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Mid-Eocene giant slope failure (sedimentary mélanges) in the Ligurian accretionary wedge (NW Italy) and relationships with tectonics, global climate change and the dissociation of gas hydrates

Andrea Festa[1*], Simona Cavagna[1], Edoardo Barbero[2], Rita Catanzariti[3] & Gian Andrea Pini[4]

[1] Dipartimento di Scienze della Terra, Università di Torino, Via Valperga Caluso, 35, 10125 Torino, Italy
[2] Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Via Saragat 1, 44122 Ferrara, Italy
[3] Istituto di Geoscienze e Georisorse, CNR – Consiglio Nazionale delle Ricerche, Via G. Moruzzi 1, 56124 Pisa, Italy
[4] Dipartimento di Matematica e Geoscienze, Università di Trieste, Via Weiss 2, 34128 Trieste, Italy
* Correspondence: andrea.festa@unito.it

Upper Lutetian–Bartonian sedimentary mélanges, corresponding to ancient mud-rich submarine mass transport deposits, are widely distributed over an area c. 300 km long and tens of kilometres wide along the exhumed outer part of the External Ligurian accretionary wedge in the Northern Apennines. The occurrence of methane-derived carbonate concretions (septarians) in a specific tectonostratigraphic position below these sedimentary mélanges allows us to document the relationships among a significant period of regional-scale slope failure, climate change (the Early and Mid-Eocene Optimum stages), the dissociation of gas hydrates and accretionary tectonics during the Ligurian Tectonic Phase (early–mid-Lutetian). The distribution of septarians at the core of thrust-related anticlines suggests that the dissociation of gas hydrates was triggered by accretionary tectonics rather than climate change. The different ages of slope failure emplacement and the formation of the septarians support the view that the dissociation of gas hydrates was not the most important trigger for slope failure. The latter occurred during a tectonic quiescence stage associated with a regressive depositional trend, and probably minor residual tectonic pulses, which followed the Ligurian Tectonic Phase, favouring the dynamic re-equilibrium of the External Ligurian accretionary wedge. Our findings provide useful information for a better understanding of the factors controlling giant slope failure events in modern accretionary settings, where they may cause tsunamis.

The downslope emplacement of medium- (10–1000 km^2) to giant- (≥1000 km^2) sized heterogeneous, mud-rich mass transport depos- its (MTDs) is documented to play a significant part in controlling and maintaining the dynamic equilibrium of the outer wedge of modern subduction–accretionary complexes (e.g. von Huene et al. 2004; Remitti et al. 2011; Festa et al. 2015b, 2018; Artoni et al. 2019). In these settings, slope failure can be triggered or favoured by several concomitant and/or interlinked factors, such as shaking by earthquakes (e.g. Brothers et al. 2013), the subduction of asperities (e.g. seamounts or ridges; see Ruh 2016), a warming climate and rising sea-levels (e.g. Urgeles & Camerlenghi 2013) and the dissociation of gas hydrates (e.g. Maslin et al. 1998; Brown et al. 2006). However, the relationships between mass transport processes and these different factors are still a matter of debate and contrasting interpretations. For example, observations that the frequency of submarine landslides seems to increase during periods of sea-level rise, lowstand or rapid subsidence (e.g. Paull et al. 1996; Piper et al. 2003; Lee et al. 2010) suggest that variations in sea-level might potentially be more important triggers than the dissociation of gas hydrates (Urgeles & Camerlenghi 2013). This is supported by evidence that the headwalls of many giant submarine MTDs appear to be located in water depths (between c. 1000 and 1300 m; see Huhnerbach et al. 2004) that are too deep for triggering by the dissociation of gas hydrates, at least at under present day conditions (Grozic 2010; Talling et al. 2014). However, reconstruction of the stability field for the dissociation of gas hydrates in the past is a complex task and depends on the pressure and temperature as well as the temperature of the seawater at the sea bottom and the geothermal gradient (e.g. Tréhu et al. 2006). Other observations indicate that the occurrence of submarine slope failure events is either weakly (or not) linked to global changes in sea-level and the dissociation of gas hydrates in open continental slope settings (e.g. Urlaub et al. 2013; Talling et al. 2014). Because of their geohazard potential (e.g. tsunamis and damage to the infrastructure of the seabed), it is important to better understand and constrain the relationships among submarine slope failure and active tectonics, climate change, the dissociation of gas hydrates and variations in sea-level.

Mid-Eocene mud-rich submarine MTDs, corresponding to sedimentary mélanges (olistostromes), are widely distributed along the exhumed outer part of the External Ligurian accretionary wedge (ELAW) in the Northern Apennines of Italy over an area c. 300 km long and tens of kilometres wide. They mark a significant period of regional-scale instability at the end of the Ligurian Tectonic Phase (early–mid-Lutetian). The time interval between the earlier part of this tectonic phase and the regional-scale emplacement of these sedimentary mélanges encompasses the Early (EECO; c. 53–52 to 50 Ma) and Mid- (MECO; c. 40 Ma) Eocene Climatic Optimum, two global warming events which temporally interrupted the long-term Cenozoic cooling trend (e.g. Shackleton & Boersma 1981; Miller et al. 1987; Bohaty & Zachos 2003; Boscolo Galazzo et al. 2014). These events were characterized by a perturbation in the global carbon cycle (Payros et al. 2015) and a negative carbon isotope excursion, for which methane hydrate dissociation has been argued to be the cause (Dickens et al. 1995), among other hypotheses (e.g. Higgins & Schrag 2006; DeConto et al. 2012).

Using new and revised field structural and stratigraphic data and palaeontological analyses, we document and correlate methane- derived carbonate concretions (septarians) on a regional-scale. We interpret these septarians as the product of the dissociation of gas hydrates during the Eocene. We define the stratigraphic and structural position of these septarian concretions and investigate and discuss the relationships between the dissociation of gas hydrates, climate change (EECO and MECO) and active tectonics, and their role in preconditioning or triggering the mid-Eocene (late Lutetian– Bartonian) giant slope failure event at the wedge front of the ELAW. Our field-based findings provide useful information for a better understanding of the role of submarine slope failure in restabilizing the dynamic equilibrium of the outer wedge of the ELAW at the end of the Ligurian Tectonic Phase. They may therefore provide significant information for a better understanding of the causative links among different factors promoting giant slope failure in modern subduction–accretionary complexes.

Regional setting

The Northern Apennines (Fig. 1) represent the product of a complete orogenic cycle from the Mid- to Late Jurassic opening of the Alpine Tethys (Ligurian–Piedmont) oceanic basin to the Late Cretaceous to mid-Eocene oceanic subduction stage and up to the Cenozoic continental collision between the European plate and the Adria microplate (African plate) and subsequent intra-continental deformation (e.g. Coward & Dietrich 1989; Elter et al. 2003; Marroni et al. 2010; Festa et al. in press a). Since the mid-Eocene, the involvement of the thinned continental margin of Adria in the west-dipping Apennine subduction formed the ENE-facing ELAW (Molli et al. 2010; Marroni et al. 2010), consisting of the tectonic piling of different External Ligurian Units (ELUs). The latter represent deposition at the ocean–continent transition zone between the Ligurian–Piedmont ocean and the thinned passive margin of Adria and mainly consist of Cretaceous broken formations, tectonic and sedimentary mélanges (the Basal Complexes) and an Upper Cretaceous–lower Eocene flysch succession (e.g. Bettelli et al. 1987; Bettelli & Panini 1989; Pini 1999; Vescovi et al. 1999; Festa et al. 2010; Marroni et al. 2010; Catanzariti & Perilli 2011, 2015). The accretionary stage, known as the Ligurian Tectonic Phase (e.g. Elter 1975), is constrained to the early to mid-Lutetian by the age of the unconformity at the base of a mid- to late Eocene (i.e. late Lutetian–Bartonian) to Miocene wedge-top basin succession (Fig. 1a) – the Epiligurian Units (e.g. Ricci Lucchi 1986) and the Tertiary Piedmont Basin (e.g., Mutti et al. 1995) – that was deposited above the deformed ELAW.

Since the Rupelian, the tectonostratigraphic architecture inherited from the Ligurian Tectonic Phase has been overprinted during different tectonic stages associated with the northern to northeastern migration of the frontal thrust system of the Northern Apennines (e.g. Pini 1999; Piana 2000; Cerrina Feroni et al. 2004; Festa et al. 2005, 2015a; Marroni et al. 2010). Sedimentary mélanges (olistostromes), which represent ancient submarine MTDs, occur at different stratigraphic levels at the base and within the wedge-top basin succession (e.g. Elter & Trevisan 1973; Bettelli et al. 1989; Panini et al. 2002b, 2013; Festa et al. 2010, 2015b; Ogata et al. 2012, 2014, in press; Festa & Codegone 2013), representing specific regional-scale failure events in the evolution of the ELAW. We focus here on a mid-Eocene sedimentary mélange and refer to Festa et al. (in press b) for the mélange terminology used.

Mid-Eocene sedimentary mélange

The boundary between the wedge-top basin succession and the underlying deformed ELUs is commonly draped by a mid-Eocene sedimentary mélange, which is bound at the base by an erosional surface, concave upwards at the kilometre scale, superposing it on different units of the accreted ELUs. In the sector between Voghera and the Emilian Apennines (Fig. 1a), it corresponds to the Baiso argillaceous breccias of Bettelli et al. (1987). These breccias (Fig. 2a) are discontinuously distributed over a large area (thousands of square kilometres), showing an increase in thickness towards the SE from a few metres to hundreds of metres. The mid-Eocene sedimentary mélange has not previously been described in the

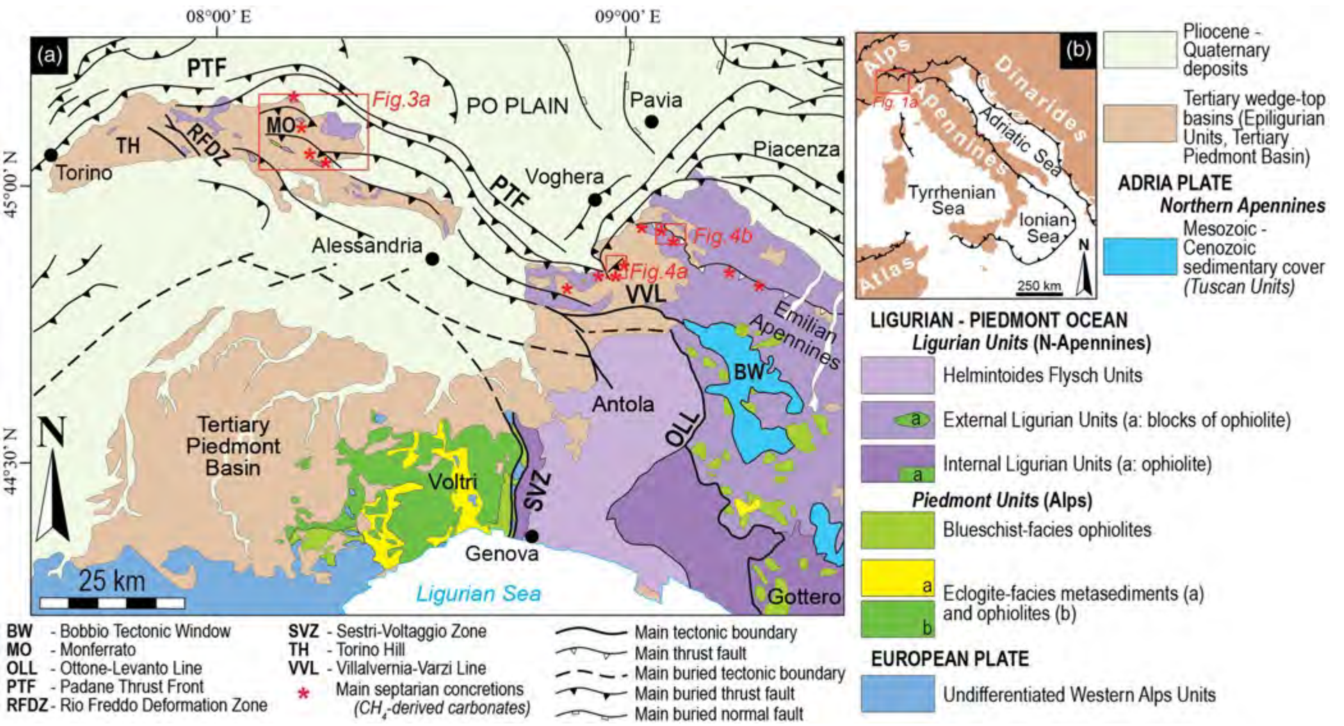

Fig. 1. Structural sketch map of the Northern Apennines (modified from Balestro et al. 2015) showing the location of the studied area and the main occurrences of septarian concretions.

Monferrato sector (i.e. towards the NW). It is very limited in extent with a maximum thickness of a few tens of metres (Fabiano sector). In all these sectors, the sedimentary mélange (referred to here as the Baiso argillaceous breccias) shows a chaotic block-in-matrix texture, defined by irregular and angular-shaped clasts embedded in a fine detrital matrix (Fig. 2a, b). The latter formed by mixed flows of mud and high-density detrital material (mud and debris flows) emplaced in deep marine basins (e.g. Bettelli & Panini 1989; Pini 1999; Remitti et al. 2012). The source material is mainly represented by the Cretaceous chaotic ELUs (i.e. the Basal Complex) and, in some cases, by slide blocks of poorly consolidated Monte Piano marls (late Lutetian–early Rupelian), which emerged at the core of thrust-related anticlines and tectonic ridges within the ELAW.

The age of the Baiso argillaceous breccias is mid-(?) to late Lutetian to early Bartonian, as constrained by the ages of the younger clasts embedded within the matrix and the age of the overlying and underlying sediments (e.g. Bettelli et al. 1987; Cerrina Feroni et al. 2002; Panini et al. 2002a; Papani et al. 2002; Vescovi 2002; Di Dio et al. 2005; Gasperi et al. 2005). Although this sedimentary mélange is commonly followed by the hemi-pelagic Monte Piano marls, which represent the lower part of the wedge-top basin succession, complex relationships locally occur between the two lithostratigraphic units, with both the Baiso argillaceous breccias above the Monte Piano marls and/or the Monte Piano marls embedded within the Baiso argillaceous breccias (e.g. Panini et al. 2002a, 2002b). The Monte Piano marls consist of lower varicolored clays and clayey marls (Varicolored Member) and upper greyish silty marls (Gray Member). At the regional scale, the age is late Lutetian–early Rupelian, with a discontinuous top to the unit, ranging in age from late Priabonian to early Rupelian from the western (inner) to eastern (outer) sectors of the Northern Apennines (e.g. Vescovi 1993; Mancin & Pirini 2002). This variation in age is locally associated with changes in thickness, ranging from tens of metres to several hundreds of metres, according to deposition on a rugged and articulated seafloor inherited from the Ligurian Tectonic Phase (e.g. Mancin et al. 2006). The Varicolored and Gray members of the Monte Piano marls record a regressive trend from lower (c. 2000–1000 m) to lower–middle (c. 1000–600 m) bathyal depths, respectively (Mancin & Cobianchi 2000; Di Giulio et al. 2002; Mancin et al. 2006).

Remnants of the mid-Eocene ELAW and distribution of septarian concretions

We describe the key sectors (Figs 3 and 4) in which remnants of the tectonostratigraphic architecture of the ELAW are preserved below the unconformity at the base of the wedge-top basin succession (i.e. the Monte Piano marls and Baiso argillaceous breccias). Particular attention is paid to the tectonostratigraphic position of several carbonate concretions, characterized by septarian cracks, which have previously been contrastingly attributed to the Paleocene, early Eocene and/or late Eocene (e.g. Sacco 1888, 1891; Taramelli 1916; Boni 1962; Beatrizzotti et al 1964; Vanossi 1964; Labesse 1979). These contrasting interpretations are closely related to the very rare occurrence in outcrop of septarian concretions with respect to a more common scattered distribution on grass and ploughed fields.

Monferrato sector

Few remnants of the Ligurian Tectonic Phase are preserved at the core of the NW-striking thrust-related anticlines and tectonic ridges (Fig. 3). Along the NW-striking Piancerreto–Ottiglio anticline (Fig. 3a), the ELUs – previously attributed to the upper Eocene Gassino Formation (Bonsignore et al. 1969), the 'Eocene' marls and clays (Franchi et al. 1925) and/or Upper Cretaceous–Paleogene(?) La Pietra Complex (Dela Pierre et al. 2003) – consist of a broken formation. The latter, here informally named the Ottiglio clay, is made of shaly marls, mainly greyish–greenish and locally yellowish in colour, alternating with light grey calcareous marls, yellowish to light brown turbiditic sandstones and calc-arenites, in decimetre- thick beds (see Barbero et al. 2019). Analyses of calcareous nannofossils show an age ranging from Selandian and Thanetian (NP9 zone) to Ypresian (NP12 zone) in the Ottiglio and Fabiano sectors, respectively. In both those sectors, septarian concretions occur at the core of NW-striking thrust-related anticlines (Figs 2d, 3b, c) in the uppermost part of the Ottiglio clay, tens of metres below

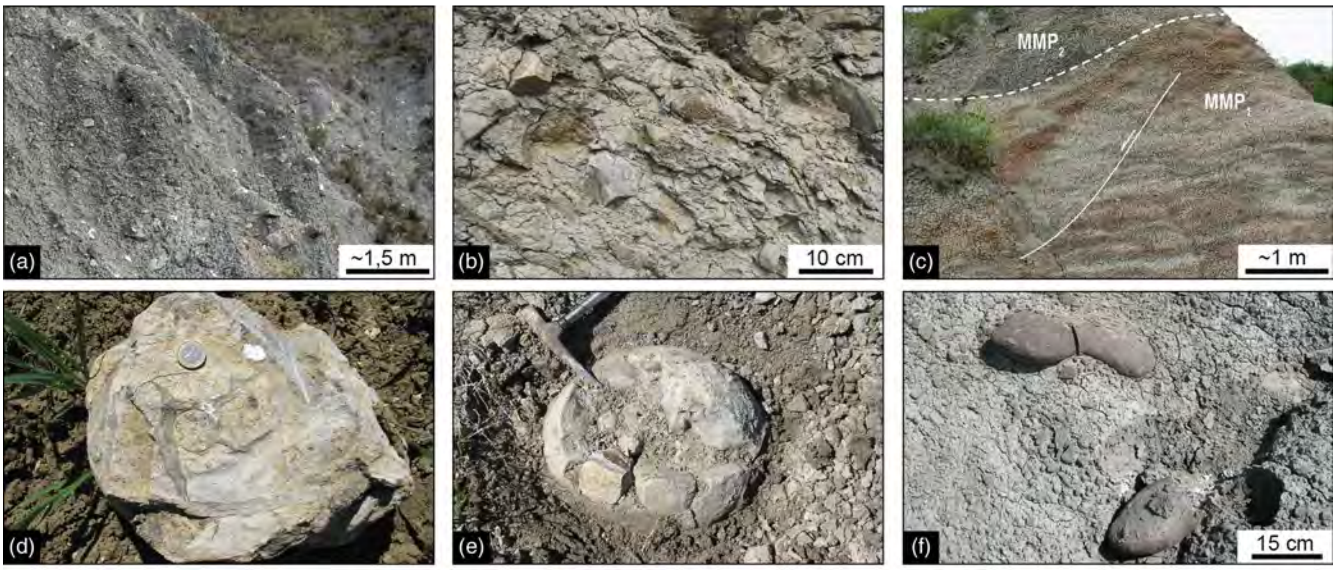

Fig. 2. Field images of (a) the middle Eocene sedimentary mélange (Baiso argillaceous breccias) showing a chaotic block-in-matrix texture defined by (b) irregular to angular-shaped clasts embedded in a fine detrital matrix (Voghera sector, close to Boiolo). (c) Stratigraphic contact (white dashed line) between the Varicolored Member (MMP_1) and the Gray Member (MMP_2) of the Monte Piano marls. Note the gravitational related folding and faulting (white line) within MMP_1 (Voghera sector, close to Boiolo). Different occurrences of sepatarian concretions showing (d) an irregular shape and carbonate veins on the external surface (Fabiano sector in Monferrato; coin for scale) and (e) sub-spherical to (f) discoidal shapes (Scagni and San Desiderio sectors, respectively, in the Voghera sector; hammer for scale in part (e)).

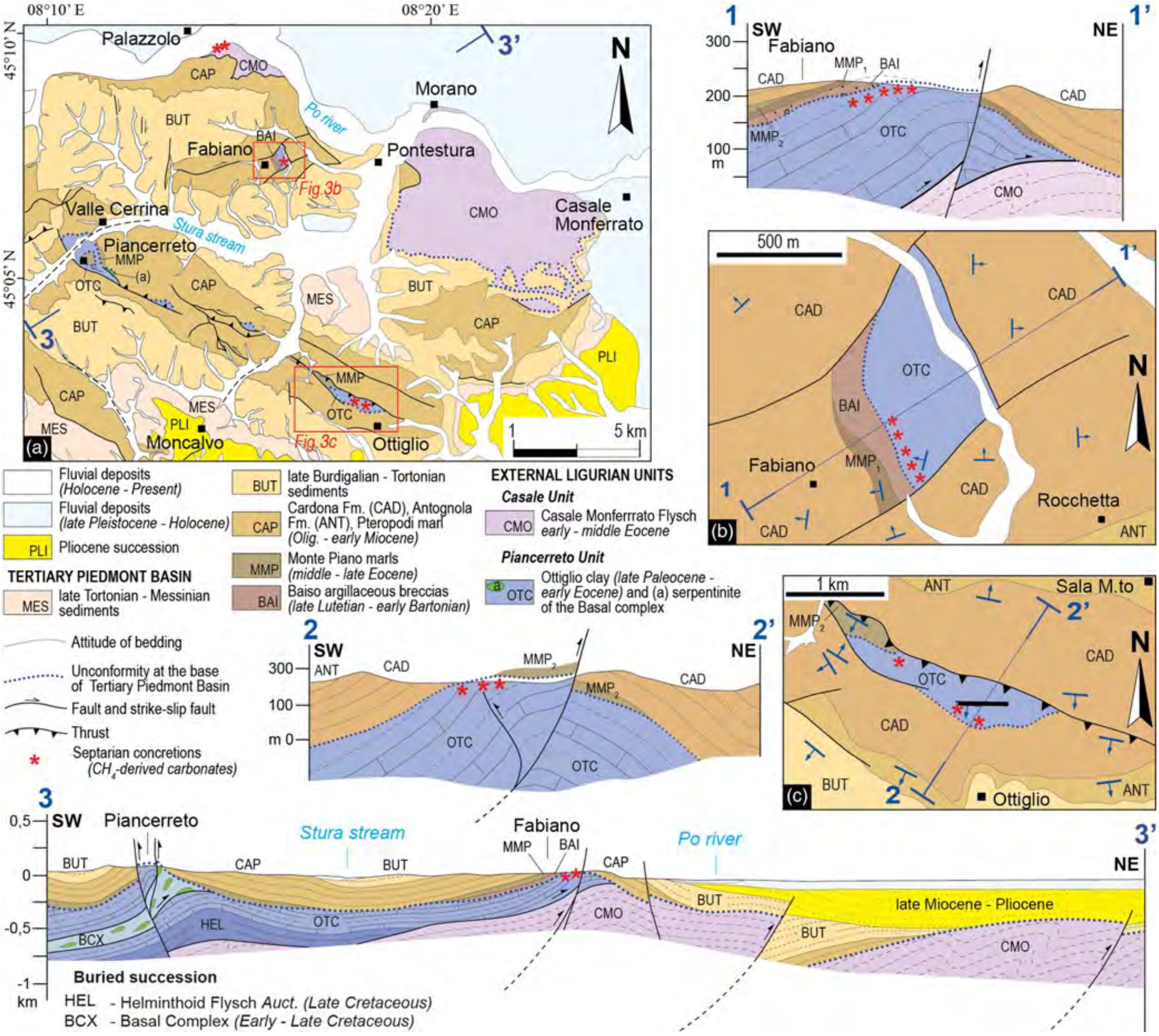

Fig. 3. (a) Simplified geological–structural map of the Monferrato sector (modified from Bonsignore et al. 1969; Dela Pierre et al. 2003) and details and cross-sections of the (b) Fabiano and (c) Ottiglio sectors showing the tectonostratigraphic position of septarian concretions below the unconformity at the base of the wedge-top thrust succession of the Tertiary Piedmont Basin (see Fig. 3 for location within the ELAW).

the unconformity surface at the base of the Monte Piano marls (Bartonian–Priabonian).

Other septarian concretions were also documented by Sacco (1888) and Beatrizzotti et al. (1964) within the shaly marl of the Casale Monferrato Flysch (i.e. early–-middle Eocene), pertaining to the ELUs, along the northern bank of the Po River close to Palazzolo (Fig. 3a). Unfortunately, these occurrences are no longer preserved. The boundary between the Monte Piano marls and the Ottiglio clay is locally marked by a sedimentary mélange (Fig. 3b), tens of metres thick, which has not previously been described in Monferrato. It consists of exotic blocks sourced from both the Cretaceous Basal Complexes of the ELUs, which are randomly distributed within a poorly exposed brecciated, greyish to reddish marly clay matrix. Importantly, the preserved and outcropping mélange does not include any septarian concretions or related fragments. This sedimentary mélange is comparable with the late Lutetian–early Bartonian Baiso argillaceous breccias (sensu Bettelli et al. 1987) of the Emilian Apennines based on its stratigraphic position and internal texture and composition.

Voghera sector

In this sector (Fig. 4) the ELUs (i.e. the Cretaceous Basal Complexes, the upper Campanian Monte Cassio Flysch and the upper Maastrichtian–upper Paleocene Viano clay) emerge at the core of thrust-related anticlines, ENE- to NW-striking (see Barbero et al. 2019), which are unconformably sealed by the Varicolored Member of the Monte Piano marls (late Lutetian). Along the limbs of these anticlines, the Baiso argillaceous breccias (late Lutetian– early Bartonian) drape the boundary between the Monte Piano marls and the deformed ELUs (Fig. 4), showing a gradual increase in thickness from a few metres to c. 100 m towards both the north and south (Barbero et al. 2017).

Septarian concretions (Fig. 2e, f) are always clustered in the hanging wall of thrust faults (Fig. 4). In the Staffora Valley (Fig. 4a), they are embedded in the upper part of the Viano clay (late Maastrichtian–late Paleocene), a few metres to tens of metres below the erosional base of the Baiso argillaceous breccias and/or the Monte Piano marls. Palaeontological analyses show a late

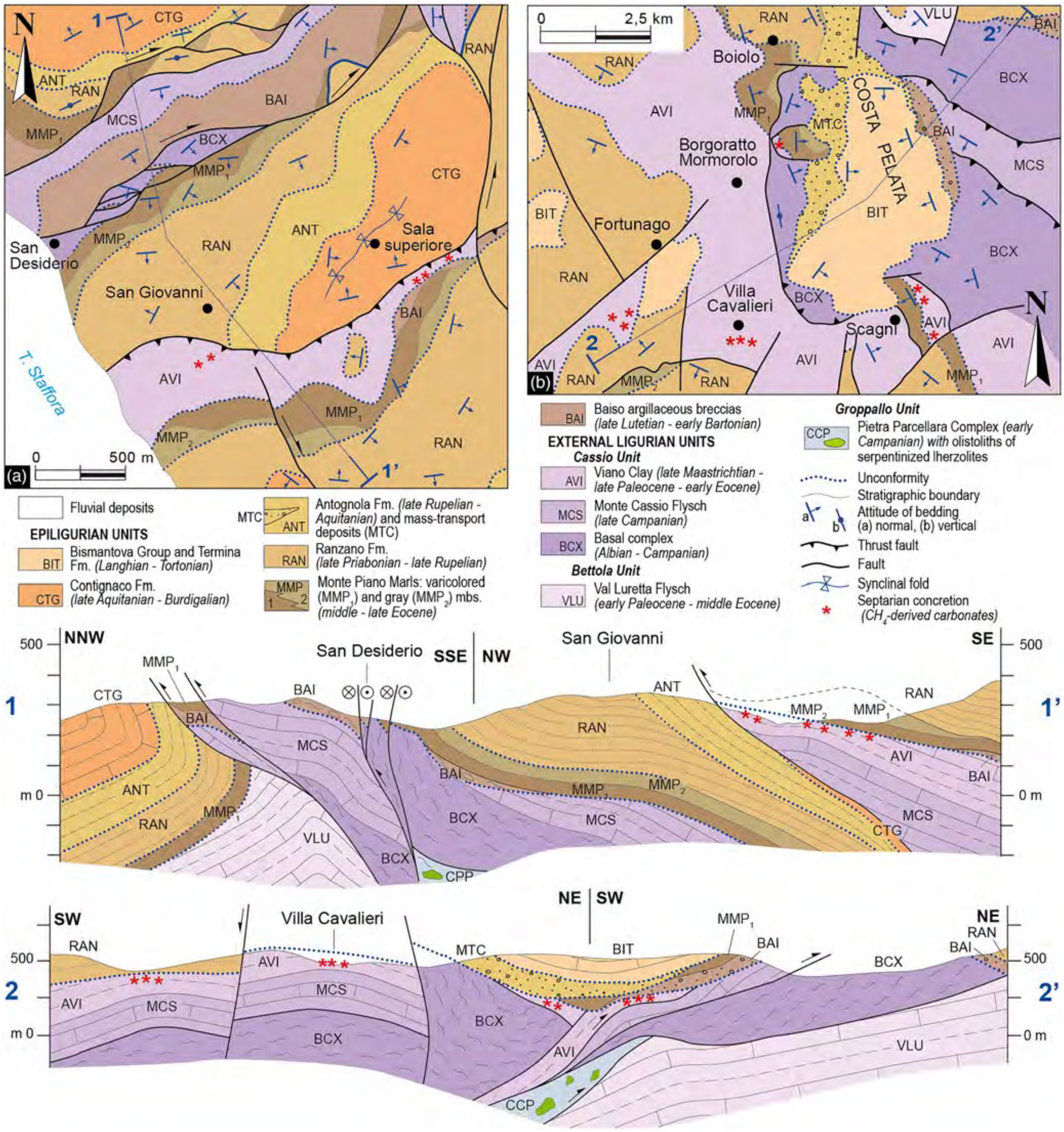

Fig. 4. Simplified geological–structural maps and related cross-sections of the (a) Staffora Valley and (b) Costa Pelata sectors showing the tectonostratigraphic position of septarian concretions below the unconformity at the base of the wedge-top thrust succession of the Epiligurian Untis. See Figure 3 for location within the ELAW.

Paleocene age (Thanetian, NP9 zone) for the sediments hosting septarian concretions. A similar stratigraphic position is documented for several other septarian concretions towards the NE, between Boiolo and Scagni (Fig. 4b; see Beatrizzotti et al. 1964; Vanossi 1964; Labesse 1979; Panini et al. 2002b). Here, the uppermost portion of the Viano clay, which was sampled just below the unconformity at the base of the Epiligurian Units, reaches the early to mid-Eocene boundary (NP14 zone) (see Panini et al. 2002b) and consists of strongly disrupted greenish–greyish clay and marl. As at Monferrato, septarian concretions and/or their disrupted fragments never occur in association with both the preserved and outcropping Baiso argillaceous breccias and Monte Piano marls.

Septarian concretions

Macroscopic features

Concretions mainly show a sub-spherical and/or a lobate or discoidal shape (Fig. 2e, f), ranging in size from 10 to 50 cm and rarely up to 1 m. The contact between the concretions and the host sediments is always sharp. Cuts through their central part show a complex network of internal fractures, partially or completely filled with carbonate cements and sometimes by sediments, resulting in the so-called ‘septarian’ structure (Fig. 5a–c). Cement-filled cracks, forming septa, cut across the concretions, which, in turn, display a breccia-like aspect. The areas of the concretions surrounded by

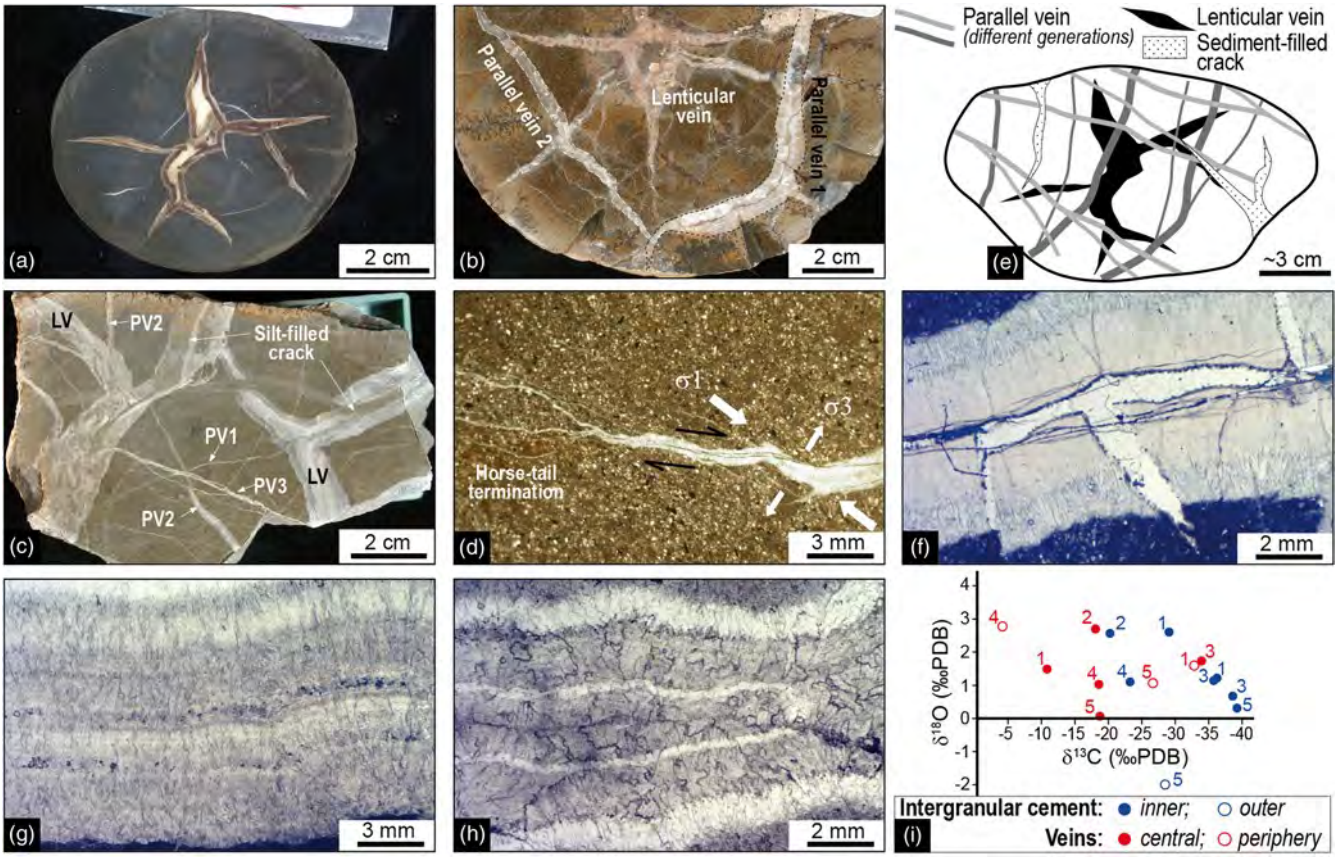

Fig. 5. Close-up view of polished slabs of septarian concretions. (a) Lenticular-type veins with a radial growth in a section perpendicular to bedding. (b) Cross-cutting relationships between lenticular (radial)-type veins and two sets of parallel-type veins, differently oriented (cut perpendicular to bedding). (c) Complex cross-cutting relationships between lenticular-type (LV) and two main generations of parallel-type (PV1 and PV2) veins and sediment-filled cracks (cut parallel to bedding). (d) Close-up view of a parallel-type vein showing along-strike deflection and horsetail termination coherent with shear-induced deformation (black arrows), as indicated by the orientation of the axes of maximum (σ1) and minimum (σ3) shortening. (e) Schematic drawing showing the cross-cutting relationships between the different types and generations of calcite veins. Photomicrograph of calcite veins showing (f) a polyphase vein infilling characterized by a first fibrous calcite rim followed by blocky calcite; a later limpid calcite infilling is present in the inner portion of the fracture due to reactivation of the fracture. (g) Typical polyphase banded infilling of calcite vein in which fibrous, calcite-rich inclusions are alternating with more limpid, inclusion-free calcite rims. (h) Symmetrical regular concentric infilling characterizing parallel-sided veins; banded calcite rims are similar to those in part (g). (i) Oxygen and carbon isotopic composition of methane-derived septarian concretions from the Monferrato and Voghera sectors. Numbers indicate the location of the samples analysed for the Voghera. 1, Scagni; 2, Villa Cavalieri; 3, Sala Superiore–San Giovanni) and Monferrato (4: Fabiano; 5: Ottiglio) sectors (see sample location in Figs 3 and 4). PDB, Peedee belemnite standard.

cracks have an irregular polyhedral shape and are composed of sediments similar to the external portion, except for their hardness. Their matrix consists of siliciclastic silt and clay. This appears to be similar to the host sediments, with the addition of an intergranular calcite microspar cement, which envelops and displaces the terrigenous particles. The occurrence of bioturbations within the concretions indicated that the precipitation of the carbonate cement occurred at shallow depths within the sedimentary column.

Fractures cross-cutting the septarian concretions can be divided into two main sets according to the classification of Pratt (2001) and depending on their geometry with respect to both the margin of the concretion or its main elongation axis: (1) lenticular radial cracks and (2) parallel-sided cracks. The lenticular cracks (Fig. 5a–c), up to 1–2 cm wide, are commonly radially oriented and rarely cross-cut all the concretion. They generally decrease in width, ending before the margin of the concretion. The parallel-sided cracks may be isolated or interconnected and are commonly visible on the external surface of the concretions, suggesting fracture episodes with associated fluids that involved the entire concretion from the outside. In general, they cross-cut the lenticular cracks (Fig. 5c, e). They commonly form two main sets filled by carbonate cement (Fig. 5b, c, e), which are oriented from subvertical to subhorizontal or oblique to the septarian concretions and the surrounding beds.

Most of parallel-sided cracks represent mode I opening fractures, as suggested by the almost exact match of their opening sides (see Pratt 2001 and references cited therein). The subhorizontal cracks commonly cut the subvertical cracks, locally showing horsetail terminations suggesting the occurrence of a shear component at the time of formation, in agreement with the along-strike deflection and growth of the vein (Fig. 5d). When present, silt- and mud-filled cracks show mutual cross-cutting relations with parallel-sided cracks (Fig. 5c, e).

Microscopic features

The examined thin sections reveal an early precipitation of microcrystalline cement within the pores of a siliciclastic silt and clay affected by low compaction. Isolated burrows due to bioturbation are present in some samples. The veins in lenticular radial cracks cross-cut a previously cemented sediment and are filled with different generations of calcite cement. Veins develop across the concretions, starting from the centre, and display a progressive decrease in width towards the rim. The decrease in width is observed at the vein tip and is characterized by a gradual transition from several thin fractures to an outer ‘normal’ encasing sediment (Fig. 5a, b). This is consistent with the first cracking of a cemented area, located in the core of the concretion, which then proceeds outwards towards the still unconsolidated portions of the sediments. As the first generations of fibrous cements are commonly broken by subsequent episodes of cracking, a history of multiple episodes of cracking and fluid circulation seems to be evident (Fig. 5f). Parallel veins that appear homogeneous on the hand sample scale are instead characterized by polyphase banded infilling (Fig. 5g), with calcite-rich inclusions alternating to clear calcite in different parts of the fracture. Parallel-sided veins show a regular concentric infilling characterized by a symmetrical alternation of turbid and clear calcite rims (Fig. 5h). A late injection of mud through a late network of fractures is rarely observed.

Stable isotope geochemistry

A total of 15 thin sections were examined by transmitted and cathodoluminescence microscopy (CITL 8200 mk3, operated at c. 17 kV and 400 mA). About 20 powder samples were obtained using a microdrill for C and O stable isotope analyses of different portions of the rock. Stable C and O isotopes of the carbonate fraction were analysed following the classical method of McCrea (1950) using a Finnigan MAT 250 mass spectrometer. The isotopic ratios are expressed as $\delta^{13}C$ and $\delta^{18}O$ per mil v. the Peedee belemnite (PDB) standard; the analytical errors are ±0.5 and ±0.1‰ for $\delta^{13}C$ and $\delta^{18}O$, respectively.

The occurrence of depleted $\delta^{13}C$ values of intergranular micritic cements, ranging from −20.61 to −39.59 $\delta^{13}C$ (Fig. 5i), is consistent with a significant organic matter or methane source of carbon. The centre of the concretions commonly displays more depleted values, according to the progressive precipitation of cement migrating from the centre of the concretion outwards (Pratt 2001). Differences in $\delta^{13}C$ values between concretions sampled in different localities probably result from the involvement of variable proportions of isotopically light CO_2 derived from methane and heavier normal marine CO_2. The oxygen isotope analyses of micritic cements are generally shifted towards positive values (Fig. 5i).

The coupling of negative $\delta^{13}C$ values with positive $\delta^{18}O$ values points to a possible origin of fluids from the destabilization of gas hydrates. These are generally composed of methane and water and are characterized by an anomalous enrichment in $\delta^{18}O$ with respect to 'normal' marine waters (Ussler & Paull 1995). Similar isotopic values of carbonates reported in the geological record have previously been interpreted to be related to gas hydrates (Pierre et al. 2002). Although less depleted, most of the $\delta^{13}C$ values of veins, coupled with the positive $\delta^{18}O$ values, clearly show that they also involved methane-rich fluids, similar to those favouring the formation of concretions, suggesting that they are also derived from the destabilization of gas hydrates.

Discussion

The recognition and regional-scale correlation of septarian concre- tions, resulting from the dissociation of gas hydrates, and the definition of their stratigraphic and structural position within the ELAW, allow a discussion of the potential links among global climate change (EECO and MECO), the dissociation of gas hydrates and active tectonics in controlling slope failure and, consequently, the dynamic equilibrium of the wedge during the Ligurian Tectonic Phase.

Tectonostratigraphic position of septarian concretions revisited

Although very rarely preserved in their primary stratigraphic position, geological map constraints clearly show that the septarian concretions are clustered in a specific tectonostratigraphic position over a large sector (thousands of square kilometres) from the Monferrato to the Voghera sectors (Fig. 1a). The structural position always corresponds to the core of thrust-related anticlines and tectonic ridges (Fig. 6a; see also Figs 3 and 4) formed during the Ligurian Tectonic Phase, a few metres to tens of metres below the unconformity at the base of the Monte Piano marls (late Lutetian–early Rupelian in the Voghera sector; Bartonian–Priabonian in Monferrato sector) and/or of the erosional surface at the base of the Baiso argillaceous breccias (late Lutetian–early Bartonian). The stratigraphic position in which the septarian concretions are embedded corresponds to that of the younger sediments preserved below the unconformity at the base of the wedge-top basin succession (Fig. 6b). These sediments range in age between upper Thanetian (NP9 zone) and Ypresian–Lutetian (NP14 zone). Therefore, considering that the stratigraphic position of septarian concretions corresponds to the locus in which methane-rich fluids concentrated within the stratigraphic column and not to the age of the dissociation of gas hydrates event, the latter can be interpreted as probably occurring after the Ypresian–Lutetian boundary (i.e. younger than the NP14 zone). This age is indirectly supported in considering the potential early to mid-Eocene age of the septarian concretions in the Casale Monferrato Flysch (see Sacco 1888; Beatrizzotti et al. 1964), which are no longer preserved. In addition, the lack of any fragments of septarian concretions within both the Monte Piano marls and the Baiso argillaceous breccias constrains the process before the deposition of the late Lutetian–Bartonian wedge-top basin succession. In fact, examples in which the dissociation of gas hydrates is documented to have occurred contemporary to the emplacement of gravity-induced chaotic units (sedimentary mélanges), or to have triggered slope instabilities, are commonly characterized by the large occurrence of methane-derived carbonate blocks, which are randomly distributed and embedded within the matrix of the MTDs (Dela Pierre et al. 2002; Conti et al. 2010). Therefore an early to mid-Lutetian age is proposed (Fig. 6b) for the dissociation of gas hydrates event and the formation of septarian concretions in the Monferrato and Voghera sectors. This age corresponds to that of the Ligurian Tectonic Phase.

Origin of septarian concretions and their significance

The depletion in ^{13}C of both the intergranular micritic cements and carbonate veins (Fig. 5i) reveals an involvement of methane-rich fluids during both the diagenesis of unconsolidated sediments, forming septarian concretions, and their subsequent cracking by different generations of veins. The $\delta^{18}O$ values can be interpreted in terms of the destabilization of gas hydrates, which liberates ^{18}O-rich waters. During the formation of gas hydrates from interstitial water, there is a preferential incorporation of water molecules with heavier isotopes within this structure (Ussler & Paull 1995). The destabilization of gas hydrates liberates ^{18}O-rich waters, which can enrich the interstitial solutions in ^{18}O.

Although the cracking of septarian concretions is commonly related to different and, in some cases, concomitant factors (e.g. clay sediment desiccation, shaking by earthquakes or syneresis; Plummer & Gostin 1981; Pratt 2001; Clari et al. 2004), the close association and cross-cutting relationships between lenticular and parallel-sided cracks, and the local injection of liquidized sediments in most of the documented septarian concretions (Fig. 6c), suggest that they formed as repeated forceful and dramatic phenomena, probably related to syndepositional tectonic activity. The lack of any traces of organic remains inside our documented concretions seems to exclude a genetic association with the degradation of organic matter. Concretions formed during stages of tectonic quiescence typically lack septarian cracks (e.g. Coniglio & Melchin 1995).

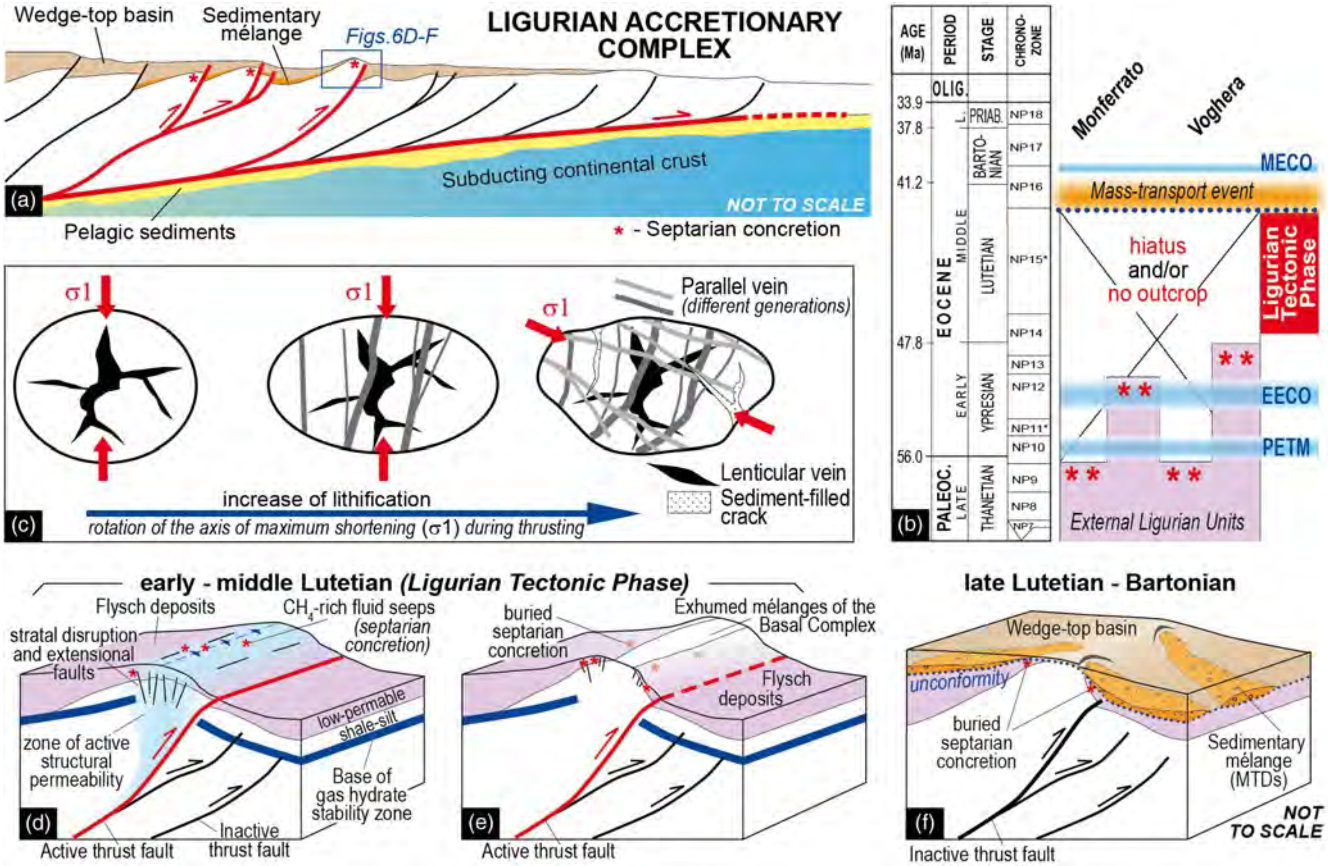

Fig. 6. (a) Conceptual cross-section of the External Ligurian accretionary wedge during the early to mid-Eocene accretionary stage showing the stratigraphic and structural positon of methane-derived septarian concretions at the core of thrust-related anticlines and below the unconformity at the base of wedge-top basins. (b) Temporal relationships between the mid-Eocene mass transport event, the Ligurian Tectonic Phase, the main changes in global climate and the outcrop position of septarian concretions. Note that the age of the septarian concretions represents a structural position rather than a stratigraphic position (i.e. the age of the stratigraphic units containing septarians; see text for explanation). (c) Temporal evolution and growth of calcite veins and cracks in relation with the rotation of the axis of maximum shortening and the increase of lithification during the accretionary stage (Ligurian Tectonic Phase). (d–f) Block diagrams (modified from Barnes et al. 2010) showing (d) the relationships between active accretionary tectonics, the dissociation of gas hydrates and the formation of septarian concretions and (e) the subsequent exhumation of mélange units at the core of thrust-related anticline. (f) Slope failure occurred during the tectonic quiescence stage and sea-level rise; see text for explanation. MECO, (Middle Eocene Climate Optimum; EECO, Early Eocene Climate Optimum; PETM, Paleocene–Eocene Thermal Maximum.

The shape of the lenticular cracks indicates that the interior of the concretions was brittle–plastic at time of shrinkage (see Pratt 2001), whereas parallel-sided cracks occurred under brittle conditions, cutting the former cracks. Similar relationships are observed among most of septarian concretions of the studied sectors, suggesting that cracking occurred simultaneously throughout a wide area as a result of large-scale phenomena rather than a diagenetic evolution of each single concretion.

Considering that the parallel-sided cracks represent extensional features (mode I opening fractures), their different subvertical and subhorizontal orientations document a rotation of the stress field during their formation (Fig. 6c), according to the shift in the maximum shortening axis from an extensional stage to a compressional stage. This commonly occurs during the progressive involvement of sediments within the shear zone of an accretionary wedge, in parallel with an increase in lithification (e.g. Festa et al. 2013). The local occurrence of horsetail features at the vein tip is consistent with the occurrence of shear strain during accretion.

The distribution and characteristics of these cracks are consistent with hydrofracturing by the build-up of high pore pressures caused by strong shaking related to earthquake events in soft to poorly consolidated water-rich clay sediments (Pratt 2001). The local injection of silt and mud, which cut the parallel-sided cracks, via fracturing of the margins, is also consistent with shaking events (Pratt 2001).

Relationships among slope failure, global climate change and tectonics

Two main phases can be differentiated on the basis of the relationships between the septarian concretions and the tectono- stratigraphic architecture of the ELAW, allowing a discussion of the contribution of warming climate events (EECO and MECO), the dissociation of gas hydrates, active accretionary tectonics (Ligurian Tectonic Phase) and post-tectonic stress release (quiescence tectonic phase) to the mid- Eocene giant slope failure event.

Ligurian Tectonic Phase (early to mid-Lutetian)

The age and distribution of septarian concretions in a specific tectonostratigraphic position (Fig. 6a) and their particular isotopic values agree with the occurrence of a significant pulse of methane- rich fluids concentrated over a large area (thousands of square kilometres) during a short time interval in the early to mid-Lutetian (i.e. after the NP14 biozone and before the emplacement of the Baiso argillaceous breccias). Therefore a correlation with the EECO (c. 53–52 to 50 Ma; Cramer et al. 2009; Payros et al. 2015 and references cited therein) is excluded considering that the age of the host sediments and the surrounding septarian concretions represents the position at which methane-rich fluids concentrated within the stratigraphic column and not the age of the dissociation of gas hydrates event. By contrast, evidence that septarian concretions always lie on anticlines developed in the hanging wall of thrust faults supports the view that active thrusting (i.e. the Ligurian Tectonic Phase) caused the rapid uplift of the base of the gas hydrate stability zone (Fig. 6d), favouring the dissociation of gas hydrates through variations in temperature and pressure and, probably, seismic-induced shaking. This induced the upwards rise of methane-rich fluids in these specific structural positions (Fig. 6d). These relationships are comparable with those described in New Zealand (e.g. Barnes et al. 2010), where a conspicuous break in the bottom-simulating reflector, which corresponds to the base of gas hydrate stability zone (Fig. 6d), beneath active seep sites located on top of thrust-related anticline cores triggered the dissociation of gas hydrates (e.g. Barnes et al. 2010; Pecher et al. 2010).

In the studied part of the ELAW, fluid expulsion occurred through the combination of stratal disruption, forming broken formations, and the compression of poorly consolidated clay to clayey marl deposits (Fig. 6a; the Viano clay in the Voghera sector and the Ottiglio clay in the Monferrato sector) entering the accretionary wedge and/or deformed along thrusts (e.g. Conti et al. 2010; Codegone et al. 2012). Brittle faulting and fracture, forming broken and disrupted formations, facilitated fluid flow and internal cracking of the septarian by creating structural permeability (e.g. Moore & Byrne 1987; Codegone et al. 2012; Festa et al. 2012, 2013), as documented in the frontal wedge of the Hikurangi subduction margin in the proximity of major seismically imaged thrust faults (e.g. Barnes et al. 2010; Ogata et al. 2014). The occurrence of both low-permeability shale to clay horizons (i.e. the Viano clay and Ottiglio clay) and surfaces with marked anisotropy along the thrust faults bounding the accreted ELUs also favoured different pulses of fluid expulsion as an additional factor, and their vertical migration throughout the tectonic pile. These fluids were probably over-pressured, as suggested by the occurrence of lenticular and parallel-sided cracks within the septarian concretions (Fig. 6b, d).

Amplification of seismic ground-shaking could have occurred in the hanging wall of a thrust fault (the hanging wall effect of Abrahamson & Somerville 1996), where the septarian concretions formed and concentrated, if the fault rupture acted co-seismically (e.g. the Nankai out-of-sequence megasplay and other fault systems; Kawamura et al. 2009; Strasser et al. 2011) with a minimum magnitude >5 M_W (e.g. Atkinson et al. 1984). Hence the widespread occurrence of such structures over a broad area (thousands of square kilometres) in a specific structural position may suggest earthquake-shaking, which may have triggered the dissociation of gas hydrates, working in conjunction and cumulatively with the subsequent generalized upwards rise of methane-rich fluid flows.

The lack of any methane-derived carbonate concretions within sediments above the mid- to late Eocene unconformity (i.e. the Monte Piano marls and Baiso argillaceous breccias) further constrains the dissociation of the gas hydrate event to pre- to late Lutetian–Bartonian time during the Ligurian Tectonic Phase.

Tectonic quiescence phase (late Lutetian–Bartonian)

From the late Lutetian, the unconformable deposition of the hemipelagic sediments of the Monte Piano marls and the emplacement of the Baiso argillaceous breccias onto the ELAW clearly mark the end of the Ligurian Tectonic Phase and the beginning of a phase of tectonic quiescence. The variation in thickness of both the sedimentary mélanges and the Monte Piano marls suggests the sedimentation of a fairly rugged slope (Fig. 6e, f; Mancin et al. 2006; Remitti et al. 2012; Barbero et al. 2017). The chaotic rock units of the Basal Complexes, which were exposed and tectonically juxtaposed onto each other at the core of thrust-related anticlines and tectonic ridges, provided the source material for the emplacement of the Baiso argillaceous breccias (Fig. 6e, f). Their distribution along the limbs of these positive structures and their increase in thickness far from their core are consistent with the downslope sliding of mud and debris flows, reworking the previously formed chaotic rock units (broken formations and mélanges). The lack of any trace of methane-rich fluids (e.g. carbonate concretions, chemosymbiotic communities or veins) within both the preserved and outcropping Baiso argillaceous breccias and Monte Piano marls suggests that the dissociation of gas hydrates did not play a prominent part in triggering gravitational sliding.

Although the time of slope failure in ancient geological settings is not easy to constrain with a detail comparable with present day submarine landslides, the prevalent concentration of sedimentary mélanges at the base of the Monte Piano marls on a regional scale clearly suggests that the main slope failure event occurred in the late Lutetian (c. 42 Ma according to the timescale of Cohen et al. 2013) and/or at the Lutetian–Bartonian boundary (c. 41.2 Ma according to Cohen et al. 2013), at least c.1–2 Ma before the MECO (c. 40 Ma) and c. 8–10 Ma after the EECO. Thus the preconditioning and triggering factors for the regional-scale mid-Eocene slope failure event should be associated with other factors with respect to changes resulting from global warming (the MECO and EECO). Although possible, the regional-scale distribution of the Baiso argillaceous breccias seems to exclude a correlation with minor peaks of warming events with respect to the global EECO and MECO, affecting the stability of gas hydrates, sea-level and, consequently, triggering submarine slope failure as documented for younger (Miocene) MTDs and mélanges in the Northern Apennines (e.g. Dela Pierre et al. 2002; Conti et al. 2007; Artoni et al. 2014). Factors controlling the mid- Eocene slope failure event can be identified in the post-accretionary stress release, affecting the emergent core zone of elevated tectonic ridges and thrust-related anticlines, probably in combination with residual minor tectonic activity in the Ligurian Tectonic Phase. Their collapse and downslope sliding (Fig. 6f) worked to restabilize the dynamic equilibrium of the ELAW through the morphological reshaping of its rugged and strongly articulated architecture, inherited from the Ligurian Tectonic Phase. This restabilization seems to have occurred at the beginning of a regressive depositional trend started in the late Lutetian, as documented by the decrease in depositional depth from the lower Varicolored Member (c. 2000–1000 m) to the overlying Gray Member (c. 1000–600 m) of the Monte Piano marls (Mancin & Cobianchi 2000; Di Giulio et al. 2002; Mancin et al. 2006). These data indirectly suggest that the emplacement of the Basio argillaceous breccias occurred at depths (c. 2000–1000 m) that were too deep to trigger the dissociation of gas hydrates.

The steady accumulation of water-rich sediments above an articulated seafloor topography in a deep marine environment was probably a significant prerequisite for large submarine landslides to occur, as documented in some modern analogues of the ELAW (e.g. the Nankai accretionary prism, Strasser et al. 2011). In addition, the slow rate sedimentation of the lower part of the Monte Piano marls (<0.02–0.03 mm a^{-1}; see Mancin et al. 2006) may also have developed a high excess pore pressure as a result of the low permeability of the Varicolored Member. The loss of structure within layers of sediments could have contributed to rapid compaction during burial, generating a high excess pore fluid pressure and favouring slope failure (Urlaub et al. 2013).

Although presently scattered and discontinuous, the distribution of the Baiso argillaceous breccias documents that the dynamic and morphological re-equilibration of the ELAW occurred over a wide area, which is now exposed from Monferrato to the Voghera sector and southeastwards to the Emilia Apennines (see Bettelli et al. 1987, 1989). The increase in thickness of these sedimentary mélanges towards the SE (i.e. to the Emilia Apennines), as well as the increase in their distribution, also suggests that the instability of the ELAW increased in the same direction during the mid-Eocene.

Conclusions

The wide distribution of mid-Eocene sedimentary mélanges, which represent ancient submarine MTDs, over an area of thousands of square kilometres in the Northern Apennines, allows us to improve our understanding of the relationships among submbarine land- slides and accretionary tectonics, the dissociation of gas hydrates and changes in the global climate during the evolution of the ELAW. These factors were not effective in triggering the mid- Eocene slope failure event. By contrast, although residual minor tectonic activity could be present, a period of large-scale instability occurred after the Ligurian Tectonic Phase – that is, during the following tectonic quiescence phase (i.e. since the late Lutetian). The emplacement of cohesive MTDs reshaped the rugged seafloor topography, dynamically re-equilibrating its slope instability. These submarine landslides occurred in a deep marine environment, probably at the beginning of a regressive trend, and were not related to either the EECO or MECO global warming events and the dissociation of gas hydrates. Slope failure probably occurred at an average depth of c. 2000–1000 m, at which gas hydrates are predicted to be stable.

Considering that the scale, style and distribution of the mid-Eocene sedimentary mélanges are directly comparable with those observed in modern subduction–accretionary complexes (e.g. the Hikurangi margin in New Zealand and the Nankai accretionary wedge, Middle America Trench, Peru margin.; Festa et al. 2014, 2016; Moscardelli & Wood 2016 and references cited therein), our documented relationships among slope failure, climate change, the dissociation of gas hydrates and tectonics represent an important baseline on which to better evaluate the impact of these factors on the frequency and magnitude of submarine failures in modern subduction–accretionary wedges. Our examples also show that the exhumation of heterogeneous material, such as mélanges, broken formations and poorly consolidated argillaceous successions (e.g. the ELUs), which commonly occur in modern accretionary wedges, represent a significant factor in providing sufficient material that is prone to be downslope remobilization. However, although easily unstable and prone to remobilization downslope, this material is only involved in slope failure after the main tectonic phase has ended and contractional stress has been released, with only minor residual tectonic pulses.

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