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THE BRECCE DELLA RENGA FORMATION: AGE AND SEDIMENTOLOGY OF A SYN-TECTONIC CLASTIC UNIT IN THE UPPER MIOCENE OF CENTRAL APENNINES. INSIGHTS FROM FIELD GEOLOGY

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Abstract. In the NE Simbruini Mountains, the "Brecce della Renga Fm." is a clastic unit documenting sedimentation controlled by late Miocene extensional tectonics. The unit has been subdivided into three lithofacies and six sublithofacies, based on the arenite/rudite/pelite ratio. Massive and coarser (up to megablock size) intervals are interpreted as rockfall deposits (likely induced by earthquakes) at the toe of steep submarine escarpments. By contrast, finer levels are interpreted as having been sedimented through avalanching and turbidity flows in more distal settings, and are partly lateral to basinal hemipelagites and siliciclastic turbidites. Pelite lenses, found at various stratigraphic levels, are the result of ponded sedimentation along the clastic margin. Calcareous nannofossils analyses have been performed for age determinations on 60 fossiliferous samples, which were collected in each sublithofacies of the "Brecce della Renga Fm.". The unit ranges from early Tortonian (MNN8b) to early Messinian (MNN11c). The age and field geometries of the older breccias document the existence of a Tortonian extensional phase, which predated the late Messinian thrusting. The distribution curve of clastics over time can, given the number of synsedimentary faults mapped in the area, be put in relation with the seismicity induced by the activity along such faults, which after reaching an acme in the Tortonian gradually reached a quiescent state in the early Messinian, causing the backstepping of clastic facies.

Introduction

A recent geological mapping project in the north-eastern Simbruini Mts. (Central Apennines, Italy) was aimed at gathering a new set of constraints for interpreting the late Miocene tectono-sedimentary evolution of the area (Fabbi 2013). The study was based on the analysis of the "Brecce della Renga Fm.", a prominently clastic unit that has been interpreted as a marker of syn-sedimentary deformation (Santo & Sgrosso 1988; Cipollari & Cosentino 1991; Compagnoni et al. 1990; Fabbi 2013). The "Brecce della Renga Fm." (Devoto 1967; Compagnoni et al. 1990) covers more than 100 square kilometres resting unconformably on the Meso-Cenozoic carbonate platform succession, and is coeval with the lateral late Miocene Latium-Abruzzi terrigenous succession, that is the typical succession in this area of the Central Apennines during this time span. Despite the significant role played by the "Brecce della Renga Fm." in the regional stratigraphy, relatively little analytical work has been published, describing its field geometries, sedimentology and biostratigraphy (Devoto 1967; Santo & Sgrosso 1988; Compagnoni et al. 1990, 1991). This probably explains why a surprisingly wide number of interpretations (syn-thrusting, syn-extension) has been offered regarding its genesis. The present paper gives a dataset regarding the age and sedimentology of the "Brecce della Renga Fm.", along with a tentative reconstruction of its stratigraphic evolution, which takes into account the significance of lateral (coeval) and vertical (diachronous) facies changes within the basin. The data have been collected during a three year-long geological survey, aimed at the production of a detailed geological map at the 1:10.000 scale (Fabbi 2013). A systematic sedimentological study of this unit was difficult for two reasons: 1) the lack of continuous outcrops of breccias suitable for stratigraphic logging due to the original discontinuity of these deposits, as well as to recent tectonics and to intense vegetation, and 2) the poorly organized – to chaotic – texture of the main facies of the "Brecce della Renga Fm." so much

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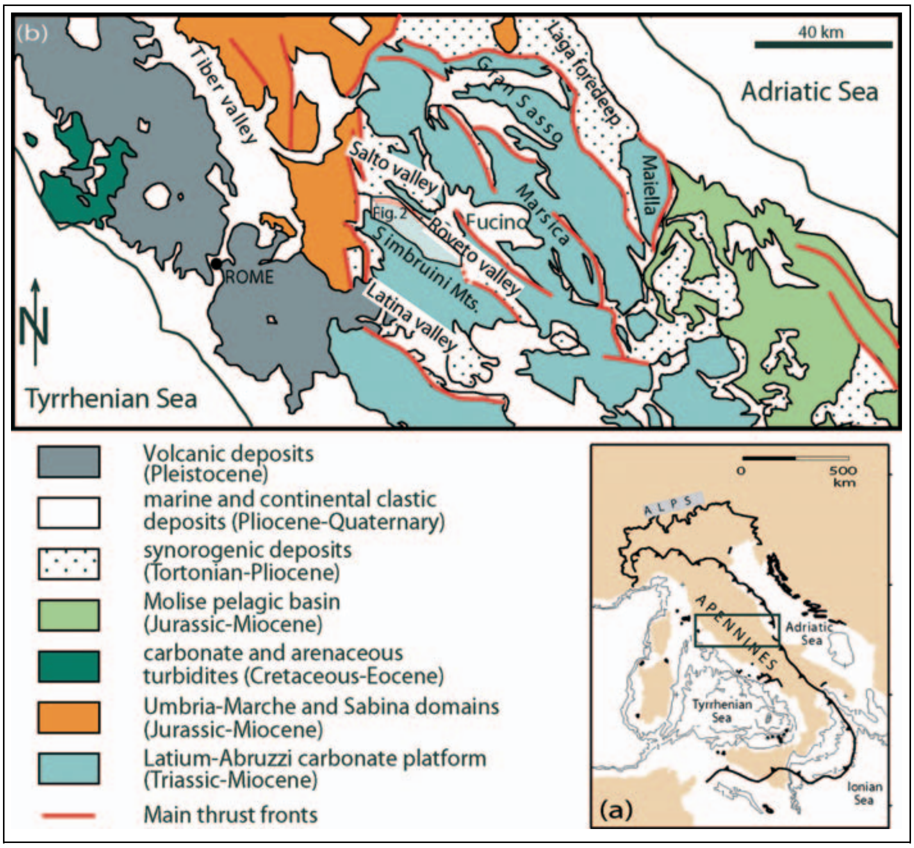

Fig. 1 - Schematic geological map of the Central Apennines; the area covered by the map in Fig. 2 is shown.

so that defining a preferential direction for log measurement and sampling is often tricky, even in those localities where successions are well exposed. For the these reasons, and for the extreme lateral variability of the deposits linked with the "Brecce della Renga Fm.", a detailed geological mapping is the only practical tool to support studies about facies and basin analysis of this unit.

Geological setting

The central-northern Apenninic chain developed from the Late Oligocene to Present, incorporating both Mesozoic to Miocene pre-orogenic units and younger synorogenic ones. The chain formed with a northeastward migration of deformation fronts and, on a greater scale, of foredeep depocenters (Ricci Lucchi 1986; Boccaletti et al. 1990; Patacca & Scandone 2001). The Simbruini Mts. are located in the intermediate sector of Central Apennines (Fig. 1). In this region, mountain ridges commonly trend NW-SE, and are made up of a carbonate succession comprising Mesozoic limestones and dolostones, paraconformably covered by Miocene limestones. In contrast, in the valleys separating ridges, the upper Miocene siliciclastic sediments are commonly well exposed, and stratigraphically follow the carbonates.

The study area is part of the Latium-Abruzzi carbonate platform (Fig. 1), and follows its evolution at least until the middle Miocene. This wide carbonate platform (thousands of square kms) documents carbonate deposition from the latest Triassic to the late Cretaceous, producing a relatively thick (> 3 km) shallow-water succession (D'Argenio 1974; Parotto & Praturlon 1975, 2004; Accordi & Carbone 1988; Damiani 1990; Damiani et al. 1998; Chiocchini et al. 2008). Carbonate sedimentation ended in late Cretaceous times, with the development of the so-called "Paleogene hiatus", likely due to subaerial exposure (Damiani et al. 1990, 1991; Cipollari & Cosentino 1995; Cosentino et al. 2010). Carbonate sedimentation resumed only during the early Miocene, when a carbonate ramp, characterized by heterozoan communities, developed on the Mesozoic rock substrate (Brandano 2002; Civitelli & Brandano 2005).

During the late Miocene, the Latium-Abruzzi platform became involved in the Apennine chain building (Bally et al. 1986; Mostardini & Merlini 1986; Royden et al. 1987; Patacca et al. 1991, 1992; Doglioni et al. 1999). Gradual conversion to foredeep conditions caused the drowning of the ramp and the deposition of hemipelagic marls and siliciclastic turbidites (Patacca & Scandone 1989; Cipollari & Cosentino 1991; Milli & Moscatelli 2000; Bigi et al. 2003; Carminati et al. 2007; Critelli et al. 2007). Later, through the Messinian and late Pliocene, uplift and subaerial exposure of this part

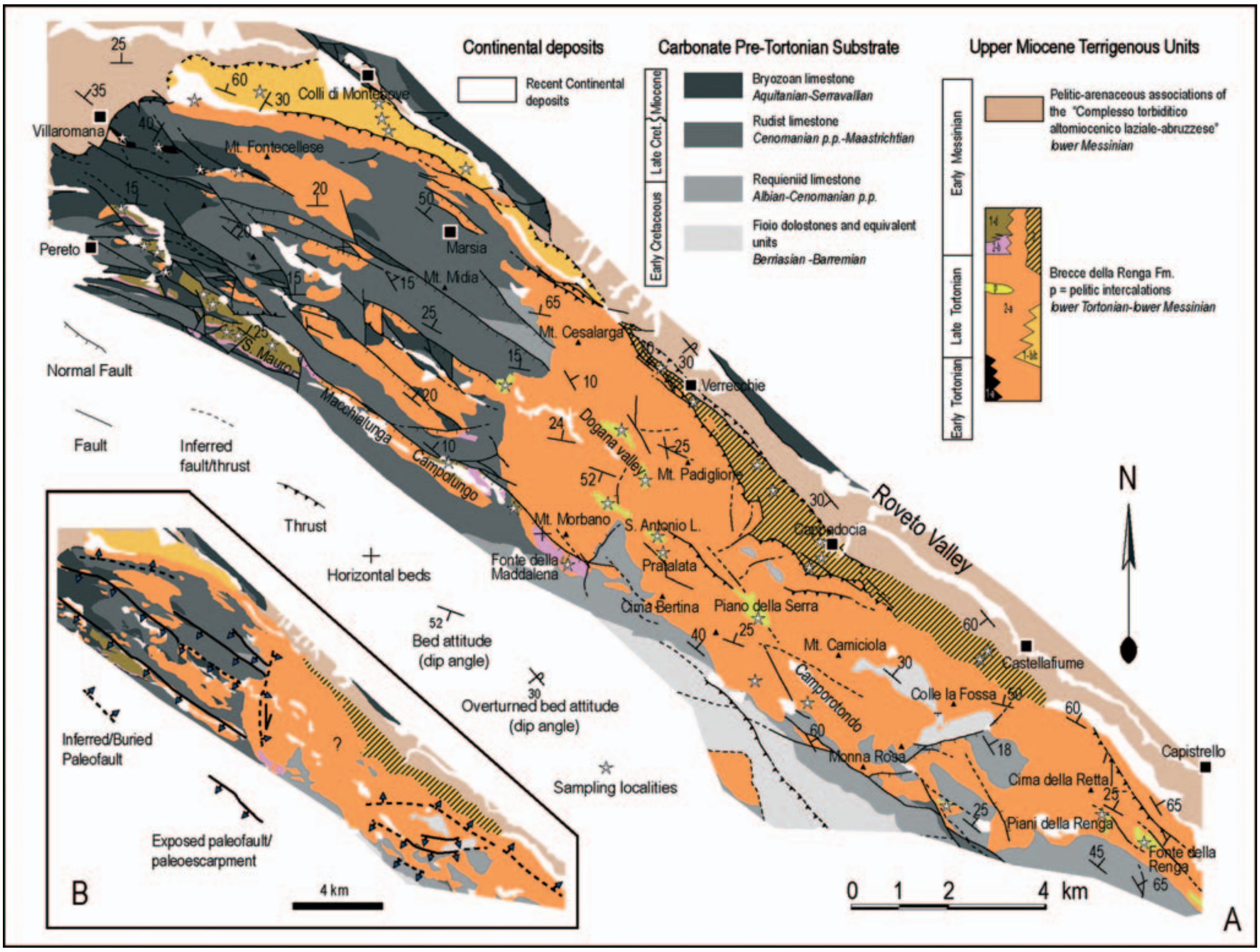

Fig. 2 - A) Geological map of the study area with sampling localities. B) Location of main paleoescarpments/paleofaults exposed in the field or inferred (modified after Carminati et al. 2014).

of the chain occurred, soon after followed by extensional tectonics linked with the opening of the Tyrrhenian basin (Gueguen et al. 1998; Doglioni et al. 1999; Carminati & Doglioni 2012). It has been described in the literature, that prior to thrust development, during the conversion from foreland to foredeep conditions (flexure), the foreland can be affected by extensional tectonics (Bradley & Kidd 1991). Evidence for Miocene (pre-compressional) extension in Central and Northern Apennines has long been recognized or inferred in various localities across the region (Bonarelli 1899; Compagnoni et al. 1990; Tavarnelli et al. 1999; Tavarnelli & Peacock 2002; Bigi & Costa Pisani 2002, 2005; Bigi et al. 2003; Critelli et al. 2007). In the studied area, a pattern of Miocene normal faults, which produced the development of an extensional structural high has been recently identified (Fabbi 2012, 2013). This pre-orogenic extension most likely produced the sedimentation of the "Brecce della Renga Fm." (Fabbi 2013; Fabbi et al. 2014; Carminati et al. 2014), and has been considered a consequence of slab-bending (Carminati et al. 2014).

Miocene stratigraphy

After the drowning of the Miocene carbonate ramp, the shift from carbonate to siliciclastic sedimentation in Central Apennines is documented by a ~30 m thick hemipelagic unit (Unità argilloso-marnosa - "Marne a *Orbulina*" *auctt.*), which overlies a phosphatic hardground developed at the top of the Bryozoan limestone (Brandano et al. 2009 and references therein). This hemipelagic unit is mainly constituted of shales and marls and is followed by siliciclastic turbidites that form the "Complesso torbiditico altomiocenico laziale-abruzzese". This succession represents the typical basin-floor terrigenous succession of the Latium-Abruzzi domain. In the study area, the "Unità argilloso-marnosa" is early Tortonian-early Messinian in age (Pampaloni et al. 1994; Compagnoni et al. 2005; Fabbi et al. 2014), while the age of the base of siliciclastic turbidites ranges from late Tortonian in the Latina Valley to early Messinian in the Roveto Valley (Fig. 1 for locations) (Cipollari & Cosentino 1991, 1995, 1999; Milli & Moscatelli 2000; Compagnoni et al. 2005; Cosentino et al. 2010; Fabbi et al. 2014).

In the northeastern Simbruini Mts. the "Brecce della Renga Fm." (BDR hereafter) replaces the basin-floor succession due to the peculiar paleotectonic evolution of this area, which in the late Miocene represented a prominent extensional fault-bounded structural high in the subsiding central Apennines foredeep basin (Critelli et al. 2007; Fabbi 2013; Fabbi et al. 2014; Carminati et al. 2014). The BDR drapes a complex paleotopography *via* strongly erosional contacts.

In the following section, the stratigraphy and main sedimentological characters of the BDR are described.

The Brecce della Renga Formation (BDR)

The BDR outcrops across an area that exceeds 100 square km in the northeastern Simbruini Mts. (Fig. 2). In addition to very coarse-grained breccias (including boulder beds), whose clasts were derived from Meso-Cenozoic carbonate rocks, the BDR comprises rudite-arenite-pelite alternances.

As the breccias represent an "*unicum*" in the Central Apennines geology, an array of theories have been proposed by different authors to explain their origin. They were related either to compressional tectonics (Patacca et al. 1991; Cipollari & Cosentino 1991, 1995, 1999; Cosentino et al. 2010), or to extensional tectonics (Compagnoni et al. 1990, 1991, 2005; Critelli et al. 2007; Carminati et al. 2014) or to sedimentation in a piggyback basin (Santo & Sgrosso 1988; Sgrosso 1998). As we mentioned earlier, a new geological mapping of the area (Fabbi 2013) clearly documents that the deposition of the BDR was consequential to the early Tortonian development of a large extensional structural high (Fabbi 2012, 2013; Carminati et al. 2014).

Compagnoni et al. (1990, 1991, 2005) described for the first time the sedimentology of the BDR. These authors defined the chronostratigraphic boundaries of the unit (early Tortonian-early Messinian) and proposed the subdivision in three lithofacies and six sublithofacies, based on their peculiar map distribution, often in discrete compartments, as well as on the rudite/arenite/pelite ratio, and on sedimentological features. This paper embraces the subdivisions introduced by Compagnoni et al. (2005). The areal distribution of each lithofacies and sublithofacies is depicted in the map of Fig. 2.

Lithofacies 1 (pelite-arenite-rudite association)

The first lithofacies is made up of a pelite-arenite-rudite alternance, with pelites often dominating, and is widely exposed in the northern sector of the study area, between Roccacerro and Villaromana, and between Pereto and Fonte della Maddalena (Fig. 2).

It is subdivided into four sublithofacies (1-a, 1-b, 1-c, 1-d) mainly differentiated based on pelite/rudite ratio. Lithoclasts are fragments of Miocene and, subordinately, Cretaceous limestones.

Arenites (mainly hybrid arenites, *sensu* Zuffa 1980) are composed of fragments of bivalves, echinoids, balanids, bryozoans and red algae, along with *Ditrupa* sp., benthic foraminifers and rare planktonic foraminifers; siliciclastic grains are present, being a byproduct of basinal turbiditic sedimentation (Fabbi et al. 2014), and are mainly represented by quartz and micas.

Sublithofacies 1-a. Along the SW side of Mt. Fontecellese, from Villaromana to the top of the hill, sublithofacies 1-a typically occupies erosional morphologies carved in the substrate, along a mappable normal fault paleoescarpment (Compagnoni et al. 1991; Fabbi 2012, 2013). It resembles examples described by Santantonio (1993), Galluzzo & Santantonio (2002) and Santantonio & Carminati (2011) for depositional settings in the Jurassic of the Umbria-Marche pelagic domain. This sublithofacies is characterized by pelite-rudite alternations with minor arenites; near Villaromana it contains a large olistholith (longer axis >15 m) of Bryozoan limestone. The rudites are composed almost exclusively of Miocene lithoclasts, associated with large fragments of bivalves. Yellow rounded pelite intraclasts also occur, along with plankton-rich marl chips. The thickness of the sublithofacies 1-a is undeterminable, due to the laterally discontinuous nature of the outcrops, but is within a few tens of meters.

Sublithofacies 1-b and 1-c. These two sublithofacies outcrop extensively along the NE side of the Simbruini Mts. (Fig. 2). They are described jointly and are undifferentiated in the map, due to the transitional nature of their boundary in the field.

Poor outcrop conditions (dense vegetation) and logistic difficulties (landslides), prevent any accurate observations at present, whereas Compagnoni et al. (1991, 2005) were able to produce a fairly detailed stratigraphy.

Marls and shales with subordinate arenites, siltites and fine sandstones constitute Sublithofacies 1-b. Its lower part shows several characters in common with the "Unità argilloso-marnosa". The upper 20 meters are characterized by the presence of common calcarenite intercalations within the pelites. Individual intercalations are 10 to 30 cm thick and show $T_{b\text{-}d}$ and T_c Bouma sequences. Internal angular unconformities (clearly observed near Colli di Montebove, Fig. 3) are interpreted as slide-induced intraformational truncations. Sublithofacies 1-b evolves upwards into sublithofacies 1-c, which is composed by abundant breccias and arenites embedded in a pelitic deposit. The breccias form lenses up to some tens of meters thick. The thickest lenses have a massive appearance, but pass sharply to

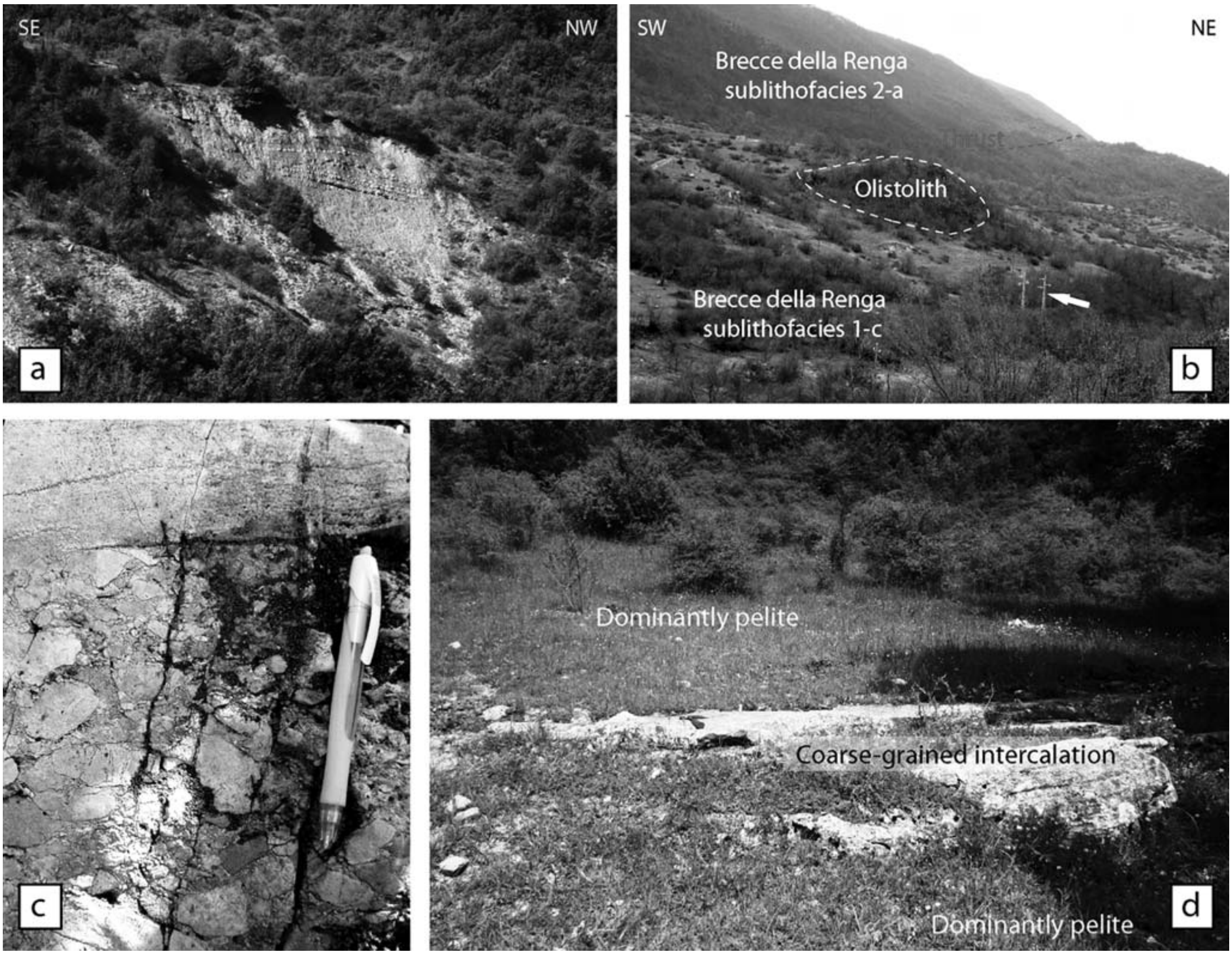

Fig. 3 - a) Panoramic view of several calcarenite beds embedded within a pelite interval of sublithofacies 1-b (note internal unconformities interpreted as erosional truncatures). b) Field view of a large olistolith of Bryozoan limestone encased in sublithofacies 1-c; arrow indicates high-voltage pylons for scale. c) Abrupt contact between breccias and overlying laminated arenites (coarse-grained intercalation within the sublithofacies 1-b near Colli di Montebove). d) Characteristic outcrop of the sublithofacies 1-d of the BDR: coarse lensoid bodies are embedded in a dominantly pelitic deposit.

laminated arenites (Fig. 3); finer-grained beds commonly show normal grading, with T_a, T_{a-b}, T_{a-c} Bouma sequences. Their base contains marl-chips and is characterized by large bryozoans and echinoids, along with fragments of bivalves. South of Colli di Montebove, several large olistoliths of bryozoan limestone, even more than 50 m in diameter (Fig. 3) are embedded in this deposit.

The two described sublithofacies can be seen forming one continuous coarsening upwards sequence, with maximum measured thickness of ~300 m.

Sublithofacies 1-d. The sublithofacies 1-d outcrops along a discontinuous belt from Pereto to Fonte della Maddalena, and is composed of dominant dark pelites with subordinated breccias and arenites. The breccia outcrops (often with lensoid geometry) are commonly well-bedded (Fig. 3). This sublithofacies commonly overlies the sublithofacies 2-b (see below). The maximum thickness of this unit (a few tens of meters estimated) is observed at S. Mauro.

Lithofacies 2 (clast-supported breccias)

The second lithofacies of the BDR is the most widely exposed, and consists of clast-supported breccias. It is subdivided into a massive sublithofacies (2-a) and a well bedded sublithofacies (2-b) (Fig. 4).

Sublithofacies 2-a. The sublithofacies 2-a outcrops extensively in the study area, with a maximum thickness that exceeds 300 meters. It is made up of thick stacks of markedly heterometric breccias (Fig. 4) that unconformably overlie a substrate represented by the Cretaceous and Miocene carbonate succession (Fabbi 2013).

The matrix includes loose (coeval) bryozoans and large echinoids, balanids and bivalve fragments (Fig. 5), while little siliciclastic components are present. Clast dimensions range from small granules to large or very

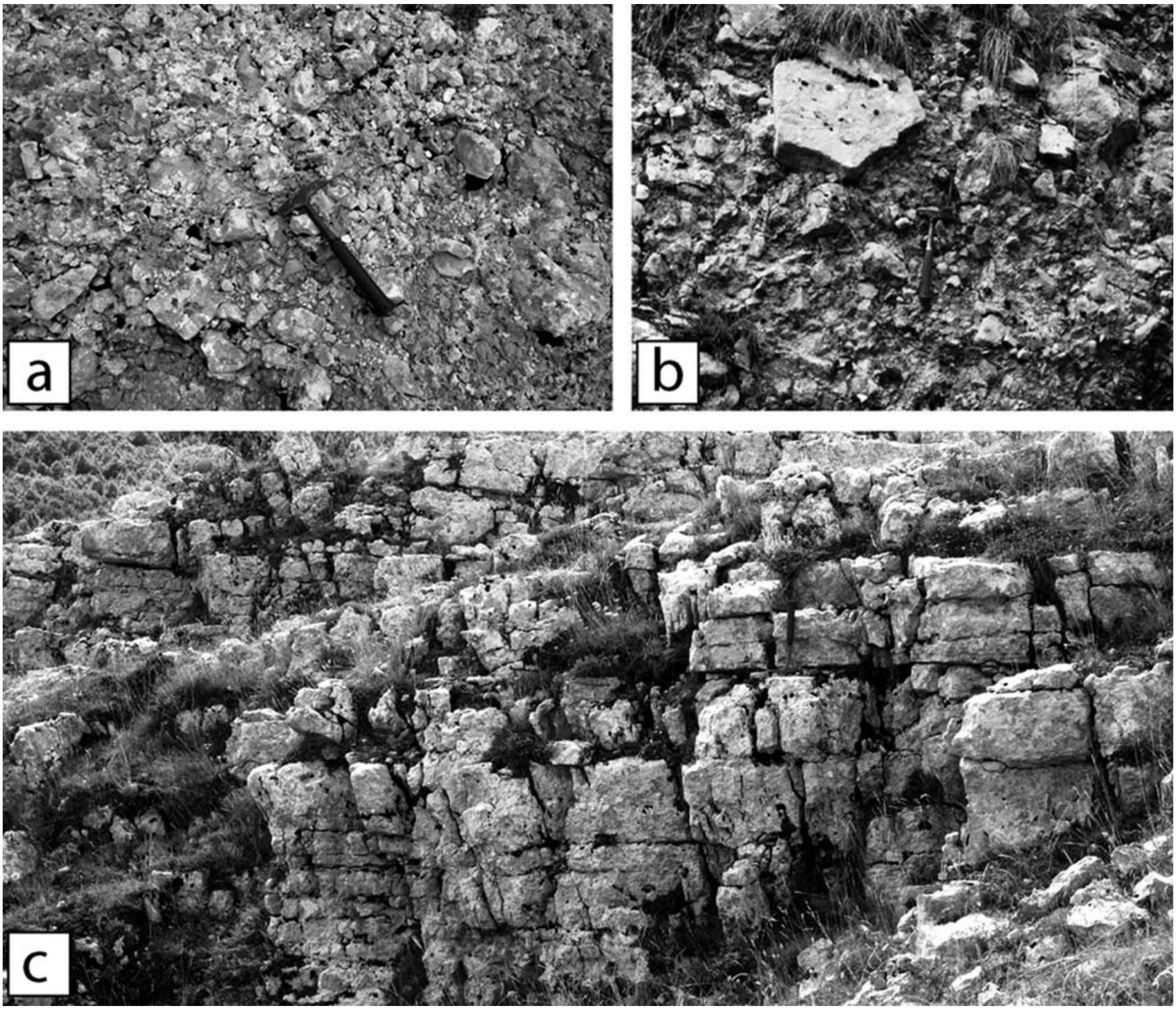

Fig. 4 - Lithofacies 2 of the BDR: a) massive sublithofacies 2-a; b) typical chaotic and markedly heterometric breccia of sublithofacies 2-a; c) bedded sublithofacies 2-b (hammer for scale).

large boulders. Near Mt. Fontecellese, a large Bryozoan limestone olistolith exceeds 200 m in maximum size (Compagnoni et al. 2005), while at Piani della Renga and in the Dogana Valley several large olistoliths of Cretaceous limestones are beautifully exposed.

This lithofacies is composed of chaotic beds that commonly lack any internal organization. A peculiar character of sublithofacies 2-a is the presence of yellow lensoid pelite interbeds (Devoto 1967, 1970; Parotto 1969; Compagnoni et al. 1990, 2005), with associated graded and laminated calcarenites and siltites (Fig. 6). In an almost exclusively clastic deposit, these fine intercalations provide the only reliable age information, through their planktonic content. Fragments of bivalves, bryozoans, echinoids, red algae, benthic forams and rare planktonics, along with abundant Miocene and Cretaceous lithoclasts, compose the fine calcarenites within the pelites.

Pelite intercalations have an impact on present-day morphology, producing small valleys and hollows within the vast area covered by the sublithofacies 2-a of the BDR (Fig. 6a). The main outcrops are at Valle della Dogana, St. Antonio Lake, Pratalata, Piano della Serra, Camporotondo and Fonte della Renga. The thickness of these pelite intercalations is very variable and ranges from a few centimetres (Fig. 6b) to more than 10 meters (inferred).

Sublithofacies 2-b. Sublithofacies 2-b of the BDR is exposed in the inner portions of the Simbruini ridge, away from the thrust front, namely along a belt that runs from Pereto to Cima Bertina. At Fonte della Maddalena and Cima Bertina it rests on the massive sublithofacies 2-a, while in the northern sector it disconformably overlies the Meso-Cenozoic substrate.

In marked contrast with the massive sublithofacies 2-a, sublithofacies 2-b is well bedded, with both

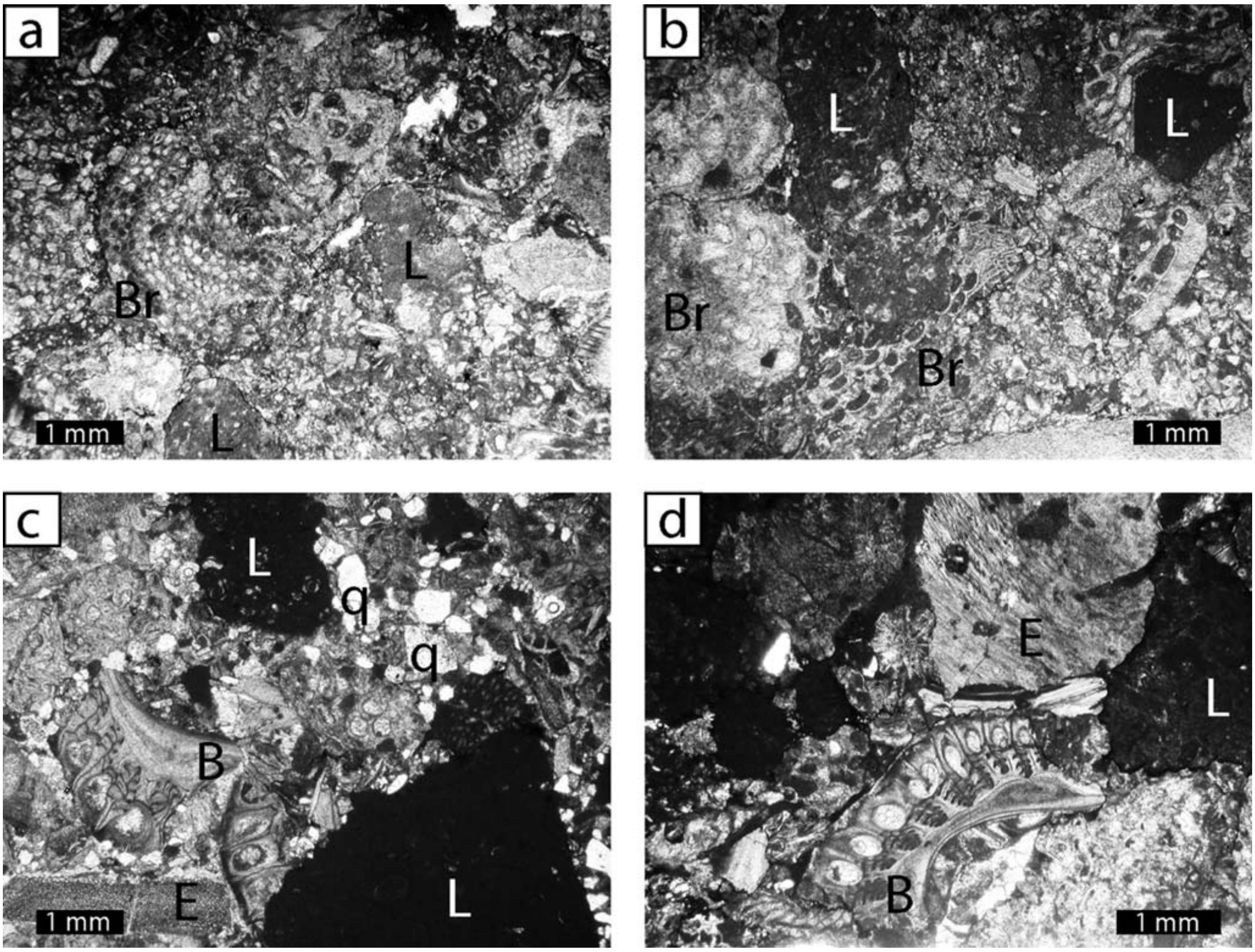

Fig. 5 - Thin section views of the breccia matrix in sublithofacies 2-a; note the association of lithoclasts (L), siliciclastic grains (q=quartz) and bioclasts (Br=bryozoans, E=echinoids, B=balanids).

lensoid and tabular beds (Fig. 7). The deposits display a general fining-upward trend, accompanied by an increase of siliciclastic elements in the matrix and in the lithoclasts (Fig. 7). Loose large ostreids, pectinids, balanids, echinoids and bryozoans are common components of the breccias.

At Fonte della Maddalena this sublithofacies is well exposed (Fig. 7) (see also Compagnoni et al. 1990, 1991), with dominantly lensoid beds having an average thickness of 10-50 cm and bearing rounded chert lithoclasts (Fig. 7c), unknown in the substrate (Compagnoni et al. 1990).

In thin section (Fig. 7e, f) the matrix of the breccia is composed of fragments of balanids, bryozoans, bivalves, echinoids, red algae, rare benthic forams and abundant siliciclastic grains (mainly quartz). Locally, this sublithofacies grades laterally to sublithofacies 1-d.

Lithofacies 3 (breccias and calcarenites interbedded with siliciclastic turbidites)

The third lithofacies of the BDR crops out along the Simbruini side of the Roveto Valley, overthrusting the siliciclastic turbidites of the "Complesso torbiditico altomiocenico Laziale-Abruzzese" (Compagnoni et al. 1991, 2005; Ciotoli et al. 1993; Critelli et al. 2007). This lithofacies is made up of breccias and arenites, encased in the siliciclastic turbidite succession.

The breccia beds are decimetre to metre thick, locally graded, or form very thick (up to some tens of meters) bodies, where large boulders cause load deformation in the underlying sediment (Fig. 8). Graded and laminated calcarenite levels (described by Devoto 1967, 1970; Parotto 1969; Bellotti et al. 1981; Civitelli & Corda 1988) are organized in stacks up to 3-5 metre thick (Castellafiume). The arenites are composed by poorly preserved fragments of echinoids, balanids, bryozoans, red algae and benthic forams. Lithoclasts are fragments of both Miocene and Cretaceous limestone. Inorganic components are abundant and include quartz, micas, dolomite and glauconite. Sole marks of sandstone levels

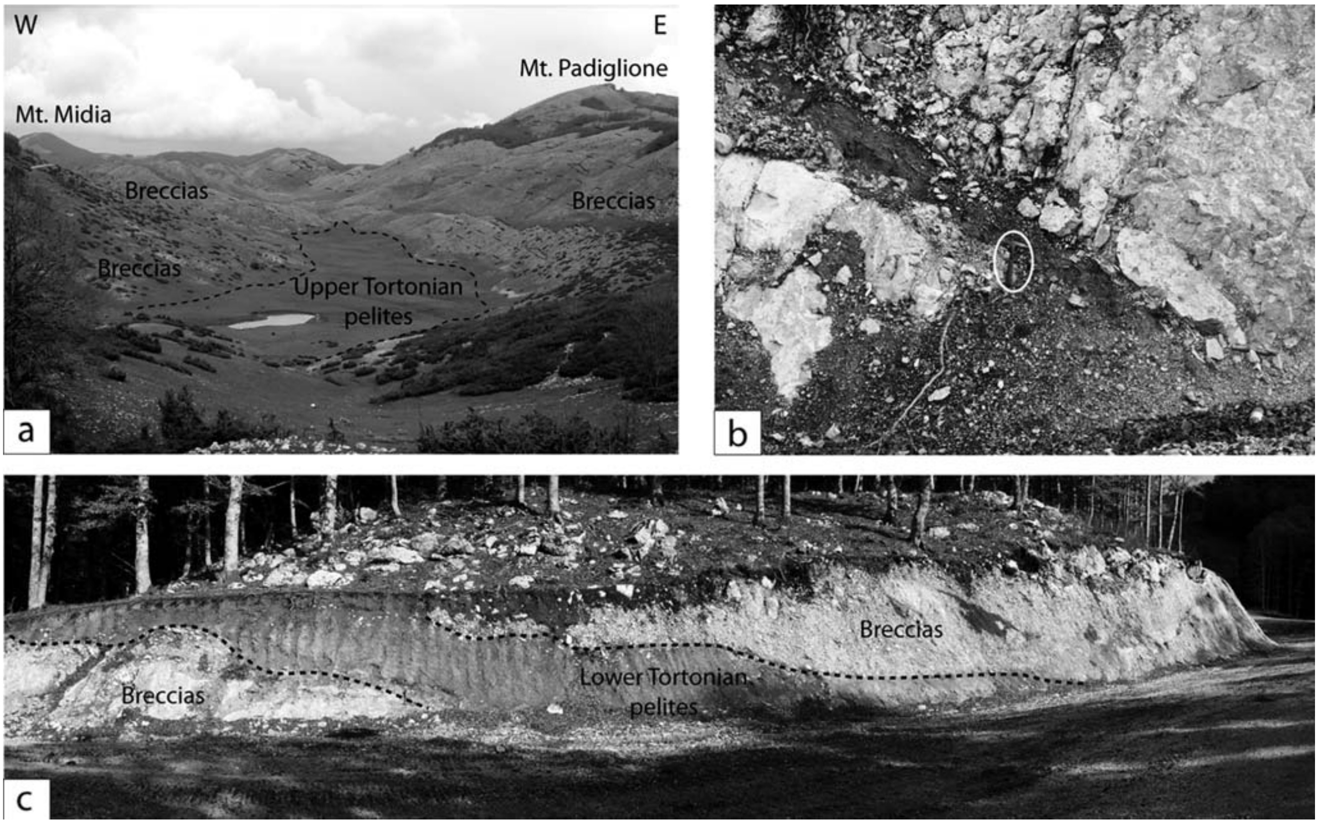

Fig. 6 - Pelite intercalations in massive breccias (sublithofacies 2-a) at various scales: a) Panoramic view of the Pratalata lake; b) Thin pelite intercalation at Camporotondo (hammer circled for scale); c) Pelite intercalation along the Camporotondo ski slope.

are NNW-SSE directed, subparallel to the Simbruini margin.

Sedimentology of the Brecce della Renga Fm

Sedimentary environments across the Simbruini high paleomargins were dominated by gravity driven processes, induced by the strong tectonic activity occurring in the study area during the late Miocene (Carminati et al. 2014). Among those processes, rockfall was dominant, as evidenced by both the dominance of chaotic piles of angular lithoclasts and the presence of megablocks within the BDR, indicating minimal transport. This process originates through the detachment and free-fall of boulders along a steep slope, and commonly produces a thick poorly organized deposit at the slope-toe (Nardin et al. 1979; Surlyk 1984; Reading & Richards 1994; Reading 1996; Richards et al. 1998). Rockfall was the most likely primary process that led to sedimentation of the massive and disorganized sublithofacies 2-a of the BDR. Sublithofacies 2-a is consequently interpreted as being a proximal deposit, forming a huge (or multiple discontinuous) clastic wedge(s) ("gravel rich aprons" in Richards et al. 1998) at the toe of submarine normal fault scarps (Fig. 2 for location), and testifies the dismantling of huge volumes of the carbonate succession which was exposed along those escarpments. By contrast, sublithofacies 2-b is organized in discontinuous wedges, developed in more distal settings with respect to the sublithofacies 2-a, and was likely sedimented through the avalanching of coarse loose material along the clastic slope, as testified by the presence of lensoid beds with cut-and-fill structures.

Several secondary processes (both gravity- and fluid-driven, *sensu* Ricci Lucchi 1985) must have induced sediment remobilization along the clastic apron. Due to the lack of cohesion among granules (a result of the scarcity or total unavailability of mud) these secondary processes mainly occurred as "grain flows" and "fluidal flows" (Middleton & Hampton 1976; Lowe 1976, 1979; Nardin et al. 1979; Talling et al. 2012). The last category includes turbidity flows, whose importance had to increase in distal portions of the clastic depositional system, away from the escarpments that were being dismantled (Fig. 9). The described processes ruled over the sedimentation in distal settings of the Simbruini paleomargins, in particular the coarsening upwards sequence represented by the sublithofacies 1-b and 1-c of the BDR, and the lithofacies 3, which represents the development of distal wedges interfingered with the siliciclastic turbiditic basinal deposits. Carbonate lithoclasts were likely reworked from sedi-

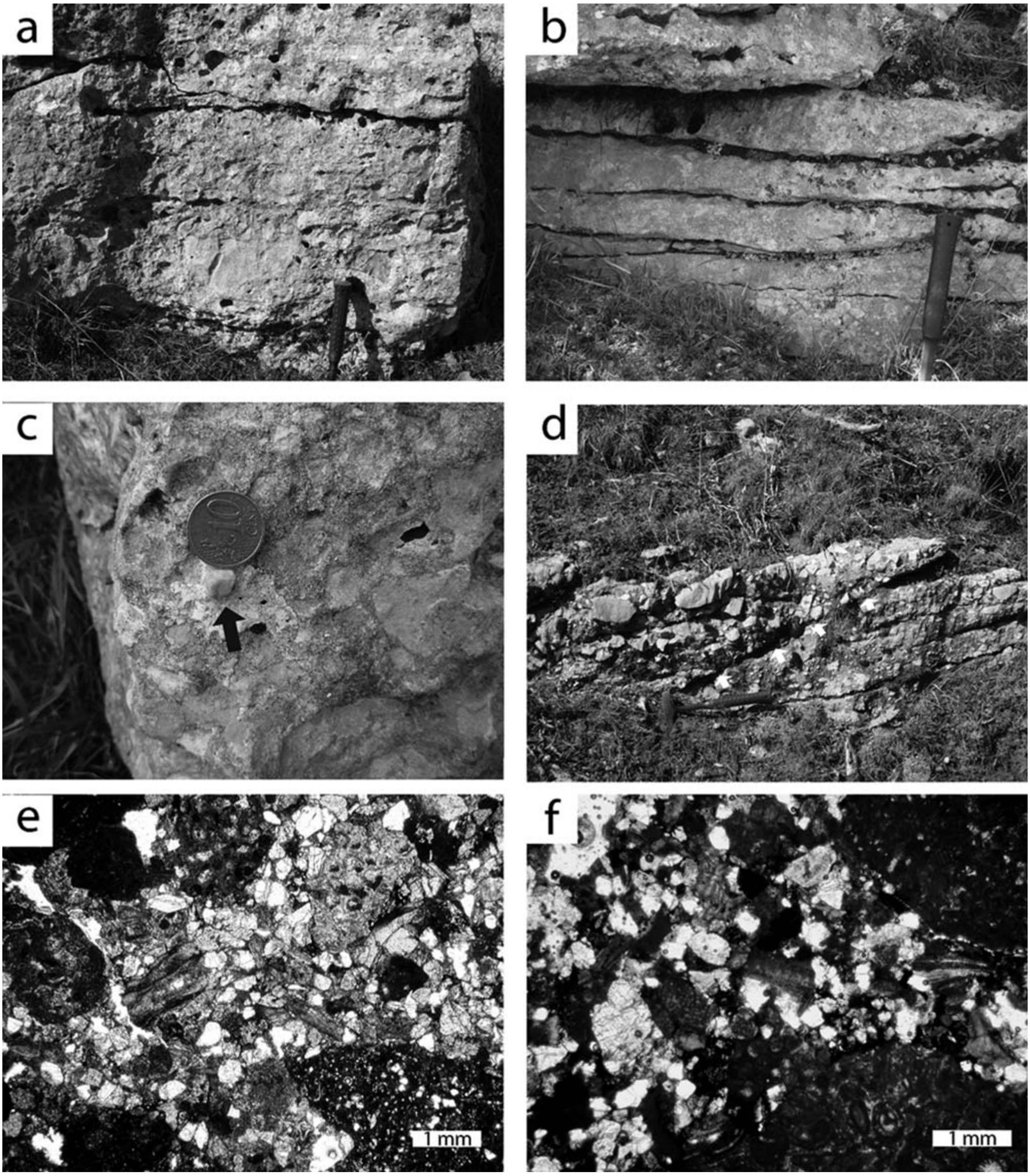

Fig. 7 - Overview of the main characters of sublithofacies 2-b of the BDR: a) Plane-parallel amalgamated beds; b) Markedly lensoid beds; c) Rounded chert granule (arrow); d) Cut-and-fill structure; the erosional truncature is indicated by arrows; e, f) thin section views of sublithofacies 2-b; note the abundance of quartz (white lucent granules).

ment existing along the clastic slope, while abundant siliciclastic material derived from basinal turbidites.

The presence of both discrete pelite intervals and siliciclasts in the breccia matrix must be considered a byproduct of turbidite sedimentation in the basin. Siliciclastic turbidite plumes can be some hundreds of meters thick (Reading 1996; Mulder et al. 1997) and could cause the deposition of suspended fine sediment in ponded basins along the clastic margin (sublithofacies 1-d) or within erosional loci along the normal fault escarpments (sublithofacies 1-a).

Abundant coeval bioclastic grains were sourced by active carbonate factories and sedimented through grain flows or turbidity flows (Fabbi et al. 2014).

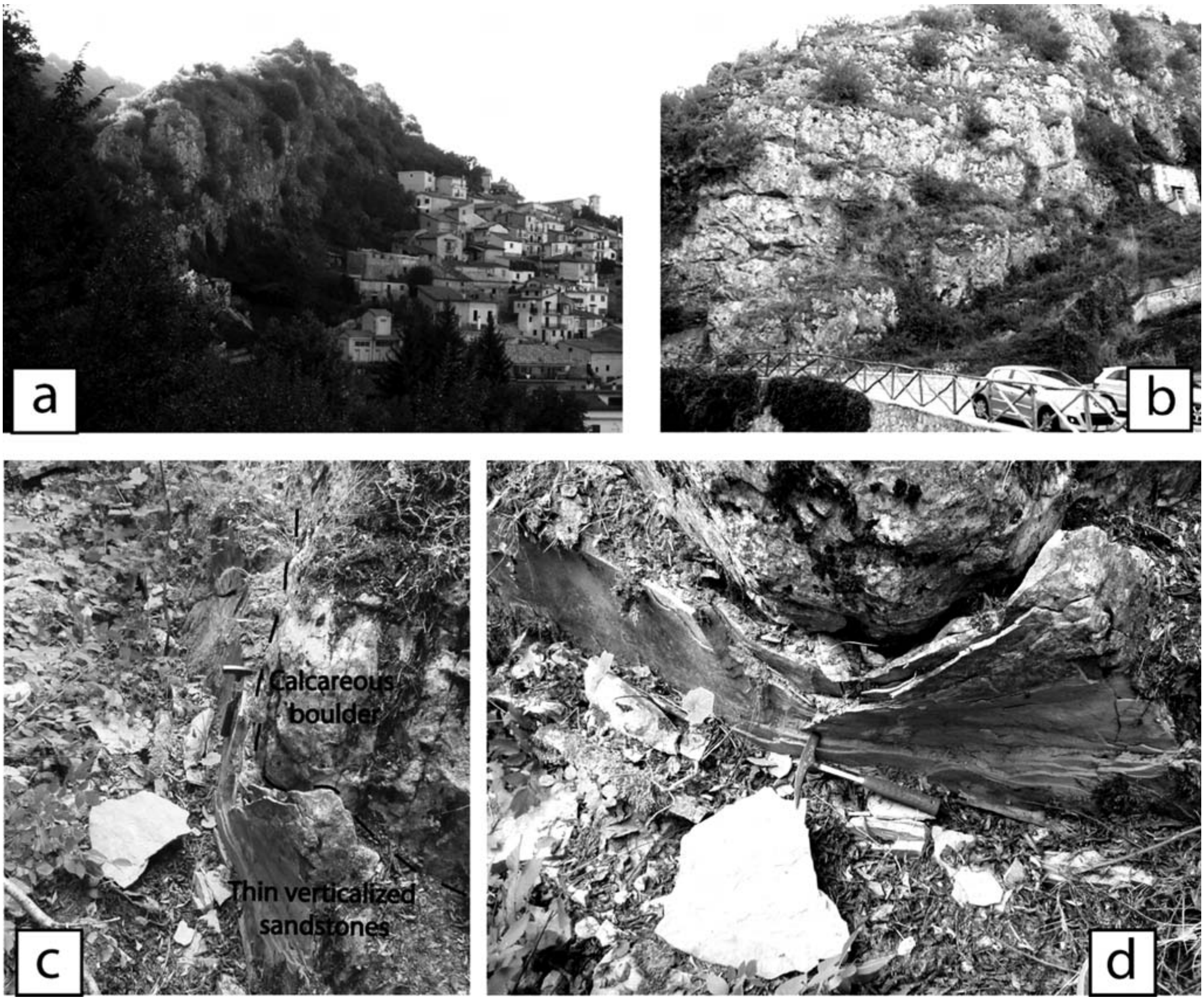

Fig. 8 - Lateral (a) and frontal (b) view of a verticalized breccia megabed, which form the ridge where the village of Verrecchie is built (lithofacies 3). Frontal view shows the top of the megabed, cut by several low-angle fracture sets; at its base (backside of the ridge) is possible to observe load deformation of thin sandstone layers under large calcareous boulders (c, d).

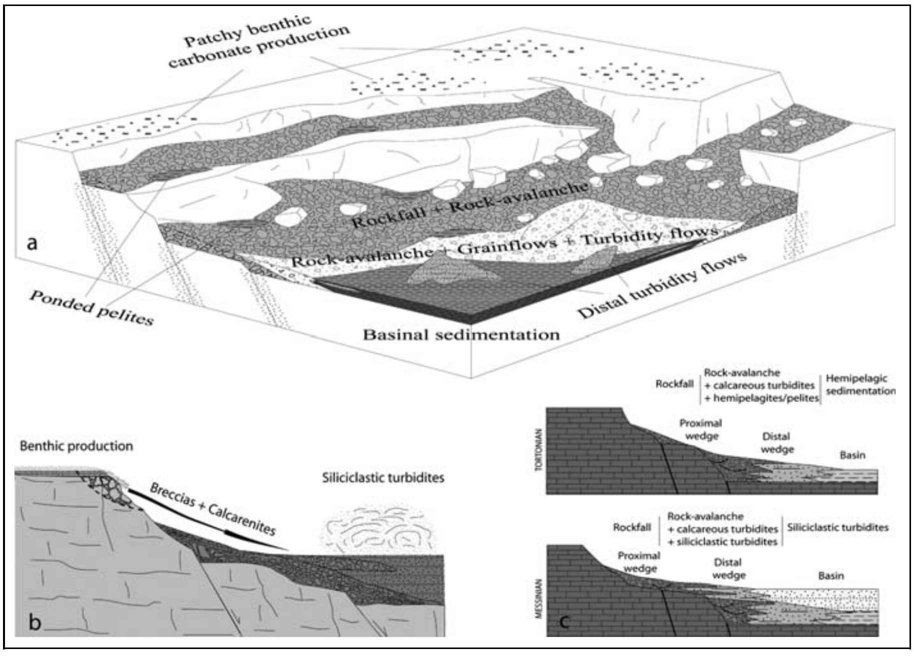

Fig. 9 - a) Block-diagram that schematize the complex BDR sedimentary environment. The main depositional processes are indicated; b) Different modalities of sediment production and sedimentation along the Simbruini paleomargins; c) Cartoon displaying an array of processes that occur along the Simbruini margin and a zonation of the clastic wedge. A reconstruction of its evolution from Tortonian to Messinian is provided

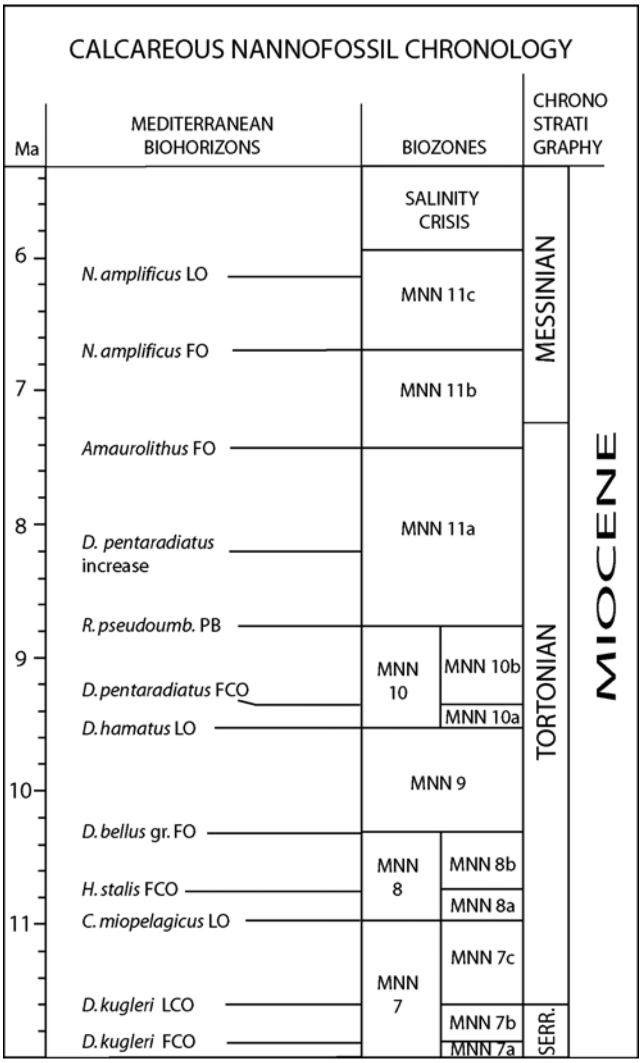

Fig. 10 - Late Miocene calcareous nannofossils events, redrawn and partly modified after Raffi et al. (2003) and Lourens et al. (2005).

Age of the Brecce della Renga Fm

Coarse material of the BDR was mainly derived from coeval upper Miocene carbonate factories (Fabbi et al. 2014) or from older exposed carbonate rocks. Biostratigraphically, significant taxa are very rare in the upper Miocene benthic assemblages and such assemblages are unfortunately duplicated in the matrix of the BDR. This occurrence, coupled with the lack of well preserved planktonic foraminifers, makes it difficult to define the age of the BDR using foraminifer-based biostratigraphical schemes. Consequently, age information has essentially been obtained from calcareous nannofossil assemblages, studying the pelites sampled in each lithofacies and sublithofacies of the BDR. Sixty fossiliferous samples has been collected and analyzed. The age calibration has been performed using the biostratigraphic schemes by Raffi et al. (2003) and Lourens et al. (2004) (Fig. 10).

No one complete stratigraphic section exists, as we mentioned, displaying both the lower and upper boundaries of each sublithofacies. Defining the ages of these boundaries implies therefore extensive use of correlation (Fig. 11), which can be far from obvious in a unit that characterizes itself through dramatic three-dimensional facies changes.

Due to this, some degree of uncertainty exists regarding the exact age spanned by each sublithofacies. Smear slides have been prepared from the collected samples following standard techniques and analyzed at x1000 magnification with a microscope, under cross-polarized and transmitted light. Fossiliferous samples display assemblages characterized by abundant reworked Cretaceous to Paleogene material (in average >50%) and by a rich inorganic fraction. Some samples by contrast are barren or sub-barren. The preservation of late Miocene nannofossils is generally medium to good, although specimens of the genus *Discoaster* are commonly broken or recrystallized. Small placolites (*Dictyococcites* spp., *Reticulofenestra* spp.) are the most abundant forms. Most significative nannofossils used in this paper for age determinations are displayed in Fig. 12. The nannofossils assemblages have been qualitatively and semiquantitatively characterized to evaluate the state of preservation and abundance.

We must note that a controversy exists in the literature, regarding the actual presence in the Mediterranean region of certain key late Tortonian marker species of the standard zonations (Martini 1971; Okada & Bukry 1980): typical specimens of *Discoaster berggreni,* and *D. quinqueramus* are missing (Theodoridis 1984; Pampaloni et al. 1994; Raffi et al. 2003, 2006). While these markers (*D.* cf. *quinqueramus, D.* aff. *quinqueramus*) have been used in the past to determine the age of the upper Miocene terrigenous units of the study area (Cipollari & Cosentino 1993, 1995; Cosentino et al. 1997), their reported occurrences are considered dubious by Raffi et al. (2003). Due to this, we decided to use the Mediterranean calcareous nannofossils zonation for the late Miocene of Raffi et al. (2003), based on standard markers and additional regional events.

The identified assemblages fall within a time interval ranging from the early Tortonian (MNN8b biozone) to the early Messinian (MNN11c biozone) (Fig. 13).

Lithofacies 1 is the best constrained, due to the abundance of pelite intervals, and covers a time interval from the middle Tortonian to the early Messinian (MNN10-MNN11c).

Sublithofacies 1-a covers a limited stratigraphic interval: assemblages in this sublithofacies consist of *Helicosphaera carteri*, *Calcidiscus macintyrei*, *Sphenolithus abies* gr., *Dictyococcites* spp., *Reticulofenestra* spp., *Coccolithus pelagicus, Discoaster bellus*, *D. variabilis*, *D. pentaradiatus, D. brouweri,* six rayed *Discoaster* spp. and *Geminilithella rotula.* The presence of *D. pen-*

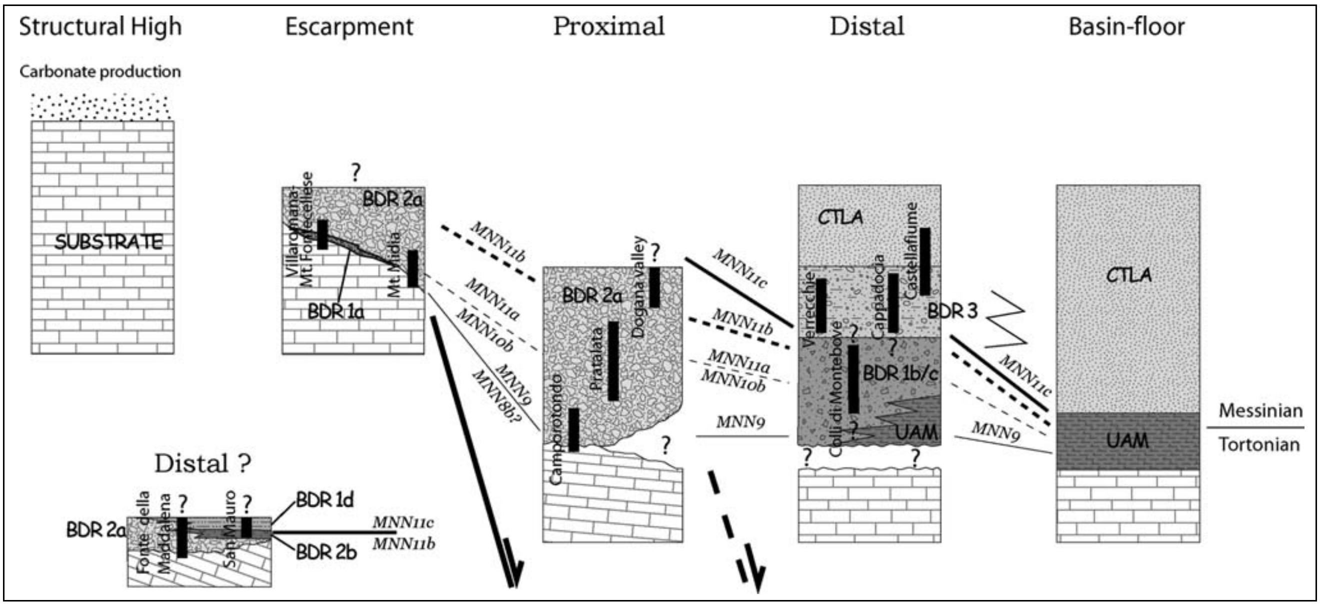

Fig. 11 - Simplified stratigraphic sketch depicting the complex depositional system of the "Brecce della Renga Fm.", with biostratigraphic ranges, correlation and locations of the most significative outcrops. BDR=Brecce della Renga Fm.; UAM=Unità argilloso-marnosa; CTLA= Complesso torbiditico altomiocenico laziale-abruzzese.

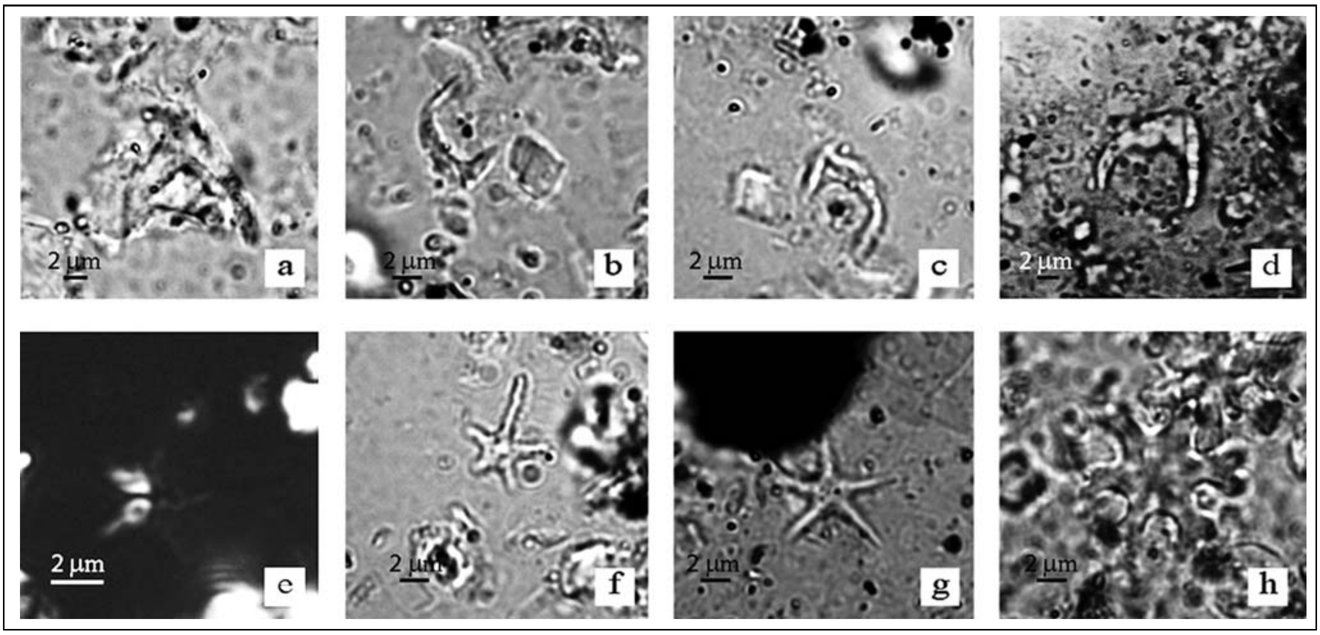

Fig. 12 - Most significant nannofossils used for age determinations: a) *Amaurolithus primus*; b) *Amaurolithus* sp.; c) *Amaurolithus* sp.; d) *Nicklithus amplificus*; e) *Discoaster pentaradiatus*; f) *Discoaster pentaradiatus*; g) *Discoaster bellus* gr.; h) *Discoaster variabilis* gr.

taradiatus indicates a middle-late Tortonian age for this unit (MNN10b-MNN11a biozone).

The following assemblages have been found within the sublithofacies 1-b and 1-c: *Helicosphaera carteri*, *Calcidiscus macintyrei*, *C. premacintyrei*, *Sphenolithus abies* gr., *S. moriformis*, *Dictyococcites* spp., *Reticulofenestra* spp., *Coccolithus pelagicus*, *Discoaster variabilis*, *D. pentaradiatus*, *D. brouweri* and poorly preserved six-rayed *Discoaster* spp. (*D.* cf *surculus*, *D.* cf. *pansus*, *D.* cf. *exilis*). This fossil association can be related to a middle-late Tortonian age (MNN10b - MNN11a biozones).

The dominantly pelite-rich sublithofacies 1-d produced more abundant assemblages, made by *Amaurolithus primus*, *Helicosphaera carteri*, *Calcidiscus macintyrei*, *Sphenolithus abies* gr., *Dictyococcites* spp., *Reticulofenestra* spp., *Coccolithus pelagicus*, *Discoaster variabilis*, *D. brouweri*, *D. pentaradiatus*, *D. bellus* gr., *D. pentaradiatus*, *Discoaster* cf. *intercalaris*, *Discoaster* spp., *Lithostromation perdurum*, and *Nicklithus amplificus*. The presence of *A. primus*, in association with rare *N. amplificus*, gives an early Messinian age for this sublithofacies (MNN11b – MNN11c biozones).

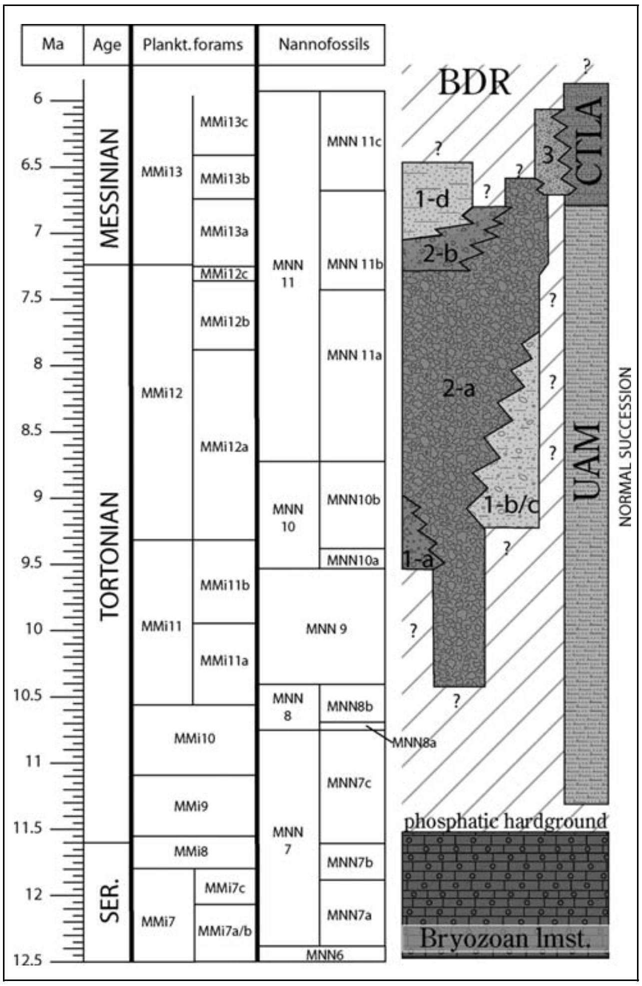

Fig. 13 - Chronostratigraphic chart of the upper Miocene terrigenous units exposed in the study area. BDR=Brecce della Renga Fm.; UAM=Unità argilloso-marnosa; CTLA=Complesso torbiditico altomiocenico laziale-abruzzese.

The massive lithoclastic sublithofacies 2-a was dated using fossil associations from samples collected within the pelitic intercalations. Different pelitic intercalations can have a different age, not unexpectedly due to the discontinuous nature of the sedimentary processes governing deposition of the Brecce della Renga (see above). The oldest pelites were found in the Camporotondo area, and bear an assemblage made up of *Dictyococcites* spp., *Reticulofenestra* spp., *Coccolithus pelagicus*, *Sphenolithus moriformis*, *S. abies* gr., *Calcidiscus macintyrei*, *Coccolithus miopelagicus, C. pelagicus*, *Dictyococcites* spp., *Discoaster* cf. *variabilis*, *D.* cf. *exilis*, *D.* cf. *intercalaris, D.* cf. *brouweri, Discoaster* spp., *Geminilithella rotula, Helicosphaera carteri*, *H. stalis* (rare). The remarkable absence of five-rayed *Discoaster* (*D. bellus* gr. and *D. pentaradiatus*), even in the more fossiliferous samples, suggests at least an early Tortonian age (MNN8b biozone?, older in any case than the MNN9 biozone), which is the oldest age determined for the BDR.

The assemblages produced by samples collected at St. Antonio Lake, Pratalata, and other localities along the wide outcrop area of the sublithofacies 2-a, are extremely poor and mostly reworked, and are constituted by *Helicosphaera carteri*, C*alcidiscus premacintyrei, Sphenolithus abies* gr., *Dictyococcites* spp., *Reticulofenestra* spp., *Coccolithus pelagicus, Discoaster* spp., *Discoaster variabilis* and *D. pentaradiatus*. We ascribe these assemblages to the middle-late Tortonian (MNN10b - MNN11a biozones). Similar associations are described at Dogana Valley, but with the significant addition of rare *Amaurolithus primus*, which testifies a younger age for the pelites sampled in this locality (not older than the late Tortonian-early Messinian – MNN11b biozone). In conclusion, sublithofacies 2-a covers an interval ranging from the early Tortonian to the early Messinian (MNN8b – MNN11b biozones).

Sublithofacies 2-b has been dated only based on its stratigraphic position, being found almost invariably at the base of, or interfingered with, sublithofacies 1-d. Therefore it could be referred to the latest Tortonian or early Messinian.

Lithofacies 3 produced rich assemblages, with *Nicklithus amplificus, Dictyococcites* spp., *Reticulofenestra* spp. *Helicosphaera carteri, Coccolithus pelagicus, Sphenolithus abies* gr., *Discoaster pentaradiatus, Discoaster* cf. *intercalaris, D. variabilis, Calcidiscus macintyrei* and *Dictyococcites* spp. The occurrence of *Nicklithus amplificus* suggests an early Messinian age for this unit (MNN11c biozone).

Discussion

Accurate age determinations of the BDR demonstrate that this formation developed from the early Tortonian to the early Messinian, predating the development of the Simbruini thrust (Bigi et al. 2003). The discovery of sound field evidence for pre-thrusting extensional faulting in the study area implies that the foreland flexure, i.e. the switch from foreland to foredeep conditions across the region, was accompanied by the development of an extensional system, whose physical expression was the formation of submarine fault escarpments. Earthquakes made these escarpments markedly unstable, and a preferential site of gravitative collapse, producing the impressive clastic sequence represented by the BDR (Fabbi 2013).

The BDR record sedimentary processes that occurred along the paleo-Simbruini clastic slopes, coeval with the “Unità argilloso-marnosa” and the overlying “Complesso torbiditico altomiocenico Laziale-Abruzzese”, representing basin-filling units. Most of the observed sedimentological features suggest deposition largely through “event processes” (like earthquakes),

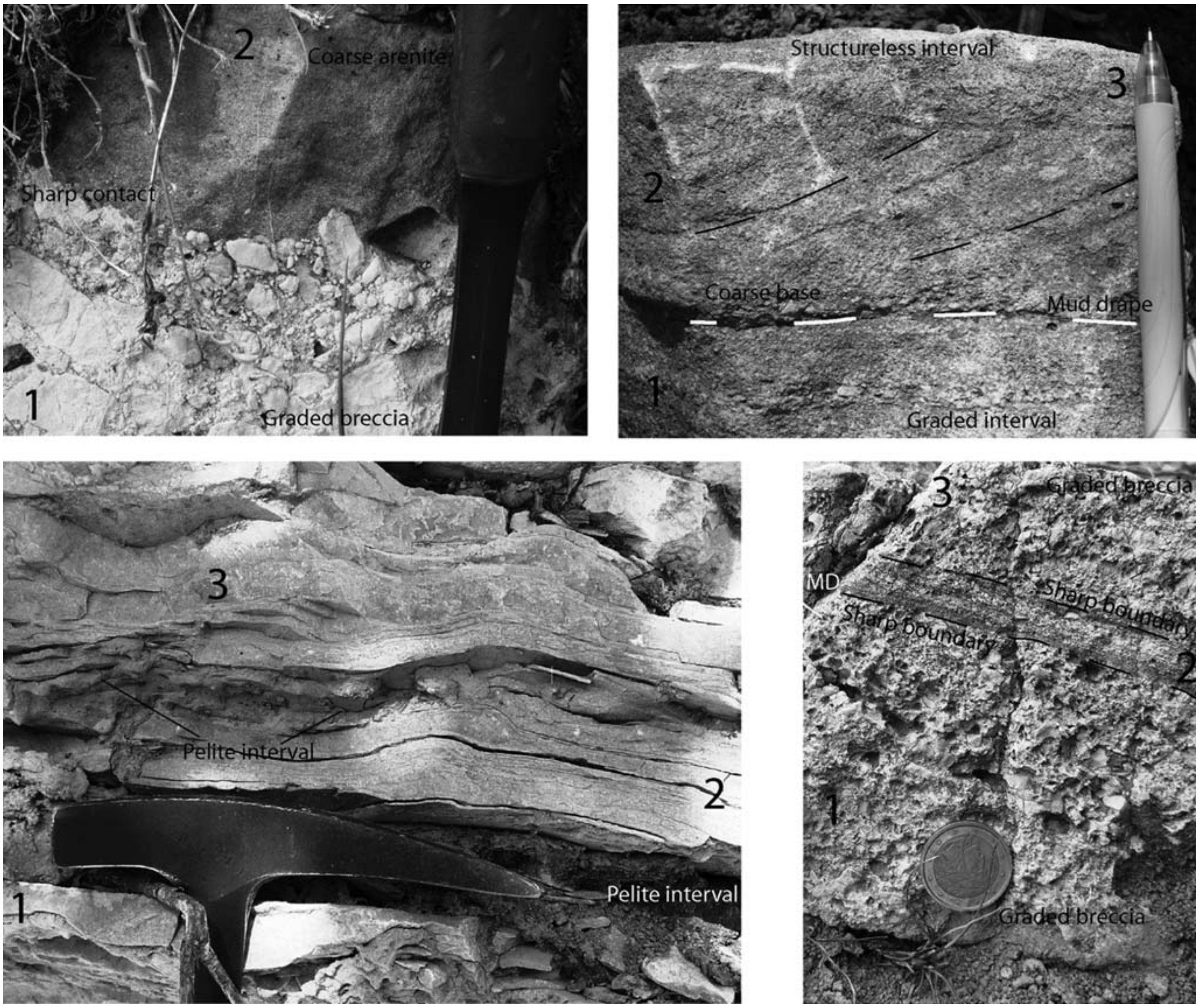

Fig. 14 - Examples of composite beds and sedimentary structures in the arenites of Brecce della Renga Fm. a) Abrupt passage from graded breccias to coarse arenites (sublithofacies 1-d). b) Composite bed where at least three different intervals can be observed: over a graded very coarse arenite ('1') the presence of a mud drape testifies a temporary halt of carbonate/clastic sediment supply; the following interval '2' is at the base a structureless arenite, which evolves in a cross-laminated arenite, in turn abruptly covered by the structureless interval '3'; the latter can be interpreted as the erosional base of a subsequent gravity flow (sublithofacies 2-c). c) Three cross-laminated fine-grained arenite levels are separated by pelite intervals, testifying multiple pulses of sand-size carbonate/clastic sediment input in the basin (lithofacies 3). d) Composite bed made by two graded breccia intervals ('1' and '3'), separated by a laminated coarse arenite which partly eroded a poorly preserved mud drape (MD) at the top of the lower breccia; the arenite interval is in turn eroded by the base of the upper breccia.

which is consistent with a syntectonic late Miocene scenario. Each triggering event caused the simultaneous activation of different depositional processes (Schaefer & Smith 1987; Lee et al. 1993; Locat et al. 2003; Vanneste et al. 2006). It is common to observe composite beds, where chaotic to faintly graded coarse breccias are abruptly overlain by thin parallel- to cross laminated arenites (Fig 9b, Fig. 14). These deposits can be interpreted as the product of collapse along an escarpment, accompanied by downward flow of the loose carbonate sediment originally topping the escarpment (Hendry 1973; Surlyk 1984), which was being produced on the structural high. As mentioned earlier, in effect, the top of the Simbruini paleo-high could locally host survived benthic carbonate factories, which sourced the abundant loose bioclastic granules found in the arenites and in the rudite matrix (Fabbi et al. 2014).

The discontinuous nature of sedimentation is also evidenced by mud drapes that often punctuate the clastic succession. These levels could be reworked forming rip-up clasts occurring within the fine breccias and at the base of calcarenite beds.

Within this scenario, one paleoescarpment tract could locally represent the envelope surface of an eroded set of fault scarps along the structural high margin, as proposed by Compagnoni et al. (1990) and Fabbi (2013).

Summarizing, the stepwise erosional retreat of escarpments produced huge volumes of proximal rockfall deposits, forming a complex clastic wedge. Towards the depocenters, the importance of rockfall deposits decreased, and sedimentation was dominated by rock avalanche and grain flow processes, producing more organized and well bedded deposits (Surlyk 1984). In more distal settings the carbonate clastic levels, largely sedimented through turbidity flows, became interfingered with basinal units, which were made of hemipelagic marls and siliciclastic turbidites. Very thick coarse-grained breccia beds in distal settings were likely produced by rockslides (Hendry 1972) likely linked with major, destructive seismic events.

An overview of the processes taking place when the BDR were sedimented, and a tentative schematic evolution from the Tortonian to the Messinian, is given in Fig. 9c. This reconstruction takes into account that the Simbruini extensional high developed during the Tortonian (Fabbi 2013). The coarsening upwards evolution observable in the Tortonian is likely the result of coarse proximal facies progradation due to paroxystic phases of fault activity, while a fining upwards evolution evidences overall backstepping of the depositional system. In the early Messinian this backstepping was conceiveably related to gradual reach of a quiescent state by the faults bounding the high, with consequent minor erosion of submarine escarpments and lesser abundance of coarse clastic material.

Conclusions

The "Brecce della Renga Fm." is a clastic unit resulting from "catastrophic" sedimentation along the margins of the Simbruini structural high, and covers as a whole a time span ranging from the early Tortonian (MNN 8b) to the early Messinian (MNN 11c). The Simbruini high developed as a product of extension in the early Tortonian, and sedimentation at its margins was controlled by the presence of submarine normal fault escarpments. Coarse rockfall sediments (sublithofacies 2-a) are widespread throughout the entire time span covered by the unit, while finer-grained deposits (sublithofacies 1-a/d, sublithofacies 2-b, lithofacies 3) are time- and space- segregated, and show different characters from the early Tortonian to the early Messinian. Tortonian sublithofacies 1-a/c (MNN 9/MNN 11a) are exposed in the northern sector of the study area, while Messinian sublithofacies 1-d, 2-b and lithofacies 3 (MNN11b-c) outcrop in the inner portion of the structure and in the Roveto valley.

Dismantling of the escarpments produced huge volumes of lithoclastic sediment. A clastic wedge flanked the Simbruini high, lateral to the basin-bottom deposits, which are represented by hemipelagic marls and then siliciclastic turbidites. The strong variability of sediment types and clast size help define the architecture of the clastic margin, and are the result of an array of sedimentary processes. Sedimentation was dominated by rockfall processes, along with a variety of secondary processes including rock-avalanche/rockslides, non-cohesive grainflows and turbidity flows. The relative importance of the various processes changed generally in relation to the distance from the source area of clasts (the steep escarpments). The very large area covered by chaotic proximal deposits is best explained by assuming that multiple source areas had to exist, arguably a dense system of closely spaced normal fault escarpments forming a stepped margin, whose dismantling and burial must have produced one extensive coarse proximal wedge. Finer and better organized deposits characterize the more distal areas. Composite beds (e.g. chaotic coarse breccias with a thin turbidite cap) could either result from single events involving both lithified and unconsolidated sediment or represent amalgamated beds due to the superimposition of consecutive flows. Mud drapes testify quiescence periods, their sparse occurrence being also due to their laterally variable preservation potential. In distal settings, coarse lithoclasts likely derived from the remobilization of sediments forming the proximal clastic wedge, while the provenance of bioclasts was from the productive structural high, and siliciclastic grains were sourced by the basinal turbidites.

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