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The Lower Miocene spongolitic sequence of the Central Apennines: a record of the Burdigalian siliceous event in the Central Mediterranean

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(With 6 figures)

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Abstract

A stratigraphic and sedimentological analysis of the Miocene spongolitic unit from Central Apennines is presented. The spongolitic succession of the Latium-Abruzzi Platform (informally named Guadagnolo Formation) represents the sedimentation along the platform margin domain. In all sectors of the platform, at least two informal members are distinguishable. The lower member, Chattian to Early Burdigalian in age is characterized by deposits dominated by larger benthic foraminifera. This member is divided in two intervals by a first spongolitic horizon of few meters thick. The more siliceous intermediate member ("spongolitic"), spanning the Burdigalian to Langhian, mostly consists of spongolitic marls and marly limestones. The upper member is only present in the north-western and northern margin and it is characterized by cross-bedded calcarenites.

The Burdigalian time interval in Central Apennines is characterized by: a) spread of terrigenous spongolitic facies on the platform-to-basin zone and cherty-rich facies in the pelagic realm, b) spread of bryozoan-dominated facies on the platform domain, and c) positive C-isotope excursion related to high primary production

The Oligo-Miocene volcanic activity in the western Mediterranean and its related increase in atmospheric CO_2 might have induced decreases in pH and carbonate ion concentrations in surface waters, favoring siliceous production in acidic seawaters. An increase in terrigenous material from the neighboring Apennine foredeep system, promoted a $CaCO_3$ reduction induced by terrigenous dilution.

The combined effect of volcanism, changes in oceanic circulation and the Apennine foredeep-related siliciclastic input, favoured the spreading for marly-spongolitic facies in the Central Apennines, as well as throughout the Mediterranean area.

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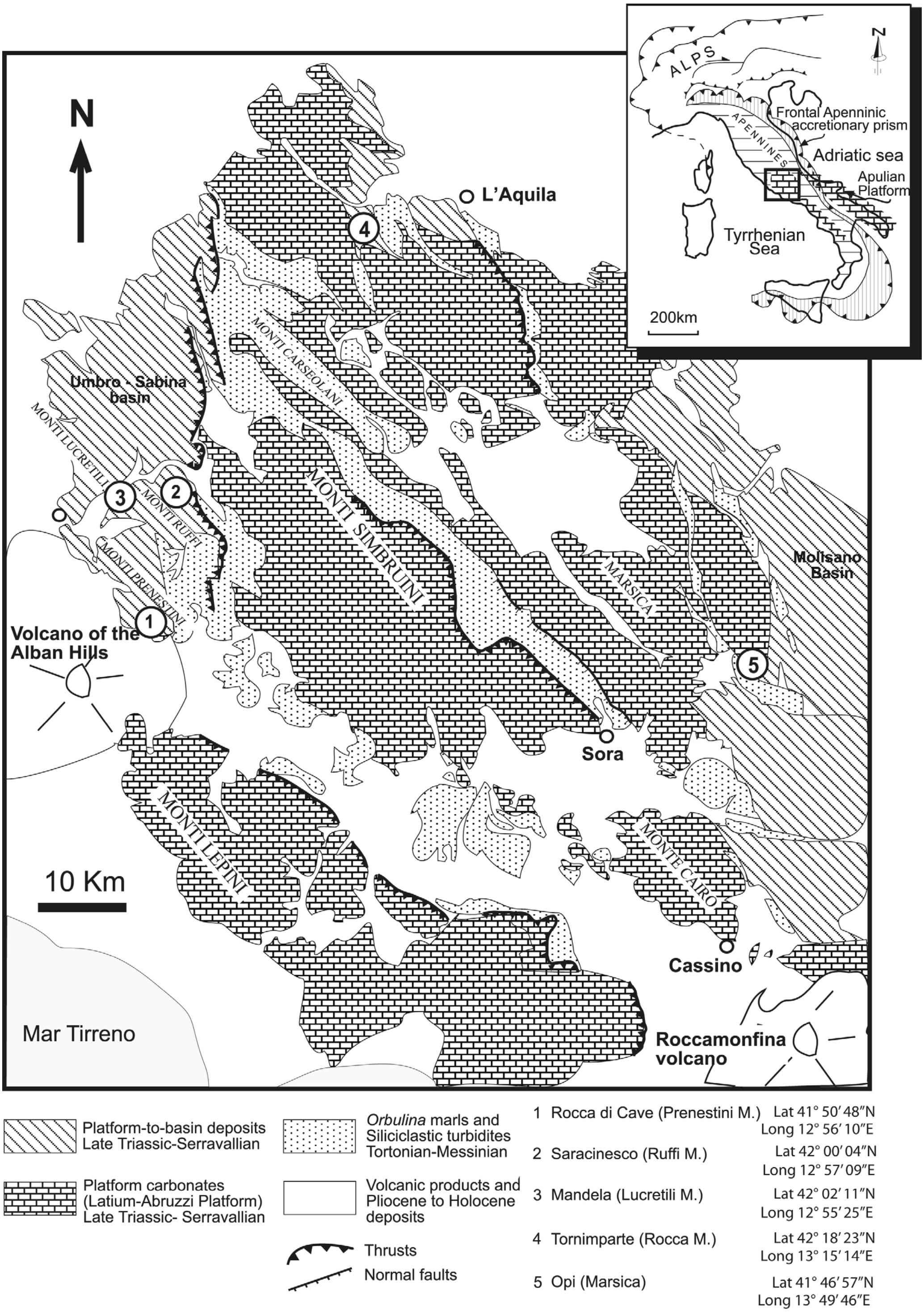
Introduction

The oceanography of the Chattian and Aquitanian to Burdigalian Mediterranean Sea favoured the expansion of larger benthic foraminifera (LBF) and red algae as biota producing carbonate sediment with various coral episodes (Pedely 1998; Brandano & Corda 2002; Nebelsick et al 2005; Bosellini & Perrin 2006; Pomar & Hallock 2008; Brandano et al. 2010a,b). Since the mid-Burdigalian, LBF became subordinate, corals were very rare, and carbonate platform sedimentation was dominated by coralline algae (Halfar & Mutti 2005; Pomar & Hallock 2008; Brandano et al. 2009, 2010b). At the same time, from the Burdigalian to the Langhian, predominantly marly-siliceous products were deposited all round the distal sectors of the central Apennine carbonate platforms and in the pelagic realm (Carboni et al. 1982; Civitelli et al. 1986a, b). Sponge-siliceous spicules are the main constituents of the platform-to-basin zone (Guadagnolo Formation, outcropping along the western margin of the Latium-Abruzzi platform), whereas radiolarians dominate the pelagic realm (Bisciaro Formation). Lower Miocene siliceous facies are reported across the entire Mediterranean (Civitelli et al. 1987, and references therein).

During the Early to Middle Miocene, two large-scale paleogeographic changes took place in the embryonic Mediterranean area. In the Late Burdigalian, the gradual closure of the Tethyan passage between the Central Atlantic and Indian Oceans, with collision between the Arabian and Eurasian plates, may have had a direct effect on circulation patterns in the Mediterranean (Rögl 1999; Harzhauser et al. 2002). The second paleogeographic change was the counter-clockwise rotation of the Sardinia-Corsica block, which led to the creation of the Western Mediterranean. Subduction-related roll-back in this area was associated with lithospheric stretching of the Southern European paleo-margin (Gueguen et al.1998; Rollet et al. 2002; Carminati et al. 2010). Huge subaerial and submarine volcanic activity was associated with this block rotation (Gueguen et al. 1998; Lustrino et al. 2004, 2009; Carminati et al. 2010).

The aim of this paper is to highlight the role of various controlling factors on the spreading of siliceous facies in the Central Mediterranean in Miocene times. Three sectors of the Latium-Abruzzi carbonate platform domain are examined here, located respectively in the north-western (Monte Prenestini, Ruffi, Lucretili), northern (Tornimparte) and eastern margins (Opi, Marsica) (Figs 1, 2).

Fig 1. Simplified geological map of the Latium-Abruzzi carbonate platform and neighbouring basins. The locations of the analyzed stratigraphic sections are indicated by numbers and are referred to in the subsequent figures. Modified from Brandano & Corda (2002). ►


N
10 Km
L'Aquila
Umbro - Sabina basin
MONTI LUCRETILI
MONTI RUFFI
MONTI PRENESTINI
MONTI CARSEOLANI
MONTI SIMBRUINI
MARSICA
Molisano Basin
Volcano of the Alban Hills
Sora
MONTI LEPINI
MONTE CAIRO
Cassino
Mar Tirreno
Roccamonfina volcano
ALPS
APENNINES
Frontal Apenninic accretionary prism
Adriatic sea
Apulian Platform
Tyrrhenian Sea
200km
N
Platform-to-basin deposits Late Triassic-Serravallian
Platform carbonates (Latium-Abruzzi Platform) Late Triassic- Serravallian
Orbulina marls and Siliciclastic turbidites Tortonian-Messinian
Volcanic products and Pliocene to Holocene deposits
Thrusts
Normal faults
1 Rocca di Cave (Prenestini M.) Lat 41° 50′ 48″N Long 12° 56′ 10″E
2 Saracinesco (Ruffi M.) Lat 42° 00′ 04″N Long 12° 57′ 09″E
3 Mandela (Lucretili M.) Lat 42° 02′ 11″N Long 12° 55′ 25″E
4 Tornimparte (Rocca M.) Lat 42° 18′ 23″N Long 13° 15′ 14″E
5 Opi (Marsica) Lat 41° 46′ 57″N Long 13° 49′ 46″E

Geological setting

The Central Apennines represent a fold-and-thrust belt which developed from the Oligocene on top of an eastward-retreating westward-dipping slab, composed of the continental Adriatic plate (Boccaletti et al. 1971; Doglioni 1991; Gueguen et al. 1998; Carminati & Doglioni 2005). Mesozoic and Cenozoic units were detached at the Upper Triassic evaporites (Burano Anhydrite) and accreted to the belt.

The Neogene to Recent evolution of the Northern-Central Apennines is characterized by the subsequent ENE-ward migration of deformation fronts and related foredeeps (Ricci-Lucchi 1986). The eastward migration of the Apennines fold-and-thrust belt was accompanied by extensional tectonics in the hinterland, leading to the opening of progressively younger back-arc basins: the Provencal (e.g., Rehault et al. 1985; Gueguen et al. 1998), Tyrrhenian and Tuscan Basins, and several intramontane basins (Bartole 1995; Barchi et al. 1998; Cavinato & de Celles 1999).

The Central Apennine belt is composed of Triassic to Middle Miocene sediments derived from the deformation of various paleogeographic domains represented by the Apenninic carbonate platforms and the Umbro-Sabina and Molisano Basins (Fig. 2). The Apennine carbonate platforms are mostly represented by the wide Latium-Abruzzi carbonate platform and the northward extension of the Apulia Platform, which has several small platforms (Majella, Morrone-Porrara) (Fig. 2). The Latium-Abruzzi Platform was bounded to the west and north-west by the Umbria-Sabina Basin and to the east by the small basin of the Monte Genzana Corridor, which connected the Gran Sasso Basin northward to the Molisano Basin southward (Patacca et al. 1991, 2008).

The Latium-Abruzzi Platform consists of Triassic to Cretaceous carbonates deposited on a persistent tropical-subtropical carbonate platform. After a long hiatus in the Palaeogene, from the early Miocene onwards, shallow-water carbonates began to deposit over the Cretaceous limestone. They are represented by the Calcari a Briozoi e Litotamni Formation (Aquitanian to Tortonian) deposited in a carbonate ramp environment (Brandano & Corda 2002; Corda & Brandano 2003). Along the western side of the Latium-Abruzzi Platform, a thick siliceous unit (informally called the Guadagnolo Formation) was deposited in the platform-to-Sabina basin transition zone (Chattian to Serravallian) (Fig. 1) (Civitelli et al. 1986 a, b). Similar but thinner siliceous units were deposited during the same time interval along the northern and eastern sectors of the platform (Carboni et al. 1982). The Oligo-Miocene pelagic deposits, representative of basinal sectors, are the Scaglia Cinerea Formation (Rupelian to Chattian), consisting of well-bedded biomicritic limestone, and the overlying Bisciaro Formation (Aquitanian to Burdigalian). The latter is made up of alternating cherty-calcareous beds containing sporadic volcanoclastic layers. The upper part is dominated by marl and passes upwards to the Schlier Formation, characterized by a rhythmic sequence of foraminiferal, marly limestone grading into marlstone, with fewer marly limestone intercalations (Centamore & Deiana 1986; Damiani et al. 1991).

During the Late Miocene, the sedimentation of the Latium-Abruzzi Platform was terminated by plate flexure-related drowning and the coeval input of terrigenous sediments, first Tortonian to Messinian hemipelagic marl ("*Orbulina*" marl) and then turbibitic siliciclastic deposits ("Argilloso-Arenacea" Formation) of Early Messinian age (CIPOLLARI & COSENTINO 1991).

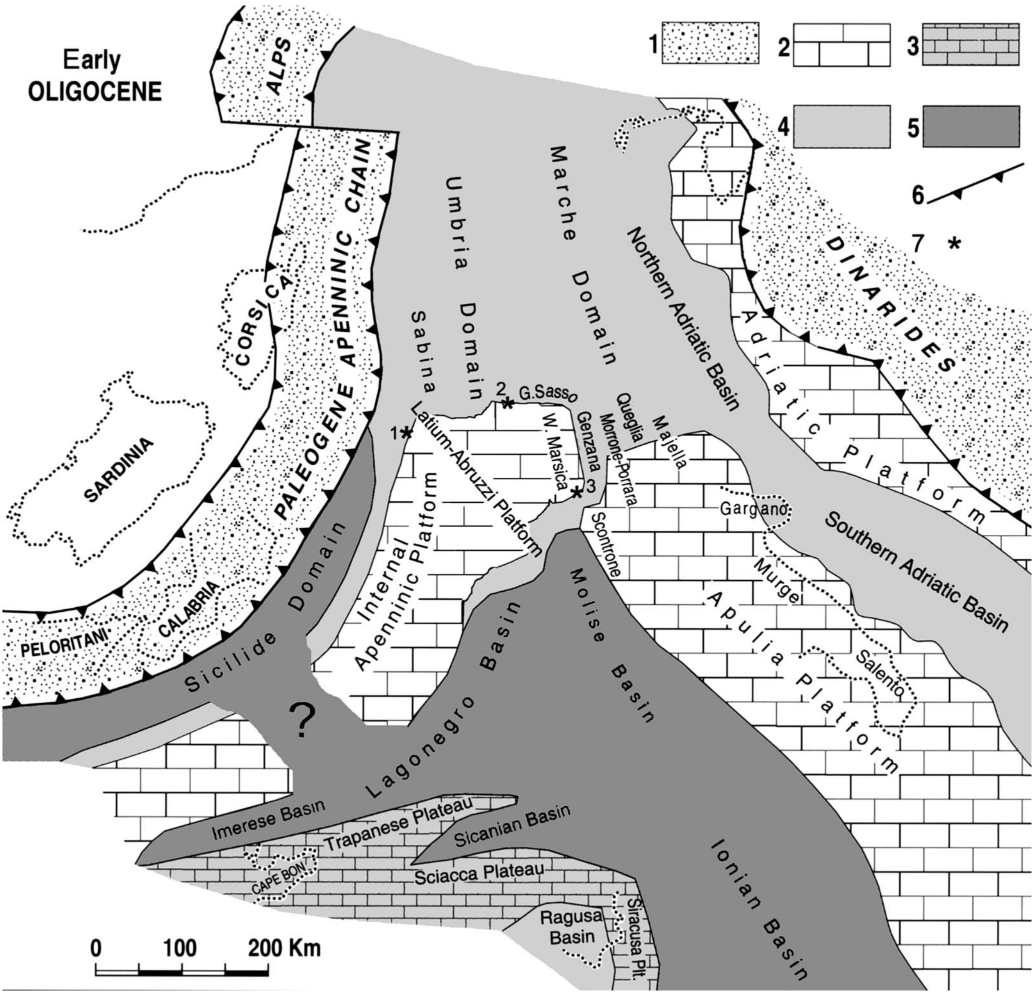


Fig. 2. Palaeogeographic map of the western Mediterranean area during the Early Oligocene. Modified from PATACCA et al. (2008): **1**: Paleogene mountain chains; **2**: Mesozoic-Cenozoic carbonate platform domains; **3**. pelagic plateaux; **4**: basin domains; **5**: deep-water basins floored by oceanic or thinned continental crust; **6**: front of orogenic belts; **7**: investigated areas: 1* Prenestini-Ruffi-Lucretili Mountains (Rocca di Cave, Saracinesco and Mandela sections), 2* Tornimparte (La Serra M. section), 3* Marsica (Opi section)

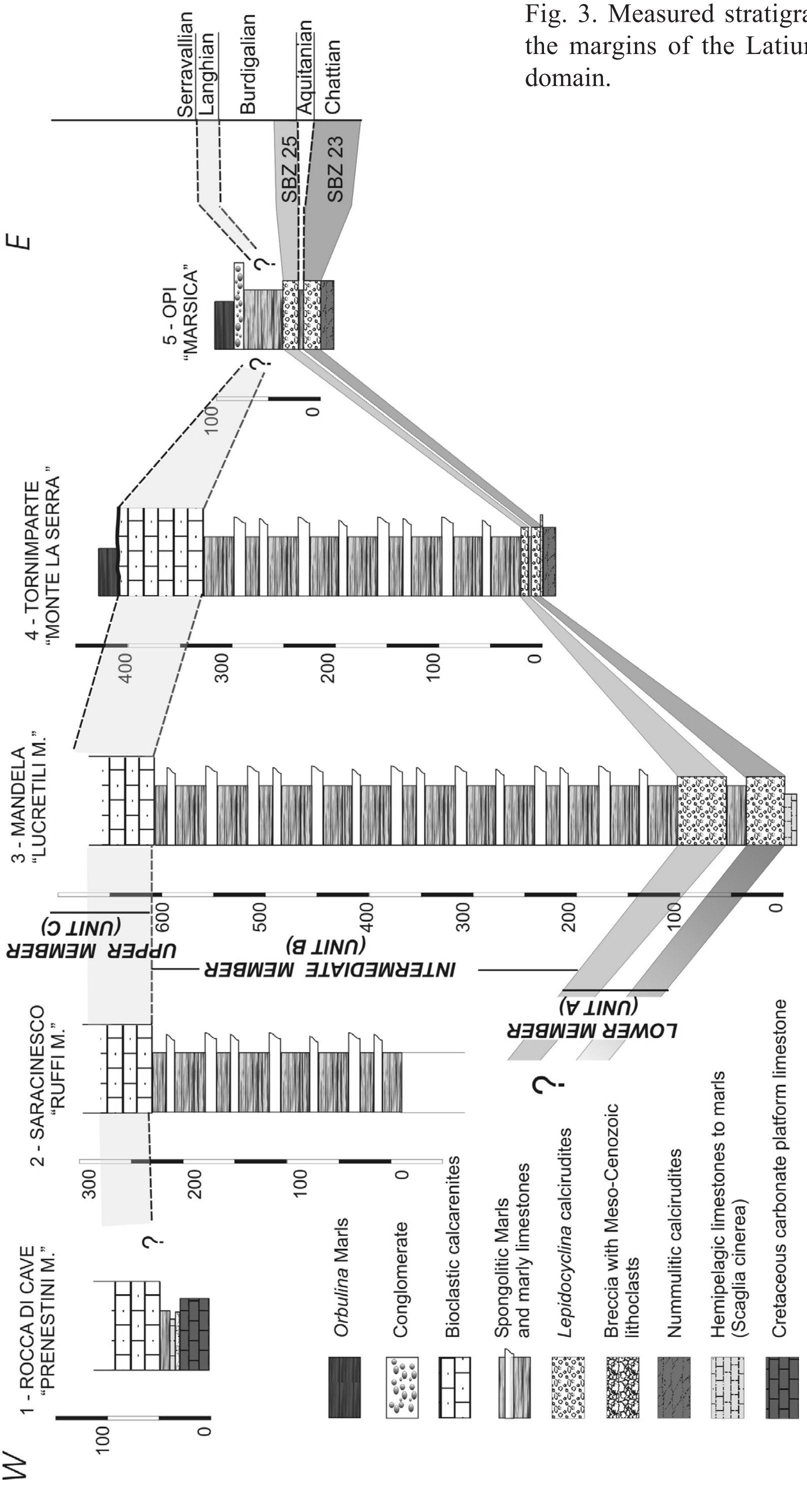


Fig. 3. Measured stratigraphic sections along the margins of the Latium-Abruzzi Platform domain.

Methods

Results from stratigraphic and sedimentologic analyses of five logged sections, two of which (Rocca di Cave and Saracinesco sections) have been discussed in previous studies (BARBIERI 2003–2004; BRANDANO et al. 2005), are discussed in the present study (Fig. 3). The examined sections are subdivided into three groups: Prenestini-Ruffi-Lucretili Mountains; Tornimaparte, and Opi (Marsica), which represent respectively the northwestern, northern and eastern margins of the Latium-Abruzzi Platform (Fig. 2).

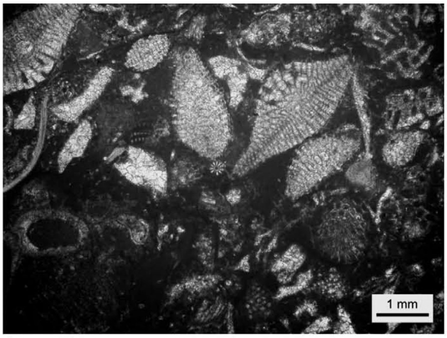
Petrographic examination of 200 thin sections for textural characterization and identification of skeletal components was carried out. The studied thin sections come from the five presented stratigraphic sections (40 samples from Rocca di Cave section, 24 samples from Saracinesco section, 63 samples from Mandela section, 31 samples from M. Serra section and 42 samples from Opi section). The overall facies description is based on lithology, sediment constituents, sedimentary structures, stratification, and geometric relationships. For Oligo-Miocene larger foraminifera biostratigraphy, we employed the Shallow Benthics Zones (these biochronozones are presently referred to as SBZ or SB) proposed by Cahuzac and Poignant (1997). The analysed thin sections are stored at the Department of Earth Science, La Sapienza University of Rome, Italy.

Results

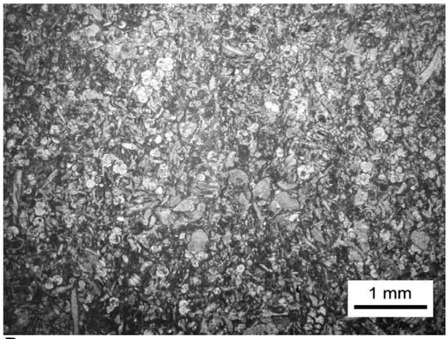
Prenestini – Ruffi – Lucretili Mountains

The siliceous unit varies in thickness in the Prenestini-Ruffi-Lucretili Mountains. Basinward, the Guadagnolo Formation may reach more than 700 m and overlies the hemipelagic sediments of the Scaglia Cinerea Formation (Mandela section, Fig. 3); towards the shelf, its thickness decreases to a few tens of meters and directly rests on Upper Cretaceous shallow-water carbonates with local interposition of condensed Palaeogene pelagites (Rocca di Cave section, Fig. 3). In these mountains, the Guadagnolo Formation is divided into three informal members (Unit A, B, C). The basal member (Unit A) is 100 m thick and is characterized by gravity-flow deposits. It consists of alternating rudstone, packstone to grainstone and marl (planktonic wackestone) with cherty nodules. Beds are up to 2 m thick. The rudstone and packstone to grainstone beds represent turbidites and other gravity-flow deposits containing lithic and bioclastic sand and gravel transported downslope from the shelf. The lithoclasts mainly derive from Mesozoic and Cenozoic sediments. Larger benthic foraminifera and red algae are the main bioclastic components (Fig. 4A).

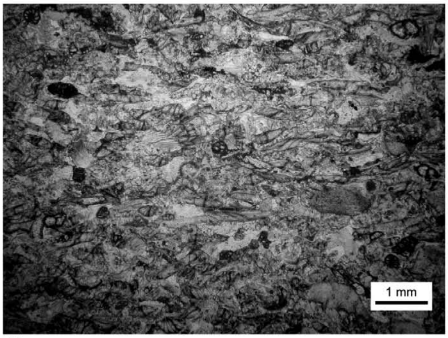
According to the larger foraminiferal assemblages, two intervals are distinguished in the basal member. The lower one is characterized by *Eulepidina dilatata* (MICHELOTTI, 1861), *Nephrolepidina morgani* LEMOINE & DOUVILLÉ 1904 and *Miogypsinoides complanatus* (SCHLUMBERGER, 1900). It is separated from the upper interval by a 10–m thick horizon



A



B



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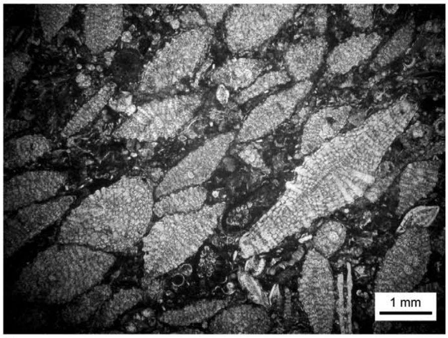
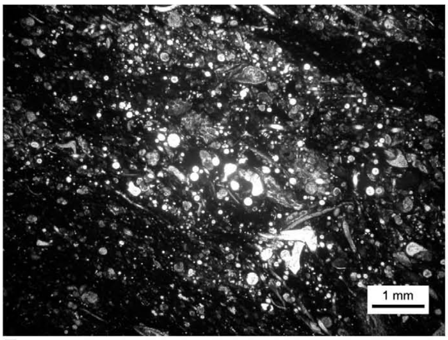
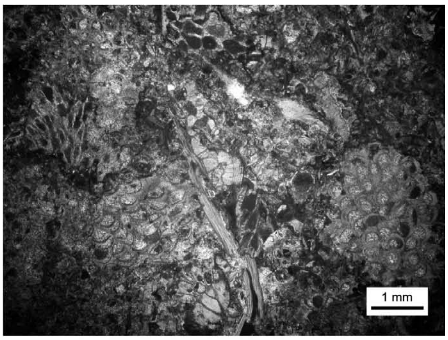


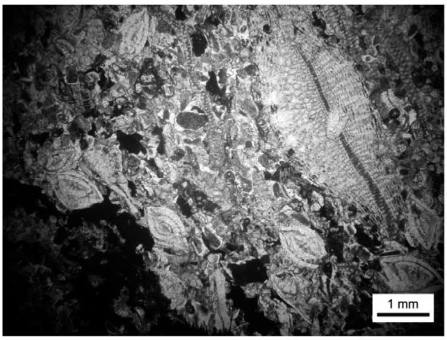
D



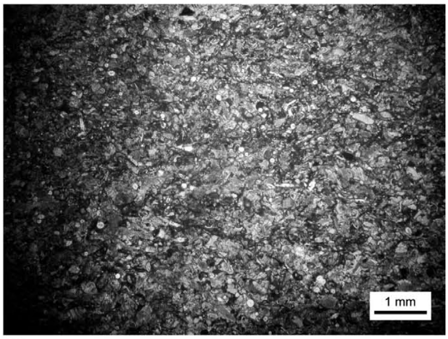
E



F



G



H

of wackestone with planktonic foraminifera and sponge spicules. The upper interval is characterized by *Nephrolepidina tourneri* LEMOINE & DOUVILLÉ 1904 and *Miogypsina globulina* (MICHELOTTI, 1841). The ascribed ages are Chattian (SBZ 23 Shallow Benthic Zones by CAHUZAC & POIGNANT 1997) for the lower interval and Aquitanian/Early Burdigalian (SBZ 25) for the upper one.

The intermediate member ("spongolitic") (Unit B) consists of about a 600–m thick monotonous stack of calcareous marly deposits. Three main lithofacies are identified. The first is represented by marl to calcareous marl, with textures ranging from mudstone to wackestone, frequently bioturbated. The main components are planktonic foraminifera, sponge spicules and subordinate fragments of echinoderms and bivalves. The second lithofacies consists of marly limestone characterized by a wackestone-packstone texture, locally bioturbated. The main components are planktonic and benthic foraminifera, sponge spicules, fragments of echinoderms, bryozoans and bivalves (Fig. 4B). The third lithofacies is represented by cross-bedded bioclastic calcarenites. They consist of packstone-grainstone with medium to coarse-grained fragments of bryozoans, echinoderms, bivalves, balanids, benthic foraminifera, and rare larger foraminifera and red algae debris. In this portion, 15– to 20–cm thick graded beds with a major, coarse-grained, bioclastic components (abundant bryozoans) and undulating, hummocky laminae have been observed. On the basis of Sr-isotope stratigraphy, BARBIERI et al. (2003–2004) dated this member to the Burdigalian-Langhian interval.

The uppermost member (Unit C) of the Guadagnolo Formation consists of about 50 m of coarse-grained bioclastic grainstone-packstone resting on the underlying calcareous marl. The skeletal fraction is represented by bryozoans, echinoderms remains and small benthic foraminifera (rotalids) (Fig. 4C). The basal contact with the underlying spongolitic member is marked by a major unconformity. In the lower part, these bioclastic carbonates include a 10–m thick horizon with abundant cherty nodules. This uppermost portion forms a quite homogenous unit which caps the Guadagnolo Formation throughout the study area.

◀ Fig. 4. **A**: Larger benthic foraminiferal (*Nephrolepidina* and *Miogypsina*) packstone of lower member of Guadagnolo Formation in Lucreteli Mountains (Mandela section, sample 1/20), coral fragments and bryozoan are present; **B**: bioclastic packstone of spongolitic member, the main components are planktonic and benthic foraminifera, sponge spicules, fragments of echinoderms (Saracinesco section, sample SR3D); **C**: bioclastic grainstone of the uppermost member of Guadagnolo Formation in Ruffi Mountains (Saracinesco section, sample SR6A); **D**: *Miogypsina* packstone of lower member (Tornimparte section, sample T7); **E**: sponge spicules rich wackestone to packstone of the spongolitic member in the Tornimaparte section (sample T8); **F**: calcarenitic bed rich in bryozoans (celleporids) in the upper portion of spongolitc member (Tornimparte section, sample BL1); **G**: larger benthic foraminifera (LBF) packstone of the lower member in the eastern margin of Latium-Abruzzi platform domain (Marsica), *Nephrolepidina* and *Amphistegina* dominate the LBF assemblages (Opi section, sample O6); **H**: bioclastic packstone with sponge spicules and echinoderms fragments in the spongolitc interval of lower member (Opi section, sample O19).

Tornimparte

Located on the eastern flank of Monte La Serra, this outcrop features the siliceous unit of the Oligo-Miocene sequence of the northern Latium-Abruzzi carbonate platform domain (Figs 1, 2). Three informal members are identified in the Monte La Serra section.

The lower member (Unit A), lying on Middle to Upper Eocene LBF limestone, is Oligocene to Early Miocene in age (Schiavinotto 1979; Matteucci 1992). In particular, based on LBF assemblages, it is ascribed to the Late Rupelian-Early Burdigalian. The base of the lower member is characterized by a glauconitic planktonic-rich wackestone horizon a few centimetres thick, passing upward to bioclastic grainstone with rotalids, articulate red algae, echinoderms, bryozoans and rare *Microcodium* fragments. An unconformity marks the passage to a 1.4–m thick fining-upward sequence. The base of the sequence is represented by a conglomerate with glauconitized lithoclasts deriving from the underlying Eocene and Rupelian substrate. The conglomerate gradually passes upward into bioclastic calcarenites made up of LBF, corallinacean algae, coral fragments, molluscs and echinoderms. The subsequent 1.3–m thick interval is represented by fine calcarenite (packstone) with scattered LBF. This interval is followed by 8 m of cross-bedded lepidocyclinid grainstone with abundant corallinacean algae, cortoids, echinoderms and rotalids; porcelaneous foraminifera (*Peneroplis*, *Borelis*, *Austrotrillina* and miliolids) are subordinate. The carbonate sedimentation is interrupted by 1 m of planktonic-rich spongolitic marl. The lower member ends with 7 m of calcarenites with miogypsinids (Fig. 4D), alternating with thin marly beds rich in echinoderms; planktonic foraminifera are scarce. This interval is characterized by low-angle cross-stratification; the strata are 50–70 cm thick and appear homogenous and without sedimentary structures. The presence of *Miogypsina globulina* and *Nephrolepidina tourneri* indicates a late Aquitanian to early Burdigalian age (Schiavinotto 1979; Matteucci 1992).

The intermediate member ("spongolitic") (Unit B) consists of spongolitic marl, for a total thickness of 311 m. The basal portion is characterized by alternating marl and marly limestone (wackestone to packstone) and subordinate calcarenitic interbeds (packstone to grainstone). The marly limestone consists of a bioturbated tabular bed (*Thalassinoides*) up to 3 m thick (Figs 5A, B). Lepidocyclinids and miogypsinids still occur in the calcarenitic beds and are associated with bryozoans, echinoderms and molluscs, whereas the skeletal fraction of marly beds is dominated by sponge spicules and planktonic foraminifera (Fig. 4E). The subsequent portion is characterized by alternating calcareous marl and thin calcarenite. The upper portion of this intermediate member exhibits increased thickness of the calcarenitic beds (up to 3 m), although the topmost part consists of 14 m of calcareous marl. Low-angle cross-lamination is a characteristic feature of the calcarenitic beds: their skeletal fraction is dominated by bryozoans (celleporids, adeoniforms and, subordinately, lunulitiforms and cellariiforms). Well-preserved skeletal parts of siliceous sponges (*Laocaetis* and *Aphrocallistes*) are also found (Matteucci 1992) (Fig. 5C). The planktonic association of the intermediate "spongolitic" member suggests a Burdigalian-Langhian age (Matteucci 1992).

The upper member (Unit C) is represented by 100–m thick, cross-bedded calcarenite. The beds are a few centimetres thick (up to 10 cm) and are characterized in the basal 10 m by thin cherty layers (Fig. 5D). The skeletal fraction is mainly represented by bryozoans, echinoderms and, subordinately, by corallinacean fragments (Fig. 4F). On top of this unit is a phosphatic hardground overlain by Serravallian hemipelagic marls (*Orbulina* marl) which mark the drowning of this sector of the Latium-Abruzzi platform (Corda 1990).

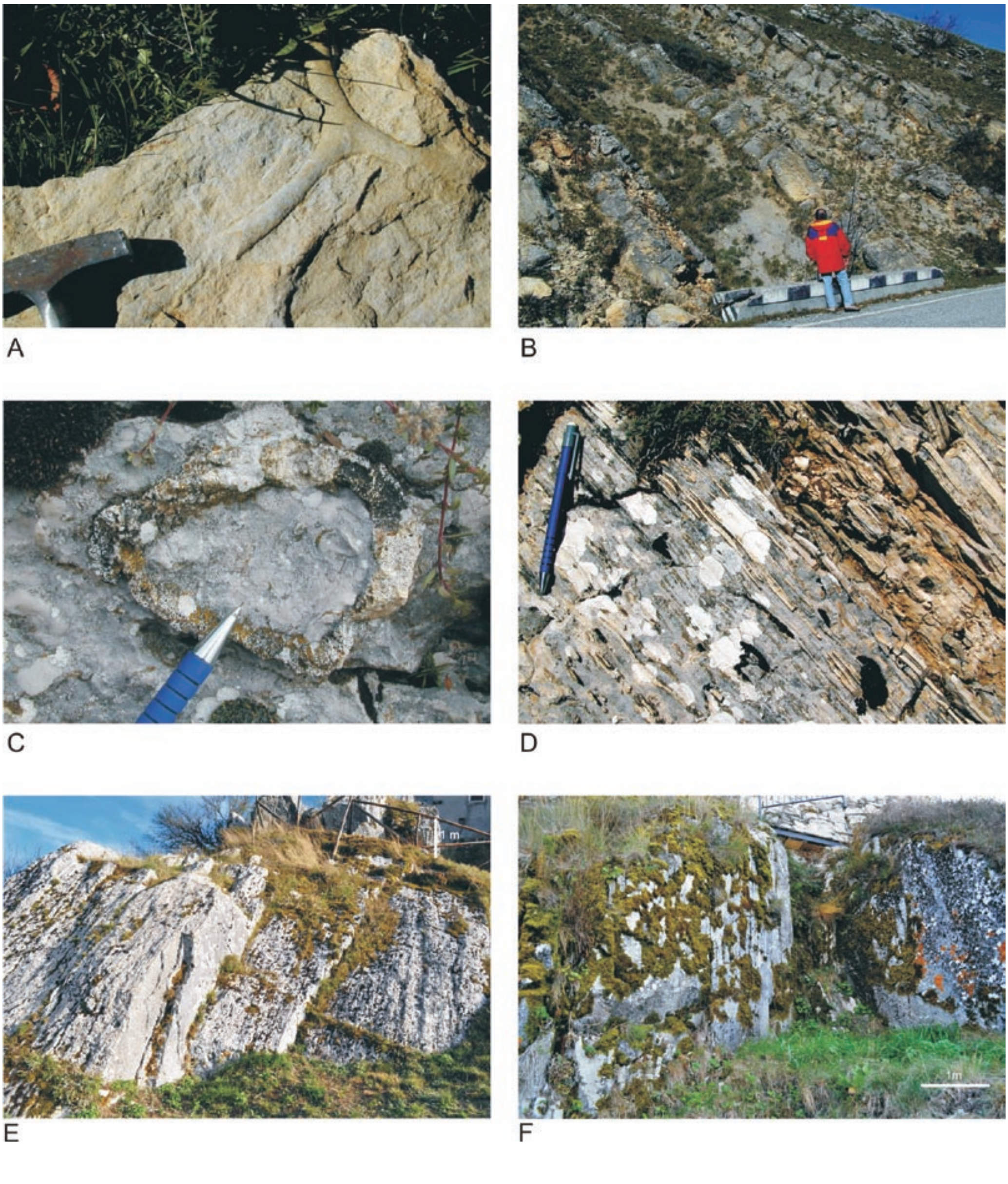
Opi (Marsica)

The Opi section, located in the valley of the Sangro near the Opi village (Fig. 1), is representative of the siliceous Oligo-Miocene unit outcropping along the eastern sector of the Latium-Abruzzi platform domain.

The Oligo-Miocene sediments lie on Eocene nummulitic limestone. The basal contact is represented by a discontinuity surface marked by a sharp compositional and textural change. The Oligo-Miocene sequence is subdivided into two informal members.

The lower member (Unit A) is 37 m thick and consists mainly of cross-bedded alternating larger benthic foraminifera (LBF), packstone and red algal rudstone to floatstone facies (Figs 4G, 5E). It is characterized by a 5–m thick spongolitic calcareous-marly horizon occurring at 14 m from the Eocene boundary (Fig. 3). The spongolitic horizon is represented by laminated fine to medium-grained bioclastic packstone with abundant sponge spicules (Figs 4H, 5 F), echinoderm fragments, planktonic and small benthic foraminifera, and subordinate bryozoans. Microstylolites rich in iron oxides, indicating pressure-solution phenomena, occur as well.

The LBF packstone is charaterized by a calci-siltite matrix; grain-sizes range from 200 µm to 1 cm. The main components are LBF, represented by *Amphistegina*, *Spiroclypeus*, *Heterostegina*, *Operculina*, *Lepidocyclina* (*Nephrolepidina*), *Eulepidina dilatata*, *Miogypsinoides complanatus* and miogypsinids. Red algae occur only as small nodules and detritus, mainly of the Melobesioid subfamily and the genus *Sporolithon*. Other components are bryozoans and mollusc fragments, echinoderm plates, rotaliids such as *Neorotalia viennoti* (Greig 1935), *Cibicides*, lageniids and serpulids (*Ditrupa*). Weaker biolamination may be formed of LBF tests. The preservation of LBF is good; in particular, *Amphistegina* specimens show limited abrasion. The red algal rudstone to floatstone displays a poorly sorted packstone to grainstone matrix. The dominant biota are coralline red algae and LBF; coralline red algae form nodules, branches and small ellipsoidal to sub-spherical rhodoliths. These rhodoliths are characterized by a growth-form ranging from laminar to columnar, and are represented mainly by encrusting thalli of *Sporolithon* and *Lithothamnion*. Encrusting foraminifera (e.g., acervulinids) are often associated with rhodolith thalli. LBF assemblages are similar to the LBF packstone. Other components are encrusting foraminifera and small benthic foraminifera, textulariids, discorbaceans, bryozoans, as well as echinoderm and mollusk fragments. The packstone to grainstone matrix is composed of unidentified skeletal fragments and peloids. The fine fraction of the microfacies is represented by calci-siltite. Some microstylolites rich in iron oxides are also found; the voids between grains are filled with drusy equant calcite mosaic. According to PIERONI (1965) and CARBONI et al. (1982), the LBF associations indicate a Chattian to Aquitanian age for the lower member of the Opi section. The presence of *Eulepidina dilatata*, *Miogypsinoides complanatus*, *Spiroclypeus* and *Nephrolepidina morgani* (SCHIAVINOTTO, pers.comm. 2010) points to a Chattian age (SBZ23 of CAHUZAC & POIGNANT 1997).



The second member (spongolitic) (unit B) is represented by 40–m thick spongolitic marly limestone, passing upward to calcareous marl. This member, characterized by 60 to 70–cm thick tabular beds, does not show marl-calcarenite alternation. Each bed exhibits an upward increase of bioturbation (*Thalassinoides*). Microfacies are represented by fine wackestone to packstone with planktonic foraminifera spread out in a brown micritic matrix. The main components are sponge spicules and planktonic foraminifera, especially globigerinoids and globigerinids; small benthic foraminifera, bryozoans, and echinoderm and serpulid fragments also occur. The base of this member is characterized by well-preserved specimens of *Miogypsina globulina*; its top is marked by a 3–m thick conglomeratic horizon, characterized by Mesozoic carbonate platform lithoclasts ranging in size from 10 to 50 cm, scattered in a glauconitic-rich matrix. According to CARBONI et al. (1982), an early Burdigalian age is indicated for the base of the member, whereas no age constraints are available for the top. The overlying *Orbulina* marls are Tortonian in age (CARBONI et al. 1982).

Discussion

The siliceous unit in the examined sectors of the Latium-Abruzzi platform shows comparable lithological and stratigraphic characters. The lower (Unit A) and the intermediate “spongolitic” members (Unit B) are distinguishable in all the areas whereas the uppermost, mainly calcarenitic member (Unit C) is only present in the northern (Tornimparte) and northwestern (Prenestini-Ruffi Mountains) sectors.

The lower members are characterized by a small spongolitic horizon (up to 5 m thick). Its biostratigraphic markers in the three sectors are *Eulepidina dilatata*, *Miogypsinoides complanatus*, *Spiroclypeus* and *Nephrolepidina morgani.* The range of *M. complanatus* is given by CAHUZAC & POIGNANT (1997) as SBZ 23, the most recent zone of the Oligocene corresponding to the Chattian stage. The spongolitic horizon inside the lower member is dated by MATTEUCCI (1992) as Aquitanian, according to planktonic foraminferal assemblages. The top of this lower member is characterized by *Miogypisna globulina* and *Nephrolepidina tourneri*, pointing to SBZ 25 and corresponding to the early Burdigalian stage (Fig. 3). Definitely the lower member in all the sectors, range in age from Chattian to early Burdigalian.

◄ Fig. 5. **A**: marls and marly limestones of spongolitic member are intensely bioturbated (*Thalassinoides*) (Tornimparte section); **B**: in the north-western and northern margin of Latium-Abruzzi domain the spongolitic member is characterized by alternating marl and marly limestone and subordinate calcarenitic interbeds (Tornimparte section); **C**: in the upper portion of the spongolitc member well-preserved skeletal parts of siliceous sponges (*Laocaetis*) occur in the calcarenitic beds (Tornimparte section); **D**: the upper member of Tornimparte section is characterized in the basal 10 m by thin cherty layers; **E**: The lower member in the eastern margin (Marsica) consists of cross-bedded LBF packstone and red algal rudstone to floatstone facies (Opi sections); **F**: the first spongolitic interval occurs in the lower member, in the Opi section it consists of laminated fine to medium-grained packstone.

The main difference between the eastern and northern sectors with respect to the northwestern margin is the depositional environment during the Chattian-early Burdigalian interval. Facies, skeletal assemblages (cortoids, coralline algae and LBF), strong grain fragmentation, and relative enrichment in echinoderm fragments resistant to mechanical abrasion all indicate that sedimentation took place within the oligophotic zone in the northern and eastern sectors (*sensu* Pomar 2001) of a middle ramp environment, resulting from the combined accumulation of *in situ* production and sediments swept from the shallower inner ramp by waves and currents, as documented by sedimentary structures (planar cross-bedding) (Fig. 5 E).

Conversely, the deposits of the northwestern margin during this interval show clear reworking. Sedimentary structures typical of gravity flows (debris flows, calciturbidites), bioclast fragmentation and frequent interbedding between calciturbidites and planktonic-rich mudstones indicate a productive carbonate factory on the platform and recurrent shedding of reworked sediments into the slope up to the basin (calciturbidites) (Civitelli et al. 1986 a, b). The presence of debris flow-related deposits at the base of the member, passing into calciturbidites in the upper part, point to a progressive decrease of the initial phase of erosion.

The intermediate "spongolitic" member (Unit B) is marked at the base, in all sections, by the presence of *Miogypsina globulina*, indicating a Burdigalian age. The planktonic foraminiferal assemblage in the Tornimparte section and isotopic data from the Prenestini area indicate a Langhian age for the top of this member (Matteucci 1992; Barbieri et al. 2003–2004). According to skeletal components and sedimentary structures, deposition in the aphotic distal zone of an outer ramp is suggested by Brandano & Corda (2002), Barbieri et al. (2003–2004) and Brandano et al. (2010b)

The marl, marly limestone and calcarenitic alternation is interpreted by Brandano et al. (2005) as metre-scale siliciclastic-carbonate cycles, each cycle showing an upward decrease in terrigenous input and a parallel increase in benthic fauna. The cycles are interpreted by the authors as high-frequency subtidal carbonate cycles produced by cyclical oscillations in water depth, hydrodynamic energy and siliciclastic input vs. carbonate production. Sea-level rise together with more humid conditions promoted the reduction/demise of carbonate heterozoan producers. Spectral analysis results indicate high-frequency cycles controlled by orbital, mostly oblique forces in the Milankovitch frequency band, matching the obliquity signals in the Miocene Mediterranean sedimentary record (Hilgen et al. 1995).

Barbieri et al. (2003–2004) reconstructed the stratigraphic architecture of the "spongolitic" member in the Prenestini Mountains. Four third-order composite sequences were identified by these authors, consisting of several fourth-order sequences whose stacking pattern defines transgressive and highstand systems tracts. The entire succession displays a clear-cut wedge-shaped geometry towards the SSE, inside which every third-order sequence shows a pinched-out configuration. The four third-order sequences, as a whole, represent a complete transgressive-regressive cycle developing from the late Aquitanian to the late

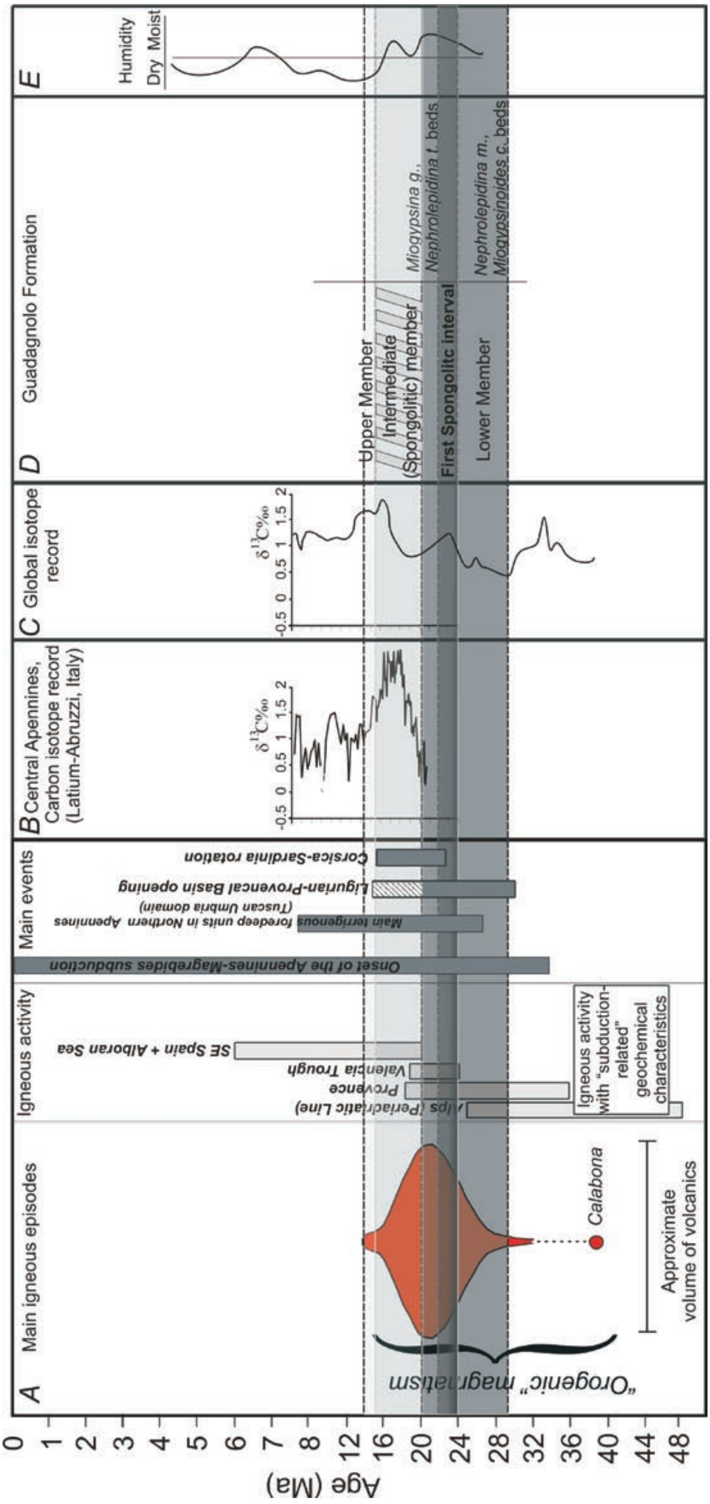


Fig. 6. **A**: Chronodiagram showing qualitative volumes of igneous rocks emplaced during the Late Eocene-Middle Miocene igneous activity in Sardinia and main events characterizing the western Mediterranean and Apennines (modified from LUSTRINO et al. 2009); **B**: Carbon isotope record of the Latium-abruzzi carbonate succession (BRANDANO et al., 2010); **C**: Global deep-sea carbon isotope record (ZACHOS et al. 2001), **D**: stratigraphic diagram of Guadagnolo Formation; **E**: Qualitative humidity and temperature changes in the Spanish continental basins (from CALVO et al. 1993).

Burdigalian, during which the ramp depositional system underwent aggradation and backstepping between 21 and 18.0 My, and aggradation and forestepping between 18.0 and 16.4 My. This overall architecture of the ramp system, with aggradation and forestepping, indicates progressive infilling of the basin and a decrease in accommodation space.

In the eastern sector (Opi), cyclicity is expressed by increased bioturbation traces at the top of each bed, whereas no important change of lithology or of lithofacies and microfacies is evident. Another element typical of the Opi section is the reduced thickness of the "spongolitic" member when compared with that of the other two areas (40 m in Opi vs. 310 m in Tornimparte and 600 m in M. Prenestini-Lucretili-Ruffi). This difference is ascribed to the different sedimentation rate and accommodation space in the two main sectors (north-western and eastern) of the Latium-Abruzzi Platform, located in a paleogeographical domain affected by Neogene tectonics. During the Middle Miocene, the Latium-Abruzzi Platform was progressively involved in the eastward-migrating foredeep of the Apennine thrust belt (Carminati & Doglioni 2004; Carminati et al. 2010). Starting from the Oligocene and particularly during the Early Miocene, increased terrigenous input characterized the Central Apennine successions, probably due to the fine sedimentary fraction infilling the Apennine foredeep system. The Latium-Abruzzi Platform may represent a morphological barrier which induced a sort of trap in the outer ramp zone, corresponding to the M. Prenestini- Lucretili-Ruffi (north-western sector), favoring rapid accumulation of the continuous input of fine terrigenous material from the neighboring Apennine foredeep system (Civitelli et al. 1986 b). Regarding this point, it is interesting to note that, according to Carminati et al. (2007), the Miocene subsidence history of the Latium-Abruzzi Platform records an eastward-migrating period of moderate tectonic uplift, followed by increased subsidence. These authors, who interpreted this behaviour as the result of the early phases of deformation linked to the eastward migration of the Apennine thrust belt-foredeep system, report a period of tectonic uplift in the western sector of the platform (M. Ernici) during the Burdigalian. Even if it had been moderate, this uplift may have favored "trapping" of terrigenous supplies in the platform-to-basin zone.

Lastly, the upper member (Unit C) of the siliceous unit, missing in the eastern sector (Opi), represents the progradation of the more proximal environment of the Latium-Abruzzi carbonate ramp on to the outer ramp deposits after the Langhian. Carbonate production was later terminated by plate flexure-related drowning and coeval input of terrigenous sediments, represented by the "*Orbulina*" marl (Civitelli et al. 1986b).

As mentioned above, the "spongolitic" member was deposited during the Burdigalian-Langhian interval, crucial for Western Mediterranean palaeogeography (Fig. 2). The Ligurian-Provençal and Balearic continental rifting evolved towards continental drifting during the Early Miocene, possibly with the formation of oceanic crust in the Ligurian-Provençal Basin, after the ~60º counter-clockwise rotation of the Sardinia-Corsica block (Gueguen et al. 1998; Gattacceca et al. 2007; Lustrino et al. 2009). According to several different authors (e.g., Gattacceca et al. 2007; Carminati et al. 2010) most of the rotation is constrained between ~22 and 15 Ma, with large-scale igneous activity, associated with the formation of the Ligurian-Provençal Basin and Valencia Trough (Beccaluva et al. 2005; Lustrino et al. 2009) (Fig 6). This interval corresponds to the development of the siliceous facies in the Central Apennines, both along the platform margins (the "spongolitic" member) and in the pelagic realm (the Bisciaro Formation), as well as across the entire Mediterranean as far as the Ionian Islands (Civitelli et al. 1987, and references therein).

Volcanic activity may have triggered siliceous neritic and pelagic production. Volcanic activity in the Western Mediterranean indicates that significant amounts of CO_2 and Si could have entered the atmosphere-ocean system during the Early and Middle Miocene (Brandano et al. 2010a). Although increased CO_2 levels in the atmosphere may cause warming as a consequence of the greenhouse effect, it should be noted that direct links between Miocene warming and CO_2 levels have not yet been established (Flower 1999). Kürschner et al. (2008) suggest that elevated CO_2 levels contributed significantly to the Middle Miocene climatic optimum; a similar rise occurred in the Early Eocene (Pearson & Palmer 2000). Extensive volcanic activity has been interpreted as a significant driving force for the increased Early and Middle Miocene CO_2 levels (Kürschner et al. 2008). A rise in atmospheric CO_2 may have induced weathering, accelerated hydrological cycling, consequent fertilization in coastal environments, leading to increased nutrient inputs (Weissert & Erba 2004). The combination of a rise in atmospheric CO_2 and warm shallow waters would also have created the potential for increased rates of photosynthesis and surface-water productivity (Pomar & Hallock 2008), reducing light penetration and favoring filter-feeding biota (heterozoan skeletal assemblages) (Brandano et al. 2010a).

The geochemical consequence of a CO_2 rise in seawater is represented by the rising P_{CO2}, contributing excess amounts of CO_2 to the atmosphere-ocean system and affecting ocean chemistry. Repeated volcanic CO_2 pulses may induce decreases in pH and carbonate ion concentrations in surface waters. An increase in CO_2 causes a reduction in seawater carbonate saturation, favoring calcite-dominated skeletal assemblages (heterozoans), but overall favoring siliceous production in acidic seawaters. Widespread development of heterozoan associations in carbonate systems took place during the Early Miocene, particularly in the Western and Central Mediterranean (Pomar et al. 2004). During this time, magmatic activity contributed significantly to SiO_2 availability in seawater, increasing both nutrient levels and siliceous organisms (diatoms and sponges).

It is interesting to note that the C-isotope excursion recorded in the Central Apennines (Mutti et al. 1997; Brandano et al. 2010b) reaches its highest values during the Burdigalian (around 18–17 Ma) (Fig. 6). This widespread positive shift is interpreted to be caused by high primary productivity in seawater (Brandano et al. 2010b). It corresponds to the spread of bryozoan-dominated facies in the proximal outer ramp, to the spread of terrigenous spongolitic facies in the distal outer ramp, and to the cherty-rich Bisciaro Formation in the pelagic realm.

There is probably a correlation between all these phenomena which occurred during the Burdigalian: high primary production, siliceous production, increased terrigenous input, and volcanic activity. MUHONG et al. (2008) report a different correlation between volcanic activity and $CaCO_3$ precipitation in the Late Pleistocene-Holocene of Southern China, from analysis of deep-sea cores. According to these authors when terrigenous input decreases, $CaCO_3$ and opal precipitation increase, indicating optimal water conditions for the growth of calcareous and siliceous organisms. Sudden changes in the abundance of Opal and $CaCO_3$ occurred concomitantly with volcanic activity. This activity increased downslope transfer of terrigenous material. During this period the percentage of most calcareous organisms decreased. At that time, $CaCO_3$ reduction was not caused by calcite dissolution but by terrigenous dilution. In contrast, increased opal content during this period indicates that the concomitant volcanic material favored the growth of siliceous microbiota such as radiolarians and diatoms, which also maintained higher opal contents in sediments after the eruption events. In the Apenninic domain it is difficult to discriminate the role of single factor (volcanic CO_2, siliciclastic dilution or nutrient input) influencing the seawater carbonate saturation, however, it is evident that Burdigalian to Langhian interval was characterized by a biocalcification crisis.

Conclusions

The Cenozoic siliceous unit outcropping in the Central Apennines is characterized by three members (Unit A, B, C), in the northwestern and northern sectors of the Latium-Abruzzi domain and two members (Unit A, B) in the eastern zone. The lower member (Unit A) is subdivided into two portions, separated by a small spongolitic horizon (up to 5 m thick). The basal portion is Chattian in age, whereas the upper one is Aquitanian to early Burdigalian. The intermediate "spongolitic" member (Unit B) was deposited in the Burdigalian-Langhian. The upper member (Unit C) represents the progradation of the more proximal environment of the Latium-Abruzzi carbonate ramp on to the outer ramp deposits after the Langhian.

The time interval of the "spongolitic" member (Burdigalian to Langhian) is also marked by the spreading of Lower-Miocene spongolitic facies across the entire Mediterranean. During this interval, continental drift affecting the southern European continental margin promoted the formation of oceanic crust and volcanic activity, both submarine and subaerial, whose paroxysm in the Western Mediterranean was concentrated during the Aquitanian-Burdigalian interval. The concomitant occurrence of siliceous facies development and volcanic activity points to Lower Miocene volcanism in the Western Mediterranean as one of the triggering factors. Volcanic activity would have given rise to siliceous neritic and pelagic production, and significant amounts of CO_2 and Si would have consequently entered the atmosphere-ocean system during the Early-Middle Miocene. A rise in atmospheric CO_2 would have induced weathering, accelerating hydrological cycling, and consequent fertilization in coastal environments, producing increased nutrient inputs. Repeated volcanic CO_2 pulses would have induced decreases in pH and carbonate ion concentrations in surface waters, favoring siliceous production in acidic seawaters.

The foredeep-related siliciclastic input increased the trophic resources and produced carbonate dilution. Both factors enhanced the influence of volcanism and favoured the marly-spongolitic facies spreading in the Central Apennines, as well as throughout Mediterranean area, and to accumulate particularly along the north-western sector of the Latium-Abruzzi carbonate Platform.

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