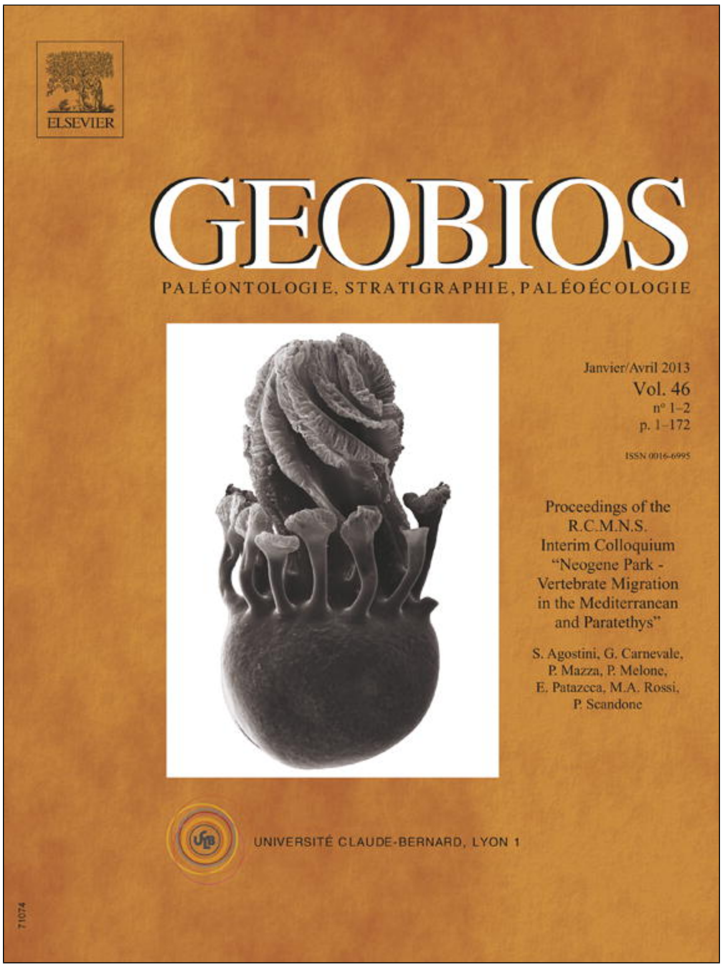
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UNIVERSITÉ CLAUDE-BERNARD, LYON 1
71074

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Original article

The Miocene vertebrate-bearing deposits of Scontrone (Abruzzo, Central Italy): Stratigraphic and paleoenvironmental analysis☆

Etta Patacca [a], Paolo Scandone [a], Giorgio Carnevale [b,*]

[a] Dipartimento di Scienze della Terra, Università di Pisa, Via Santa Maria 53, 56123 Pisa, Italy
[b] Dipartimento di Scienze della Terra, Università degli Studi di Torino, Via Valperga Caluso 35, 10125 Torino, Italy

A R T I C L E I N F O

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A B S T R A C T

The Miocene carbonate deposits of Scontrone (Abruzzo, Central Italy) are well known among palaeontologists because of their fossil vertebrate content that exhibits striking similarities to those of the remarkable "Terre Rosse" faunal complex of the Gargano region, defining the existence of the Miocene Central Mediterranean Apulia paleobioprovince. The main goal of this paper is to establish the age and environment of the Scontrone vertebrate bonebeds. The vertebrate remains are embedded in the basal portion of the *Lithothamnion* Limestone, a widespread carbonate-ramp lithosome representative of the Tortonian-early Messinian transgression over the entire Apulia Platform. The bonebeds belong to marginal-marine deposits (here called "Scontrone calcarenites") preserved in a small area below transgressive ravinement surfaces. The rapid vertical and lateral facies variations displayed by the "Scontrone calcarenites", together with paleoenvironmental considerations deriving from the vertebrate association, document a complex wave-dominated river-mouth depositional setting developed over a large, flat and semi-arid carbonate ramp. The "Scontrone calcarenites" have been split herein into five facies associations representing the stratigraphic response to a discontinuous or punctuated transgression within an overall rise of the relative sea level. Because of the absence of age-diagnostic fossils, the age of the "Scontrone calcarenites" cannot be directly defined through their paleontological content. However, a regional stratigraphic correlation between the *Lithothamnion* Limestone of Scontrone and the *Lithothamnion* Limestone of northern Majella, which is biostratigraphically well constrained, allows the attribution of the "Scontrone calcarenites" to the Tortonian.

1. Introduction

The Miocene deposits of Scontrone are renowned for the large amount of vertebrate remains collected in a site located on the eastern side of the Monte Civita, about 1180 m above sea level (Patacca et al., 2008a). These fossils attracted the attention of vertebrate palaeontologists since their discovery in 1990, when the first remains of reptiles and mammals were brought to light (Rustioni et al., 1992). Since that time, several excavations carried out on a yearly basis resulted in the accumulation of a vast collection of vertebrate remains currently housed in the Centro di Documentazione Paleontologica of the town of Scontrone. Phosphatic vertebrate remains, enclosed in a fine calcarenite matrix, come from three fossiliferous layers that can be interpreted as "multitaxic bonebeds" (Behrensmeyer, 2007). These fossiliferous layers belong to a marginal-marine carbonate sequence and are sandwiched between a basal sheet of transgressive bioclastic sandbars and overlying muddy flat deposits. The bones are always disarticulated, unsorted and scattered; most of them are broken but well preserved, lacking any evidence of prolonged transport, abrasion or polishing. Based on the taphonomic parameters elaborated by Behrensmeyer (1975) and Korth (1979), Mazza and Rustioni (2008) suggested that the vertebrate-bearing layers might be interpreted as lag deposits formed by the gradual removal of bony elements by tides and/or storms in a coastal lagoon setting. Despite the taxonomic identification of all vertebrate remains has not been completed, the known diversity (Mazza and Rustioni, 1996, 2008; Delfino and Rossi, 2013) includes crocodiles (cf. *Crocodylus* sp.), pond turtles (*Mauremys* sp.), a possible land turtle (Testudines indet.), indeterminate birds, the giant hedgehog *Deinogalerix freudenthali*, an indeterminate otter, and what appears to be a species flock of the enigmatic artiodactyl genus *Hoplitomeryx*. Cranial and postcranial bones belonging to *Hoplitomeryx* are by far the most abundant remains in the assemblage. This rich and heterogeneous vertebrate fossil assemblage indicates the existence of a fresh-water environment not far from the marginal-marine setting.

Overall, the fossil assemblage of Scontrone exhibits striking similarities with the remarkable "Terre Rosse" faunal complex of

☆ Corresponding editor: Gilles Escarguel.
* Corresponding author.
E-mail address: giorgio.carnevale@unito.it (G. Carnevale).

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the Gargano region (Masini et al., 2010). It is currently accepted that the Scontrone vertebrate assemblage, together with those of the Gargano region and Capo di Fiume (Palena, Abruzzo; Mazza et al., 1995), defines the existence of a Miocene central Mediterranean Apulia paleobioprovince (Abruzzo-Apulia paleobioprovince in Rook et al., 2006).

The Gargano "Terre Rosse" faunal complex displays a diverse assemblage of amphibians, reptiles, birds and mammals, many of which exhibit extraordinary morphological adaptations clearly representing the effect of insularity (Freudenthal, 1971, 1972, 1985; Ballmann, 1973, 1976; Butler, 1980; Leinders, 1984; Daams and Freudenthal, 1985; Mazza, 1987; Parra et al., 1999; Van der Geer, 2005; Masini et al., 2010). Based on poorly documented ancestor-descendant relationships and biogeographical arguments, as well as on indirect stratigraphic data, the age of the Gargano vertebrates was estimated to be Messinian or early Pliocene (Freudenthal, 1976, 1985; De Giuli and Torre, 1984; Valleri, 1984; Abbazzi et al., 1996; Pavia et al., 2010). However, the uncertain stratigraphic position of the Gargano vertebrates, which are enclosed in a paleokarst system, makes extremely difficult to unambiguously estimate the precise age of the faunal complex and, as a consequence, to evaluate the age of immigration of the continental vertebrates from the Balkan region. Actually, the origin of this very peculiar faunal assemblage has been the subject of a cogent debate mostly focused on the timing and mode of colonization of the Apulia paleobioprovince (De Giuli et al., 1986, 1987; Patacca et al., 2008b; Mazza and Rustioni, 2008; Van den Hoek Ostende et al., 2009; Freudenthal and Martín-Suárez, 2010). Conversely, age and environmental setting of the Scontrone vertebrate assemblage can be confidently defined because of its precise stratigraphic position. For this reason, the aim of this paper is to provide a detailed stratigraphic and paleoenvironmental analysis of the Miocene vertebrate-bearing deposits of Scontrone, which can be used as a basis for further studies about the ecological and biogeographical features of the Apulia paleobioprovince.

2. Regional geological framework and palinspastic restoration of the Abruzzo and Apulia domains in Miocene times

The Scontrone area is located in one of the most intriguing geological regions of the Central-Southern Apennines (Fig. 1), characterized by excellent exposures and deeply investigated subsurface structures that concur to make possible to decipher the quite complex tectonic architecture of the area (Patacca et al., 1992; Patacca and Scandone, 2007). A NNE-SSW trending major geological lineament that goes through a few kilometres east of Scontrone, physically corresponding to the emergence of the lateral ramp of a stack of rootless nappes (Molise and Sannio Nappes), divides the Central-Southern Apennines into two areas characterized by different structural architectures. In the north-western area the bulk of the mountain chain consists of an imbricated fan of thrust sheets transported towards the Adriatic Sea. These thrust sheets, grouped into major tectonic units (Majella, Queglia, Morrone-Porrara, Gran Sasso-Genzana, Western Marsica-Meta and Simbruini-Matese Units), consist of thick piles (up to 5–6 km) of Meso-Cenozoic shallow-water and basinal carbonates capped by siliciclastic flysch deposits. The age of the flysch deposits, Tortonian in the most internal (western) units, Messinian in the intermediate units and Pliocene in the most external ones, marks the flexure-hinge retreat of the lower plate and the progressive forward migration of the thrust belt-foredeep-foreland system in the region. The sedimentary sequence of Scontrone, pertaining to the Gran Sasso-Genzana Unit, underwent compressional deformation and was incorporated in the Apennine mountain chain during the Messinian. In the south-eastern area, the Majella, Queglia, Morrone-Porrara and Gran Sasso-Genzana

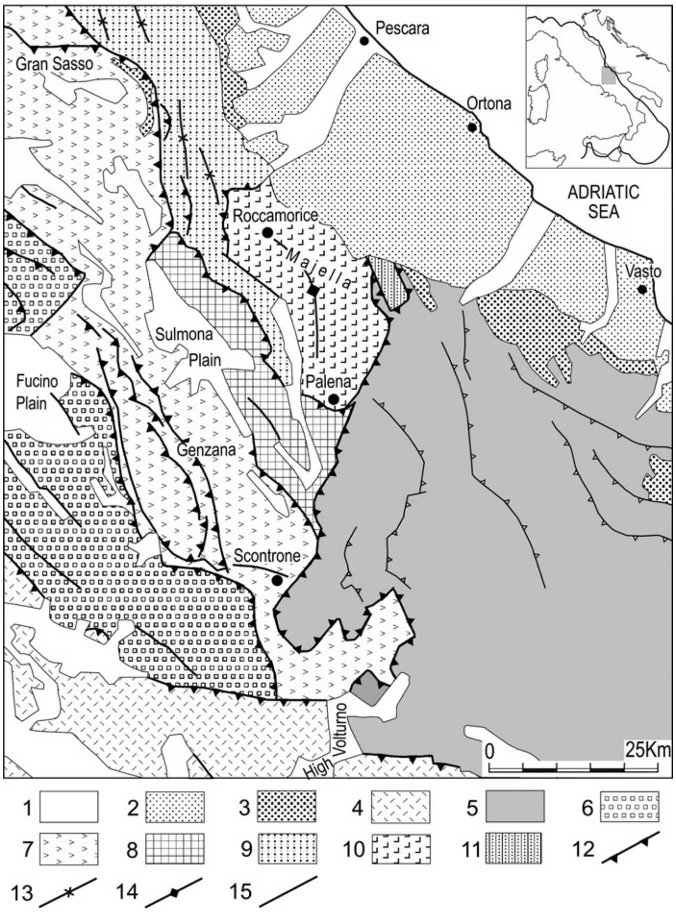

Fig. 1. Simplified geological-structural map of the Abruzzo-Molise region (modified from Patacca et al., 2008a). **1**. Holocene continental deposits; **2**. Pleistocene marine and continental deposits; **3**. Pliocene marine deposits; **4**. Simbruini-Matese Unit: Meso-Cenozoic shallow- to deeper-water carbonates overlain by Tortonian siliciclastic flysch deposits; **5**. Sannio and Molise Nappes: Meso-Cenozoic basinal carbonates overlain by Langhian-Serravallian (Sannio) or by uppermost Tortonian-lower Messinian (Molise) siliciclastic flysch deposits; **6**. Western Marsica-Meta Unit: Meso-Cenozoic shallow- to deeper-water carbonates overlain by a lower Messinian siliciclastic flysch deposited before the salinity crisis; **7**. Gran Sasso-Genzana and Montagna dei Fiori Units: Meso-Cenozoic shallow- to deeper-water carbonates overlain by a Messinian siliciclastic flysch deposited before, during and after the salinity crisis; **8**. Morrone-Porrara Unit: Meso-Cenozoic shallow- to deeper-water carbonates overlain by a Messinian siliciclastic flysch deposited during and after the salinity crisis; **9**. Queglia Unit: Upper Cretaceous-Miocene basin and ramp carbonates followed by Messinian evaporites and by uppermost Messinian-lower Pliocene siliciclastic flysch deposits; **10**. Majella Unit: Meso-Cenozoic shallow- to deeper-water carbonates followed by Messinian evaporites plus brackish-water marls (Lago-Mare facies) and by lower Pliocene siliciclastic flysch deposits; **11**. Pliocene marly clays overlying the Meso-Cenozoic carbonates plus Messinian evaporites of the Casoli-Bomba structural high; **12**. Thrusts; **13**. Syncline axis; **14**. Anticline axis; **15**. Normal faults and strike-slip faults.

Units are not exposed since they have been incorporated in a huge duplex system (Apulia-Carbonate Duplex System) buried beneath the Molise and Sannio Nappes (Fig. 1). These allochthonous sheets, forming the roof of the Apulia-Carbonate Duplex System, are all composed of Meso-Cenozoic basinal deposits.

Before tectonic shortening, the carbonate sequences of Scontrone, central-southern Majella and central-southern Morrone, together with the thrust sheets making up the buried duplex system, were located in a vast paleogeographic domain known as the Apulia Platform. From the Early Jurassic (early Sinemurian) to the Paleogene the Apulia Platform and the surrounding paleogeographic domains were parts of a complex system of platforms and basins whose bulk originated as a consequence of the extensional processes that caused the separation of Africa from Europe. During the Miocene, large portions of the platform-and-basin system were incorporated in the Apennines, until the internal margin of the Apulia Platform was reached by the compression front in Messinian times. Between the late Messinian and the Pleistocene two thirds of the Apulia Platform realm were telescopically shortened and incorporated in the mountain chain. The complex kinematic history of Apulia clearly indicates that paleogeographic reconstructions only based on stratigraphic analysis, even though organized in a sequence stratigraphy framework, are incomplete and inadequate in the absence of palinspastic restoration and structural retrodeformation. Fig. 2 illustrates a step of the complex kinematic evolution of the region having particular relevance for the reconstructions of the paleoenvironments colonized by the Scontrone and Gargano vertebrates. This picture is a palinspastic restoration referred to the Tortonian, a moment in which the transgressive event of the *Lithothamnion* Limestone influenced large portions of the Apulia Platform. At that time the platform was about 90 km SE of its present-day location and the compression front was about 150 km west of Scontrone, i.e., about 300 km west of the present-day Apennine margin. During the Tortonian the Scontrone domain was still part of a stable foreland with carbonate deposition persisting up to the early Messinian. At that time, just before the salinity-crisis event, the area underwent flexural subsidence and was incorporated in the Apennine foredeep. Carbonate sedimentation, however, continued east of the foredeep basin on the wide homoclinal ramp that included the undeformed Morrone-Porrara, Queglia and Majella depositional domains, as well as the Gargano, Murge and Salento realms (Fig. 2). After the Tortonian, the compression front moved about 150 km eastwards and large portions of the shallow marine ramp-and-basin system surrounding Apulia illustrated in Fig. 2 were incorporated in the Apennines together with two thirds of the Apulia Platform itself. Presently, a foreland segment about 430 km-long and 70–80 km-wide is what remains of the original Apulia Platform. In addition, about two parts out of three of this belt are not exposed because covered by seawater or buried beneath Plio-Pleistocene deposits, but fortunately their geological features are well known because of the extensive petroleum exploration in the region. Before tectonic shortening and mountain building, the Apulia Platform measured around 240 km in width, but two thirds of them have been telescopically shortened and stacked into the buried Apulia-Carbonate Duplex System.

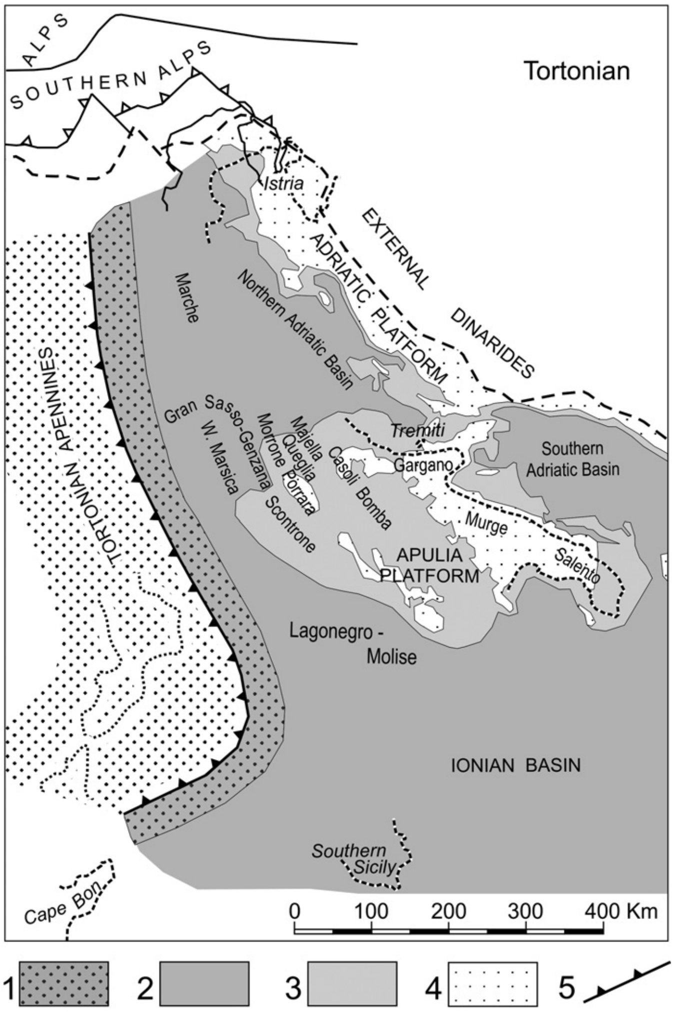

Fig. 2. Palinspastic restoration and paleogeographic reconstruction of the Apulia Platform and adjacent platform-and-basin system referred to the Tortonian, when the *Lithothamnion* Limestone transgressed over large portions of the Apulia Platform. Solid lines and triangles in the upper left side of the picture provide the present-day position of some geographic (coastline) and structural features (thrust front of the Southern Alps, major faults). Small-spacing dashed lines (coastlines of Istria, Apulia, South-Sicily and Cape Bon) and large-spacing dashed lines (northern margin of the Po Plain, front of the External Dinarides) are mobile reference elements indicative of the relative position of Africa with respect to Europe during Tortonian times. The dotted area indicates the Tortonian Apennine mountain chain with the Calabrian Arc (dotted line) as reference element. The relative position of stable Africa relative to stable Europe follows Rosembaum et al. (2002). The criteria used for palinspastic restoration in thrust-belt areas are described in Patacca and Scandone (2007). The areal distribution of the *Lithothamnion* Limestone is based on surface geology data and on the analysis of about 400 exploration wells, as well as on the interpretation of several reflection seismic profiles in the Adriatic and Ionian offshore areas. **1**. Foredeep basin bordering the Tortonian Apennines; **2**. Basinal areas and pelagic plateaux; **3**. Shallow-marine homoclinal carbonate ramps; **4**. Carbonate platform areas undergoing subaerial exposure; **5**. Front of the Apennine mountain chain.

3. Geologic lineaments of the Scontrone area

A thick sequence of Meso-Cenozoic carbonates overlain by siliciclastic flysch deposits of Messinian age crops out with good exposures in the Scontrone area (Fig. 3). This stratigraphic succession belongs to the Gran Sasso-Genzana tectonic Unit, a cover nappe that extends from Northern Abruzzo to Alto Molise, forming a large part of the backbone of the Central Apennines (Fig. 1). Before being incorporated in the mountain chain, the Scontrone depositional realm was located in correspondence to the north-western margin of the Apulia Platform, facing the southward termination of the Gran Sasso-Genzana Basin (Fig. 2). The schematic platform-to-basin cross section of Fig. 4 derives from a stratigraphic and facies-architecture analysis of the Mesozoic carbonate sequences of the Gran Sasso-Genzana Unit north and south of Scontrone, moving along the strike of the tectonic structures. The depositional features of the pre-Miocene deposits cropping out in the Scontrone area evidence a platform-margin/proximal-basin setting. Just in the north of Scontrone more distal basinal carbonates crop out (Monte Genzana area; Figs. 1 and 4). South of Scontrone, towards the High Volturno Valley, the platform-edge limestones are laterally substituted by interior-platform carbonates. Both platform-margin and interior-platform Cretaceous carbonates are stratigraphically overlain, locally with an evident angular unconformity, by the upper Miocene carbonate deposits of the *Lithothamnion* Limestone. The latter is a lithosome representative of the upper portion of a widespread shallow-marine lithostratigraphic unit (Bolognano Group) that transgressed all around the margin of the Apulia Platform between the late most Oligocene and the late Miocene (Patacca et al., 2008b).

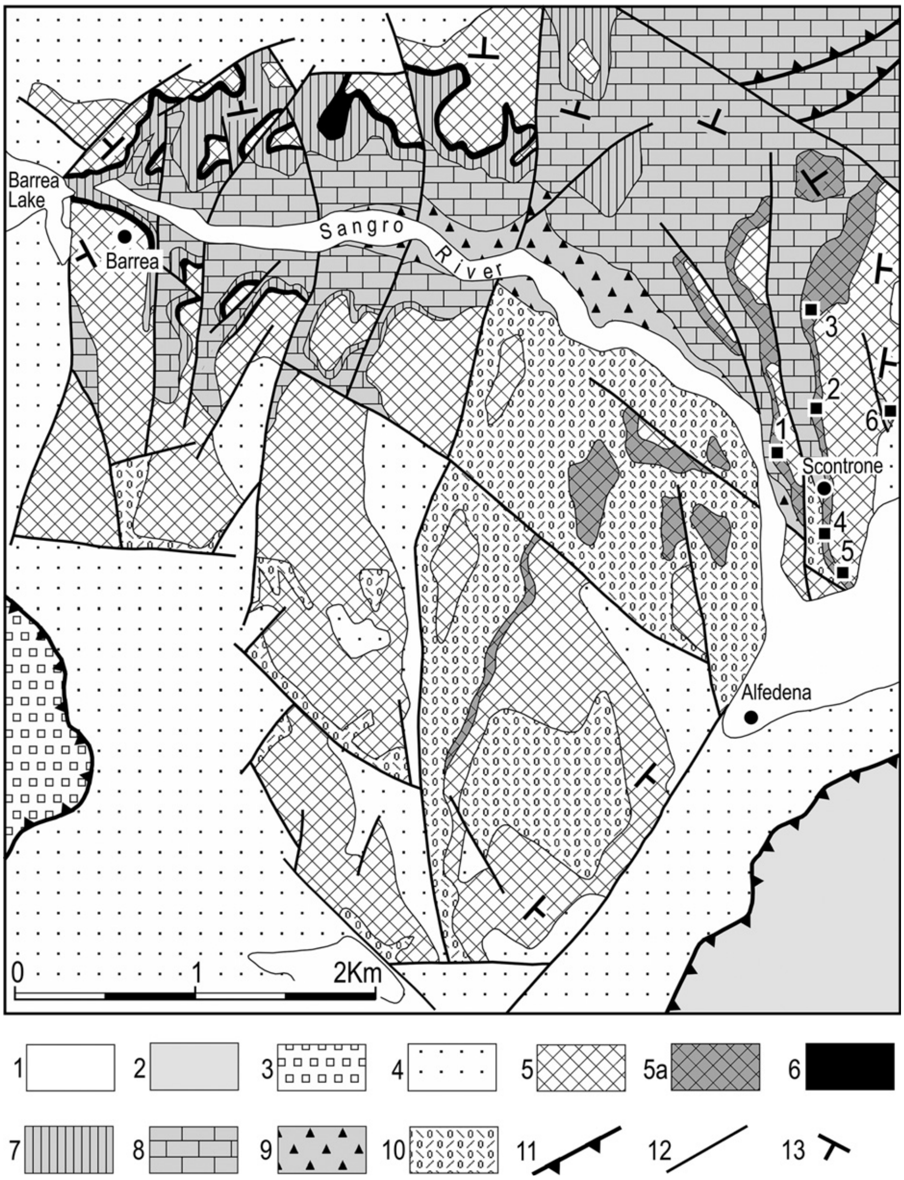

Fig. 3. Geological map of the Scontrone area (after Patacca et al., 2008a, with slight modifications). Bold Arabic numerals indicate the location of the stratigraphic columnar sections of Fig. 5: 1. "Sangro Gorge"; 2. "Scontrone North"; 3. "Scontrone Fossil Site"; 4. "Scontrone South-West"; 5. "Scontrone South"; 6. "Scontrone Cemetery". **1**. Quaternary continental deposits; **2**. Molise Nappes; **3**. Western Marsica-Meta Unit; **4–10**. Gran Sasso-Genzana Unit; 4. Siliciclastic flysch deposits with olistostromes derived from the Molise Nappes (Castelnuovo al Volturno Wildflysch, Messinian *p.p.*); 5. Rhodalgal ramp carbonates and overlying condensed marly limestones and marls (*Lithothamnion* Limestone and *T. multiloba* Marl, Tortonian *p.p.*-lower Messinian); 5a: Marginal-marine carbonates ("Scontrone calcarenites", Tortonian *p.p.*); 6. Breccias with blocks of reefal limestones (Coral-algal Limestone, upper Paleocene); 7. Hemipelagic limestones and lime resediments with fragments of rudists (Scaglia Formation, Coniacian-Campanian); minor outcrops of outer-ramp bioclastic calcarenites (Saccharoidal Limestone, Maastrichtian); 8. Base-of-slope-apron bioclastic calcarenites (Rudist-bearing Calcarenite, upper Albian-Turonian); 9. Marginal slope-breccias (Coral-bearing Calcirudite, Berriasian-Barremian); 10. Platform-edge coralgal limestones and subordinate oo-bioclastic grainstones (upper portion of the Terratta Formation, Berriasian-Barremian); **11**. Base thrust of the Molise Nappes and of the Western Marsica-Meta Unit; major thrusts in the Scontrone carbonates; **12**. Normal faults and strike-slip faults; **13**. Attitude of strata.

The Mesozoic terms of the stratigraphic succession of Scontrone are very well exposed in the Sangro Gorge (Fig. 3), where Berriasian to Barremian reefal limestones (uppermost portion of the Terratta Formation) and coeval megabreccias with blocks of coralgal boundstones (Coral-bearing Calcirudite) are overlain by a thick fining-upward package of upper Albian-Turonian redeposited bioclastic calcarenites and calcirudites (Rudist-bearing Calcarenite) followed by well-bedded Coniacian-Campanian calciturbidites and hemipelagites (Scaglia Fm.). The Neocomian-Campanian stratigraphic succession, featuring as a whole a retreating margin, grades upward into outer-ramp calcisphaerulid-rich calcarenites of Maastrichtian age (Saccharoidal Limestone). Upper Paleocene fore-reef calcirudites with redeposited coral-algal limestones discontinuously overlie the Saccharoidal Limestone. Upper Miocene carbonate-ramp deposits (*Lithothamnion* Limestone) cover the discontinuous veneer of upper Paleocene coral-bearing resediments, as well as the Cretaceous platform and platform-margin carbonates. The prominent unconformity at the base of the *Lithothamnion* Limestone in the whole Scontrone area corresponds to a time gap spanning from 40 myr in the most complete sections (a time interval encompassing the Eocene, Oligocene and early to middle Miocene) to about 120 myr.

The uppermost portion of the *Lithothamnion* Limestone consists of a thin package of lower Messinian hemipelagic carbonate deposits ending with a thin veneer of intensively bioturbated marly limestones rich in planktonic foraminifers and glauconite.

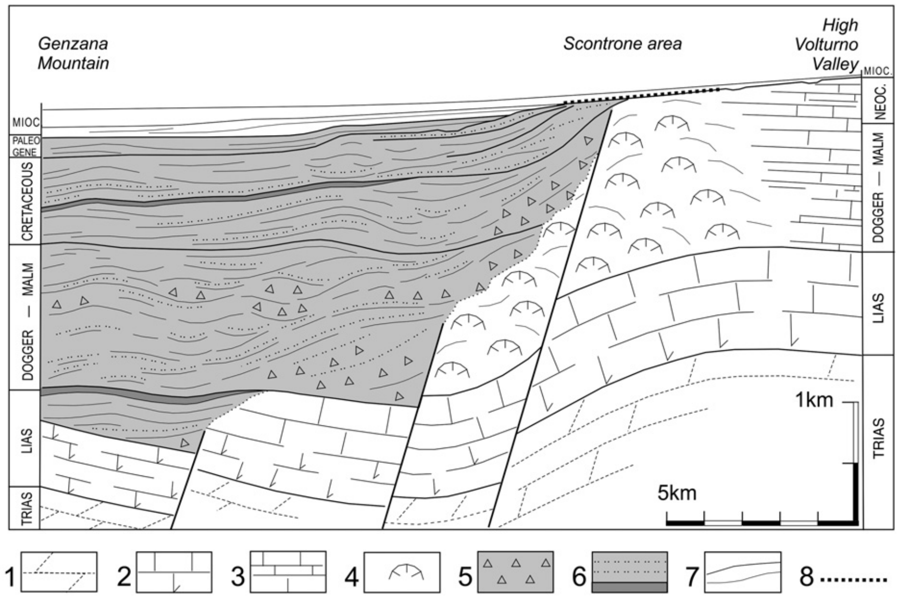

Fig. 4. Depositional architecture of the Meso-Cenozoic carbonates of the Gran Sasso-Genzana Unit between the Genzana Mountain and the High Volturno Valley (modified from Patacca et al., 2008a). The location of Mt. Genzana and High Volturno Valley are provided in Fig. 1. **1**. Peritidal carbonates (epeiric shelf); **2**. Open shallow-marine limestones and dolomitic limestones (low-relief platform); **3**. Restricted shallow-subtidal limestones (platform interior); **4**. Coralgal boundstones (platform margin); **5**. Talus breccias and thick-bedded debrites; **6**. Redeposited calcarenites and hemipelagic limestones; the dark-grey colour indicates anoxic to disoxic marly deposits; **7**. Ramp carbonates; **8**. "Scontrone calcarenites".

These hemipelagic deposits are followed by foraminiferal marls containing *Turborotalita multiloba* (*T. multiloba* Marl). In turn, the latter grades upwards into a thick pile of siliciclastic flysch deposits which include Molise-derived huge olistostromes (Castelnuovo al Volturno Wildflysch in Patacca et al., 1990). Redeposited gypsum is sporadically present in the middle portion of the flysch sequence. The conformable transitional contact between the *T. multiloba* Marl and the Castelnuovo al Volturno Wildflysch is well exposed near the Scontrone Cemetery. The occurrence of *T. multiloba* also in the clayey lower portion of the Castelnuovo al Volturno Wildflysch ties the moment in which the Scontrone stable foreland domain turned into a tectonically-controlled foredeep basin after the first common occurrence of *T. multiloba* (6.30 Ma; Kouwenhoven et al., 2006) and before the onset of the salinity crisis (5.96 Ma; Krijgsman et al., 1999a, 1999b).

4. Stratigraphic analysis and paleoenvironmental reconstruction of the vertebrate-bearing "Scontrone calcarenites"

The Scontrone vertebrate remains are contained in carbonate deposits ("Scontrone calcarenites") locally present at the base of the *Lithothamnion* Limestone. A preliminary lithologic description and microfacies documentation of the vertebrate-bearing deposits is contained in Patacca et al. (2008a).

The "Scontrone calcarenites" unconformably overlie different terms of the Cretaceous-Paleocene carbonate sequence cropping out in the outskirts of Scontrone (Figs. 3–5). The most complete section is exposed in the Sangro Gorge (Fig. 6(A) and columnar section 1 in Fig. 5). In this locality the Miocene "Scontrone calcarenites" disconformably overlie the upper Paleocene Coral-algal Limestone. In the "Scontrone North" and "Scontrone Fossil Site" sections (columnar sections 2 and 3 in Fig. 5, respectively) the "Scontrone calcarenites" lie on top of the upper Albian-Turonian Rudist-bearing Calcarenite. In the "Scontrone South-West" and "Scontrone South" sections (columnar sections 4 and 5 in Fig. 5, respectively), the "Scontrone calcarenites" lie above the Berriasian-Barremian platform-edge carbonates of the Terratta Formation (Fig. 6(B)).

Overall, the "Scontrone calcarenites" are marginal-marine carbonates representing a relic of the early stages of the Tortonian transgression. They escaped ravinement surfaces commonly present at the base of the *Lithothamnion* Limestone. In the outskirts of the town of Scontrone, these deposits display rapid lateral and vertical facies variations over relative small distances (Fig. 5). Because of the complexity of the facies variations, stratigraphic correlations from one site to another resulted quite problematic. In the "Sangro Gorge" section (columnar section 1 in Fig. 5), the "Scontrone calcarenites" have been split into five intervals characterized by distinctive lithobiofacies associations (intervals a–e in Fig. 5). These intervals feature as a whole a transgressive succession punctuated by repeated short-term regressions partly cannibalized by ravinement. The conceptual aspects of this type of transgression (punctuated transgression) in low-gradient settings are developed in Cattaneo and Steel (2003). In the "Sangro Gorge" section the stratigraphic succession can be divided into two portions characterized by different stratal architectures. The lower portion is represented by a transgressive basal sheet of coastal sandbars (interval a) evolving upwards into marsh/tidal flat deposits (interval b) and finally into coastal lagoon and tidal-channel-fill deposits (interval c). This portion of the succession, reaching a maximum thickness of about 13 m, is characterized by a stack of thinning-upwards beds and bedsets. The Scontrone vertebrates have been recovered at the top of the interval a. The upper portion of the stratigraphic succession (intervals d–e) is represented by sandbars (interval d) which in turn grade upwards into lagoon deposits (interval e). This portion of the "Scontrone calcarenites" is featured by a stack of thickening-upwards bedsets bounded at the base and at the top by ravinement surfaces (Figs. 5 and 6). The maximum thickness averages six metres. The broadly symmetric thinning-upward/thickening-upward stratal stacking pattern, evident in the Sangro Gorge, is recognizable also in other, less complete sections (see columnar sections 2–4 in Fig. 5). This stratal architecture has not been recognized in the "Scontrone

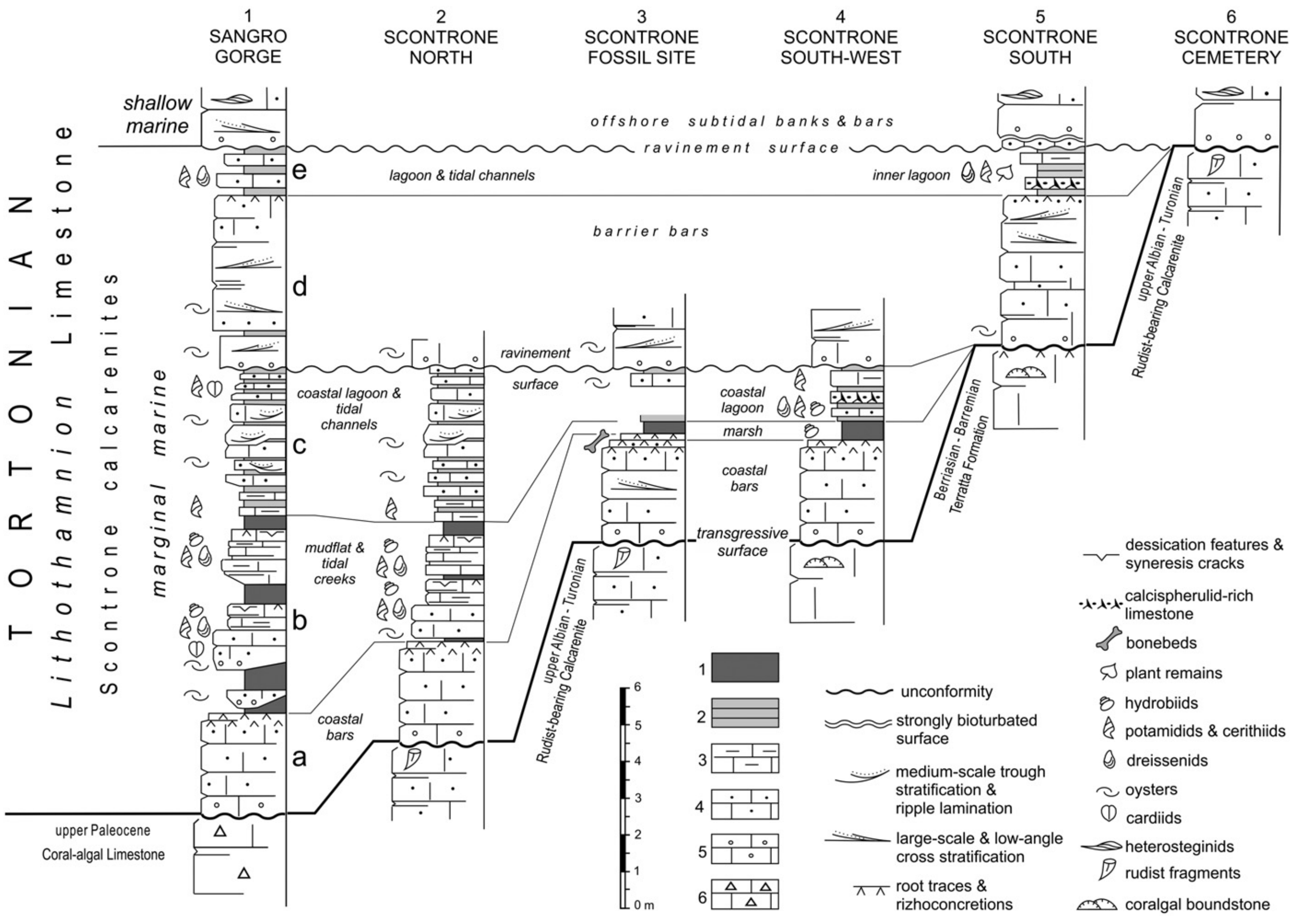

Fig. 5. Columnar sections showing the position of the bonebeds in the Scontrone fossil site and the lateral facies variations of the "Scontrone calcarenites" in the study area (see location in Fig. 3). **1**. Colour-mottled green and yellow marly mudstones; **2**. Thinly laminated tan clayey marls and marls; **3**. Marly limestones and limey marls; **4**. Fine- to medium-grained litho-bioclastic calcarenite; **5**. Medium-grained bioclastic calcarenite with oversized rounded calcareous extraclasts; **6**. Lime breccias.

South" section (columnar section 5 in Fig. 5) owing to the ravinement surface at the base of the interval d that removed the intervals a–c, which are preserved in the other sections. In this locality, the interval d lies directly over the Lower Cretaceous carbonates of the Terratta Fm. The second important transgressive ravinement surface is placed at the base of the shallow-marine sandbars overlying the "Scontrone calcarenites". In the Sangro Gorge and "Scontrone South" sections, this surface cuts across the entire succession of the "Scontrone calcarenites" so that in the "Scontrone Cemetery" section also the intervals d and e are missing and the Miocene shallow-marine calcarenites lie directly on the upper Albian-Turonian Rudist-bearing Calcarenite (columnar section 6 in Fig. 5).

4.1. Interval a

This interval consists of 2.5 m of buff to off-white mottled calcarenites showing a faint large-scale and low-angle cross stratification frequently hidden by bioturbation. Discontinuous strings of pebbly calcarenites are locally present at the base of the calcarenite beds. In thin section the calcarenites are represented by litho-bioclastic grainstones/packstones with a mixohaline biofacies assemblage including abundant large-sized *Ammonia* and *Elphidium crispum* associated with relatively common porcellanaceous benthic foraminifers (Fig. 7(A)). The lithoclasts, always very well-rounded and frequently bored, are extraclasts derived from older shallow-marine and basinal carbonates, indicating strong subaerial erosion of a lithified substrate and severe physical reworking of the eroded material. In addition, the presence of sparse, isolated and abraded specimens of Upper Cretaceous globotruncanids and of micritized Paleogene-lower Miocene large foraminifers indicates winnowing of not yet lithified older carbonates. These bio-lithoclastic calcarenites have been interpreted as high-energy coastal sandbars. Close to the top, the calcarenites are affected by an evident strong bioturbation and are crosscut by vertically-elongated root traces usually evidenced by their micritic coating (Fig. 7(C, D)). A thin horizon (20–25 cm) of pervasively-rooted, yellow-to-pink fine-grained calcarenite lies everywhere on top of the basal sheet of the transgressive sandbars. The calcarenite drape is composed of two portions: a quite well-sorted, highly-packed yellow-to-pink grainstone, and an overlying very thin coat of colour-mottled pink-to-red-brownish packstone. Both grain-supported and matrix-supported calcarenites contain well-rounded, scattered heterogeneous bioclasts (benthic and planktonic forams) and non-skeletal abraded calcareous grains coated by iron oxides. Rare monocrystalline, clean detrital quartz grains ranging in size from fine to medium sand are also present (Patacca et al., 2008a: pl. 1, fig. d). The fine-grained, light-coloured litho-bioclastic grainstone, in addition, contains sparse large-sized vertebrate remains (Fig. 7(B)). In thin section these carbonates show a distinctive early vadose cement and a still recognizable faint oblique lamination evidenced by oriented elongated grains

Fig. 6. The "Scontrone calcarenites" in the Sangro Gorge, where the unit reaches its maximum thickness (**A**), and along the road Alfedena-Scontrone, south of Scontrone, where the minimum thickness has been observed (**B**). Labels a–e correspond to the intervals distinguished in the columnar sections of Fig. 5. The boundaries at the base of the interval d and at the top of the interval e are ravinement surfaces.

and by a feeble grain-sorting of downward-dipping laminae. In the overlying pink to red-brownish packstones the mottled appearance is related to the presence of a patchy-distributed FeO-stained dense matrix of pedogenic origin. This layer contains sparse calcified roots still preserving their cellular structure (Fig. 7(E)) and frequently shows large alveolar structures always associated with rhizocretions (Patacca et al., 2008a: pl. 1, fig. e). The indisputable subaerial origin of this rubified horizon indicating a minor regressive event at the top of the transgressive basal calcarenite sheet, is proven by the presence of a net of desiccation cracks geopetally filled with micrite and early vadose blocky-spar cement (Fig. 7(F)). The Scontrone vertebrates are enclosed in the pinkish-to-reddish calcarenite horizon (main bonebed in Fig. 8). The best preserved remains have been recovered in the fossil site from the thin coat at the top of this rubified horizon. Sparse badly-preserved vertebrate remains have also been found in the pinkish-to-red calcareous horizon at the top of the interval a in the "Sangro Gorge" section. The co-occurrence of well-rounded medium sand-sized calcareous lithoclasts and of fine sand-sized quartz grains associated with reworked and broken tests of isolated planktonic and benthic foraminifers indicates active deflation processes. In conclusion, the thin-section analysis shows that the vertebrate remains are embedded in an eolian calcarenite draping the transgressive coastal sandbars. The petrographic features and the small-scale sedimentary structures still preserved in the vertebrate-rich calcarenite horizon reveal strong affinities with modern eolian carbonates, which are common along arid to semi-arid wind-exposed coastlines located in wide carbonate-ramp settings (Abegg et al., 2001; Frébourg et al., 2008).

4.2. Interval b

In the "Scontrone Fossil Site" and "Scontrone SW" sections the eolian calcarenite (main bonebed in Fig. 8) is overlain by yellowish to grey-green mud-rich deposits (interval b in the columnar sections of Figs. 5 and 8) containing small pieces of flushed bones. These deposits are primarily represented by mudstones and wackestones displaying local crude, discontinuous laminations. These lithotypes contain small thin-shelled hydrobiids and dreissenids, ostracods and thick-walled *Ammonia*, frequently

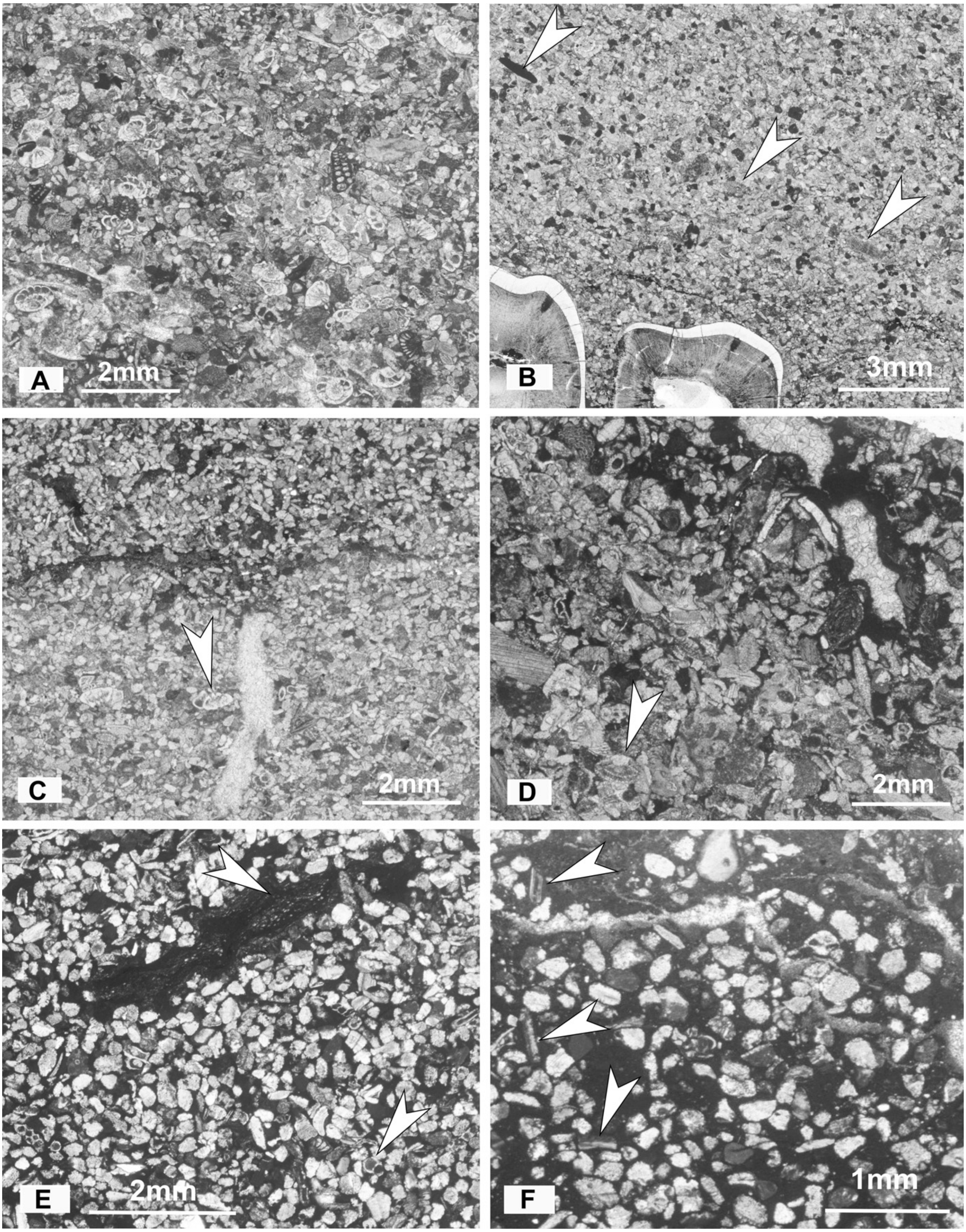

Fig. 7. Characteristic microfacies of the interval a of the ‘‘Scontrone calcarenites’’ in the ‘‘Scontrone North’’, ‘‘Scontrone Fossil Site’’, ‘‘Sangro Gorge’’, and ‘‘Scontrone South-West’’ sections. **A**. ‘‘Scontrone North’’ section: litho-bioclastic grainstone/packstone with numerous thick-shelled *Ammonia* and porcellanaceous benthic forams. ‘‘Scontrone calcarenites’’, interval a; **B**. ‘‘Scontrone Fossil Site’’ section: well-sorted and highly-packed litho-bioclastic grainstone with well-preserved vertebrate teeth (lower-left side) showing the characteristic brownish (greyish in the picture) dentine surrounded by a thick rim of colourless enamel. A faint downdip lamination is outlined by a few oriented elongate grains (white arrows). ‘‘Scontrone calcarenites’’, upper portion of the interval a; **C**. ‘‘Scontrone Fossil Site’’ section: bioclastic grainstone (lower part of the picture)

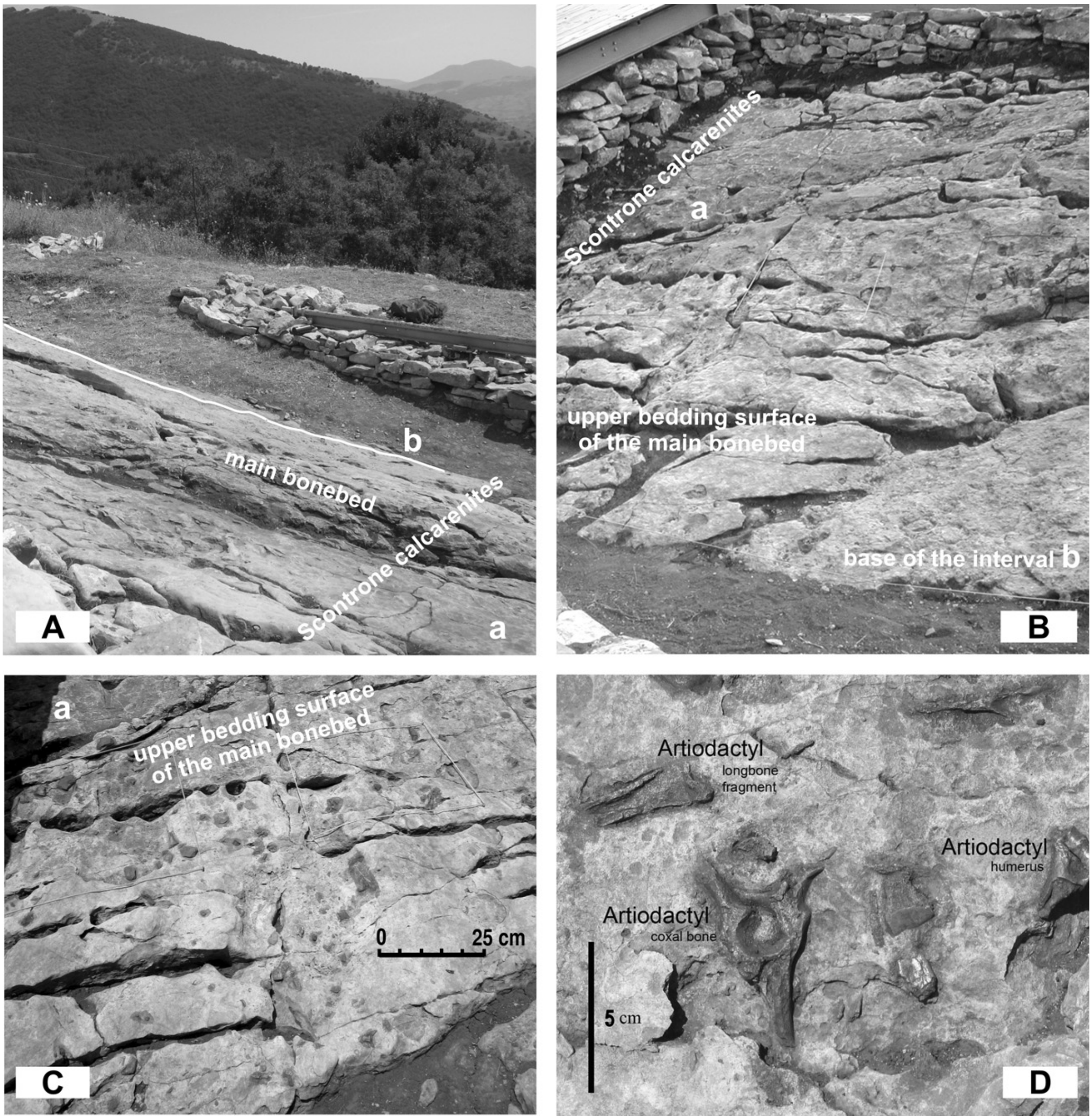

Fig. 8. Scontrone Fossil Site. **A**, **B**. Eolian calcarenite drape at the top of the interval a (upper bedding surface of the main bonebed in the picture) and contact with the overlying muddy marsh deposit (b in the picture); **C**, **D**. Details of the upper bed surface of the eolian calcarenite with vertebrate remains. Labels a and b correspond to the intervals defined in the columnar sections of Fig. 5.

associated with coprolites and charophyte gyrogonites concentrated in thin laminae (Fig. 9(A)). Thin-section analyses have revealed that vague, irregular laminations are also related to the presence of crinkled laminae of clotted micrite likely representing relics of microbial mats disrupted by root activity. In some cases the mudstones show a grey-green to yellowish-green mottled appearance. The patchy colour is partly related to the presence of a thin irregular pattern of micrite-filled fissures interpreted as

with large specimens of *Ammonia* (white arrow) crossed by a vertical, bifurcating spar-filled root mould. A dark irregular string above the root mould marks the contact with the overlying FeO-stained packstone interpreted as a wind-blown subaerial deposit. ''Scontrone calcarenites'', top of the interval a; **D**. ''Sangro Gorge'' section: bioclastic packstone with *Ammonia* and *Elphidium* (white arrow in correspondence to a specimen of *Elphidium*). The thinning-downward large tubular structure coated by a thick dense micrite is a rhizolith structure. ''Scontrone calcarenites'', upper portion of the interval a; **E**. ''Scontrone South-West'' section: well-sorted bioclastic calcarenite with marine biogenic detritus and well-rounded grains sparse in a dense FeO-stained micrite matrix of pedogenic origin. A large dark-brown root is present in the upper-central part of the picture (white arrow). At very high magnification, the root still retains a well-preserved cellular structure, also visible at lower magnification in the central part of the root remain. Note also the presence of sparse isolated planktonic foraminifers with micrite infilling (one of them is indicated by the white arrow in the lower-left side of the picture) which have been evidently blown during storms. ''Scontrone calcarenites'', top of the interval a; **F**. ''Scontrone South-West'' section: comminuted fragments of vertebrates (white arrows) associated with micritized marine fossil remains and with small rounded abraded grains set in a rubified dense micrite. The latter has likely derived from subaerial weathering processes. A net of geopetally-filled desiccation cracks is evident in the central-upper part of the picture. ''Scontrone calcarenites'', top of the interval a.

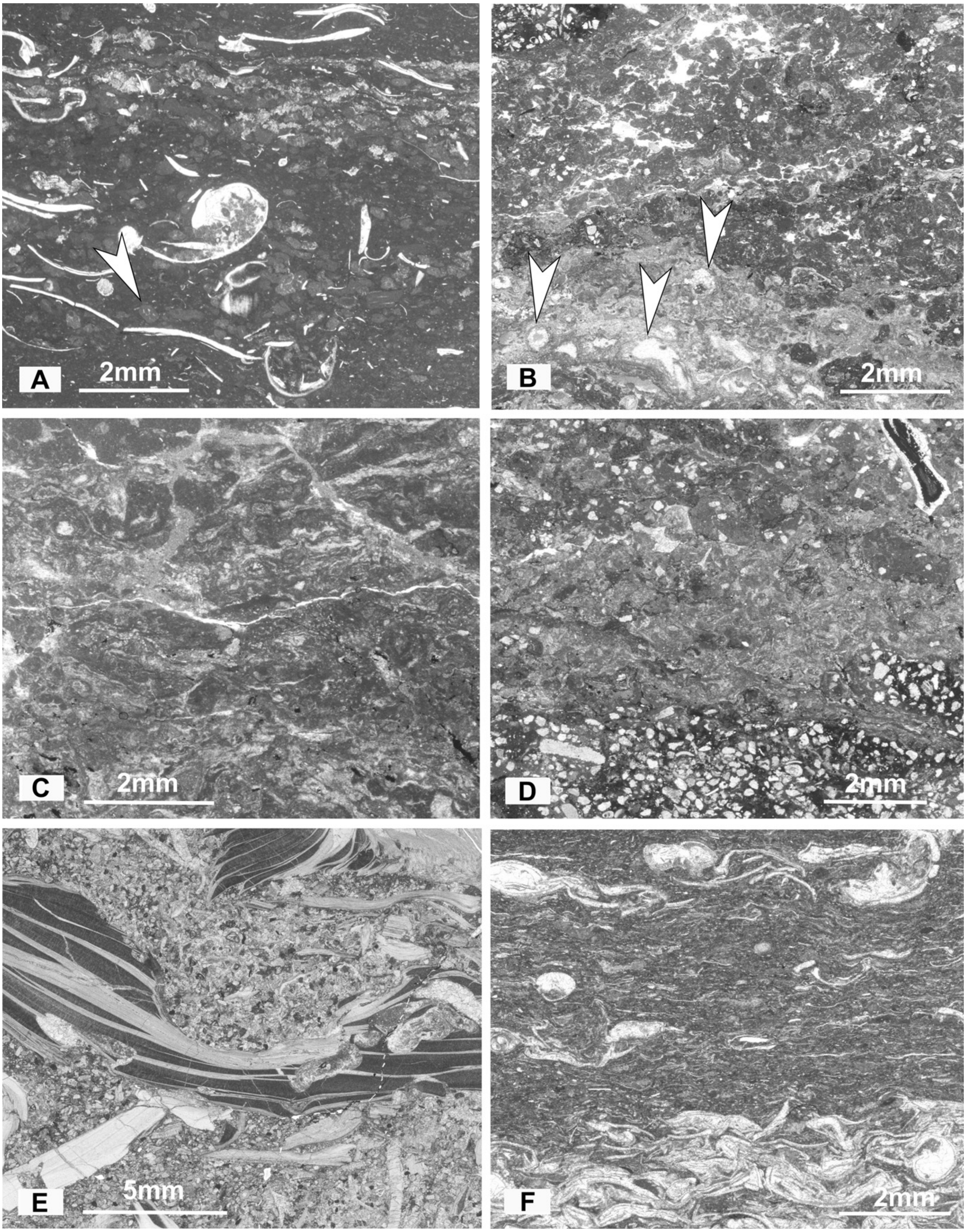

Fig. 9. Characteristic microfacies of the interval b of the ''Scontrone calcarenites'' in the ''Scontrone South-West'', ''Scontrone Fossil Site'' and ''Scontrone North'' sections. **A**. ''Scontrone South-West'' section: wackestone with ostracods and hydrobiids associated with small rounded micritized grains mainly represented by coprolites with their internal spar-filled pores recognizable at high magnification. A transversal section of a large coprolite with its circular outline and the internal tubular structure has been arrowed. Note in the upper part of the picture a lamina rich in coprolites. ''Scontrone calcarenites'', marsh deposit of the interval b; **B**. ''Scontrone Fossil Site'' section: dark-brown to pale-yellow (dark-grey to light-grey in the picture) mottled mudstone affected by intense pedogenic process. Note the circumgranular cracks (central-upper part of

syneresis cracks, and partly to the presence of yellowish to pinkish flakes of calcarenite removed from the early-lithified subaerially-exposed substrate (Fig. 9(D)). The thin deeply-rooted muddy deposits overlying the vertebrate-rich subaerial calcarenite of the Scontrone fossil site and the transgressive basal calcarenite of the "Scontrone South-West" section contain sparse ostracods, *Ammonia*, hydrobiids and comminuted worn fragments of vertebrates (Fig. 9(D)). The facies of these muddy deposits, affected by intense pedogenesis, is indicative of a standing-water depositional environment belonging to intermittently flooded, well-vegetated mudflats/marshes. The abundance of dreissenid mussels associated with small, delicate shells of hydrobiids suggests hypo- to oligohaline waters possibly with low oxygen content. The interval b exhibits remarkable changes in facies and thickness within small distances, as well as rapid lateral pinch-out terminations (Fig. 5). In the "Sangro Gorge" and "Scontrone North" sections the interval b contains channel-fill deposits represented by pebbly calcarenites organized into three stacks of fining-upward and thinning-upward beds and bedsets characterized by erosive base. The lower part of every stack is made up of pebbly calcarenites with lithoclasts derived from the lithified substratum, overlain by shell lags of brackish-water molluscs. The lumachella layer associated with the lowest channelized layer is characterized by a monospecific-accumulation of convex-up oriented, disarticulated thick valves of ostreids apparently belonging to *Ostrea lamellosa*. The oyster shells have been extensively affected by borings (Fig. 9(E)) related to the ichnogenus *Entobia*, a marine bioerosion made by clionid sponge (Bromley and D'Alessandro, 1984). An oligotypic assemblage of cerithiids and potamidids, together with dreissenids, scattered cardiids and subordinate oysters, dominates the shell layers associated with the channelized beds in the upper portion of the interval b. This assemblage is typical of subtropical paralic domains (sensu Guelorget and Perthuisot, 1992; see also Plaziat, 1989; Barnes, 1999; Kowalke, 2006). A monotypic shell accumulation of hydrobiids (Fig. 9(F)) is always present in the upper muddier portion of the channel deposits. Evidence of desiccation cracks and root activity systematically affecting the top of the shell layers (Fig. 10(A, B)) is indicative of recurrent episodes of subaerial exposure related to short-term regressions. The facies analysis of the interval b allows the reconstruction of marshes and mudflats incised by ephemeral small creeks in which shell lags associated with sporadic conglomerates were accumulated by strong tidal currents. In the "Sangro Gorge" section the first and the second channels have an evident SW-NE direction.

In conclusion, the greatest part of the well-preserved fossil vertebrates of Scontrone is embedded in a rooted subaerial calcarenite draping coastal sandbars (top of the interval a). The main bonebed is sealed by marsh muddy deposits (interval b) containing only scattered and abraded comminuted bone fragments.

4.3. Interval c

This interval represents the upper portion of the transgressive tract of the "Scontrone calcarenites", characterized by thinning-upwards stratal stacking patterns. It has been distinguished from the underlying interval b because of the greater thickness of the beds and because of the higher sand/mud ratio (Figs. 5 and 6). Muddy interlayers are here constituted of tan foetid marls and clayey marls with flattened complete shells of prevalent cerithiids and subordinate potamidids, associated with a high percentage of thick-walled *Ammonia*, ostracods and sparse *Elphidium* (Fig. 10(C)). This biofacies, dominated by a mixohaline assemblage of *Ammonia* and *Elphidium* indicative of a subtidal environment with near normal salinity conditions, highlights the overall transgressive trend of the "Scontrone calcarenites". The bulk of the interval c consists of even-parallel thin storm layers rich in fragmented cerithiids and of decimetric to pluridecimetric channelized beds of medium- to fine-grained grey litho-bioclastic calcarenites evidently accumulated in shallow-subtidal channels. The calcarenite beds display medium-scale trough cross stratification and ripple laminations. In the lowest channelized bed rare fragments of vertebrate remains have been found. Under the microscope the litho-bioclastic calcarenites contain fine-grained biodetritus of marine organisms such as fragmented echinoid spines and serpulids, as well as barnacle debris always associated with *Ammonia* and *Elphidium*. In the Sangro Gorge the uppermost portion of the interval is characterized by the common occurrence of sparse cardiids associated with cerithiids which indicate an upward increase in salinity and a more open circulation. Concentrations of thick-shelled oysters stacked as densely-packed lumachella layers are quite common at the top of the interval (see "Scontrone North" and "Scontrone Fossil Site" sections in Fig. 5). The oyster banks appear to be concentrated in correspondence to tidal channels connecting the coastal lagoon with the open sea. The thick oyster shells, systematically affected by intense marine bioerosion, are characterized by prominent growth lines indicative of warm, high-energy environments (Morrison and Brand, 1986). The interval c reaches its maximum thickness (about 4 m) in the "Sangro Gorge" and "Scontrone North" sections and rapidly reduces moving towards the north and the south. In the "Scontrone South-West" section, the interval c is represented by 1.5 m of thinly laminated tan foetid marls and clayey marls characterized in the lower portion by abundant cerithiids, potamidids and hydrobiids. The presence in these layers of dreissenids associated with hydrobiids, together with the fresh-water gastropod *Melanopsis*, suggests a depositional setting with hypohaline conditions and vegetated substrate. In thin-section the foetid marls are characterized by laminae enriched in calcisphaerulid small bodies (Fig. 10(D)), likely documenting episodic blooms of calcareous resting cysts of algae or calcitized sporomorphs commonly confined in more protected embayments of lagoons.

4.4. Interval d

The interval d, very well exposed in the "Sangro Gorge" and "Scontrone South" sections (Fig. 6), is primarily composed of off-white medium-grained litho-bioclastic calcarenites with a relatively diverse biogenic content essentially characterized by euryhaline organisms. The calcarenites consist of well-sorted, high-energy bioclastic grainstones containing thick-walled gastropods (Fig. 11(A)) and sparse oversized, very well-rounded and locally bored calcareous clasts (Fig. 10(E, F)). Large-scale low-angle tabular cross stratification is locally present, usually obliterated by

the picture) and the calcified thick root mat (lower part of the picture) with well-preserved transverse and oblique sections of spar-filled root moulds (circular and elongated white hollows with grey micrite or microsparite centre indicated by the arrows). "Scontrone calcarenites", marsh deposit of the interval b; **C**. "Scontrone South-West" section: dark-brown to pale-yellow (dark-grey to light-grey in the picture) mottled mudstone affected by intense syneresis processes (upper part of the picture). "Scontrone calcarenites", marsh deposit of the interval b; **D**. "Scontrone Fossil Site" section: colour-mottled mudstone with flakes of rubified rooted eolianite crust (darker clasts in the picture). The groundmass is represented by a dense network of calcified root mat. In correspondence to the upper right corner, worn fragment of vertebrate. "Scontrone calcarenites", marsh deposit of the interval b; **E**. "Scontrone North" section: fine-grained bioclastic packstone including deeply-bored oyster thick shells. "Scontrone calcarenites", oyster lumachella bed in the lower portion of the interval b: **F**. "Scontrone North" section: densely-packed gastropod-rich monotypic lumachella layer with flattened and crushed shells of hydrobiids. The background sediment is represented by a packstone with thin-walled disarticulated ostracods. "Scontrone calcarenites", interval b.

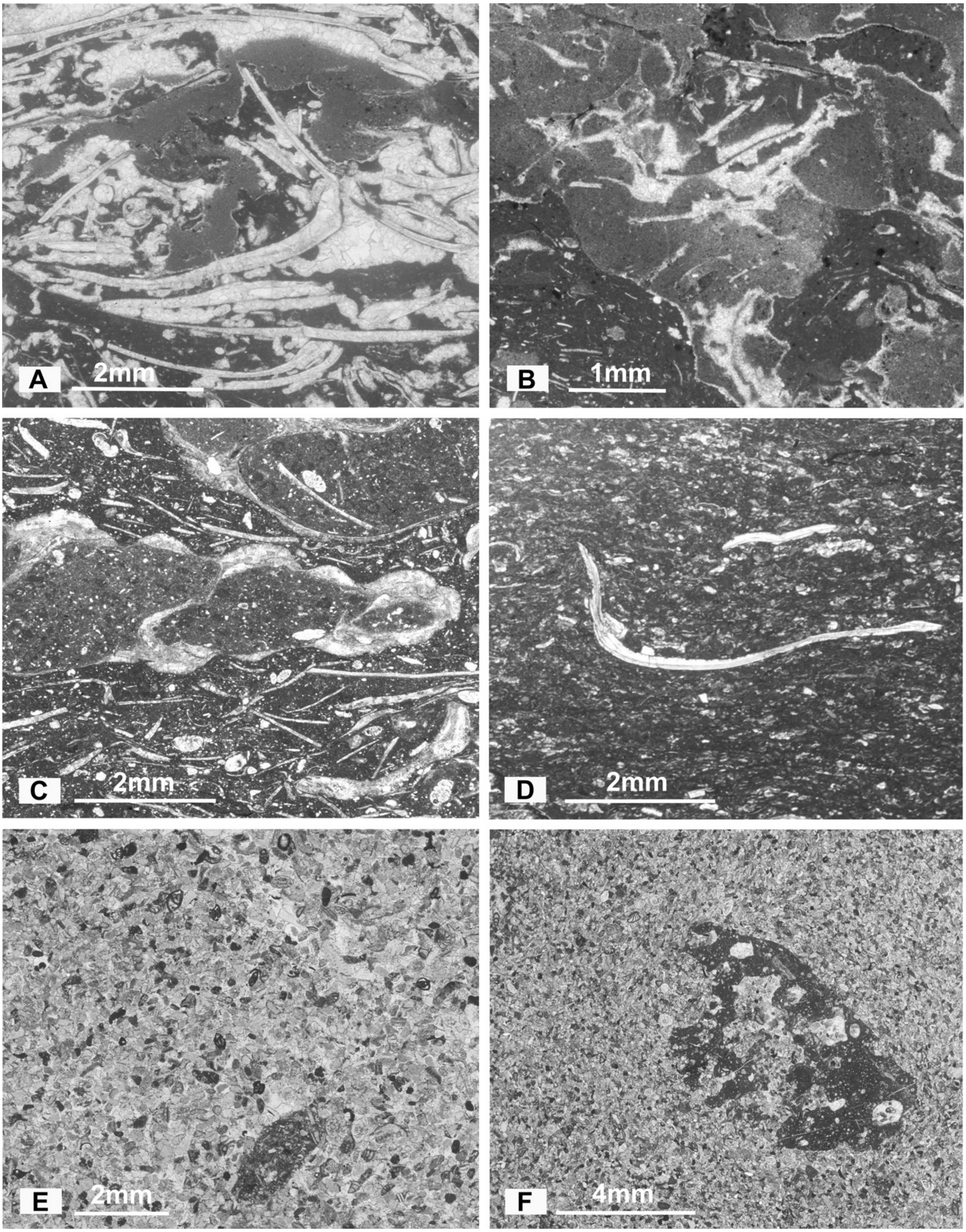

Fig. 10. Characteristic microfacies of the intervals b, c and d of the "Scontrone calcarenites" in the "Sangro Gorge", "Scontrone North", "Scontrone South-West", and "Scontrone South" sections. **A**, **B**. "Sangro Gorge" section: lumachella layer showing large geopetally-filled vugs and cracks. "Scontrone calcarenites", interval b; desiccated and brecciated top of a channel deposit; **C**. "Scontrone North" section: bioclastic wackestone/packstone with sparse crushed cerithiids, large-sized *Ammonia* and ostracods. "Scontrone calcarenites", interval c; brackish-water lagoon; **D**. "Scontrone South-West" section: very fine-grained bioclastic packstone with sparse disarticulated valves of dreissenids. Alignments of white dots mainly evident in the upper part of the picture are calcisphaerulid-rich laminae. "Scontrone calcarenites", interval c; inner-lagoon

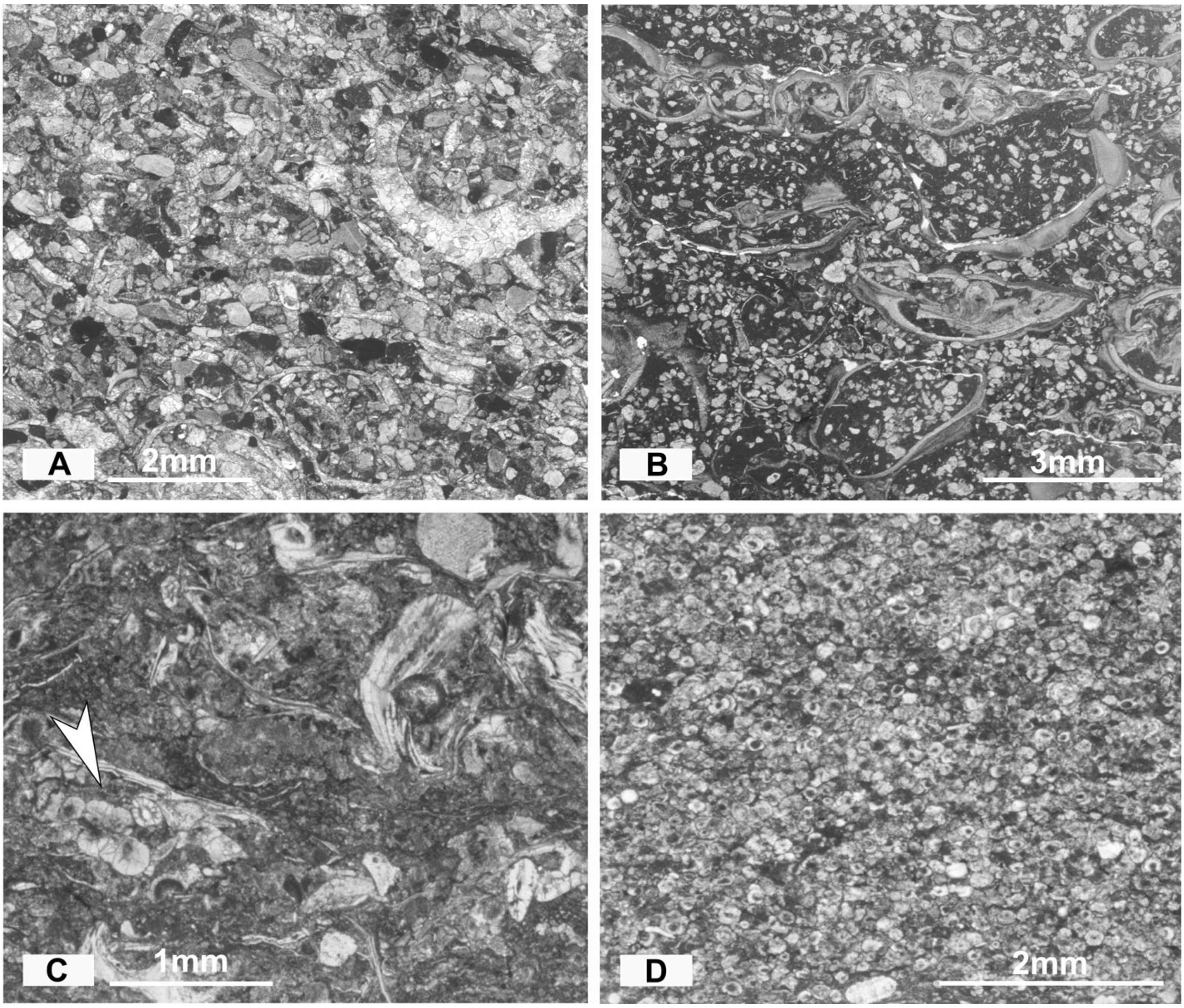

Fig. 11. Characteristic microfacies of the intervals d and e of the "Scontrone calcarenites" in the "Scontrone South-West", "Sangro Gorge", and "Scontrone South" sections. **A**. "Scontrone South-West" section: bio-lithoclastic packstone with well-rounded sand-sized lithic grains (darker grains in the picture) and abraded bioclasts. In the central-upper right part of the picture, transversal section of a spar-filled thick-walled gastropod. "Scontrone calcarenites", tidal bar deposit of the interval d. **B**. "Sangro Gorge" section: crushed cerithiids preserving their original aragonite shell in a fine-grained bioclastic wackestone/packstone rich in *Ammonia*. "Scontrone calcarenites", interval e; storm layer accumulated in a coastal lagoon. **C**. "Scontrone South" section: bioclastic packstone with large shell fragments. In the lower-left side of the picture, cluster of calcisphaerulids representing calcareous resting cysts of algae or calcitized sporomorphs (white arrow). Immediately above the cluster, well-preserved white dehisced cysts. "Scontrone calcarenites", interval e; restricted inner part of a coastal lagoon. **D**. "Scontrone South" section: densely-packed calcisphaerulid packstone. The exceptional abundance of these spherical calcareous bodies may be related to a phytoplankton bloom in waters with high level of eutrophication. "Scontrone calcarenites", interval e; restricted inner coastal lagoon.

an intense bioturbation. Nests of thick-walled oysters (*Ostrea lamellosa*) frequently occur at the base of the calcarenite beds. Root traces are present at the top of the interval in the "Sangro Gorge" section. In the "Scontrone South" section the top of the interval d is marked by a thin horizon of extensively rooted fine-grained calcarenite with vertically-developed root tubules filled with dark organic material. These lithosomes are interpreted as vegetated sandbars facing higher-energy and open marginal-marine settings. The flat sharp base of interval d, together with the presence of coarse-grained pebbly calcarenites and the common occurrence of shell lag accumulations, evidences a basal transgressive ravinement surface.

4.5. Interval e

In the Sangro Gorge the high-energy sandbar calcarenites are overlain by 1.5 m of lagoon deposits (interval e) represented by calcarenites thinly interlayered with laminated foetid marls and clayey marls rich in a hypo- to mixohaline fossil association represented by potamidids, melanopsids and

deposit with oligohaline to hypohaline water; **E**. "Scontrone North", and **F**. "Scontrone South" sections: very well-sorted fine-grained bio-lithoclastic grainstones with oversized well-rounded calcareous clasts. Note the intense boring affecting the large calcareous clast in picture F. Rounded dark micritic grains in picture E partly correspond to reworked older extraclasts. "Scontrone calcarenites", tidal bar deposit of the interval d.

dreissenids (Fig. 11(B)). In the ''Scontrone South'' section, lagoon deposits (interval e) overlie the rooted, dark upper surface of the sandbar calcarenite. Interval e is here represented by dark clayey marls and calcareous marls containing scattered micritized bioclasts, crushed potamidids, melanopsids and dreissenids together with plant remains and numerous thick-walled ostracods. At high magnification the clayey marls reveal the presence of numerous sphaerical to ovoidal calcareous bodies (Fig. 11(C)) possibly representing intact or partly dehisced calcareous resting cysts of algae or calcitized sporomorphs (Patacca et al., 2008a). A thin bed (30 cm) of foetid dark-brown calcisiltite with a characteristic microscopic fabric is present at about 20 cm from the base of the muddy deposits. In thin section the calcisiltite appears as a dense aggregate of calcareous microspheres probably representing an unusual *in situ* accumulation of algal cysts or calcitized sporomorphs in a protected innermost part of the lagoon (Fig. 11(D); Patacca et al., 2008a: pl. 5, figs. d, e). The return to protected lagoon conditions after the high-energy sandbar deposition adds evidence to a quite complex paralic environment with peripheral sandbar units adjacent to narrow protected coastal embayments.

In the ''Sangro Gorge'' and ''Scontrone South'' sections the interval e is evidently truncated by an erosional surface developed at the base of the overlying high-energy shallow-marine calcarenites. The basal portion of these calcarenites always consists of medium to coarse-grained litho-bioclastic grainstones/packstones with a diverse fossil content characterized by abundant stenohaline organisms (echinoid spines, fragmented *Heterostegina* and scattered coralline algal rhodoids) associated with large-sized *Elphidium*, scattered *Ammonia*, and fragmented barnacles. These high-energy marine deposits have been interpreted as subtidal offshore bars in a shallow-marine environment.

4.6. Conclusion

The palinspastic restoration of the Apulia Platform domains and the facies analysis of the Miocene deposits present in the study area suggest that the ''Scontrone calcarenites'' represent the sedimentary record of a complex marginal-marine environment developed over a large, flat and semi-arid plain bordering low-relief, subaerial vast areas of the Apulia Platform (Fig. 2). Following Walther's rule on the horizontal and vertical facies changes in relatively conformable successions of strata, the depositional features of the ''Scontrone calcarenites'' allow a quite good reconstruction of the sedimentary environments in the time in which vertebrates colonized the study area. The recognized depositional units include coastal marine bars, which underwent subaerial exposure and winnowing in semi-arid climate conditions (interval a with the reddish/pale-brown pedogenic horizon at the top), narrow mudflats curved by shallow creeks and bordered landward by marshes (interval b), and narrow coastal lagoons incised by tidal channels (intervals c and e) and separated by small low barriers (interval d). These sedimentary units have been recognized integrating facies analyses and paleoenvironmental evidence provided both by the vertebrate and invertebrate associations. As a whole, we envisage a wave-dominated marginal-marine environment (derived from the facies analysis of the different intervals making up the ''Scontrone calcarenites'') close to a river mouth and linked to a vast continental area (testified by the rich fossil vertebrate assemblage). This complex environment hosted prosperous communities of large vertebrates. Crocodiles and pond turtles inhabited the fresh water portion of the delta, as well as the protected brackish paleobiotopes. Morphofunctional considerations on the skeletal structures of *Hoplitomeryx* seem to indicate that this artiodactyl was adapted for living in a fairly closed forest or woodland (Mazza and Rustioni, 1996), suggesting that the floodplain that surrounded the main channel and other aquatic biotopes of the deltaic environment was densely vegetated by bushes and shrubs.

The reconstructed sedimentary environment shows analogies with the Gascoyne delta of Western Australia (Carnarvon region) developed on a semi-arid, wave-dominated coast influenced by occasional wasting tropical storms (Johnson, 1982). This kind of environment includes a river with a narrow direct entrance to the sea surrounded by swampy areas, lagoons associated with tidal creeks and a vegetated floodplain (Alongi et al., 1999). Wave-dominated deltas typically support estuarine species able to tolerate a wide range of salinity conditions (Rainer and Fitzhardinge, 1981) and, depending on river flow dynamics, also support euryhaline transient visitors from the marine environment (Roy et al., 2001). The energy of the waves often results in the distribution of sediments along the coastline, with the production of coastal bars conditioning the connection of the river with the sea. In a semi-arid context, the wave-dominance of the delta front may be enhanced by the intermittence of the river flow (Johnson, 1982). In addition, the role of the tidal action on the sediment distribution should not be underestimated in this kind of delta, since it often influences the biotopes that flank the main river channel(s), such as marshes, mudflats and creeks, in many cases supported by the baffling effect of the standing vegetation. In such a paleoenvironmental setting, it is reasonable to suppose that the lag features of the Scontrone bonebeds resulted from the progressive selective removal of bony elements operated by winnowing on unsorted bone concentrations. These amassments were previously accumulated supratidally on the coastal bars by episodic floods after a limited transport from the paleobiotopes where the animals died, and perhaps inhabited. The intense pedogenesis displayed by the rubified vertebrate-bearing horizon obviously implies long subaerial exposure and reduced sedimentation rates. However, much more taphonomic information would be desirable in order to properly understand the genesis of the bonebeds.

5. The age of the ''Scontrone calcarenites''

The age of the ''Scontrone calcarenites'' cannot be defined through their paleontological content because of the obvious absence of age-diagnostic marine fossils due to the depositional setting in a marginal-marine environment. As pointed out by Patacca et al. (2008a), the abundance of the benthic foraminifer *Elphidium crispum* from the base of the unit only suggests an indeterminate age not older than the middle Miocene. Such an indication appears to be extremely weak to establish the age of the ''Scontrone calcarenites'' and, as a consequence, the age of their vertebrate fossil content. Only the upper portion of the *Lithothamnion* Limestone contains an age-diagnostic benthic foraminifer association indicating the early Messinian *Bulimina echinata* Zone.

In order to solve the age problem we propose a regional stratigraphic correlation between the *Lithothamnion* Limestone of the Scontrone area and other sections of the *Lithothamnion* Limestone belonging to the Apulia Platform in which the base of this lithostratigraphic unit is biostratigraphically well constrained. This approach is possible because during the Miocene the entire Apulia Platform (to which the Scontrone domain belongs; Fig. 2) was a stable carbonate-ramp setting that only in the early Messinian began to be influenced by tectonic activity (flexural subsidence and onset of the Castelnuovo al Volturno siliciclastic flysch deposits in the Scontrone domain). Consequently, major facies variations had to be controlled by sea-level changes at a global scale. In addition, the entire Apulia Platform constituted in Tortonian times a vast low-gradient shelf area with a flat coastal plain (Scontrone area) bordering subaerial low reliefs which included the Morrone-Porrara domain and its southward continuation, the southern Majella-Casoli domains and the Gargano, Murge and Salento regions (Fig. 2). With such a physiographic configuration characterized by vast shallow-marine areas bordered by low-lying coastal plains, we expect during a sea-level rise a rapid transit of the transgressive shoreline, and thus an almost synchroneity of the transgression over large areas.

The reliability of the stratigraphic "event" correlation proposed in this paper is conditioned by the validity of two basic assumptions:

- the "Scontrone calcarenites" are part of the *Lithothamnion* Limestone and do not belong to an older sedimentary cycle. According to our interpretation they represent the oldest transgressive deposits accumulated during the landward movement of the coastline in the early stages of the *Lithothamnion* Limestone transgression. This interpretation is supported by the overall transgressive, deepening-upward trend of the entire stratigraphic succession;
- the landward shift of the transgressive facies occurred in a very short time interval. The modest thickness of the "Scontrone calcarenites" supports this assumption.

The *Lithothamnion* Limestone is a Tortonian-lowermost Messinian lithosome widespread over vast areas of the Apulia Platform (Fig. 2) and together with the overlying *T. multiloba* Marl occupies the upper portion of an uppermost Oligocene-Miocene carbonate-ramp succession known as the Bolognano Group or Bolognano Fm. (e.g., Crescenti et al., 1969; Centamore et al., 2003). Primarily based on a sudden change in the benthic foram biocenosis observed in the uppermost portion of the *Lithothamnion* Limestone cropping out in northern Majella, which was considered indicative of the base of the Messinian, Di Napoli Alliata (1964) suggested that the bulk of this lithosome should be attributed to the Tortonian. The change observed by this author corresponds to the change in the benthic foraminifer association that characterizes the *Bulimina echinata* Zone. Sedimentary features and fossil content of the *Lithothamnion* Limestone are quite homogeneous over large portions of the Apulia Platform. All along the outer border of the Tortonian homoclinal carbonate-ramp setting (light-grey areas in Fig. 2), the *Lithothamnion* Limestone overlies a carbonate-ramp succession of Chattian *p.p.*-lower Tortonian age deeply investigated in the Majella region (Vecsei, 1991; Della Porta, 1998; Vecsei and Sanders, 1999). Moving towards the subaerial areas (dotted areas in Fig. 2), the *Lithothamnion* Limestone overlies pre-Miocene carbonates of the Apulia Platform with onlap terminations. In Southern Majella, for instance, the *Lithothamnion* Limestone overlies Upper Cretaceous and lower Paleogene carbonate deposits (Palena in Fig. 1). In this case the unit, only four metres-thick and Messinian in age (Danese, 1999), displays facies architecture very different from those characterizing the Scontrone area. On the contrary, the *Lithothamnion* Limestone exposed in Northern Majella (Roccamorice; Fig. 1), where the Apulia Platform faced the Northern Adriatic-Marche Basin (Fig. 2), show thickness, sedimentary features and facies architecture closely comparable with those of the *Lithothamnion* Limestone of Scontrone. Therefore, we correlate the most complete section of the *Lithothamnion* Limestone of Scontrone (the "Scontrone Cemetery" section) with a section well exposed in the Roccamorice area, with the aim of establishing some constraints on the age of the early transgression of the *Lithothamnion* Limestone in the Scontrone area. In the Roccamorice section, as everywhere in Northern Majella, the *Lithothamnion* Limestone disconformably overlies a Langhian *p.p.*-Tortonian *p.p.* lithostratigraphic unit (the *Orbulina* Limestone) made up of thin-bedded hemipelagic limestones and marly limestones rich in planktonic and hyaline benthic foraminifers. The *Lithothamnion* Limestone of the two sections shows the same progression of deepening events (Fig. 12) and comparable facies characteristics (Vecsei, 1991), except for the high-energy inner-ramp calcareous sheet developed at the base of the *Lithothamnion* Limestone of the "Scontrone Cemetery" section. The latter is actually laterally substituted in the Roccamorice section by *Heterostegina*-rhodoid calcarenites indicative of a proximal mid-ramp setting.

In the "Scontrone Cemetery" section the high-energy transgressive deposits at the base of the *Lithothamnion* Limestone consist of about 3 m of highly-packed litho-bioclastic calcarenites rarely preserving large-scale and low-angle cross stratifications (interval A in Fig. 12). The microfacies, represented by fine to medium-grained bioclastic packstones/grainstones with large-sized thick-walled *Ammonia* and *Elphidium crispum*, evidence some winnowing of the sediment (picture A in Fig. 12) in a nearshore environment. The overlying two metres of crudely stratified bioclastic calcarenites (interval B in Fig. 12) are characterized by an association of *Elphidium crispum*, fragmented and abraded *Heterostegina* and small red algal rhodoids (picture B in Fig. 12) similar to those present in the calcarenites at the base of the *Lithothamnion* Limestone in the Roccamorice area.

The *Heterostegina*-rhodoid calcarenites are overlain by 8 m of rhodolith-rich limestones (interval C in Fig. 12) in which two portions can be distinguished. The lower portion consists of about five metres of thick-bedded limestones and marly limestones with thin, bioturbated nodular marly interbeds. This portion, characterized by very large composite red algal-bryozoan rhodoliths floating in a bioclastic silty mud, indicates a low-energy mid-ramp setting. The upper portion consists of about three metres of more massive limestones characterized by the presence of small rhodoliths and fragmented branches of *Lithothamnion* set in a quite well-sorted bioclastic matrix. The lithofacies of the upper portion of the interval C testifies to an evident upward increase in the winnowing and a higher energy of the hydrodynamic conditions in more proximal sectors of the middle-ramp setting. It likely reflects the regressive event near the Tortonian-Messinian boundary (Fig. 12). A comparable shallowing-upward episode in the same stratigraphic position is recognizable also in northern Majella (Roccamorice Section; Vecsei, 1991).

The rhodolith-rich interval is overlain by two metres of medium-bedded marly limestones separated by thin marly interlayers (interval D in Fig. 12). This interval, containing dispersed *Lithothamnion* thallii, pectinids, echinoid spines, occasional stands of unbroken tests of *Heterostegina* and scattered planktonic foraminifers (picture D in Fig. 12), is indicative of a distal mid-ramp setting. The uppermost portion of the *Lithothamnion* Limestone is everywhere represented by two metres of bioturbated marly limestones with thin clayey interlayers containing pectinids and abundant forams (interval E in Fig. 12) belonging to large-sized *Orbulina universa* (picture E in Fig. 12) associated with bolivinids, buliminids and other hyaline benthic forams. A thin veneer of heavily bioturbated, condensed nodular limestones rich in planktonic foraminifers, phosphatic faecal pellets and rounded glauconite grains at the top of the *Lithothamnion* Limestone highlights a scarcely subsiding, starved outer-ramp setting. The upper half portion of the interval e has been attributed to the Messinian because of the occurrence of a rich and diversified benthic foram association dominated by *Rectuvigerina* sp., *Brizalina* spp. and *Bulimina* spp. which defines the *Bulimina echinata* Zone of Colalongo et al. (1979). In the Mediterranean region this characteristic benthic foram association slightly predates the FO of *T. multiloba* (Kouwenhoven et al., 2006; Manzi et al., 2007). *Bulimina echinata* has been found in the Roccamorice section and in the whole Majella area in the same stratigraphic position near the

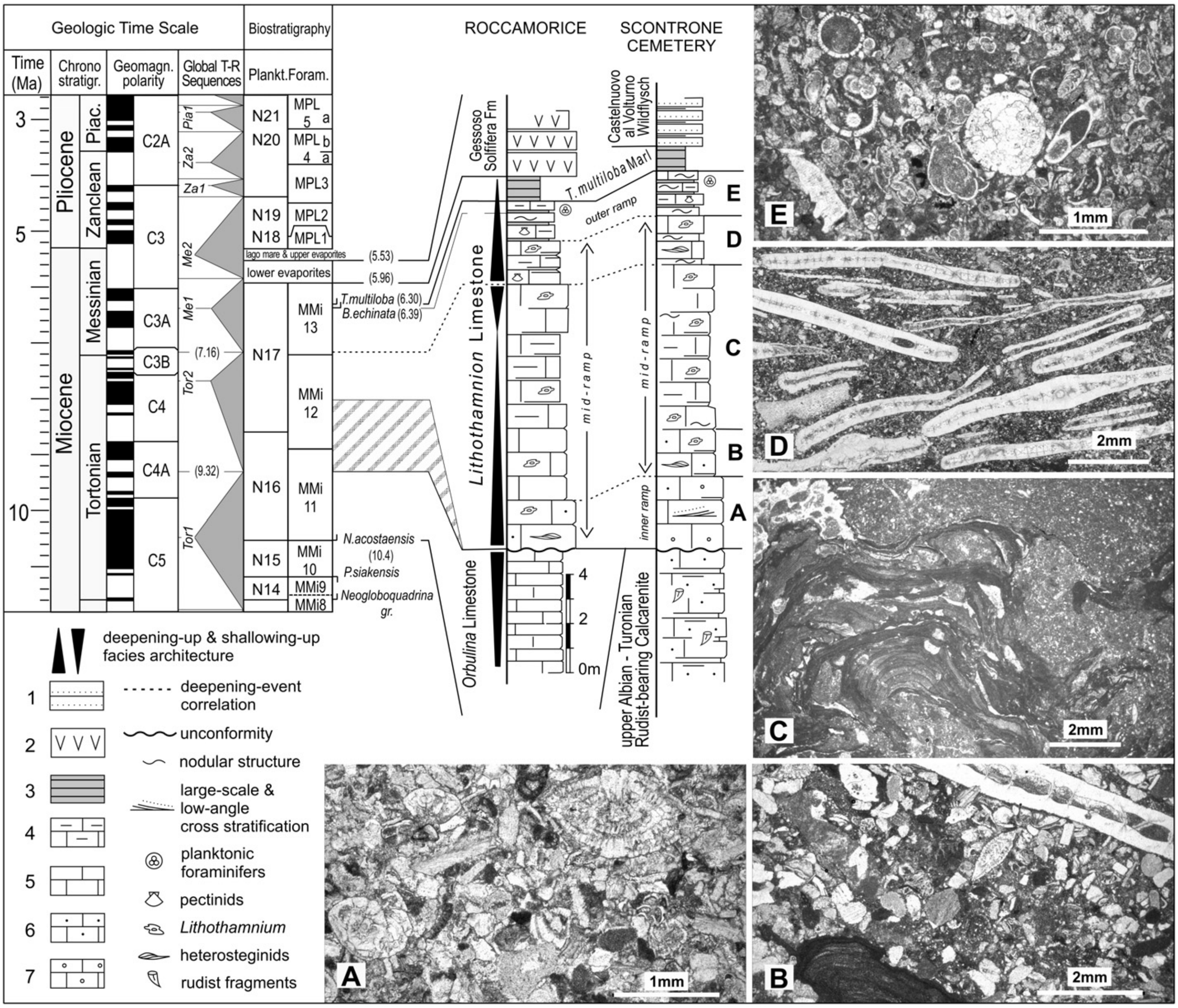

Fig. 12. Stratigraphic correlation between the *Lithothamnion* Limestone of the ''Scontrone Cemetery'' section and the *Lithothamnion* Limestone exposed in the Roccamorice area (northern Majella). The Roccamorice section has been calibrated on the standard geological time scale (GTS) in Gradstein et al. (2004), compiled using the software Time Scale Creator 5.4 made available by A. Lugowski and J. Ogg at the site http://www.tscreator.org. Magnetic reversals and stage boundary ages derive from the geomagnetic polarity scale of the ATNTS 2004 in Lourens et al. (2004a). Global T-R Sequences (3rd order depositional sequences) follow Hardenbol et al. (1998), recalibrated to the 2004 time scale by Snedden and Liu (2011). Alphanumeric abbreviations of the T-R Sequences and ages of the maximum regressive events derive from Snedden and Liu (2011). Planktonic foraminiferal N-zones according to Blow (1969); MPL-zones according to Cita (1975), Iaccarino (1985), Sprovieri (1992, 1993) and Iaccarino et al. (2007); MMi-zones according to Iaccarino (1985), emended and renamed by Foresi et al. (1998), Sprovieri et al. (2002) and Gradstein et al. (2004). Age calibration of the *N. acostaensis* FRO (First Regular Occurrence) derived from Lourens et al. (2004b). Ages of the CO of the benthic foraminifer *Bulimina echinata* and of the planktonic foraminifer *T. multiloba* derived from Kouwenhoven et al. (2006). Messinian physical events derived from Odin et al. (1997), Krijgsman et al. (1999a, 1999b, 2004), Roveri et al. (2003, 2008), Hilgen et al. (2007), Manzi et al. (2007), and Hüsing et al. (2009). Slanted parallel grey bands between 8.0 and 9.26 Ma indicate the maximum amplitude of the time interval during which the deposition of the ''Scontrone calcarenites'' took place (see explanation in the text). **1**. Fine-grained turbidite sandstones; **2**. Gypsum; **3**. Marls and calcareous marls; **4**. Marly limestones; **5**. Calcilutites; **6**. Bioclastic calcarenites; **7**. Bioclastic calcarenites with oversized lithoclasts. The pictures labelled **A**–**E** are thin-section photographs showing the microfacies characteristics of the facies units distinguished in the *Lithothamnion* Limestone of the ''Scontrone Cemetery'' section. A. Medium-grained bioclastic packstone with thick-walled *Ammonia* sp. (left side of the photograph) and *Elphidium crispum* (upper right side). Inner carbonate ramp. B. Coarse-grained litho-bioclastic packstone showing a large fragment of *Heterostegina* (upper right side), *E. crispum* (centre of the photograph) and a red algal rhodoid (large dark patch in the lower left side). Proximal mid-ramp setting. C. Rhodolith floatstone with a large rhodoid set in a silty bioclastic matrix. The rhodoid, largely bored, appears discontinuously encrusted by bryozoans. D. Bioclastic packstone representative of a *Heterostegina* shell bed. Distal mid-ramp setting. E. Bioclastic packstone rich in *Orbulina universa* (e.g., in the centre and at the upper left side of the microphotograph) and bolivinids. Outer-ramp setting.

top of the *Lithothamnion* Limestone (Bellatalla, 1992; Danese, 1999). The pelagic condensed deposit at the top of the *Lithothamnion* Limestone corresponds, at the regional scale, to a moment of maximum flooding and maximum landward encroachment of the shoreline in the innermost portions of the carbonate ramp. It represents a key horizon useful for temporal correlations over vast areas of the Apulia Platform.

In the Scontrone area, as well as in the whole Majella region, the *Lithothamnion* Limestone is conformably overlain by spicule-rich marls (*Turborotalita multiloba* Marl) containing the marker *T. multiloba*, the common occurrence of which has been dated at 6.30 Ma (Kouwenhoven et al., 2006). In the ''Scontrone Cemetery'' section the *Lithothamnion* Limestone overlies the upper Albian-Turonian basinal resediments of the Rudist-bearing Calcarenite by means of a disconformity marking a remarkable lacuna. In the Roccamorice section the *Lithothamnion* Limestone overlies the middle-upper Miocene pelagic deposits of the *Orbulina* Limestone.

Detailed biostratigraphic investigations performed in northern Majella (Merola, 2007) led to the recognition of several important bioevents allowing the age definition of the upper portion of the *Orbulina* Limestone. In the Roccamorice section these events include:

- the first occurrence of the *Neogloboquadrina* group at 38 m from the base of the *Lithothamnion* Limestone;
- the last occurrence of *Globigerinoides subquadratus* at 31 m;
- the last occurrence of *Paragloborotalia siakensis* at 25 m;
- the first occurrence of *Neogloboquadrina acostaensis* at 18 m.

The first occurrence of the *Neogloboquadrina* group falls very close to the GSSP of the Tortonian stage, formally established in the Monte dei Corvi section (Ancona, Italy) and dated astronomically at 11.61 Ma (Hilgen et al., 2005). The last occurrence of *P. siakensis* marks the top of the N14 Zone of Blow (1969). The first regular occurrence of *N. acostaensis*, dating back to 10.4 Ma (Lourens et al., 2004b), is a base marker of the N16 Zone (Fig. 12). Therefore, the base of the *Lithothamnion* Limestone in the Roccamorice section is not older than the early Tortonian, while the top of the unit reaches the early Messinian both in the Roccamorice and Scontrone areas. Additional age constraints may be provided by the Cenozoic-Sequence Chronostratigraphy. The 3rd order Global T-R Sequences represented in Fig. 12 show in the Tortonian-early Messinian maximum regression surfaces at 9.32 Ma and 7.16 Ma. The unconformity between the *Orbulina* Limestone and the *Lithothamnion* Limestone recognized in the Roccamorice section 25 m above the FO of *N. acostaensis* should correspond to the base of the Tor2 Global T-R Sequence, while the massive upper portion of the interval c of the Roccamorice and "Scontrone Cemetery" sections most likely represents the regressive portion of the same Tor2 Sequence (Fig. 12). If this calibration is correct, the "Scontrone calcarenites" should correspond to the transgressive tract of the Tor2 T-R Sequence. Considering that during the Tortonian the Apulia Platform was a shelf characterized by a low-gradient ramp profile, we should expect that the sea-level rise caused a rapid transgression and an associated shoreline retreat over large areas of the platform. Consequently, the fossil vertebrates contained in the lower portion of the "Scontrone calcarenites", the latter representing the early transgression of the Tor2 T-R Sequence, should be slightly younger than 9.32 Ma.

Summing up the thickness of the "Scontrone calcarenites" (16–17 m) and the thickness of the rhodolith-rich facies of the *Lithothamnion* Limestone belonging to the Tor2 T-R Sequence (11–12 m) and considering the duration of the Tor2 Sequence (2.16 Myr), we obtain a value of the sedimentation rate (which in a shallow-water setting approximates the subsidence rate) ranging from 12.50 to 13.42 mm/ky. This value does not basically differ from the value of the subsidence rate (14.4 mm/ky) calculated by Carminati et al. (2007) on carbonate-ramp deposits cropping out in more western areas of the Central Apennines, temporally bracketed between 20 and 9.5 Ma. Applying the sedimentation-rate values obtained in the Scontrone area, the base of the rhodolith-rich limestones should lie at about 8 Ma. Therefore, the age of the "Scontrone calcarenites" is confined between 9.32 and 8 Ma.

The Scontrone bonebeds have recently been attributed to the Messinian by Freudenthal and Martín-Suárez (2010) based on similarities between the Scontrone vertebrate remains and the Gargano "Terre Rosse" faunal complex which is supposed to have a Messinian (or younger) age. This age attribution conflicts with the sedimentation-rate value estimated in carbonate-ramp systems not affected by flexural subsidence. If we assume that the "Scontrone calcarenites" have a Messinian age from their base (thus reducing the time interval from 2.16 to 0.86 Myr, i.e., from the base of the Me1 Global T-R Sequence and the FO of *T. multiloba*), the sedimentation rate changes from 12.50–13.42 to an unrealistic value of 34.88–37.20 mm/kyr.

In conclusion, we think that a Tortonian age around 9 Ma is the most reliable age for the Scontrone fossil vertebrates. This chronological attribution does not change significantly if we consider the vertebrate-bearing subaerial calcarenites lying on top of the transgressive, thin basal lithosome (interval a in Fig. 5), the expression of the Sequence Boundary between Tor1 and Tor2. In this case the transgressive calcarenites of the interval a would represent the highstand tract of the Tor 1 Sequence. Based on this evidence, we believe that an age revision of the Gargano vertebrate associations is highly desirable, considered the position of the fossil remains in "Terre Rosse" karstic-fissure fillings.

6. Summary

The Miocene deposits of Scontrone are well known among paleontologists for their conspicuous content of continental vertebrate remains (Rustioni et al., 1992). Most of these remains belong to peculiar tetrapod taxa, which in many cases show the effect of insularity and exhibit a striking similarity to those recognized in the "Terre Rosse" of the Gargano region. New detailed stratigraphic analyses have been carried out in the Scontrone area. The results of this study can be summarized in the following points:

- the Scontrone vertebrate remains are contained in marginal-marine carbonate ("Scontrone calcarenites"), locally present at the base of the *Lithothamnion* Limestone (Patacca et al., 2008a). The principal bonebed is represented by an eolian calcarenite draping the top of subtidal bars that mark the beginning of the Miocene transgression in the Scontrone area;
- the "Scontrone calcarenites" represent relic marginal-marine deposits that have escaped erosive ravinement during the early stage of the Tortonian transgression of the *Lithothamnion* Limestone over the Apulia Platform;
- based on a stratigraphic and paleoenvironmental analysis, the "Scontrone calcarenites" have been interpreted as originated in a wave-dominated river-mouth setting developed on a large, flat and semi-arid plain with low carbonate reliefs. Several facies associations have been recognized and a variety of habitats has been identified. They include subtidal swampy areas, intertidal flat dissected by creeks, tidal channels, and barrier bars;
- although a detailed taphonomic analysis of the vertebrate remains would be desirable to properly understand the genetic mechanisms that led to the origin of the bonebeds, we tentatively suggest that the lag features of the bonebeds resulted from the progressive removal of bony elements operated by winnowing on unsorted bone amassments that were previously accumulated on supratidal coastal bars by episodic floods;
- the age of the "Scontrone calcarenites" cannot be estimated through their paleontological content because of the absence of age-diagnostic fossils. However, correlations with the lower part of the *Lithothamnion* Limestone exposed in the Roccamorice area (northern Majella) indicate for the "Scontrone calcarenites" a Tortonian age around 8–9 Ma, and for the fossil vertebrates an age of about 9 Ma.

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