The stratigraphy of seep-impacted sediment in the Verghereto marls (Santa Sofia, Italy): insights into the Late Miocene evolution of the Romagna foredeep

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ABSTRACT

The paper focuses on the stratigraphy of the upper portion of the Verghereto marls cropping out in the S. Sofia area of the Northern Apennines in order to highlight the evolution of the Middle Miocene Romagna foredeep. The examined succession is mainly composed of quite homogeneous and structureless marls with a fining-upward grain-size trend. The upper portion of the Verghereto marls hosts numerous bedding-concordant seep-carbonate bodies, aligned parallel to the tectonic contact with the overlying Ligurian and Epiligurian units. The biostratigraphic study indicates an age spanning from the late Serravallian (MNN7) to early Tortonian (MNN8). This new dating completes the previous studies on adjacent outcrops and constrains the age of the Ligurian emplacement in this area. The examined Verghereto marls represents the sedimentation on a structural high (the Verghereto high) characterised by hemipelagites, fine-grained turbidites and seep-carbonates associated with sedimentary instability. Moderate sediment instability of fine-grained deposits is confined to the temporary slopes of the structural high, triggered by methane-rich fluid expulsion exploiting structural elements of the ridge, rather than to gravitational emplacements from more internal areas. During the lower Tortonian, the fine-grained sedimentation draping the Verghereto high ended, interrupted by the emplacement of the Ligurian-Epiligurian overthrust.

KEY-WORDS: foredeep, seep-carbonates, calcareous nannofossils, Miocene, Northern Apennines.

INTRODUCTION

The Marnoso-Arenacea formation is a spectacular turbiditic succession (about 3000 m thick) deposited in the Umbro-Marchean foredeep between the late Burdigalian and the early Messinian (Ricci Lucchi, 1986). The enormous quantity of sediment records the progressive migration of the foreland system due to the propagation of the thrust front of the Apennine accretionary wedge towards the north-east (Argnani & Ricci Lucchi, 2001; Roveri et al., 2002). Such propagation determined the formation of a complex foredeep, segmented by synsedimentary structural highs. Synsedimentary detachment folds, related to blind reverse faults, have been proposed to explain the genesis of the intrabasinal highs, successively evolved in fault-propagation folds and in thrusts delimiting a series of partially connected sub-basins, due to the limited lateral continuity of the submarine structural reliefs (Delle Rose et al., 1991; Benini et al., 1991; De Donatis & Mazzoli, 1994).

Sedimentation on structural highs is mainly characterised by hemipelagites, fine-grained turbidites, glauconite-rich sediments and seep-carbonates associated with sedimentary instability and testifying a strict relationship between the growth of structural highs and circulation of fluids (Dela Pierre et al., 2010; Argentino et al., 2019; Conti et al., 2021a). The fine-grained sediments and their enclosed seep-carbonates have been interpreted by some authors as mass transport complexes derived by more internal areas and fully detached from their original intrabasinal highs (Landuzzi, 2004; Lucente & Pini, 2008; Tinterri & Tagliaferri, 2015). Nevertheless, the constant occurrence of unreworked seep-carbonates within the fine-grained sediments draping the structural highs (pelitic interval of Conti et al., 2021a) suggests that these sediments are in primary position and the moderate sedimentary instability is related to methane-rich fluid expulsion (Atwood, 2015; Argentino et al., 2019; Conti et al., 2021b). In the Romagna Apennines (S. Sofia area) well exposed outcrops of the pelitic succession closing the Marnoso-Arenacea formation (Verghereto marls) host many seep-carbonates at the contact with the Ligurian nappe. This specific situation is particularly favorable to investigate the relationships among the evolution of structural highs, the release of methane-rich fluids and the genesis of deformed, slumped bodies enclosed in the succession. We report a detailed field stratigraphy and new biostratigraphic data on the Verghereto marls enclosing seep impacted deposits and their occurrence, with the aim of (i) highlighting the lithostratigraphy of the Verghereto marls, still poorly defined, and (ii) to better understanding the evolution of the Verghereto intrabasinal high that conditioned the sedimentation of the Marnoso-Arenacea formation. Moreover, the precise dating of the sediment hosting seep-carbonates is a significant tool to constrain the temporal relation among the Apennine tectonic structures, the expulsion of fluids and the overriding of the accretionary wedge in this area.

GEOLOGICAL SETTING

The Northern Apennine chain is an orogenic NE-verging wedge, formed by the convergence and collision between the European and Africa plates, with the interposition of Adria and Corsica-Sardinia microplates. During the collision (late Oligocene-to Recent) the internal oceanic units (Ligurian nappe), previously deformed and accreted, were thrust over the continental units deposited on the Adria microplate, represented by Tuscan and Umbro-Romagna-Marchean units (Peccerillo & Frezzotti, 2015; Malusà et al., 2016). Collisional stage is realised by the subduction of the Adria under the Corsica-Sardinia lithosphere coupled with the flexuring of the foreland and the formation of foredeep basins, progressively migrating towards NE (Argnani & Ricci Lucchi, 2001; Barchi et al., 2012). The turbidites of the Marnoso-Arenacea formation are deposited in a Miocene foredeep basin formed in front of the migrating Northern Apennine orogenic wedge (Fig. 1). The migration of the wedge, made up of thrusts progressively involving the foredeep, produced a segmentation of the Middle Miocene Marnoso-Arenacea basin forming a complex series of sub-basins progressively younger towards the foreland (Muzzi Magalhaes & Tinterri, 2010). Large seep-carbonate bodies are enclosed in mudstones draping the intrabasinal highs of the segmented foredeep (Conti et al., 2017).

Two types of intrabasinal highs formed in two successive stages of foredeep evolution (Ricci Lucchi, 1975): 1) a late

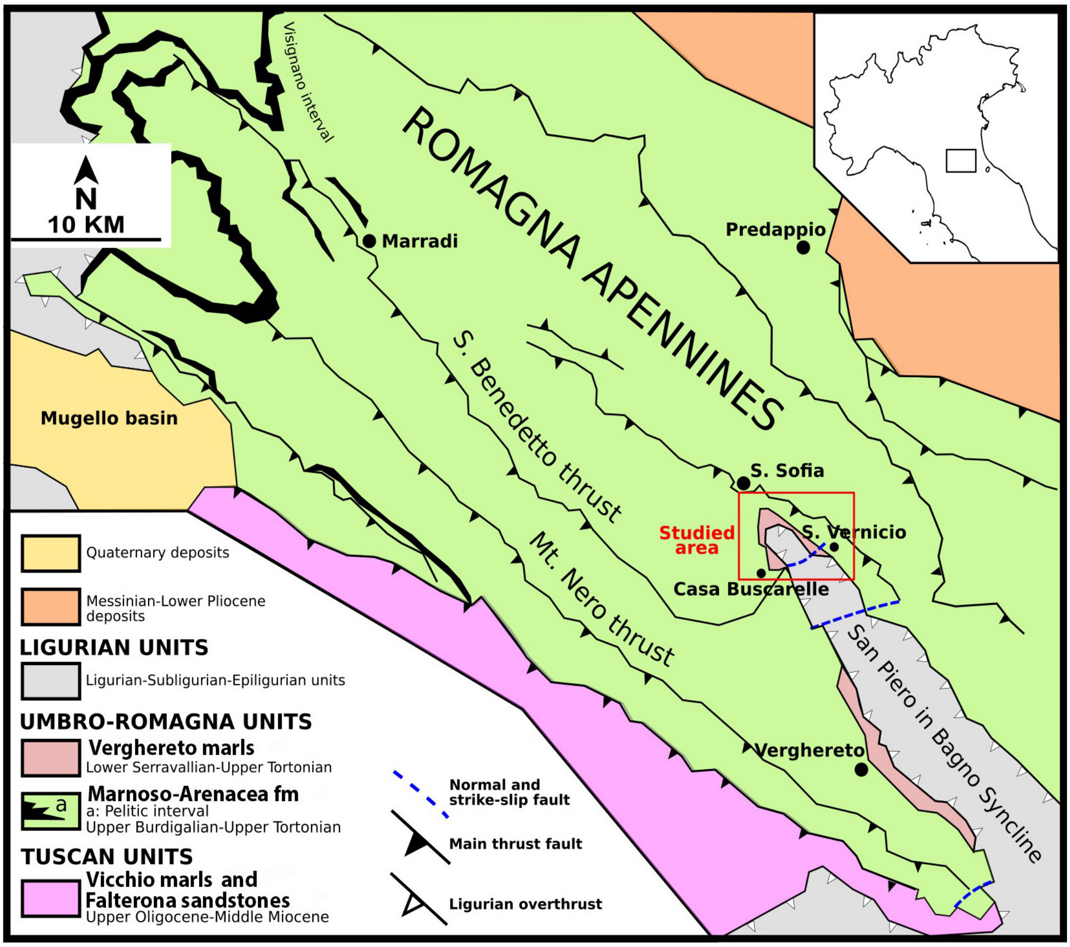

Fig. 1 - Simplified geological map of the Romagna Apennines with the main structural elements. Foredeep pelitic intervals are reported as black stripes. The studied area is indicated.

Burdigalian-Serravallian inner basin, controlled by small and ephemeral structural reliefs; 2) a Tortonian-early Messinian outer basin of limited axial and lateral continuity characterised by sand-rich ponded turbidites confined by large structural reliefs. The passage between these two stages during the late Serravallian is marked by a transitional phase (Tagliaferri & Tinterri, 2016) with the foredeep sedimentation controlled by both types, ephemeral minor (Visignano-Prati Piani) and long-lived major highs (Verghereto high). Both types of intrabasinal highs are preferential sites of fluid expulsion as demonstrated by the occurrence of seep-carbonates (Conti et al., 2021a, b). The Verghereto high was draped by several hundred metres of fine-grained sediments known as Verghereto marls and for this reason it is considered a major high (Delle Rose et al., 1991; Bendkik et al., 1994; Bonini, 2006; Conti et al., 2020).

THE STUDY AREA

As shown in figures 1 and 2, the area is characterised by thrusts and folds trending NW-SE, parallel to the structural trend of the Apennine chain. Folds are represented by NE-verging hangingwall anticlines and by NE overturned footwall synclines (Boccaletti et al., 1990; Cerrina Feroni et al., 2008). The main thrusts are the M. Nero thrust and the Mt. Benedetto thrust: in the first one the inner Marnoso-Arenacea formation overthrusts the Montecoronaro member, whereas in the second the inner Marnoso-Arenacea formation overrides the San Paolo member of the Verghereto marls. The studied area comprises the northwestern periclinal closure of the huge San Piero in Bagno syncline; in this area the Verghereto marls are transversely cut by normal and strike-slip faults (Bendkik et al., 1994; Bonini, 2006). The most important transverse structure (strike-slip faults with an important transtensional component) is the Casa Buscarelle-Spinello fault: it played an important role in preserving Ligurian and Epiligurian units, as demonstrated by their huge thickness on SE side with respect to the NW side (Figs. 1, 2).

In the studied area the Verghereto marls are truncated by the overthrust of the Ligurian and Epiligurian units of the Apennine accretionary wedge (Conti et al., 2016; Cornamusini et al., 2015, 2017). The Ligurian units (Cretaceous-middle Eocene) are almost entirely made up of the Varicolored clays formation and by minor marly carbonates belonging to Sillano formation and Mt. Morello formation; they were interpreted by Martelli (2002) as a chaotic mélange (Val Savio Complex) attributed to the middle Eocene-Oligocene interval. The Epiligurian sequence (Aquitanian) is represented by the Poggio Carnaio sandstone (Di Staso et al., 2009), 500 m in thickness. Thrusts and related fold axis plunge southwestward under the tectonic contact of the Ligurian-Epiligurian units.

The Verghereto marls are composed for more than 90% of calcareous marls with minor siliciclastic intercalations, mainly concentrated at the lateral transition with the Marnoso-Arenacea formation. They are organised in an overall thinning upward trend: the basal part is made of fine-grained turbidites with a relatively more abundant arenaceous component laterally discontinuous (pinch-out closures are frequent), alternating with thick pelitic turbidites. Several intrabasinal slumps as Susinello and Nasseto (Bonini, 2006) occur in the basal portion of the Verghereto marls and show evidence of transport to SW and NE (Lucente, 2004). Towards the top, the sandstone/pelite ratio progressively decreases and the Verghereto marls are made of marly, laminated pelites and light grey hemipelagites with rare and thin arenaceous beds. The upper part of the structural high is draped by hemipelagites, frequently intertongued with thin tabular turbidites; trace fossils are well preserved (Milighetti et al., 2009; Monaco & Checconi, 2010; Monaco et al., 2010). The high has been considered a starved high by Amy & Talling (2006) with only thin and dilute turbidity currents able to surmount the high. The upper marly pelitic portion of Verghereto marls includes several tens of carbonate bodies interpreted as authigenic seep-carbonates object of this study.

The ambiguous lithostratigraphic definition of the Verghereto marls

The Verghereto marls (VM) belong to the Umbro-Romagna units, from Santa Sofia (FC) to Sestino (AR) and represent the fine-grained sedimentation on top of a major structural relief (the Verghereto high) correlatable towards the NE with the Castelvecchio high segmenting the Middle Miocene foredeep. The Verghereto marls were dated to Serravallian-Tortonian by Martelli (2002) and precisely to the biozones MNN6a-NN10 by Catanzariti et al. (2002). The sedimentation on the Verghereto intrabasinal high started in the late Serravallian, recorded by mudstones interfingering with the basinal deposits (Tagliaferri & Tinterri, 2016). During the Serravallian-Tortonian, the Verghereto high bounds the inner turbidite basin of the Marnoso-Arenacea formation (Amorosi et al., 1996; Monaco & Checconi, 2010; Tinterri & Tagliaferri, 2015) (Fig. 1). The lithostratigraphy of the Verghereto marls has been repeatedly revised: some authors (Amorosi, 1987; Van Wamel & Zwart, 1990) maintain the Verghereto marls name but the formation was subdivided in two distinctive members: the basal Montecoronaro member (500 thick), and the upper San Paolo marls member (400 m thick). Differently, Martelli (2002), Bortolotti et al. (2014) and Cornamusini et al. (2015, 2017) included the basal part of the Verghereto marls in the Marnoso-Arenacea formation and named the terminal part as San Paolo Marls formation, thus erasing the historical name of Verghereto marls. The name Verghereto remains as structural high (Tagliaferri & Tinterri, 2016) thus creating uncertainty in the geological nomenclature. In this paper we refer to Verghereto marls as a usable lithostratigraphic unit.

MATERIAL AND METHODS

A detailed field work (Fig. 2) was focused on the upper marly pelitic portion of the Verghereto marls, hosting seep-carbonates. We measured a 150 m thick stratigraphic section in the San Vernicio area (Fig. 3), extending from the Marnoso-Arenacea

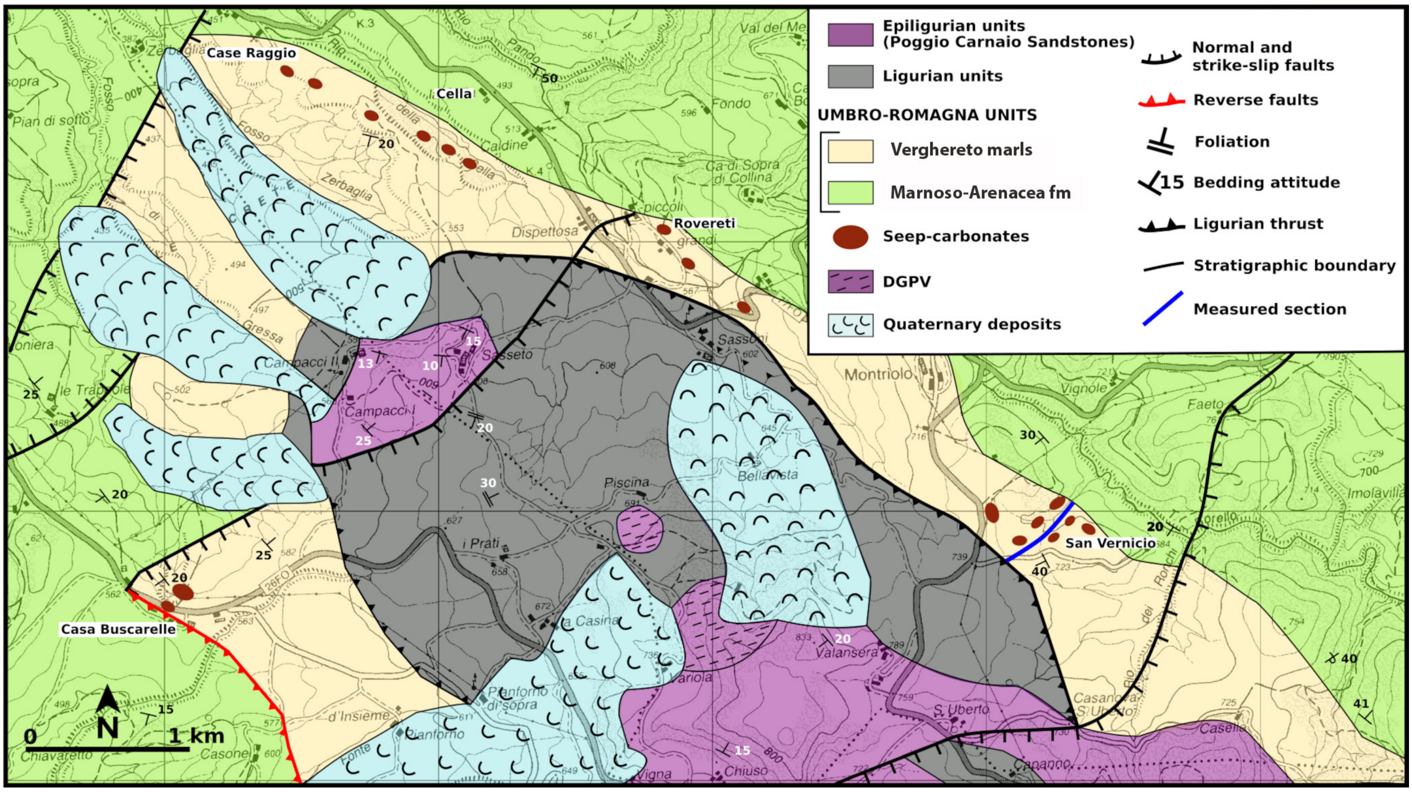

Fig. 2 - Geological map of the studied area showing the distribution of the Verghereto marls enclosing numerous seep-carbonate bodies (in red). The map area corresponds to the red rectangle in Fig. 1. Note that the seep-carbonate stratiform bodies are aligned to structural elements. The location of the measured log is reported. DGPV in the legend refers to gravitative lateral spread deformations of Epiligurian rocks.

formation to the Ligurian overthrust. Along the stratigraphic section and in the Santa Sofia area, we examined lithology, facies and petrography of the numerous seep-carbonates bodies enclosed in the upper Verghereto marls. The section was sampled for biostratigraphic purposes. Calcareous nannofossil analyses were carried out on 22 samples. The procedure for processing the samples followed the standard smear-slide technique outlined by Bown & Young (1998). Quantitative analyses were conducted using a light microscope at 1250X magnification, under cross-polarised and plane-transmitted light. In each slide, about 300 specimens were counted to estimate species abundance, then converting the number of index species normalised to a prefixed area (1 mm^2) to allow a detailed assessment of the biostratigraphic signal. In order to include rare species additional 200 fields of view were also scanned. The recognised biohorizons are defined following Raffi et al. (2003), and identified as First Occurrence (FO), Last Occurrence (LO), First Common Occurrence (FCO) and Last Common Occurrence (LCO) (Fig. 3). Sixteeen samples of seep-carbonates from the San Vernicio outcrop and contiguous localities were analysed for C and O isotopes (Tab. 1; Fig. 2). The carbonate fraction (whole rock) was analysed following the standard technique: the $\delta^{13}C/^{12}C$ and $\delta^{18}O/^{16}O$ ratios of the CO_2 were obtained using Finnigan MAT 251 and 252 mass spectrometers. Results are reported in standard δ notation relative to the Vienna-Pee Dee Belemnite (V-PDB) standard. Precision is 0.1‰ (1σ) for both $\delta^{13}C$ and $\delta^{18}O$ values.

RESULTS

Stratigraphic log

The examined succession, corresponding to the upper part of Verghereto marls, is 150 m thick, continuous and relatively well exposed. The stratigraphic log with the position of samples for the biostratigraphic study is reported in Fig. 3. The basal contact with the Marnoso-Arenacea formation is badly exposed for 50 m and was not sampled for this study. The succession is abruptly truncated by the Ligurian overthrust. The sampled section is mainly composed of homogeneous and structureless marls (Fig. 4) alternated with thin laminated arenite beds (Fig. 4A), more frequent in the lower part. About 20 metres above, seep-carbonate bodies occur embedded in the marly matrix, as blocks ranging in size from centimetres to decimetres. At about 50 metres, seep-carbonates become more abundant, made up of metric blocks (Fig. 4C) and of thin concretionary intercalations of sandstones cemented by authigenic carbonates. Carbonates are characterised by the presence of lucinid and bathymodiolid bivalves as well as serpulids (Moroni, 1965; Fig. 4D). In the middle portion, marly lithologies are homogeneous with few thin arenite intercalations. The upper 40 metres are richer in clay, associated with the presence of thick (few metres) carbonate blocks, in many cases brecciated (Fig. 4B) and with pervasive veins and conduits. In the upper part of the section trace fossils like *Thalassinoides* spp. are frequent as described in other intrabasinal highs (Conti & Serventi, 2023). The succession abruptly ends truncated by the tectonic contact with the Ligurian units.

Table 1 - Isotopic values of the analysed samples.

Samples	δ18O	δ13C
Case Raggio 1	3,47	-38,36
Case Raggio 2	-4,74	-33,61
Rovereti 1	2,44	-32,74
Rovereti 2	1,21	-27,91
Rovereti 3	2,21	-30,33
Cella 1	1,53	-30,28
Cella 2	2,45	27,23
S.Vernicio 1	0,13	-29,79
S.Vernicio 2	-4,17	-30,56
S.Vernicio 3	2,12	-31,27
S.Vernicio 4	1,68	-41,79
S.Vernicio 5	2,90	-33,17
S. Vernicio 6	3,55	-30,06
Case Buscarelle 1	-0,32	-36,39
Case Buscarelle 2	1,51	-35,15
Poggio Campane 1	2,20	-32,20

Results are reported in standard δ notation relative to the Vienna-Pee Dee Belemnite (V-PDB) standard. Precision is 0.1‰ (1σ) for both $\delta^{13}C$ and $\delta^{18}O$ values.

Seep-carbonates in the studied area

Several tens of carbonate bodies are enclosed at different levels within the upper portion of the Verghereto marls, in proximity of the tectonic contact with the Ligurian and Epiligurian units. As in other seep-carbonate outcrops, their distribution runs parallel to the tectonic contact confirming the relationships between the frontal thrust of the accretionary wedge (i.e., Ligurian and Epiligurian units) and the synsedimentary blind thrust-faults (Fig. 5). Seep-carbonates are more abundant and developed on the frontal Adriatic side of the tectonic contact in accordance with the direction of tectonic transport from SW to NE that convoyed fluids sourcing seepage. Laterally, carbonate occurrence is limited by the transverse structure of Casa Buscarelle-Spinello (Fig. 2). Carbonates are of various dimensions and shapes from stratiform to irregular metric blocks and lenses, aligned and concordant with the bedding attitudes of the enclosing marls and concentrated in the early Tortonian (Biozone MNN8b). They consist of lightly colored, indurated micritic limestones rich in mussels and clams with subordinate gastropods and tube worms. Authigenic carbonates exhibit various mineralogical compositions (calcite, aragonite and dolomite) and form thin concretions, pavements and nodules, similar to other seep-carbonates within the Marnoso-Arenacea formation (Conti et al., 2008). Common chemofacies are polygenic and monogenic breccias with isolated articulated or disarticulated clams, vuggy fabrics locally pervading the entire rock, centimetric conduits and doughnut fabric, network of conduits filled by calcite cements, laminated micritic limestones with alternance of whitish and brownish laminae, micritic mottled limestones. Clasts in polygenic breccias derive from the underlying Marnoso-Arenacea formation and from previously formed seep-carbonates (Fig. 4B). Monogenic breccias derive from autoclastic fragmentation of carbonate crusts, testifying an intense phase of expulsion of fluids. The isotopic signatures of samples from the studied outcrops indicate depleted $\delta^{13}C$ (Table 1; Fig. 2).

Biostratigraphy of the hosting marls

In the studied samples, calcareous nannofossil abundance varies from rare to common and preservation ranges from moderate to good. Some taxa such as *Discoaster* spp. show strong diagenetic overgrowth, often hampering the identification to species level. The nannofossil biozonation for the Miocene Mediterranean area as defined by Fornaciari & Rio (1996) and Raffi et al. (2003) is applied to the studied section that spans from the MNN7 Zone (*pars*) to the MNN8 Zone (*pars*), thus encompassing the Serravallian-Tortonian boundary. This result is in general agreement with previous biostratigraphic data collected in the Verghereto marls. Our data deriving from sparse samples collected recently in a nearby area indicate the MNN8 zone (Conti et al., 2021a). The abundance patterns of selected species plotted against the lithostratigrapy of the sampled sections, are reported in Fig. 3.

The nannoflora assemblage consists mainly of placoliths (*Dictyococcites* spp., *Coccolithus* spp. and *Reticulofenestra* spp.), while the biostratigraphically important species are *Coccolithus miopelagicus*, *Discoaster kugleri* and *Helicosphaera stalis.* Reworking from Cretaceous, Eocene and Lower Miocene although with low values, is always present. Among Helicosphaerids, *H. carteri* prevails, reaching up to 20% of the entire assemblage, with a mean value of about 5%. Less common and discontinuous are *H. intermedia* and *H. euphratis*, both representing less than 2% of the assemblage. *H. walbersdorfensis* is present all along the section with a clear decrease in correspondence of the first occurrence (FO) of *H. stalis*. Other species such as *H. orientalis* and *H. mediterranea* are rare and discontinuously present. The genus *Discoaster* is always rare and poorly preserved, often affected by overgrowth, making difficult the recognition at specific level. In the investigated section, we identified in two samples very few specimens of *D. kugleri*. This taxon is generally rare in the Mediterranean but its presence allows the MNN7 zone to be divided in three subzones (Hilgen et al., 2000; Raffi et al., 2003). Due to the scarcity in our material, the MNN7 zone is tentatively subdivided in three subzones only informally, as previously suggested by Sprovieri et al. (2002). *Calcidiscus premacityrei* was discontinuous and detected in the lower part of the section with very low values, (below 1% of the assemblage), interpreted as the tail after the LCO of this taxon. Since *Calcidiscus macintyrei* is rare and very discontinuous along the section, it was not considered a useful biohorizon, however its presence confirms a stratigraphic interval above the LCO of *C. premacintyrei*. (Fornaciari & Rio, 1996).

The nannofossil biostratigraphy indicates the MNN7-8 biozone (San Vernicio outcrop) and MNN8 (Case Buscarelle outcrop, Conti et al., 2021a).

DISCUSSION

Many papers studied the basal part of the Verghereto marls, but only a few dealt with the uppermost fine-grained portion. These hemipelagic deposits are widely exposed and can be traced in a NW-SE direction from Santa Sofia to Poggio delle Campane near Sestino (Marchean Apennines); in all outcrops the marls enclose seep-carbonates.

Our stratigraphic and biostratigraphic study of the upper hemipelagic portion of the Verghereto marls indicates a clear fining-upward grain-size trend and an age spanning from the late Serravallian (MNN7) to early Tortonian (MNN8). This new dating confirms and details the previous studies in adjacent area (Santa Sofia and Case Buscarelle, Conti et al., 2021a) and highlights the difference with the age of the upper hemipelagites in the southeastern areas (at Poggio Campane, Conti et al., 2021a) which are older (Serravallian). This is in accordance to the fact that the frontal sector of the Ligurian overriding in the study area is successive to the southern one. The uppermost portion of the succession (early Tortonian) is marked by numerous seep-carbonate bodies. These results allow some considerations on the evolution of the Verghereto intrabasinal high that conditioned the sedimentation of the Marnoso-Arenacea formation, and on the age of the emplacement of the Ligurian units of the accretionary wedge in this area (Fig. 1). The relative increase in the pelitic component and the occurrence of seep-carbonates suggest that the Verghereto structural high was still active during the early Tortonian, after the closure of the inner stage of the Marnoso-Arenacea formation, hypothesised at the boundary Serravallian-Tortonian (Ricci Lucchi, 1986; Tinterri & Tagliaferri, 2015), thus creating some discrepancy in the palaeogeographic reconstruction of the inner Marnoso-Arenacea foredeep. The

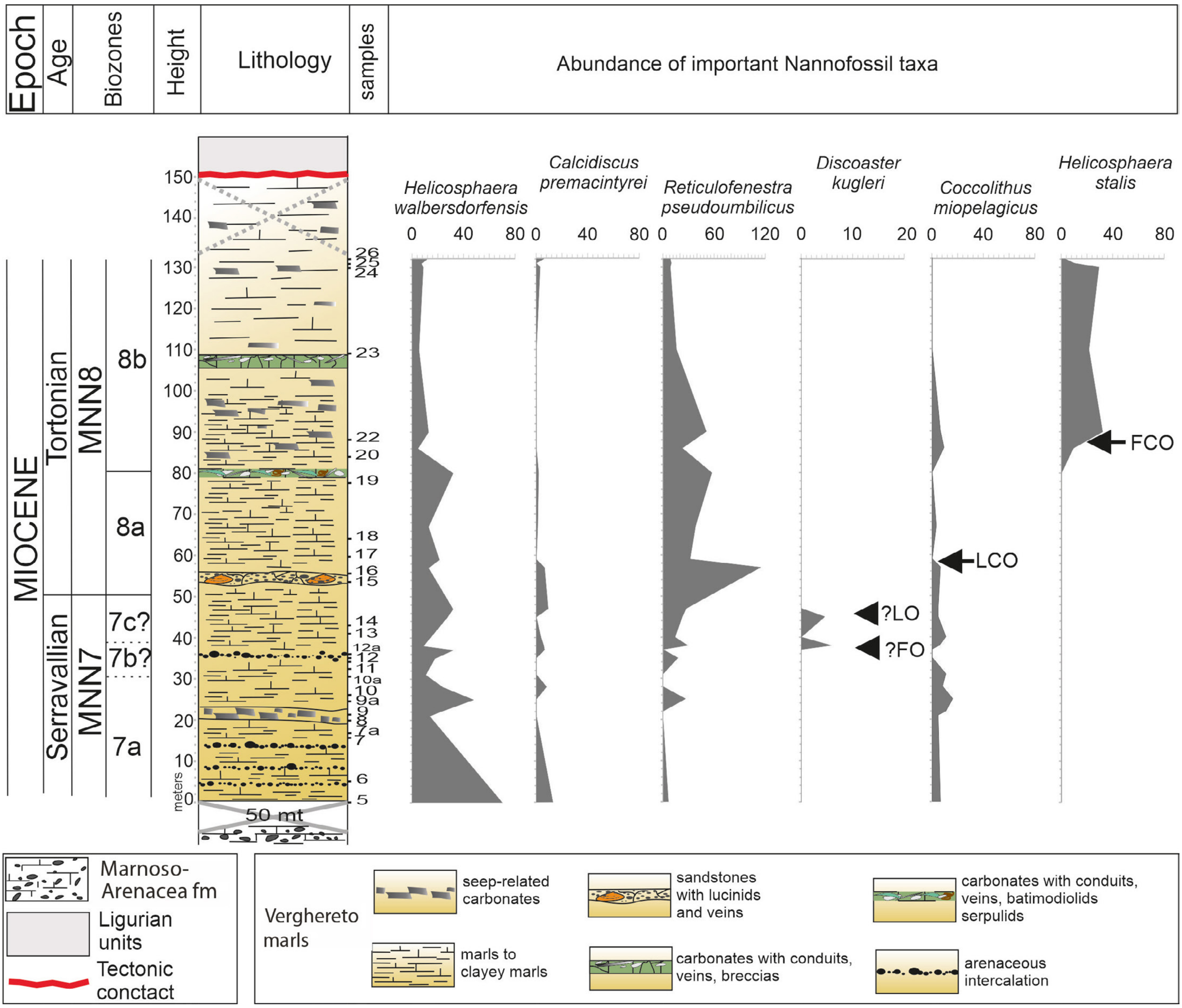

Fig. 3 - A) Measured stratigraphic log of the upper portion of the Verghereto marls hosting seep-carbonates. The basal contact with the Marnoso-Arenacea formation is covered. B) Distribution patterns of selected nannofossil species expressed as number of specimens per mm^2, and position of biostratigraphic events (FO: first occurrence; LO: last occurrence; FCO: first common occurrence; LCO: last common occurrence).

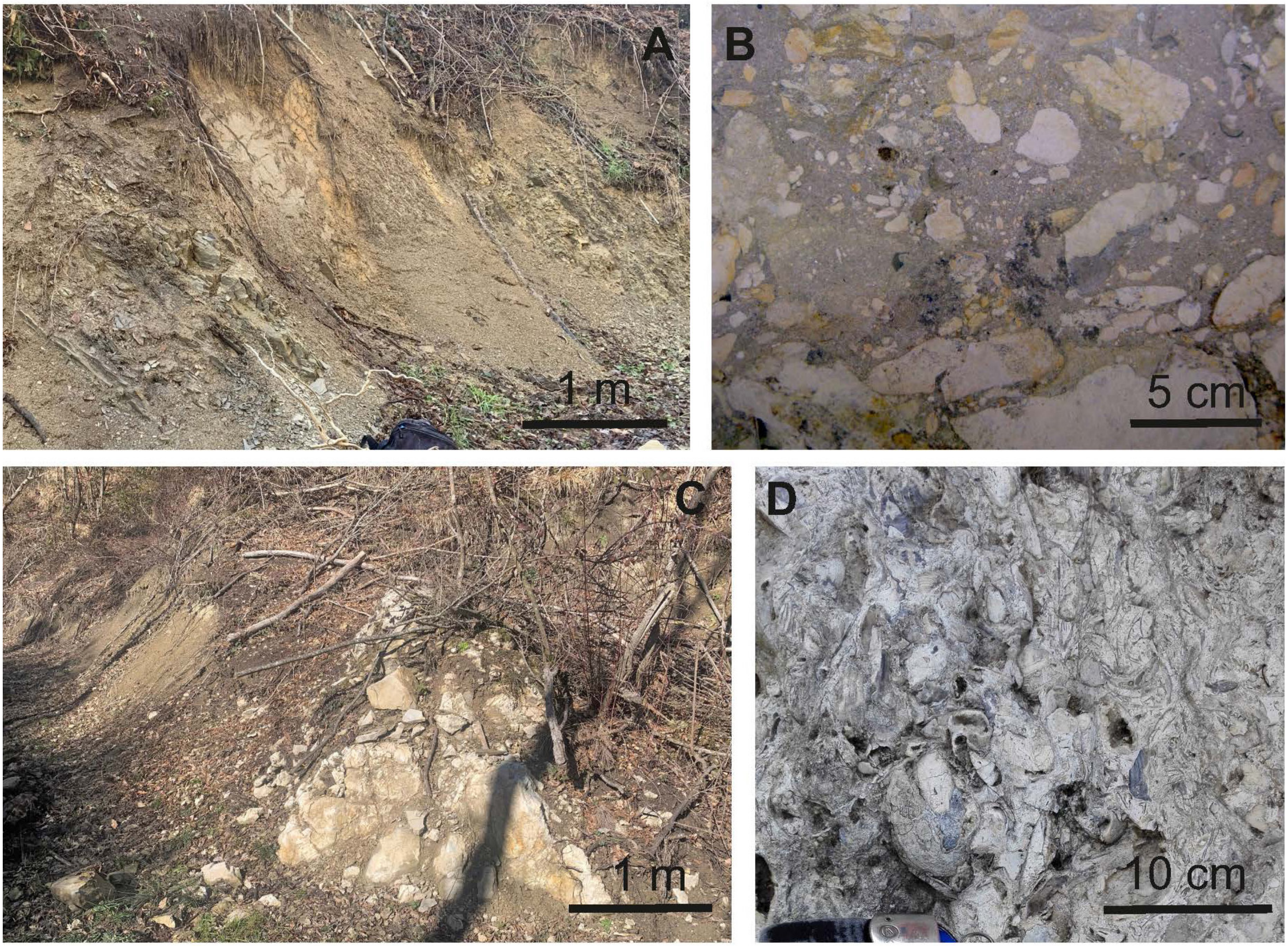

Fig. 4 - Main rock types in the examined Verghereto marls. A) Marls, homogeneous and devoid of structures, interbedded with thin laminated sand beds (in the left side). B) Brecciated facies in seep-carbonates ranging in size from centimetres to decimetres, embedded in a micritic authigenic matrix. C) Seep-carbonate body intercalated in the marls at about 50 metres from the base. D) Seep-carbonates with abundant lucinids and bathymodiolis.

extensive bed continuity with fine-grained sediments draping the inner foredeep highs is consistent with the topmost dilute part of a turbidite flow, suggesting that the intrabasinal bathymetric relief was subtle, substantially less the thickness of flows (Amy et al., 2005; Amy & Talling, 2006; Milighetti et al., 2009; Monaco et al., 2010). This is an important constrain for the origin of fine-grained intervals within the Marnoso-Arenacea foredeep and, more in general, on the age and emplacement mechanism of the accretionary wedge in this area.

Pelitic sediments above the intrabasinal highs were interpreted by some authors as mass transport complexes derived by more internal areas and fully detached by their original position (Lucente & Pini, 2008; Tinterri & Tagliaferri, 2015). In the considered modest bathymetric relief there was not the adequate space to contain gravitative bodies up to two hundred metres thick, as previously proposed. The presence of thin diluted turbidites demonstrates that the Verghereto high did not hamper the flux of density currents between the different sectors of the basin. At the end of the Serravallian, the passage from fine-grained turbidites to hemipelagites coincides with the mature stage of the structural high. The constant occurrence of unreworked seep-carbonates within the fine-grained sediments draping the structural highs is further evidence that these sediments are mostly in primary position, and a moderate sedimentary instability was confined to the slopes, internal and external, of the temporary structural highs, largely due to methane-rich fluid expulsion (Fig. 5).

The age constrain of the Verghereto high development from this work also allows some considerations on the emplacement of the Apennine accretionary wedge in the Santa Sofia area. Previous studies considered the Ligurian units of the San Piero in Bagno syncline entirely as a chaotic mass transport deposits emplaced in a depressed basin, as in the interpretation of the origin of the mélange of the Val Savio in Benini et al. (1991). The fine-grained sedimentation and the seep-carbonate occurrence indicate that the Verghereto high was still effective before the emplacement of the accretionary wedge, and therefore it was still an elevated area outstanding the basin floor and not a depressed area. In addition, the varicoloured clays outcropping in the S. Sofia area preserve their original structure, hardly referable to debris flow or mélange. Furthermore, it is important

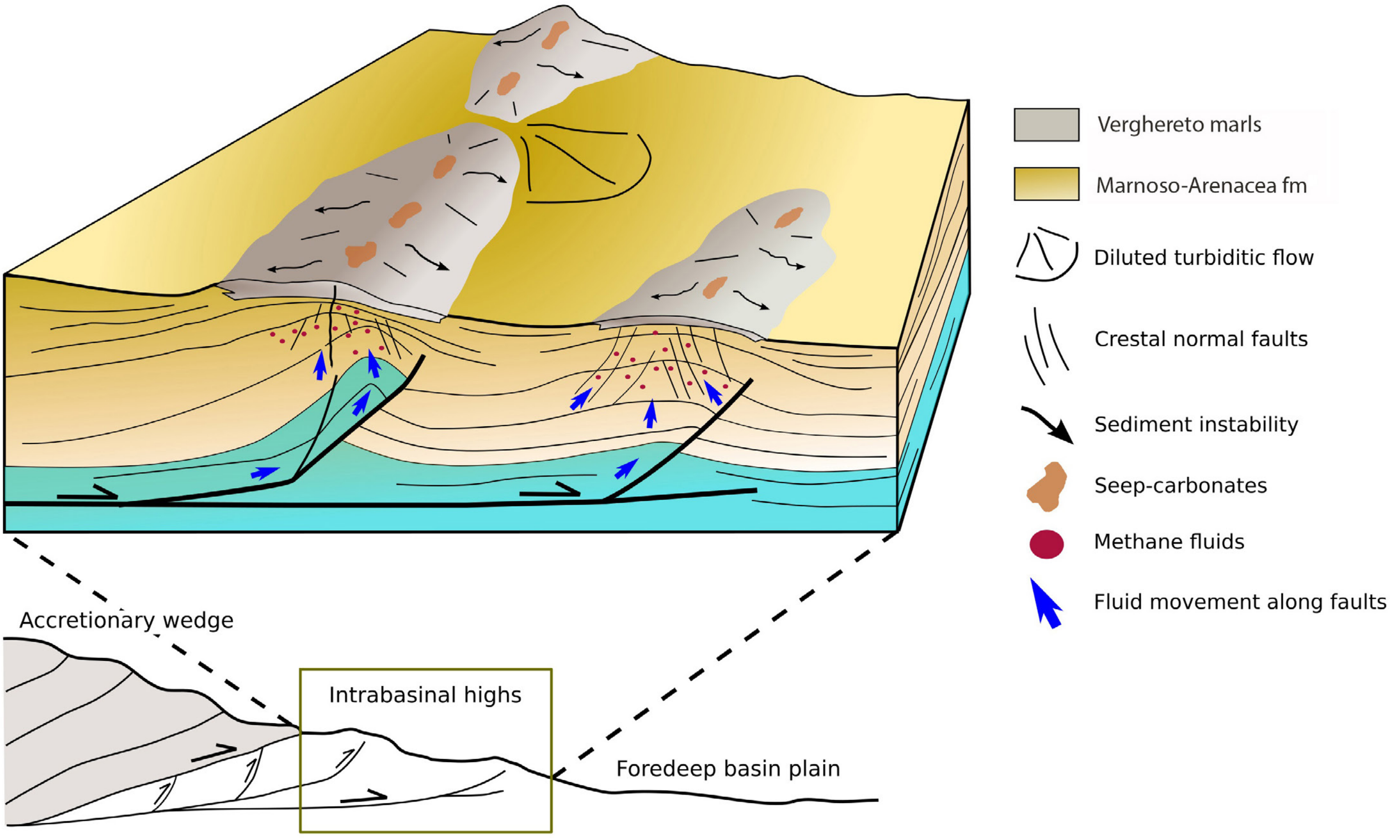

Fig. 5 - Schematic reconstruction of the intrabasinal highs segmenting the Marnoso-Arenacea foredeep showing the main fluid pathways. The sedimentary instabilities triggered by fluid expulsion are localised along the temporary slopes of the ephemeral highs.

to consider that blind sedimentary thrusts that generated the intrabasinal highs could not have generated the slope necessary for triggering the landslides hypothesised by various authors from more internal structural highs (Lucente & Pini, 2008; Tinterri & Tagliaferri, 2015). The tectonics that generated the main folds in the Romagna Apennines is subsequent to the instability as can be deduced from the outcrops visible in the Santerno valley showing the vertical attitude of the Visignano-Prati Piani pelitic interval in the Marnoso-arenacea formation (Fig. 1), postdating the synsedimentary folds of the structural high.

Finally, numerous papers on Miocene Apennine seep-carbonates evidenced the relation between expulsion of fluids, registered by seep-carbonate outcrops, and the main Apennine tectonic structures (Dela Pierre et al., 2010; Conti et al., 2017). Our case study confirms that seep-carbonate distribution is related to the overriding of the accretionary wedge, with huge stratiform bodies elongated and aligned to the main structural elements (Figs. 2, 5). The overburden by the Apennine accretionary wedge migrating over the Verghereto marls generated a major fluid expulsion exploiting tectonic pathways. In addition, the distribution of the outcrops clearly indicated that they are limited to the western side of the transverse structure (tear fault) running near Santa Sofia zone (Spinello-Panicaglia structure) and confirms the previous interpretation of Bonini (2006) that postulated a synsedimentary activity of the tectonic structures deforming the Umbro-Romagna sequence.

CONCLUSIONS

- The upper hemipelagic portion of the Verghereto marls in the S. Sofia area of the Romagna foredeep features a fining-upward grain-size trend and hosts numerous seep-carbonate bodies in its uppermost part.
- Based on calcareous nannofossils the age of the studied succession ranges between the late Serravallian (MNN7) to the early Tortonian (MNN8).
- These results allow some considerations on the evolution of the Verghereto intrabasinal high that conditioned the sedimentation of the Marnoso-Arenacea formation and on the age of the emplacement of the Apennine accretionary wedge in this area.
- The extensive bed continuity with fine-grained sediments draping the inner foredeep highs and the exclusive occurrence of in-situ seep-carbonates, indicates that these sediments are mostly in primary position and a moderate sedimentary instability was confined to the temporary slopes of the structural highs due to methane-rich fluid expulsion.

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