

PALEOENVIRONMENTAL RECONSTRUCTION OF THE OLIGOCENE TRANSGRESSION IN THE CENTRAL-EASTERN TERTIARY PIEDMONT BASIN (NW ITALY): INSIGHTS FROM STRATIGRAPHY, PALEONTOLOGY AND GAMMA-RAY EMISSIONS

LUCA ARENA^{1*}, MICHELE PIAZZA¹, KEI OGATA¹, FRANCESCA BOSELLINI² &
ANTONINO BRIGUGLIO¹

¹Dipartimento di Scienze della Terra, dell'Ambiente e della Vita, Università di Genova, Corso Europa 26, I-16132 Genova, Italy. E-mail addresses: luca.arena@edu.unige.it; michele.piazza@unige.it; kei.ogata@unige.it; antonino.briguglio@unige.it

²Dipartimento di Scienze Chimiche e Geologiche, Università di Modena e Reggio Emilia, Via Campi 103, I-41125 Modena, Italy. E-mail address: francesca.bosellini@unimore.it

*Corresponding author

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Abstract. This study presents the first integrated lithostratigraphical, paleontological and spectral gamma-ray (SGR) dataset from the central-eastern sector of the Tertiary Piedmont Basin (TPB). The TPB is a late- to post-orogenic sedimentary basin system deposited during a widespread marine transgression. The Molare Formation of the TPB records the evolution of shallow-marine depositional systems developed within a tectonically active basin during the Oligocene. By integrating stratigraphic, sedimentological, and paleontological observations, together with SGR data, from four stratigraphic sections (Sottovalle, Bric Rive, Lemme, and Bosio; Southeastern Piedmont, Italy), this work reconstructs paleoenvironmental conditions and assesses lateral variability in the central-eastern sector of the basin. The studied intervals are dominated by conglomerates and medium- to coarse-grained sandstones, recording high-energy shallow-marine sedimentation. Paleontological assemblages are dominated by Larger Benthic Foraminifera (LBF) and scleractinian corals, providing complementary constraints on water depth and energy conditions. SGR of Potassium (K), Uranium (U), Thorium (Th) and the derived Th/U ratio, measured along each succession, were used to evaluate terrigenous input and redox conditions. Results reveal pronounced lateral variability among the sections, with fossil-rich intervals corresponding to phases of reduced sediment input and relatively stable shallow-marine conditions, alternating with barren or poorly fossiliferous intervals associated with high-energy sedimentation and enhanced continental influence. The integrated dataset documents a siliciclastic system characterized by rapid environmental fluctuations driven by variable sediment supply and active tectonics. This study highlights the importance of combining paleontological and gamma-ray proxies to resolve complex depositional architectures in tectonically influenced shallow-marine basins such as the TPB.

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INTRODUCTION

Shallow-marine sedimentary systems developing along active basin margins commonly display complex depositional architectures resulting from the interaction of tectonics, sediment supply, and relative sea-level changes. Distinguishing the relative contributions of each one of these factors can be challenging, and the task becomes even more complex when attempting to isolate the influence of global climatic forcing imposed on local and regional controls. In this context, the Oligocene represents a transitional period, marked by short- and long-term oscillations between warmer and colder climatic phases, driving significant shifts in biodiversity and geochemical cycles (Lear et al. 2004; O'Brien et al. 2020). These environmental variations are recorded in sedimentary successions as modifications of biotic associations and lithological elements (Pälike et al. 2006; Alegret et al. 2008; Zachos et al. 2008; Zhang et al. 2013; Beddow et al. 2016).

The Tertiary Piedmont Basin (TPB), which developed at the junction between the Alpine and Apennine structural domains during the Oligocene, represents a particularly suitable setting in which to investigate these interactions. Its early sedimentary evolution was characterized by spatially variable continental to shallow-marine deposits accumulated during the progressive marine transgression, while tectonic activity strongly influenced basin geometry, accommodation space, drainage organization, and sediment dispersal (Mutti et al. 1995; Gelati et al. 1998; Quaranta et al. 2009; Maino et al. 2013; Soutter et al. 2022; Di Giulio et al. 2024). Under such boundary conditions, lateral facies variability may occur over short distances, complicating paleoenvironmental reconstructions based only on vertical stratigraphic successions (Mutti et al. 1995; Quaranta et al. 2009; Ghibaudo et al. 2014a, 2014b, 2019; Bahamonde et al. 2017; Matenco & Haq 2020; Zhu et al. 2024). Integrated, multi-proxy approaches are therefore essential to unravel the lateral and temporal heterogeneity of these systems.

Lithostratigraphic analysis provides the primary framework for identifying depositional processes, hydrodynamic conditions, and variations in sediment supply. Additionally, in tropical to subtropical shallow-marine settings of the Cenozoic, Larger Benthic Foraminifera (LBF) and scleractinian corals are widely used to reconstruct depositional envi-

ronments: whilst foraminifera are sensitive to water depth, hydrodynamic energy, light availability, substrate type and trophic conditions (Hallock & Glenn 1986; Cahuzac & Poignant 1997; Geel 2000; Beavington-Penney & Racey 2004; Briguglio & Hohenegger 2011; Oron et al. 2018; Gandolfi et al. 2023, 2025; Duijser et al. 2025; Eshed et al. 2025; Reymond et al. 2025), corals provide constraints on photic-zone conditions and sedimentation rates (Barnes & Lough 1996; Sanders & Baron-Szabo 2005; Eakin & Grottoli 2006; Allison et al. 2007; Lokier et al. 2009; Morsilli et al. 2012; Hibbert et al. 2016; Bosellini et al. 2024; Unger et al. 2026). Additionally, Spectral Gamma-Ray (SGR) analysis has proven to be an effective tool for identifying variations in terrigenous input and redox conditions, particularly in mixed carbonate-siliciclastic systems (Adams & Weaver 1958; Ruffell & Worden 2000; Fabricius et al. 2003; Schnyder et al. 2006; Giraldo-Gómez et al. 2024). Such integrated and combined approach is particularly effective in settings strongly shaped by tectonic activity and climatic changes, which act as primary controls on fluctuations in riverine sediment supply, as observed in the basal section of the TPB (Gelati et al. 1998; Quaranta et al. 2009; Maino et al. 2013; Di Giulio et al. 2024).

The central-eastern sector of the TPB provides an ideal target for applying this integrated approach because it preserves laterally variable, coarse-grained shallow-marine deposits formed during the earliest stages of the Oligocene transgression. This study therefore aims to reconstruct the paleogeography, paleoenvironments, and the sedimentary settings of the first stages of the transgression that characterized the central-eastern sector of the TPB during the early Oligocene. In this framework, the local tectonic and climatic modulation produced thick and localized coarse-grained deltaic deposits that are here investigated with a focus on the interaction between sedimentary settings and benthic communities.

GEOLOGICAL SETTING

The TPB is a late- to post-orogenic sedimentary basin that evolved in a wedge-top position on the Alpine thrust belt. From the late Eocene to the Miocene, it was filled predominantly by marine deposits recording a widespread marine transgression,

which characterized the entire Northwestern Italy (Lorenz 1969; Gelati & Gnaccolini 1987; Mutti et al. 1995; Quaranta et al. 2009; Capponi et al. 2013). The development of the TPB was strongly influenced by both tectonic and eustatic controls, with syn-sedimentary tectonics and regional sea-level changes shaping its depositional history (Gelati & Gnaccolini 1987; Quaranta et al. 2009; Ghibaudo et al. 2014a, 2014b, 2019 and references therein). The tectonic evolution of the Alpine arc and Apennine chains during Oligocene-Miocene time played a decisive role in driving subsidence and structural reconfiguration of the basin and surrounding Western Alps, resulting in its complex stratigraphic architecture (Maino et al. 2013; Federico et al. 2014, 2015; Di Giulio et al. 2024). As a result, the TPB displays numerous features indicative of syn-sedimentary tectonic activity, including erosional surfaces, angular unconformities, and mass transport deposits (Ghibaudo et al. 2014a, 2014b, 2019 and references therein). These features point to a dynamic depositional system influenced by both tectonic activity and fluctuating sediment supply potentially driven by Oligocene climatic oscillations (Pälike et al. 2006; Alegret et al. 2008; Zachos et al. 2008; Zhang et al. 2013; Beddow et al. 2016).

In the study area, the TPB depositional history starts with the continental deposits of the Costa di Cravara Breccia (upper Eocene?) and the continental to shallow-marine deposits of the Molare Formation (Oligocene) that unconformably rest on a crystalline basement represented by the structural stacking of Ligurian Alps units, here composed of Voltri Massif and Sestri-Voltaggio Zone units (Capponi et al. 2001, 2008, 2009, 2016; Federico et al. 2022; Fioraso et al. 2023 and references therein). These units are formed by metaophiolites and related metasedimentary covers, together with metasedimentary rocks belonging to the paleoeuropean margin and strongly involved in the tectono-metamorphic events linked to the Alpine Orogeny (Federico et al. 2022; Fioraso et al. 2023 and references therein). Moreover, both the Ligurian Alps and the related oldest sedimentary cover (i.e.: the Costa di Cravara Breccia and Molare Formation), are affected by the Oligocene tectonics characterized by WSW-ENE to SW-NE shortening, realized by a very complex fault system linked to the movement of the Sestri-Voltaggio Line (Capponi et al. 2001, 2008, 2009, 2016 and references therein).

The Molare Formation often lies directly on the metamorphic substrate, because of the discontinuous areal distribution of the Costa di Cravara Breccia, and is characterized by an overall transgressive trend that continues upward into the Rigoroso Marl Formation (upper Oligocene-Lower Miocene, sandy to silty and marly deposits of relatively deep marine environment) (Lorenz 1969; Gelati & Gnaccolini 1987; Mutti et al. 1995; Capponi et al. 2013; Federico et al. 2022; Fioraso et al. 2023; and references therein). The Molare Formation (thickness 50-150 m) is largely composed of generally coarse clastic rocks including conglomerates and breccias deriving from the underlying substrate, here largely made by metaophiolites (Lorenz 1969; Mutti et al. 1995; Quaranta et al. 2009; Briguglio et al. 2021a). The lowermost portion of the Molare Formation is characterized by fluvial to alluvial deposits, deltaic sedimentation, small and scattered coral buildups, and a general coarse-grained deposit (Bonci et al. 2021; Briguglio et al. 2021b; Bosellini et al. 2024 and references therein). Such characteristics are all visible in the here considered four stratigraphic sections located in southeastern Piedmont, between the towns of Sottovalle to the east and Bosio to the west (Fig. 1).

MATERIALS AND METHODS

Stratigraphy and lithology

Detailed field logging was conducted at each outcrop to document lithology, fossil content, and possible key markers for stratigraphic correlations (Fig. 2). The four studied sections (Sottovalle, Bric Rive, Lemme, and Bosio) are arranged along an approximately east-west alignment. The GPS coordinates were recorded for each outcrop to precisely locate the studied sections and to assess the geographical distances between them and place them within the regional geological and structural framework: Sottovalle (44°38'53.509"N, 8°52'12.691"E), Bric Rive (44°39'6.721"N, 8°50'40.819"E), Lemme (44°38'54.222"N, 8°49'54.232"E), and Bosio (44°38'29.839"N, 8°47'19.601"E). The points were mapped in QGIS on a geological sketch map derived from the original data of "Banca Dati Carta Geologica del Piemonte, 2021" (Piana et al. 2017) and with the Digital Terrain Model (DTM) from Tarquini et al. (2023) (Fig. 1).

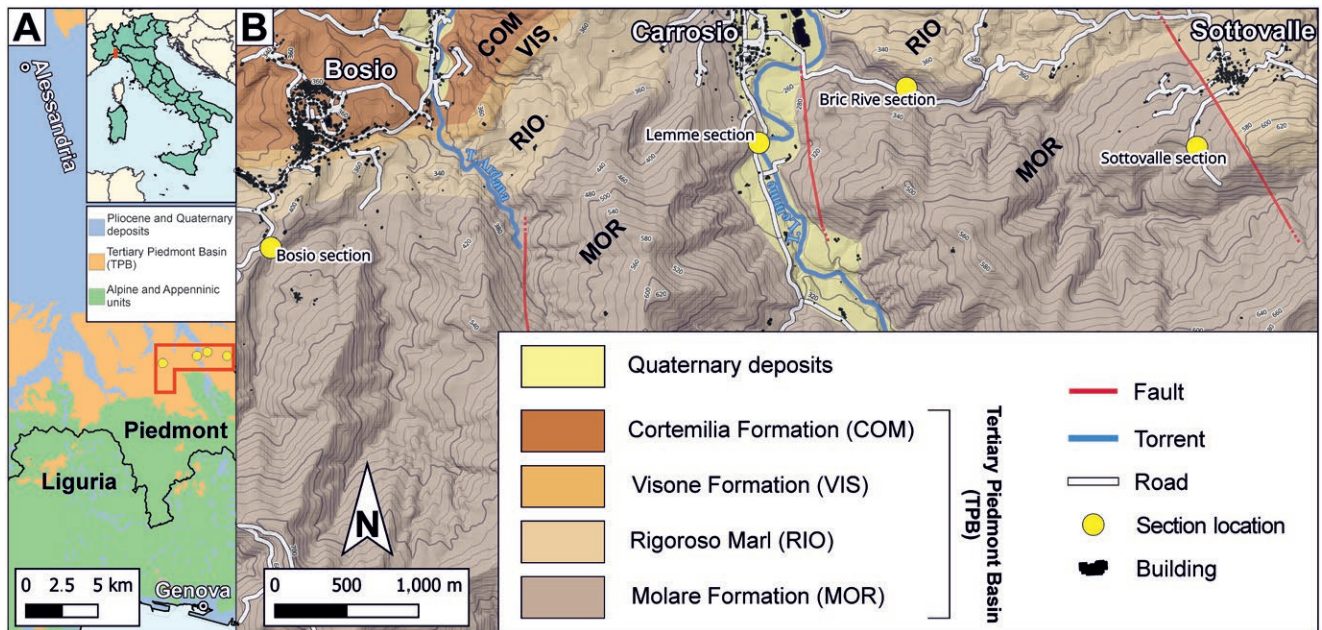


Fig. 1 - A. Location of the investigated sites along the Piedmont-Liguria sector (NW Italy) of the TPB, with the study area outlined in a red square and section localities marked by yellow dots. B. Geological sketch map of the studied area, showing the studied sections.

Fossils analysis

Paleontological analyses were carried out to characterize fossil assemblages and assess their stratigraphic distribution. Macrofossils were examined in the field through qualitative analysis to characterize the fossil content of the studied successions and to distinguish specimens preserved *in situ* from those transported. Samples were collected from all sections, treated with hydrogen peroxide (70% H_2O , 30% H_2O_2) to disaggregate the sediment, and then wet-sieved using a series of meshes with sizes of 2 mm, 500 μm , 250 μm , 125 μm and 63 μm . The coarser residues (2 mm, 500 μm , and 250 μm fractions) were examined under a custom-made Optech GZ808 optical stereomicroscope for qualitative analysis of the micro-fossils content, with particular attention to Larger Benthic Foraminifera (LBF), while the presence or absence of other fossil groups was also recorded. For taxonomic identification of the LBF, equatorial sections were prepared (Fig. 3), whereas both longitudinal and transverse thin sections were made for the colonial corals (Fig. 4).

Gamma-ray analysis

Natural gamma-ray spectra were measured along all sections using a portable Codevintec Gamma Ray Surveyor Vario (VN6 NaI(Ti)), characterized by a collimated analytical spot of 5 cm radi-

us, to quantify the concentrations of Uranium (U) and Thorium (Th), expressed in parts per million (ppm), and Potassium (K), expressed in percentage (%). Natural gamma radiation originates from the decay of mineral-hosted radioisotopes (^{238}U , ^{232}Th , and ^{40}K) which emit specific energy levels unique to each isotope (e.g., Giraldo-Gómez et al. 2024). U and Th measured concentrations were used to calculate the Th/U ratio, a commonly applied proxy that provides insight into depositional environments (Adams & Weaver 1958; Jones & Manning 1994; Wignall & Twitchett 1996; Basu et al. 2009; Kouamelan et al. 2020; Briguglio et al. 2021a; Giraldo-Gómez et al. 2024). The interpretation of the Th/U ratio varies according to its value: Th/U < 2 indicates marine reducing settings and anoxic water conditions; Th/U ratios between 2 and 7 are associated to normal marine conditions; Th/U > 7 suggests sedimentation influenced by continental inputs and oxygenated conditions (Adams & Weaver 1958; Cowan & Myers 1988; Wignall & Twitchett 1996; Ruffell & Worden 2000; Dypvik & Harris 2001; Fabricius et al. 2003; Basu et al. 2009; Kouamelan et al. 2020; Cao et al. 2021; Giraldo-Gómez et al. 2024).

Because values reported as zero may represent concentrations below the effective detection or reporting limit of the gamma-ray instrument rather than the true absence of the measured el-

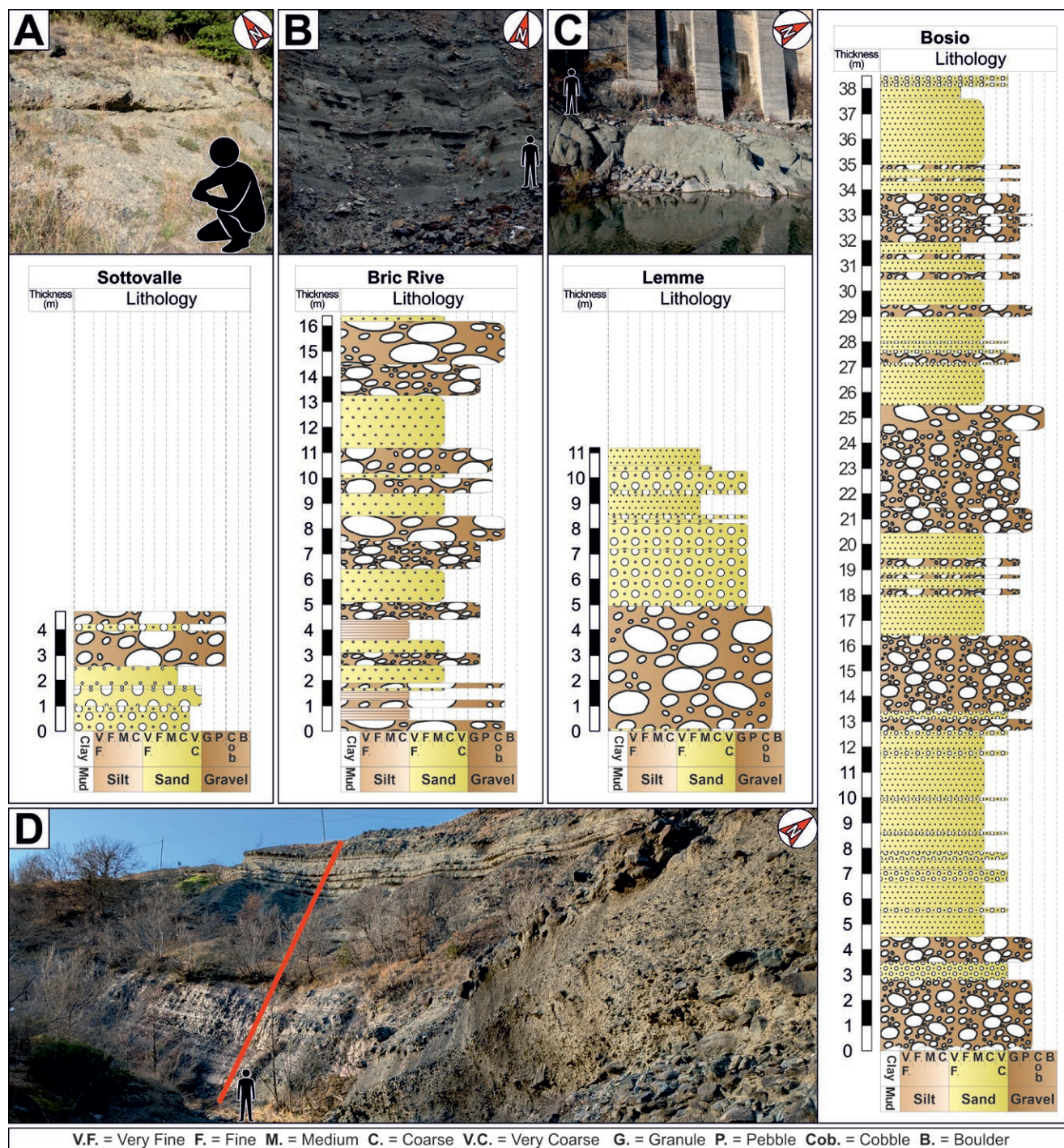


Fig. 2 - A. Photo of the Sottovalle outcrop and measured section. B. Photo of the Bric Rive outcrop and measured section. C. Photo of the Lemme outcrop and measured section. D. Photo of the Bosio outcrop and measured section. Sediment grain-size classification modified from Wentworth (1922).

ement (Chiozzi et al. 2000), treating them as true zeros could produce undefined Th/U ratios and consequently bias their paleoenvironmental interpretation (Martín-Fernández et al. 2003; Palarea-Albaladejo et al. 2014). To minimize these numerical artefacts, a constant value of $C = 0.009$, slightly lower than the minimum non-zero value recorded by our gamma-ray instrument (0.01), was added to

all measurements prior to ratio calculation.

The SGR measurements were performed along all successions avoiding those conglomeratic beds where the matrix was scarce. Gamma ray emissions from large metaophiolitic clasts would have provided misleading data and have therefore been omitted. Also, diagenetic processes may have locally modified the original SGR signal through the

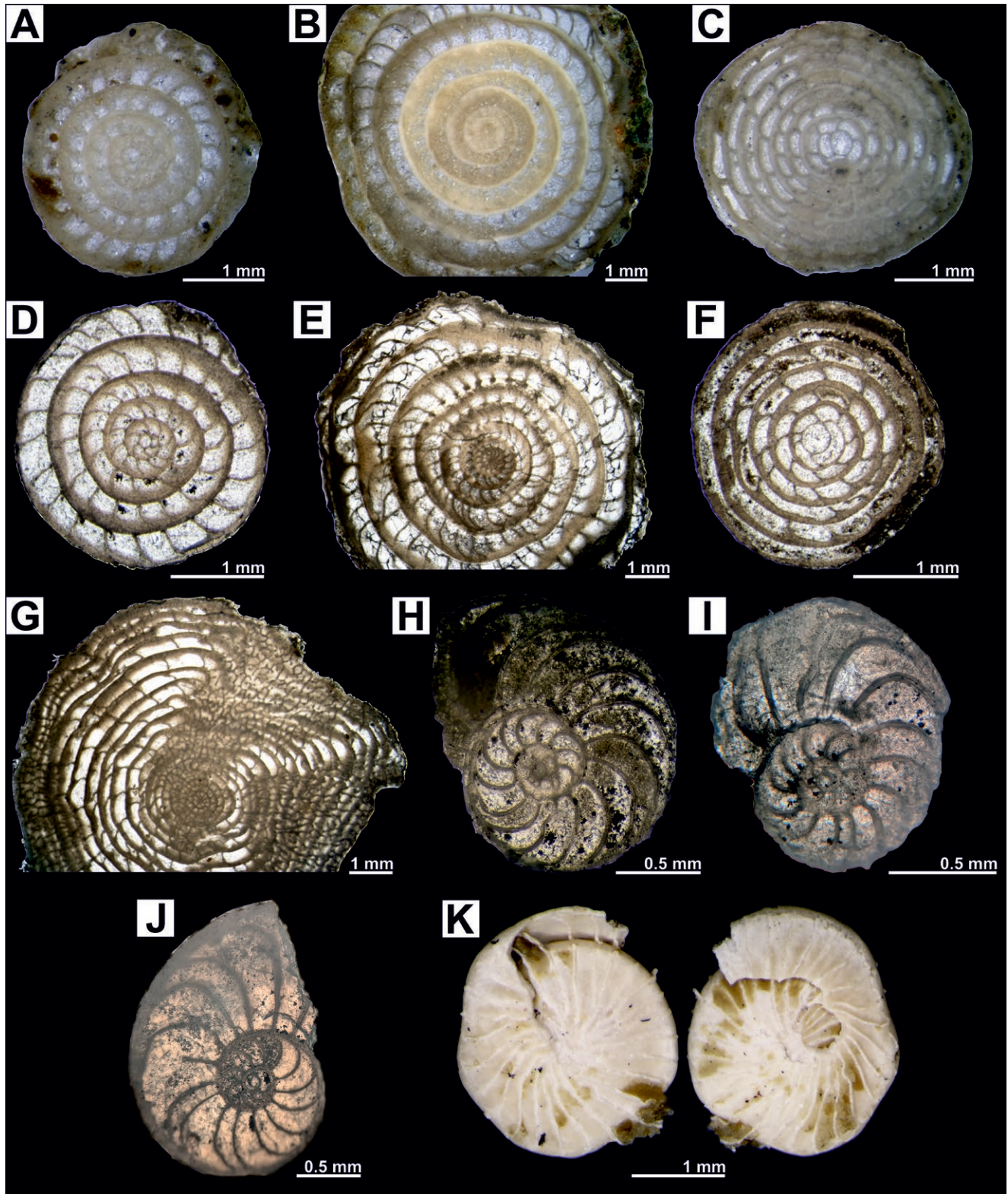
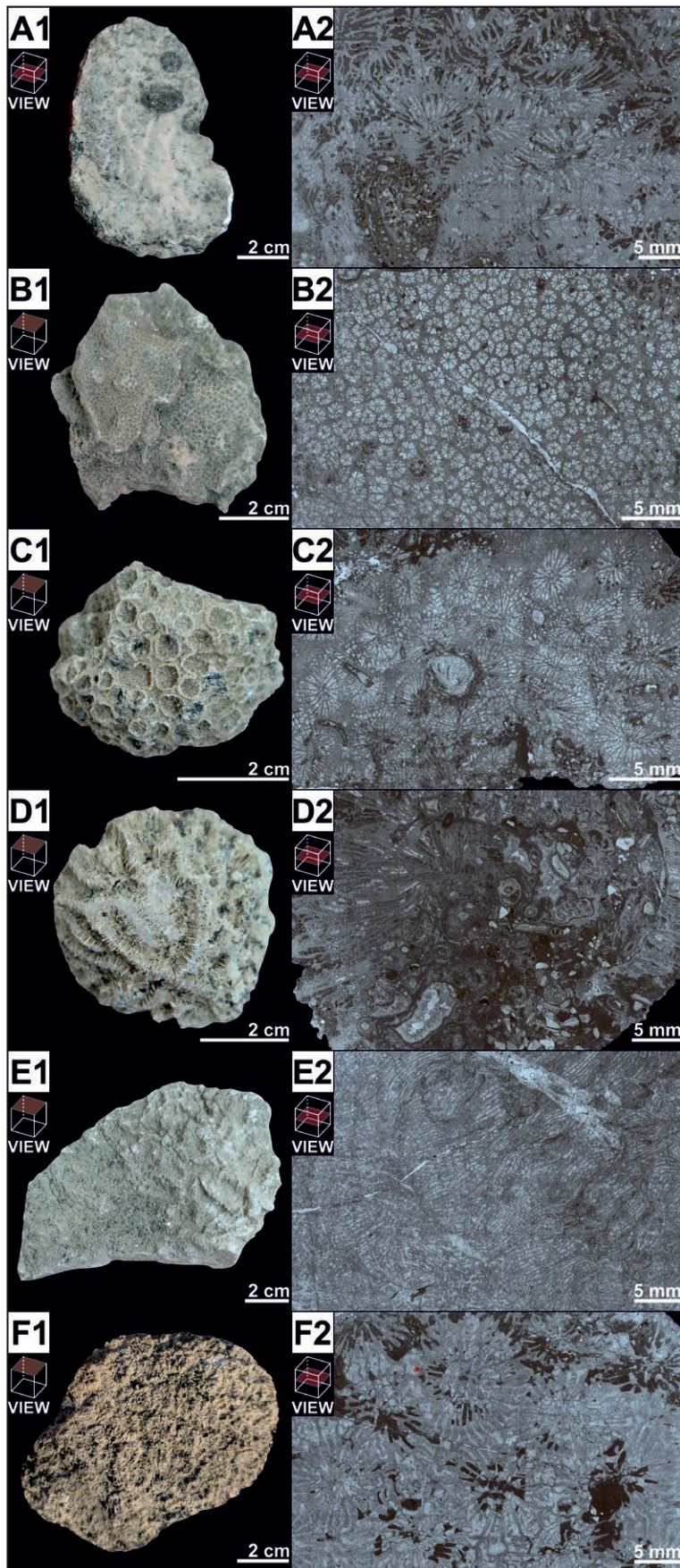


Fig. 3 - A. *Nummulites vascus* (A form) from the Sottovalle section (sample SOT.001). B. *Nummulites vascus* (B form) from the Sottovalle section (sample SOT.004). C. *Nummulites fichteli* (A form) from the Sottovalle section (sample SOT.004). D. *Nummulites vascus* (A form) from the Lemme section (sample LM.010). E. *Nummulites vascus* (B form) from the Lemme section (sample LM.008). F. *Nummulites fichteli* (A form) from the Lemme section (sample LM.010). G. *Nummulites fichteli* (B form) from the Lemme section (sample LM.010). H. *Nummulites kecskemetti* from the Bosio section (sample BOS.017). I. *Nummulites kecskemetti* from the Sottovalle section (sample SOT.001). J. *Operculina complanata* from the Sottovalle section (sample SOT.004). K. *Amphistegina* sp. from the Bosio section (sample BOS.025).



post-depositional redistribution of radioactive elements, particularly U, whose mobility is strongly influenced by redox conditions and fluid circulation (Ehrenberg & Svana 2001; Hladil et al. 2003; Raddadi et al. 2005). In the Lemme section, measurements were acquired at 10 cm intervals owing to the favorable morphology of the outcrop. In the remaining sections, variable measurement intervals were adopted due to the limited accessibility in certain areas.

RESULTS

Stratigraphy and Lithology

The studied sections record gravelly-to-sandy sedimentation, resulting in coarse- to fine-grained conglomerates and sandstones. These rocks exhibit both skeletal and interstitial fractions largely consisting of serpentinite clasts (single broken crystals and rock fragments) supplied from the local substrate. In agreement with this provenance, the washed residues contain variable amounts of serpentine fibrous

Fig. 4 - A1. Photo of *Variabilifavia confertissima* (polished slab) from the Bric Rive section (sample BRV.CR.1). A2. Thin section of *Variabilifavia confertissima* from the Bric Rive section (sample BRV.CR.1). B1. Photo of *Astrocoenia bistellata* from the Bric Rive section (sample BRV.CR.2). B2. Thin section of *Astrocoenia bistellata* from the Bric Rive section (sample BRV.CR.2). C1. Photo of *Antiguastrea lucasiana* from the Bric Rive section (sample BRV.CR.3). C2. Thin section of *Antiguastrea lucasiana* from the Bric Rive section (sample BRV.CR.3). D1. Photo of *Variabilifavia confertissima* from the Bric Rive section (sample BRV.CR.4). D2. Thin section of *Variabilifavia confertissima* from the Bric Rive section (sample BRV.CR.4). E1. Photo of *Hydnophyllia* sp. from the Lemme section (sample LM.CR.1). E2. Thin section of *Hydnophyllia* sp. from the Lemme section (sample LM.CR.1). F1. Photo of *Agathiphyllia apenninica* from the Lemme section (sample LM.CR.2). F2. Thin section of *Agathiphyllia apenninica* from the Lemme section (sample LM.CR.2).

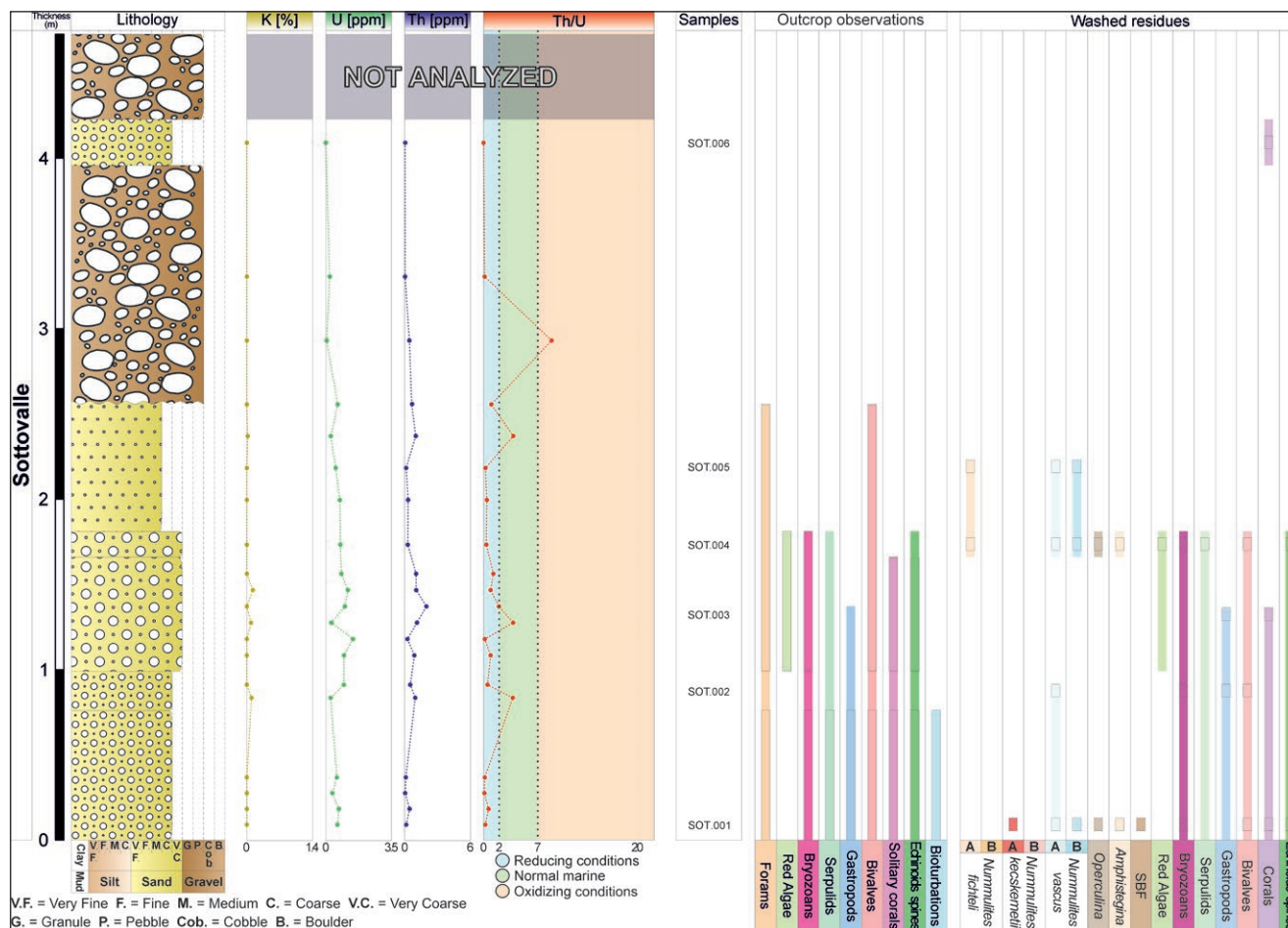


Fig. 5 - Sottovalle measured section, SGR data and paleontological content. Sediment grain-size classification modified from Wentworth (1922).

broken crystals (i.e., asbestos), with the highest concentrations occurring in the Bric Rive samples, and progressively lower amounts found in those from the Lemme, Sottovalle, and finally Bosio sections.

The Sottovalle section (Fig. 5), the easternmost one, is characterized by a potentially coarsening-upward trend. The lower part of the succession consists of very coarse sandstone, which is overlain by an interval consisting of two sharp-based conglomeratic beds separated by a medium-grained sandstone layer (Fig. 2A).

The Bric Rive section (Fig. 6) consists of conglomerate beds interbedded with coarse sandstones. Finer-grained intercalations are rare and mainly restricted to the basal part of the section (Fig. 2B).

In the Lemme section (Fig. 7), the succession starts with a basal conglomerate overlain by an alternation of medium- and coarse-grained sandstones. Toward the upper part of the section, medium-grained sandstones become more frequent (Fig. 2C).

Further west, the Bosio section (Fig. 8), the thickest one here studied, displays a higher degree of vertical variability, with repeated alternations of conglomeratic and medium- to coarse-grained sandstone layers. Finer-grained intercalations occur in the upper part of the section (Fig. 2D).

The studied sections display distinct vertical stacking patterns from east to west, consistent with lateral variability in depositional conditions within the fan-delta system. Although differences in logged thickness and the absence of an unequivocal marker bed preclude direct bed-by-bed correlation, comparison at the scale of facies associations, fossil assemblages, and overall depositional trends remains meaningful.

Paleontological results

Fossil abundance and preservation vary markedly among the sections and across stratigraphic intervals along the studied transect. The easternmost section, Sottovalle (Fig. 5), is fossilif-

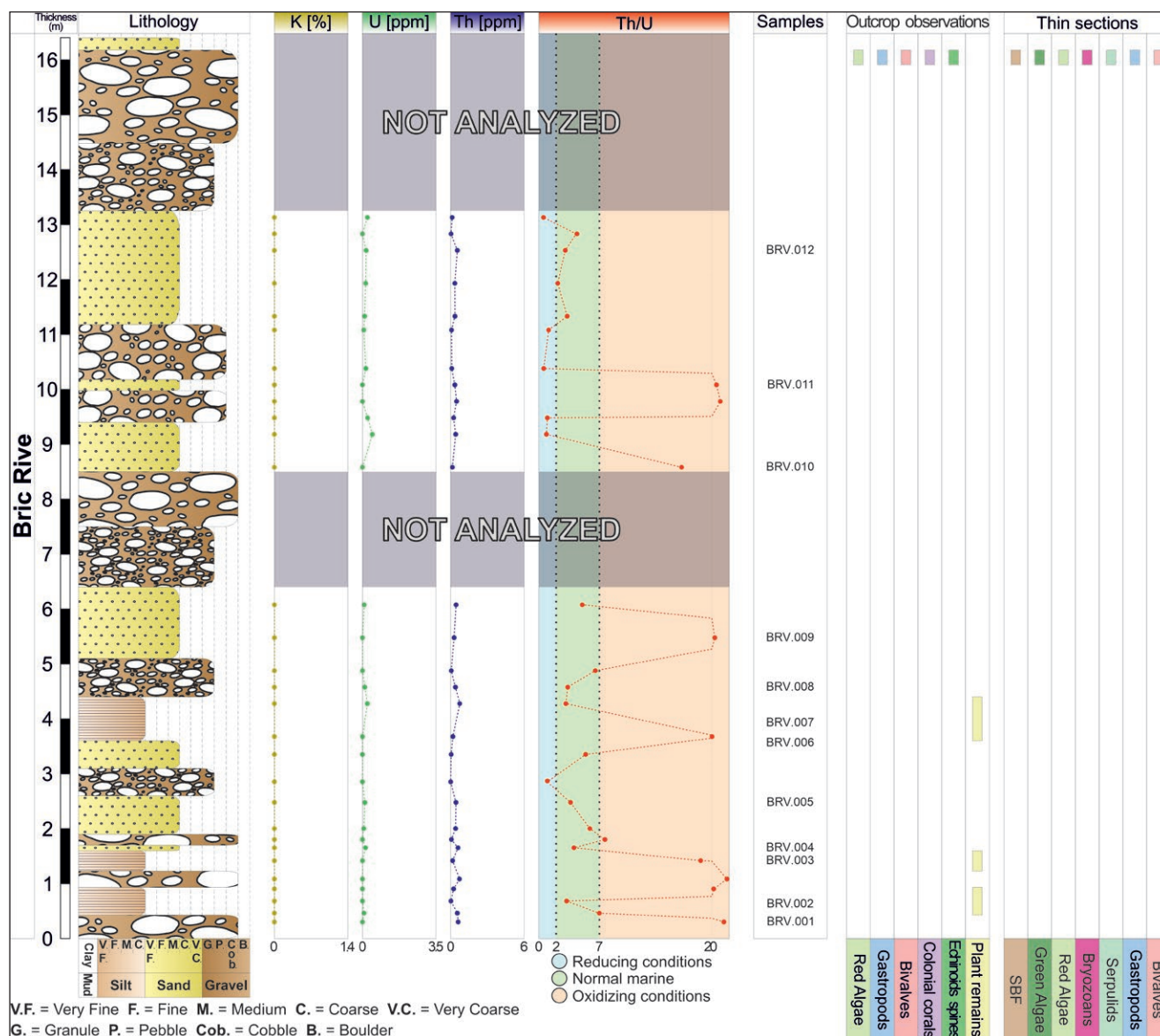


Fig. 6 - Bric Rive measured section, SGR data and paleontological content. Sediment grain-size classification modified from Wentworth (1922).

erous throughout its entire thickness, except within the conglomeratic layers, and contains a diversified, well preserved assemblage including bivalves, gastropods, serpulids, solitary corals, bryozoans, echinoid spines, and nummulitids, together with intense bioturbation. The nummulitid assemblage consists exclusively of *Nummulites vascus* Joly & Leymerie, 1848 (both A and B forms) (Fig. 3A, B), *Nummulites fichteli* Michelotti, 1841 (A form) (Fig. 3C), rare *Nummulites kecskemetii* Less, 1991 (Fig. 3I) and *Operculina complanata* (Defrance in Blainville, 1822) (Fig. 3J). This site is the only one where abundant solitary corals occur; in contrast with all other sections where colonial corals are present as well.

The Bric Rive section (Fig. 6) is almost barren, fossils occur only at the top of the uppermost

conglomeratic bed, where red and green calcareous algae, colonial corals, rare gastropods, small benthic foraminifera (SBF), and serpulids are present. The corals occur in growth positions, and they are represented by *Variabilifavia confertissima* (Reuss, 1868) (sample BRV.CR.1 and BRV.CR.4) (Fig. 4A1, A2, D1, D2), *Astrocoenia bistellata* (Catullo 1856) (BRV.CR.2) (Fig. 4B1, B2), and *Antiguastrea lucasiana* (Defrance, 1826) (BRV.CR.3) (Fig. 4C1, C2). The encrusting red algae assemblage was documented by Fravega et al. (1988) (mainly Sporolithales and Corallinales), who also reported *Dipsastraea* (*Favia*) cf. *irregularis* and *Mycetoseris* sp. as components of the coral association. The coral assemblage consists of prevailing encrusting forms and subordinate, small, massive coral colonies.

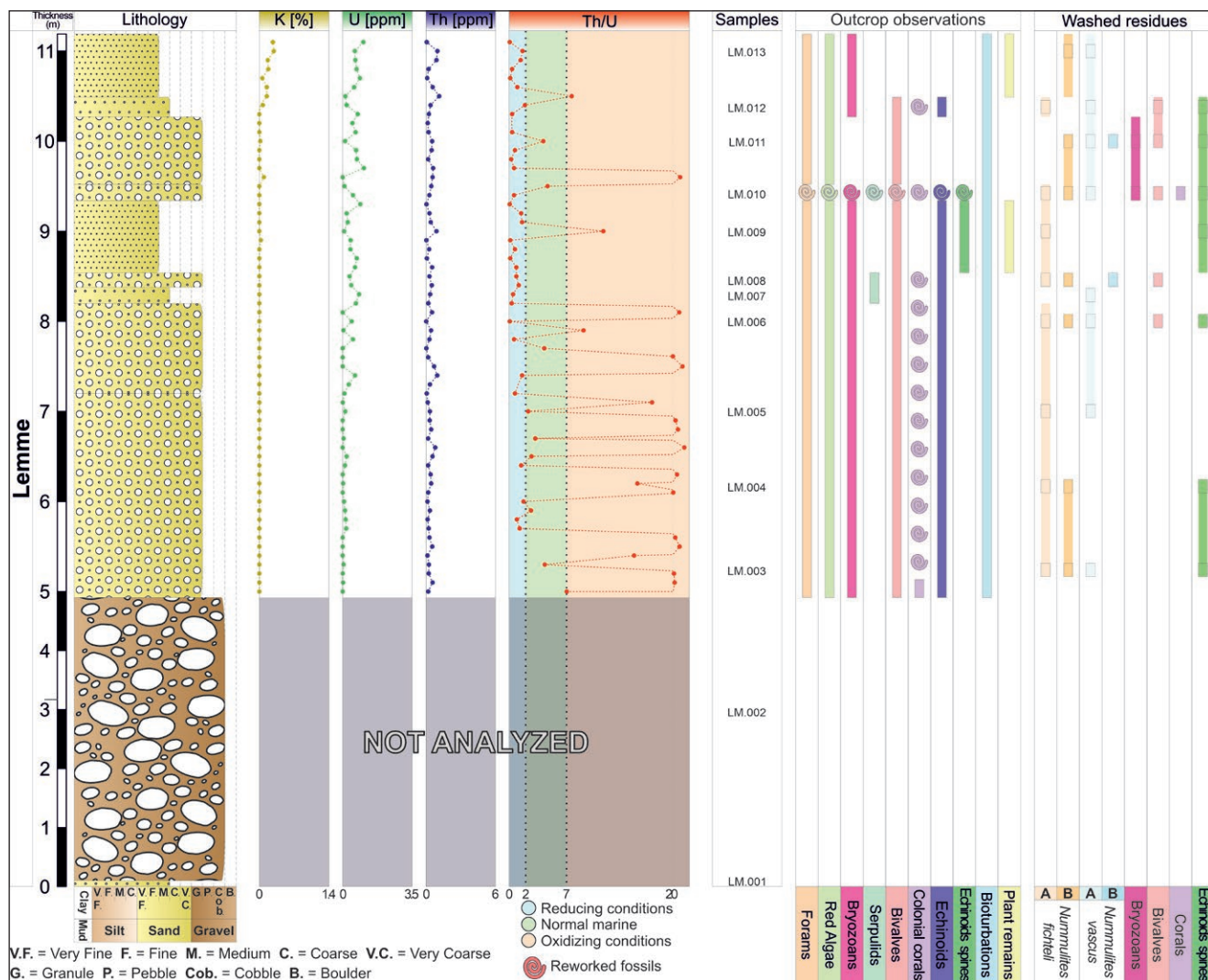


Fig. 7 - Lemme measured section, SGR data and paleontological content. Sediment grain-size classification modified from Wentworth (1922).

The basal conglomerate of Lemme section (Fig. 7) is colonized by massive coral colonies, among which *Hydnophyllia* sp. (sample LM.CR.1) (Fig. 4 E1, E2) and *Agathiphyllia apenninica* (d'Achiardi, 1868) (LM.CR.2) (Figure F1, F2) are present. The overlying coarse sandstones contain abundant LBF, infaunal echinoids, and bivalves, associated with bryozoans, and red algae. Serpulids and plant remains occur in the uppermost intervals. Washed residues contain only nummulitids and echinoid spines, whereas SBF and planktonic foraminifera (PF) are absent. The nummulitid assemblage includes *N. vascus* (Fig. 3D, E) and *N. fichteli* (Fig. 3F, G), both represented by A and B generations.

Westward, the Bosio section (Fig. 8) is characterised by a basal fossil-barren interval followed by ichnofossil-bearing sandstones, fossiliferous sandstones, and conglomerates alternations. These

fossiliferous strata display a skeletal assemblage including bivalves, red algae, LBF, SBF, very rare PF, gastropods, serpulids, and both solitary and colonial corals (small, massive and branching colonies). Among the colonial ones, due to poor preservation, only the genus *Stylophora* could be identified. The LBF assemblages include *Nummulites kecskemetii* (Fig. 3H), and *Amphistegina* spp. (Fig. 3K).

Overall, the east-west transect exhibits an unevenly distribution of the fossil content, i.e.: abundant and well diversified in the eastern part (Sottovalle section), rare and concentrated in few beds in the central sector (Bric Rive section), and abundant and regularly distributed in the westernmost part (Lemme and Bosio sections).

Gamma-ray results

A total of 192 SGR measurements were

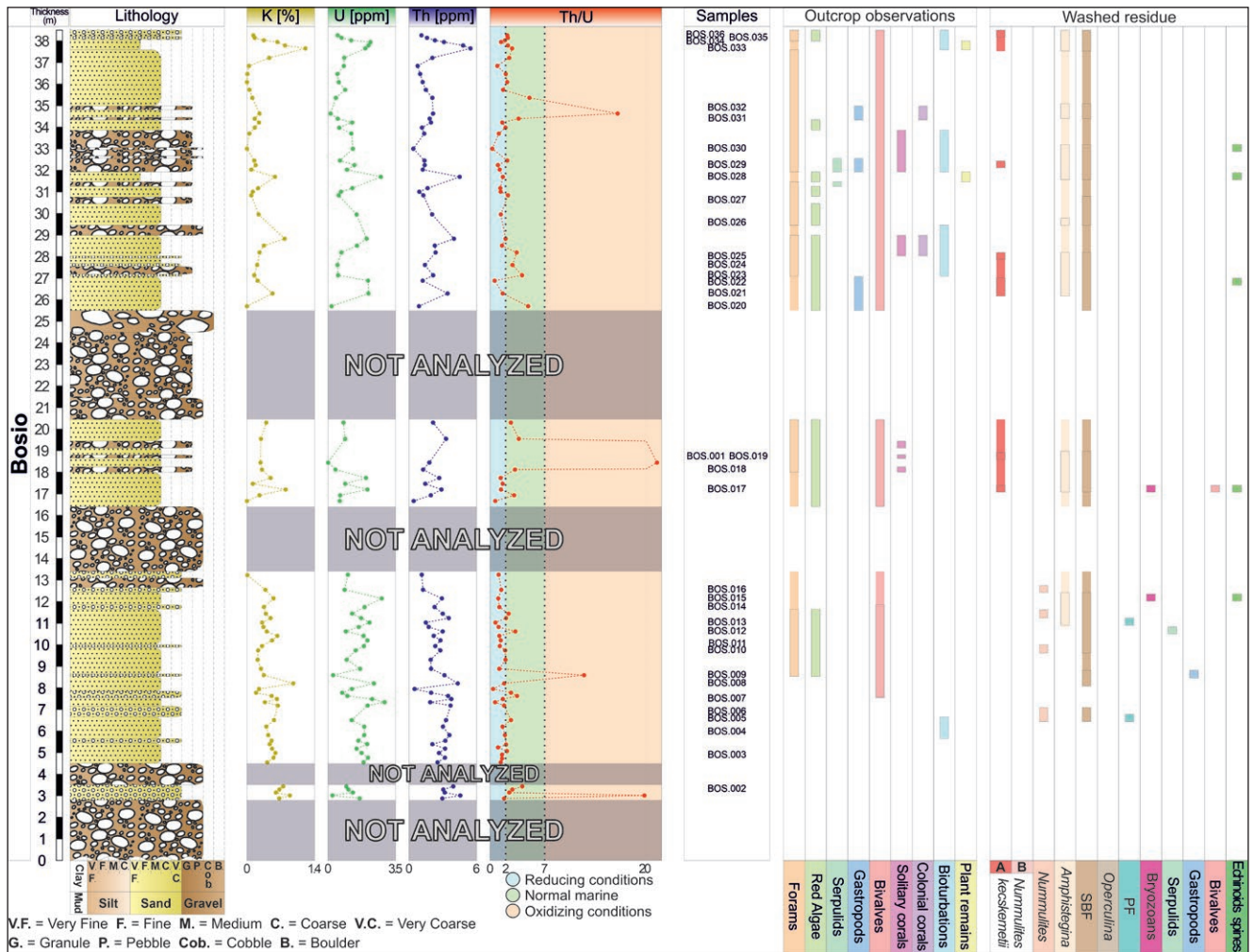


Fig. 8 - Bosio measured section, SGR data and paleontological content. Sediment grain-size classification modified from Wentworth (1922).

collected along the four studied sections. Element concentrations show significant inter-section variability along the transect. In the easternmost section, Sottovalle ($n = 20$) (Fig. 5), K values are very low (0–0.13%), U is low (0–1.45 ppm), and Th ranges from low to moderate values (0.02–1.98 ppm), with all elements generally decreasing upward in the section. Th/U ratios are mostly < 2 , with a single value > 7 associated with a conglomeratic level.

In the central part of the study area, Bric Rive ($n = 30$) (Fig. 6) is characterized by the absence of K, very low U (0–0.47 ppm), and low Th values (0–0.74 ppm). Th/U ratios show wide variability (0.54–54.33), with the highest values corresponding to conglomeratic beds.

The Lemme section ($n = 62$) (Fig. 7) shows low K values (0–0.29%) that increase upward toward sandy intervals. U concentrations (0–1.07 ppm) progressively increase up-section, while Th (0.03–1.14 ppm) remains consistently present, with

local peaks in finer sandstones. Th/U ratios range from 0.05 to 64.33, with higher values concentrated between 5 and 8 m.

In the westernmost section, Bosio ($n = 80$) (Fig. 8) K exhibits higher values (0–1.21%) compared to the other sections. U (0.01–2.74 ppm) and Th (0.38–5.46 ppm) are continuously present and show broadly covariant fluctuations. Th/U ratios range from 0.29 to 180, though most values are < 7 . Overall, SGR values increase westward along the transect, from very low concentrations in the eastern part to higher K, U, and Th contents in westernmost one, i.e. the Bosio section.

DISCUSSION

Biostratigraphy

The nummulitid assemblages provide biostratigraphic constraints for the studied sections.

Species of the genus *Nummulites* are the most abundant, particularly *N. fichteli* and *N. vascus*, while *N. kecskemetii* rarely occurs. *N. fichteli* ranges from SBZ21 to SBZ22A, *N. vascus* from SBZ21 to SBZ22B (Cahuzac & Poignant 1997), and *N. kecskemetii* from SBZ22B to SBZ23 (Özcan et al. 2009, 2010; Less et al. 2018; Parente & Less 2019). The co-occurrence of these species constrains the studied sections to the middle to upper Rupelian (Oligocene) (Briguglio et al. 2026; Arena & Briguglio 2026). This result refines the chronostratigraphy of the Oligocene marine transgression in this sector of the TPB with a slightly younger age than previously reported (Quaranta et al. 2009; Maino et al. 2013; Ghibaudo et al. 2019). However, the taxonomic composition and stratigraphic ranges of the available assemblages do not permit high-resolution correlation among the four sections.

Paleontology

LBF play a key role in reconstructing the depositional environments of the studied successions, as they are extremely abundant except in the Bric Rive section, and dominate the foraminiferal assemblages (Fig. 3). The presence of LBF indicates shallow marine conditions, characterized by depths well within the photic zone. Symbiont-bearing foraminifera are best adapted to highly illuminated seafloors and warm oligotrophic conditions but can easily occur in occasionally turbid waters with sustained mesotrophic conditions (Hallock & Glenn 1986; Hohenegger et al. 2000; Renema & Troelstra 2001; Beavington-Penney & Racey 2004; Hohenegger 2004; Briguglio et al. 2017; Goeting et al. 2018). The association of symbiont-bearing taxa such as LBF with filter-feeding organisms, particularly bivalves and serpulids, supports fluctuating trophic conditions at the seafloor that did not consistently support a strictly oligotrophic fauna (Mutti & Hallock 2003; Zabihi Zoeram et al. 2015; Arena et al. 2024).

Another key taxon for the current paleoenvironmental reconstruction is represented by scleractinian corals (Fig. 4). They occur in all investigated sections and constitute the only fossil remains readily observable in the Bric Rive section. Scleractinian zooxanthellate reef corals typically thrive in clear shallow-water environments, although several of them are known to partially tolerate elevated turbidity and increased sedimentation under persis-

tent terrigenous input (Lokier et al. 2009; Sanders & Baron-Szabo 2005; Bosellini et al. 2024). In the TPB, during the Oligocene, coral reefs (including fringing, barrier, and patch reefs) were widespread (Pfister 1980, 1985; Fravega et al. 1987; Quaranta et al. 2009; Bosellini et al. 2024). These reef ecosystems display a relatively high taxonomic diversity, with approximately 10–15 genera and 12–20 species reported (Perrin & Bosellini 2012). In contrast, the coral assemblages observed in the sections described here exhibit extremely low taxonomic richness and are mainly composed of scattered colonies belonging to taxa able to withstand turbid waters, including *Antiguastrea lucasiana*, *Variabilifavia confertissima*, *Agathiphyllia apenninica*, *Hydnophyllia* sp., and *Dipsastraea (Favia)* cf. *irregularis*, as well as small coral thickets and carpets of limited lateral extent (Fantini Sestini 1960; Nebelsick et al. 2000; Silvestri et al. 2011). Massive and meandroid corals, particularly those characterized by robust skeletons, high morphological plasticity, and relatively large calices, may efficiently remove deposited particles and tolerate intermittent sediment veneering (Rogers 1990; Stafford-Smith & Ormond 1992; Stafford-Smith 1993; Sanders & Baron-Szabo 2005). The occurrence of *A. lucasiana* and *V. confertissima* is particularly significant because these taxa have also been documented as major components of sediment-resistant, massive to domal coral assemblages developed in turbid prodelta environments elsewhere in the TPB (Bosellini et al. 2024). The small size, scattered distribution, and limited lateral continuity of the colonies, together with the absence of a dense interlocking framework, suggest that coral growth was repeatedly interrupted by terrigenous sediment input.

Paleoenvironmental reconstruction

The four investigated sections, although located within a limited geographic area, record markedly different depositional histories. Because high-resolution correlation among the sections is not possible, the available data do not allow the observed variability to be uniquely partitioned into spatial and temporal components. This pronounced lateral variability reflects the nature of the Molare Formation depositional system, where shallow-marine environments were repeatedly influenced by episodic progradation of localized fan deltas (flood-dominated systems; Mutti et al. 2003), variable hydrodynamic

energy, and tectonically and climatically modulated sediment fluxes (Gelati & Gnaccolini 1987; Quaranta et al. 2009; Ghibaudo et al. 2019; Piana et al. 2021). Within this context, different depositional environments can be distinguished based on lithological evidence, sedimentological interpretation, and finally paleontological associations (Fig. 9).

Inner Fan-Delta. The Bric Rive succession (Fig. 6) is dominated by conglomerates and coarse-grained sandstones and displays a highly discontinuous lateral and vertical sedimentary record with very limited fossil content. The near absence of fossils suggests deposition under highly energetic and unstable conditions, likely linked to strong terrigenous input and proximity to an active deltaic system. Such conditions are widely recognized as unfavorable for the establishment and preservation of benthic communities (Fravega et al. 1988; Mutti et al. 1995; Barbieri et al. 2020; Bhattacharya et al. 2020). The Bric Rive section is thus interpreted as the more proximal and axial part of a fan-delta system (Fig. 9).

The sudden appearance of a coral assemblage (Fig. 4) at the top of the last conglomeratic layer of the measured section marks a significant paleoenvironmental shift (Fig. 6). The presence of colonial corals in growth position and red algae indicates temporary stabilization of the substrate and reduced sedimentation rates, allowing benthic colonization of the seafloor (Fravega et al. 1988). Comparable short-lived colonization phases have been documented in shallow-marine settings subjected to fluctuating sediment supply, where brief reductions in terrigenous input permit the development of coral communities even in otherwise stressed environments (Sanders & Baron-Szabo 2005; Lokier et al. 2009; Silvestri et al. 2011; Briguglio et al. 2021a; Bosellini et al. 2024).

Gamma-ray data further support this interpretation (Fig. 6): the absence of K throughout the section, together with very low U and Th concentrations, suggests a sedimentary system dominated by coarse-grained detrital input, limiting the retention of radioactive elements typically associated with fine-grained sediments (Fabricius et al. 2003). The highly variable Th/U ratios, frequently exceeding 7, indicate strong and recurrent continental influence under oxidizing conditions (Adams & Weaver 1958; Ruffell & Worden 2000; Basu et al. 2009). The variability of these ratios reflects unstable depositional

conditions, consistent with sedimentation in a proximal deltaic or nearshore environment.

Overall, the Bric Rive section records an environment dominated by high-energy sedimentation and strong continental input, punctuated by a brief but stable interval that allowed for coral colonization (Fig. 9). This section exemplifies the extreme lateral variability of the depositional environments occurred during the sedimentation of the lowest part of the Molare Formation (Lorenz 1969; Gelati & Gnaccolini 1987; Mutti et al. 1995; Gelati et al. 1998; Quaranta et al. 2009; Maino et al. 2013; Federico et al. 2014, 2015; Ghibaudo et al. 2014a, 2014b, 2019; Di Giulio et al. 2024).

Distal Inner Fan-Delta. The Bosio section (Fig. 8), due to its large thickness, records the most complex and heterogeneous sedimentation among the studied successions. The basal part of the section, characterized by thick conglomeratic and coarse-grained sandstone layers is completely devoid of fossils: this suggests deposition under high-energy conditions, likely related to strong continental input and proximity to the axial part of an active deltaic system. Similar sedimentary architectures, dominated by coarse-grained deposits and barren fossil intervals, have been widely interpreted as indicative of unstable, high-energy settings influenced by syn-sedimentary tectonics and high sediment supply during the early stages of deposition of the Molare Formation (Mutti et al. 1995; Gelati et al. 1998; Quaranta et al. 2009; Ghibaudo et al. 2014a, 2014b). The absence of both body fossils and bioturbation structures in this lowermost interval supports the interpretation of a dynamic and unstable seafloor, unfavourable for benthic colonization (Fig. 8).

The first evidence of biological activity appears immediately after the first conglomerates, where well-preserved ichnofossils indicate a temporary stabilization of the substrate and the establishment of benthic communities. Sandy to muddy sedimentation and reduced hydrodynamic energy are well-known factors promoting the development and preservation of trace fossils in shallow-marine environments affected by variable sediment supply (Gingras & MacEachern 2012; MacEachern et al. 2012; La Croix et al. 2022). These finer intervals occurring in the Bosio section likely represent a relative local decrease in hydrodynamic conditions, allowing benthic organisms to colonize the seafloor (Fig. 8).

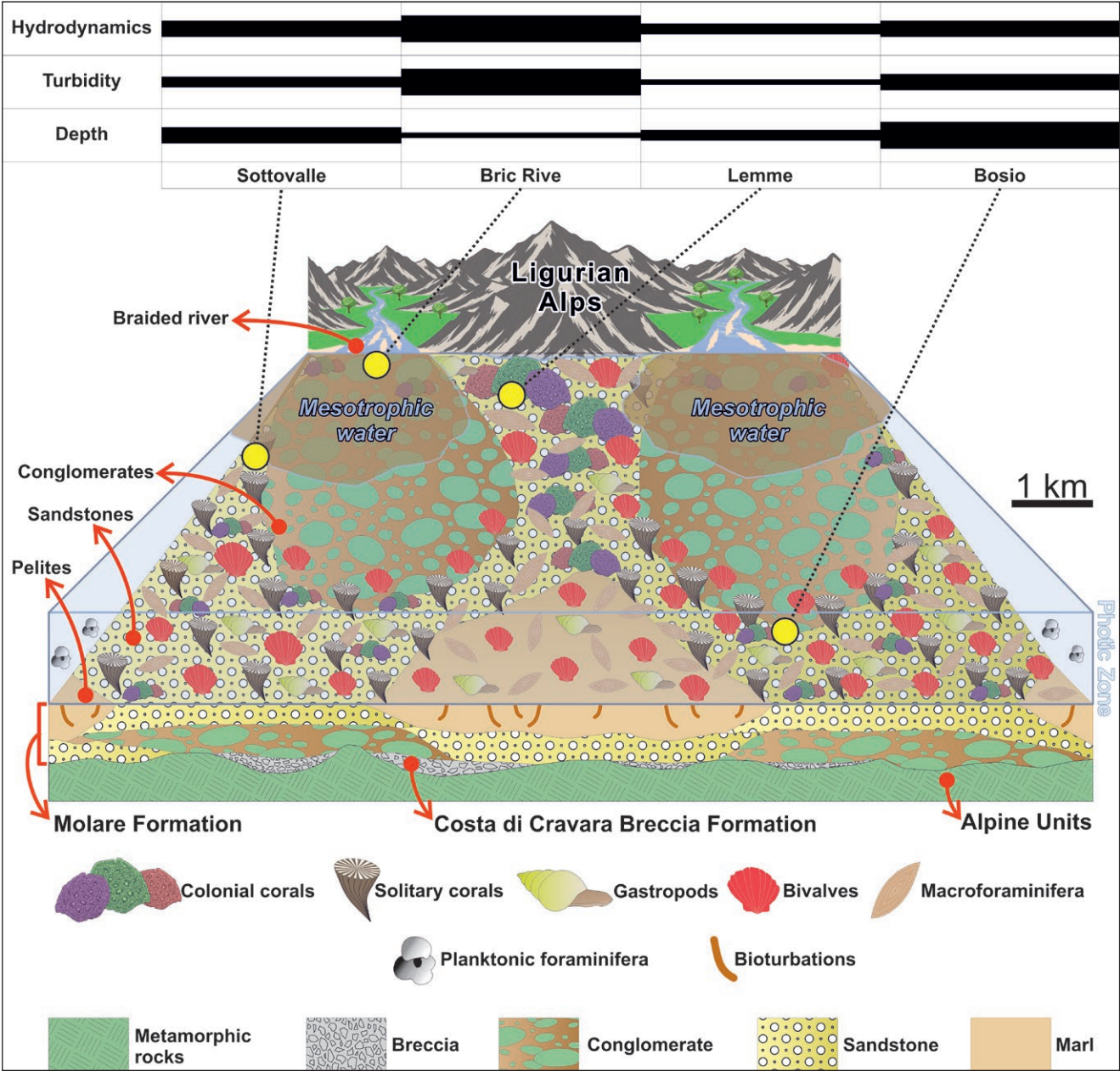


Fig. 9 - Paleoenvironmental reconstruction of the central-eastern TPB.

The continuous alternation of sandstone and conglomerate bed packages, together with the recurrent presence of bivalves, red algae, LBF (Fig. 3), and corals, reflects fluctuating environmental conditions. Such bedsets alternations are typical of shallow-marine settings periodically influenced by deltaic progradation, retreat and lateral migration, where episodic increases in sediment supply and energy levels alternately promote biotic colonization and ecological stress (Mutti et al. 1995; Bizzarri & Baldanza 2020; Di Bella et al. 2021). The occurrence of colonial corals further supports deposition within the photic zone, under conditions of moderate to

high turbidity compatible with intermittent terrigenous input (Sanders & Baron-Szabo 2005; Quaranta et al. 2009; Briguglio et al. 2021a; Bosellini et al. 2024). The rare occurrence of PF and SBF such as lagenids and bolivinids may indicate direct connection to the open sea and perhaps slightly deeper-water conditions, possibly enhanced by an increase of the delta slope or a tectonic compartmentalization of the depocenter (Fig. 9).

Gamma-ray data are consistent with this interpretation (Fig. 8), showing persistent but highly variable concentrations of K, U, and Th throughout the section. The predominance of Th/U ratios below

7 indicates generally marine depositional conditions, whereas short-lived peaks above this threshold suggest intermittent continental influence and oxidizing conditions related to enhanced detrital input (Adams & Weaver 1958; Ruffell & Worden 2000; Basu et al. 2009).

Overall, the Bosio section documents a transitional shallow-marine environment strongly influenced by nearby deltaic systems, where repeated shifts between high-energy sedimentation and quieter phases controlled the distribution, diversity, and preservation of fossil assemblages (Fig. 9). Such a framework is compatible with deposition in a distal inner fan-delta setting and highlights the spatial complexity of depositional environments within the earliest depositional stages of the basal TPB, a characteristic feature of its tectono-sedimentary evolution (Lorenz 1969; Gelati & Gnaccolini 1987; Mutti et al. 1995; Gelati et al. 1998; Quaranta et al. 2009; Maino et al. 2013; Federico et al. 2014, 2015; Ghibaudo et al. 2014a, 2014b, 2019; Di Giulio et al. 2024).

Outer Fan-Delta with increasing deltaic influence. The Sottovalle section (Fig. 5) consists of a relatively continuous sandstone-dominated succession containing a rich and diverse fossil assemblage. The abundance of both macro- and microfossils, including symbiont bearing taxa and filter feeders, LBF (Fig. 3), solitary corals, bryozoans, echinoid spines, and red algae, suggests deposition within the photic zone in a shallow-marine environment affected by moderate hydrodynamic energy and fluctuating trophic conditions (Hallock & Glenn 1986; Mutti & Hallock 2003; Beavington-Penney & Racey 2004; Briguglio et al. 2017; Ayyat 2022).

Gamma-ray data (Fig. 5) indicate very low K values throughout the section. In contrast, U and Th concentrations show an inverse relationship, a pattern commonly observed in marine settings where redox conditions and organic matter availability exert strong control on U enrichment (Cochran et al. 1986; Jones & Manning 1994; Khaustova et al. 2021). The predominance of Th/U ratios below 7 supports a marine depositional environment, with only one value exceeding this threshold within a conglomeratic layer, suggesting a brief episode of enhanced continental sediment input (Adams & Weaver 1958; Basu et al. 2009; Gama & Schwark 2022).

The upward increase in grain size and the replacement of fossiliferous sandstones by largely fossil-barren conglomeratic beds record a shift to-

ward higher-energy conditions and stronger deltaic influence. A localized Th/U excursion within one conglomeratic bed is consistent with enhanced detrital input, although it does not define a systematic upward trend. This facies change is compatible with progradation or lateral migration of an active fan-delta lobe. However, because of the limited logged interval and lithostratigraphic constraint, an episodic sediment-supply pulse or the preservation of only part of a larger stacking cycle cannot be excluded. This section thus records an outer fan-delta succession showing a local tendency toward increasing deltaic influence (Fig. 9). Similar vertical alternations, from relatively stable shallow-marine conditions to more proximal delta-influenced settings, have been documented elsewhere during the early stage of the basal TPB depositional history and interpreted as the result of combined tectonic and sedimentary controls (Gelati et al. 1998; Quaranta et al. 2009; Ghibaudo et al. 2019).

Outer Fan-Delta with waning deltaic influence. The Lemme section (Fig. 7) documents a complex depositional history marked by significant environmental fluctuations. The basal conglomeratic layer indicates high-energy conditions and intense sediment transport, likely associated with proximal deltaic or high-relief coastal systems. Well-developed coral colonies (Fig. 4) preserved in growth position at the top of this conglomerate suggest a short-lived phase of environmental stabilization during which reduced sedimentation rates temporarily allowed coral communities to develop before being buried by renewed sediment influx (Pfister 1980; Sanders & Baron-Szabo 2005; Briguglio et al. 2021a; Bosellini et al. 2024).

The overlying succession is dominated by fossil-rich sandstones containing abundant LBF, bivalves, irregular echinoids, red algae, and bryozoans. The dominance of *Nummulites fichteli* and *Nummulites vascus* (Fig. 3) indicates shallow-marine conditions within the photic zone, characterized by moderate energy levels and fluctuating trophic conditions (Hallock & Glenn 1986; Beavington-Penney & Racey 2004; Hohenegger 2004; Briguglio et al. 2017; Renema 2018; Ayyat 2022). The absence of SBF and PF suggests environmental stress related to high sedimentation rates or turbidity, a pattern commonly observed in mixed carbonate-siliciclastic systems (Nebelsick et al. 2000; Leckie & Olson 2003; Di Bella et al. 2021). However, a hydrody-

namic and taphonomic control cannot be excluded, because wave- and current-induced sorting may redistribute foraminiferal tests according to their size, shape, and density and preferentially winnow smaller tests from high-energy coastal deposits (Kontrovitz et al. 1978; Li et al. 1998; Fischel et al. 2018).

Gamma-ray data show a progressive increase in K content toward the upper part of the section, coinciding with finer-grained sandy layers (Fig. 7). This trend reflects an increase in clay-rich sedimentation and a relative deepening or reduction in hydrodynamic energy (Fabricius et al. 2003; Giraldo-Gómez et al. 2024). Several Th/U peaks exceeding 7 in the lower part of the section indicate strong continental influence and oxidizing conditions related to enhanced deltaic input (Adams & Weaver 1958; Ruffell & Worden 2000; Basu et al. 2009). Upsection, the decrease in Th/U values suggests a transition toward more stable marine conditions, although intermittent terrigenous input persisted.

Overall, the Lemme section records the evolution from an initial high-energy, delta-influenced environment to a quieter shallow-marine setting, periodically disrupted by renewed sediment supply (Fig. 9). Such a framework suggests the progressive deactivation of an outer fan-delta setting, or an inner fan zone depositional area. This evolution highlights the dynamic interplay between sedimentation, ecological colonization, and environmental stress in the basal TPB (Lorenz 1969; Gelati & Gnaccolini 1987; Mutti et al. 1995; Gelati et al. 1998; Quaranta et al. 2009; Maino et al. 2013; Federico et al. 2014, 2015; Ghislaudo et al. 2014a, 2014b, 2019; Di Giulio et al. 2024).

Paleogeographic reconstruction of the study area

The integration of sedimentological, paleontological, and SGR data allows the four studied sections to be placed within a coherent paleogeographic framework (Fig. 9). Despite their close geographic proximity, the sections record markedly different depositional conditions, reflecting the lateral variability that characterized the earliest shallow-marine sedimentation of the Molare Formation. The Sottovalle, Bric Rive, and Lemme sections are interpreted as different sectors of the same flood-dominated fan-delta system. Within this system, Bric Rive represents the most proximal and high-energy inner fan-delta setting, whereas

Sottovalle and Lemme record outer fan-delta environments characterized by different degrees of activity and sediment supply. In contrast, the Bosio section displays a distinct lithostratigraphic, paleoecological, and geochemical signature and is therefore interpreted as part of a separate fluvial system.

This interpretation is consistent with the spatial distribution of the studied sections within the inner sector of the eastern Ligurian Alps, comprising the Voltri Massif and the Sestri-Voltaggio Zone. In this area, late-orogenic Oligocene tectonics was chiefly governed by the activity of the Sestri-Voltaggio Line, which gave rise to a complex faults system that segmented the tectonic pile and influenced the early stages of TPB sedimentation (Capponi et al. 2001, 2009, 2016 and references therein). Such tectonic activity produced, even over short distances, a rugged substrate and an articulated hydrographic network, that determine a rather complicated depositional setting. Consequently, the Sottovalle, Bric Rive, and Lemme sections, which record deposition related to a single fluvial system, occur in close geographic proximity to the Bosio section, which instead documents sedimentation within a distinct sediment-routing system (Fig. 9).

CONCLUSIONS

The integrated analysis of lithostratigraphic, paleontological, and SGR data from the Sottovalle, Bric Rive, Lemme, and Bosio sections provides new insights into the paleoenvironmental evolution of the Molare Formation within the central-eastern sector of the TPB. Biostratigraphic data based on LBF constrain the studied successions to the middle to upper Rupelian (Oligocene), indicating that sedimentation occurred during the early stages of the TPB marine transgression.

The combined sedimentological and paleontological evidence reveals both vertical and lateral variability in depositional environments across a relatively small area. The easternmost sections (Sottovalle, Bric Rive, and Lemme) record different sectors of a flood-dominated fan-delta system fed by the same drainage, likely defined by tectonically structured, small-scale catchments with high slope gradients. In this framework, the Bric Rive section represents the most proximal conditions, interpret-

ed as an inner fan-delta environment characterized by coarse-grained sedimentation and scarce fossil abundance and preservation. The Lemme section reflects an inactive outer fan-delta sector, where phases of reduced sedimentation allowed the temporary development of coral colonies and diverse benthic assemblages. The Sottovalle section records a more stable outer fan-delta environment characterized by fossil-rich sandstones and relatively continuous shallow-marine conditions.

In contrast, the Bosio section displays a markedly different sedimentary and paleoecological signature. Its lithostratigraphic organization, fossil assemblages, and geochemical patterns suggest deposition within a distinct distal fan-delta system fed by the same clastic source as the previous system. The occurrence of more persistent finer sandy intervals, higher SGR values, and a more diverse microfaunal assemblage indicate a depositional setting controlled by a different fluvial system. The Bosio section represents a separate system located across the Sestri-Voltaggio structural zone. This configuration emphasizes the influence of inherited topography and Oligocene tectonic activity on the early shallow-marine sedimentation of the TPB.

Overall, the results highlight the importance of lateral facies variability in the Molare Formation and demonstrate how closely spaced sections may record distinct sediment-routing systems within tectonically active shallow-marine basins. The integration of paleontological proxies with spectral gamma-ray data proves particularly effective in resolving these complex depositional patterns and provides new constraints on the paleogeographic organization of the central-eastern sector of the TPB during the Rupelian.

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Data Availability Statement. The data supporting the results of this research are available upon request. Interested researchers may contact the corresponding author to obtain access.

TAXONOMIC APPENDIX

Larger Benthic Foraminifera

Amphistegina d'Orbigny, 1826
Nummulites fichteli Michelotti, 1841 †
Nummulites kecskemetii Less, 1991 †
Nummulites vascus Joly & Leymerie, 1848 †
Operculina complanata (Defrance in Blainville, 1822)

Corals

Agathiphyllia apenninica (d'Achiardi, 1868) †
Antiguastrea lucasiana (Defrance, 1826) †
Astrocoenia bistellata (Catullo, 1856) †
Dipsastraea (Favia) cf. *irregularis* (Chevalier, 1971)
Hydnophyllia Reis, 1889 †
Mycetoseris Reis, 1889 †
Stylophora Schweigger, 1820
Variabilifavia confertissima (Reuss, 1868) †

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