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ORIGINAL PAPER

Relationships between seep-carbonates, mud volcanism and basin geometry in the Late Miocene of the northern Apennines of Italy: the Montardone mélange

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Abstract The Montardone mélange (Mm) is a chaotic, block-in-matrix unit outcropping in the Montebaranzone syncline in the northern Apennines. The Mm occurs in the uppermost part of the Termina Fm, the Middle–Late Miocene interval of a succession deposited in a wedge-top slope basin (Epiligurian succession). The Mm is closely associated with bodies of authigenic carbonates, characterized by negative values of $\delta^{13}C$ (from −18.22 to −39.05 ‰ PDB) and chemosynthetic benthic fauna (lucinid and vesicomyid bivalves). In this paper, we propose that the Mm is a mud volcano originated by the post-depositional reactivation and rising of a stratigraphically lower mud-rich mass transport body (Canossa–Val Tiepido sedimentary mélange or olistostrome) triggered by fluid overpressure. We base our conclusion on (1) the Mm pierces the entire Termina Fm and older Epiligurian units and represents the direct continuation of the underlying Canossa–Val Tiepido mélange; (2) the geometry and facies distribution of the Montebaranzone sandstone body, which are compatible with a confined basin controlled by the rising of the Mm; (3) the systematic presence of large-scale (lateral extension 300–400 m) seep-carbonates associated with the mélange, suggesting a persistent gas-enriched fluid vent from the ascending overpressured mud; (4) blocks and clasts sourced from the Mm, hosted by the authigenic carbonates, conveyed by ascending mud and gas-enriched fluids. The Mm represents one of the few fossil examples of reactivation of a basin-scale sedimentary mélange (olistostrome); a three-stage model showing mechanisms of Mm raising is proposed.

Keywords Mud volcanism · Olistostrome · Seepage · Northern Apennines · Authigenic carbonates

Introduction

Chaotic rock units defined as mélanges in the geologic literature are widely present in orogenic wedges and mountains worldwide (e.g., Raymond 1984; Cowan 1985; Şengör 2003; Festa et al. 2010a). These units are characterized by stratal disruption up to block-in-matrix fabric, where the matrix is mostly made up of clays/argillites, shales and silt/sandstones, and by mixing of rocks of different degree of compaction, age and provenance (e.g., Silver and Beutner 1980). Mélanges are thought to originate from processes related to contractional tectonics and sedimentary mass transport. The latter are known as sedimentary mélanges, olistostromes or argillaceous breccias (Camerlenghi and Pini 2009; Remitti et al. 2011).

Sedimentary mélanges can be also the product of the rise of overpressured clay-/shale-rich sediments from a deeper stratigraphic horizon(s) piercing the overlying sedimentary cover. The bodies originating from these processes are known as mud diapirs and volcanoes (Camerlenghi and Pini 2009). Mud volcanoes originate when the overpressured sediments and rocks reach the surface, either onshore or offshore in the submarine environment (Brown 1990; Milkov 2000; Kopf et al. 2001;

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Kopf 2002; Dimitrov 2002; Mazzini 2009). The extrusive apparatus of mud volcanoes is composed by stacks of debris flow deposits composed of a fluid-rich, fine-grained matrix including lithoclasts of various size, shape, age, and composition, often defined as “mud breccia” (Camerlenghi et al. 1992; Staffini et al. 1993).

Present-day submarine mud volcanoes are often associated with fluid flow and vents. Spectacular carbonate chimneys, representing escape conduits for hydrocarbon-enriched fluids, were observed and recovered from the mud volcanoes of the Gulf of Cadiz (Diaz-Del-Rio et al. 2003). Seep-carbonates (Campbell 2006) have also been documented in several areas where active mud volcanism takes place worldwide (Black Sea, in Mazzini et al. 2004; Norwegian Sea, in Perez-Garcia et al. 2009; Makran accretionary complex, in von Rad et al. 2000; Gulf of Mexico, in Roberts 2001; offshore California, in Orange et al. 1999; Costa Rica margin, in Kutterolf et al. 2008; Barbados prism, in Olu et al. 1997; Eastern Mediterranean Sea, in Lykousis et al. 2009) and where a large amount of rising methane provides an ideal environment for the formation of gas hydrates (Mazurenko and Soloviev 2003; Han et al. 2004; Chen et al. 2004).

Although the relationship between mud volcanoes and the debris flows forming their extrusive apparatus is obvious and well described in both subaerial and submarine environments (see e.g., Van Rensbergen et al. 2005), the origin of mud diapirs/volcanoes from buried, mud-rich mass transport bodies has been only suggested by a few authors (Brown 1990; Talukder et al. 2003; Camerlenghi and Pini 2009). In addition, some fossil examples of olistostromes triggering mud mobilization have been preliminary recognized in the northern Apennines (Festa et al. 2010b and references therein), but the importance of mud diapiric reactivations is not yet understood completely. Similar situations may explain the origin of chaotic bodies which are still matter of debate (Di Giulio 1992).

High porosity characterizes the sediments participating in mass transport processes, as well as the latter are triggered and sustained by high pore pressure (Mulder and Alexander 2001; Ogata 2010). In mud-rich mass transport bodies (olistostromes), a residual high porosity can remain long after their emplacement, due to the slow rate of self-compaction and dewatering of the predominant clayey matrix (Camerlenghi and Pini 2009). Moreover, gas hydrates can be entrapped inside the mass transport bodies (Paull et al. 2003). The presence of fluids within submarine slump and slides is also indicated by chemosynthetic communities occurring atop some fossil mass transport deposits, as observed in Miocene sedimentary record of the northern Apennines (Lucente and Taviani 2005; Panieri et al. 2009; Conti et al. 2010). The chemosymbiotic bivalve assemblage and the presence of seep-carbonates are indicative of methane-rich fluids venting at the sea floor, released as a consequence of the emplacement of the deformed and chaotic slide mass.

The Montardone mélange (Mm) in the Termina Fm of the northern Apennines is one of the few fossil examples that can permit to document genetic relationships between diapirism and seep-carbonates in the field. Large mud-rich mass transport bodies (olistostromes) exist at the base and inside the Epiligurian succession below the Termina Fm (Remitti et al. 2011). The contacts between the Mm and the marls/sandstones cannot be easily explained, since they often occur along a vertical surface in the eastern part of the syncline, cutting off the lower Termina Fm and the underlying units, and become layer parallel in the western side. Well-exposed and preserved fossil cold seeps hosting chemosynthetic communities are diffusely present in that area, and the more continuous bodies are concentrated close to the vertical contacts, in which the Mm seems to pierce the other members of the Termina Fm. The activity of methane associated with the carbonates is also stressed out by the negative values of δ^{13}C.

Geological setting

The northern Apennines

The northern Apennines orogenic wedge consists of several, imbricated tectonic units bound by thrusts, generally verging to the northeast (Fig. 1). The farthest-travelled structural unit, the Ligurian nappe, presently occupies the highest position in the chain. The main component units of the nappe, the Jurassic-Eocene Ligurian and Subligurian units, are the remnants of the oceanic seaways of the Alpine Tethys (Ligurian Ocean) and of the adjacent continental margin of the Adria microplate (Bortolotti et al. 2001; Marroni and Pandolfi 2007). Some of these units were deformed in a Late Cretaceous–Eocene accretionary wedge, before the continental collision between the European plate and Adria microplate occurred (Pini 1999; Marroni and Pandolfi 2001; Catanzariti et al. 2007).

The post-collisional deformation of the western part of the Adria microplate took place during distinct tectonic phases of Oligocene, Early Miocene, Late Miocene, Pliocene and Pleistocene ages (e.g., Castellarin et al. 1992). These deformational phases were responsible for the onset of thrust-bounded structural units, such as the diverse Tuscan units and the Umbria–Romagna unit (Boccaletti et al. 1990; Conti and Gelmini 1994; Vai 2001). During the northeastward migration of the thrust belt system, deposition occurred not only in the foredeep but also in smaller basins located atop the Ligurian nappe (the so-called

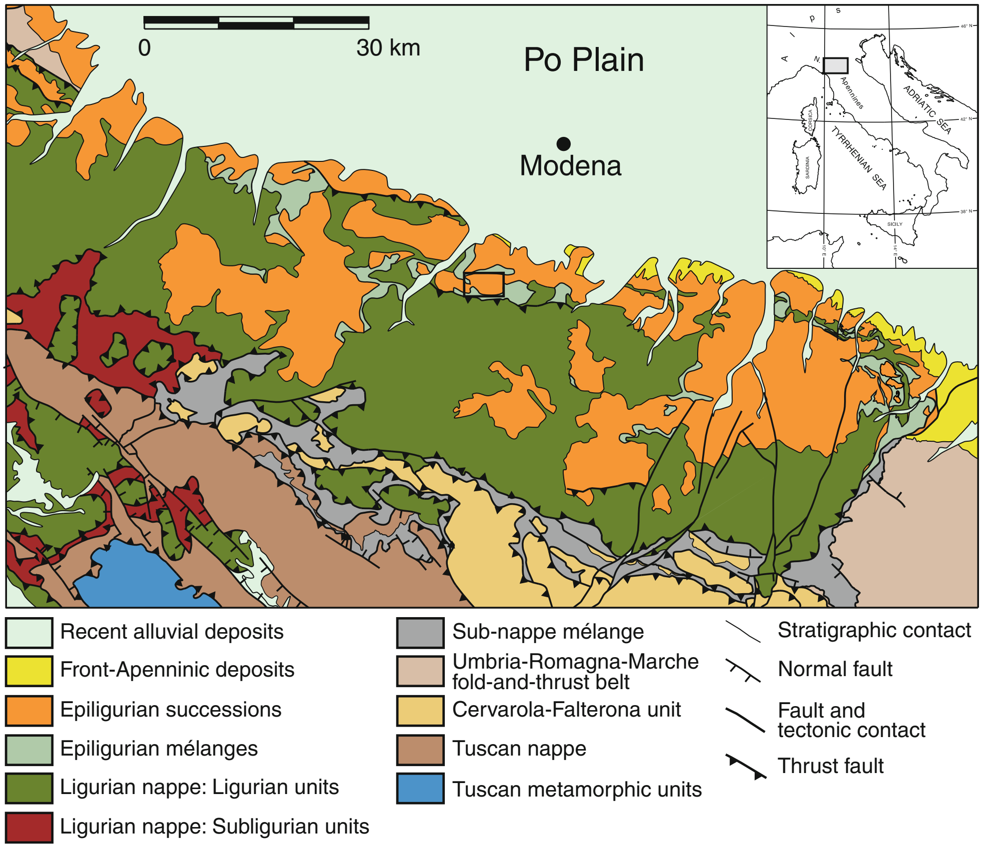

Fig. 1 Schematic geological map of the Emilia portion of the northern Apennines and location of the studied area

Epiligurian succession, see Ricci Lucchi 1986) (Fig. 2). These sediments are separated by the underlying Ligurian units by an angular unconformity of Middle–Late Eocene age; their deposition continued until the Late Pliocene, interrupted by several regional-scale unconformities. Epiligurian deposits are interpreted as the infilling of thrust-top basins, which evolved during the collisional stages (wedge-top or satellite basins). During the advancement of the Ligurian nappe system, materials constituting olistostromes slide off the front of the nappe from intrabasinal structural highs and were intercalated in both foredeep and Epiligurian sequences (Conti and Fontana 2002; Lucente and Pini 2008; Remitti et al. 2011).

The Epiligurian succession in the Emilia Apennines

The most extensive and widespread outcrops of the Epiligurian succession have been preserved in the Emilia Apennines (Figs. 1, 2). The succession may be subdivided into two different portions by a major Burdigalian unconformity. Below the Burdigalian unconformity, a Middle Eocene to Early Miocene shallowing-upward sequence has been recognized. This sequence is mainly composed of pelagic, hemipelagic mudstones and turbidites, representing a slope apron facies association with significant thickness variations. Above the Burdigalian unconformity, the Epiligurian sequence (Burdigalian to Early Messinian) shows a deepening-upward trend: Shallow-water deposits at the base gradually pass upward to outer shelf and upper slope deposits of the Termina Fm (Fig. 2).

Several chaotic bodies, interpreted as submarine debris flows and defined as “olistostromes” or “argillaceous breccias” in the literature, are intercalated within the Epiligurian succession at different stratigraphic levels (Gasperi et al. 2005). The main chaotic bodies occur (1) at the base (Baiso mélange), (2) just below the Burdigalian unconformity (Val Tiepido–Canossa mélange), and (3) at the top (Mm). The first two bodies are widely spread over the Emilia Apennines, whereas the Mm is strictly limited to the Montebaranzone syncline, enclosed in the upper portion of the Termina Fm. These mélanges are chaotic mass containing submillimetric to decametric blocks of beds floating in a fine-grained detrital shaly matrix. The main sources of blocks are the underlying Ligurian units; subordinate contributions are from older deposits of the Epiligurian succession (Remitti et al. 2011).

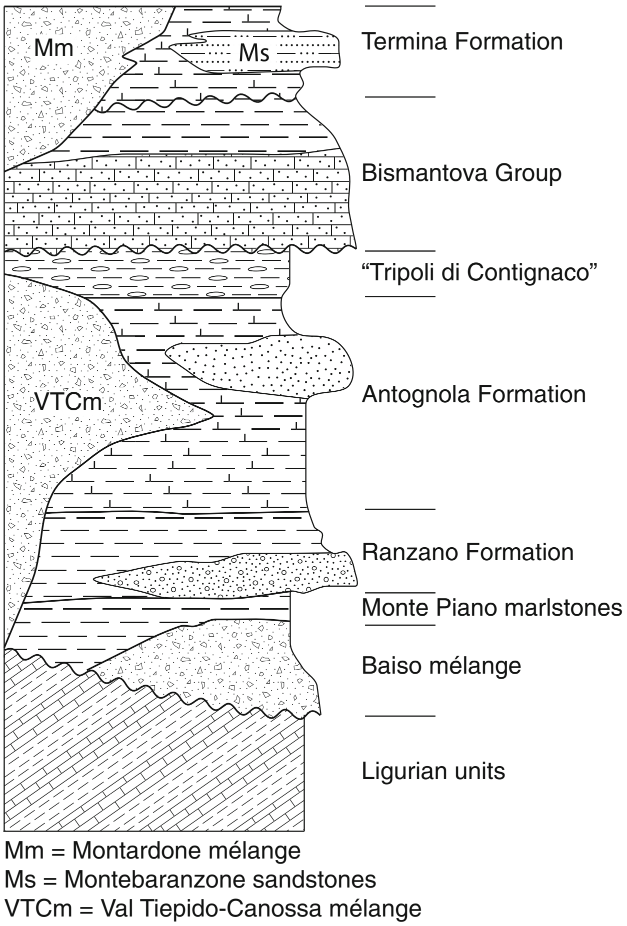

Fig. 2 Schematic stratigraphic column showing the Epiligurian succession of the Emilia sector of the northern Apennines

Results

The Montardone mélange

A detailed field work allowed us to draw the geological map of the Mm and associated deposits in the Montebaranzone syncline (Fig. 3). The map shows the distribution and stratigraphic relationships between the mélange and seep-carbonates in the Termina Fm. The 3D reconstruction of the structure is reported in Fig. 4.

The Termina Fm is composed of up to 500-m-thick Serravallian–Early Messinian (Amorosi et al. 1996) slope deposits predominantly made up of gray argillaceous poorly bedded marls and dark gray marlstones. The Montebaranzone sandstones and the Mm are two members distinguished in the upper portion of this formation.

The Montebaranzone sandstones occur as lens-shaped bodies inside the pelitic slope deposits. They show two different lithofacies: medium-to-coarse-grained arenites in thick amalgamated beds (lithofacies A) and fine-grained arenites in thin beds (lithofacies B) (Fig. 5). The two lithofacies are heterophic: The progressive lateral transition is evident at the scale of large outcrops (some hundreds of meters). Lithofacies A outcrops in the core of the Montebaranzone syncline (Fig. 5b), whereas lithofacies B characterizes the flanks of the syncline (Fig. 5a). They represent the depocenter and marginal deposition in a small, syntectonic basin, respectively. Lithofacies B shows lateral confinements testified by pinch-out, onlapping and lateral facies changes in sandstone lobes.

The Mm (Fig. 6) consists of polygenic and heterometric blocks dispersed in a fine-grained matrix. Blocks are chunks or fragments of single beds or bed packages and span in dimension from 1 to 2 cm to some meters. Clasts and blocks are composed of calcilutites, siltstone–sandstones, marlstones and claystones. The matrix is typically made up of clays with an open texture (edge-to-face contacts), containing millimetric-to-submillimetric clasts of various composition including indurate clays (brecciated or clastic matrix, see Bettelli and Panini 1985; Pini 1999). The general fabric has fractal characters (Ogata 2010), being the limit of 1 cm assumed as boundary between clasts/blocks and clasts belonging to matrix (microclasts) (Swarbick and Naylor 1980). Typically, the matrix is structure less and isotropic. Only weak banding due to changes in color is observable. A weak iso-orientation of the long axes of the slightly anisotropic blocks is observable close to the contacts (Fig. 6). Flow structures, such as mesoscale banding of the matrix, microclasts flattening and stretching and simple shear structures, and the systematic development of (scaly) cleavage (Orange 1990; Dela Pierre et al. 2007; Codegone et al. 2012; Pini et al. 2012), have not been observed so far. Blocks and clasts are mainly sourced from the Ligurian units underlying the Epiligurian succession, with special contribution from the Cretaceous Argille a Palombini and Argille Varicolori broken formations (Remitti et al. 2011). The Upper Eocene to Lower Miocene Epiligurian formations (Monte Piano, Ranzano and Antognola) also supplied non-consolidated or poorly consolidated sediments.

Distribution and thickness of the mélange change dramatically in the two sectors of the syncline (Figs. 3, 4). In the eastern sector, the mélange exhibits a thickness of more than 200 m; in the west sector, it reaches a maximum thickness of 40 m becoming progressively thinner toward the west. This reflects on the stratigraphic position of the mélange in the frame of the Termina Fm, passing from a narrow horizon atop the Termina Fm to a more thick body substituting the entire succession.

The Mm is similar in composition and general fabric to the Val Tiepido–Canossa and Baiso sedimentary mélanges (olistostromes or argillaceous breccias, see Bettelli and Panini 1985); these bodies have been considered to

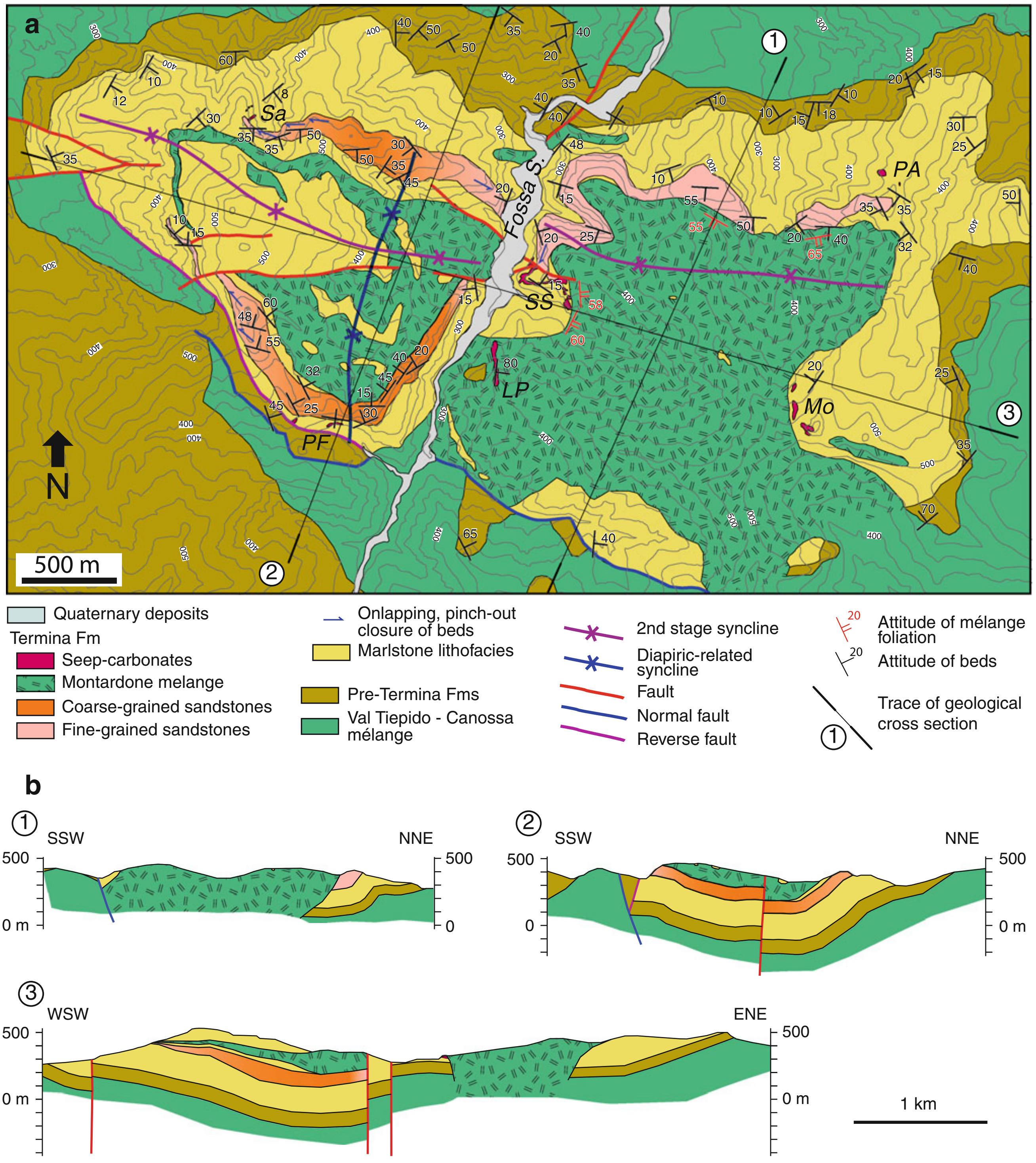

Fig. 3 Detailed geological map (**a**) and sections (**b**) of the Montebaranzone syncline (main outcrops of seep-carbonates: *SS* Sasso Streghe, *LP* Le Prade, *Mo* Montardone, *PA* Poggio Andretti, *Sa* Sarsetta, *PF* Prato Fiore)

originate from mass transport processes (matrix-dominated cohesive debris flows or blocky flows, see Mutti et al. 2006 and Ogata et al. 2012) in confined slope basins atop the Ligurian nappe and the paleo-Apennine wedge (wedge-top basins) (Remitti et al. 2011 and references therein).

Seep-carbonates associated with the Mm

Numerous seep-carbonate bodies crop out extensively in the Montebaranzone syncline, beneath and aside the Mm (Conti and Fontana 1999, 2005). Figures 3, 7 and 8 depict

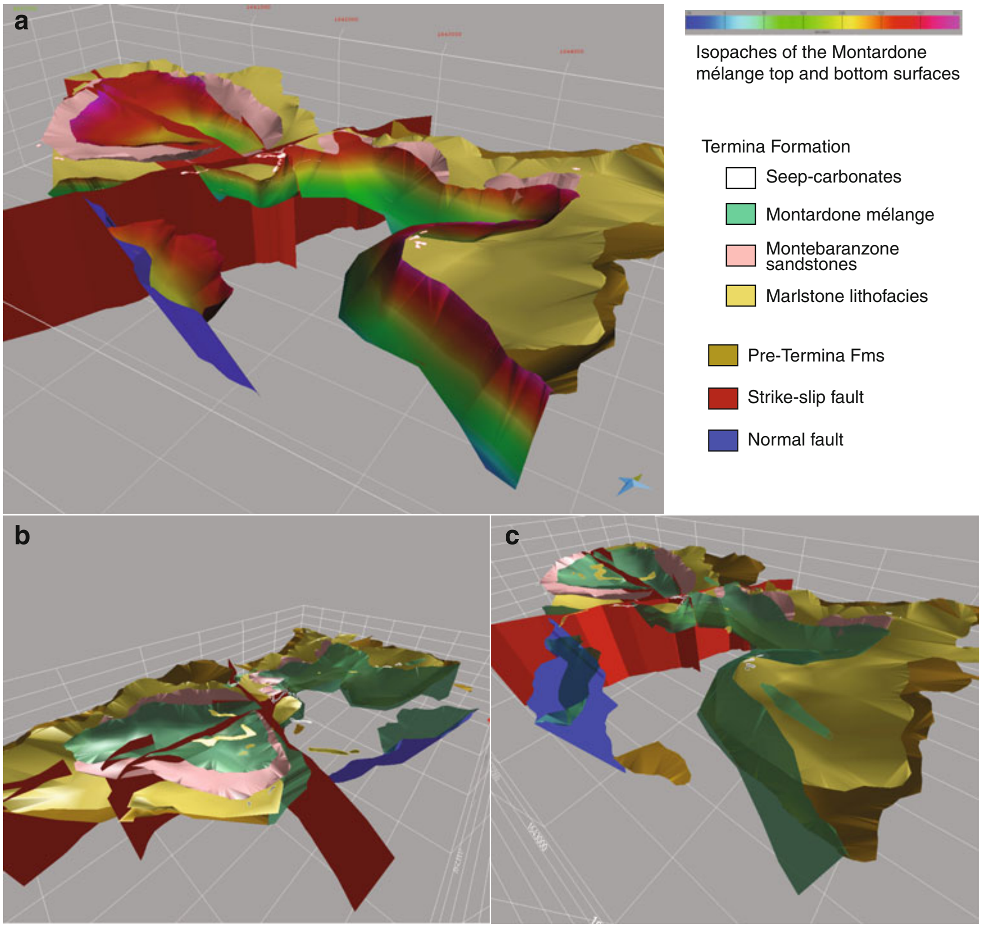

Fig. 4 3D reconstruction of the Montebaranzone structure from the geological map and geological cross-sections **a** aerial view from SE, **b** view from SW, **c** view from ESE), realized with the software Move 2011

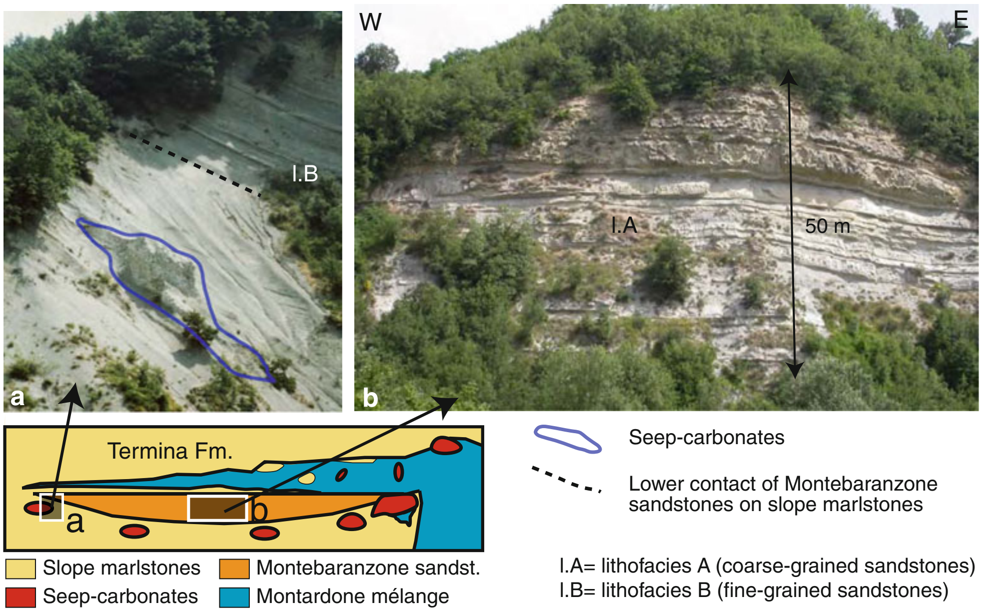

Fig. 5 Outcrop characteristics of the lithofacies A and B of the Montebaranzone sandstones, Termina Fm. The diagram in the lower left shows the position of the two pictures (**a**, **b**) in respect to the reconstructed stratigraphic relationships with seep-carbonates and the melange

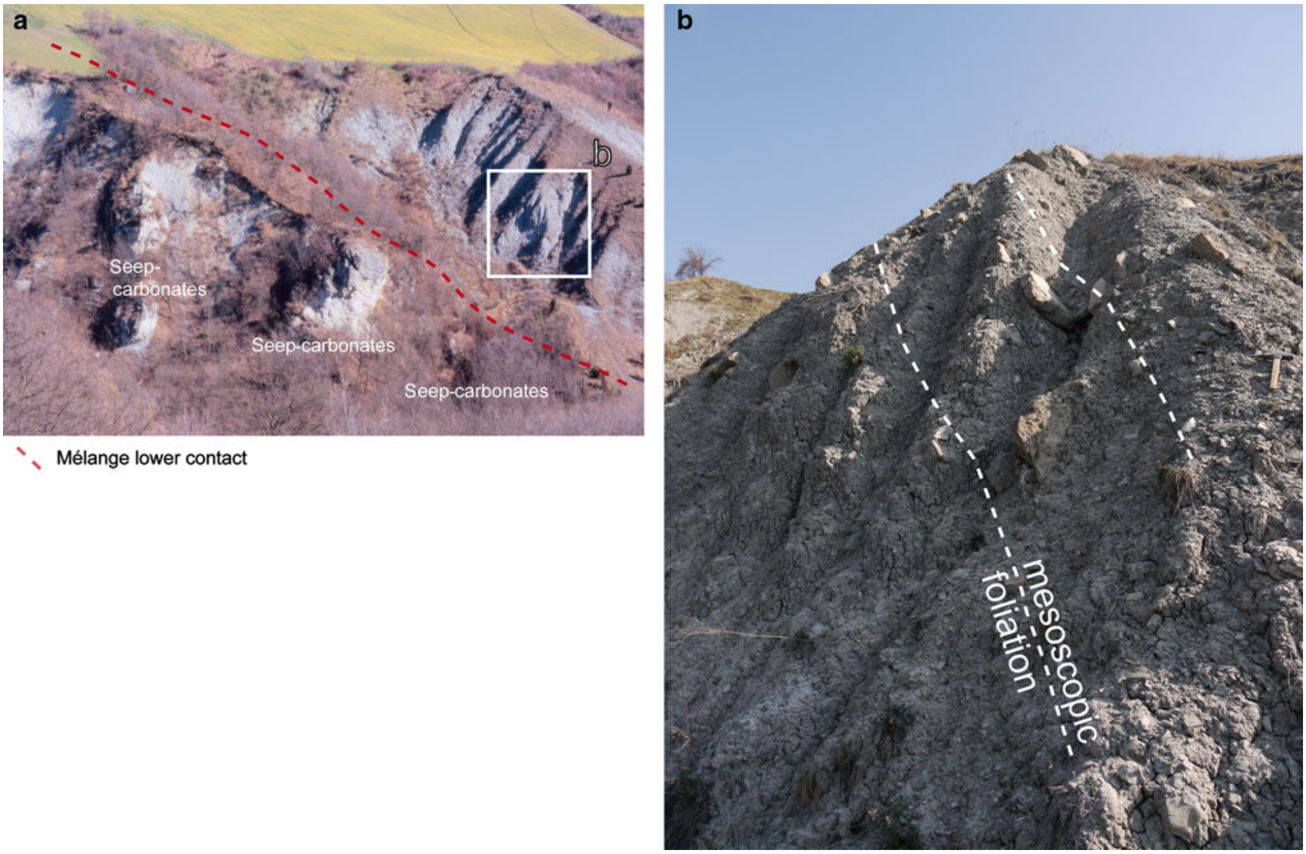

Fig. 6 Contact between Mm and seep-carbonates (**a**) and enlargement of the melange (*squared area*) showing the orientation of more elongated blocks in the clayey matrix (**b**)

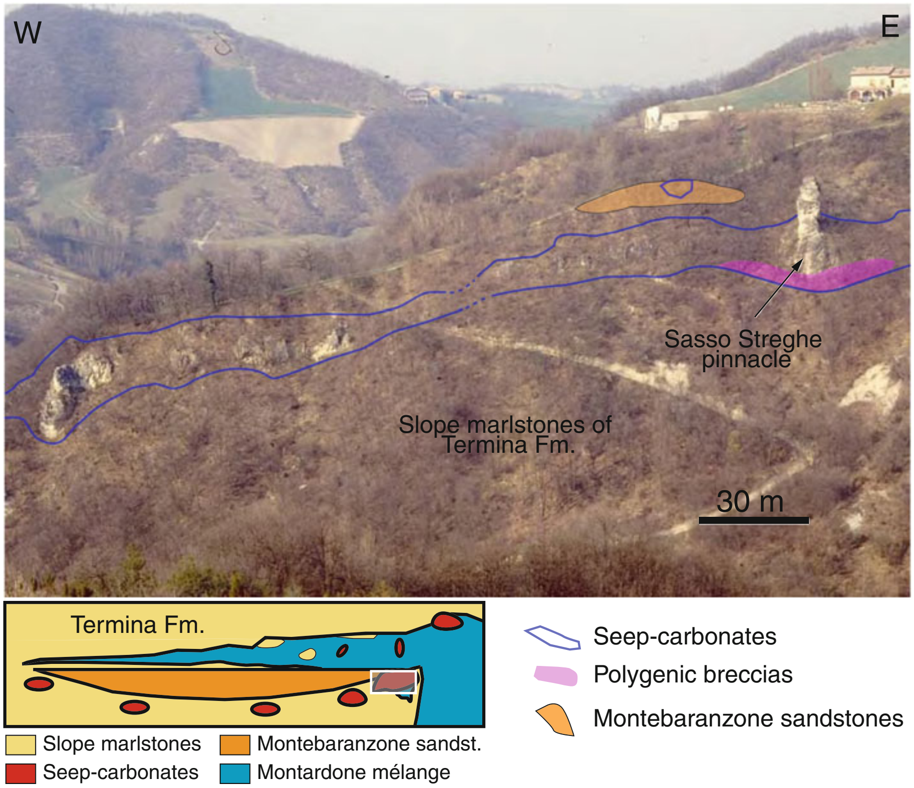

Fig. 7 Sasso Streghe carbonates (SS of Fig. 3): note the large pinnacle and the wide lateral extent of the body. *Bottom left* the reconstructed stratigraphic position of the SS carbonates in the Termina Fm

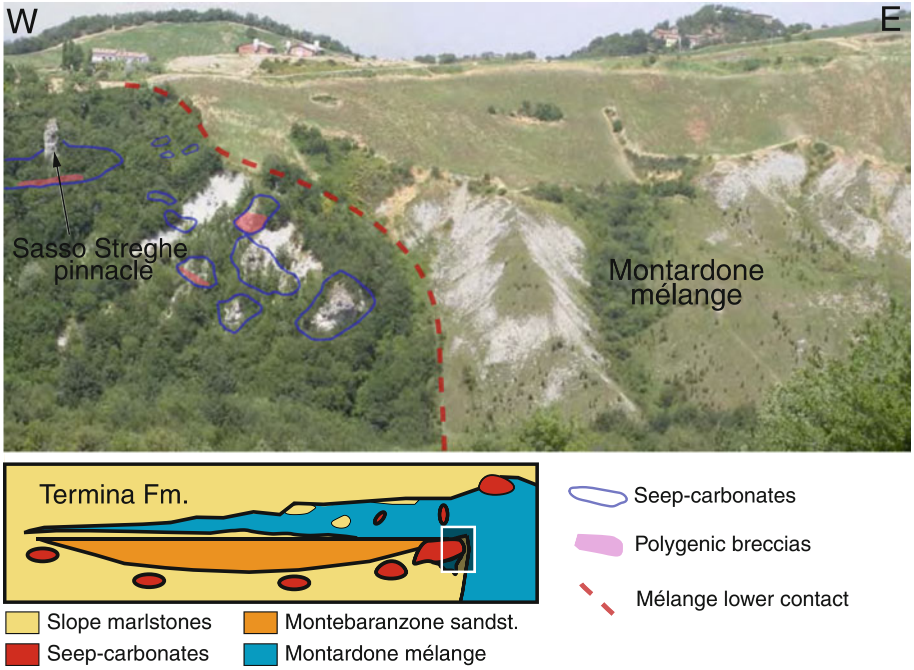

Fig. 8 Vertical contact between the Termina slope marlstones, the enclosed seep-carbonate bodies and the Mm (*on the right*). See the box in the bottom for the reconstructed location

the stratigraphic relationships among the Termina slope marlstones, the sandstone member, the Mm and seep-carbonates in the examined area. The largest number of seep-carbonate bodies is in the Termina Fm, with the maximum concentration and the largest and continuous bodies within a 50-m-thick stratigraphic interval of slope marlstones. The interval has been dated as Serravallian to Early Tortonian (Conti and Fontana 1999), suggesting a prolonged activity of seepage. New biostratigraphic data based on planktonic foraminiferal assemblages from two sections in Sasso Streghe outcrops (Grillenzoni 2011, see figures 7.4, 7.5 and 7.6) seem to indicate older ages (Serravallian) recorded in bodies closest to the vertical contact with the mélange. Seep-carbonates are in primary position, with the exception of the Le Prade outcrop, which seems to be reworked, involved in the Mm.

Carbonates from all the examined outcrops show common features reported below, such as the depletion in $\delta^{13}C$ isotope and the occurrence of chemosynthetic communities, which are consistent with seepage-associated carbonates, following the definitions of Teichert et al. (2005) and Han et al. (2008). Conversely, they show significant differences in terms of body geometry, brecciation, and amount of detritus incorporated within authigenic carbonates.

Typology of carbonate bodies

Seep-carbonates outcropping in the eastern side of the mélange (Sasso Streghe, Montardone, Le Prade, east of Fossa Stream in Fig. 3) consist of amygdaloid, stratiform bodies and large pinnacles ranging in extension from various meters to 100 m and with a maximum thickness of about 25–30 m. They describe wide and continuous horizons (Type 1 of Conti and Fontana 1999). The lithologies are calcarenites and calcareous marls, with wide portions of carbonate breccias. The lateral contact with host sediment varies from sharp to transitional. Conversely, seep-carbonates occurring on the western side of the mélange (Sarsetta, Prato Fiore, west of Fossa Stream in Fig. 3) consist of small and laterally isolated marly and marly -calcareous bodies (Type 2 of Conti and Fontana 1999); these bodies exhibit a lenticular, domed, columnar to irregular shape. Their dimensions vary from some decimeters to 4–5 m; lateral contact to enclosing sediment is gradual.

Dense localized chemosynthetic faunas (mainly lucinid and vesicomyid clams) are present in all outcrops, often in living position (Conti and Fontana 1999). These findings show that active chemohermal communities were living during the long time span of the seepage, suggesting a continuous spill over of methane-enriched fluids.

Composition of carbonates

Authigenic minerals include micro- to cryptocrystalline micrite and sparry calcite with minor dolomite. Micrite is volumetrically the dominant authigenic phase and includes abundant seep macrofossils (whole to fragmented lucinids), associated with planktonic foraminifera and bioturbation structures. Micrite also inglobes siliciclastic, silt-sand-sized, terrigenous particles. This detritus is particularly abundant in carbonates from eastern outcrops (Sasso Streghe, Montardone). In western outcrops (Sarsetta), the detrital fraction is scarce or absent, and finely laminated micrite lining pores and cavities is a common fabric, similar to the microbial fabric described by Peckmann et al. (1999) for the Piedmont seep-carbonates. Sparry calcite fills several generations of fractures and cavities and is pervasive in the brecciated portion of the seep-carbonates.

Table 1 Carbon and oxygen isotopic composition for samples from the Sasso Streghe outcrops

Sample	Lithology	δ^{13}C versus PDB	δ^{18}O versus PDB
SPO 9	Calcareous marl	−25.03	4.26
SPO12m	Marly limestone	−39.05	4.45
SPO12c	Weakly marly limestone	−38.47	4.77
SPO14	Calcareous marl	−32.78	4.14
SC571	Marly limestone	−26.59	0.74
SC570	Marly limestone	−29.16	0.10
MO5	Marly limestone	−30.46	2.88
RG 840	Calcareous marl	−26.44	1.41
SC576	Marly limestone	−36.76	4.39
RG839	Marly limestone	−37.49	5.45
SSW	Marly limestone	−18.22	−0.27
SSP	Weakly marly limestone	−32.18	4.78
SSPm	Marly limestone	−36.68	5.39

The δ^{13}C values in the Sasso Streghe outcrops (Table 1) range from −18.22 to −39.05 ‰ PDB; the amount of depletion differs for various carbonate bodies and inside single mass, with the most negative values in the brecciated portions. The δ^{18}O values indicate that seep-carbonates are slightly but significantly enriched in ^{18}O compared to carbonates of surrounding sediments (δ^{18}O values from −0.27 to 5.45 ‰ relative to the PDB standard); the ^{18}O enrichment reaches the highest values in the brecciated portions of seep-carbonates close to the contact with the Mm.

Seep-carbonate breccia

A peculiar polygenic breccia (Fig. 9) occurs at the base of seep-carbonates bodies outcropping in the southern flank of the Montebaranzone syncline, close to the contact with the Mm. Polygenic breccias are characterized by a mixing of carbonate, arenitic and pelitic clasts, changing in dimensions and provenance, chaotically floating in a micritic matrix. Intraformational clasts are made of various lithotypes derived from seep-carbonates and Termina marls. Extraformational clasts derive from different sources,

Fig. 9 The basal polygenic breccias of the seep-carbonates: clast dimensions vary from some mm to about 25 cm. Sasso Streghe (**a**, **c**, **d**) and Montardone (**b**) outcrops

primarily from the mélanges (limestones and sandstone–siltstones from Argille a Palombini and Argille Varicolori). Clasts are heterometric (from a few millimeters to 50 cm in diameter), generally very angular, rarely subangular. Polygenic breccias are matrix-supported, and only in few cases, they are clast-supported. Spaces between clasts are filled by sandy sediment from the surrounding rocks or, in the case of wide spaces, by bivalve coquina. Gradation is visible in some outcrops, with clast size gradually decreasing from the base to the top of carbonate masses. Fossils are scarce to absent and commonly disarticulated or isolated shells, represented by bivalve coquina in packstone or grainstones. Pseudofluidal textures and soft sediment deformations are observed. The polygenic breccias occur at the base of the seep-carbonates cropping out along the eastern part of the Montebaranzone syncline, close to the contact with the mélange. In these outcrops, breccias form units ranging in thickness from some centimeters to a few meters, often interdigitated with fine-grained carbonate-cemented sediments. The thickness of polygenic breccias is maximum, about 10 m, near the central part of the mélange, in seep-carbonates of Montardone and Sasso Streghe. It decreases in the peripheral parts of the mélange (1 m in Prato Fiore Stream and 20–30 cm in Poggio Andreotti outcrops) (Fig. 3). In the western seep-carbonate outcrops, polygenic breccias are absent.

Discussion

Field relationships: olistostromes versus mud volcanoes

The Mm has been interpreted in the geological literature as a sedimentary mélange (olistostrome) that is a sedimentary body emplaced by mass transport processes, interbedded within the Termina Fm. Following this interpretation, the Mm should represent a roughly lens-shaped body interbedded within the Termina Fm, as typical of other Epiligurian olistostromes (Pini 1999; Festa et al. 2010a, b, 2012). Therefore, a substantial concordance between the bedding of the Termina Fm, the Montebaranzone sandstones and the base of Mm should be expected (see discussion in Festa et al. 2012). Different angles and relationships can be assumed if the olistostromes deposited on an irregularly deformed (faulted and folded) substratum (see, e.g., Remitti et al. 2011).

Generally speaking, the emplacement of olistostromes leads to the iso-orientation of the more elongated blocks parallel to the basal contact and to the general attitude of bedding of the other stratigraphic units. It also implies meter-thick three-dimensional horizons (belts) of concentrate deformation showing block iso-orientation and banding and fluidal structures in the matrix above the basal contact (Einsele 2002; Pini et al. 2012). In olistostromes, the basal contact, in spite of the non-erosional nature of the mass transport on the substratum, is often characterized by metric-scale scours, but the flow-induced deformed horizon is normally parallel to the general basal surface, not being influenced by the scours (Pini 1999; Pini et al. 2012). The field relations between the Mm and the other stratigraphic units of the Termina Fm do not obey to the above-described criteria.

- First, the areal and stratigraphic distribution and the changes in thickness of the Mm do not conform to a normal stratigraphic superposition, the Mm substituting the entire Termina Fm normal succession in the central area of Fig. 3. Moreover, the contacts between the Mm and the encasing marls/sandstones of the Termina Fm (Figs. 3, 4) occur along a vertical surface in the eastern part of the syncline, cutting off the entire lower Termina Fm and the underlying Epiligurian succession. In particular, in the eastern sector where the Mm exhibits its maximum thickness, the contact changes in the inclination along dip and in the direction of strike, describing a funnel shape general attitude and cutting the Epiligurian strata at different angles. The contact is low angle with respect to the bedding when the latter is high angle (northeast side) (Fig. 8) and is high angle when bedding is subhorizontal, as in the case of the seep-carbonate main body of Sasso Streghe. The contact with the slope marlstones is noticeably more flat in the western sector, where the mélange has the lower thickness. The large-scale reverse cone shape suggested for the main body, piercing at high angle the Termina Fm, should correspond to the main conduits or to the now exhumed diapiric body supplying the conduits (diatremes) (Kopf 2002; Van Rensbergen et al. 1999). The low-angle contacts could correspond to zones of mud venting at the sea floor (localized lobes from secondary conduits) and to secondary conduits. The lower contact of Mm becomes layer parallel in the western of the study area and the Mm conformably rests on the top of the Termina Fm, following the general attitude of bedding (Fig. 4). This area could represent the depositional product of mudflow lobes erupted from the central crater.
  The "Christmas tree" structure of the Mm with numerous lateral interdigitations with the Termina marls at different stratigraphic levels (Figs. 3, 4) suggests a long-lasting period of growing of a mud volcano rather than multiple episodes of mass transport deposition.
- As for the composition and the fabric, the Val Tiepido–Canossa mélange is the main source rock for the Mm. A direct continuity is evident in field (intramélange

contact in Fig. 3) because due to the geometry of the contacts, the Mm cuts off the entire Epiligurian successions including the older units. In this case, the fabric of the mélange is not distinctive of the nature of the processes of emplacement, that is the classic block in "brecciated" and "clastic" matrix of the olistostromes (see Abbate et al. 1981; Festa et al. 2010b, 2012 and references therein; Pini et al. 2012) versus the "mud breccia" of the mud volcanoes (Cita et al. 1981; Orange 1990; Camerlenghi et al. 1992; Orange et al. 1993; Staffini et al. 1993; Camerlenghi and Pini 2009). Also the issue of composition and the changes in the distribution of thermal maturity of blocks (see, e.g., Orange and Underwood 1995) cannot help, since the mud volcano and its plumbing system are basically fed by an olistostrome as the source layer.

- In the mélange, an iso-orientation of the long axes of the slightly anisotropic blocks can be observed (mesoscopic foliation of Figs. 3, 6). Block iso-orientation is low angle with respect to the contact in most of the observed situations. High-angle, cross-cutting relationships are evident in proximity to the eastern side of the Sasso Streghe outcrop, where angular clasts are common and the mélange shows a higher clast-to-matrix ratio.
- The occurrence of δ^{13}C-depleted seep-carbonates (Table 1), with polygenic breccias in the peripheral parts of the mélange within the marls alongside the contact and at the top of the mélange, clearly indicates methane-rich fluid seepages. This feature can be the fossil, on land equivalent of the "halo of high-amplitude reflections" of (Van Rensbergen et al. 1999), supposed to be hydrocarbon accumulation. Moreover, only the carbonates close to the contact with the mélange have polygenic breccias with the same composition as the Mm at their base. Stratigraphic data show that seepage was active from the Lower Serravallian to the Lower Tortonian (Conti and Fontana 1999; Grillenzoni 2011), confirming a long-lasting period of fluid expulsion processes. The living position of benthic chemosynthetic fauna is more consistent with the interpretation of a diapiric emplacement respect to the olistostrome.
- The overall geometry of the Montebaranzone sandstone bodies is coherent with the progressively pinching out of arenaceous beds and the fining and thinning of sand beds toward the edge of the sandstone bodies. This evidence suggests a control by NNE-oriented intrabasinal topographic highs related to the raising diapir, bounding more depressed portions of a small ponded basin, corresponding to the western area of the Montebaranzone syncline. The present shape of the syncline, with an ESE component trend, should be assumed later, by thrusting of the Ligurian units and the older mélanges on the younger Epiligurian succession (Fig. 3). Submarine slides are detached from the topographic high due to the growing of the mud volcano apparatus involving portions of the Termina marls and blocks of seep-carbonates.

The mud volcano hypothesis

On the basis of the above evidences, we are proposing the ascent of overpressured mud from an older mud-rich mass transport deposit for the emplacement of the Mm (Fig. 10). This does not exclude the contribution of mass gravity processes that are systematically associated with mud volcanoes, such as lobes of erupted mud breccias, as observed in submarine and subaerial modern examples (Van Rensbergen et al. 2005; Roberts et al. 2011). Most likely, the seafloor expression was the one of a mud volcano or a mud ridge supplying mud breccia lobes to form coalescent debris flows (olistostromes).

According to this model, the flank of the mud volcano was affected by diffuse slope instability, involving also

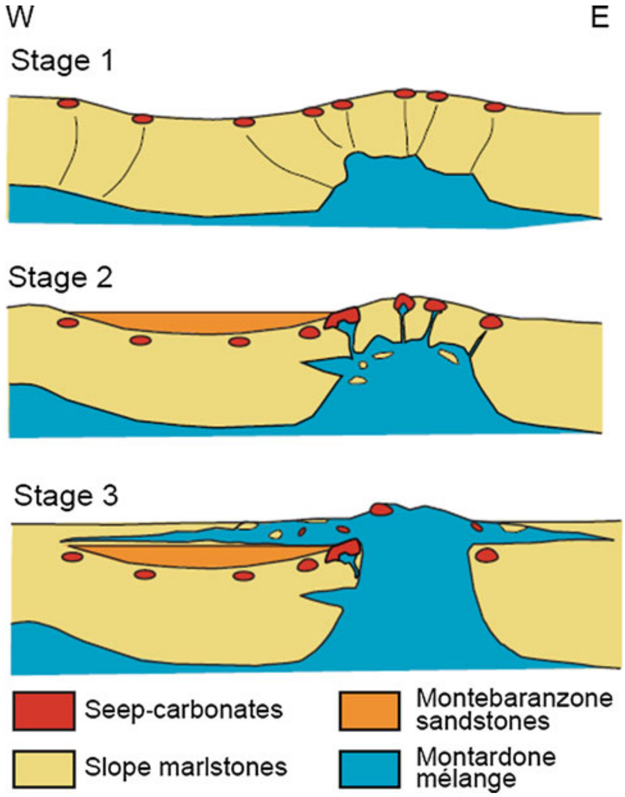

Fig. 10 Evolutionary stages of the proposed mud volcano emplacement showing the relationships among Mm, seep-carbonates, sandstones and hosting slope marlstones of the Termina Fm. Stage 1: beginning of the diapiric process. Stage 2: fast seepage, explosive phase. Stage 3: slope failures (debris flows) along the flanks of the mud volcano

blocks of authigenic carbonates. The minor lens-shaped bodies of Mm at the base of largest carbonate bodies could be explained as intrusions of diapiric material through the major conduits of fluid venting. The presence of isolated masses of mélange inside the Termina slope deposits may also be related to sill-like lateral intrusion at shallow depth (see, e.g., Westbrook and Smith 1983; Van Rensbergen et al. 1999).

The possible genetic scenario for the Mm and its relationship with seep-carbonates can be the following (Fig. 10):

Stage 1 Beginning of the diapiric process involving old Epiligurian olistostromes with the subsequent development of seep-carbonates characterized by well-developed chemosynthetic fauna (slow seepage). Mechanical discontinuities (faults) acted as conduits for the ascending methane-rich fluids. Diapirism could be promoted by thrust loading of underconsolidated mud breccias. The presence of methane-rich fluid probably increased the overpressures of mud breccias.

Stage 2 Polygenic breccias coming from the ascending mélange (fast seepage, explosive). Breccias are developed inside the carbonates during the carbonate deposition/fluid seepage and are not merely blocks felt from the Mm. The diapirism creates a topographic high, giving rise to a confined small basin. In this depressed sectors of the basin, a thick sandstone body was deposited.

Stage 3 The mélange reached the sea bottom and a large amount of slope failures (debris flows, olistostromes) occurred along the flanks of the mud volcano involving also slabs of the hosting slope marlstones and blocks of authigenic carbonates. Lastly, the normal sedimentation is restored at the top of the mélange.

Conclusions

The Mm is a chaotic, block-in-matrix unit cropping out in the Montebaranzone syncline in the northern Apennines. The chaotic body of Mm covers the entire syncline with strong lateral thickness changes: In the western sector, Mm reaches a maximum thickness of 40 m becoming progressively thinner toward west. In the eastern sector, the Mm exhibits its maximum thickness, exceeding 200 m, and has a vertical contact with the Termina marls.

Bodies of seep-carbonates occur closely associated with the Mm. They are present in the peripheral parts of the mélange, within the marls alongside the contact, and at the top of the mélange. Carbonate bodies are characterized by negative values of δ^{13}C (from −18.22 to −39.05 ‰ PDB) and by chemosynthetic fauna (lucinid and vesicomyid bivalves). Authigenic carbonates close to the contact with the mélange systematically have polygenic breccias at their base of the same composition of the Mm.

In contrast to previous studies that suggested a gravity-derived emplacement for the Mm, which was interpreted, as a large mass transport deposit (olistostrome), we propose here that the main body of the Mm emplaced as a mud volcano originated by the post-depositional reactivation and rising of a stratigraphically lower mud-rich mass transport bodies triggered by fluid overpressure. We base our interpretation on (1) distribution and geometry of the mélange, (2) the vertical abrupt contact with the hosting marls, (3) the occurrence of huge seep-carbonates associated with the mélange, (4) the presence of polygenic breccias at the base of seep-carbonates close to the melange.

A genetic three-step scenario for the Mm emplacement includes the following: stage 1, beginning of the diapiric process involving old Epiligurian olistostromes with the subsequent development of seep-carbonates; stage 2, fast seepage, explosive, polygenic breccias coming from the ascending mélange. The diapirism creates a topographic high, giving rise to a confined small basin; stage 3, the mélange reached the sea bottom and slope failures (debris flows, olistostromes) occurred along the flanks of the mud volcano. As a last stage, the normal sedimentation is restored at the top of the mélange.

The formation of a mud volcano is here attributed to the tectonic loading by overthrusting and the consequent generation of a large amount of methane-rich fluid in the source rocks, i.e., an older large olistostromal body. The occurrence of methane-rich fluids, testified by authigenic carbonates, contributed to generate overpressured shales ascending along syn-sedimentary faults.

This paper highlights that (1) many large chaotic bodies with the characters of mud-rich mass transport bodies (olistostromes) could have also been affected by post-depositional vertical mobilization, explaining anomalous side contacts; (2) the close association of mud volcanoes, seep-carbonates and chemosynthetic biological communities may be related to remobilization of olistostromes triggered by fluid overpressure; (3) care must be taken to interpret large chaotic and irregularly distributed masses of polygenic breccias simply as the result of mass gravity processes (olistostromes, debris flows).

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