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Natural laboratories for field observation about genesis and landscape effects of palaeo-earthquakes: a proposal for the Rocca Busambra and Monte Barracù geosites (W Sicily)

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Corresponding Author:	Luca Basilone Universita degli Studi di Palermo Dipartimento di Scienze della Terra e del Mare ITALY
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Universita degli Studi di Palermo Dipartimento di Scienze della Terra e del Mare
Corresponding Author's Secondary Institution:	
First Author:	Luca Basilone
First Author Secondary Information:	
Order of Authors:	Luca Basilone
	Alessandro Bonfardeci
	Pierangelo Romano
	Attilio Sulli
Order of Authors Secondary Information:	
Funding Information:	
Abstract:	Earthquakes are phenomena that are still being learned by the scientific community, and poorly known, especially as regard the prevention, by the population. Having a more complete knowledge is a basic step in understanding the vastness and intensity of the destructive phenomenon that involves a great amount of people. The recent earthquakes occurred in Central Italy (L'Aquila and Amatrice earthquakes) are examples that demonstrate the importance of having knowledge about these phenomena to contrast their destructive effects. We present a geological field trip to recognise causes and landscape effects of palaeo-earthquakes recorded in the Mesozoic rock successions outcropping in Sicily. The isolated carbonate reliefs of Rocca Busambra and Monte Barracù (Sicani Mts.) are spectacular sites of a passive continental margin where synsedimentary tectonic features – as paleofaults, neptunian dykes, morphostructural scarps, submarine landslide, soft sedimentary deformation structures – document earthquake causes and effects. Field evidence show in detail as the several paleofaults mapped in the Rocca Busambra stepped margin triggered the soft-sediment deformation structures recorded in the coeval deep-water rock succession of the Monte Barracù. In this view, the proposed field trip can represent a powerful tool to enhance the naturalistic and geological importance of the study areas by establishing geosites and protected areas for a proper fruition of geological-natural heritage and/or for geoconservation. Thus, through the proposed field trip it is possible to observe paleo-earthquakes activity and landscape products, having an educational training purpose also for public administrators, whose rapid and skilled action is necessary for the prevention and reduction of the geohazard.
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Natural laboratories for field observation about genesis and landscape effects of palaeo-earthquakes: a proposal for the Rocca Busambra and Monte Barracù geosites (W Sicily)

Luca Basilone*, Alessandro Bonfardeci, Pierangelo Romano, Attilio Sulli

Department of Earth and Marine Science, University of Palermo, Via Archirafi 22, 90123 Palermo, Italy

*corresponding author: luca.basilone@unipa.it

Abstract

Earthquakes are phenomena that are still being learned by the scientific community, and poorly known, especially as regard the prevention, by the population. Having a more complete knowledge is a basic step in understanding the vastness and intensity of the destructive phenomenon that involves a great amount of people. The recent earthquakes occurred in Central Italy (L'Aquila and Amatrice earthquakes) are examples that demonstrate the importance of having knowledge about these phenomena to contrast their destructive effects.

We present a geological field trip to recognise causes and landscape effects of palaeo-earthquakes recorded in the Mesozoic rock successions outcropping in Sicily. The isolated carbonate reliefs of Rocca Busambra and Monte Barracù (Sicani Mts.) are spectacular sites of a passive continental margin where synsedimentary tectonic features – as paleofaults, neptunian dykes, morphostructural scarps, submarine landslide, soft sedimentary deformation structures – document earthquake causes and effects. Field evidence show in detail as the several paleofaults mapped in the Rocca Busambra stepped margin triggered the soft-sediment deformation structures recorded in the coeval deep-water rock succession of the Monte Barracù.

In this view, the proposed field trip can represent a powerful tool to enhance the naturalistic and geological importance of the study areas by establishing geosites and protected areas for a proper fruition of geological-natural heritage and/or for geoconservation. Thus, through the proposed field trip it is possible to observe paleo-earthquakes activity and landscape products, having an educational training purpose also for public administrators, whose rapid and skilled action is necessary for the prevention and reduction of the geohazard.

Keywords: geotourism; geoconservation; earthquake; synsedimentary faults; seismogenic slumps; field trip

1. Introduction

An earthquake is ‘the shaking of the surface of the Earth, resulting from the sudden release of energy in the Earth's crust or upper mantle usually caused by movement along a fault plane and resulting in the generation of seismic waves, which can be destructive’ (Bolt 1993; Moczo et al. 2014). Earthquakes can trigger landslides, occasionally volcanic activity and, if located offshore, they can displace the seabed sufficiently to cause a tsunami (Keefer 2002; Malamud 2004; Walter and Amelung 2007; Posamentier and Martinsen 2011; Nishimura 2017).

Seismites are very important geological structures representing the evidence of the effects of earthquake in the sedimentary records (Seilacher 1969). These deformational structures, formed during seismic events of various values of magnitude, interested unconsolidated sediments. They also provide information about the responsible faults and the frequency of the earthquakes in a particular geological region (Seth et al.1990; Mastalerz and Wojewoda 1993; Martinez et al. 2005; Gamboa et al. 2010; Strasser et al. 2011; Festa et al. 2014; Üner et al. 2017). Seismically-induced slides and slumps related to low-angle slope irregularities at the water–sediment interface have been reported from deep-water carbonates (Garcia-Tortosa et al. 2011; Mastrogiacomo et al. 2012; Bergerat et al. 2011; Ortner and Kilian 2016; Basilone et al. 2014, 2016a). By the way, other triggering mechanisms (e.g., storm waves, floods, overpressure, gravitational instability, tidal shear), which are “virtually” dependent of the depositional environment, may lead to sediment deformation structures (e.g., Owen et al. 2011; Van Loon and Pisarska-Jamroży 2014; Kopf et al. 2016; Lunina and Gladkov 2016).

Rocca Busambra (1613 m a.s.l.) and Monte Barracù (1420 m a.s.l.) are isolated carbonate reliefs, located in the W Sicani Mountains near Corleone (Palermo, Figs. 1a, 2a), representing an ancient passive margin (i.e. the Southern Tethyan continental margin) where causes and effects of possible Mesozoic earthquakes are observable. They consist in neptunian dykes, paleofaults, unconformities and soft-sediment deformation structures (SSDSs) which are possible effects of synsedimentary tectonics and that could give information about the occurrence of earthquake shocks and their intensity (Allen 1986; Obermeier 1996; Bourrouilh 1998; Leeder 2010; Alsop et al. 2016).

Neptunian dykes are enlarged fractures of lithified deposits that are subsequently filled by younger sediment. Rocca Argenteria, the westernmost sector of the Rocca Busambra ridge (Figs. 2a, b), is an excellent site to observe these features. Here, the several neptunian dykes cutting the Lower Jurassic peritidal limestone are filled by different generation of sediments that record the effect of a polyphased extensional tectonics (Wendt 1965, 2017; Martire and Montagnino 2002; Basilone 2009).

Paleofaults are recognizable when angular unconformity between faulted beds and undeformed younger deposits occur (Davies and Reynolds 1996; Miall 2016). Rocca Busambra, especially the Piano Pilato region (Figs. 2a, b), includes spectacular sites where morphostructural scarps and paleofaults draped by younger sediments are observable.

SSDSs record sedimentary and tectonic processes in various geological provinces. They develop when primary lamination and stratification is deformed by a system of driving forces, such as gravitational instability, during/after sedimentation and before complete lithification (Allen 1986; Leeder 1987). Among the various SSDSs, those induced by earthquakes, initially called seismites by Seilacher (1969), are common in different depositional environments, when the sediment is temporarily in a weakened state due to the action of a deformation mechanism, such as liquefaction and fluidization (Lowe 1976; Maltman 1984; Martinsen 1994; Owen and Moretti 2011; Moretti et al. 2016). At Monte Barracù, SSDSs related to tectonic events and attributed to earthquake shocks are well represented (Figs. 2a, c, Basilone 2017).

The main purpose of this work, which describes the results of detailed field investigation and new data about the outcropping Mesozoic carbonates, is to give new information about the geological heritage of the region. This approach allows us to emphasize the scientific and geotouristic attraction of those features indicating the occurrence of synsedimentary tectonics and the landscape effects of paleo-earthquakes.

Recent researches, highlighting geological, geomorphologic, naturalistic and cultural heritages of Rocca Busambra region (e.g., the Royal Palace of Ficuzza, the hunting lodge of Ferdinand III of the Kingdom of Sicily, since the 1799) and Monte Barracù (Mascle 1979; Agate et al. 1998; Basilone 2009; 2011; Bertok and Martire 2009; Catalano et al. 2010; 2011), are adequate to justify the proposition of Geosite for the areas. As indicated by the IUGS (International Union of Geological Science) and by the UNESCO, a geosite is a place characterised by relevant naturalistic features that should be preserved as geological heritage (Wimbledon 1997). Geoconservation is an activity of importance to all geologists: it is a vital support to the prosecution of geological research, education and training (ProGEO 2011). In this view, the present paper should be used as a field trip guide for the observation and study of the main characteristics related to the occurrence of earthquakes. It aims to the development of economic and touristic interests with the proposition of geological itineraries for geotourism (e.g., Strasser et al. 1995; Eder and Patzak 2004; Basilone and Di Maggio 2016).

2. Geological setting

The Sicilian orogen, located in the centre of the Mediterranean at the NE corner of the Pelagian platform of North Africa, links the Southern Apennine and the Calabrian Arc to the Tellian and Atlas systems (inset in Fig. 1a). The Sicilian Fold and Thrust Belt (FTB) is a segment of the Apennine-Tyrrhenian System (Amodio-Morelli et al. 1976; Grandjacquet and Mascle 1978; Bigi et al 1990; Vai and Martini 2001), whose up-build is referred both to the post-collisional convergence between Africa and a complex “European” crust and the coeval roll-back of the subduction hinge of the Adriatic Ionian-African lithosphere (Malinverno and Ryan 1986; Kastens et al. 1988). The Sicilian FTB originates from the piling-up of tectonic bodies, underway since the Miocene, deriving from the deformation of the paleogeographic domains developed during the Mesozoic in the Southern Tethyan rifted continental margin. In western Sicily the geometry of the thick-skinned accretionary wedge, as shown by geological mapping (Broquet 1968; Mascle 1979; Catalano et al. 2010; 2011; Basilone 2011) and by several regional seismic profiles (Catalano et al. 1998, 2008), displays a pile of thrust sheets formed by different structural elements separated by S- and SW-vergent regional thrusts (Figs. 1a, b) and accompanied by clockwise rotation of the allocthonous sheets (Oldow et al. 1990). They are characterized by: i) imbricated thrust wedge of Meso-Cenozoic shallow-water carbonate units, up to 10 km thick (Trapanese tectonic units); ii) up to 3 km-thick mostly flat-lying Meso-Cenozoic deep-water carbonate units (Sicanian units), overthrusting the deformed carbonate platform rock units; iii) thin nappes of Cretaceous to Neogene deep-water (oceanic) deposits of the Sicilide domain (Ogniben 1960) and Numidian flysch, detached from their mainly carbonate substrate. The upper Miocene to Lower Pleistocene clastics, carbonates and evaporites unconformably seal the underlying shortened tectonic units, filling wedge-top basins (Broquet et al. 1984; Roure et al. 1990; Gasparo Morticelli et al., 2015). The Pleistocene-Holocene continental and marine deposits (Di Maggio et al. 2009; Agate et al. 2017), frequently mask the original tectonic contacts.

2.1. Study area

The study area (Fig. 1a) is comprised in the Sicanian thrust system, where the imbrication has repeatedly involved the whole Sicanian succession (Mascle 1970, 1979; Roure et al. 1990; Catalano et al. 1998; Monaco et al. 2000). In this tectonic frame, the Rocca Busambra tectonic unit extends for about 15 km with an E–W-trending large antiform slightly rotated to the NW–SE on its eastern side (Pizzo Marabito). The structure is bounded by two E–W major reverse faults, with right-handed strike-slip movements (Fig. 1a). The Barracù ridge, consisting of two main adjacent morphological culminations, is an arcuate structure formed by the emplacement of two tectonic units along a low-angle thrust, displaying inside the typical characteristics of a duplex deformation (Agate et al. 1998). Based on field observations (mesoscopic structural data and stratigraphy) and on seismic profile interpretation, the S- and SW-vergent Sicanian Barracù tectonic unit, overlies the carbonate platform Busambra tectonic unit along a partly buried low-angle thrust surface (Fig. 1b, Catalano et al. 1998). In this region, the Rocca Busambra structure appears pushed up to the surface, breaching the tectonically-overlying basinal Sicanian Units (Barracù and buried units).

2.2. Lithostratigraphy and facies analysis

The Rocca Busambra rocks pertain to the Meso-Cenozoic Trapanese succession, where shallow-water and pelagic carbonates deposited progressively (Giunta and Liguori 1975; Mascle 1979; Wendt 2017). Many lithostratigraphic units, outcropping at the Rocca Busambra ridge, compose the stratigraphic column (Fig. 1c, Basilone 2018). Upper Triassic-Lower Liassic carbonate platform dolomites and limestone (Sciacca and Inici Formations, Marabito reef limestone) are followed by Late Liassic to Late Jurassic condensed to pelagic deposits. These deposits, informally named Rosso Ammonitico and known as Buccheri Formation, are characterised by Fe-Mn crusts and condensed pelagites; they also fill a very dense network of neptunian dykes. They are followed by Latest Jurassic-Eocene pelagic carbonates (Lattimusa, Hybla and Amerillo Formations). Lower Miocene biocalcarenites, coastal glauconitic calcarenites (Corleone calcarenites) and open shelf marls (San Cipirello marls) unconformably cover the Meso-Cenozoic carbonates.

The Permian-Tortonian deposits of the Sicanian domain, largely outcropping in the Sicani Mountains, are characterised by a typical deep-water carbonate succession (Mascle 1979). A detailed stratigraphy and lithostratigraphy was recently revised, correlating wells and outcropping data from the Sicani Mts and their buried prolongation in the subsurface of central Sicily (Basilone et al. 2016b). The main bulk of the Mesozoic Sicanian rock assemblage (Fig. 1c) consists of deep-water Carnian-to-Lower Oligocene mudstone, carbonates and pelagic marlstone (Mufara, Scillato, Barracù, Lattimusa, Hybla and Amerillo Formations), with intercalations of resedimented carbonate breccias (Lower Jurassic Prizzi breccias and oolitic crinoidal calcarenites), followed by Upper Oligocene-Middle Miocene clastic carbonates and marls (Cardellia marls, Corleone calcarenites and San Cipirello marls).

3. Detailed observations

3.1. Synsedimentary tectonics at Rocca Busambra (itinerary 1, Fig. 2b)

The field trip, relatively to the itinerary 1, can be expired in a day. Starting from the Ficuzza village (Fig. 2a, coord.: 37°53’04.62”N 13°32’35.01”E, elev.: 643m a.s.l.), this itinerary permits to observe the naturalistic and cultural heritage of the Rocca Busambra-Corleone region. The Ficuzza wood, dominated by oak tree, the historical Royal Palace of the Kingdom of Sicily, and the carbonate ridge of Rocca Busambra are the main attractions of the area. The Rocca Busambra ridge is a carbonate structural unit of the Sicilian Chain and records a variety of tectono-sedimentary features. Stratal discontinuities, buttress unconformities, onlap and downlap stratal terminations, gaps, condensed sequences, hardground crusts, ‘in situ’ breccias, dissolution surfaces and resedimented clastic carbonates, characterise the Meso-Cenozoic carbonate succession (Fig. 3).

The geomorphologic configuration of this region can be summarized in two different landscape types, related to the outcropping lithologies and to the prevailing morphogenetic processes:

- the carbonate highland landscape (Rocca Busambra, 1613 m a.s.l.) shows geomorphic forms due to tectonics and morphoselection, such as the several paleo-surfaces, and the wide, structurally controlled, scarps, hundreds of metres high;
- the marly-clayey hill landscape, surrounding the carbonate ridge, consists of reliefs with gentle slopes, where landslides and water processes prevail. The mapped landslides, mostly due to rotational creep, are both active and inactive (no recent movements in the last few decades). The largest landslide bodies are more than 2 km long and 1 km wide, and some tens of metres thick. Spectacular examples are mapped in the region south of Monte Cardellia, where marly-clayey deposits (Cardellia marls), embedded between limestone layers ("Corleone calcarenites" and Amerillo Fm), are repeatedly mobilized. Consequently the "Corleone calcarenites" displays to be deformed mostly with lateral spreading processes (Fig. 4, Agnesi et al. 1978; Basilone 2011). Fluvial processes originated several orders of alluvial terraces (mapped along the main rivers) and spectacular erosional canyons in the Corleone village area.

3.1.1. Panoramic view of the Nicolosi graben

At the km 24 of the SS118, the road crossing the Rocca Busambra ridge, we have a beautiful view of the NW cliff of Pizzo Nicolosi (Stop 1 in Figs. 2a, b, coord.: 37°52'39.68''N 13°19'01.56"E, elev. 521 m. a.s.l.). Here a very impressive paleotectonic structure is exposed, offering a spectacular example of graben (geological section I in Fig. 3c and Fig. 5a). The carbonate platform sub-horizontal beds of the Inici Formation (INI) are cut by WNW-ESE steeply dipping antithetic faults, originating depression with relative displacement of more than 50 m. The morphotectonic depression is filled by Upper Cretaceous pelagic limestone (Amerillo Formation, AMM). These pelagites abut in buttress unconformity against the fault planes and drape the horst eroded margins (Fig. 6, coord.: 37°51'46.98"N 13°19'22.70"E elev.:

929m. a.s.l., see location on Fig. 2b). Other structures, variously oriented, occur in the northern side of Pizzo Nicolosi, where the tectonic depression, bounded by fault planes, originated the Rocca Ramusa graben (Fig. 7, see point of observation in Fig. 2b, coord.: 37°51'57.44"N 13°20'19.46"E elev.: 935m. a.s.l.). This latter structure shows, only the southern flank of the graben, the Jurassic and Upper Cretaceous pelagites that directly onlap and downlap the floor of the depressions (Fig. 7a). They crop out, in buttress unconformity (Davies and Reynolds 1996), against the sub-vertical walls (Fig. 7b) and drape the horst structures (Fig. 7c).

3.1.2. The dykes of Rocca Argenteria

In the Rocca Argenteria quarry (Stop 2 in Figs. 2a, b, coord.: 37°51'52.18"N 13°19'13.17"E, elev.: 604 m. a.s.l.) we observe a dense network of neptunian dykes, cutting the white peritidal limestone (Inici Formation). The latter consists of algae and mollusc-bearing wackestone and oolitic packstone-grainstone organized in shallowing upward cycles, up to 400 m thick. Benthic foraminifera, echinoderms, rare crinoids, calcareous algae (*Cayeuxia* sp., *Thaumatoporella parvovesiculifera* (Raineri), *Paleodasycladus mediterranus* (Pia)), gastropods, pelecypods, brachiopods and ammonites represent the main fossil content of the Lower Liassic Inici Fm (Gemmellaro 1878; Gugenberger 1936; Arkell 1956). A regional unconformity, marked by a cm-thick blackish Fe-Mn crust, characterises the top of the formation, which is overlain by the *Bositra* pelagic limestone rich in ammonites (Fig. 9a).

The dense network of sub-vertical, oblique, and bed-parallel fractures with polyphasic fill of Jurassic, Cretaceous and Miocene sediments, dissects and penetrates the topmost portion of the Inici peritidal limestone (Fig. 9b, c, d). These sedimentary dykes, some of which appear siphon-like structures (Mascle 2008), mutually crosscut displaying various colour. We distinguished three main orientations: a) WNW-ESE trending dykes filled by mostly Jurassic mudstone with ammonoids; b) NNW-SSE and N-S oriented dykes, mostly filled by planktonic foraminifera-bearing wackestone of the Amerillo Formation; c) E-W and NNE-SSW trending dykes, filled by glauconitic sandstones (Corleone calcarenites). Repeated re-opening of individual dykes proves the tectonic control of the dyke formation (Wendt 2017).

Similar features may be observed in other places such as at Monte Kumeta (Mallarino et al. 2002; Gasparo Morticelli et al. 2017), in the Sciacca area (Rocca Porcaria, Mascle 1964), or in Eastern Sicily (Truillet 1966)

3.1.3. Paleofaults at Piano Pilato

The region of Piano Pilato, located in the westernmost side of Rocca Busambra (Stop 3 in Figs. 2a, b, coord.: 37°51'36.63"N 13°19'59.70"E, elev. 763 m. a.s.l.), and continuing uphill to the minor reliefs of Rocca del Drago, Rocca Argenteria and Pizzo Nicolosi is characterized by a Jurassic condensed pelagic facies association. It is followed by the Upper Cretaceous pelagic and Lower Miocene reworked pelagic facies associations (Fig. 3a). The pelagic succession covers, unconformably, the sub-horizontal beds of the Lower Jurassic peritidal limestone.

Several, south dipping, sub-vertical (60-80° steep) WNW-ESE oriented paleofaults (with some metres of downthrown) cut the carbonate platform deposits (geological section II in Fig. 3c). These features, either fault planes or morphotectonic scarps (Fig. 5b), are sealed by Jurassic-Cretaceous pelagites and resedimented deposits, which lie with buttress unconformity against the hanging-wall scarp (Fig. 9, coord.: 37°51'27.39"N 13°20'42.88"E, elev.: 891m. a.s.l.).

At the southern scarp of Piano Pilato, a half-graben structure bounded by E-W and WNW-ESE fault planes outcrops (Figs. 3b, c, 5b). The faults cut the sub-horizontal beds of Lower Liassic peritidal limestone and are sealed by Lower Miocene glauconitic reworked pelagic beds that rest in buttress unconformity (geological section II in Fig. 3c); basal breccias, with angular to subrounded lithoclasts of Lower Liassic peritidal limestone, embedded into Lower Miocene yellowish glauconitic packstone, are present. On the southern side of the half-graben, the Lower Miocene glauconitic “reworked pelagic” facies association unconformably covers the Jurassic condensed pelagic facies association, with downlap relationships, and is conformably followed by Langhian marls, which here display their maximum thickness (Fig. 3a and geological section II in Figs. 3c).

In the adjacent Pirrello region, located in the central part of the ridge (Figs. 2a, b, 3), deeply eroded elongated channels and WNW-ESE paleofaults and morphotectonic scarps with large displacement, are the main tectono-sedimentary features (geological section III in Fig. 3c and Fig. 5c). The channels, showing a semi-circular cross-section of 2-3 km^2, correspond to a concave-upward erosional surface that is carved into the top of the Lower Liassic peritidal limestone. The erosional surface is draped by Jurassic and/or Upper Cretaceous pelagites. Lower Miocene calcarenites abut, in buttress unconformity, the sub-horizontal white peritidal limestones beds along a south dipping fault scarp with a few tens of metres of downthrow (geological section III in Fig. 3c and Fig. 5c). The top of the Lower Liassic peritidal limestones is crosscut by neptunian dykes mostly filled by reddish crinoidal and *Bositra* limestone (Fig. 5c). Cm-thick anastomosing veins, filled with reddish or dark iron-manganese-rich carbonate mudstone, also occur.

3.2. Submarine paleo-landslides at Monte Barracù (itinerary 2, Fig. 2c)

Along the state roads (SS118 and SS188c) connecting Corleone to Campofiorito it is possible to observe spectacular examples of tectonic folds. The clastic-carbonates of the Lower Miocene “Corleone calcarenites”, embedded between two marly-clayey layers (Cardellia and San Cipirello marls, Fig. 1c), outcrop with variable dip, mostly sub-vertical, highlighting a complex fold system where narrow anticline and syncline are repeatedly following one another. The itinerary 2 (Figs. 2a, c), which can be expired in a day, starts from Campofiorito village (coord.: 37°45’07.70”N 13°16’05.36”E) and develops along a motorable country road (via Papa Giovanni XXIII), up to reach the next stops (stops 4, 5 in Figs. 2a, c). This road crosses a wood, mainly dominated by pine and fir trees, making part of the larger Sicanian Regional Park.

3.2.1. Panoramic view of the Barracù section

The study section, located along the western side of the Monte Barracù (Figs. 2a, c), is a NNW-SSE outcropping section, where the whole stratigraphic setting of the Mesozoic Sicanian deep-water succession is visible (inset in Fig. 10).

From the panoramic view of the Barracù section (Stop 4 in Figs. 2a, c, coord.: 37°41’55.89”N 13°19’07.24”E, elev. 1063 m. a.s.l.), it is possible to observe in detail the geometries, stratigraphic relationships and internal characteristics of the 15-30 m-thick white calpionellid pelagic limestone of the Lattimusa Formation, interested by various synsedimentary deformational structures (Fig. 10). The lower boundary of the formation is an erosional truncation surface with the underlying Jurassic radiolarites and the Kimmeridgian-lower Tithonian resedimented packstone-grainstone with *Saccocoma* sp. and *Protopeneroplis striata*. On this surface, affected by stepped normal faults, the Lattimusa strata lie with onlap and downlap stratal terminations or in buttress unconformity, also showing lateral pinch-out (Fig. 10).

The Lattimusa Fm displays two main lithofacies association: the marl-dominated facies (horizons a, c in Fig. 10) and the carbonate mudstone-dominated lithofacies (horizons b, d in Fig. 10). Some deformed units are localized in distinct multilayer horizons (a b, d in Fig. 10). They are separated from undisturbed and weakly deformed horizons (c and e in Fig. 10) by unconformable or detachment surfaces. Undeformed beds drape and unconformably overlie the deformed units, showing onlap and infilling geometries. Each deformed unit can be traced laterally along the cliff for hundreds of metres, with thickness values ranging between 0.5 to 5 m, varying in morphology and degree of deformation (Fig. 10).

The deformed units were differentiated in two main types of slump sheets, on the basis of the SSDSs, brittle deformations, morphology and geometry, involved lithofacies, sediment properties and deformation mechanisms.

- Type 1 deformed units (horizon a in Fig. 10), involving the marl-dominated lithofacies, display wedge-shaped morphology with increasing thickness towards the northern side of the section, thinning up to disappear towards the south. The beds package shows pinch-out geometry. From S to N, the deformed units display a thinner head sector mostly characterised by extensional listric faults and a thicker toe sector characterised by thrusts and folds (Figs. 10, 11). The basal surface of the deformed units displays concave morphology, sometimes with steep slope segments that rapidly flatten where they dip under the deformed masses (Fig. 10). Folds, several of which are restricted to distinct slump horizons, show a wide variety of shapes and sizes ranging between dm- to several m-thick (Figs. 10, 11a). Many folds are cylindrical with straight fold axes and only some of them display box geometries in the hinge zone. Asymmetrical folds, including recumbent ones and overturned beds, are diffused and are frequently associated with small-scale thrusts that, on the whole, show preferential N-ward orientations (Fig. 10). Isoclinal and recumbent folds and reverse faults/thrusts are the shortening features that balance the stretching of the listric normal faults that mostly occur in up-slope parts of the slump (S-ward); here, the missing beds slid down N-ward, thickening the toe of the slumped bodies (Fig. 10).

- Type 2 deformed units, involving the carbonate mudstone-dominated lithofacies, appear as elongated bodies with tabular morphology. They, while maintaining similar thickness values along direction, display a thinning in their lateral boundaries especially towards the northern side (inset in Fig. 10). Several steep scars cut the whole beds package involved in the deformation. The scars, with planar to concave geometry, flatten downward and merge in the main basal detachment surface (Figs. 10, 11c). These scars confer an overall steeped morphology of the deformed units. The main internal deformational features are represented by large-scale brittle and minor plastic deformations (Fig. 10). These slump sheets, appear as slides that, as they moved downslope, glided on bedding surfaces (translational slump sheets). They were completely decoupled from the underlying undeformed beds as result of the low viscosity of the basal marl layers.

3.2.2. Close view of the SSDSs

Moving towards the cliff to reach the outcropping section it is possible to observe in detail the SSDSs and brittle deformations characterising the slump sheets (Stop 5 in Figs. 2a, c, coord.: 37°44'58.29"N 13°19'23.39"E, elev. 1202 m. a.s.l.).

In the basal beds of the section, representing the Type 1 slump sheet, the main internal deformations are (Fig. 11): i) contorted and disrupted beds of the thin mudstone intercalations, which also display sigmoidal and concave geometry (Figs. 11a, b); ii) chaotic stratification, internal stratal discordance and discontinuous beds (Fig. 11b); iii) several concave erosional depressions, dm- to m- size, infilled by marl/mudstone alternations; iv) laterally discontinuous, rows of ribbon-shaped deformation structures, which alternate with the small deformed horizons involving the marl-dominated lithofacies comprised in the overall undeformed horizon c (Figs. 10, 11c). Folds range between slightly deformed layers, defining simple and open harmonic folds, to strongly contorted layers outlining tight/isoclinal disharmonic ones. Sometimes, the folds include well-developed detachment surfaces and some minor sub-vertical fractures (e.g., tension gashes, Fig. 11a). They pass laterally into other deformational features, as contorted and disrupted beds, or undeformed intervals (Fig. 11b). Faults and fractures affecting the Type 1 slump sheets are structures in the range of cm to 1 m. The throw is variable, from a few centimetres to several decimetres (Figs. 10, 11a, b). In detail, we can observe: i) sub-vertical extensional fractures and normal faults; ii) dm- to m-scale listric normal faults dipping N-wards. They show concave geometry, dip decreases with depth, merging into sub-horizontal or low-dipping detachments, and are associated with roll-over anticlines (Fig. 10); iii) high angle reverse faults and thrusts, most of which show a modest displacement, are associated with asymmetric folds (Figs. 10, 11a).

Moving up-wards, along the natural section, is possible to observe in detail the Type 2 slump sheet internal deformations. The most common SSDSs (Figs. 11c, d) are: i) undulate beds with lens to sigmoidal geometry; ii) truncated beds and concave erosional features; iii) few harmonic isoclinal and asymmetrical folds. They are several centimetres to a few decimetres high and laterally extended for a few metres (Figs. 10, 11c). The brittle deformational features are: i) stepped normal faults with listric geometry affecting multiple beds (Figs. 10, 11c); ii) antithetic normal faults that develop small horst and graben structures. Downwards, these faults tend to merge into the main detachment surface and, towards the top, they are sealed unconformably by the undeformed strata displaying onlap and infilling geometry (Figs. 10, 11d). These closely spaced normal faults are, locally, associated with reverse faults and thrusts affecting the beds package in the immediately downslope sector. Bulges at the toe of these faults and small antithetic reverse faults are developed to accommodate the rotational component of slip that generates rollover anticlines, in the hanging wall of listric faults (Figs. 10, 11c).

4. Discussion

4.1. Seismic activity caused by synsedimentary tectonic

In the Piano Pilato region, the several WNW-ESE oriented fault planes with small displacements (geological sections I-III in Fig. 3c and Fig. 5) produced a stepped margin morphostructural setting (Santantonio 1993; Basilone 2009). This interpretation is supported by: i) stratigraphic buttress unconformities occurring between the faulted peritidal limestone and the younger deposits, ii) subangular breccias at the fault scarps, originated from the breaking up of the faulted peritidal limestone, iii) sub-vertical fault planes most of which show homogeneous orientation. The faults, formed as fractures of the top of the Lower Liassic peritidal limestone, were later reactivated during the Kimmeridgian, Tithonian and Late Cretaceous tectonic pulses (Figs. 3, 5). They, occurring with various values of downthrown, caused strong instability of the Tethyan continental margin and particularly the brittle carbonate platform rocks, which could be triggered by associated earthquakes with various degrees of intensity (Allen 1986; Basilone and Sulli 2016, 2018; Alsop et al. 2016).

7.2. Earthquake effects

The described features of the Type 1 slump sheets, recognized along the Barracù section, reflect the configuration of the classical model of rotational slump sheets that locates major shortening at the toe of the deformed bodies (Martinsen and Bakken 1990; Strachan and Alsop 2006; Ortner 2007; Alsop et al. 2017). The alternation of deformed and undeformed units indicates that deformation occurred as separate events alternated with long periods of undisturbed sedimentation (e.g., Sims 1975; Mastrogiacomo et al. 2012; Alsop et al. 2016). The synsedimentary extensional tectonics that affected the Upper Triassic-Jurassic deep-water deposits of the Barracù section caused tilt-block and instability of the seafloor through fluidization processes, triggering ~~the~~ rotational slumps (Fig. 10). Seismic shocks, induced by outside sector tectonics, like those recorded in the Busambra stepped carbonate platform margin, possibly triggered the rotational slumps that are not related to the local-scale faults (see Basilone 2017 for further details).

As the mudstone strata of the Type 2 slump sheets were partially cemented and had become semi-consolidated, the gravity flow resulted in a downslope movement of the whole beds package controlled by gliding-related simple shear (Ortner and Kilian 2016). The slump scars, which appear to be roughly crescent-shaped (Martinez et al. 2005), have listric geometries that root downwards into an underlying flat detachment surface and down-step the multilayer slumps (Fig. 10, e.g., Ortner 2007; Alsop et al. 2016). The observed structures suggest that the Type 2 translational slides (glides) can be included in the sediment creep model (e.g., Booth et al. 1984; Silva and Booth 1984; Shillington et al. 2012; Ortner and Kilian 2016). To explain the translational glides of the upper portion of the section (Fig. 10), the aforementioned outside sector earthquakes could produce instability of the sea-floor through thixotropy of marls.

7.3. Geoconservation

Many of the modern landslides, developing both onshore and offshore, are triggered by earthquakes (Agnesi et al, 2005; Paparo et al, 2017). Wideworld examples reflect strong similarities with the studied features, both in geometries and trigger mechanisms (Fig. 12a). The Mesozoic Busambra and Barracù structures reflect strong similarities with modern continental margins, where stepped normal faults and submarine landslides are highly diffused (Fig. 12b).

This comparison suits the principle of actualism ("the present is the key of the past", Leyll, 1830-1833) and represent an important turning point that enhance the geological interest of the two sites. Furthermore, the described structures and the related processes help to identify the geological province where faults and landslides can develop and how can be observed their effects on the landscape.

Considering both the good exposition of the sedimentary and structural features related to paleo-earthquakes and their geological interest, the conservation of this heritage is a necessity not only as scientific objects, but also as important educational resources and/or attractive geotourism products. Thus, promoting the institution of these geosites may have a coupled fruition. The naturalistic-cultural purpose is justified by the spectacular landscape characterised by variable geomorphological setting, occurrence of ancient woods and the architectural-historical significance of the Royal Palace of Ficuzza. Furthermore, the geological heritage may be used for the observation of the described features both for geotourists and for educational training. The latter assumes a crucial role also considering the disaster due to recent earthquakes in Central and Southern Italy (Figs. 12c-d, Belice, Amatrice, Irpinia earthquakes). An educational training, made on the field, may have a key role to understand the described phenomena and their effects on the landscape. It may be a useful tool for the prevention of the geohazard. In this view, this paper and the suggested field trip are also addressed to an institutional audience consisting both of politicians and public administrators.

Conclusions

The Rocca Busambra and Monte Barracù, located in the western Sicani Mountains, near Corleone (Palermo), are adjacent carbonate reliefs where causes and effects of Mesozoic earthquakes are spectacularly exposed.

They consist of Mesozoic shallow-water to condensed-pelagic and deep-water carbonate successions, respectively. In the western side of Rocca Busambra (Piano Pilato and Nicolosi regions), the several WNW-ESE oriented paleofaults produce horst and graben and steeped margin tectonic setting. These faults, cutting the Lower Liassic carbonate platform deposits, are draped by the younger pelagites with buttress unconformity. In the Barracù section, several tectonic features, including synsedimentary faults and seismically-induced submarine slump sheets, characterised the outcrop. Some of these gravitational deformations have been interpreted as rotational and translational slides.

Therefore, the features described along the itineraries 1 and 2, and relative stops, allow us to propose a field trip to recognise causes and landscape effects of earthquakes. In this view, as suggested by the IUGS (International Union of Geological Science) and by the UNESCO, geosite proposition for the two areas is recommended to promote geotourism and to preserve the cultural and geological heritage (geoconservation).

The recent earthquakes occurred in Central and Southern Italy require more attention to these problematics. An educational training, as that proposed in this field trip, could represent a useful tool to understand earthquakes activity and landscape products. Moreover, the focus highlighted by this paper could be of specific interests for public administrators, whose rapid and skilled action is necessary for the prevention and reduction of geohazards.

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Captions

Fig. 1. Simplified geological map of the Central-Western Sicily (a). Inside, the tectonic map of the Central Mediterranean (after Catalano et al., 2000); legend: 1. Corsica-Sardinian units; 2. Calabrian Arc and Kabylian units; 3. Maghrebian-Sicilian-Southern Apennine FTB and deformed foreland; 4. Foreland and mildly folded foreland; 5. Areas with superimposed extension; 6. Plio-Quaternary volcanites. (b) Geological cross-section showing the tectonic relationships among the outcropping Barracù (Sicanian) and Rocca Busambra (Trapanese) tectonic units (after Catalano et al. 1998; Basilone 2011). (c) Chronostratigraphic scheme showing the lithostratigraphic units of the Trapanese and Sicanian successions (after Basilone 2018).

Fig. 2. Map of the proposed field itineraries and relative stops.

Fig. 3. Measured stratigraphic sections along the Rocca Busambra ridge (a). See Fig. 1c for the legend. In the inset map are reported the location of the study stratigraphic sections and the reconstructed tectonic profiles (I-III). Structural map of the Rocca Busambra ridge that displays different trending faults and their age (b). NNE-SSW tectonic profiles showing the depositional setting of the different regions along the Rocca Busambra ridge (c).

Fig. 4. Panoramic view showing landslides, where blocks of various dimension of the "Corleone calcarenites" are moved by lateral spreading processes.

Fig. 5. (a) Graben structures at Pizzo Nicolosi. The Upper Cretaceous pelagic limestone (*AMM*, coloured in green) abut, in buttress unconformity, the sub-horizontal Lower Liassic peritidal limestone beds (*INI*) and the *Bositra* limestone (BCH_1) along WNW-ESE faults, thus forming depressions with relative downthrown of more that 50 m (Rocca Ramusa and Pizzo Nicolosi grabens) and draping the horst erosional margins. (b) Panoramic view of the southern slope of Piano Pilato showing stepped faults and paleoscarps; *INI* lower

Jurassic peritidal limestone; *J* Jurassic deposits. (c) The Pirrello region is characterized by scalloped margin features, showing unconformable relationships between the infilling Upper Cretaceous pelagic limestone (coloured in light green, AMM), Lower Miocene glauconitic grainstone (coloured in yellow CCR) and the faulted Lower Jurassic platform beds (INI). Panoramic picture shows neptunian dykes (in white), E-W and ENE-WSW paleofault trends (coloured in red).

Fig. 6. View of the angular contact in buttress unconformity between the sub-vertical Upper Cretaceous pelagic beds (AMM) and the faulted Lower Jurassic platform beds (INI); fault plane is coloured in red (Pizzo Nicolosi, westernmost side of Rocca Busambra).

Fig. 7. Close-up of the “Rocca Ramusa graben” filled by the Upper Cretaceous pelagic limestones (*AMM*, in green) that onlap the peritidal limestones on the floor of the graben (a) and abut, in buttress unconformity, the sub-horizontal beds of *INI* in the southern flank of the structure (b); fault plane is the area coloured in red. Angular relationships between *AMM* and *INI* along the horst (c).

Fig. 8. a) Blackish Fe-Mn crust (hardground) capping the top of the white peritidal limestone (Inici Formation, INI) and followed by the *Bositra* limestone (BCH_1) at Rocca Drago (see Fig. 2b for location). Detail of the Fe-Mn crust showing pinnacle structures (b). Topmost portion of the Lower Liassic white peritidal limestone of the Inici Formation (INI) at Rocca Argenteria (see Fig. 2b for location) characterised by reddish neptunian dykes subparallel and orthogonal to the stratification (c). Close view of the network of neptunian dyke filled by reddish *Bositra* limestone where angular fragments of the host rock, eroded by the sides of the fracture, are merged (d-e). f) Paleokarst cavities carved in the white peritidal limestone (INI) and filled by Upper Cretaceous reddish pelagic limestone (AMM) and by the Lower Miocene green-yellowish glauconitic calcarenites (CCR).

Fig. 9. Field evidence and sketch of the fault plane that dissected the Lower Liassic peritidal limestone of the Inici Fm (*1*) and *Bositra* limestone (*2*) in the Piano Pilato region. The Upper Jurassic *Saccocoma* limestone (*3*) lie with a buttress unconformity against the hanging-wall scarp of the fault plane and in downlap on the sub-horizontal *Bositra* limestone of the footwall block (after Basilone 2009).

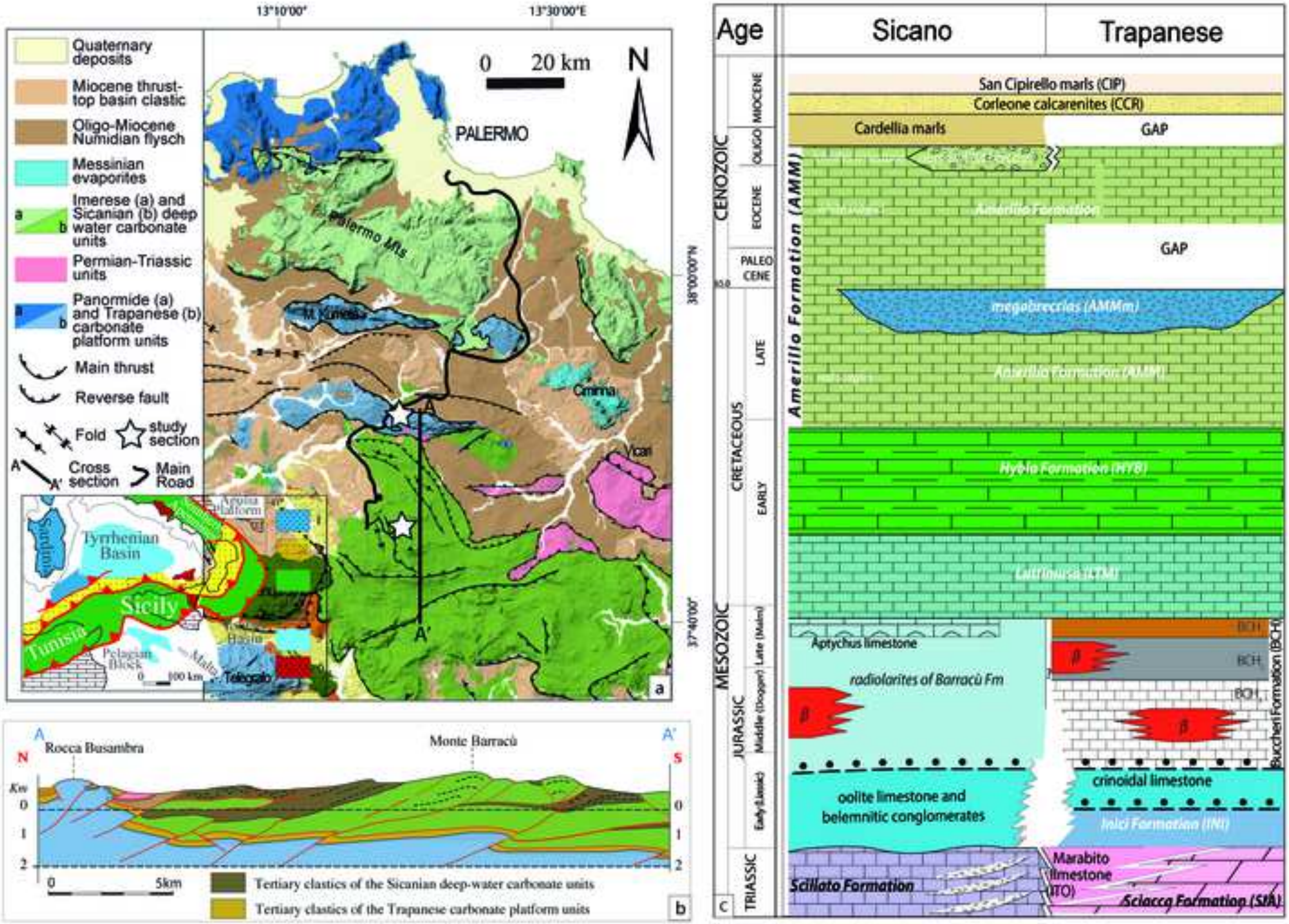
Fig. 10. Panoramic view and line drawing of the upper Tithonian-Berriasian deformed calpionellid limestone of the Lattimusa Fm., showing the differentiated slump sheets, SSDSs and brittle deformations. Inside, panoramic view of the western side of Monte Barracù, showing the whole Triassic-Lower Oligocene Sicanian carbonate succession. The upper Tithonian-Berriasian calpionellid limestone, towards the North, displays an undeformed thin-bedded succession passing southwards to a deformed succession and thinning in its southernmost portion (after Basilone 2017).

Fig. 11. Field photographs and line drawings of the SSDSs recognised in the slump sheets of Monte Barracù: a) fault and fold deformation restricted to a distinct slump horizon; various structures, including disrupted, discontinued and cross-laminated beds are observed in the limestone interlayered with marls. On the right, an ENE-WSW oriented symmetric anticlinal fold is affected by sub-vertical tension gashes and sedimentary injections of marls. NNW-thrusted beds and NNW-dipping extensional faults also occur; b) contorted and disrupted beds with oblique laminations and internal discordance. The deformation structures are concentrated along a detachment surface parallel to the bedding (bold line) that was the original marl level (grey). Normal spineless faults are also present; c) listric normal faults and scar cutting the whole beds package of the B and D horizons (see Fig. 10). Faults flatten downward merging into the main detachment surfaces, which locally are dissected by reverse faults; d) SSDSs in the deformed horizon

B, including internal stratal discordance with downlap and toplap stratal termination, truncated features and infilling geometry.

Fig. 12. Examples of landslides induced by earthquakes: a) aerial view of the landslide triggered by the Santa Tecla earthquake (2001) in El Salvador (after Garcìa-Rodriguez and Malpica 2010); b) 3D bathymetric model from North-eastern Sicily offshore. The Multibeam data show earthquake-induced submarine landslides in a modern active continental margin. The main scarp affects the shelf edge, at -125 m, and the continental slope, while the landslide deposits lie at the toe located at about 450-500 m in an intra-slope basin; c) landslide related to the fault with 1 m of downthrow observable at the top of the hill and formed during the Amatrice earthquake (2016) in Central Italy (Sibillini Mts., Apennines, ©Google); d) rockfalls in the Peistocene calcarenites of the Agrigento Fm, triggered by the Belice earthquake (1968) in Sicily (Montevago – AG, photo S. Monteleone).

Figure 1 Click here to access/download;Figure;Fig. 1.tif



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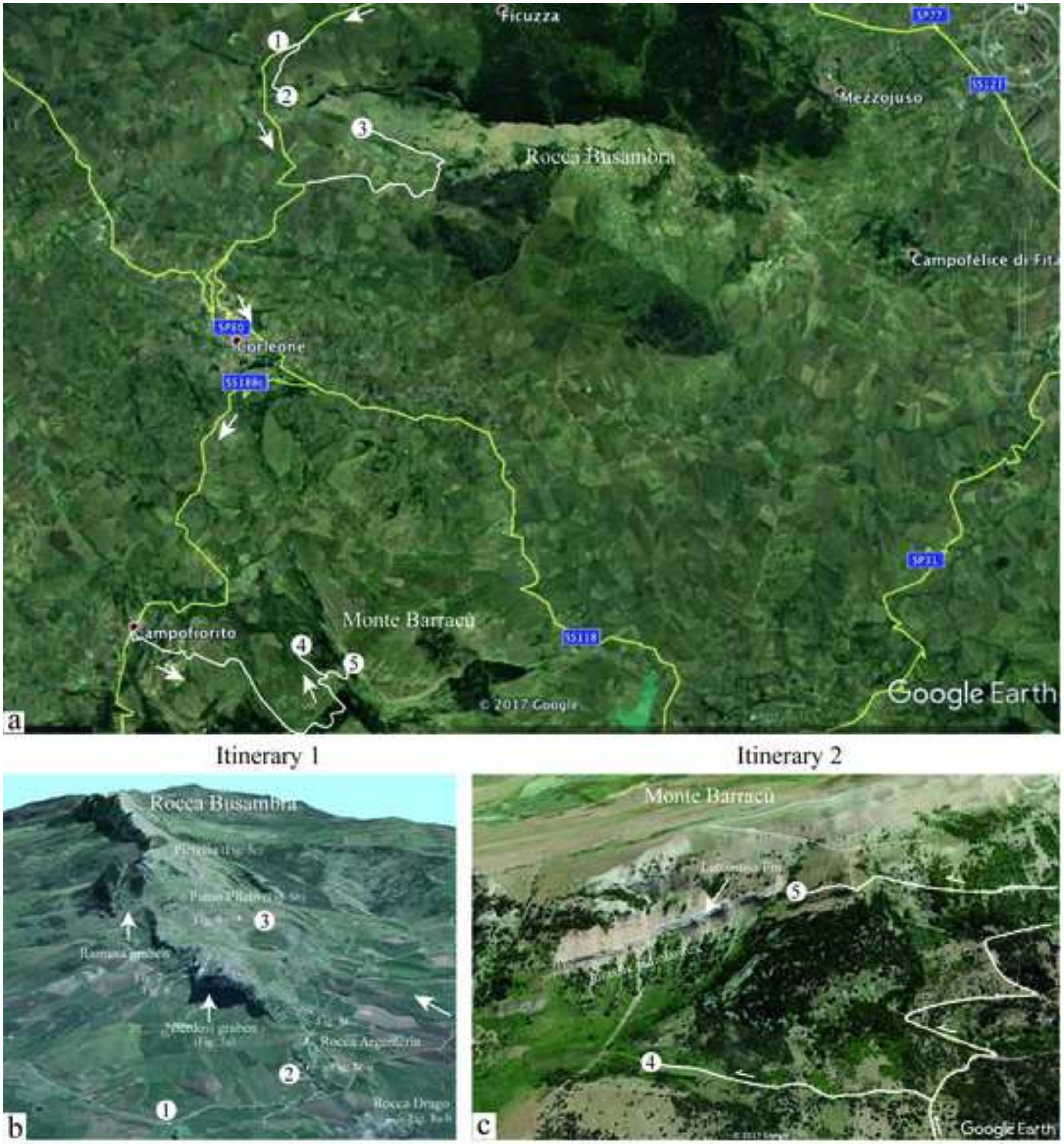
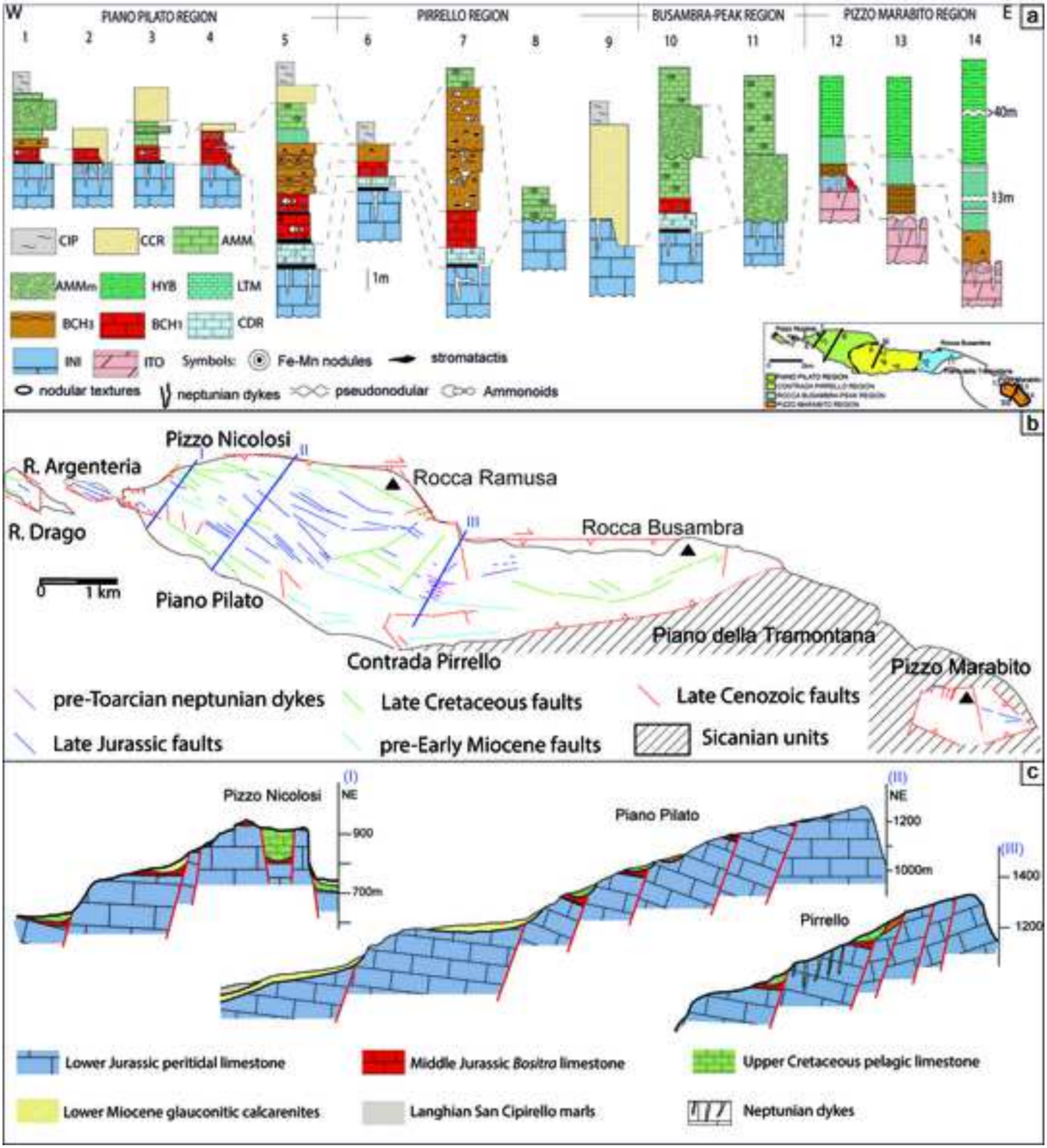


Figure 3



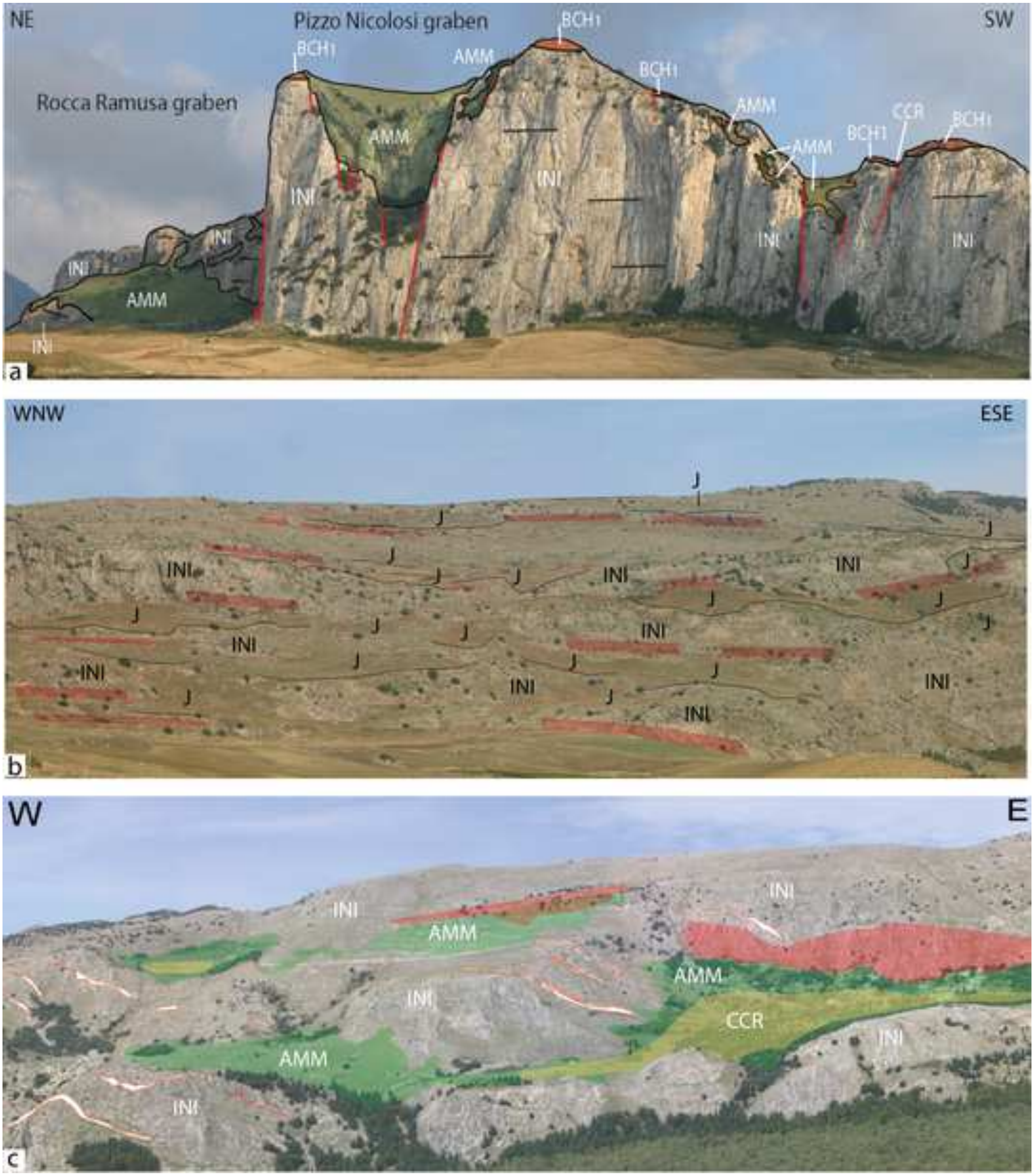
W
PIANO PILATO REGION
PIRRELLO REGION
BUSAMBRA-PEAK REGION
PIZZO MARABITO REGION
E
a
1
2
3
4
5
6
7
8
9
10
11
12
13
14
>40m
13m
1m
CIP
CCR
AMM
AMMm
HYB
LTM
BCH3
BCH1
CDR
INI
ITO
Symbols:
Fe-Mn nodules
stromatactis
nodular textures
neptunian dykes
pseudonodular
Ammonoids
b
Pizzo Nicolosi
R. Argenteria
R. Drago
Rocca Ramusa
Rocca Busambra
Piano Pilato
0
1 km
Piano della Tramontana
Contrada Pirrello
Pizzo Marabito
pre-Toarcian neptunian dykes
Late Jurassic faults
Late Cretaceous faults
pre-Early Miocene faults
Late Cenozoic faults
Sicanian units
c
Pizzo Nicolosi
(I)
NE
900
700m
Piano Pilato
(II)
NE
1200
1000m
(III)
1400
1200
Pirrello
Lower Jurassic peritidal limestone
Middle Jurassic Bositra limestone
Upper Cretaceous pelagic limestone
Lower Miocene glauconitic calcarenites
Langhian San Cipirello marls
Neptunian dykes

Figure 4


W
E
"Corleone calcarenites"
Corleone
landslide
spreading blocks
Cardellia marls

Figure 5

Click here to access/download;Figure;Fig. 5.tif



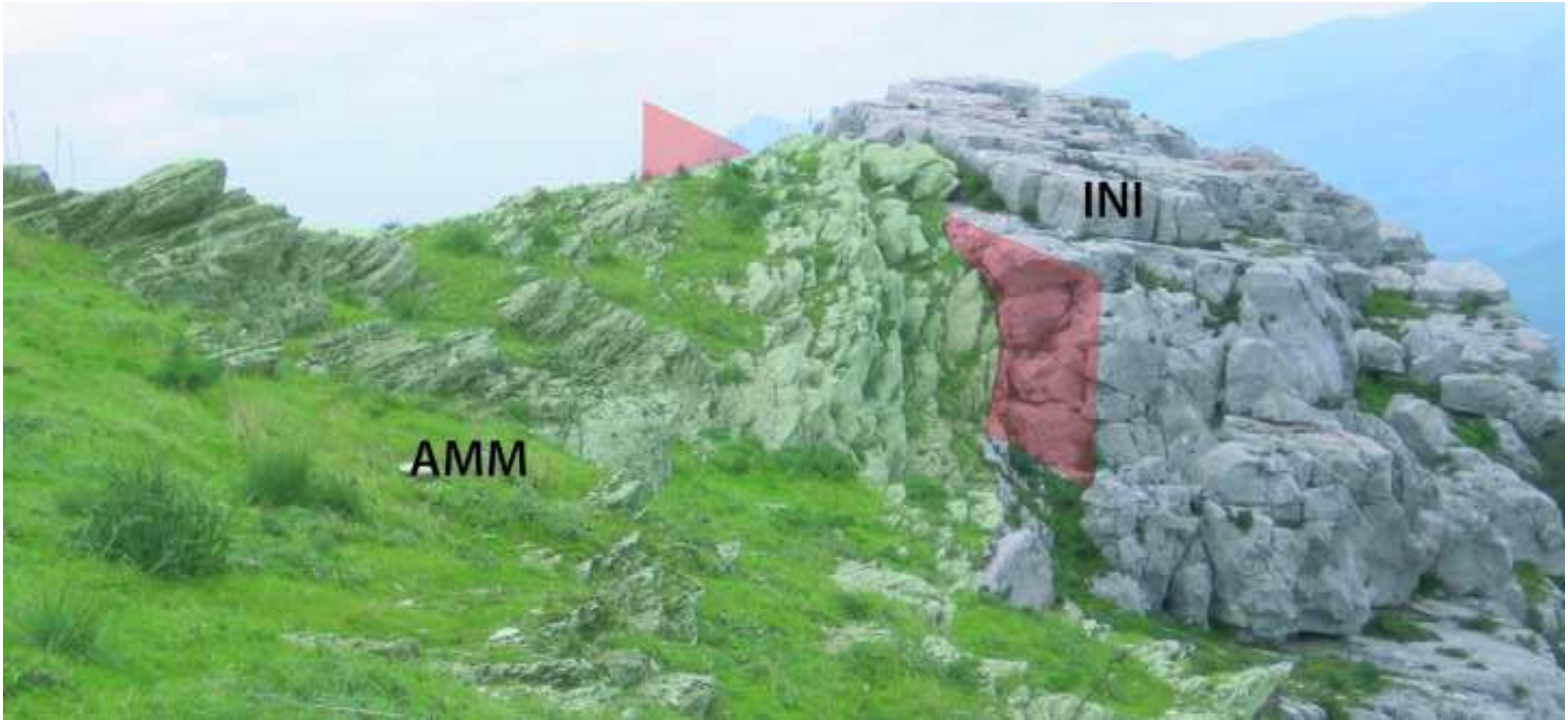

INI
AMM

Figure 7

Click here to access/download;Figure;Fig. 7.jpg

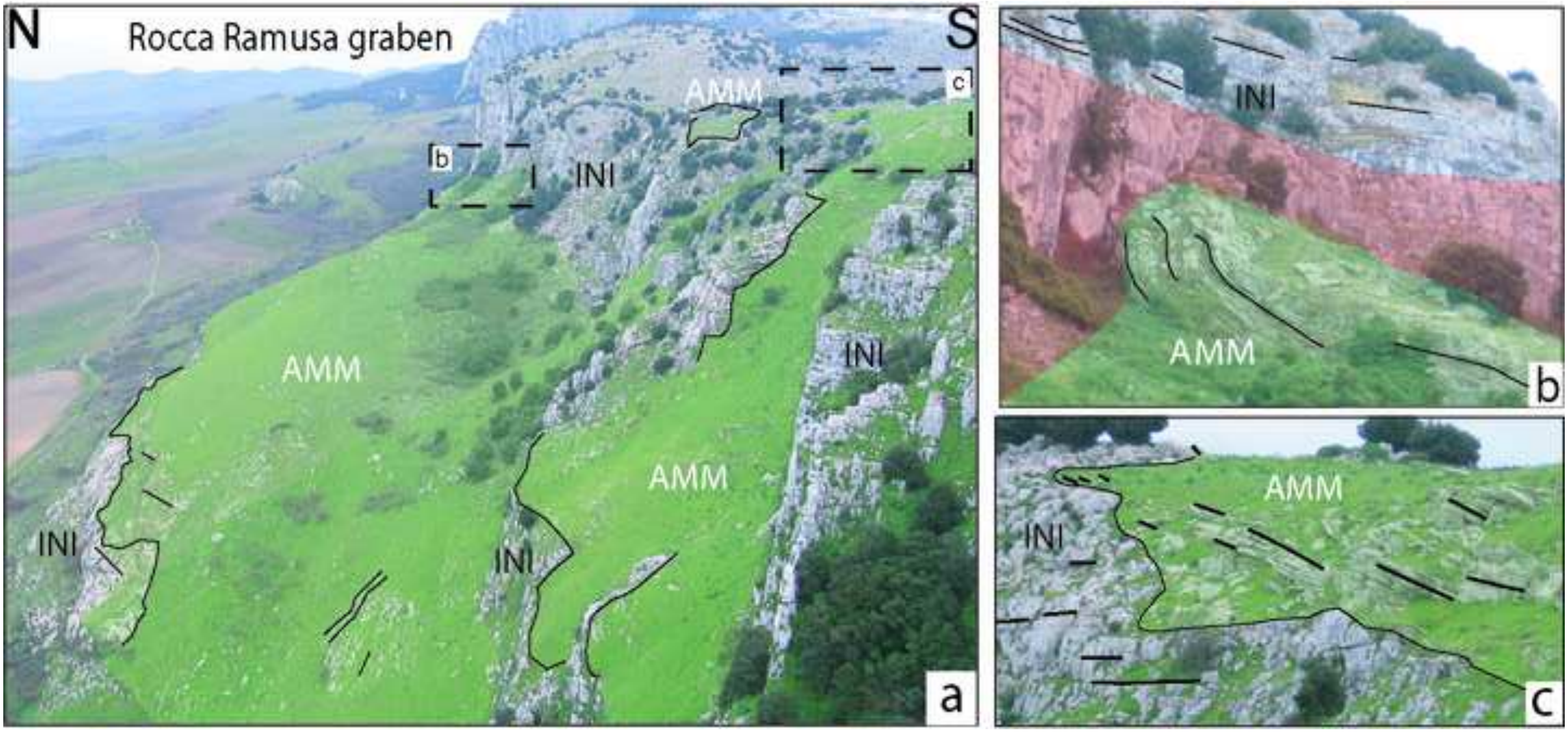


Figure 8

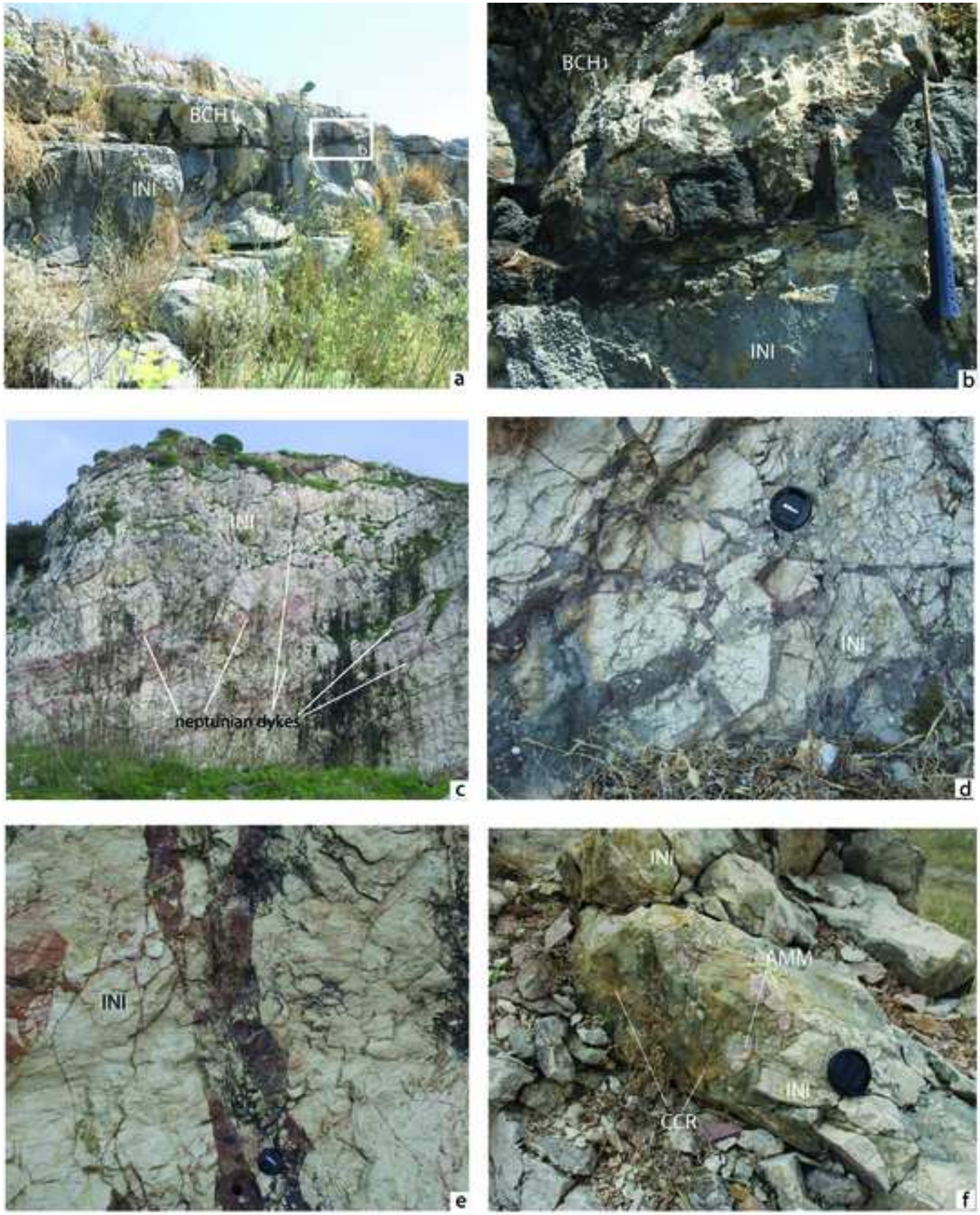

BCH1
b
INI
a
BCH1
INI
b
INI
neptunian dykes
c
INI
d
INI
e
INI
AMM
INI
CCR
f

Figure 9

Click here to access/download;Figure;Fig. 9.tif

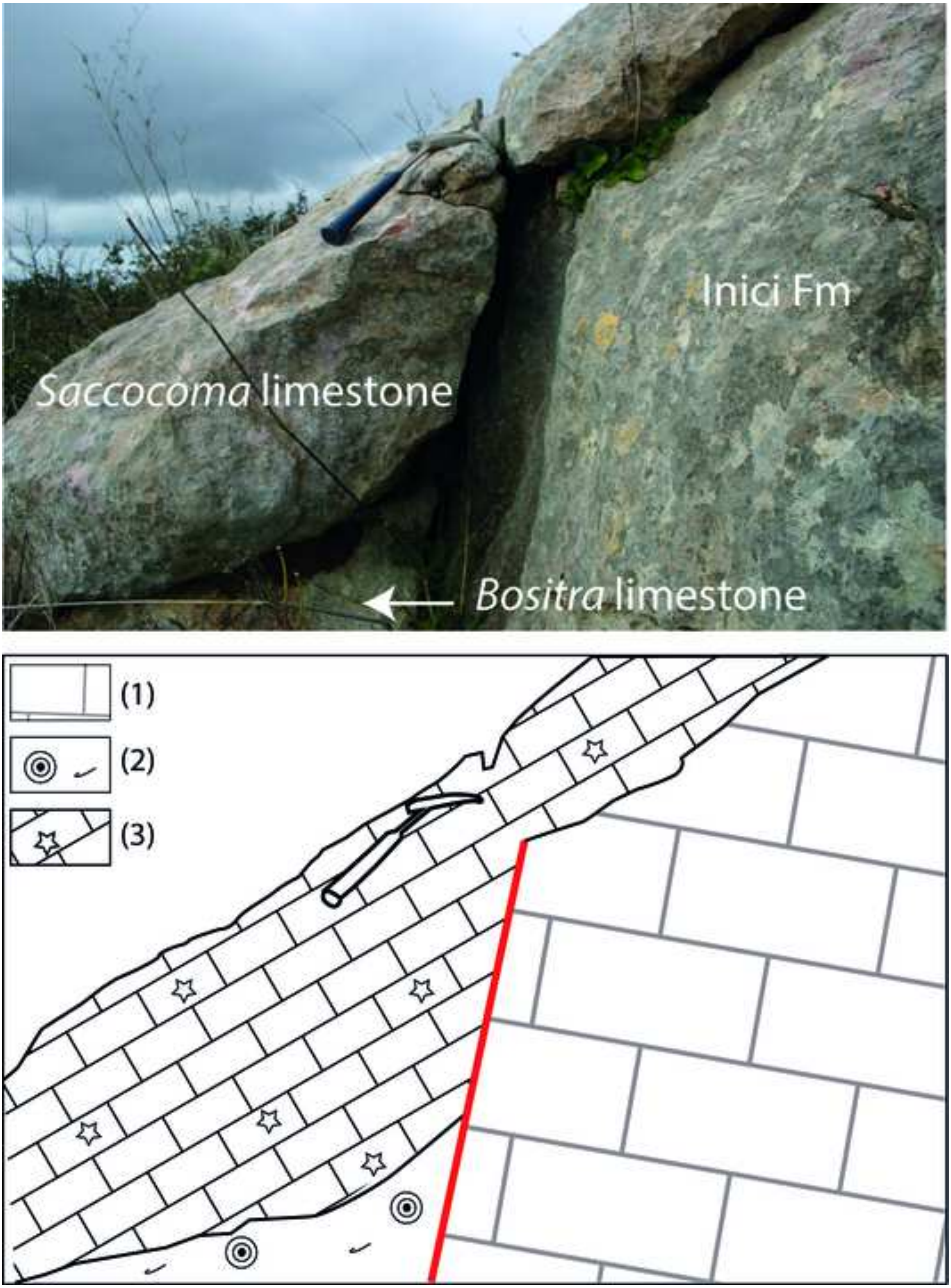


Figure 10

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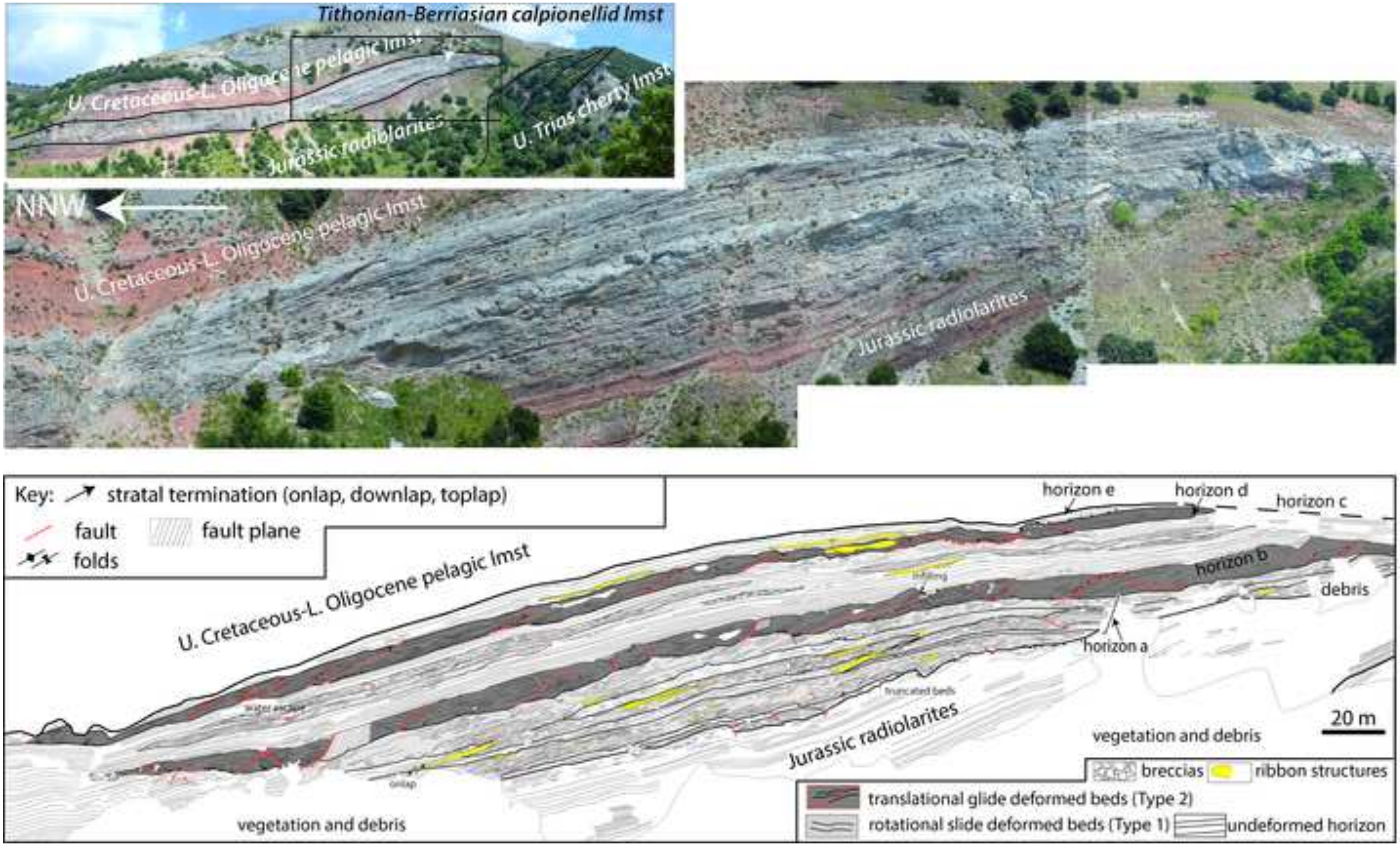


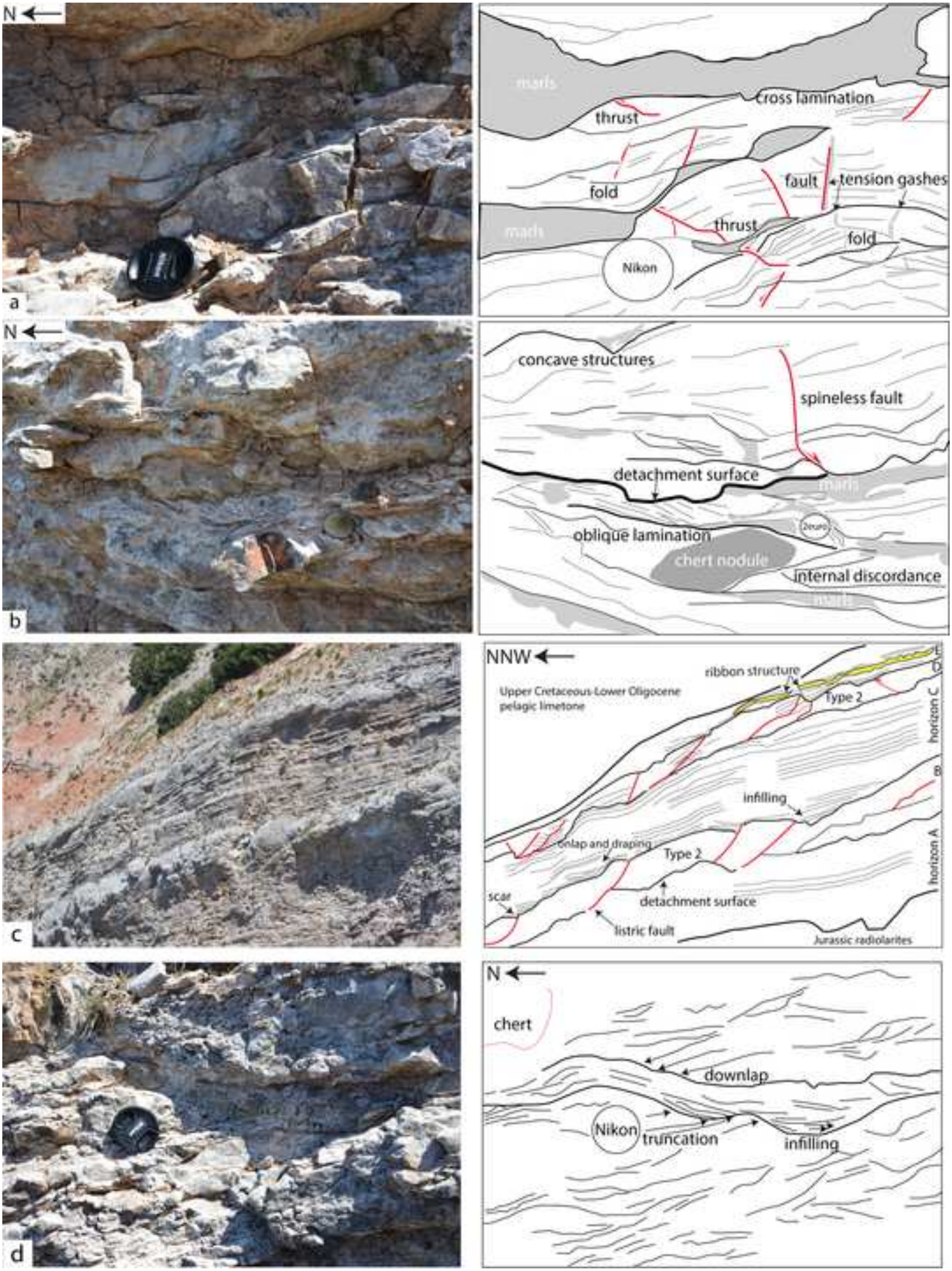
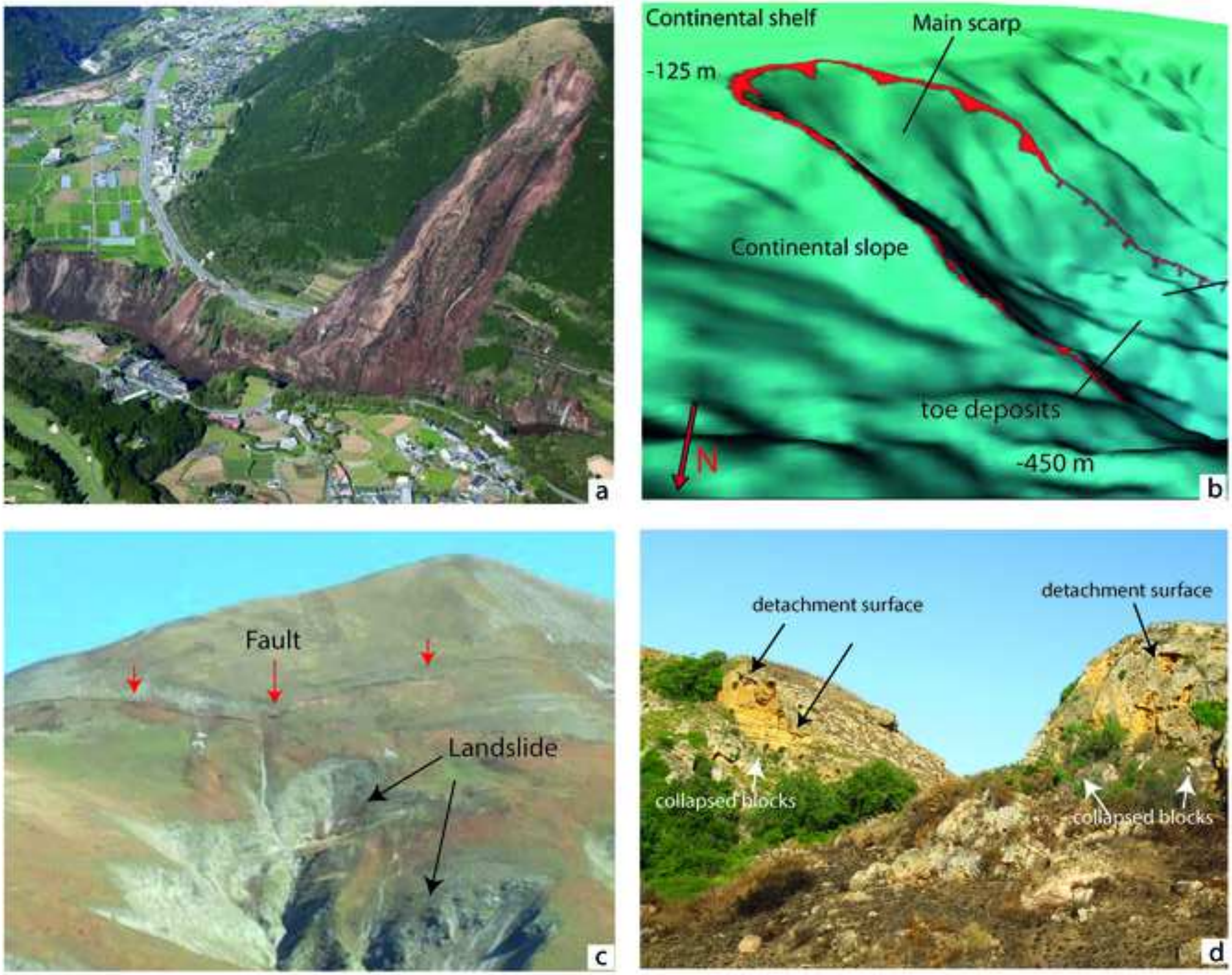

N
a
marls
cross lamination
thrust
fold
fault
tension gashes
marls
thrust
fold
Nikon
N
b
concave structures
spineless fault
detachment surface
marls
oblique lamination
2euro
chert nodule
internal discordance
marls
c
NNW
ribbon structure
Upper Cretaceous-Lower Oligocene
pelagic limetone
Type 2
horizon C
B
infilling
onlap and draping
Type 2
horizon A
scar
detachment surface
listric fault
Jurassic radiolarites
d
N
chert
downlap
Nikon
truncation
infilling

Figure 12


a
Continental shelf
Main scarp
-125 m
Continental slope
toe deposits
-450 m
N
b
Fault
Landslide
c
detachment surface
detachment surface
collapsed blocks
collapsed blocks
d