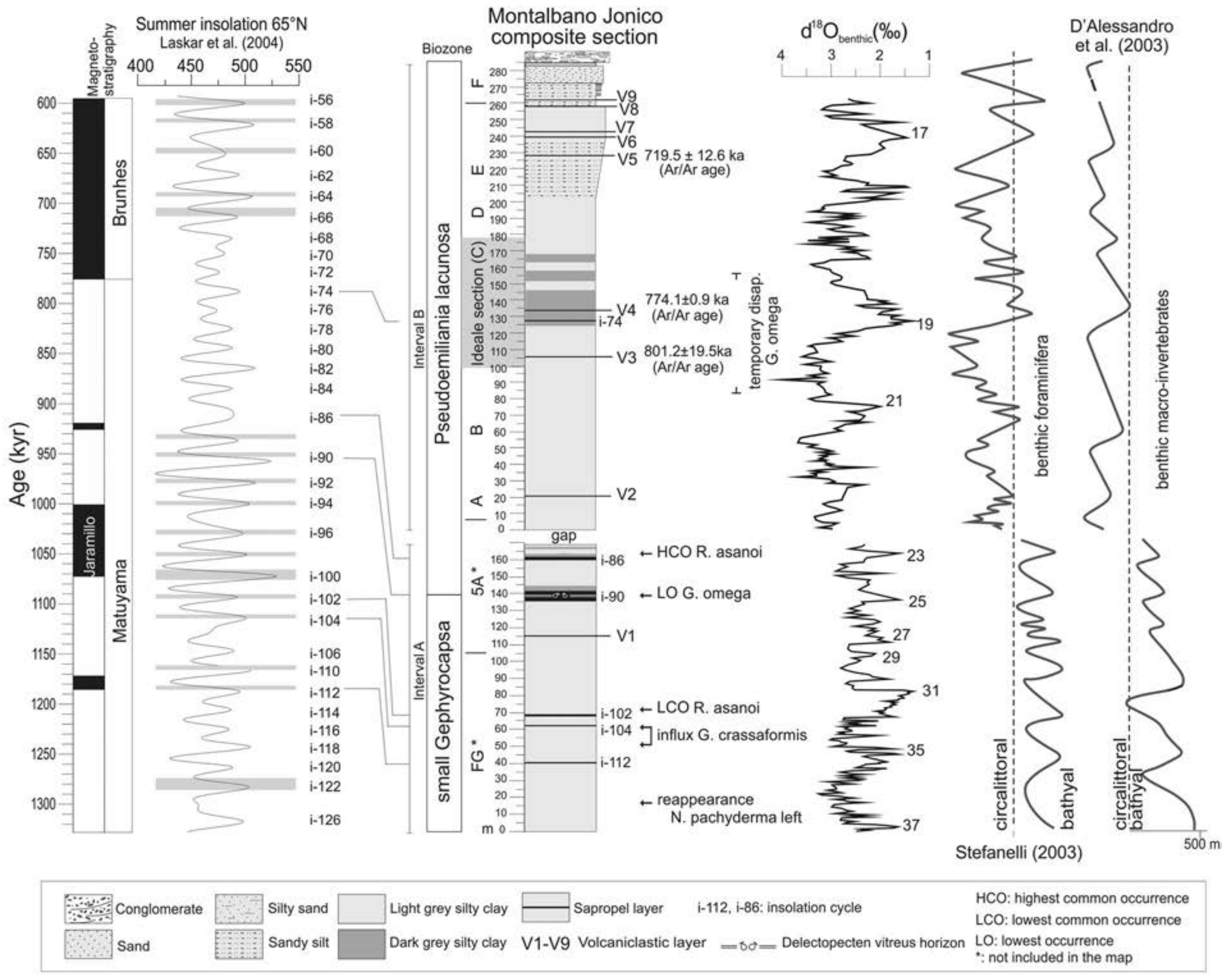

Figure 2. Stratigraphical features of the composite *Montalbano Jonico* section (intervals A and B). Biostratigraphic and paleoenvironmental details are traced according to Ciaranfi et al. (2001, 2010), Stefanelli (2003, 2004), D'Alessandro et al. (2003), Maiorano et al. (2004, 2010), Girone et al. (2013). $\delta^{18}O$ benthic record is from Ciaranfi et al. (2010). The correlations to sapropel stratigraphy are according to Lourens (2004), Lourens et al. (2004) and Konijnendijk et al. (2020). Summer insolation is from Laskar et al. (2004). The $^{40}Ar/^{39}Ar$ ages of V3-V5 are from Ciaranfi et al. (2010), Maiorano et al. (2010), Marino et al. (2015) and Nomade et al. (2019). Partial sections: FG (*Fosso Giuseppe* section), 5A (*5 agosto* section), A (*Venus Bassa* section), B (*Dito del Diavolo* section), C (*Ideale* section), D (*Salvatore* section), E (*Vecchietto* section), F (*Molino* section).

the geological and geomorphological mapping is represented by sheets n° 507072 and n° 507071 of the *Carta Tecnica Regionale*, at 1:5000 scale, available at http://rsdi.regione.basilicata.it (accessed 10 November 2022), and by printed orthophotos from Google Earth. Aerial photographs of IGMI (*Istituto Geografico Militare Italiano*) at 1:33,000 scale (years 1955 and 1990) have been also analysed by using an office mirror stereoscope, to identify the spatial distribution of landforms (e.g. terraces, landslides and badlands). We imported all data in QGIS (EPSG: 32633), and finally, we used CorelDraw Suite to set the final map. At last, to show a 3D representation of the geological and geomorphological elements, two geological cross-sections were drawn.

4. Results

The map, at 1:5000 scale, includes an area of about 6.5 km^2, located on the western slope of *Montalbano Jonico* hill, along the left side of the lower *Agri* valley. It comprises the area containing the major stratigraphic, morphological and structural elements of the Special Nature Reserve of *Montalbano Jonico* Badlands. In particular, the areal distribution of the outcropping stratigraphic units with its tephra marked beds, the main landforms (badlands, terraces and landslides) and the major tectonic elements were represented on the Main Map.

4.1. Stratigraphy

The local outcropping sedimentary succession is represented by the following informal lithostratigraphic units; (i) *argille subappennine*; (ii) ionian marine terrace deposits; (iii) alluvial and Agri terrace deposits and (iv) colluvium. The marine and alluvial terrace deposits, the colluvium and the present-day alluvial deposits unconformably overlie the *argille subappennine* which represents the substratum of the area.

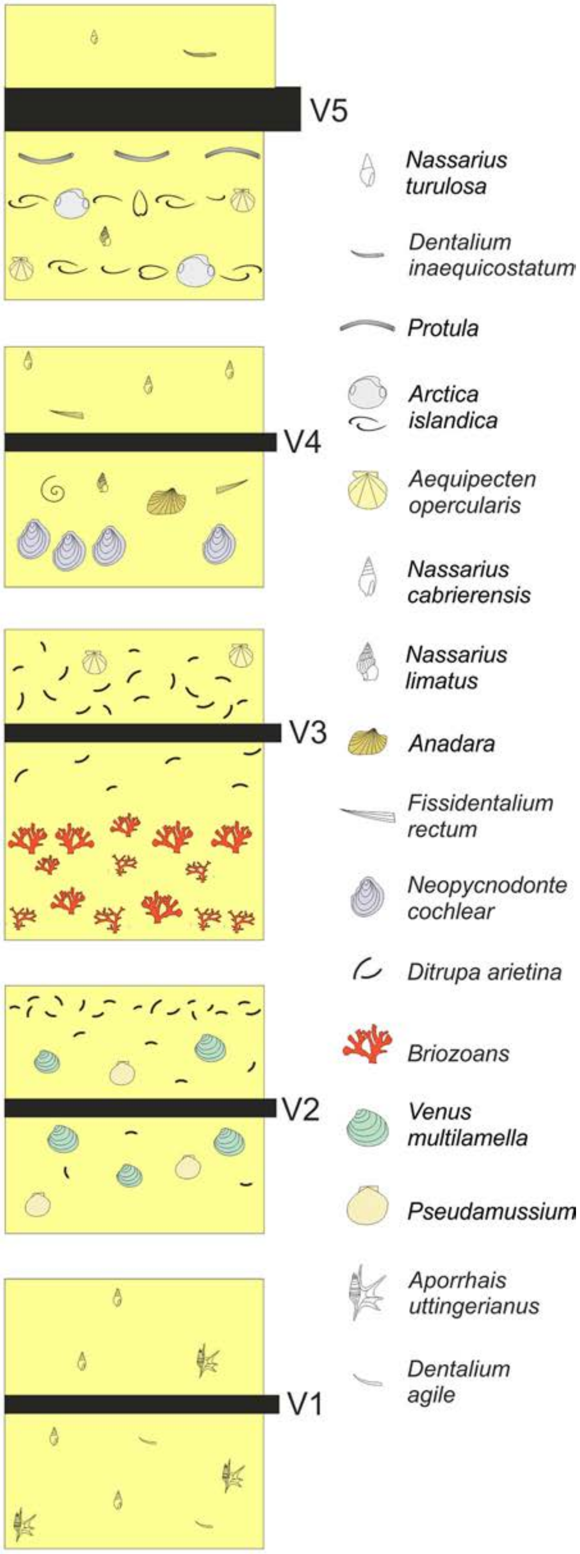

Figure 3. Macro-invertebrate fossil assemblages characterizing the V1–V5 tephra marker beds. Modified from Ciaranfi et al. (2001).

4.1.1. Argille subappennine

The *argille subappennine* informal unit outcrops extensively in the map area with a thickness of about 300 m, representing the upper portion of interval A and interval B of the *Montalbano Jonico* Section (Figure 2).

The older part of the unit outcrops in the northern area of the map, along '*Fosso cin cin*'; moving up the slope until '*Dito del diavolo*' crest, a stratigraphic interval with a thickness of about 100 m outcrops. In particular, V1 tephra layer stands out on the right side of *Fosso cin cin* at about 130/140 m a.s.l.; this marker bed is a few centimetres thick and is characterized by a macrofossil association represented by *Aporrhais uttingerianus*, *Nassarius cabrierensis* and *Dentalium agile*. Up dip, the succession is interrupted by a high-angle fault of unknown displacement. Moving towards '*Dito del diavolo*', the succession is marked by some rich layers of macrofossils represented by *Aequipecten opercularis*, *Psedamussium septemradiatum* and bryozoans; the top of the succession is characterized by the presence of the V3 tephra layer.

The intermediate and younger intervals of the outcropping *argille subappennine* have good exposures in the central part of the area, between *Fosso Venus* to the north and *Fosso della Bauta* to the south. In this area, all the main stratigraphic features of the formation are well exposed. The outcropping stratigraphic interval is marked by several tephra layers represented, from bottom to top, by V2, V3, V4, V5 and by V6-9 tephra interval containing four thin and closely spaced tephra layers. The stratigraphy of this portion of the *argille subappennine*, which shows a thickness of about 285 m, has been studied in detail along different correlatable partial sections represented from the bottom to the top by section A (*Venus Bassa* section), section C (*Ideale* section), section C1 (*Ciaranfi* Master section), sections D–E (*Salvatore-Vecchietto* sections) and section F (*Molino* section). The V2 tephra layer marks the lower portion of this part of the succession; this tephra layer is 5 cm thick and is identified along the right side of *Fosso Venus* at about 80 m a.s.l., thanks to the presence of a macrofossil assemblage represented by *Venus multilamella* and *Ditrupa*. The most important stratigraphic interval of the *argille subappennine* is represented along *Fosso Ideale*. Here, the succession marked by the presence of V3 and V4 tephra layers has a thickness of about 8 m and spans a time interval between MIS 20 and MIS 18 (about 100,000 years). Several layers with bryozoan colonies occur below V3, whereas between V3 and V4 tephras, *Aequipecten opercularis*, *Neopycnodonte cochlear*, *Cassidaria echinophora* happen among macrofossils. Above V4, 3 dark intervals ascribable to interstadial periods of MIS 19a (Nomade et al., 2019) are present. This stratigraphic interval is correlated with section C1 (Ciaranfi Master section) outcropping on the right side of Fosso Grotte. Up dip from section C1, the stratigraphic interval including tephra V5 (sections D and E) outcrops; this tephra layer can be observed by walking along '*appiett u Mulin*' route at about 190 m a.s.l. The uppermost

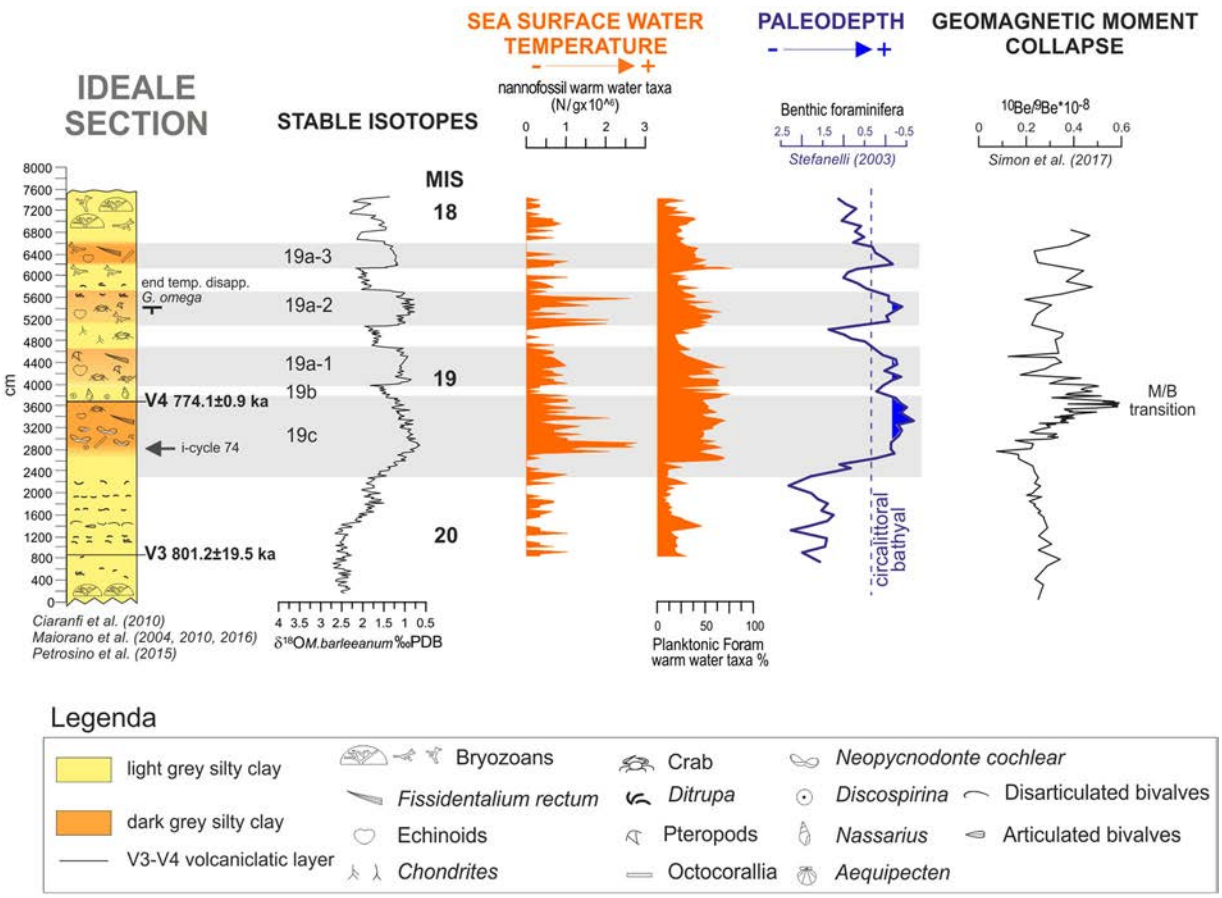

Figure 4. Stratigraphic log of the *Ideale* Section showing the high-resolution benthic stable oxygen isotope results (Nomade et al., 2019) correlated with the main stratigraphic, chronological and paleoenvironmental constraints. Substages (MIS 19 a, b and c) and interstadials of MIS 19a (19a-1, 19a-2, 19a-3) are indicated according to Nomade et al. (2019).

part of the *Montalbano Jonico* succession is represented in section F at about 270 m a.s.l. along the '*appiett u Mulin*' route. In this section, the clayey deposits are replaced by sandy sediments containing a shell bed some dm thick represented by different fauna and clumps of *Arctica islandica* and ophiuroids.

A silty – sandy lithofacies of about 10 m thick characterizes the top of the *Montalbano Jonico* Section.

The most representative fossil content from the *Montalbano Jonico* Section is shown in Figure 5.

4.1.2. Ionian marine terrace deposits

These deposits outcrop at the top of *Montalbano Jonico* hill, and belong to two distinct orders: the higher terrace develops between 290 and 280 m a.s.l. while the lower develops between 255 and 224 m a.s.l. They are mainly represented by sandy and gravelly coastal deposits about 15–20 m thick, transgressively lying on the *argille subappennine*. The main body of the two terrace clastic wedges (lower and middle part) is represented by sediments deposited in inner shelf and beach environments while the upper part consists of alluvial or lagoonal deposits. On the whole, they are characterized by vertical stacking patterns recording transgressive and progradational events, with internal high-frequency eustatic cyclicity. These depositional environments and vertical stacking patterns find analogous in the present day Ionian coastal plain, as outlined by Pescatore et al. (2009) and Tropeano et al. (2013). According to Brückner (1980) and SGI (2014b), the above-mentioned marine terraces can be referred respectively to the seventh and sixth orders of the marine terraces characterizing the hinterland of the Ionian Coast. No consensus exists regarding the ages of the two terraces, there is no consensus (e.g. Amato et al., 1997; Brückner, 1980; Caputo et al., 2010; Sauer et al., 2010; Westaway & Bridgland, 2007; 2009) on the base of regional considerations, we propose for the two terraces, an age corresponding respectively to MIS 13 and MIS 11, in accordance with Westaway and Bridgland (2007) and Sauer et al. (2010).

4.1.3. Alluvial and Agri terrace deposits

The *Agri* terrace deposits outcrop in the lower hillside of *Montalbano Jonico* and belong to two different orders. The higher terrace develops at about 150–140 m a.s.l. (about 80 m higher than the actual river), the lower one is at 60–50 m a.s.l. (10–15 m above the actual river); they correspond respectively to FT3 and FT0 of Brückner (1980).

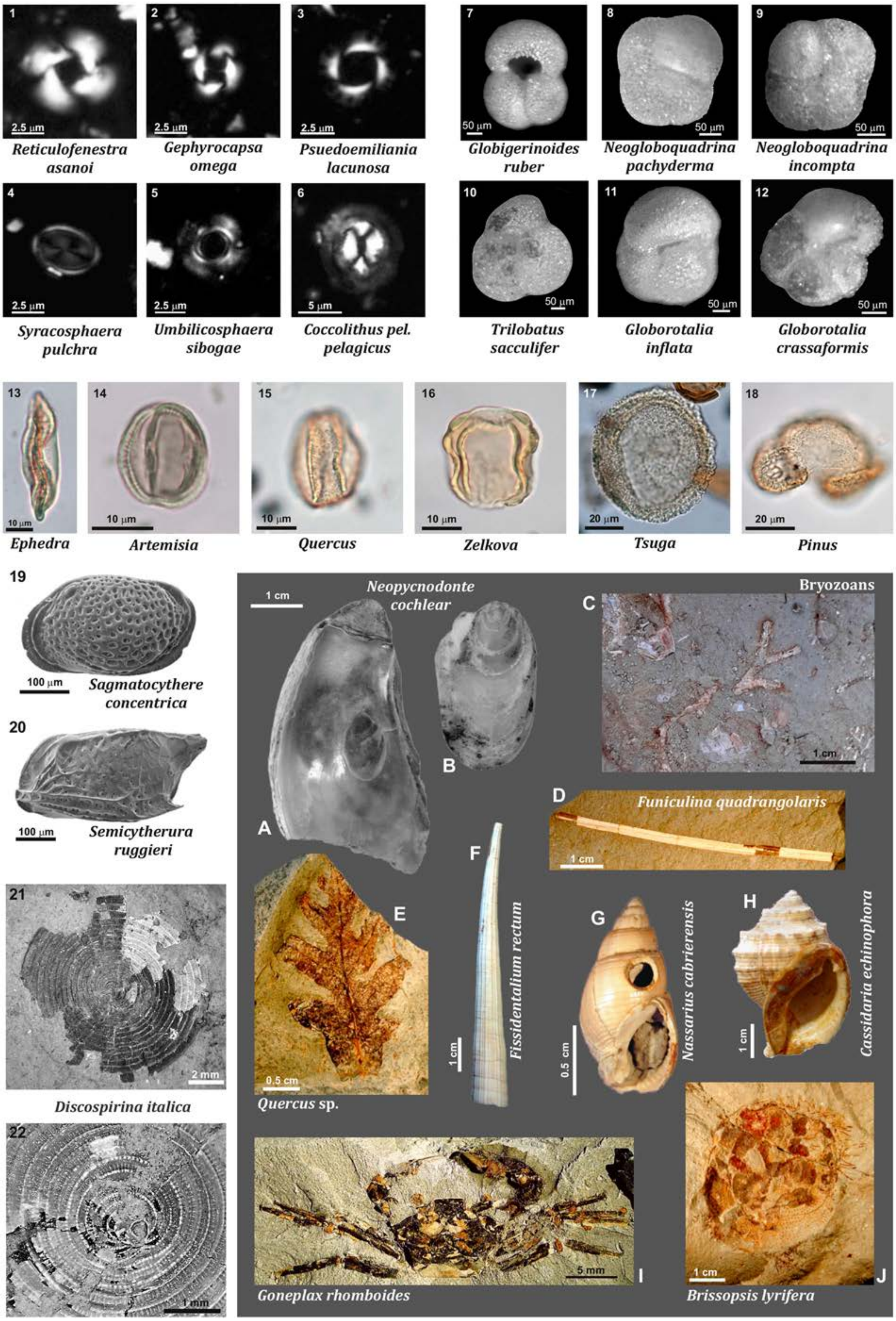

Figure 5. Representative fossil content from *Montalbano Jonico* Section. 1-6: calcareous nannofossils; 7-12: planktonic foraminifera; 13-18: pollen grains; 19-20: ostracods; 21-22: benthic foraminifera; A-J: Fossil remains of macro-invertebrates and plants.

The higher one has a maximum thickness of about 30 m. The lower and middle parts of the terrace are represented by coarse-grained alluvial deposits, while the upper part is represented by fine grained deposits characterized by the presence of a discontinuous tephra layer represented on the map as Vt.

The lower terrace is represented mainly by fine-grained alluvial deposits with a maximum thickness of about 30 m (Gallicchio & Miraglia, 2011). Both terraces can be referred to the late Pleistocene.

The Present-day alluvial deposits characterize the major incisions of the *Montalbano Jonico* hillslope. They are mainly represented by silty sands of grey–yellow colour and rare pebbles. The thickness is few m.

4.1.4. Colluvial deposits

These deposits are located within a morphological low between the town of *Montalbano* Jonico and the cemetery. It is represented by few metres thick of brownish silty and clayey loam with rare siliciclastic and calcareous pebbles. The age can be attributed to the Late Pleistocene–Holocene.

4.2. Structural features

The *argille subapennine*, representing the substrate of the study area, has an overall homocline attitude gently dipping towards the east/southeast (dip angle varies from 10° to 6°); this structure is locally interrupted by extensional high angle faults striking both N 30/40 E and N140/160E, and dipping towards the southern quadrants. A major vertical displacement of about 70 m is shown by the fault outcropping in the northern portion of the map along *Fosso cin-cin* (at the two sides of the fault, V4 and V5 are at the same elevation; at about 250 m a.s.l.). The presence of the mapped faults was highlighted by the identification and mapping of the different tephra layers, see Main Map and geological cross-section CD.

4.3. Geomorphological features

From the geomorphological point of view, as described above, the area is characterized by the presence of two sets of marine and fluvial terraces.

The widespread landforms of the reserve are badlands (Figure 6a). They derive from erosion, due to water washout, in clay-rich lithologies of the hillslopes surrounding *Montalbano Jonico* town. High drainage density and scarce vegetation cover generally characterize these landforms.

In the reserve, two main morphologies of badlands can be distinguished: '*Calanchi*' and '*Biancane*'.

'*Calanchi*' (Figure 6b) are reliefs characterized by a network of rills, separated by ridges that have a 'knife-edge' geometry (e.g. Piccarreta et al., 2006). These forms are found in the northeast of the area and generally at high elevations, connected with the terrace deposits that act as a caprock, maintaining the slopes at a steep constant angle. They are asymmetrical and the southern slopes are steeper than those oriented to the north and are more affected by intense erosion.

'*Biancane*' (the name derives from white salt efflorescence), are dome-shaped forms that have been interpreted by some authors as the end-product of '*calanchi*' erosion (e.g. Alexander, 1982), Figure 6c. For this reason, '*biancane*' dominate at the base of the slopes and is found at lower elevations, such as, near '*Fosso Ideale*' and in the northwest of the area.

There are also intermediate forms, called hummocky (Del Prete et al., 1997) or '*mammellonari*', that are arguably transitional between '*calanchi*' and '*biancane*', due to their intermediate morphological and physic-chemical characteristics (Piccarreta et al., 2006).

The distribution of badlands is also controlled by the combination of structural discontinuities (fractures and faults) and mass movements, detected and mapped in several field surveys.

The morphology of hillslopes is also characterized by widespread gravitational deformations due to active and ancient landslides (Figure 6d). Active landslides are localized in the upper part of the slope. They generally start from the top of the clayey deposits belonging to the *argille subappennine*, triggered by intense and long-term rainfall, with rapid flow movement and retrogressive evolution involving the upper sandy gravel marine terraces with slides and/or rock falls. Ancient landforms are mostly represented by two deep-seated gravitational slope deformations affecting large and thick portions of the hillslope substratum; the attitude of individual beds of the landslide bodies reveals a rotational-slide mechanism (see A-A′ geological cross-section in the Main Map). The landslide bodies are represented by large and very thick (up to several tens of metres) rotated blocks of the continuous succession represented by the *argille subapennine* and the marine terraces. Their possible controlling factors could have been of different types (landscape incision during glaciation, deglaciation, exceptional rainfall, seismicity). The age of this large landslide could be broadly referred to as late Pleistocene.

Together with desiccation cracks, highly reticulated network of subsurface horizontal pipes and micro-pipes can be identified. These elements can be easily seen along the '*Appiett u Castiedd*', the final part of the following proposed geotouristic itinerary.

5. Geo-touristic itinerary

The identification of a well-defined geo-touristic itinerary draws attention to the geological and cultural heritage and leads towards the establishment of

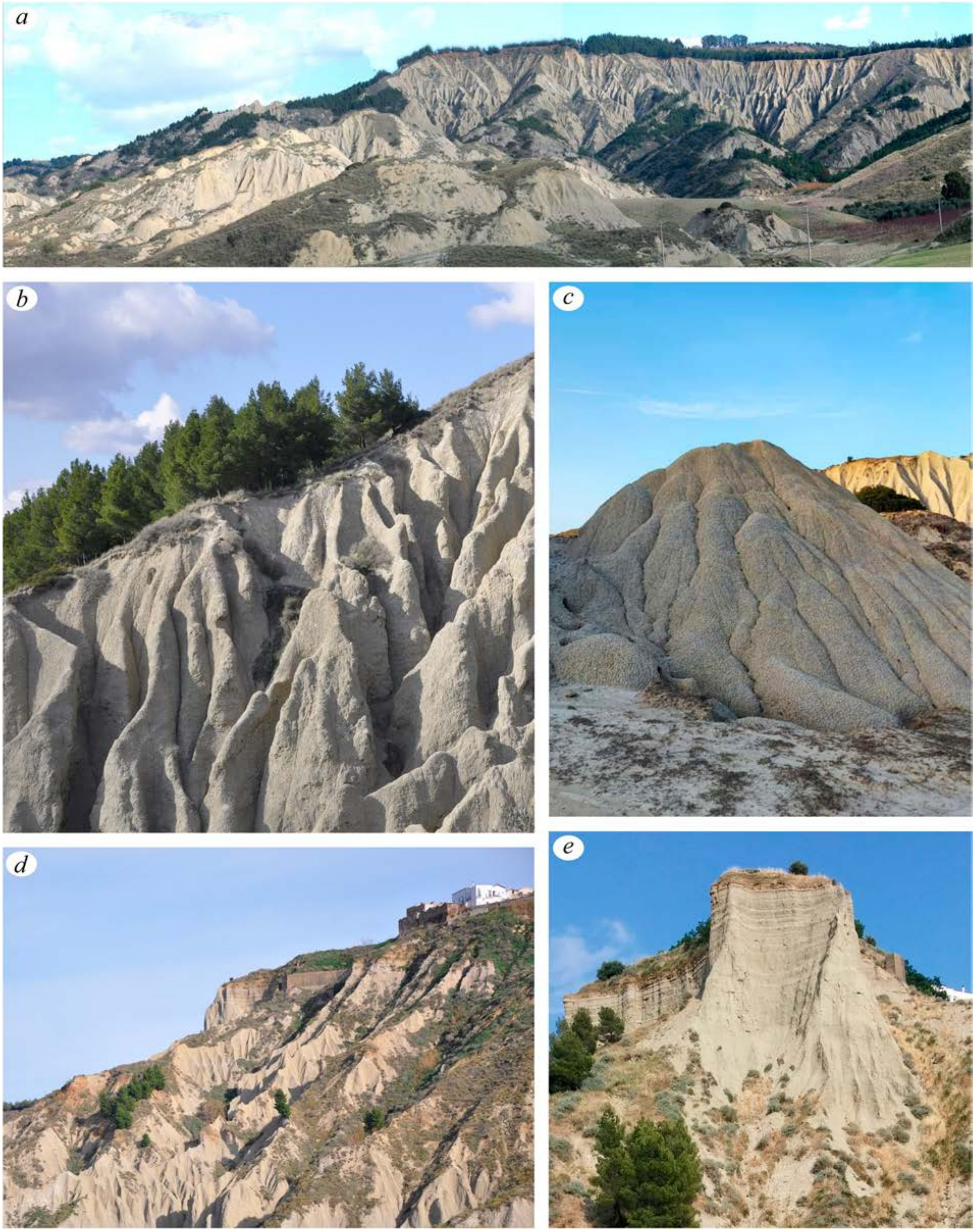

Figure 6. Characteristic landforms of the Reserve. (a) panoramic view of the badland landforms; (b) 'knife-edge' shaped badlands (*calanchi*); (c) dome shaped badlands (*biancana*); (d) ancient landslides (red-brown terrains) on the hill slope; (e) cliff in the sandy portion of the hillslope.

sustainable tourism activities (e.g. Sacchini et al., 2018). The map proposes an itinerary, approximately 2 km long, that can be completed by walking in 3 h, featured with observation points of stratigraphic, palaeontological and panoramic interest. Departing and arriving in the historic centre of *Montalbano Jonico*, the itinerary starts along the historic mule track known as '*Appiett u Mulin*': in the first part of the itinerary (observation points 1 and 2), it is possible to view the main stratigraphical features of the upper part of the *Montalbano Jonico* Section, all the geomorphological features typical of clayey slopes, and appreciate the wide floodplain of the *Agri* River. In particular, *Molino* section (Figure 7A) and V5 tephra

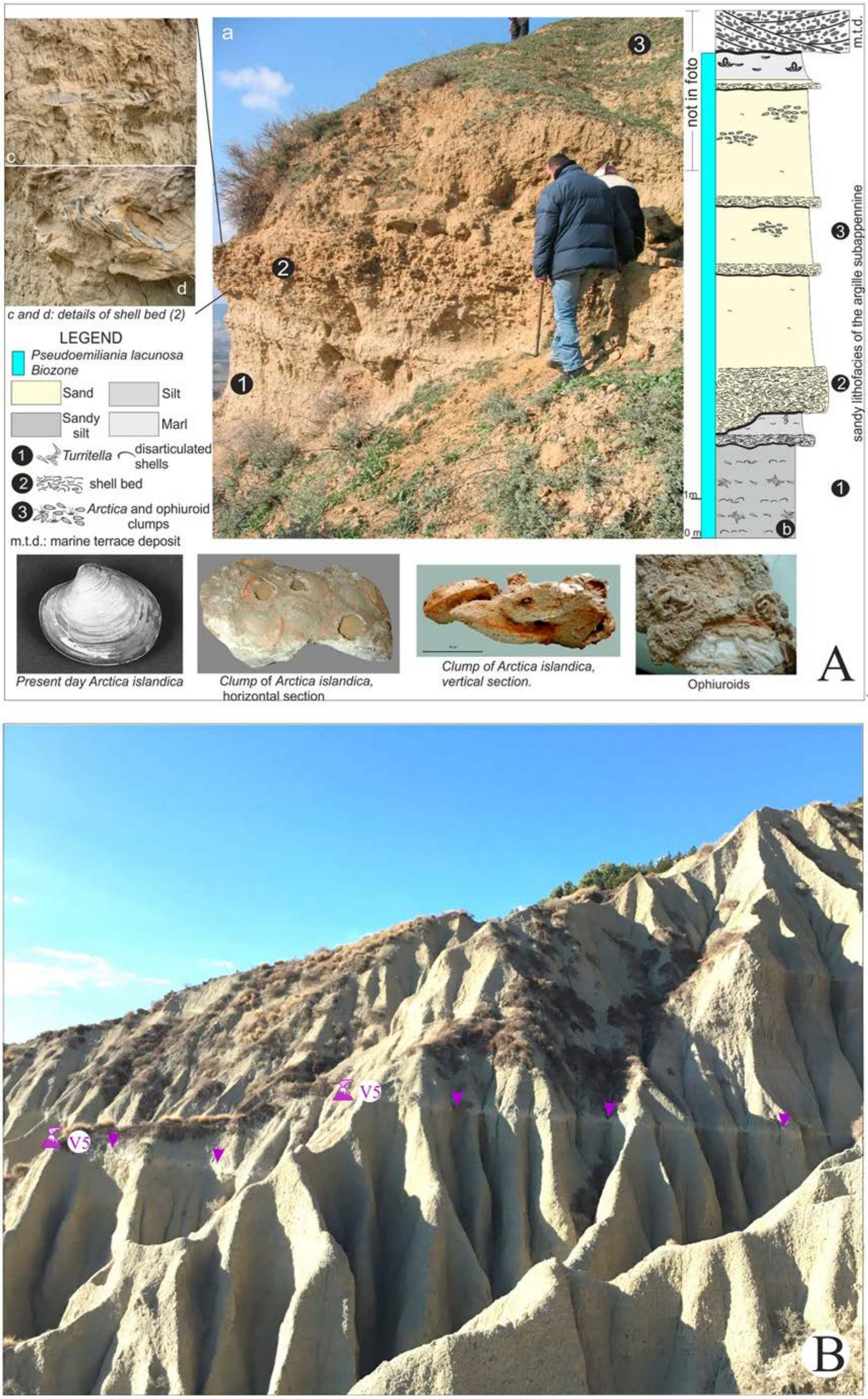

Figure 7. (A) Main features of *Molino* section: (a) main outcrop, (b) lithostratigraphic column, (c) and (d) close-up of shell bed; modified from Ciaranfi et al. (2011); (B) View of the faulted V5 volcaniclastic marker bed.

marker bed can be observed in detail respectively in observation points 1 and 2. Moving towards Masseria Rizzi numerous skeletal remains of macroinvertebrates (mainly valves of pectinids such as *Aequipecten opercularis*) can be observed, as well as the volcaniclastic level V3 and fossil remains of bryozoans, serpulids (*Ditrupa arietina*) and scaphopods, such as *Fissidentalium rectum* that characterize the stratigraphic layers nearby the volcaniclastic layer (observation points 3, 4 and 5). Proceeding up the canyon of *Fosso Ideale*, in observation point 6 it is possible to observe the main outcrop of the *Ideale Section*, including V3 at the base, and V4 at about 2.5 m above it. The main macroscopic features of the section can be divided as follows: (i) a few metres above V3, pavements of *Aequipecten opercularis* representative of inner-middle shelf environment and (ii) a few metres below V4, stratigraphic layers rich in *Neopycnodonte cochlear* that indicate a deepening phase in the shelf environment (observation point 7).

Going up along the '*Appiett u Castiedd*', towards *Montalbano* Jonico town, in addition to several fossil remains of macroinvertebrates and bryozoans, a landscape characterized by badlands, can be seen (observation point 8). Moreover, the volcaniclastic marker beds can be observed interspersed with clay sediments, being V5 the most visible; it appears dissected by high-angle extensional faults revealing Quaternary tectonic activity (Figure 7B). Finally, observation points 9, 10 and 11, out of the proposed itinerary show respectively the tephra layers V2, V1 and V3, as well as a boundless view of a badland landscapes towards the north.

6. Discussion and conclusions

New large-scale geological and geomorphological field mapping, realized with the use of high-tech equipment for collecting and management of data, and integrations with unpublished data collected during the last 30 years by the research group of Prof. Neri Ciaranfi (e.g. Ciaranfi et al., 1996; Marino et al., 2020) allowed for development at this first 1:5000 scale cartographic representation of the area. Here, the outcropping of particular geological and geomorphological features enabled the establishment of the 'Special Nature Reserve of *Montalbano Jonico* Badlands'. In particular, the map includes: (i) the planimetric extension of the outcropping lithostratigraphic units and their reciprocal boundaries; (ii) the location of the stratigraphic logs which enabled the reconstruction of the composite stratigraphic column of the *argille subappennine* sedimentary succession, in the area of the map; (iii) the location and extension of tephra marker beds (V1-V6-9 and Vt) which allowed the correlation between the different partial sections and the identification of new faults; (v) the areal extension of the badland landforms and (vi) the distribution of recent and paleo landslides.

Furthermore, the main roads that allow access to the Reserve and a geotouristic itinerary, with the locations of the main stratigraphic, palaeontological and morphological interest points of the Reserve, are indicated. This new graphical representation of the Reserve provides added value both for future scientific advances and the protection and enhancement of this territory. This protection could favour, in addition to appropriate environmental management, a source of employment and development.

A future regional geothematic map representing some of the main geological and morphological elements of scientific values in close areas to the *Montalbano Jonico* Badlands (e.g. the Early – Middle lacustrine clayey succession and the badland landscapes hosted in the Carlo Levi Literary Park, Sabato et al., 2019; the Pliocene wedge-top deposits outcropping in San Mauro Forte village, Pepe & Gallicchio, 2013; and the turbidite succession of the Candela Stream in the municipal territory of Rotondella, Gallicchio et al., 2023) might promote cohesive partnership between close local communities and the development of a regional holistic and sustainable management of the territory.

Software

Data were collected, during several field surveys, by both traditional method (on physical base map) and FieldMove suit, by Petroleum Experts Limited, on Apple Tablet. MapTiler Desktop 11.3 software was used to turn raster images in georeferenced basemaps in MBTile format, which were available offline on the FieldMove suite. The Map was assembled in QGIS environment and the final editing was made using Corel Draw Suite.

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No potential conflict of interest was reported by the authors.

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Data availability statement

The main geological and geomorphological data used for the composition of the map are available within the article or its supplementary material. The GIS datasets of this study is not publicly available but is available from the corresponding author (S. G.), upon reasonable request. Topographic base, at 1:5.000 scale, is openly available at http://rsdi.regione.basilicata.it.

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