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Birth and tectono-sedimentary evolution of the Tertiary Piedmont Basin (NW Italy)

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ABSTRACT - The Tertiary Piedmont Basin (TPB), located at the Alps-Apennines junction, is a polyhistory basin representing a key area for the comprehension of the complex evolution of Alps-Apennines junction. An updated litho- and biostratigraphy of the southern part of the basin fill is presented, together with a reconstruction of the stratal architecture, main sedimentologic features, tectonic-driven sequential organization, and main unconformities. Selected units having more appeal for the sedimentology and stratal organization, and/or role played in the geologic evolution of the study area, are described in more detail, mainly with reference to measured sections. The geological evolution is viewed in both regional and supra-regional contexts. In Priabonian to earliest Rupelian times an episutural composite basin, not yet differentiated from the North-Apenninic domain, was generated in the eastern TPB (the Borbera-Grue area) located on the northward prosecution of an inferred major crustal discontinuity lining the eastern margin of the Corsica-Sardinia block; in this paleogeographic domain deposition occurred in rapidly subsiding depocentres controlled by strike-slip tectonics, and characterized by geometry and dimensions variable through time, and highly unstable source areas. An important step of this early history is the deposition of the Savignone Conglomerate interpreted as large-scale Gilbert-type delta complex prograding into a pull-apart trough subject to extremely high subsidence rate. In the middle Rupelian crustal stretching concurrent with post-orogenic exhumation of the Mesoalpine prism led to the generation of a horst and graben topography and expansion of coarse-grained sedimentation to the whole TPB. Extensional strain probably occurred in the rear of the nascent Apennines, in concomitance with the onset of rollback of the downgoing Adriatic slab, which is thought to have been fostered since ca. 32 Ma by the propagation of a slab tear from beneath the Alps into the Ligurian area; the extensional process is kinematically compatible with the coeval backarc rifting generated in the Liguro-Provençal area. The graben infilling conglomerates laid down during this stage show diachronous deposition with westward younging trend and facies associations changing westwards from deep-water turbiditic to continental. In the late middle Rupelian the extensional regime turned into a left-lateral strike-slip regime with probably pure sinistral motion. First activation of the left-stepping major lineaments represented by the Villalvernia-Varzi Line to the NE and the Stura fault system to the SW is thought to have caused the conversion of the TPB into a left-stepover strike-slip basin located between the opposite Alpine and Apenninic subductions. This evolution is thought to reflect the onset of NW-ward translation of the Adriatic Indenter. Since the latest middle Rupelian a dramatic drowning and accelerated subsidence in a regime of inferred right-lateral transtension affected the basin, setting up the deposition of basinwide slope hemipelagites of the Rocchetta Fm encasing bodies of coarse-grained resedimented deposits, particularly important in the Langhe and Borbera-Grue depocentres. Although already delineated during the deposition of the Molare Fm, the separation the TPB and N-Apennine Epiligurian domains was definitive with the onset of deposition of the Rocchetta Fm. Indeed, the paleocurrent pattern, geometry, and sandstone composition of the turbidite bodies are compatible with the rise at that time of a morphologic-tectonic boundary most probably corresponding in position to the VV Line. In the Late Chattian-Aquitanian the transtension turned, with a certain westward younging diachroneity, into a main left-lateral transpressional episode, attributed to the change in the direction of motion of the Adriatic Indenter with respect to Europe from NW-ward to WNW-ward, resulting in conditions of oblique convergence and increased collisional coupling. The sequence of tectonic and stratigraphic events affecting the TPB in the Rupelian to Aquitanian time span occurred with a definite E-W diachroneity expressed by a westward younging trend, thought to reflect the concurrent role of Apenninic subduction and translation of the Adriatic Indenter in controlling the geologic evolution of the basin in this time span. Siliceous deposits, occurring at several levels in the Aquitanian to lower Langhian interval of the TPB succession, represent marker horizons on regional scale and are interpreted as slope or base-of-slope hemipelagites originally rich in biosiliceous component due to events of increased organic productivity, favouring basinwide blooms of siliceous phytoplankton. The late Chattian-Aquitanian transpressional tectonics enhanced the paleogeographic differentiation between the uplifting Alto Monferrato High, and adjacent sub-basins of the Langhe and Borbera-Grue areas. The Alto Monferrato High was then the site of deposition of lower Burdigalian ramp carbonates and outer shelf marls, whereas in the flanking sub-basins continued a hemipelagic deposition punctuated by the emplacement of several bodies of resedimented, commonly coarse deposits of mixed carbonate and terrigenous composition, locally as infills of structural troughs or submarine valleys. A strike-slip regime continued in the TPB mainly as a result of the onset of counterclockwise rotation of the TPB; it is particularly reflected in the stratigraphic architecture of the Uzzone Valley area (Langhe Sub-basin), controlled by a NE-SW growth fault system. The rotation, beginning in the Burdigalian, occurred with an angle close to the that of the Sardinia-Corsica Block (~50°) and higher than that estimated for the rotation of the Adria indenter (20-25°). This indicates a partly independent behavior and supports the contention that in this stage the Sardinia-Corsica block and the Liguria area, including the TPB, behaved as a unique microplate interposed between the European and Adria plates, SE of the Ligurian Sea collapse. A major tectonic reorganization occurred in the TPB since the middle Burdigalian. A marine transgression occurred with gaps of various amplitude on the deformed substrate of the Alto Monferrato High, where it took place with a characteristic backstepping pattern linked to cyclic relative sea level fluctuations, with formation of incised shorefaces during episodes of relative stillstand. Then a dramatic acceleration of subsidence coincided with the deposition of slope deposits of the Pratolungo Fm, marking on the Alto Monferrato High an extremely fast platform drowning episode, and of the laterally equivalent Serole Fm in the Langhe area, both grading upwards to a basinwide turbidite system, the upper Burdigalian Cortemilia Fm, showing an eastward transition from lobe deposits to a basin plain facies association. This turnover probably occurred in concomitance with the onset of emplacement of the “Front of the Alpine Axial Sector” (AXF) a deep-seated, arcuate, north-verging thrust accommodating the displacement of buried elements of the axial Alpine belt. This tectonic event is thought to mark the onset of northward thrust propagation toward the Padan foredeep and is interpreted to reflect the beginning of a process of underplating. The subsequent history until recent times was one of continuing outward migration of the Padan thrust fronts toward the Padan foredeep accompanied by pronounced uplift of the TPB margins, leading to progressive reduction of extent and northward shift of basin depocentres and concomitant development of the Alessandria and Savignano basins since the Langhian. The westward tilt and uplift of the Borbera-Grue sector in the Langhian is testified by basin inversion and a major hinged margin erosional unconformity of eastward increasing importance at the base of the Cessole Formation. This unit developed as a complex sediment wedge prograded westwards into the Langhe Sub-basin and later onlapped by the turbidites of the Cassinasco Fm; this in turn shows a spectacular wedging out eastwards with onlap onto the Alto Monferrato structural high. Deposition on this high in the Serravallian was characterized by the migration of a field of sandwaves consisting of coarse hybrid arenites; the depositional setting was typified by an interaction between ephemeral storm-driven flows, and more continuous tractive flows producing sandwave trains. Sandwave migration probably occurred in a seaway between the Alps and the neo-Apennines, with formation of sandwave field controlled by strait-related tidal current amplification and occurring in concomitance with the input of coarse fan-delta detritus from the denudation of uplifted south-eastern areas. Tectonic-driven forced regression in late Serravallian is recorded by a significant coarsening trend of the fan-delta input accompanied by local development of a shelf incised valley on the Alto Monferrato High. Continuing N-S contraction was concomitant with an important episode of E-W extension in the Tortonian, leading to an incipient rifting followed by a rapid platform drowning recorded by basinwide deposition of the hemipelagic Sant’Agata Fossili Marl. The rifting, interpreted as far-reaching effect of the coeval E-W back-arc extension which affected the Tyrrhenian Basin since ~10-9 Ma, was accompanied by persisting gravity instability and important mass wasting episodes, the most important of which is the failure of the western margin of the Alto Monferrato High, wich generated the Rocca Grimalda Chaotic Complex including giant slide blocks (olistoliths) of Serravalle Sandstone and Cessole Fm. Progressive confinement of the depositional environment at the Tortonian-Messinian transition and during the early Messinian is linked with the well-known paleogeography established in the Mediterranean since the late Tortonian. A characteristic rhythm, generally interpreted as precession-driven, consists of alternating bioturbated marls with benthic faunas indicating bottom oxygenation and blackish laminites devoid of any benthic faunal element indicating bottom water anoxia. Two important erosional unconformities mark the base of the intra-Messinian Valle Versa Chaotic Complex and respectivey the base of the upper Messinian fan-delta/lagoonal Cassano Spinola Conglomerate, showing affinity with the well-known “Strati a Congerie” of the “Lago Mare”. The latter unit shows an overall trend coarsening upwards, reflecting the tectonic-driven progradation of the fan-delta system into a lagoonal-lacustrine body of water.

Keywords: Tertiary Piedmont Basin; Oligo-Miocene; continental to basinal deposits; tectono-sedimentary evolution.

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1. INTRODUCTION

The Tertiary Piedmont Basin (Fig. 1) represents a key area for the comprehension of the complex geological and geodynamic evolution of Alps-Apennines junction.

A new geological map of the southern part of the Tertiary Piedmont Basin is here presented. The map includes a large part of the Langhe, the Alto Monferrato and the western part of the Borbera-Grue area (Fig. 1). It expands the 1:20000 geological map of the Langhe Sub-basin published by Ghibaudo et al. (2014). The proposed stratigraphy and structural setting are mostly new with respect to previously published geological maps, specifically the sheets 81 Ceva (Francani et al., 1971), 70 Alessandria (Boni and Casnedi, 1970) and 71 Voghera (Bellinzona et al., 1971) of the "Carta Geologica d'Italia" at 1:100000 scale, and the new 1:50000 sheets 211 Dego (Gelati et al., 2010), 212 Spigno Monferrato (Ligurian part) (Capponi et al., 2013), 194 Acqui Terme (d'Atri et al., 2014), and Cabella Ligure (Marroni et al., 2014).

The Rupelian-Burdigalian stratigraphy, sedimentology and tectono-sedimentary evolution of the western part of the study area (Langhe Sub-basin) have been already treated in detail in a previous paper (Ghibaudo et al., 2014). Therefore, in the present work the related stratigraphy and sedimentology are only briefly treated. In this paper a thorough discussion on the stratigraphy and tectono-sedimentary evolution of the southern part of the Tertiary Piedmont Basin is followed by an assessment of the implications of the data in a supra-regional context.

The geology of the area is presented in the enclosed geological map at the 1:75000 scale lacking the topography underlying the geology (Pl. I; note 1); a cross-section oriented approximately SW-NE allows to visualize the stratigraphic architecture of the basin fill by highlighting the vertical and lateral relationships among the various units with a brief mention of their depositional setting (Pl. II). A geological map of the study area at the scale 1: 20000, with the topography in evidence, is presented in Plate III (online). Plate IV (online) displays the location of the measured sections and Plate V the biostratigraphic correlations between them. Plate VI (online) shows the map at 1:75000 scale supplemented with the specific denominations of the structural elements. Plate VII (online) is a structural map of the area presenting the structural elements and the main unconformities. An extended cross section intended to depict the basin organization supplemented with a schematic view of the geology beyond the study area, toward the south-western closure of the basin (data extrapolated from available literature, geological maps, and local reconnaissance field work), is shown in Plate VIII (online).

2. GEOLOGIC SETTING

The Tertiary Piedmont Basin (TPB hereafter) (Fig. 1) developed after the Meso-Alpine Eocene collisional event between the European and Adriatic plates. This event involved deep crustal levels belonging to the Alpine structural domain and shallow levels represented by Apenninic nappes of the "Liguride Complex", both intensely deformed during the Eo- and Meso-alpine phases (Roure et al., 1990; Dela Pierre et al., 1995; Mutti et al., 1995; Biella et al., 1997; Piana, 2000; Carrapa, 2002; Mutti et al., 2002; Rossi et al., 2009; Mosca et al., 2009; Rossi, 2017). The sedimentary succession of the TPB is predominatly terrigenous and forms a large homocline gently dipping northwards to north-westwards, reaching a maximum thickness of about 6000 m.

Recent analyses and stratigraphic reconstructions maintain the classic lithostratigraphic units and identify tectonic-driven unconformities related to major events of basin reorganization, highlighted by abrupt changes in the petrographic composition (Di Giulio, 1990, 1991), sedimentary architecture, and angular discordances recognized on the basis of field survey, stratigraphic correlation, and seismic profiles (Gelati et al., 1993; Gnaccolini et al., 1994; Di Giulio and Galbiati, 1995; Mutti et al., 1995, 2002; Martelli et al., 1998; Rossi et al., 2009; Mosca et al., 2009; Rossi, 2017). Within this approach, groups of units bounded by major unconformities have been identified by some authors as allogroups (e.g. Mutti et al., 1995). A revision of the geologic and paleogeographic evolution of the Langhe Sub-basin of the TPB during the Oligo-Miocene was presented by Ghibaudo et al. (2014).

As pointed out by Mutti et al. (2002) "high tectonic mobility is documented in the TPB by the regional stratigraphic architecture recording spectacular migrations of the source areas and depocenters with time, and complex lateral and vertical distribution of terrigenous depositional systems".

Since the late Eocene, after the main collisional phase, the TPB started to form as episutural basin (Gelati and Gnaccolini, 1988), comprising several sub-basins

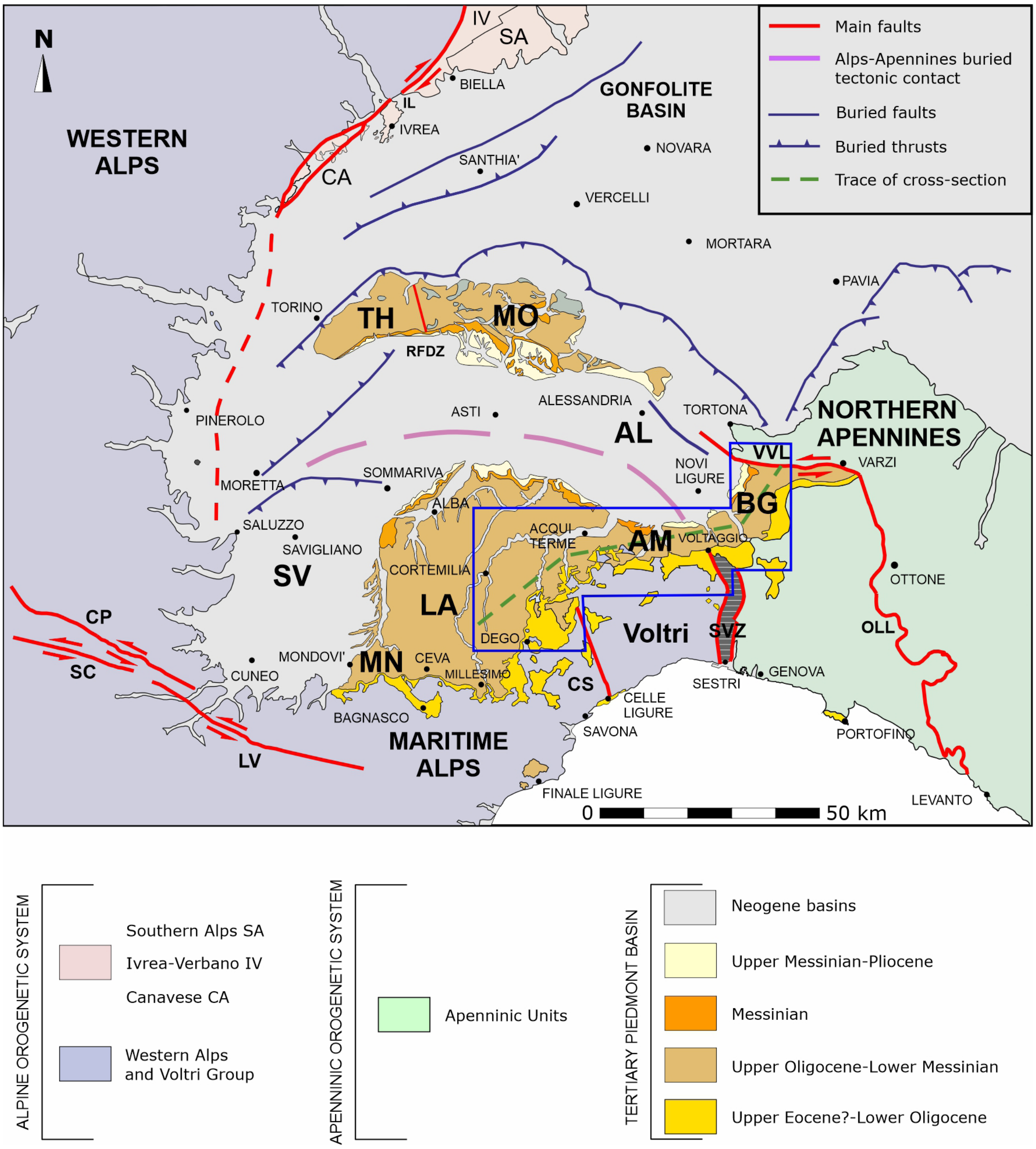

Fig. 1 - The Tertiary Piedmont Basin and the western Po plain. Simplified structural scheme. TH: Torino Hill; MO: Monferrato; MN: Monregalese; LA: Langhe; AM: Alto Monferrato; BG: Borbera-Grue; SV: Savigliano Basin; AL: Alessandria Basin; CA: Canavese Zone; IV: Ivrea-Verbano Zone; SA: Southern Alps. Major faults: IL - Insubric Line; RFDZ - Rio Freddo Deformation Zone; SVZ - Sestri-Voltaggio Zone; VVL - Villalvernia-Varzi Line; OLL - Ottone-Levanto Line; CS - Celle-Sanda Line; SC - Stura couloir; CP - Cicatrice del Preit; LV - Limone-Viozene deformation zone. The study area is indicated; dashed green line: trace of the cross section of Plate II.

and structural highs. The oldest part of the succession, ranging in age from Priabonian to early Rupelian, is well represented in the eastern TPB (Borbera-Grue area), where it is preserved in the area between the Scrivia Valley Fault and the Villalvernia-Varzi Line. Here the succession, unconformably overlying Ligurian Units with a major regional unconformity, is internally subdivided into unconformity-bounded units laid down in local basins and characterized by strong facies variation and marked compositional changes. The lower part of the succession comprises the Vigoponzo Marl (also known as Monte Piano Marl, Priabonian), the Dernice, Grue, and Rio Trebbio formations (cfr. Ranzano Sandstone *p.p.*), depositionally ranging, with regressive trend, from deep marine marls and turbidites up to siliciclastic platform sediments.

These formations are followed by the Savignone Conglomerate, a thick pile of fan-delta conglomerates (lower Rupelian) bounded at the top by a major unconformity (Marroni et al., 2010). In the western TPB coeval(?) deposits are represented by the continental succession of alluvial fan rudites and lacustrine mudstones of the Pianfolco Formation (upper Eocene?, lower Rupelian?), preserved only in a small fault-bounded intramontane depression tectonized in a time pre-dating the deposition of the marine sandstones of the Molare Fm (Charrier et al., 1964; Franceschetti, 1967; Lorenz, 1969; Gnaccolini, 1978).

A structural partition of the TPB, anticipated to some extent since the Early Oligocene (Rossi et al., 2009), became fully developed in the late Oligocene-Aquitanian, when, according to Gelati and Gnaccolini (1998), it led to the differentiation of the following paleogeographic domains from west to east: the Monregalese High, the Langhe Sub-basin, the Alto Monferrato High and the Scrivia-Borbera Trough (our Borbera-Grue Sub-basin).

Starting from ca. 32 Ma (Rupelian), an event of lithospheric stretching generated a horst and graben topography with a marked subdivision into several differentially subsiding troughs accommodating the deposition of a coarse-grained succession (Molare Fm) showing highly variable thicknesses (Gelati et al., 1993; Mutti et al., 1995; Dela Pierre et al., 1995; Mutti et al., 2002; Vignaroli et al., 2009; Ghibaudo et al., 2014). This event was accompanied by a rapid post-orogenic exhumation of HP units of the Meso-Alpine prism in the footwall of a regional-scale extensional shear (Vignaroli, 2006; Vignaroli et al., 2008, 2010). In the western and central TPB the Molare Fm consists of alluvial-fan and fan-delta deposits, sourced from an emerged land existing to the south of the TPB (Lorenz, 1969, Haccard et al., 1972; Ghibaudo et al., 2014; d'Atri et al., 2016). A deeper-water gravity-driven subaqueous sedimentation predominated in the eastern TPB (Monastero Fm *auctt.*), with coarse resedimented deposits unconformably overlying the Savignone conglomerates. A clastic contribution from the Voltri Massif is supported by compositional data (Gnaccolini, 1974) and is compatible with the hypothesis of the exhumation of this area as a result of an extensional episode occurred through low-angle detachment systems (Vignaroli et al., 2009). The lower Oligocene deposits of the TPB were accommodated in two complex structural depressions, respectively located SW and NE of a structural high, representing the precursor of the Alto Monferrato High (Rossi et al., 2009; Mosca et al., 2009).

The TPB and probably also the southern source areas were then rapidly drowned as a result of high subsidence rate leading to the deposition of hemipelagic slope to base-of-slope mudstones (the uppermost middle Rupelian-Chattian Rocchetta Fm), containing several channelized turbidite sandstone bodies of variable thickness and geometry (Dalla et al., 1992; Mutti et al., 1995; Rossi et al., 2009; Ghibaudo et al., 2014; Rossi, 2017). According to Gnaccolini and Gelati (1996) and Gelati and Gnaccolini (1998, 2003) the Langhe Sub-basin, an important paleogeographic element of the TPB, extending over an area of about 1800 km^2 and infilled with an Oligo-Miocene sedimentary succession more than 4000 m thick, was fully delineated since the late Oligocene: it was a subsiding trough bounded to the SW by the Monregalese High and its continuation towards ESE into the Finalese High, and to the NE by the Alto Monferrato High. As pointed out by these Authors, the upper Oligocene succession, up to about 1000 m thick in the Langhe Sub-basin, may be correlated with 150 m of hemipelagic mudstones in the Alto Monferrato High, and with ca. 200 m of shelf deposits in the Monregalese High. The most prominent intra-Oligocene structural element of the Langhe Sub-basin was the Dego-Spigno Monferrato High, a positive structure of the basement that separated two depocentres, the Turpino and Rocchetta Cairo depocentres, where the Rocchetta Fm reaches thicknesses of about 1000 m and encases several turbidite bodies (Ghibaudo et al., 2014). Rossi et al. (2009) suggested high denudation rates of the west-Alpine axial sector from latest Oligocene onwards, implying shedding into the TPB basin of huge volumes of coarse-textured sediments via fan-delta systems from the Saluzzese-Monregalese belt.

As suggested by Ghibaudo et al. (2014), a major change in tectonic regime occurred during the Rupelian, when the TPB was converted into a left stepover pull-apart basin.

In the Langhe Sub-basin, the Rocchetta Formation is commonly overlain by siliceous and hemipelagic sediments representing a marker horizon on regional scale (Ghibaudo et al., 2014). It was already recorded by Schüttenhelm (1976) as "blocky siliceous marl", and later by d'Atri (1990a) as siliceous member of the Rocchetta Formation, by Gelati and Gnaccolini (1998) as C. Mevie-Molino di Ovrano unit, and by Fava (2001) and Mutti et al. (2002), as siliceous lithozone.

In the late Oligocene to Early Miocene times important sinistral motion along the Villalvernia-Varzi line, together with dextral motion along the Insubric Line, accommodated the WNW-ward translation of the Adriatic Indenter (Laubscher, 1991; Schumacher and Laubscher, 1996). This occurred in concomitance with collapse and oceanization in the Provençal-Ligurian basin and counterclockwise rotation of the Sardinia-Liguria complex (Speranza et al., 2002; Maffione et al., 2008). Growth faults active during the late Aquitanian -Early Burdigalian in the Langhe area with a component of strike-slip motion generated intrabasinal highs and small-scale slope or base-of-slope basins which controlled location and orientation of turbidite sandstone bodies and their paleocurrent pattern (Ghibaudo et al., 2014). Moreover, the deposition of hemipelagic slope to base-of-slope marls of the lower Burdigalian Montechiaro d'Acqui Formation was punctuated by resedimentation of glauconitic sands and rhodalgal carbonate deposits, derived from cannibalization of coeval foramol-type carbonate platforms. The bioclastic component was associated in places to conglomerates and mass-wasting deposits as infill of structural troughs or submarine valleys (e.g. C. Mazzurini Sandstone and Rocca Crovaglia Sandstone; Gelati and Gnaccolini 1998; Ghibaudo et al., 2014).

During the late Burdigalian, deposition of a thick and extensive, highly efficient basinwide turbidite system (the Cortemilia Formation) took place, concomitantly with a drastic increase in subsidence rate (Dela Pierre et al., 1995; Rossi et al., 2009; Mosca et al., 2009; Molli et al., 2010). This large turbidite system and those activated subsequently in the Serravallian and early Tortonian, show basinwide extent and considerably more regular paleocurrent pattern with respect to the older turbidite systems (Gelati et al., 1993). The drastic basin enlargement and abrupt deepening is attributed to the onset of downwarping of the basin in a piggy-back position, due to progressive involvement of the TPB area in the deformation of the Padan fronts (Laubscher et al., 1992; Dalla et al., 1992; Castellarin, 1994; Piana and Polino, 1995; Dela Pierre et al., 1995; Schumacher and Laubscher, 1996; Piana and Dela Pierre, 2000; Mosca et al., 2009).

A marked paleogeographic reorganization took place during the Langhian. Increase in subsidence in the western sector was accompanied by pronounced uplift of the areas located east of the Scrivia Valley (the Borbera-Grue sector), which underwent a true basin inversion testified by an erosional unconformity of eastward increasing importance, truncating westward tilted upper Burdigalian basin-plain turbidites (Ghibaudo et al., 1985; Gelati and Falletti, 1996; Mutti et al., 2002). This sector became a site of shelf deposition, represented by the Cessole Fm forming a wedge which prograded SW-wards, and was then onlapped in the Langhe Sub-basin by thick turbidites of the lower part of the Cassinasco Fm (Mutti et al., 2002).

Concomitantly with northward propagation of the north-verging thrust fronts, turbidite depocentres progressively shifted northwards since the Langhian, reaching in the Serravallian the Savigliano and Alessandria basins (Mosca, 2006). During the Serravallian the Langhe Sub-basin accommodated the upper part of the Cassinasco turbidite system, bounded at the base by a tongue of mudstones (the Murazzano Fm) (Gelati, 1968). In this time the Alto Monferrato area persisted as a submarine high, where a shelf sand-wave complex of hybrid arenites interfingering with resedimented fan-delta deposits was laid down (Serravalle Sandstone) (Ghibaudo, 1984; Caprara et al., 1985).

During the Early Tortonian tectonic instability at the western margin of the Alto Monferrato High triggered the failure of giant slide blocks (olistoliths) of Serravalle Sandstone in the Rocca Grimalda area (d'Atri et al., 2016). The Vargo extensional trough, formed in the eastern area of the Alto Monferrato High, accommodated stacked lenticular bodies of resedimented fossiliferous sandy conglomerates (Ghibaudo et al., 1985).

Basinward progradation of fluvio-deltaic systems from uplifted marginal areas led to progressive narrowing of depocentres; these accommodated thick-bedded oversupplied sand-prone turbidite systems (upper part of the Cassinasco Fm) (Rossi et al., 2009; Mosca et al., 2009). The subsequent transition to the hemipelagic slope sedimentation of the Tortonian-lower Messinian S. Agata Fossili Marl marks a period of general and rapid drowning and basin homogenization.

The intra-Messinian chaotic complex (Valle Versa Chaotic Complex of d'Atri et al., 2016) is thought to record the onset of polyphasic north-verging thrusting (Piana, 2000) which continued in the Pliocene (Piana and Dela Pierre, 2000), concomitantly with a significant increase in subsidence rate in both Alessandria and Savigliano basins. The fan-delta/lagoonal Cassano Spinola Conglomerate of the upper part of the post-evaporitic Messinian succession, showing affinity with the well-known "Strati a Congerie" of the "Lago Mare", unconformably overlies the substrate with deeply erosional contact.

A general uplift of the Oligo-Miocene succession started since the late Miocene (Forcella et al., 1999; Barbieri et al., 2003).

3. METHODS

This work is based on detailed field survey and mapping at the scale of 1:10000 which lasted more than 20 years, measurement of several thousands of metres of stratigraphic-sedimentological sections accompanied by facies analysis, and the examination of many samples and smear slides for the reconstruction of the biostratigraphy based on calcareous nannoplankton assemblages. The lithostratigraphy, structural setting and biostratigraphy are partly new, and their definition provided a sound basis for the disentangling of the synsedimentary tectonics.

The mapping of the easternmost Borbera-Grue and Borlasca areas has been obtained from observation of aerial and satellite photographs and reconnaissance excursions. In these areas, therefore, fault location and lithostratigraphic boundaries may be inaccurate.

The stratigraphic units to which the rank of formation has been attributed in the geologic map correspond, in some cases, to the formations adopted in the Sheets 81 Ceva, 69 Asti, 70 Alessandria, and 71 Voghera at the scale of 1:100000 of the "Carta Geologica d'Italia" (Boni and Casnedi, 1970; Francani et al., 1971; Bellinzona et al., 1971), and in the geological maps of 1:50000 scale recently published in this area: Sheets 211 Dego, 194 Acqui Terme, and 196 Cabella Ligure. In other cases, however, they correspond to lithostratigraphic units of new proposal. The proposed lithostratigraphy comprises formations which can be traced along the entire southern part of the TPB, thus simplifying the comprehension of the basin geology and overcoming the flaw of older and new maps that, in many cases, assign local names to the same litostratigraphic unit cropping out in different areas. For lower-rank lithostratigraphic units (members), we propose in most cases new informal names. Particularly important for basin-wide correlations are the siliceous units of basinal extent cropping out at different stratigraphic levels and represented by single packages of strata or a composite group of horizons separated by turbiditic formations. These siliceous units, occurring as basinwide horizons regionally important for large-scale correlations, have been indicated with the informal term of "lithozones" (note 2).

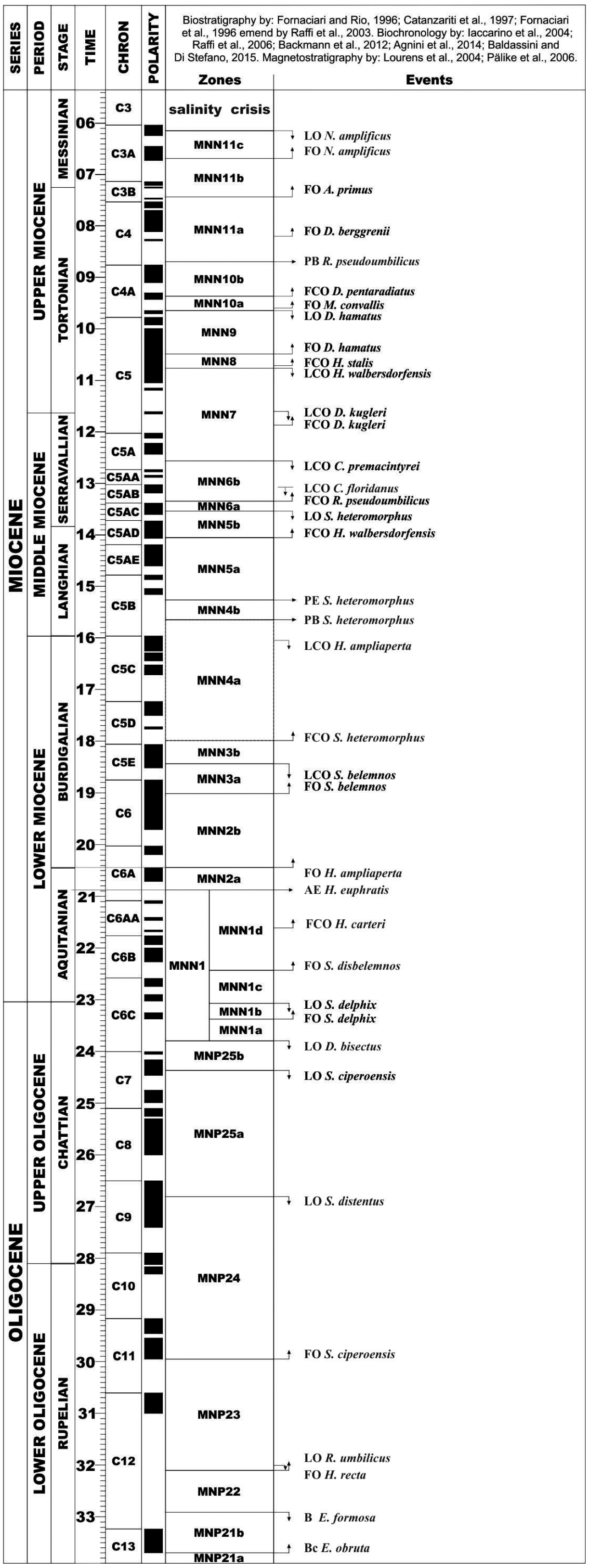

Fig. 2 - Calcareous nannoplankton biozonation adopted in this paper.

4. BIOSTRATIGRAPHY

The calcareous nannoplankton biozonation adopted in this paper (Fig. 2) is based on the Mediterranean scheme elaborated by the Fornaciari and Rio (1996), Catanzariti et al. (1997) and Fornaciari et al. (1996, emended by Raffi et al., 2003). The biochronology is based on Gradstein et al. (2004), Iaccarino et al. (2005), Raffi et al. (2006), Backman et al. (2012), Agnini et al. (2014), and Baldassini and Di Stefano (2015).

Since a general agreement on the position of the FO of *S. ciperoensis* is lacking, we chose to follow Coccioni et al. (2013) who place this bio-event at the base of magnetozone C11n.2n (29.97 Ma). The magnetostratigraphy is based on Lourens et al. (2004) and Pälike et al. (2006). Absolute ages of stage boundaries are those reported in the International Chronostratigraphic Chart 2019-05.

For sake of convenience we use a three-partition of the Rupelian and Burdigalian, with the MNP23 biozone regarded as middle Rupelian and the couple of MNN3a and MNN3b biozones as middle Burdigalian. The location of measured sections is presented in Plate IV (online) and the biostratigraphic correlations in Plate V. Dating of the Rupelian-Burdigalian stratigraphy in the Langhe area is mostly based on a number of measured sections, particularly on a composite reference section sampled from the base of the Rocchetta Fm to the base of the Cortemilia Fm along the transect Stazione di Spigno -Rocchetta-Case Mevie-Brallo and on the Cianazzo section located on the right side of the Bormida di Spigno Valley (cf. Ghibaudo et al., 2014). In the former section, the Rocchetta Fm spans the interval between the biozones MNP23 p.p. and MNN1 (uppermost Rupelian -Chattian). Only the lowermost and uppermost parts of the Rocchetta Fm have been sampled in this section, so that some bioevents related to the middle portion could not be recognized. No precise biostratigraphic data for the larger turbidite sandstone bodies of the Rocchetta Fm of the Langhe area (Mogliavacca, Brovida, Cobarello, and Noceto units) are at present available. Therefore, the ages of these sandstone bodies area are extrapolated assuming that the deep erosion at the base of the Mogliavacca unit (cf. Pl. I and II) is related to the important lowstand at the Rupelian-Chattian transition, corresponding to the Sequence Boundary Ru4/Ch1 (28.50 Ma according to Hardenbol et al., 1998, and Wornardt, 1999; 28.45 Ma according to Ogg et al., 2008) and to the isotopic event Oci-1 of Abreu and Haddad (1998). Due to the lack of precise biostratigraphic data, the ages attributed to the mentioned turbidite systems are to be considered provisional. The Montechiaro d'Acqui LS1 Siliceous Lithozone cropping out in the Langhe area is attributed to the biozones MNN1c and MNN1d of the Aquitanian, the Montechiaro d'Acqui Fm to the biozones MNN2a p.p. to MNN3a p.p. (uppermost Aquitanian-lower Burdigalian), the Serole Fm to the biozones MNN3a p.p. and MNN3b p.p. (middle Burdigalian), and the Cortemilia Fm to the biozones MNN3b p.p. and MNN4a (middle-upper Burdigalian). The biostratigraphic data from the Cianazzo section support the above chronological frame for the Montechiaro d'Acqui Siliceous Lithozone, the Montechiaro d'Acqui Fm and the Serole Fm (cf. Ghibaudo et al., 2014). The dating of the sandstone bodies of the Rocchetta Fm cropping out in the Ovrano Valley and Mombaldone area was obtained in the Ovrano Valley section which extends from the upper part of the Rocchetta Fm to the base of the Montechiaro d'Acqui Siliceous Lithozone. Biostratigraphic data from the sections measured in the Uzzone Valley area allows to date the Poggiolo Fm to the Aquitanian.

Dating of the Langhian-Serravallian stratigraphy was obtained in a number of sections located both in the Langhe area (Cessole, Vesime, Bubbio, Terzo and Tamianetto stream sections) and in the Alto Monferrato area (Visone, Lemme Valley, Piota Valley, Serravalle Scrivia and Scrivia Valley sections) (Pls. IV online and V). The top of the Cortemilia Fm in the Langhe area almost coincides with the LCO of *H. ampliaperta*, whereas in the Piota Valley and Lemme Valley sections this bioevent has been found within the T. Lemme Siliceous Lithozone LS2 (Fornaciari and Rio, 1996); in these areas the lower part of the lithozone extends significantly below the LCO of *H. ampliaperta* (Fornaciari and Rio, 1996), showing therefore a latest Burdiglian to early Langhian age for the lithozone. Conversely, in the Langhe area (Cessole, Vesime, Terzo sections) the LS2 lithozone is attributed to the lower Langhian (biozones MNN4b p.p-MNN5a p.p.). A similarly extended time span is shown by siliceous sediments of northern Apennines at the transition from the Bisciaro to the Schlier (e.g. the Moria section in the Marche Apennines: Deino et al., 1997). The LS2 unit moreover shows a regional change, being a single, thicker unit in the Alto Monferrato area, yet splitting westwards, in the Langhe area, into three horizons, defined LS2a, LS2b1 and LS2b2, respectively located atop the Cortemilia Fm (LS2a), and atop the Bubbio Tongue of the Cassinasco Fm (LS2b1, LS2b2) (cf. Pl. I). The Bubbio Tongue of the Cassinasco Fm, comprised between the above-mentioned LS2a and LS2b horizons, is also referred to the lower Langhian (MNN4b p.p-MNN5a p.p.).

The Visone Limestone is referred to the lower Burdigalian (MNN2b) (Visone area, Cava Zanoletti section); the Visone Glaucony and the Lerma Glaucony are referred to the middle Burdigalian MNN3a p.p. biozone. The Tamianetto stream section, comprising the LS3 Marchesini Siliceous Lithozone and the Borgomale Tongue of the Murazzano Fm near the pinch out of these units (cf. Pl. I), is characterized by the presence of *Reticulofenestra pseudoumbilicus* >7 µm and of *Calcidiscus praemacintyrei* indicating the MNN6b biozone of the Serravallian.

No stratigraphic sections have been measured and sampled in the Borbera-Grue area. Therefore, dating of the local Rupelian-Aquitanian stratigraphy has been mutuated from the recently published 1:50000 geological sheets Cabella Ligure and Voghera.

A chronostratigraphic diagram of the TPB units is presented in figure 3.

5. LITHOSTRATIGRAPHY

The lithostratigraphy of the area comprises, in ascending vertical order, the following units (cf. Plate I):

Alpine and Apenninic Basement (undifferentiated)
Pianfolco Formation
Savignone Conglomerate
Molare Formation
Rocchetta Formation
Montechiaro d'Acqui Siliceous Lithozone (LS1)
Poggiolo Formation
Scaletta Uzzone Formation
Visone Limestone
Montechiaro d'Acqui Formation
Visone and Lerma Glaucony
Serole Formation
Pratolungo Formation
Cortemilia Formation
T. Lemme Siliceous Lithozone (LS2)
Cassinasco Formation
Marchesini Siliceous Lthozone (LS3)
Murazzano Formation
Cessole Formation
Serravalle Sandstone
Rocca Grimalda Chaotic Complex
S. Agata Fossili Formation
Gessoso Solfifera Group
Blue Mudstone

5.1. UNDIFFERENTIATED ALPINE AND APENNINIC PRE-CENOZOIC BASEMENT (BAL, BAP)

In the study area the TPB basement rocks pertain to both Alpine and Apenninic pre-Cenozoic and eo-Cenozoic structural, metamorphic and meta-sedimentary units. Such units were deformed mainly during the Meso-Alpine Eocene collisional event. Partly following the distinctions adopted by Capponi et al. (2016), basement rocks are represented from SW to NE by a) Briançonnais basement units and Briançonnais and Pre-Piemontese metasedimentary covers; b) the oceanic unit of the Voltri Group *auct*. cropping out in the Langhe and in the Alto Monferrato area W of the Sestri-Voltaggio Line; c) both metamorphic and sedimentary Apenninic units pertaining to the so-called "Sestri-Voltaggio Zone" *auct*., developed approximately between the Lemme and Scrivia valleys in the eastern Alto Monferrato area, and d) sedimentary rocks of various Apenninic units collectively known as "Ligurian Complex" *auct*., involved in Alpine and Apenninic orogenies, located E of the "Sestri-Voltaggio Zone" in the Borbera-Grue area. In the enclosed geological map (Pl. I), the basement has been regarded as undifferentiated; only the acronyms BAL and BAP are used to distinguish between basement areas respectively located west and east of the Sestri-Voltaggio Lineament with reference to the Alpine and Apenninic basements.

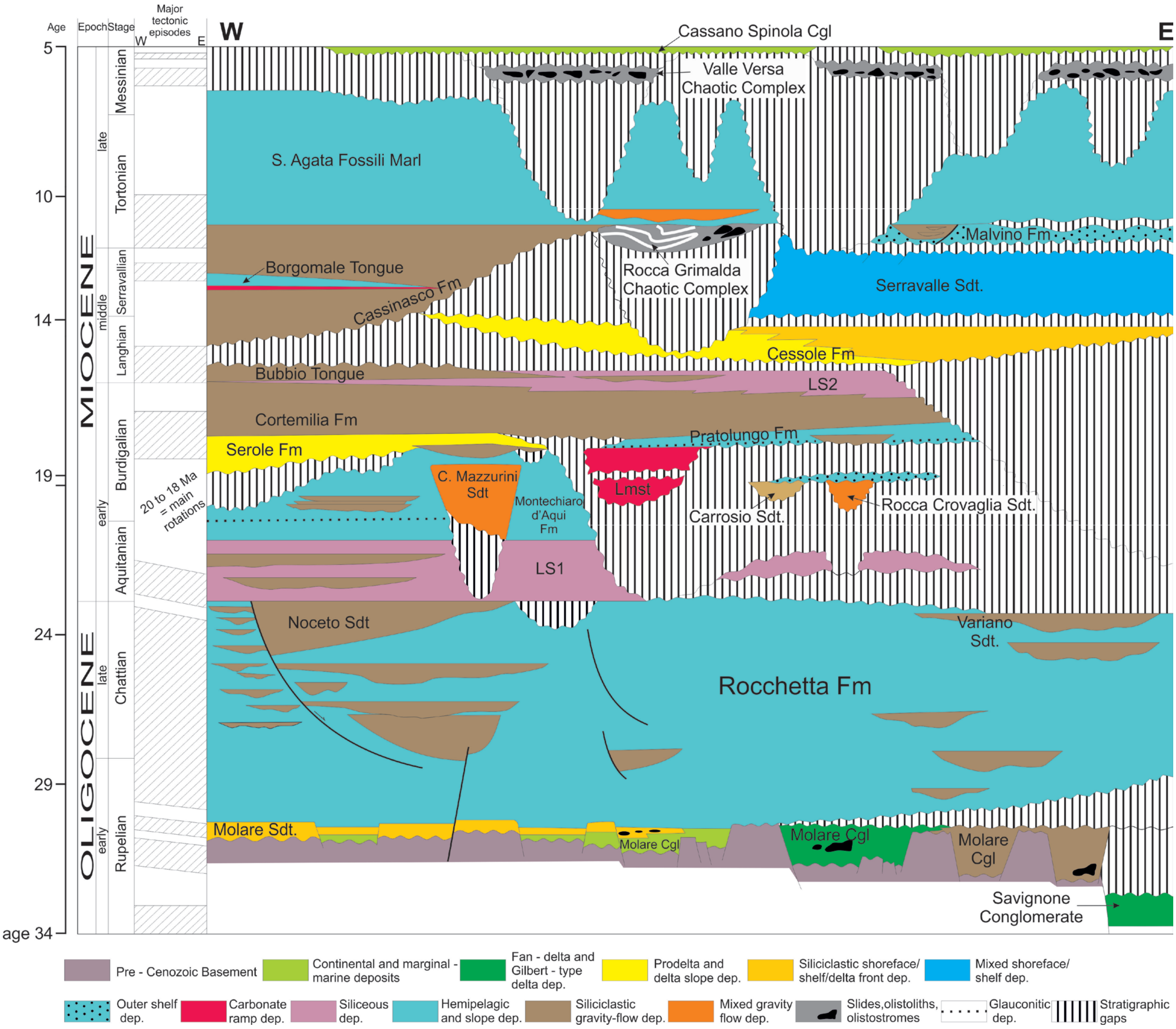

Fig. 3 - Simplified chronostratigraphic diagram of the stratigraphic succession of the study area.

5.2 PIANFOLCO FORMATION

The Pianfolco Fm crops out in a small area near the Ciglione locality (S of Grognardo, southwestern sector of the Voltri Group). The formation comprises two membres: The Costa di Cravara Breccia (CC) and the Pianfolco Mudstone and Sandstone (Pi). Charrier et al. (1964) proposed a Lattorfian (late Eocene)-lower Rupelian age based on the floral content of the latter unit, whereas Di Biase and Pandolfi (1999) proposed a Rupelian age (32 Ma). The formation is remarkably deformed and unconformably overlain by the transgressive deposits of the Molare Sandstone. Both members are associated in a small, fault-bounded area where the deposits probably represent the erosional remnant of a larger basin. In this area the formation was originally defined and carefully described by Charrier et al. (1964), who regarded the two members as distinct formations. The two units are lumped by us in a single formation, i.e. the Pianfolco Fm. The Costa di Cravara Breccia in its type-locality is present in the lowermost part of the Lerma Graben infill, and its correlation with the breccias of the Ciglione locality is doubtful. **Upper Eocene? Lower Rupelian?**

5.2.1. Costa di Cravara Breccia (CC)

Chaotic to poorly stratified, heterometric breccias with limited lateral persistence, monogenic to moderately polygenic, matrix- to framework-supported, with unsorted angular clasts and commonly reddish matrix (Fig. 4 a,b). In the upper part minor percentages of rounded pebbles are present. Thickness: about 60-80 m. The composition reflects the lithology of the metamorphic substrate. In addition to the southwestern side of the Voltri Group, the unit crops out SW of the Voltaggio Horst (Costa di Cravara area), where it forms the infill of the lowermost part of the Lerma graben (Pls. I and II). In the latter locality, which is the type area of the unit (Allasinaz et al., 1971), the breccia includes, depending on the nature of the substrate, clasts of peridotite, serpentinite, spilite and dolostone (Ibbeken 1970); clasts of lherzolite are reported by Haccard and

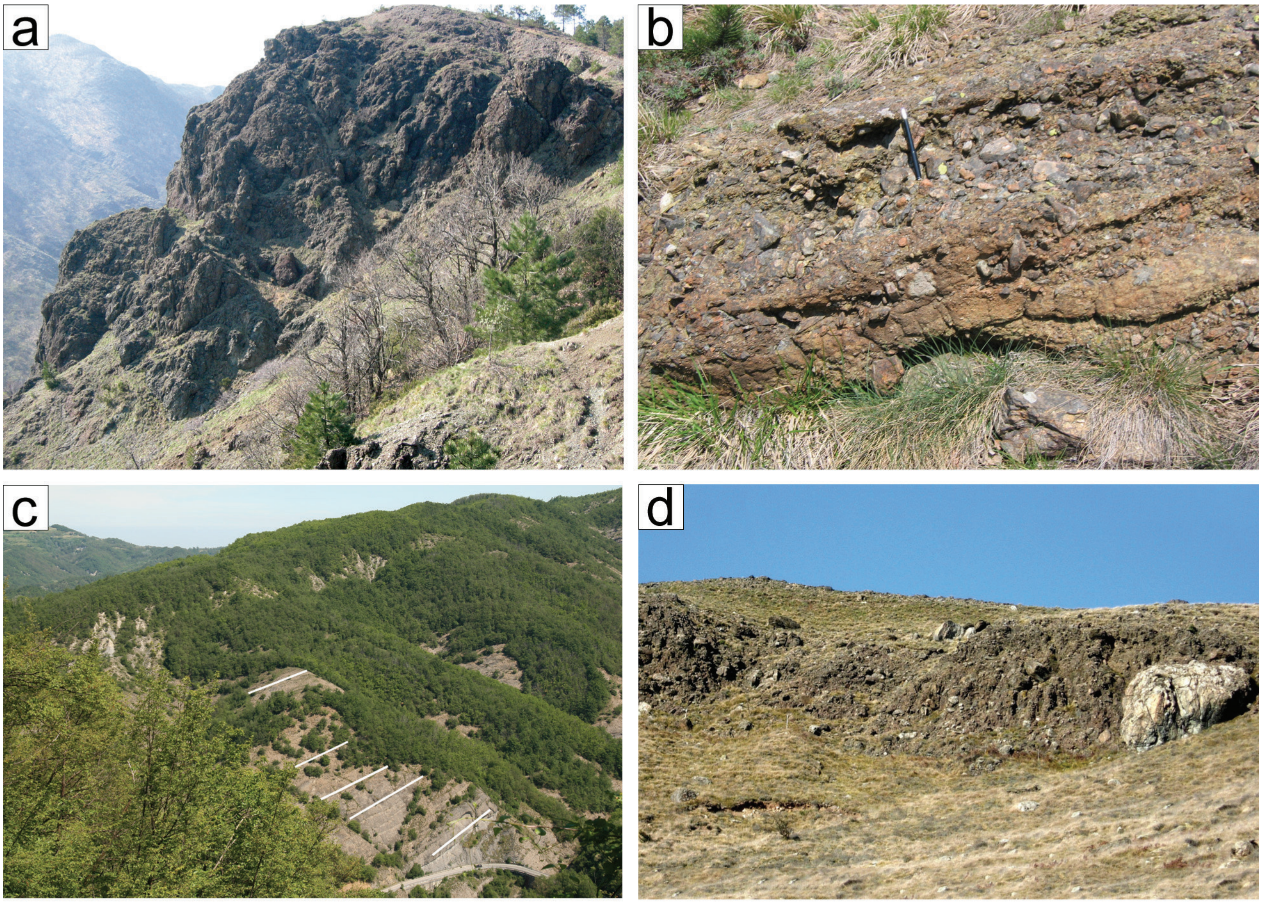

Fig. 4 - a), b) Costa di Cravara Breccia. Track of Costa di Cravara, SW of Voltaggio [pencil in b) is 15 cm long]. c) The upper part of the Borbera Valley Member of the Savignone Conglomerate viewed from the road Monteggio-Cerreto Ratti. Note the upward decrease in dip angles of the conglomerate beds (highlighted by white lines) and the upward transition to marls interbedded with turbidites (Rocchetta Fm). d) Monte Alpe Breccia: matrix-supported heterometric breccias with blocks and an olistolith of carbonate rock about 5 m high. Monte Alpe (NNE of Castagnola, Borlasca Graben).

Lorenz (1979). The rudites of the Pianfolco region include clasts mostly of serpentinite and carbonate rocks (various types of limestone, dolostone), and subordinately of quartzite, ftanite, gneiss, and diabases (Charrier et al., 1964). Significant is the presence of clasts of Cretaceous and Eocene rocks no longer cropping out in the adjacent areas. It should be noted that in the Costa di Cravara type-locality, the breccias are in places conformably overlain by the Molare Conglomerate; this suggests that in this area younger breccias pertaining to the Molare Formation, hardly differentiated from the Costa di Cravara breccias, may be locally present.

Carrapa et al. (2004), based on ^{39}Ar-^{40}Ar geochronology on detrital phengite, could establish that the depositional age of the Pianfolco rudite must be no older than 33±1.4 Ma. The dated samples came from the Lithozone A of Gnaccolini (1978), comprising deposits cropping out on the northern side of the Cravara crest, therefore attributed by him to the Costa di Cravara Breccia. Inferred age: **upper Eocene? lower Rupelian?**

Scree and mountain stream deposits infilling an intramontane basin.

5.2.2. Pianfolco Mudstone and Sandstone (Pi)

Mudstones, lignite, sandstones and minor conglomerates. Abundant remains of thermophile and igrophile Gymnosperms are present, indicating a tropical to sub-tropical, oceanic climatic setting. *Taxodiaceae, Cyperaceae* and *Carpinaceae* are dominant (Charrier et al., 1964). Inferred age: **upper Eocene? lower Rupelian?**

Fluvio-lacustrine deposits laid down in an intra-montane basin.

5.3. SAVIGNONE CONGLOMERATE (SA)

The Savignone Conglomerate corresponds to the Conglomerati della Val Borbera of Gelati and Gnaccolini (1978), to the Conglomerati di Savignone of Boni et al. (1969), and Boni and Casnedi (1970), and to the Borbera Konglomerat of Ibbeken (1970). It comprises, *pro parte*, the "Savignone Conglomerates" of Bellinzona et al. (1971) and the "Membro della Val Borbera" of the "Savignone Conglomerates" of Marroni et al. (2014). The conglomerate crops out in the eastern part of the TPB in the Borbera Valley (Fig. 4c) and Savignone-Vobbia Valley areas, with a small outcrop in between, in the locality of Montessoro. The formation is strongly tectonized by high-angle faults. In the Borbera Valley area it crops out between the NNW trending Merlassino and Lemmi faults and, subordinately, between the Lemmi and Spinti faults in a narrow strip bounded by E-W oriented faults (Pls. I and II). The main body of the Savignone Conglomerate is formed by the Val Borbera Unit, whose thickness estimate varies among authors from 1300 m (Gnaccolini, 1974) to 2500 m (Gelati and Gnaccolini, 1978; di Biase and Pandolfi, 1999). The unit mostly consists of clast-supported conglomerates, local pebbly mudstones in the upper part, and minor coarse-grained sandstones; the rudites show an almost monogenic composition characterized by predominant clasts of limestones derived from the underlying Ligurian Antola Unit. The conglomerates are characterized by thick and very thick strata and are mostly organized into clinoforms (see also di Biase, 1998 and Marroni et al., 2014) dipping approximately toward NW. Gelati and Gnaccolini (1978) documented sandy transgressive shoreface horizons in the lower part of the unit.

In the Borbera Valley area the Savignone Conglomerate was laid down in a structural depression (following Mutti et al., 1995, a pull-apart basin) originally extending between the NNW-trending Spinti and the Merlassino faults (Pls. I and II); subsequently, the infill was block-faulted by the NNW-trending Lemmi Fault, which, together with the Spinti Fault, bounded since then a minor graben which hosted gravity-emplaced deposits of the Molare Conglomerate. (Pls. I and II). The Savignone Conglomerate cropping out in the Savignone-Vobbia Valley area appears to be intensely dissected by high-angle subvertical faults resulting in fault-bounded isolated outcrops (Pl. I). It is confined between the N-trending southern inferred continuation of the Spinti Fault to the W and the similarly oriented Sorrivi-Vallemara Fault to the E. The northern outcrop area, between Griffoglieto and Vobbia, is moreover dissected by the NW-trending Scrivia Valley Fault which also displaces the Spinti Fault (Pls. I and II). Like in the Borbera area, the conglomerates show large-scale clinoforms, which presently dip to NW, W and SW. Geologic relationships with the NNW-trending, high-angle fault system bounding the adjacent Lerma and Borlasca grabens infilled and sealed by the Molare Conglomerate, demonstrate that the Savignone Conglomerate is older than the Molare Conglomerate and was tectonized before the deposition of the latter (Pl. II; Fig. 3; see also Figs. 31 and 32). Their peculiar almost monogenic lithology dominated by carbonate clasts contrasts with the polygenic composition of the Molare Conglomerate. **Lower Rupelian** (**MNP22 p.p.**).

Large, probably composite Gilbert delta with clinoforms of locally pluri-hectometric height infilling a complex structural depression.

5.4. MOLARE FORMATION

Post-orogenic breccias, conglomerates and sandstones deposited on both Alpine and Apenninic basements. Even if in the Molare type locality only the upper sandy member of the formation crops out, the name “Molare Formation” is here maintained for historical reasons. The formation comprises four members named, from the base, Monte Alpe Breccia, Molare Conglomerate, Prasco Limestone and Molare Sandstone. **Middle Rupelian**.

5.4.1. Monte Alpe Breccia (MA)

Although deposits of this unit are locally present at the base of, and interstratified with, the Molare Conglomerate, they have been mapped only at the base of the Borlasca infill (eastern part of the Alto Monferrato area), where the breccias are thicker and more extensive, (Pl. I), and are conformably overlain by the Molare Conglomerate. They consist of very coarse breccias and minor conglomerates, disorganized or crudely stratified in very thick layers, with clasts of up to plurimetric, locally decametric, dimensions, particularly abundant in the Monte Alpe area (Fig. 4d), and grey-blackish to reddish, sandy or sandy-pelitic matrix. The rudites mostly consist of greenstone clasts, particularly of serpentinite and lherzolite (Gnaccolini, 1981). In the Borlasca Graben the breccias grade laterally into conglomerates with sub-angular to sub-rounded clasts. The age of the member is here considered to be **middle Rupelian**.

Alluvial fan and, locally, scree deposits derived from accelerated erosion of a rugged landscape in the initial phases of development of the Borlasca graben.

5.4.2. Molare Conglomerate (MoC)

The Molare Conglomerate infills several grabens developed on both Alpine and Apenninic substrate, separated by basement horsts (Pls. I and II). From W to E, the deposits are confined in the Borgo, Cartosio, Albareto, Lerma, Borlasca, and Lemmi-Spinti grabens (Pls. I and II). The estimated thicknesses of the infills vary considerably with progressive increase from SW to NE, ranging from 60 m (Borgo Graben), to about 200 m (Cartosio and Albareto grabens), to over 1000 m (Lerma and Borlasca grabens), to over 800 m (Lemmi-Spinti Graben). In the eastern sector the Lerma and Borlasca grabens persisted as individualized depressions until the burial of the intervening Voltaggio Horst, later becoming part of a major, more extensive graben that accommodated the uppermost 300 metres of the local succession. The onset of deposition is diachronous, being progressively younger westwards (Lorenz, 1969). The unit consists of polygenic conglomerates with clasts ranging from pebbles to plurimetric boulders in a sandy to sandy-pelitic matrix, crudely stratified in thick to very thick beds, amalgamated or separated by discontinuous layers of medium to very coarse sandstone. The clasts are subangular to rounded and poorly to very poorly sorted. Breccias are commonly present in the lower part of the unit, as well as interstratified with the conglomerates and, typically, show maximum thickness in the proximity of inferred synsedimentary basement faults as scree deposits. The unit shows thickness and lithological and sedimentological features variable depending on the local geologic setting. In general, the clast lithologies reflect the local pre-Cenozoic substrate; important is the presence, starting from the base, of clasts of high-pressure metamorphic rocks. The conglomerates show in places synsedimentary angular unconformities interpreted as growth structures linked to uplift of the basement (such as in the Albareto Graben, in locality C. del Signore, south of the village of Albareto, see Fig. 33b, c); locally conglomerate packages appear also bounded by listric growth faults (such as NW of Monteacuto, see Fig. 33a). The conglomerates of western grabens lack marine intercalations and typically show a reddish to yellow-brown sandy to sandy-pelitic matrix (Fig. 5a), and locally show inverse grading (Fig. 5b); they are transgressively overlain in the western and central part of the TPB by the marine Molare Sandstone (MoS). The Lerma, Borlasca and Lemmi-Spinti graben infills mostly consist of marine deltaic and resedimented deposits (Figs 5c, d). In the Lerma Graben the deposits have mostly a greenish colour and are organized, starting from the base (above a local interval of basement-covering breccias), into a stack of clinostratified, Gilbert-type deltaic bodies with distinct bedding and fair granulometric sorting (Fig. 5c). In addition, the succession includes plurimetric intercalations of fossiliferous, bioturbated sandstones with littoral faunas and coarse basal transgressive lags with rounded blocks. At least two fossiliferous intercalations are present, at about 130 m above the base and in the upper part of the succession. The upper marine horizon can be traced eastwards with considerable lateral persistence (San Rocco Unit-**SR**; Pl. I). Due to the large cover, the presence of further intercalations cannot be excluded. Carbonate olistoliths of hectometric dimensions (**Ol**$_2$) are present at the head of Rio Roverno valley, and two decametric olistoliths of rocks of the Voltri Group (**Ol**$_3$) are present in locality Costa Cravara di Sotto (Pl. I). The infill of the Borlasca Graben, above a basal interval of continental M. Alpe Breccia, is characterized in the lower part by marine shelf deposits with diffuse bioturbation, local wave ripples, storm layers, and intercalated intervals of fossiliferous sandstones; this interval transitionally

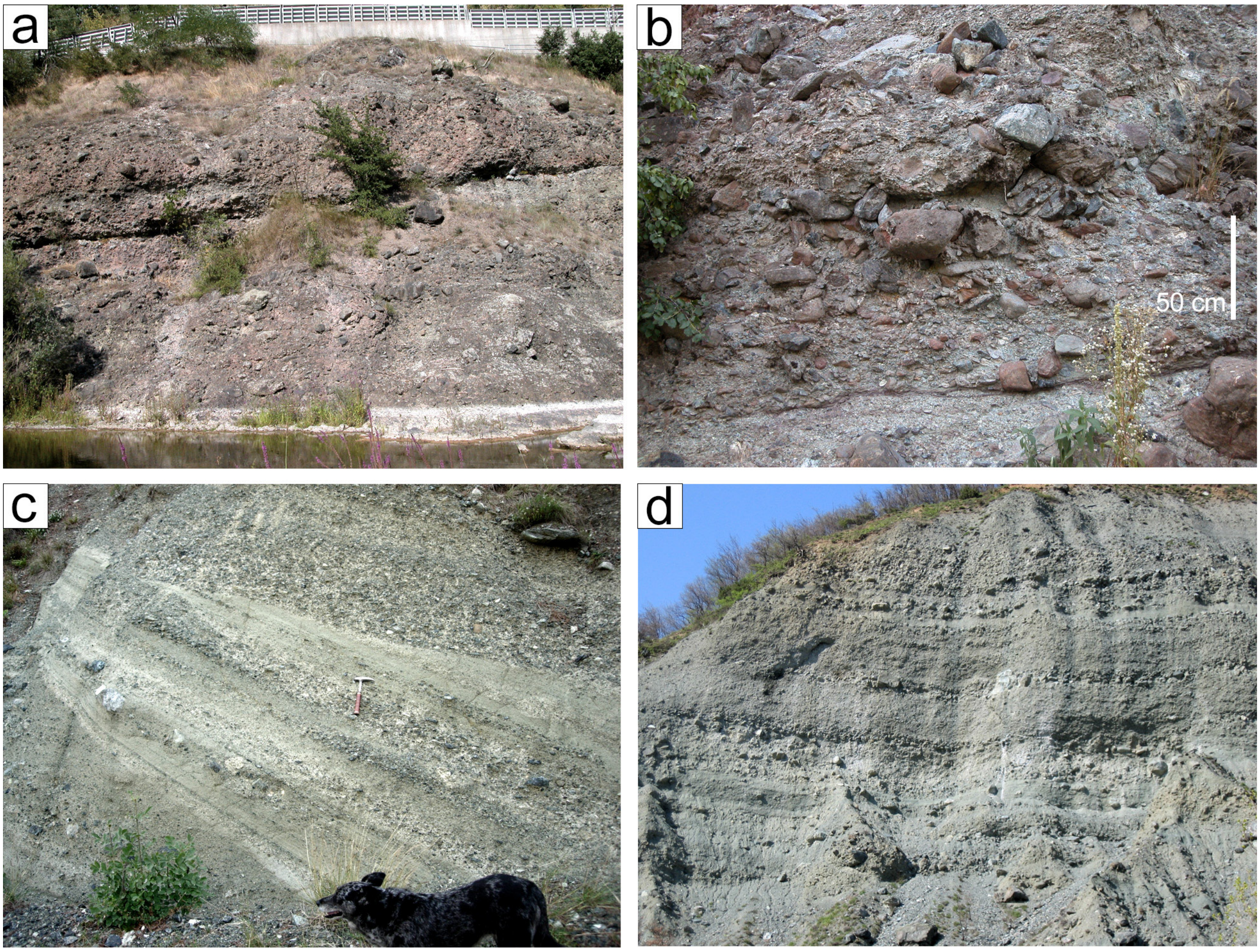

Fig. 5 - Molare Conglomerate showing different facies associations in SW-NE direction. a): Alluvial fan conglomerates in the Borgo Graben. Left bank of the Bormida di Spigno River (meander located SE of Borgo, SSE of Piana Crixia). b) Detail of inverse grading. Borgo Graben. Left bank of the Bormida di Spigno River (meander located SE of Borgo, SSE of Piana Crixia). c) Transition topsets-foresets in a small-scale Gilbert-type delta. Lerma Graben. Track NE of C. Seruggia (SSW of Mornese). d) Fan-delta front deposits. Borlasca Graben. Scarp of Bric Rive, about 10 m high, SE of Carrosio.

grades upwards into crudely stratified gravity-flow deposits represented by conglomerates (Fig. 5d) with sub-angular to sub-rounded pebbles to blocks in grey sandy matrix and common pelitic intercalations. The contact with the slope mudstones of the overlying Rocchetta Formation is characterized in this area by an erosional unconformity of pluri-kilometric lateral extent (Sottovalle slump scar) (Pls. I and II; Pl. VII online), which marks the erosive removal of an important volume of the underlying conglomerates. The infill of the Lemmi-Spinti Graben, previously attributed to the Conglomerati di Savignone in the 1:100000 Voghera Geological Sheet, is characterized by a facies association dominated by gravity-flow deposits, including turbiditic conglomerates and sandstones in medium to very thick strata, debris flow units and mudstones. Worth noting is the presence in the lower part of a characteristic lithozone, (Persi Member of the 1:50000 Geologic Sheet Cabella Ligure, Persi Lithozone-**Pe**-in the map of Pl. I), including a hectometric olistolith of the Antola Unit and two types of clast-supported breccias of pluridecametric thickness (not mapped) respectively consisting of i) basalts and subordinate gabbros (cfr. "spilitic breccias" of Ibbeken, 1974; and ii) meta-limestone and meta-dolostone. **Middle Rupelian (MNP 23 p.p.)**.

In the Borgo, Cartosio and Albareto grabens continental sediments mostly laid down by mass transport processes, i.e. mainly hyperconcentrated flows and debris flows (Fig. 5b)*, inferred to be genetically linked to catastrophic floods, were laid down as coalescing alluvial fans, local scree breccias associated with syn-depositional fault scarps and, secondarily, fluvial deposits. In the Lerma Graben fan-delta front and Gilbert-type delta deposits* (Fig. 5c) *show local intercalations of shallow-marine transgressive deposits. In the Borlasca Graben fan-delta front deposits* (Fig. 5d) *grade upwards to fan-delta slope deposits. In the Lemmi-Spinti Graben deeper-water, coarse to very-coarse, channelized, pebbly to bouldery resedimented fan-delta slope deposits are associated with sandstone/mudstone turbidite couplets. This succession contains in the lower part olistoliths and olistostromes linked to failures of inferred synsedimentary fault scarps.*

5.4.3. Prasco Limestone (Pr)

Discontinuous horizons with metric thickness of biolithite, biocalcarenite and biocalcirudite are present in the Dego, Prasco and Mongiardino areas. They contain coralline algae, corals, bivalves, bryozoans, annelids and larger foraminifers (among which *Operculina, Lepidocyclina, Amphistegina* and *Neoalveolina*), and occur atop the Molare Conglomerate (Mongiardino), or as epilithic associations on blocks of transgressive lags at the base of the Molare Sandstone (Fig. 6a), or directly on the pre-Cenozoic basement in structurally high areas only tardily reached by the Rupelian marine transgression (e.g. Bric Mazzapiedi). **Middle Rupelian?**

Biogenic transgressive carbonate deposits.

5.4.4. Molare Sandstone (MoS)

Fine to very coarse sandstones, locally micro-conglomerates or pebbly sandstones, fossiliferous (pelecypods, gastropods, echinoids, corals, bryozoans, larger foraminifers, among which *Nummulites fichteli*, *Nummulites vascus*, *Operculina complanata, Amphistegina* sp., *Eulepidina* sp., *Nephrolepidina* sp.), in medium to thick, locally amalgamated, tabular to broadly lenticular beds commonly affected by differential cementation, usually bioturbated and locally rich in vegetal remains sometimes bored by *Teredinidae* (**MoS$_a$**). Where the marine sandstones overlie continental conglomerates (Borgo, Cartosio, Albareto grabens) the basal deposits of the unit are represented by a transgressive lag up to some metres thick of polygenic well-rounded pebbles to boulders aligned on the ravinement surface (Fig. 6b). Where the transgressive marine sandstones overlie the pre-Cenozoic basement (e.g. Spigno Monferrato Horst, N of the Montaldo Fault) the nonconformity shows the typical features of a rocky shore transgression with up to several metres thick basal conglomerates characterized by monomict, pebble to boulder conglomerates reflecting the composition of the substrate (Fig. 6b) (Ghibaudo et al., 2014). The coarse-grained basal transgressive deposits are not distinguished in the geological map and are included in the Molare Sandstone.

The beds of the Molare Sandstone are usually bioturbated and structureless or graded to graded-to-laminated, or simply laminated, with either parallel laminae or low-angle oblique or hummocky cross-laminae (Fig. 6c), commonly with bioturbated tops. High-angle, medium-scale cross-laminated sets are rare. In the uppermost part of the unit, at the transition with the overlying mudstones of the Rocchetta Formation, a fining trend is present with transition to bioturbated fine sandstones.

In places (e.g. Montaldo area, E of Spigno Monferrato, Rio Granozza SE of Molare area, C. Battaglino near Cimaferle, and on the eastern flanc of the Mioglia syncline), the unit shows a facies coarser than average, with coarse and conglomeratic sandstone in thick to very thick, commonly lenticular, erosive-based and in places graded beds (Fig. 6d) with local intraformational clasts (Ghibaudo et al, 2014); in places (e.g. Mioglia area, Fig. 34), a mouth bar facies association with unidirectional trough cross bedding is present. Within the village of Molare the unit shows a clear clino-stratification. In the Toleto-Cimaferle area, the lower part of the unit contains monogenic, fine-grained breccias with common inverse grading in tabular or lenticular strata, associated to disorganized heterometric breccias with local large olistoliths (see Fig. 35a). Clasts of these rudites are sourced from the local pre-Cenozoic substrate. NW of Bandita (locality Cappelletta) the unit contains metric to hectometric olistoliths (**Ol$_1$**) of adjacent basement rocks (Pl. I). These extraformational breccias are indicated with the acronym **MoS$_b$**. **Middle Rupelian (MNP 23 p.p.)**.

Shallow-marine, mostly shoreface deposits. At the base:

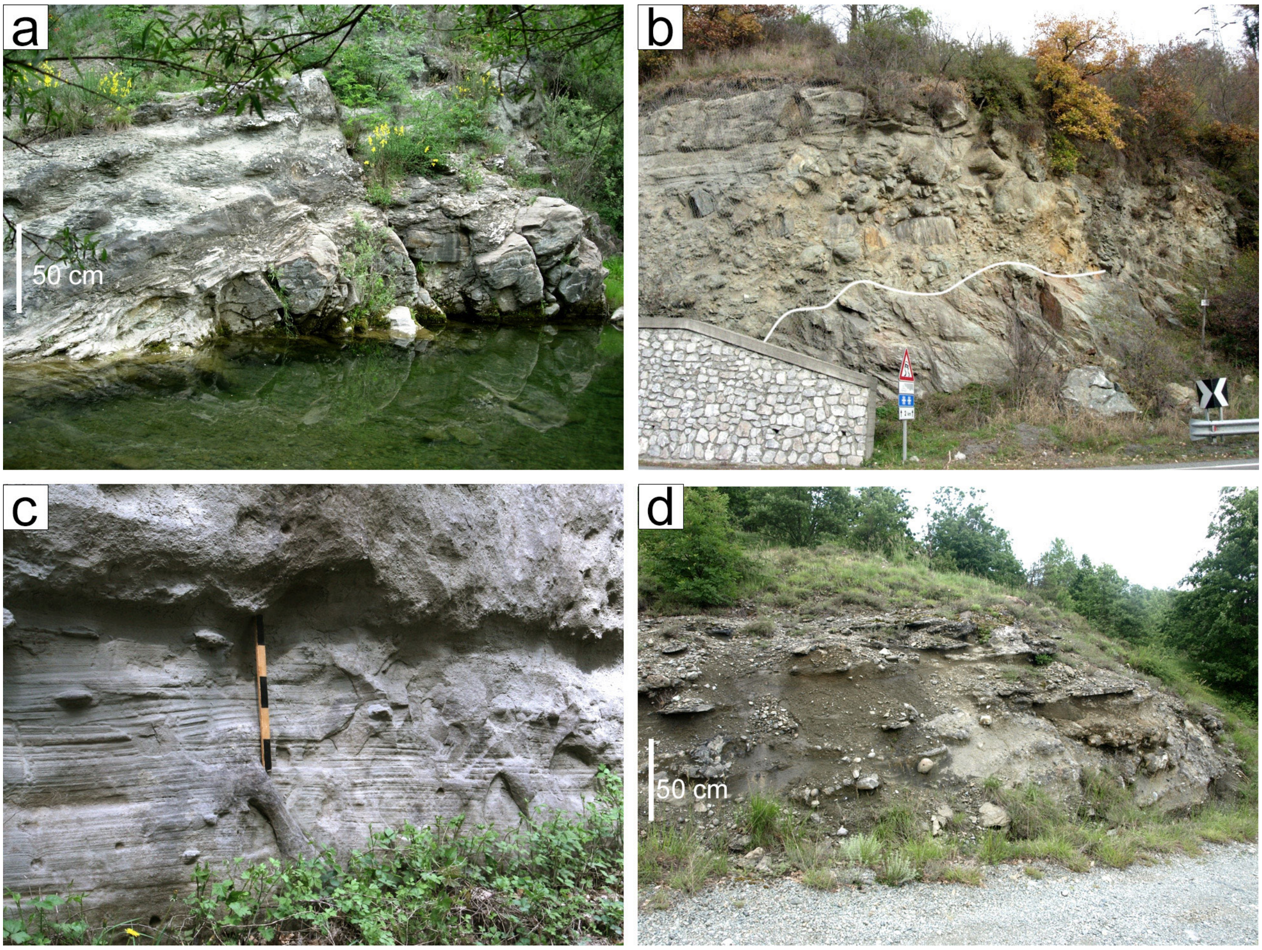

Fig. 6 - Molare Sandstone. a) Transgressive coarse lag with basement blocks, encrusted by coralline algae at the base of the Molare Sandstone. Bank of Visone stream, near C. Gazzo. b) Transgressive layer with large blocks on the pre-Cenozoic basement (the top of which is marked by a white line), grading upwards into marine sandstones. Spigno Monferrato. c) Hummocky cross lamination (Mioglia area, NE of Girini). d) Molare Sandstone in facies of fan-delta front. Note high percentage of spherical clasts indicating wave-induced shape sorting and wavy bedding near the top. Track between the village of Montaldo and Valla Stream.

transgressive coarse lag lining a ravinement surface, or boulder-beach rocky shore deposits. In the areas of Montaldo, Molare, Battaglino-Cimaferle and Mioglia: fan-delta deposits, locally as mouth bar facies sequences. In the Toleto-Cimaferle and Bandita areas gravity-emplaced breccias and olistoliths, accumulated at the toe of fault palaeoscarps, with limited transport by gravity flows in shallow marine environment.

5.5. ROCCHETTA FORMATION (RA)

The formation displays basinwide extent and is time-equivalent of the Rigoroso Fm of eastern TPB and of the Antognola Fm of northern Apennines (Note 3). In the Alto Monferrato High the formation is truncated by the transgressive unconformity at the base of the lower Burdigalian Visone Limestone, whereas in the Borbera-Grue area, S of the Villalvernia-Varzi Line, the formation is truncated at the top by an angular unconformity marking the base of the Langhian Cessole Fm (Fig. 3; Fig. 42b). The Rocchetta Fm is overlain by the Siliceous Lithozone LS1, a regional key horizon (Ghibaudo et al., 2014).

The depocentres of the formation located in the Langhe and Borbera-Grue areas are separated by a basement high known as Alto Monferrato High. Thickness is over 1000 and 1800 m respectively in the two depocentres, whereas it does not exceed a few hundreds of metres in the intermediate high. The unit consists dominantly of hemipelagic mudstones (Fig. 7a), delicately bioturbated, alternating with thin- to medium-bedded fine sandstones and siltstone turbidites, and inferred hyperpycnites (Fig. 7b). Trace fossils include *Zoophycos* (Fig. 7c) *Chondrites*, *Thalassinoides* (Fig. 7d) and cylindrical tubes with *spreiten*.

In the Langhe area the dominant fine-grained facies locally comprises plurimetric intervals of fine-grained, thin- to medium-bedded sandstone/pelite turbidites with sandstone/pelite ratio of about 1; likewise, in the Borbera-Grue area the background facies in the lower part of the unit encases intervals of medium- to thick-bedded sandstone/pelite turbidites. Hyperpycnites also are common, typically characterized by lithologies in the range of very fine-grained sand and silt and abundance of mud drapes (Fig. 7b). The formation shows an overall

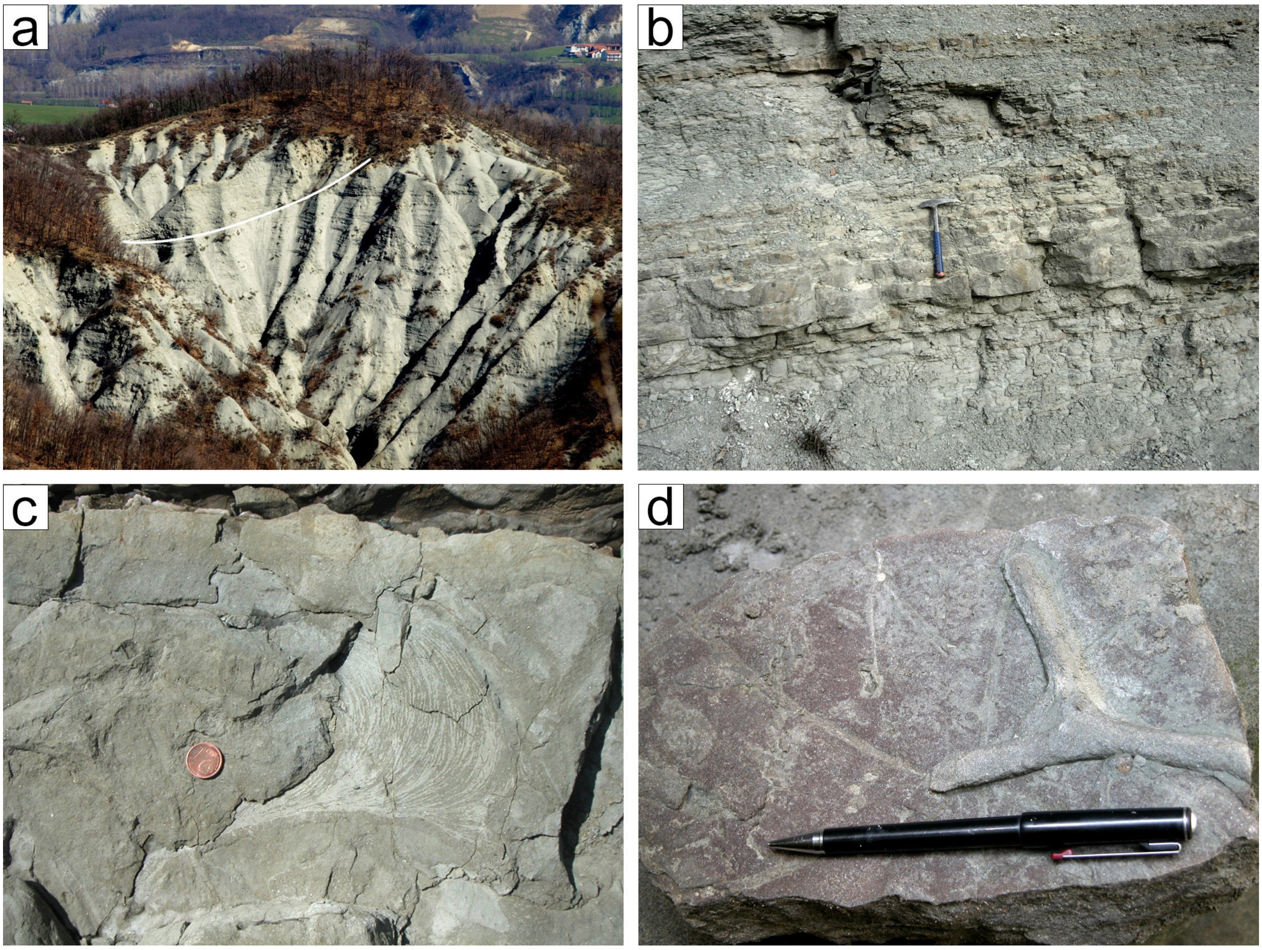

Fig. 7 - Rocchetta Formation. a): Hemipelagic mudstones of the Rocchetta Fm with slump scar in the upper part (white line). South-western side of M. Pisone. b) Inferred hyperpycnites. Note the fine grain size of the sandstones and abundance of mud drapes. Road Spigno Monferrato-Rocchetta. c) *Zoophycos*; bank of Orba River, near the village of Molare. The diameter of the coin is 1.6 cm d) *Thalassinoides*. The pencil is 15 cm long. Head of the valley of Girosa stream, W of the confluence with Teso stream.

fining upwards trend, evidenced by the preponderance in the upper part of hemipelagic marls punctuated by ash layers, the latter particularly developed in the Alto Monferrato and Borbera-Grue areas.

Particularly in the Langhe Sub-basin slump scars and slumped bed packages (S1 to S6 in Pl. I) are common (Fig. 7a). A large composite scar, about 1 km wide and up to 150 m deep, located in the Molino di Mombaldone area (see Fig. 36), evolved into a submarine canyon/slope valley system (Ghibaudo et al. 2014). In the eastern part of the Alto Monferrato area and in the Borbera-Grue area, the base of the Rocchetta Fm is characterized by an erosional unconformity taking the form of a slump scar of plurikilometric extent (Sottovalle slump scar) wich removes important volumes of the underlying Molare Formation (Pls. I and II; Pl. VII online).

The unit encases medium- to large-scale turbiditic sandstone and conglomerate bodies (Pls. I and II); the former show lateral extent of tens to hundreds of metres and thickness of tens of metres, the latter an extent of several kilometers and thickness of hundreds of metres. The bodies generally show lenticular, less commonly wedging out geometry (e.g. the Noceto Sandstone and Cassinelle Sandstone (Pls. I and II; Fig. 3) and are particularly developed in the Langhe and Borbera-Grue depocentres, generally with upward increasing width/thickness ratio. Minor turbidite bodies (Fig. 14b) and key beds (Fig. 14c) are indicated with the letters a), b), c), etc. in plate I. Particularly in the Langhe area, some examples of coarse-grained channel bodies encased in the slope mudstones of the lower part of the Rocchetta Fm show evidence of lateral accretion and are interpreted as infills of meandering channels (Fig. 8a). In the Alto Monferrato area, in locality C. Dirante (SW of Prasco), two decametric olistoliths ($\mathbf{Ol}_5$) of basement rocks are present (Pl. I).

The Rocchetta Fm comprises several members listed below from W to E, in the Langhe, Alto Monferrato and Borbera-Grue areas. The base of the unit in the Langhe area is dated to the uppermost part of the MNP23 biozone; the same age attribution is extended to the lowermost part of the Rocchetta Fm in the Borbera-Grue area. This age is also documented for the lower part of the time equivalent Antognola Fm of northern

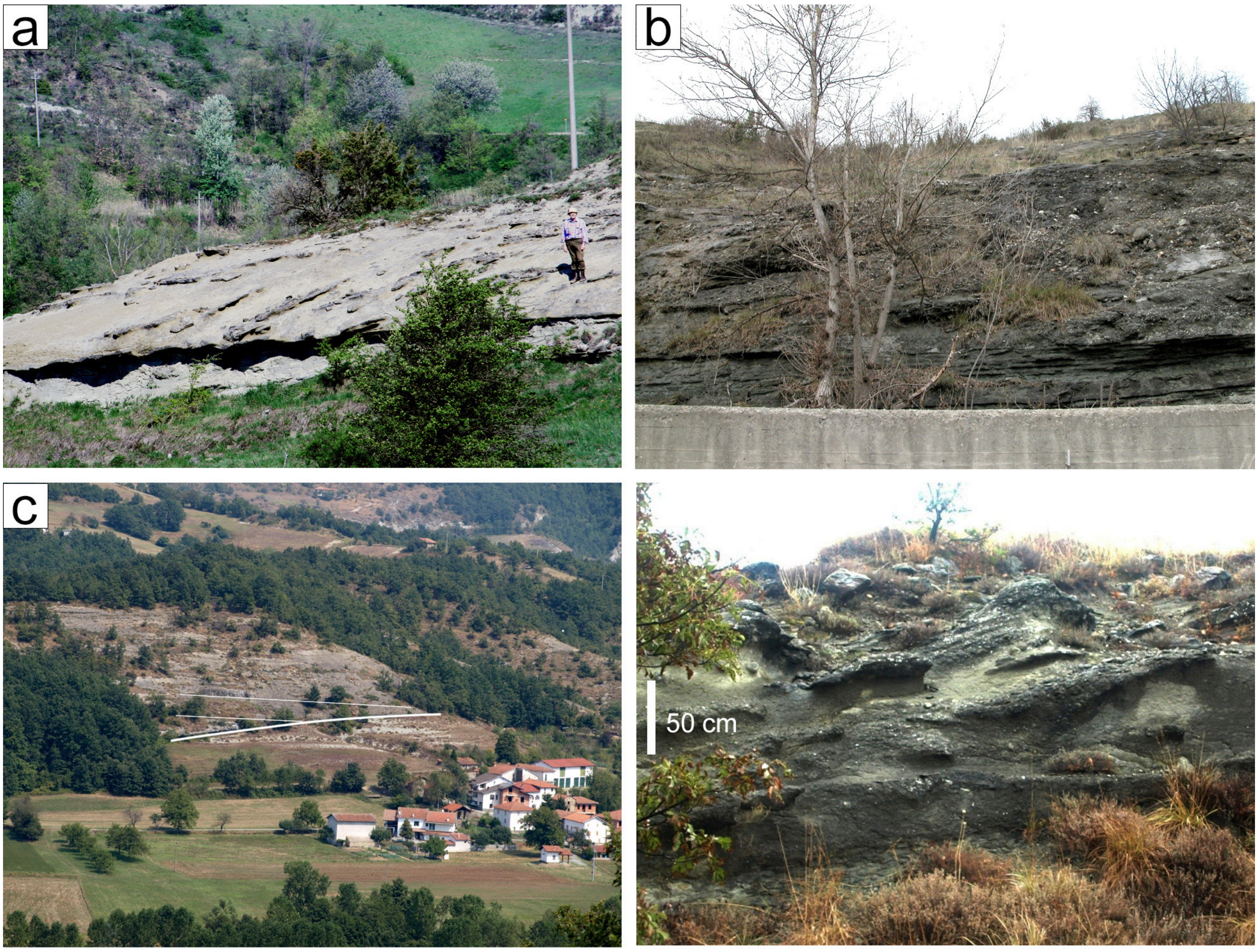

Fig. 8 - a) Frascheto Sandstones. The channel fill shows distinct lateral accretion surfaces. Man for scale. N of the village of Frascheto, Mioglia area. b) Piana Crixia Conglomerate showing inclined bedding inferred to be generated by lateral accretion. The outcrop is about 5 m high. Locality Ciazze, N of Piana Crixia. c) Piana Crixia Conglomerate body showing at the base onlap relationships (highlighted by white lines) with marls of the Rocchetta Fm. Valla area, view from hairpin bend of the road ENE of Valle di S. Ry. d) Spot height 499 Sandstone. Sandy gravel waves inferred to be generated by supercritical flow (S of Malvicino).

Apennines (Martelli et al., 1998). In the Langhe and Borbera-Grue depocenters the unit is characterized, in the lowermost part, by the First Occurrence (FO) of *S. ciperoensis* (Ghibaudo et al., 2014; Marroni et al., 2014). The topmost part of the unit is dated to the upper Chattian (MNN1). **Uppermost middle Rupelian-Chattian (MNP23 *p.p.*-MNN1 p.p.)**.

Slope and base-of-slope deposits. The marly sediments are interpreted as hemipelagic deposits. Locally interbedded: turbidite and hyperpycnite layers. Encased sandstone and conglomerate small- to large-scale lenticular bodies are interpreted as the infill of channels and respectively submarine valleys or canyons, and the wedge-shaped bodies bounded by synsedimentary listric faults as infills of half-grabens. Laterally to these bodies, packages of tabular, thin- to medium-bedded, mudstone-sandstone couplets represent overbank deposits.

5.5.1. The Rocchetta Formation in the Langhe area

In the Langhe area the Rocchetta Fm includes the following members.

5.5.1.1. Piana Crixia Conglomerate (PC)

Thick- to very thick-bedded turbidite sandstones, pebbly sandstones and conglomerates, amalgamated or separated by thin silty interbeds, locally interbedded with volumetrically subordinate thin- to medium-bedded alternating turbidite sandstones and mudstones. The unit is confined within a structural low of the pre-Cenozoic substrate. In the Piana Crixia area the internal organization is characterized by multiple, metres-thick cycles thinning- and fining-upwards, representing minor channelized sandstone bodies bounded at the base by large-scale erosional surfaces, and both vertically stacked and laterally juxtaposed. Typically, the individual channelized bodies comprise pebbly sandstones and conglomerates in the lowermost and axial parts and sandstones in the upper part. Local inclined bedding has been observed (Fig. 8b). The conglomerates grade downcurrent in the Valla area into medium- to very coarse-grained turbiditic sandstones in thick and amalgamated beds locally containing isolated boulders, with evident basal onlap relationships on the marls of the

Rocchetta Fm (Fig. 8c). **Upper Rupelian**.

Slope channel-complex conglomerates confined within a structural depression, passing downcurrent to a small-scale sandy depositional system. Local evidence of lateral accretion.

5.5.1.2. Vignaroli Sandstone (Vg)

Thick- to very thick-bedded turbidite sandstones, amalgamated or separated by thin mudstone interbeds, with minor intercalations of medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio ≤1. The unit has a lenticular geometry. **Upper Rupelian?**

Slope channel-fill deposits.

5.5.1.3. Vignazza Sandstone (Vz)

Thick-bedded turbiditic sandstones in the lower part, amalgamated or separated by thin mudstone interbeds, grading upwards into thin- to medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio near 1. The unit has a lenticular geometry. **Upper Rupelian?**

Slope channel-fill deposits.

5.5.1.4. Sassore Sandstone (Ss)

Medium- to very thick-bedded, turbidite sandstones and pebbly sandstones mostly amalgamated. In the uppermost part, medium- to thick-bedded sandstone-mudstone couplets with sandstone/mudstone ratio ≥1. The unit has a lenticular geometry and shows large-scale internal erosional surfaces. **Upper Rupelian?**

Slope channel-fill deposits.

5.5.1.5. Spot height 499 Sandstone (QtE)

Pebbly to bouldery resedimented gravelly sandstones, locally with wavy bedding (Fig. 8d), in very thick and amalgamated beds, and thick to very thick-bedded and amalgamated, turbidite sandstones. **Upper Rupelian**.

Slope channel-fill deposits.

5.5.1.6. Spot height 445 Sandstone (QtD)

Thick- to very thick-bedded and amalgamated turbidite sandstones. **Upper Rupelian**.

Slope channel-fill deposits

5.5.1.7. Spot height 501 Sandstone (QtM)

Pebbly to bouldery resedimented gravelly sandstones in very thick and amalgamated beds, associated with thick- to very-thick-bedded and amalgamated sandstones. **Upper Rupelian**.

Slope channel-fill deposits.

5.5.1.8. Frascheto Sandstone (Fr)

Thick- to very thick-bedded and amalgamated turbidite sandstones and pebbly sandstones with inclined bedding (Fig. 8a). **Upper Rupelian**.

Slope channel-fill deposits with evidence of lateral accretion.

5.5.1.9. Dogli Sandstone (Do)

Thick- to very thick-bedded and amalgamated turbidite sandstones and pebbly sandstones. **Upper Rupelian**.

Slope channel-fill deposits

5.5.1.10. Carpenaro Sandstone (Cn)

Thick- to very thick-bedded and amalgamated turbidite sandstones and pebbly sandstones. **Upper Rupelian**.

Slope channel-fill deposits

5.5.1.11. Cian del Grill Sandstone (CG)

Thick- to very thick-bedded turbidite sandstones, rarely pebbly sandstones, commonly amalgamated or separated by thin muddy intervals. In the upper part, thick- to medium-bedded alternating sandstones and mudstones with sandstone/mudstone ratio >1. The unit has a broadly lenticular geometry. **Chattian**.

Non-channelized slope or base-of-slope deposits infilling local accommodation space (lobe/fan deposits).

5.5.1.12. Fontanelle Sandstone (Fo)

In the lower part, thick- to medium-bedded, sandstone-mudstone turbidite couplets with sandstone/mudstone ratio >1. In the upper part, thick- to very thick-bedded and amalgamated turbidite sandstones passing upwards to thick- and medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio >1. Typically, the amalgamated sandstones make up a plurimetric tabular interval which stands out in the erosion profile. **Chattian**.

Non-channelized slope or base-of-slope deposits infilling local accommodation space (lobe/fan deposits).

5.5.1.13. Bric Petacchi Sandstone (BP)

Turbidite sandstones, subordinately pebbly sandstones, in thick- to very thick-bedded and amalgamated beds. In the upper part, thick- to medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio >1. The unit has a broadly lenticular geometry. **Chattian**.

Slope or base-of-slope channel-fill deposit.

5.5.1.14. Saliceto Sandstone (Sl)

Thick- to very thick-bedded turbidite sandstones commonly amalgamated or separated by thin muddy intervals. In the upper part, medium- to thick-bedded, sandstone-mudstone couplets with sandstone-mudstone ratio >1. The unit has a broadly lenticular geometry. **Chattian**.

Slope or base-of-slope deposit channelized or laterally confined.

5.5.1.15. Sorgente Alpei Sandstone (SAl)

In the lower part, medium- to thick-bedded, sandstone-mudstone turbidite couplets with sandstone/mudstone ratio >1. In the upper part, thick- to very thick-bedded and amalgamated turbidite sandstones passing upwards to thick- to medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio >1. Typically, the amalgamated sandstones make up a plurimetric tabular interval which stands out in the erosion profile. Near its NE termination (Rio Costabella) the unit shows an erosional base. **Chattian**.

Non-channelized slope or base-of-slope deposits infilling local accommodation space (lobe/fan deposits).

5.5.1.16. Brovida Sandstone (Bv)

The unit has maximum thickness of 160 m, and lateral extent of about 9 km. It erosionally overlies the Mogliavacca Sandstone. The unit has a large-scale lenticular geometry in its depocentral area, where it shows a large-scale basal erosional contact locally highlighted by onlap stratigraphic relationships, and a more tabular south-western lateral termination. The unit can be identified as a channel complex (Fig. 9a). Namely, it shows a complex architectural organization characterized by stacked, upward-thinning and -fining channel elements forming lenticular building blocks consisting of thick- to very thick-bedded and amalgamated turbidite sandstones in the lower and middle parts and medium- to thick-bedded sandstone/mudstone couplets in the upper part. Individual channel elements pinch out over distances of a few tens of metres (e.g. Rio Serre), and are separated by subordinate intervals of thin- to medium-bedded turbidites. They are locally associated to inferred channel-lobe transition units (Fig. 9b). Examples of beds internally characterized by multiple muddy drapes are interpreted to have been laid down by hyperpycnal flows (Fig. 9c). Sandstone layers are locally crossed by *Ophiomorpha* (Fig. 9d). **Chattian**.

Slope or base-of-slope channel complex infilling residual accommodation space atop the underlying Mogliavacca canyon-fill. Possible lower canyon-fan apex deposits.

5.5.1.17. Cobarello Sandstone (Cb)

The unit (Fig. 10 a,b) has a large-scale lenticular geometry in the axial portion and more tabular lateral wings. To the S it is offset by the listric Rio Girosa Fault. Maximum thickness of the unit is of about 210 m and lateral extent of about 10 km. The unit shows a complex architecture characterized by stacked sandstone bed packages separated by very subordinate, thin-bedded, turbidite intervals (Fig. 10a). In the Brovida-Noceto type-section these elements form upward-fining and -thinning

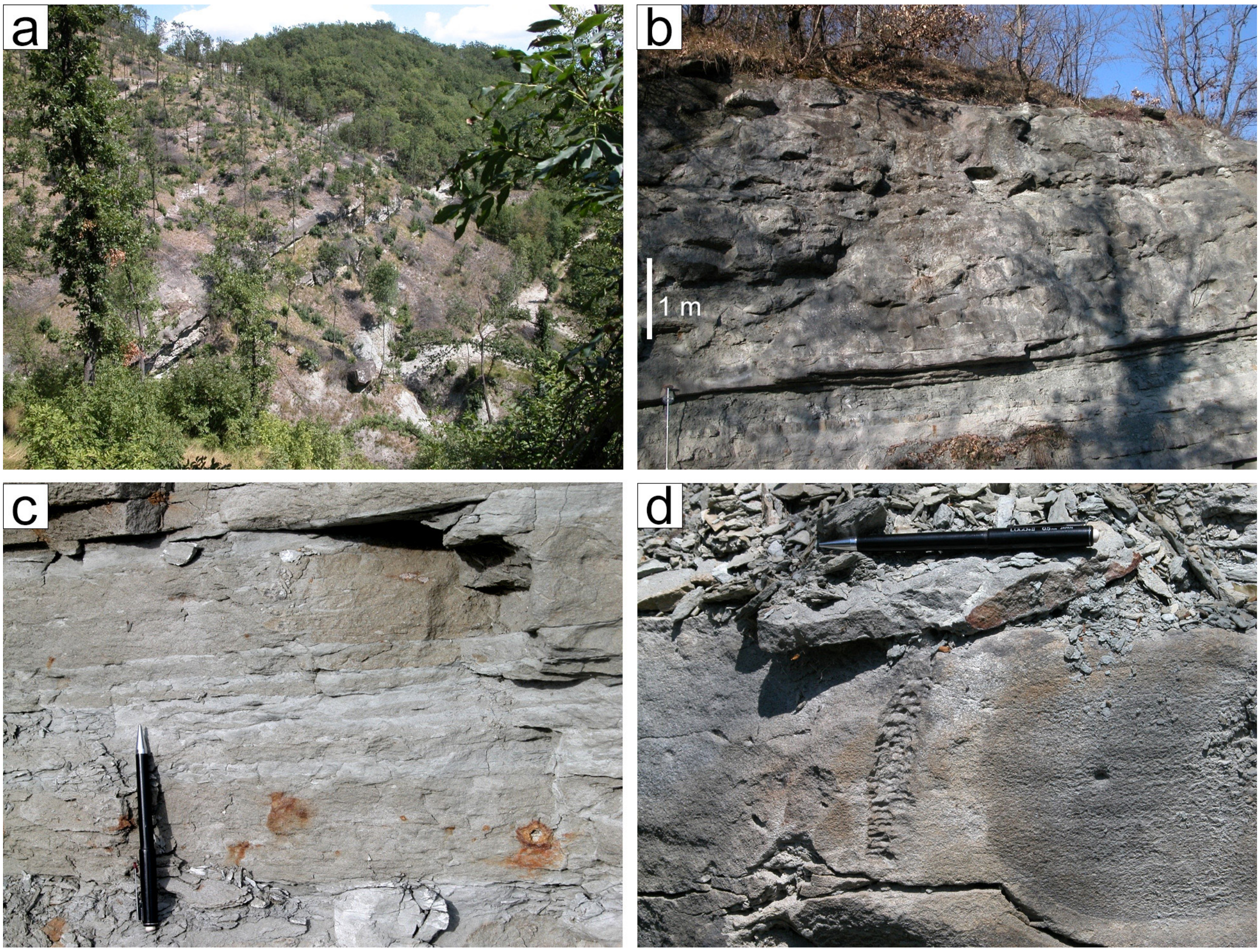

Fig. 9 - Brovida Sandstone. a) Channel complex showing multiple, mutually cross-cutting channel elements. View from the valley of Rio Serre (left tributary of Rio Gelosi). b) Inferred record of channel-lobe transition. Note the scours and the abundance of mud clasts (road between the villages of Brovida and Noceto). c) Inferred hyperpycnite with abundant mud drapes suggesting pulsating flow subject to cyclic changes in the rate of fallout. Pencil is 15 cm long. d) *Ophiomorpha* crossing a sandstone layer. Pencil is 15 cm long. Near the village of Carretto.

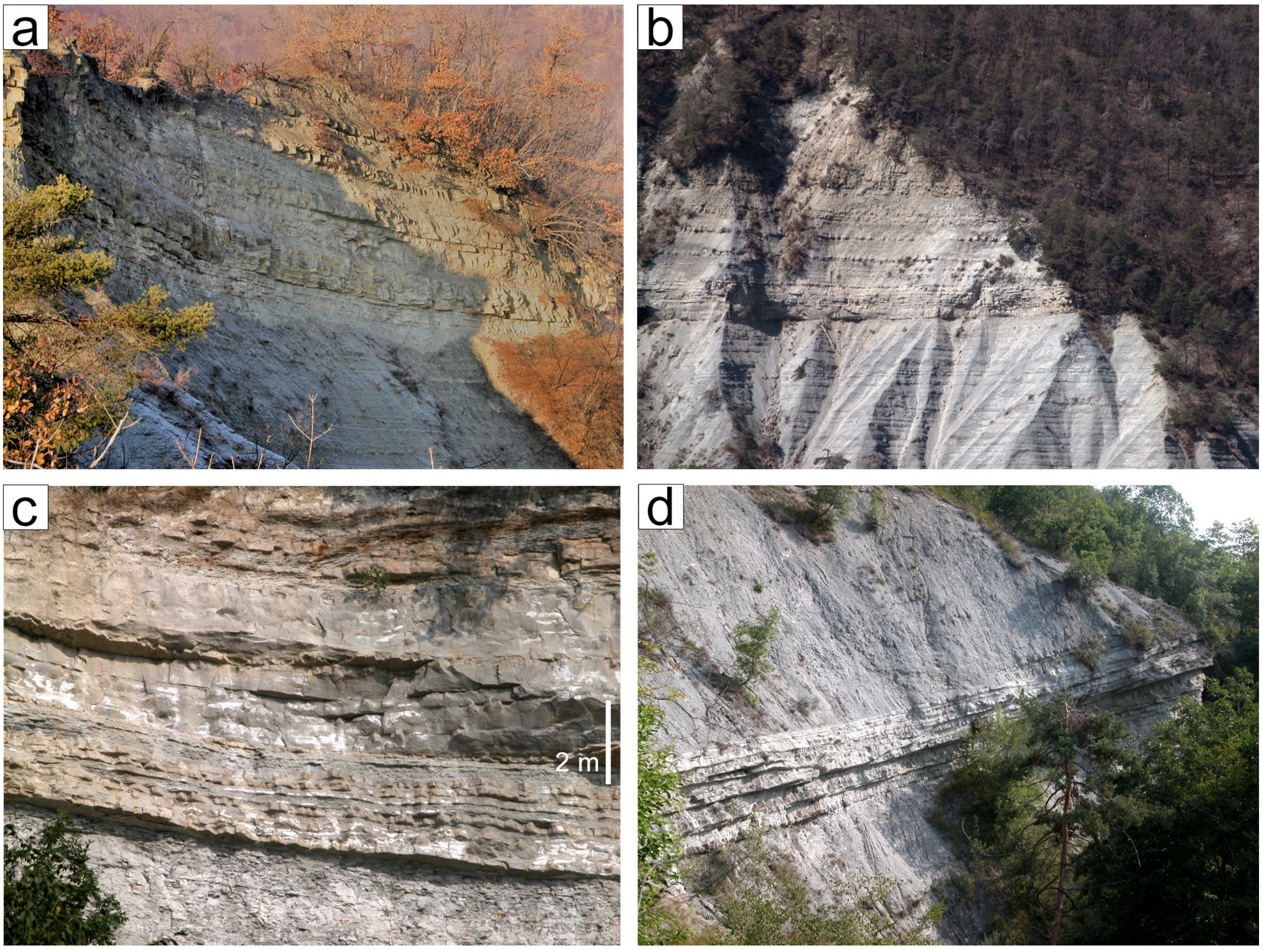

Fig. 10 - a) Cobarello Sandstone. Stack of channel elements; (road Brovida-Noceto). b) Cobarello Sandstone. Northern part of the body showing thinning out northwards (SSW of Merana). c) C. Giroso Sandstone. Inferred superposition of channelized sandstones with thick to amalgamated beds on lobe deposits. d) C. Giroso Sandstone. Note internal erosional surfaces. Western side of the body. Near Case Giroso (left side of Rio Girosa Valley).

cycles which consist in the lower part of thick- to very thick-bedded and amalgamated sandstones, rarely pebbly sandstones, with concentrations of intraformational clasts, and locally thick gravelly debris flow units, passing upwards to thinner intervals of thick- to medium-bedded sandstone-mudstone couplets. **Chattian**.

Slope or base-of-slope broad submarine depression infilled with proximal lobe deposits.

5.5.1.18. C. Giroso Sandstone (Gi)

In the lower part, medium-bedded sandstone-mudstone turbidite couplets with sandstone/mudstone ratio ≥1 (Fig. 10 c,d). In the upper part, thick- to very thick-bedded and amalgamated turbidite sandstones passing upwards to thick- to medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio >1. Typically, the amalgamated sandstones make up a plurimetric tabular interval which stands out in the erosion profile. **Chattian**.

Slope or base-of-slope deposits infilling local accommodation space (lobe/fan deposits).

5.5.1.19. Mogliavacca Sandstone (Mv)

The unit has marked lenticular geometry, erosional basal surface (Fig. 11a), maximum thickness of about 250 m, and lateral extent of 3.4 km. The upper boundary is an erosional contact with the overlying Brovida Sandstones, except for the NE termination of the body, where a wedge of Rocchetta mudstones is preserved atop the unit. The unit consists of resedimented sandstones, pebbly sandstones and conglomerates (Fig. 11b) in thick- to very-thick and amalgamated beds, locally associated to debris flow units up to several metres thick. In detail it shows a composite architecture characterized by a succession of erosionally based cycles, thinning- and fining-upwards (Fig. 11c). Typically, individual cycles are characterized by thick- to very thick-bedded pebbly to bouldery conglomerates or conglomerate-sandstone couplets in the basal parts and thick-bedded and amalgamated sandstones in the upper parts; intraformational clasts up to 1 metre in size are common. The upper part of the unit is made up of medium- to thick-bedded and amalgamated sandstones. Layers with multiple mud drapes, interpreted as hyperpycnal-flow

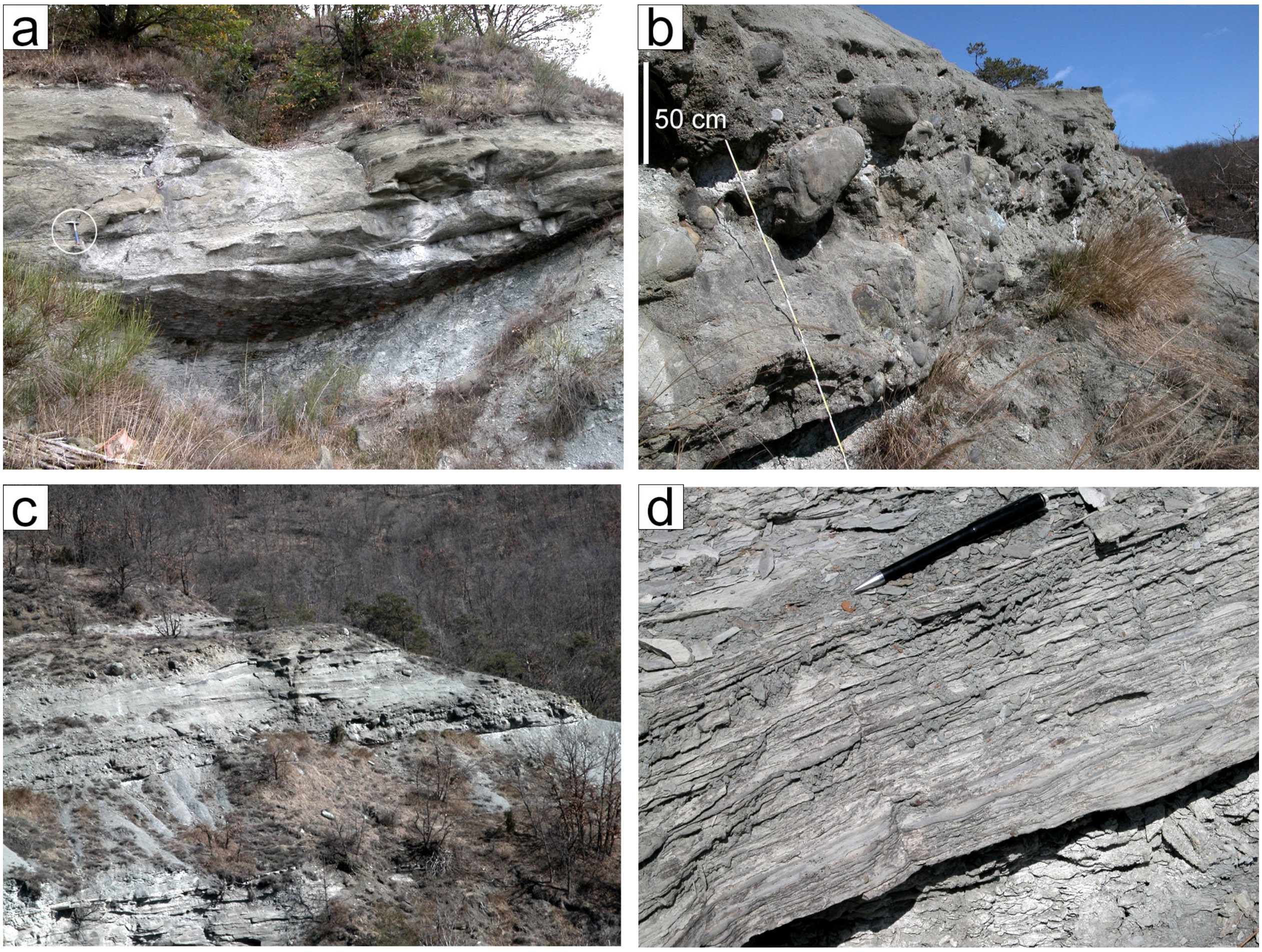

Fig. 11 - Mogliavacca Sandstone. a) Erosional basal contact of the body. Encircled hammer for scale. Near Case Chiazza, NNW of Dego. b) pebbly to bouldery debris flow deposits, commonly present in the lower part of the unit. Rio Casattana. c) Multiple channel elements. Rio Casattana. d) Inferred hyperpycnite, with multiple mud layers suggesting pulsating flow subject to cyclic changes in the rate of fallout. Rio Casattana. Pencil is 15 cm long.

deposits, have been observed (Fig. 11d). **Chattian**.

Submarine canyon-fill deposits.

5.5.1.20. Codevilla Sandstone (Cd)

Thick- to very thick-bedded and amalgamated turbidite sandstones and pebbly sandstones. In the upper part, sandstone-mudstone couplets in thick to medium beds. Minor intercalations of medium-bedded, alternating sandstones and mudstones. The unit has lenticular geometry. **Chattian**.

Slope channel-fill deposits.

5.5.1.21. M. Castello lower Sandstone (MCi)

Thick- to very thick-bedded and amalgamated turbidite sandstones and gravelly sandstones. **Chattian**.

Slope channel-fill deposits

5.5.1.22. M. Castello upper Sandstone (MCs)

Thick- to very thick-bedded and amalgamated turbidite sandstones and gravelly sandstones. **Chattian**.

Slope channel-fill deposits.

5.5.1.23. C. Fossati Sandstone (CFi)

Thick- to very thick-bedded and amalgamated sandstones. **Chattian**.

Slope channelized deposits.

5.5.1.24. Barbani Sandstone (Ba)

Thick- to very thick-bedded and amalgamated sandstones. The unit has a lenticular geometry. **Chattian**.

Slope channelized deposits.

5.5.1.25. C.se Robella W Sandstone (RoO)

In the lower part, resedimented pebbly to cobbly conglomerates and pebbly sandstones in very thick and amalgamated beds. In the upper part, thick to very thick-bedded and amalgamated sandstone beds. The unit has a lenticular geometry and consists of three stacked, channel-fill elements. **Chattian**.

Slope channel-fill deposits.

5.5.1.26. C.se Robella E Sandstone (RoE)

Thick- to very thick-bedded and amalgamated turbidite sandstones. The unit has a lenticular geometry.

Chattian.
Slope channel-fill deposits.

5.5.1.27. C. Chiappella Conglomerate (Ch)

Thick- to very-thick bedded and amalgamated, resedimented conglomerates and gravelly sandstones (Fig. 12a). **Chattian**.
Slope channel-fill deposits.

5.5.1.28. C. Zan Catie Sandstone (ZC)

Medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio <1. The unit has a tabular geometry. **Chattian**.
Slope channel-fill deposits.

5.5.1.29. Ravetta Sandstone (Rv)

Thick- to very thick-bedded, resedimented, and amalgamated turbidite sandstones and gravelly sandstones. **Chattian**.
Slope channel-fill deposits.

5.5.1.30. Pieve Sandstone (Pv)

In the lower part, pebbly to bouldery resedimented gravelly sandstone in very thick and amalgamated beds (Fig. 12b). In the upper part, thick-bedded, sandstone-mudstone couplets with sandstone/mudstone ratio <<1. The unit has a lenticular geometry. **Chattian**.
Slope channel-fill deposits.

5.5.1.31. Spot height 407 Sandstone (QtF)

Medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio <1. The unit has a tabular geometry. **Chattian**.
Slope channel-fill deposits.

5.5.1.32. C. Saliceto Sandstone (Saa)

Thick- to very thick-bedded and amalgamated turbidite sandstones. The unit has a lenticular geometry. **Chattian**.
Slope channel-fill deposits.

5.5.1.33. C. Saliceto Conglomerate (Sac)

In the lower part, thick to very-thick bedded and

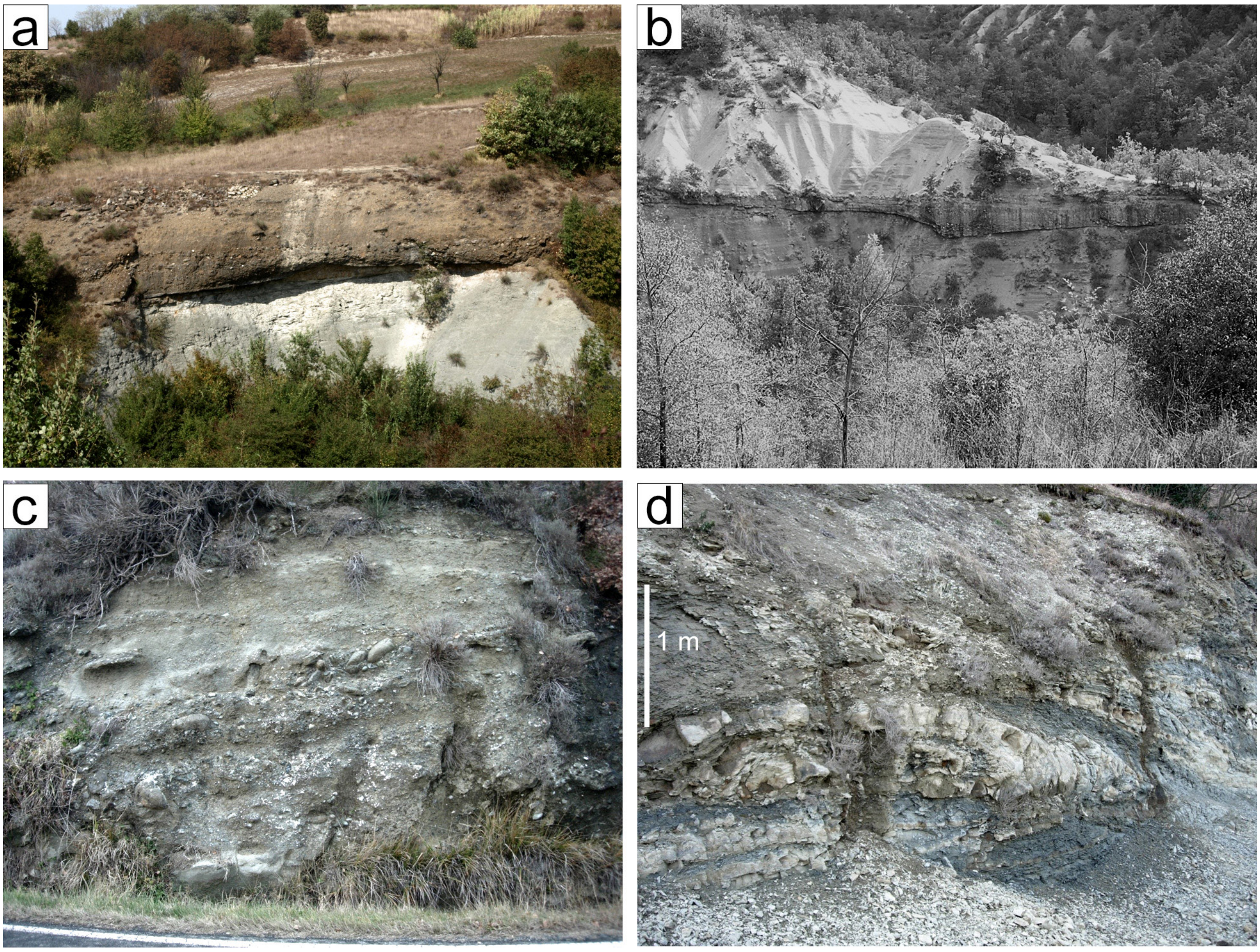

Fig. 12 - a) Sharp-based and upward-fining channelized body of C. Chiappella Conglomerate. SSE of the village of Saquana (SSE of Cartosio). b) Pieve Sandstone. Note erosional base and concentration of conglomerates in the lower-axial part of the body (SW of the village of Pieve, SSE of Cartosio). c) Grossi Conglomerate. The body contains abundant rhodoliths and fragments of coralline algae. Near Pareto. d) Recumbent fold in the slump mass S6.

amalgamated conglomerates. In the upper part, thick to very-thick bedded resedimented sandstones. The unit has a lenticular geometry. **Chattian**.

Slope channel-fill deposits.

5.5.1.34. Grossi Sandstone (Grs)

In the lower part, resedimented pebbly to cobbly gravelly sandstones in thick- to very-thick and amalgamated beds. In the upper part, thick-bedded and amalgamated sandstone beds and medium-bedded sandstone-mudstone couplets. The unit has a lenticular geometry. **Chattian**.

Slope channel-fill deposits

5.5.1.35. Grossi Conglomerate (Grc)

In the axial part, thick- to very-thick bedded and amalgamated, pebbly to bouldery conglomerate-sandstone couplets and gravelly sandstones associated with thick-bedded and amalgamated turbidite sandstones (Fig. 12c). Local inclined bedding. In places abundant rhodoliths and fragments of coralline algae and isolated blocks of crystalline rocks. In the lateral part, medium to thick-bedded laminated turbidite sandstones alternating with thin silty levels. **Chattian**.

Slope channel-levee deposits.

5.5.1.36. Spot height 474 upper Sandstone (QtG)

Thick- to very thick-bedded and amalgamated turbidite sandstones, grading upwards into medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio <<1. The unit has a lenticular geometry. **Chattian**.

Slope channel-fill deposits.

5.5.1.37. Spot height 474 lower Sandstone (QtH)

Thick- to very thick-bedded and amalgamated turbidite sandstones. The unit has a lenticular geometry. **Chattian**.

Slope channel-fill deposits.

5.5.1.38. Rio Belvicino Sandstone (RB)

Turbidite sandstones in thick to very thick and amalgamated beds, associated with sandstone/mudstone couplets in medium to thick beds. The unit has lenticular geometry. **Chattian**.

Slope channel-fill deposits.

5.5.1.39. C. Campobrioso Sandstone (Cm)

Thick- to very thick-bedded and amalgamated turbidite sandstones. **Chattian**.

Slope channel-fill deposits.

5.5.1.40. Cantalupo Sandstone (Ct)

Fine-grained turbidite sandstones in medium to thick beds with planar lamination, alternating with siltstones; sandstone/siltstone ratio <<1. **Chattian**.

Slope confined deposits

5.5.1.41. C.na Patolla Conglomerate (Pa)

Resedimented conglomerates and pebbly sandstones in thick to very thick and amalgamated beds. **Chattian**.

Slope channel-fill deposits.

5.5.1.42. M. Rosso Sandstone (MR)

Thick- to very thick-bedded and amalgamated turbidite sandstones, gravelly sandstones and pebble- to boulder-conglomerates. **Chattian**.

Slope channel-fill deposits.

5.5.1.43. Spigno Monferrato Breccia (SM)

Coarse-grained, chaotic, ophiolitic breccia with metric blocks. **Chattian**.

Submarine rockfall olistostrome derived from breakdown of a synsedimentary fault scarp.

5.5.1.44. Slump sheets (S1, ...S6)

Unconformable packages of slumped mudstones or sandstone-mudstone couplets in places intensely folded (Fig. 12d). **Chattian**.

Slump sheets.

5.5.1.45. Rodini Sandstone (Rd1, Rd2, Rd3)

Three stacked lenticular turbidite bodies made up of thick-bedded and amalgamated sandstones with local intercalations of thick- to medium-bedded sandstone-mudstone couplets. **Chattian**.

Stacked channelized slope deposits forming the composite infill of an inferred submarine valley.

5.5.1.46. C. del Bric Sandstone (DB1, DB2)

Thick- to very thick-bedded and amalgamated sandstones, pebbly sandstones and minor conglomerates. The unit is composite and consists of two lenticular sandstone bodies partially cutting each other. In detail, each unit consists, in the lower part, of pebbly sandstones and subordinate conglomerates and sandstones, and, in the middle and upper parts, of amalgamated sandstones.**Chattian**?

Channel-complex infilling a slope valley.

5.5.1.47. Spot height 524 Sandstone (QtA)

Thick- to very thick-bedded and amalgamated sandstones and pebbly sandstones, with minor intercalations of medium- to thick-bedded sandstone-mudstone couplets. **Chattian?**

Structurally confined slope deposits possibly bounded, on the NW side, by a growth fault.

5.5.1.48. C. Fossato Sandstone (CFo)

Medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio near 1. The unit has a tabular geometry. **Chattian**.

Overbank deposits.

5.5.1.49. Bergagiolo Sandstone (Be)

Medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio <1. The unit has tabular geometry. **Chattian**.

Overbank deposits.

5.5.1.50. Roboaro Sandstone (Ro)

Thick- to very thick-bedded and amalgamated turbidite sandstones, pebbly sandstones and conglomerates. The unit has a large-scale lenticular geometry. **Chattian**.

Slope valley-fill deposits.

5.5.1.51. Sorba Sandstone (So)

Thick- to very thick-bedded and amalgamated turbidite sandstones. **Chattian**.

Slope channel-fill deposits

5.5.1.52. Ovrano upper Sandstone (Ov3)

Thick- to very-thick bedded, fine-grained turbidite sandstones, generally amalgamated. In the upper part medium- to thin-bedded, alternating fine-grained turbidite sandstones and mudstones. **Upper Chattian**.

Confined slope deposits.

5.5.1.53. Ovrano middle Sandstone (Ov2)

Thick- to very-thick bedded, fine-grained turbidite sandstones, generally amalgamated. In the upper part, minor intercalations of thin- to medium-bedded, alternating fine-grained turbidite sandstones and mudstones. **Upper Chattian**.

Confined slope deposits.

5.5.1.54. Ovrano lower Sandstone (Ov1)

Alternating medium- to thick-bedded, fine-grained turbidite sandstones and bioturbated siltstones passing upwards to medium- to thin-bedded sandstone-siltstone couplets. **Upper Chattian**.

Confined slope deposits.

5.5.1.55. Molino di Mombaldone lower Sandstone (MM1)

In the lower part, thick- to very thick-bedded and amalgamated turbidite sandstones passing upwards to medium-bedded alternating turbidite sandstones and biotubated siltstones. The unit comprises three amalgamated channelized sandstone bodies. **Upper Chattian**.

Slope channel-complex deposits.

5.5.1.56. Noceto Sandstone (No)

The unit (Fig. 13 a-d) has a large-scale, wedge-shaped

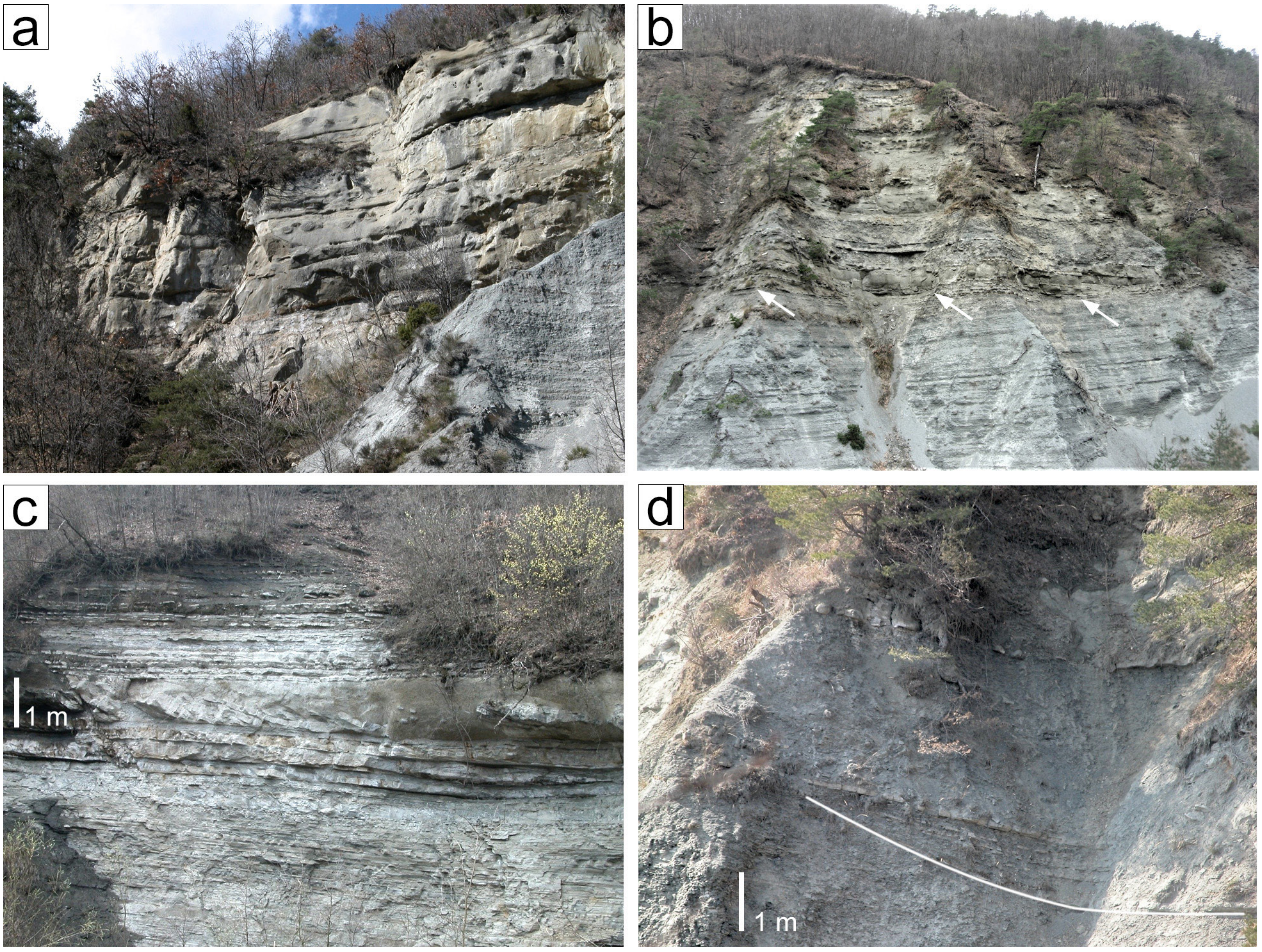

Fig. 13 - Noceto Sandstone. a) Sharp basal contact of the body. Rio degli Uvi, W of Merana. b) Onlap relationships (arrows) with the Rocchetta Fm at the base of the unit. Near the village of Valle, right side of Uzzone Valley. c) Cross-stratified set (central part of the photo) about 1m thick interbedded with tabular beds. Near the village of Valle, Uzzone Valley. d) Crevasse channel (base marked by white line). Near Erche, WSW of Merana.

geometry with gradual pinch-out to the NE and lateral extent of about 14.7 km it is bounded by the listric Rio Girosa Fault to the SW, where it reaches the maximum thickness of about 350 m (Pl. I). This unit is bounded at the base and laterally by the mudstones of the Rocchetta Fm and is capped by the Montechiaro d'Acqui Siliceous Lithozone (LS1). The basal contact is sharp (Fig. 13a), large-scale erosional, and, locally, shows onlap relationships with the Rocchetta Fm (Fig. 13b). Thick- to very thick-bedded turbidite sandstones, pebbly sandstones and rare conglomerates are usually amalgamated or alternate with thin mudstone layers. Minor intervals up to several metres thick of medium- to thin-bedded sandstone-mudstone couplets. Rare cross-bedded sets (Fig. 13c). Local crevasse channels lateral to the unit (Fig. 13d). In the basal part (Noceto - Pian del Lago areas): three pebbly to bouldery debris flow units (**NoA**). In the topmost part (Cavallini area): a chaotic debris flow unit with carbonate clasts up to several metres in diameter (**NoB**). In the upper part of the unit and only in the southwestern outcrop area: medium- to thick-bedded sandstone-mudstone couplets with sandstone/mudstone ratio >1 and rare conglomerate and paraconglomerate beds up to some metres thick. Local presence of *Ophiomorpha* in the sandstone layers. **Middle-upper Chattian**.

Deposits infilling a slope or base-of-slope half-graben bounded by a listric growth fault.

5.5.1.57. Gabutti Sandstone (Gb)

Lithologically complex unit (Fig. 14a) characterized by large-scale lenticular geometry in its axial part and more tabular lateral wings. It consists of tabular to broadly lenticular sub-units tens of metres thick. In the axial part: turbidite sandstones, locally pebbly sandstones, in thick- to very thick and amalgamated beds alternating with subordinate intervals of medium- to thick-bedded sandstone-mudstone couplets. Typically, the amalgamated sandstones make up plurimetric intervals which stand out in the erosion profile. In the lateral parts: medium- to thick-bedded, subordinately thin-bedded, sandstone-mudstone couplets and minor thick to very thick-bedded and amalgamated sandy intervals. **Chattian**.

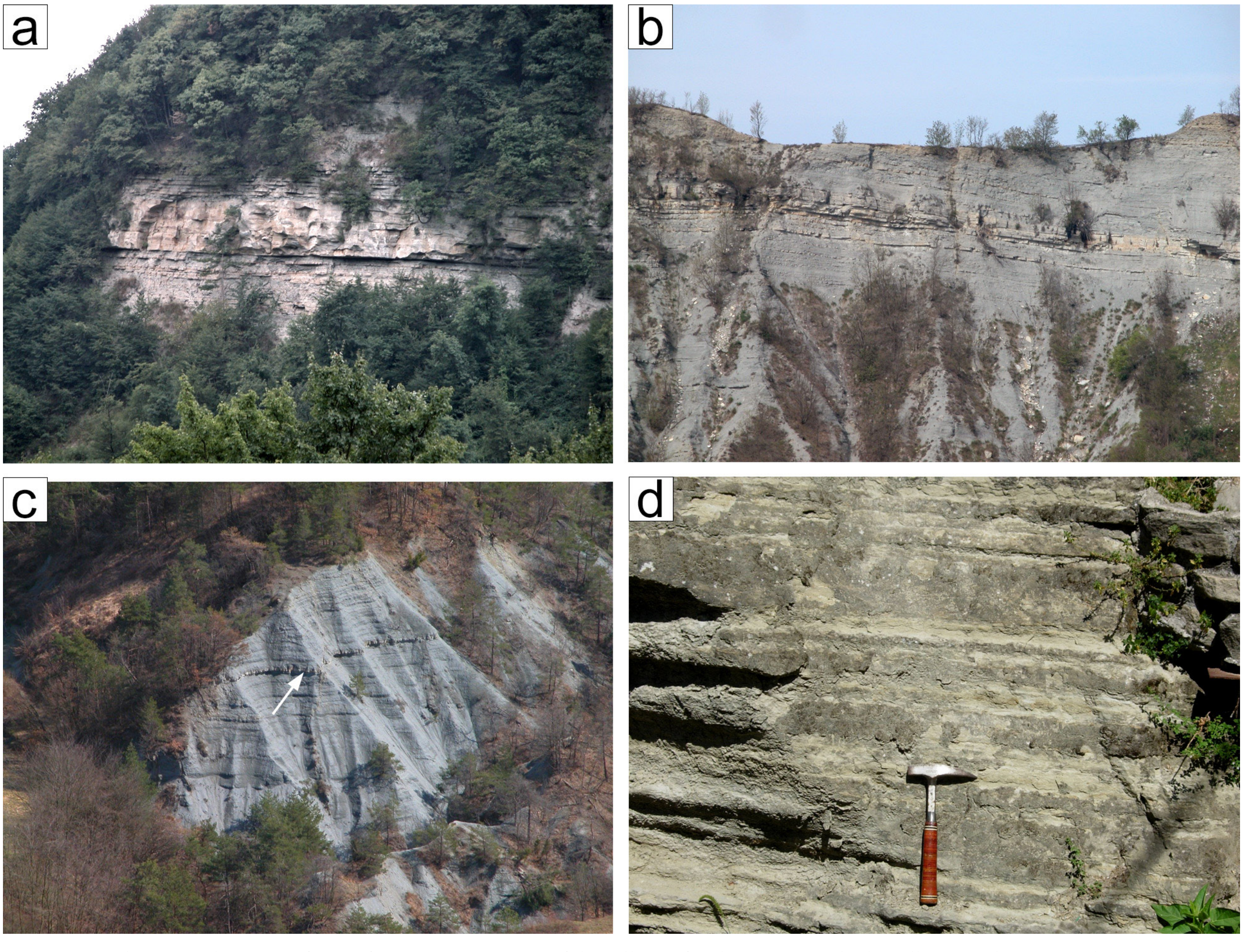

Fig. 14 - a) Gabutti Sandstone. In front of C.se Settamini (W of the village of Gabutti, Bormida di Millesimo). b) Minor channelized body. Side of the Bormida di Spigno Valley, NW of Rocchetta Cairo. c) Masseria key bed (arrow). Rio degli Uvi, near C. Ghertriti, WNW of Merana. d) Cassinelle Sandstones showing upward progressive change in the attitude of beds, related to confinement of the body in the accommodation space generated on the hanging-wall of a synsedimentary listric normal fault. Road from Cassinelle toward Rio Amione.

Slope or base-of-slope deposits inferred to be laterally confined in the axial part of a broad, base-of-slope depression and to consist of lobe/fan units, locally channelized.

5.5.1.58. Molino di Mombaldone middle Sandstone (MM2)

Thick- to very thick-bedded, fine-grained turbidite sandstones generally amalgamated with minor intercalations of thin- to medium-bedded alternating turbidite sandstones and mudstones. **Chattian**.

Confined slope deposits infilling a large-scale slump scar.

5.5.1.59. Molino di Mombaldone upper Sandstone (MM3)

Thick- to very thick-bedded, fine-grained turbidite sandstones generally amalgamated with minor intercalations of thin- to medium-bedded alternating turbidite sandstones and mudstones. **Chattian**.

Confined slope deposits infilling a large-scale slump scar.

5.5.1.60. Bric della Lasagna Sandstone (La)

In the lower part, thick-bedded, locally amalgamated, turbidite sandstones and mudstones with very high sandstone/mudstone ratio. In the upper part, alternating medium- to thin-bedded turbidite sandstones and mudstones with sandstone/mudstone ratio ≥1. **Chattian**.

Confined deposits within accommodation space generated on the hangingwall of a listric growth fault.

5.5.1.61. Pian del Lago Sandstone (PL)

In the lower part, thick- and very thick-bedded turbidite sandstones, rarely pebbly sandstones, mostly amalgamated or separated by thin mudstone intervals. In the uppermost part, thick- to medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio ≥1. **Chattian**.

Confined deposits within accommodation space generated on the hangingwall of a listric growth fault.

5.5.2. The Rocchetta Formation in the Alto Monferrato area

In the Alto Monferrato area the Rocchetta Fm includes the following members.

5.5.2.1. Cassinelle Sandstone (Cs)

The unit (Fig. 14d) has a large-scale wedge-shaped geometry and is bounded by the listric Castellamare Fault to the SW, where it reaches the maximum thickness. Medium-coarse sandstones, in thick to medium beds, locally graded and intensely bioturbated (*Thalassinoides*, *Chondrites* and *Zoophycos*). Thickness ranging from 60 to 90 metres. The unit is bounded at the base by an angular unconformity with the underlying Rocchetta mudstones, due to onlap against the hanging-wall of the fault. At the base local conglomerates (Cassinelle) and concentrations of larger foraminifers (*Nummulites fichteli, Eulepidina dilatata* and *Nephrolepidina praemarginata*). Based on this assemblage, the Geological Sheet 1: 50000 Acqui Terme attributes the unit to the SBZ22 biozone of the Rupelian. However, in our opinion the macrofaunas are reworked from the underlying Molare Sandstones. Therefore, the unit is attributed to the **Chattian**.

Resedimented fan-delta front deposits infilling a half-graben structural depression bounded by a listric normal fault.

5.5.2.2. C. Commissaria Sandstone (Com)

Medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio <1. The unit has a lenticular geometry. **Chattian**.

Slope channel-fill deposits

5.5.2.3. C. Rosario Sandstone (Rs)

Thick- to very thick-bedded turbidite sandstones, amalgamated or with thin muddy interbeds. **Chattian**.

Slope channel-fill deposits confined in a structural low.

5.5.2.4. Lerma Conglomerate (LeC)

The unit (Fig. 15 a-c) has a pronounced lenticular geometry. Thick- to very-thick bedded, amalgamated, resedimented pebbly to bouldery conglomerates and gravelly sandstones. In the upper part thick- to very-thick bedded amalgamated sandstones. Local inclined bedding (Fig. 15 a,b), wavy bedding, verticalized clast long axes, and backset bedding (Fig. 15c). Sparse rhodoliths and fragments of corallines. **Chattian**.

Inferred infill of a canyon head. Local inclined bedding is attributed to a lateral accretion process. Backset bedding and verticalization of clast long axes are thought to be genetically linked to hydraulic jumps.

5.5.2.5. Lerma Sandstone (LeS)

Turbidite sandstones in thick to very thick and amalgamated beds, graded or graded-to-laminated with planar laminae. In the upper part alternating sandstones and pelites (Fig. 15d). **Chattian**.

Slope channel-fill deposits.

5.5.2.6. C. Faghe Sandstone (Fa)

Thick- to very thick-bedded and amalgamated turbidite sandstones. **Chattian**.

Slope channel-fill deposits.

5.5.3.7. C. Monta Sandstone (Mt)

Thick- to very thick-bedded and amalgamated turbidite sandstones. The unit has a lenticular geometry. **Chattian**.

Slope channel-fill deposits.

5.5.2.8. Spot height 234 Sandstone (QtC)

Medium- to thick-bedded, locally amalgamated, turbidite sandstones with interbedded mudstones. Sandstone/mudstone ratio <1. **Chattian**.

Slope channel-fill deposits.

5.5.2.9. C. Rocchetta Sandstone (Rt)

Medium-bedded sandstone-mudstone couplets with

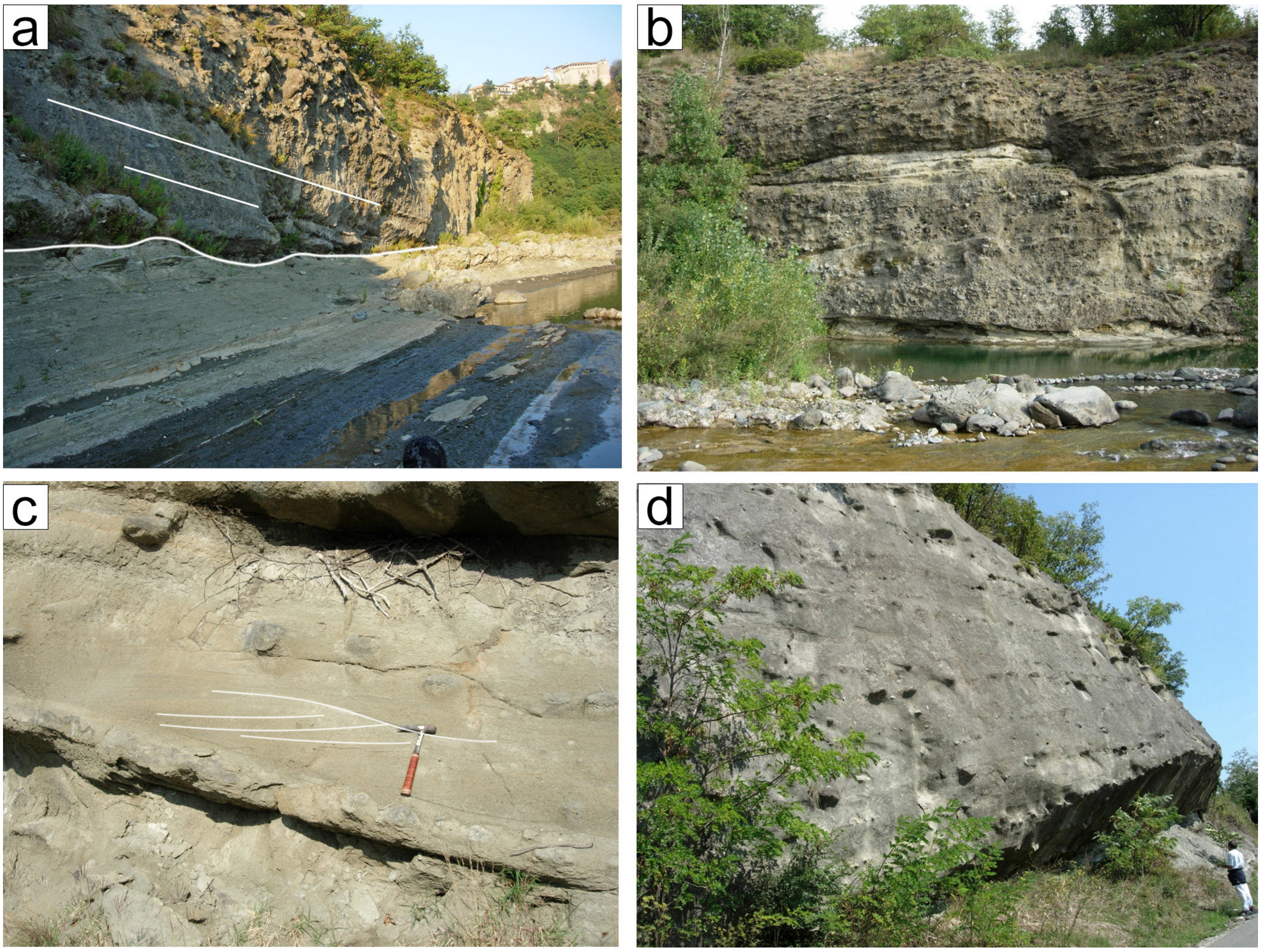

Fig. 15 - a) - c) Lerma Conglomerate (outcrops along the T. Piota, close to the village of Lerma). a), b) The erosionally-based body shows inclined bedding with respect to the underlying deposits of the Rocchetta Fm. c) Backset bedding (flow toward right). d) Lerma Sandstone (NW of the village of Lerma).

sandstone/mudstone ratio <1. The unit has a tabular geometry. **Chattian**.

Slope channel-fill deposits.

5.5.3. The Rocchetta Formation in the Borbera-Grue area

In the Borbera-Grue area the Rocchetta Fm includes the following members.

5.5.3.1. Mulino di Sopra Conglomerate (MSC)

Thick-bedded and amalgamated, resedimented conglomerates, gravelly sandstones and sandstones. In the uppermost part thick-bedded and amalgamated sandstones. **Chattian**.

Slope channel-fill deposits.

5.5.3.2. Spot height 350 Conglomerate (QtO)

Thick-bedded and amalgamated, resedimented conglomerates and gravelly sandstones. **Chattian**.

Slope channel-fill deposits.

5.5.3.3. Fontana Conglomerate (Fn)

Thick-bedded and amalgamated, resedimented conglomerates and gravelly sandstones. **Chattian**.

Slope channel-fill deposits.

5.5.3.4. E Grondona Sandstone (GRE)

Turbidite sandstones in thick and amalgamated beds with minor conglomerates in the basal part. **Chattian**.

Slope channel-fill deposits.

5.5.3.5. C. la Riva Sandstone (LR)

Turbidite sandstones in thick and amalgamated beds or separated by thin muddy interbeds and subordinate thick to- medium bedded sandstone-mudstone couplets. **Chattian**.

Slope deposits infilling a submarine valley.

5.5.3.6. W Grondona Sandstone (GRW)

Turbidite sandstones in thick and amalgamated beds, or separated by thin muddy interbeds, and subordinate thick to medium-bedded sandstone-mudstone couplets. **Chattian**.

Slope deposits infilling a submarine valley.

5.5.3.7. Garbagna Sandstone (Gr)

Lenticular unit of plurikilometric lateral extent, made up of turbidite sandstones in thick and amalgamated beds, or separated by thin muddy interbeds, and subordinate thick to- medium-bedded sandstone-mudstone couplets. **Chattian**.

Slope deposits infilling a submarine valley.

5.5.3.8. Variano Sandstone (Va)

Lenticular unit of plurikilometric lateral extent, made up of turbidite sandstones in thick to very thick and amalgamated beds, graded or graded-to-laminated with planar laminae. In the upper part alternating sandstones and mudstones. **Chattian**.

Base-of-slope deposits, infilling a broad submarine valley.

5.6. MONTECHIARO D'ACQUI SILICEOUS LITHOZONE (LS1)

This marker unit (Fig. 16 a-d) shows regional extent and consists either of a single bedset (eastern area) or a group of bedsets separated by turbidite packages (south-western area) (Fig. 3). It crops out from the Tanaro Valley (outside the study area) to the Scrivia Valley where it is truncated by the pre-Langhian unconformity. In the Alto Monferrato area, between the Caliogna and Lemme valleys, the unit has been eroded by the transgressive unconformity at the base of the lower Burdigalian Visone Limestone and, more to the East, at the base of the middle Burdigalian Lerma Glaucony. The unit consists of silicified intervals, 2-10 m thick, which become thinner- and finer-grained upwards in the stratigraphic succession, alternating with homogeneous marly intervals, 2-6 m thick. The former packages (Fig. 16 a,b) consist of partly silicified, hard and tough, medium- to very fine-grained sandstone or siltstone beds generally 2-8 cm thick, typically partitioning into parallelepiped-shaped pieces with sharp corners, weathering to red-brown, with sharp bases and tops, and planar to oblique lamination (climbing ripples, form-set ripple trains or starved, discontinuous ripples) with common mud

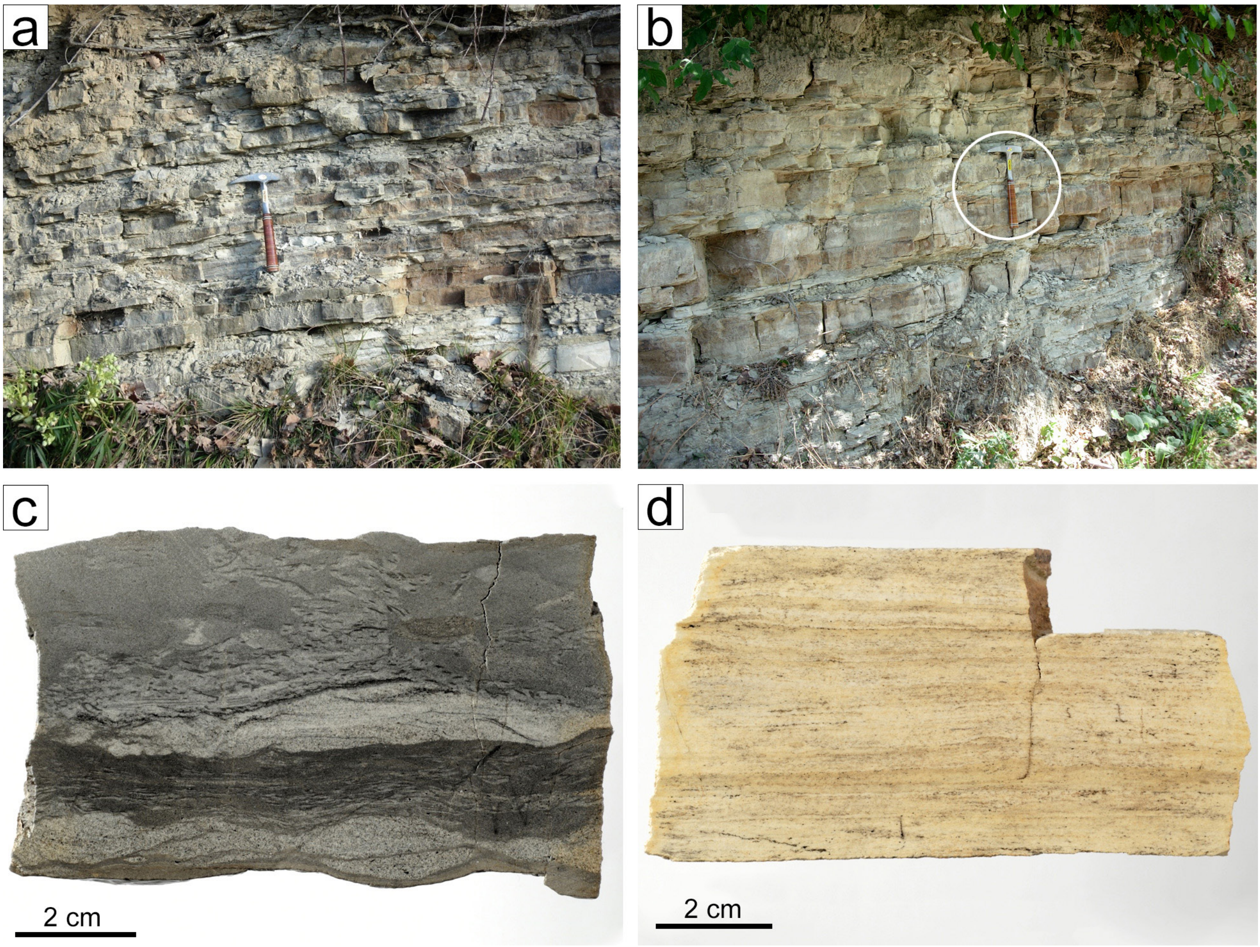

Fig. 16 - The Montechiaro d'Acqui Siliceous Lithozone LS1. a) Partly silicified bedset. Road to C.se La Pareta-SSW of Scaletta Uzzone. b) Detail (encircled hammer for scale. Case Mevie. c) LS1a: Cut and polished slab. In the lower part: wavy sandstone layer with sharp base, internal mud drapes and sharp and remoulded top, capped by bioturbated (*Phycosiphon*) siltstone; in the central-upper part: ripple-laminated sandstone layer with internal erosional surfaces (reactivation surfaces) overlain by thoroughly bioturbated (*Phycosiphon*) siltstone and fine sandstone. Rio Verosola, E of Scaletta Uzzone. d) LS1b, siliceous laminite (cut and polished slab). Road Valle-Gottasecca, WNW of Valle.

drapes, alternating with thin grey siltstone interbeds heavily bioturbated by *Phycosiphon* (Fig. 16c); soft/fissile to hard/diagenized, whitish, parallel-laminated siliceous laminites (Fig. 16d) 1-10 cm thick are locally intercalated. The fossil content is represented by pteropods, radiolarians, sponge spicules, small thin-shelled bivalves, foraminifers and calcareous nannofossils. Plant remains are locally abundant. At the head of Rio della Rocchetta (WNW of Spigno Monferrato) these lithologies grade into time-equivalent homogeneous marls **(LS1d)**. Locally (head of Ovrano Valley) the siliceous lithozone is more calcareous. Medium- to thick-bedded, resedimented glauconitic biocalcarenites **(LS1e)** are locally present at the base of the unit (Molino d'Ovrano). SW of San Massimo the siliceous horizon subdivides into three sub-units located atop turbidite formations laid down in a base-of-slope to basinal setting (Ghibaudo et al., 2014), respectively named: Bric Baraccone Siliceous Lithozone **(LS1a)**, lying on top of the Noceto Sandstone, C. Ranari Siliceous Lithozone **(LS1b)**, located atop the Poggiolo Formation, and Castelletto Uzzone Soprano Siliceous Lithozone **(LS1c)**, located atop the Scaletta Uzzone Formation. **Aquitanian (MNN1c-MNN1d p.p.)**.

Slope or base-of-slope hemipelagites, including deposits laid down by both turbidity and hyperpycnal flows, and siliceous laminites presumably derived from original diatomaceous deposits.

5.7. POGGIOLO FORMATION (PO)

Thin- to medium-bedded, alternating turbidite sandstones and mudstones (Fig. 17a). In the lower part medium- to thick-bedded alternating sandstones and mudstones with sandstone/mudstone ratio ≥1. A deep-sea trace fossil assemblage visible atop sandstone layers includes abundant *Scolicia* (Fig. 17c), *Zoophycos* (Fig. 17b), *Planolites,* and rare ?*Phytoderma* (Fig. 17d). The traces were produced by irregular echinoids, crustaceans and "worms" which colonized sandstone event beds. The formation comprises the members described below. **Lower Aquitanian (MNN1d p.p.)**.

Deposits infilling a slope or base-of-slope structural basin.

5.7.1. Rio Porcavio Sandstone (RP)

Thick-bedded and amalgamated, turbidite sandstones locally associated with medium- to thick-bedded sandstone-mudstone couplets and rare debris flow and

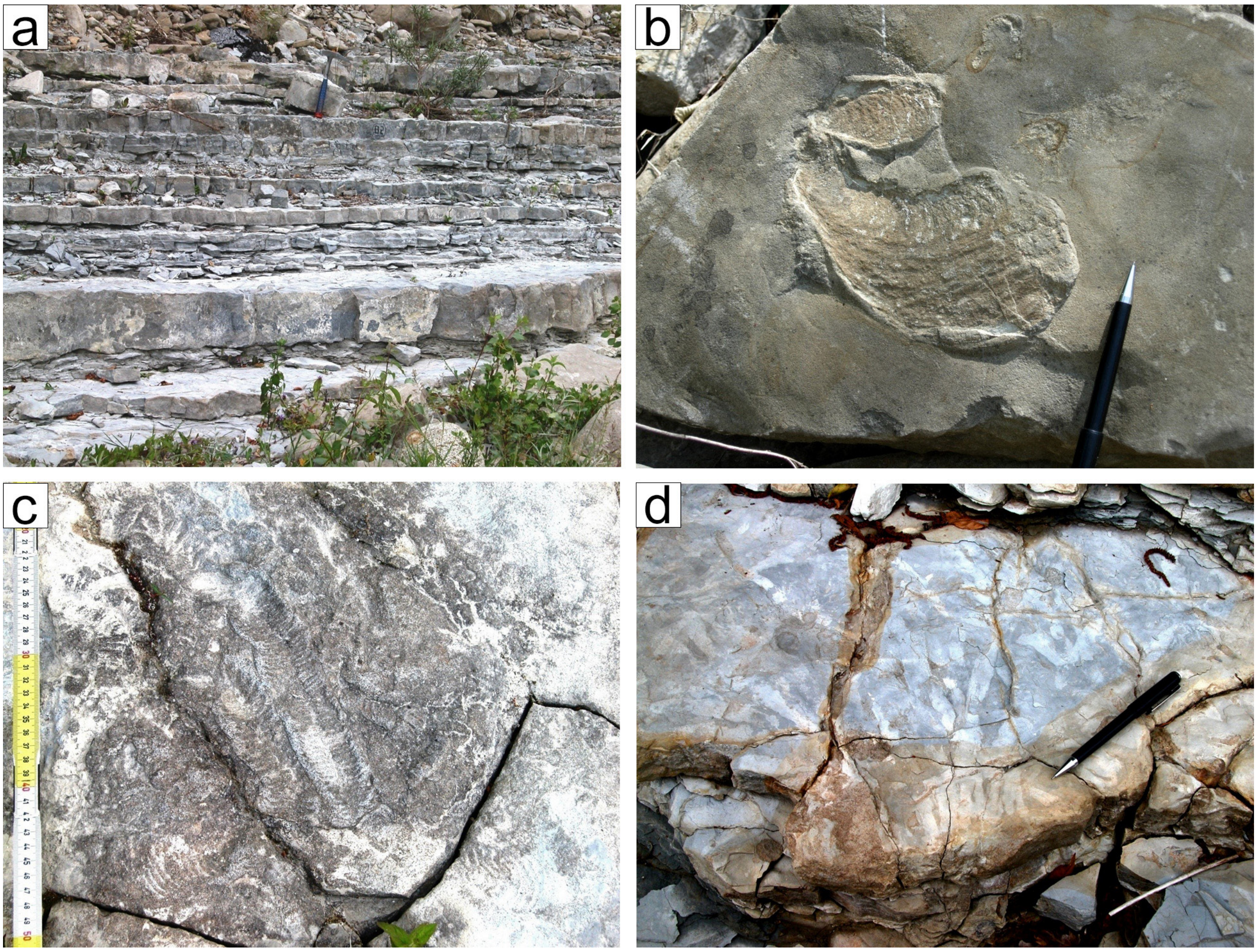

Fig. 17 - Poggiolo Fm (NW of Scaletta Uzzone, in front of Case Demanio, along the bed of the Uzzone River. a) Detail of the stratification. b)-d) Upper surfaces of beds showing intense bioturbation. b) *Zoophycos*. c) *Scolicia*. d) ?*Phymatoderma*.

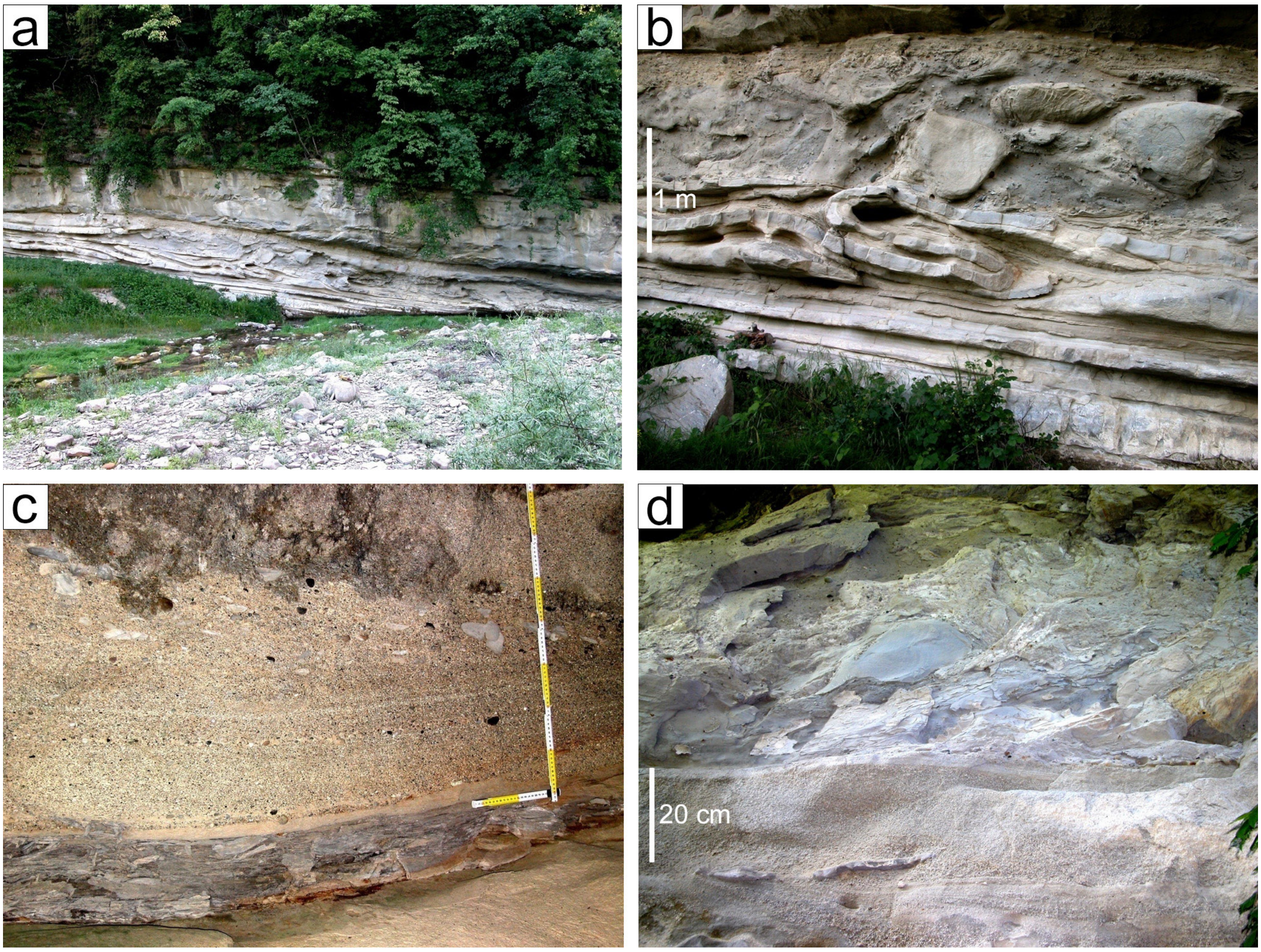

Fig. 18 - Rio Porcavio Sandstone a) A folded slump in the lower part is overlain by a thick, amalgamated package. Left side of Uzzone Valley, SSW of Valentini. b) Detail showing recumbent folds in the slumped mass, passing upwards into a coarse debrite with large intraformational blocks. c) Coarse and microconglomeratic sandstone with concave-up base, repeated grading and clay chips. Bottom of Rio Porcavio Valley. d) Graded bed overlain by pebbly and microconglomeratic sandstone with imbricated, hard and soft intraformational clasts. Bottom of Rio Porcavio Valley.

slumped units up to some metres thick (Fig. 18 a,b). The unit has an overall wedge-shaped geometry. In the Rio Porcavio section two sandstone bodies, separated by a thin-bedded interval 10 m thick, are recognizable. The lower body has a minimum observable thickness of about 20 m and consists of amalgamated sandstones, locally wavy (Fig. 18c) and layers with abundant soft and hard intraformational clasts (Fig. 18d), whereas the upper body has an overall thickness of about 80 m and is characterized by cycles thinning- and fining-upwards. **Lower Aquitanian (MNN1d p.p.)**.

Deposits confined within a slope or base-of-slope structural basin.

5.7.2. C. Carloni Sandstone (Cr)

Thick-bedded, locally amalgamated, alternating turbidite sandstones and mudstones with sandstone/mudstone ratio >1. In the upper part medium-bedded sandstone-mudstone couplets with sandstone/mudstone ratio >1. The unit has a broad lenticular geometry. **Lower Aquitanian (MNN1d p.p.)**.

Deposits confined within a slope or base-of-slope structural basin.

5.8. SCALETTA UZZONE FORMATION (SU)

Thick- to very thick-bedded bioturbated turbidite sandstones, pebbly sandstones and rare conglomerates, mostly amalgamated or separated by thin mudstone intervals. Local intercalations of thick- to medium-bedded alternating sandstones and mudstones with sandstone/mudstone ratio >1. **Middle Aquitanian (MNN1d p.p.)**.

Deposits infilling a slope or base-of-slope basin. Possible lobe/fan deposits locally channelized.

5.9. VISONE LIMESTONE (VI)

The unit is restricted to the Acqui Terme-Visone area (Acqui Terme Horst) on the western side of the Alto Monferrato High, where it is about 22 m thick. Toward S and E it decreases in thickness, passing laterally to time-equivalent outer-shelf bioturbated marls of the Montechiaro d'Acqui Fm; to the west, in the Langhe area, it grades into slope hemipelagites of the same formation (see Fig. 39). Available subsurface data indicate that the unit thickens gradually toward the N. The unit overlies the Rocchetta Fm by means of an erosional angular unconformity marking a stratigraphic gap. The formation has been described in detail by d'Atri (1990a). The lowermost deposits consist of about 2 metres of massive, clay-rich, matrix-supported calcirudite with a basal lag of rare small serpentinite pebbles and more common clasts of the Rocchetta marls, associated with larger foraminifers and skeletal remains (*Operculina*, *Amphistegina*, bryozoans, pectinids, *Echinolampas*, and scattered rhodoliths). The following deposits consist of foramol ramp carbonates made up of biocalcarenites and biocalcirudites richly fossiliferous (larger foraminifers, coralline algae, echinoids, bivalves, balanids, bryozoans and serpulids), characterized by scarce matrix and pervasive dissolution seams resulting in a pseudostratification with layers of up to decimetric thickness. The unit shows an internal erosional discontinuity draped by a coarse lag of skeletal and plant remains, exotic pebbles and soil clasts. This unconformity separates a lower sub-unit with an *Operculina* assemblage from an upper sub-unit characterized by an *Amphistegina* and *Miogypsina* assemblage, sharp increase in the abundance of coralline algae, and local medium-scale cross bedding; this sub-unit extends over a slightly larger area than the underlying one. A topmost layer with glauconitized bioclasts grades transitionally upwards to the Visone Glaucony. **Lower Burdigalian (MNN2b)**.

Carbonate ramp deposits with a heterozoan assemblage. A shallower, higher-energy setting is indicated in the upper sub-unit by local cross-bedding and more winnowed texture. The original depositional geometry of the unit is supposed to have been lobate shaped in plan view.

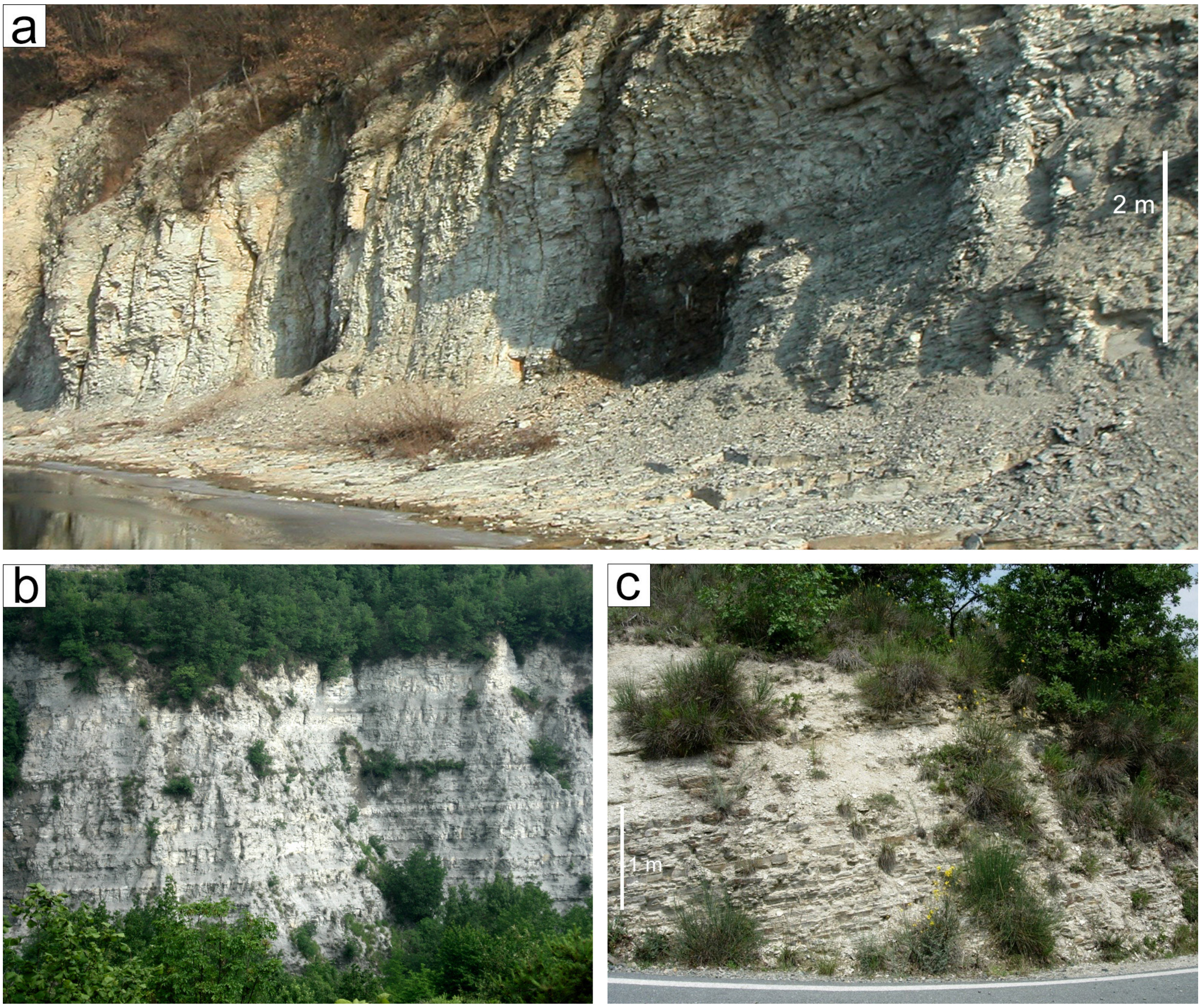

Fig. 19 - Montechiaro d'Acqui Formation. a) Hemipelagic marls in locality C.na sulla Rocca, along the Erro stream (from the Explanatory Notes of the 1: 50000 Geologic Sheet Acqui Terme, courtesy of A. d'Atri). b) metric-scale cyclicity in the formation. Scarp about 12 metres high in front of the village of Denice. c) Siliceous package at the top of the formation (NE of Montechiaro).

5.10. MONTECHIARO D'ACQUI FORMATION (MC)

The Montechiaro d'Acqui Fm is a heterogeneous unit, consisting of medium-bedded homogeneous marls (Fig. 19a), with rare intercalations of siltstones and fine-grained sandstones in thin to very thin beds. In the Langhe area a metric-scale cyclical pattern is locally evident (Fig. 19b), with marly intervals alternating with more calcareous lithologies. Wood remains, sometimes bored by *Teredo*, are locally present, particularly in the upper part. In the uppermost part two metric intervals (not represented in the enclosed geological map), consisting of competent silica-rich siltstones looking like the siliceous intervals of the underlying Montechiaro d'Acqui Siliceous Lithozone, with silica-rich beds rhythmically alternating with thin- to medium-bedded mudstones are present (Fig. 19c).

In the Langhe area the formation is bounded by the Siliceous Lithozone of Montechiaro d'Acqui (LS1) at the base and the Serole Fm at the top. In this area the upper contact of the unit is a composite erosional unconformity of pluri-hectometric extent, resulting from the coalescence of several slump scars (cf. Pl. I, Figs. 3, 39, 41 and section 6.2.6.). Along this composite erosional surface variable parts of the Montechiaro d'Acqui Fm have been removed, and only locally the original thickness is preserved. The formation extends with continuity in the Langhe Sub-basin where it is represented by slope hemipelagic mudstones up to 70-80 m thick, with planktonic and benthic foraminifers, nannofossils and radiolarians, enclosing resedimented biocalcarenitic and siliciclastic bodies with lenticular or wedge-shaped geometry. In the Acqui-Visone area the formation grades laterally into the foramol deposits of the Visone Limestone; south of this area (e.g. near Mt Capriolo) the unit is locally present as bioturbated outer shelf marls up to 8 m thick, locally with sparse glauconite. East of Visone-Acqui area, and up to the Lemme valley, the Montechiaro d'Acqui Fm is missing beneath the transgressive unconformity at the base of the middle Burdigalian Lerma Glaucony, re-appears between Carrosio and Vignole Borbera, where it is represented by outer-shelf bioturbated silty mudstones up to 40 m thick encasing resedimented biocalcarenitic and siliciclastic bodies, and is truncated farther east by the pre-Langhian unconformity. **Uppermost Aquitanian-middle Burdigalian (MNN2a p.p.-MNN3a p.p.)**.

Hemipelagic slope and outer shelf deposits.

5.10.1. The Montechiaro d'Acqui Formation in the Langhe area

In the Langhe area the Montechiaro d'Acqui Fm includes the following members.

5.10.1.1. Rio della Chiesa Glaucony (GRC)

Heavily bioturbated, hemipelagic silty mudstones, up to 1 metre thick, characterized by very abundant authigenic glauconitic grains both concentrated inside the burrows and dispersed. This level has been recognized only in the Langhe area. Most representative outcrops are in the Rio della Chiesa, Rio della Torre and Vallone valleys, NE of Contrada along the road near Campo Asinaro, along the trail descending SE of Gottasecca, and near Morozzo and Fornaci Sottane. **Uppermost Aquitanian? (MNN2a p.p.?)**.

Condensed interval.

5.10.1.2. C. Mevie Calcarenite (Me)

Two resedimented carbonate beds with coralline red algae, pelecypods, echinoids, separated by some metres of hemipelagic mudstones (Fig. 20a). The lower bed (**Me1**), is a few decimetres thick and medium- to fine-grained biocalcarenite. The upper one (**Me2**) is up to over 2 m thick and locally calciruditic. **Lower Burdigalian (MNN2b p.p.)**.

Unconfined slope deposits.

5.10.1.3. Pian Bruno Calcarenite (Pb)

Medium- to thick-bedded, resedimented biocalcirudites and biocalcarenites with coralline algae, pelecypods, echinoids. The unit has a wedge-shaped geometry. **Lower Burdigalian (MNN2b p.p.)**.

Slope or base-of-slope deposits confined within a half-graben

5.10.1.4. C. Poggi Calcarenite (Pg)

Medium- to thick-bedded, resedimented biocalcirudites and biocalcarenites with coralline red algae, pelecypods, echinoids (**Pg_C**). In the lower part fine-grained, medium-bedded, glauconitic hybrid arenites rich in planktonic foraminifers (**Pg_G**). **Lower Burdigalian (MNN2b p.p.)**.

Channelized slope or base-of-slope deposits.

5.10.1.5. Cianazzo Calcarenite (CI)

Medium- to thick-bedded, resedimented biocalcirudites and biocalcarenites with coralline algae, pelecypods, echinoids. **Lower Burdigalian (MNN2b p.p.)**.

Unconfined slope deposits.

5.10.1.6. C. del Tasso Calcarenite (Ts)

Medium- to thick-bedded, resedimented biocalcirudites and biocalcarenites with coralline algae, pelecypods, echinoids. **Lower Burdigalian (MNN2b p.p.)**.

Unconfined slope deposits.

5.10.1.7. Rio Caliogna Calcarenite (Cl)

Medium- to thick-bedded, resedimented biocalcirudites and biocalcarenites with coralline algae, pelecypods, echinoids. **Lower Burdigalian (MNN2b p.p.)**.

Unconfined slope deposits.

5.10.1.8. Spot height 483 Sandstone (QtB)

Thin- to medium-bedded turbidite sandstones and mudstones with sandstone/mudstone ratio near 1. **Lower Burdigalian (MNN2b p.p.)**.

Slope deposits confined within a structural depression.

5.10.1.9. C. Mazzurini Sandstone (Ma)

Thick- to very thick-bedded resedimented sandstones and conglomerates, generally amalgamated, containing

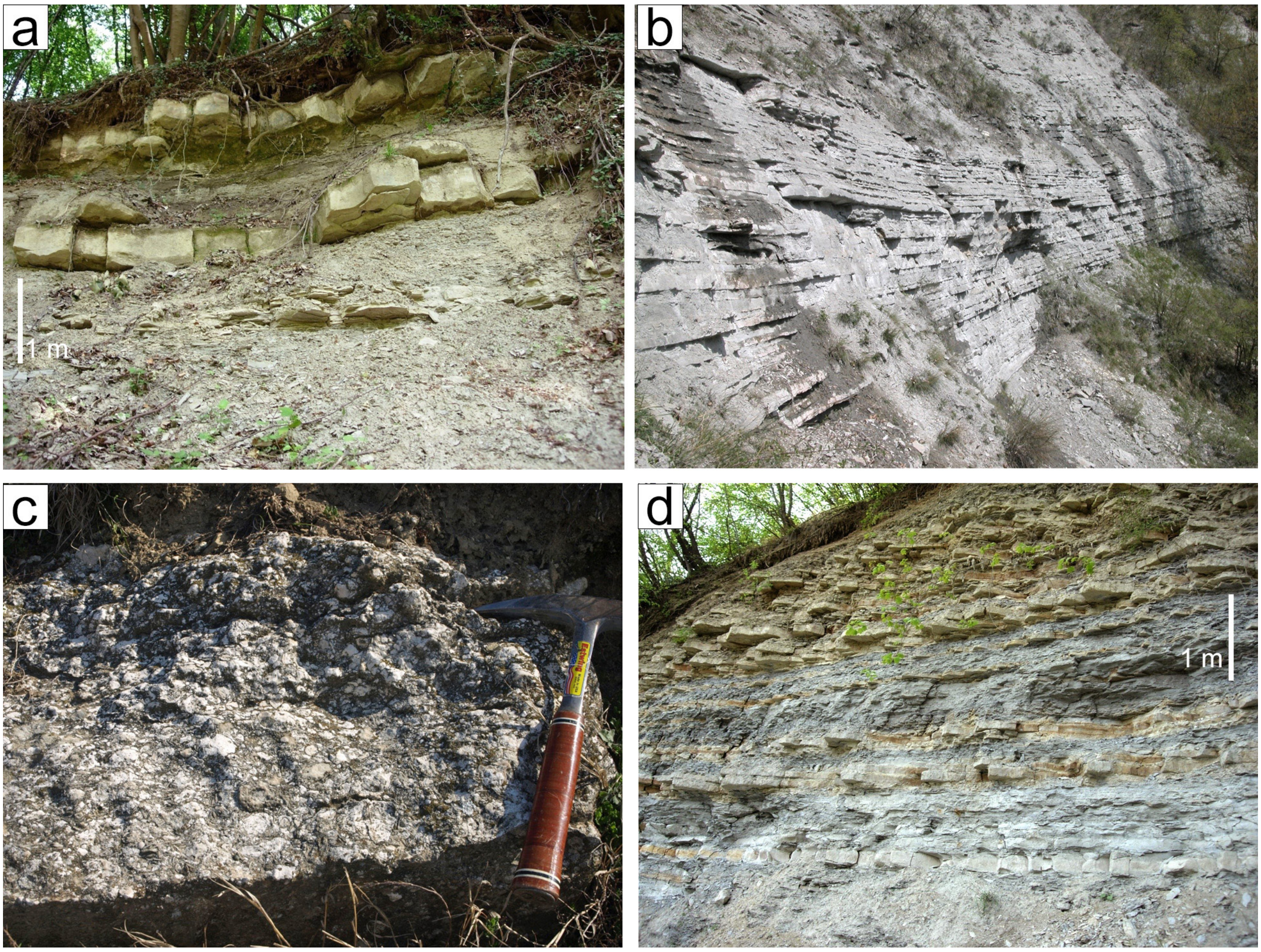

Fig. 20 - a) C. Mevie Calcarenite. Near the head of the Rio Porcavio Valley, E of Case Valentin. b) Rio della Chiesa Lower Sandstone (Rio della Chiesa Valley). c) Rhodolith conglomerate in the Chiappino Sandstone (Bric Cardinelle). d) Serole Formation: facies displaying higher than average sandstone/mudstone ratio. Near C. Ronzimero (NNE of the village of Poggiolo, Uzzone Valley).

in the intermediate and upper parts abundant bioclasts (coralline algae, pelecypods, echinoids). In the lower part very thick-bedded, pebbly mudstone levels are common. Sandstone beds are locally crossed by *Ophiomorpha.* On the left side of the Rio Bazzi valley two carbonate slide sheets (**Ma1**) are intercalated in the lower part of the succession. The unit has a large-scale wedge-shaped geometry. **Lower Burdigalian (MNN2b p.p.)**.

Deposits infilling a slope or base-of-slope half-graben.

5.10.1.10. Rio della Chiesa upper Sandstone (RC2)

Thick- to very-thick bedded alternating turbidite sandstones and mudstones passing upwards to medium- to thick-bedded alternating sandstones and mudstones. Sandstone/mudstone ratio always >1. In the lower part a debris flow layer up to 4 m thick. **Lower Burdigalian (MNN2b p.p.)**.

Deposits presumably confined within a slope or base-of-slope structural depression.

5.10.1.11. Rio della Chiesa lower Sandstone (RC1)

Turbidite unit of fine-grained, medium- to thin-bedded sandstone-siltstone couplets with sandstone/siltstone ratio ≤1 (Fig. 20b). Typically, the sandstone beds range in thickness from 5 to 20 cm. The siltstones have similar thicknesses and are commonly bioturbated. **Lower Burdigalian (MNN2b p.p.)**.

Deposits presumably confined within a slope or base-of-slope structural depression.

5.10.1.12. C. Ciappellano Sandstone (Ci)

Thin- to medium-bedded alternating turbidite sandstone and mudstone with sandstone/mudstone ratio <1. **Lower Burdigalian (MNN2b p.p.)**.

Deposits presumably confined within a slope or base-of-slope structural depression.

5.10.2. The Montechiaro d'Acqui Formation in the Alto Monferrato area

In the Alto Monferrato area the Montechiaro d'Acqui Formation includes the following members.

5.10.2.1. Chiappino Sandstone (Cp)

Turbidite sandstones, gravelly sandstones and conglomerates, locally rich in rhodoliths (Fig. 20c), in medium to very thick strata. **Lower Burdigalian (MNN 2b p.p.)**.

Slope channel-fill deposits.

5.10.2.2. Carrosio Sandstone (Car)

Diffusely bioturbated medium- and coarse-grained sandstones in medium- to thick-bedded (10-60 cm), poorly distinct strata. Planar and locally hummocky lamination, in places large clay chips and isolated pebbles and cobbles up to 10 cm long. Organization in parasequences thickening and coarsening upwards. Overall lenticular geometry with erosional base. **Lower Burdigalian (MNN2b p.p.)**.

Delta-front sediments infilling a submarine valley

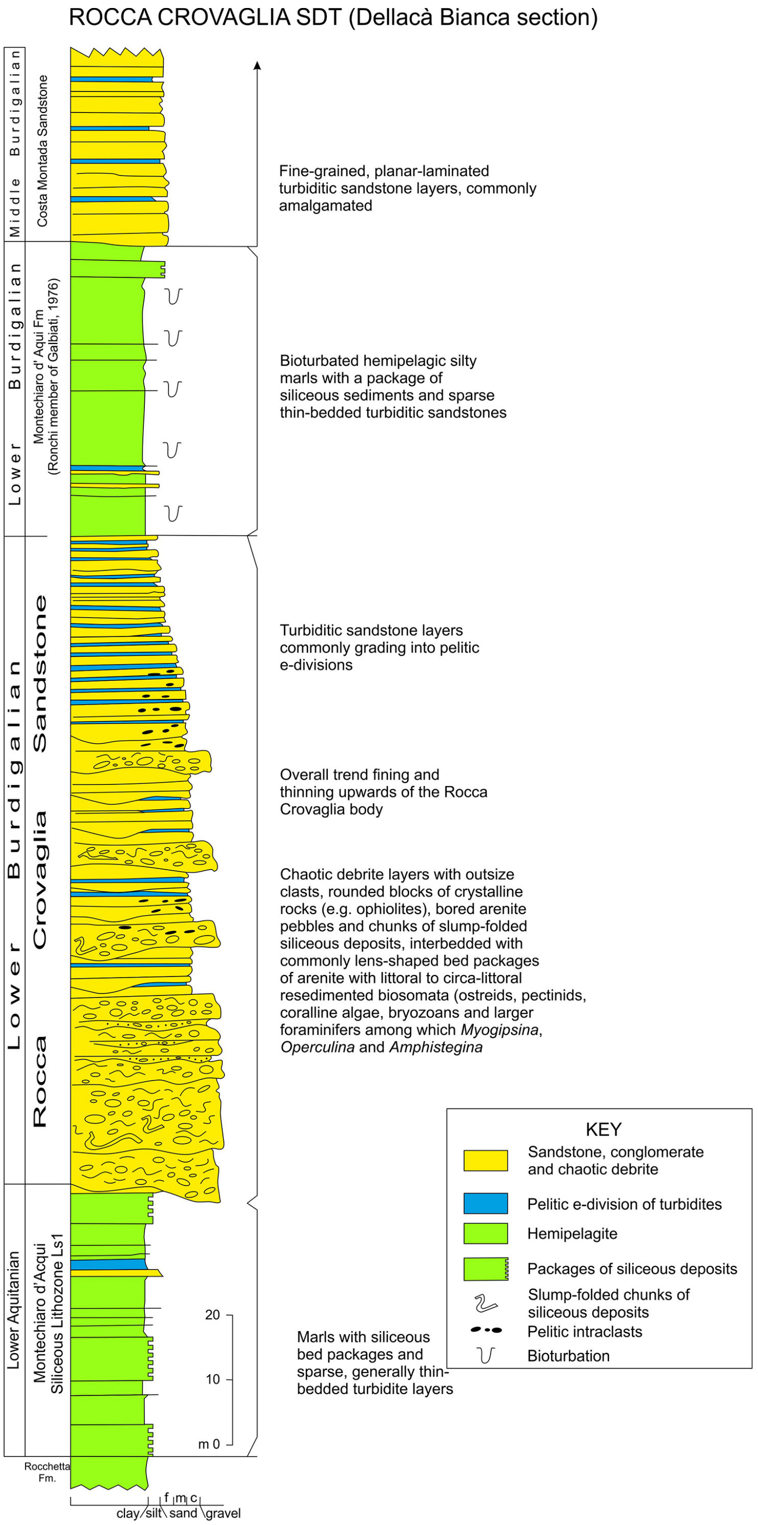

Fig. 21 - Stratigraphic log of the Rocca Crovaglia Sandstone (Dellacà Bianca section, WSW of the village of Vocemola, Scrivia Valley).

5.10.2.3. Rocca Crovaglia Sandstone (RC)

Body showing marked lenticular geometry, with erosional base truncating the horizon LS1 and locally also the upper marls of the Rocchetta Fm (Fig. 21). In the lower part it mainly consists of paraconglomerates with abundant muddy-sandy matrix and large blocks of crystalline rocks, in thick to very thick and amalgamated layers, associated with chaotic slumped masses, intraformational metre-sized clasts of marls, as well as clasts of laminated and intensely folded siliceous sediments derived from the underlying Montechiaro d'Acqui Siliceous Lithozone (LS1). Bored pebbles and resedimented littoral/circalittoral biosomata (ostreids, pectinids, coralline algae and bryozoans, associated with larger foraminifers, among which *Miogypsina*, *Operculina* and *Amphistegina*), are common. The body shows a stratal organization with upward fining and thinning trend. Specifically, in the lower part, turbidites, associated with debrites, are represented by thick to very thick and amalgamated, locally lenticular coarse- to medium-grained sandstone beds with thick planar lamination; in the upper part of the body the sandstones become progressively finer-grained with common planar lamination in layers 20-30 cm thick with thin muddy interbeds. **Lower Burdigalian (MNN2b p.p.)**.

Infill of a submarine valley.

5.10.2.4. Spot height 326 Sandstone (QtN)

Thick- to very thick-bedded and amalgamated turbidite sandstones. **Lower Burdigalian (MNN2b p.p.)**.

Slope channel-fill deposits

5.11. SEROLE FORMATION (SE)

The Serole Fm is only represented in the Langhe-Sub-basin. The unit has a wedge-shaped geometry tapering NE-wards and includes several sandstone bodies both on large (kilometric) and medium (hectometric) scale. Moreover, in the study area the unit is bounded at the base by some large-scale composite slump scars in the Denice, Bric Torrione, Case Rocchino and Uzzone Valley areas (Pls. I and II, section 6.2.6.). The Serole Fm grades upwards to the Cortemilia Formation. The unit consists of monotonous, fine-grained, alternating turbidite sandstones and mudstones (Fig. 20d) with sandstone/mudstone ratio <<1. The sandy divisions of turbidite beds are usually comprised between 5 and 20 cm. Locally, in the lower part, alternating turbidite siltstones and mudstones with siltstone/mudstone ratio <<1 are present. The muddy divisions of turbidite beds are usually comprised between 3 and 10 cm. In the lowermost part, rare decimetre-thick hemipelagic mudstone intercalations are present. The formation comprises the members described below. **Middle Burdigalian (MNN3a p.p.-MNN3b p.p.)**.

Prodelta slope deposits (possible channel-levee deposits).

5.11.1. C. Zabocci Sandstone (CZ)

Thick-bedded and amalgamated turbidite sandstones passing upwards to medium- to thick-bedded, alternating sandstones and mudstones with sandstone/mudstone ratio ≥1. The unit has a slightly lenticular geometry. **Middle Burdigalian (MNN3a?)**.

Slope or base-of-slope deposits probably channelized.

5.11.2. Bric Torrione Sandstone (BT)

Medium- to thick-bedded, alternating turbidite sandstones and mudstones with very high sandstone/mudstone ratio. In the middle and lower parts medium- to thick-bedded and amalgamated sandstone beds are present. **Middle Burdigalian (MNN3a?)**.

Deposits infilling the lower part of a large-scale slump scar.

5.11.3. Piantivello Sandstone (Pt)

In the lower part turbidite sandstones, pebbly sandstones and minor pebbly mudstones in thick-bedded and amalgamated beds. In the upper part medium- to thick-bedded, alternating turbidite sandstones and mudstones with sandstone/mudstone ratio >1. The unit has a large-scale lenticular geometry. **Middle Burdigalian (MNN3a p.p.)**.

Slope or base-of-slope valley-fill deposits.

5.11.4. Vignazze Sandstone (Ve)

Alternating turbidite sandstones and mudstone in thick and very thick beds with sandstone/mudstone ratio >1. **Middle Burdigalian (MNN3a)**.

Deposits infilling the lower part of a slump scar.

5.11.5. Rio della Torre lower Sandstone (RT1)

Fine-grained, medium-bedded, alternating turbidite sandstones and mudstones with sandstone/mudstone ratio ≥1. In the lower part medium- to thick-bedded and amalgamated, fine-grained sandstone beds and subordinate debris flow units. Local presence of *Zoophicos* and *Thalassinoides* (Fig. 22a). The unit has a slightly lenticular geometry and pinches-out depositionally towards SE. **Middle Burdigalian (MNN3a)**.

Slope or base-of-slope non-channelized sandstone lobe confined on the SE side by a growing anticline.

5.11.6. Rio della Torre upper Sandstone (RT2)

Thick- to medium-bedded, alternating turbidite sandstones and mudstones with sandstone/mudstone ratio >1. In the lower part, thick-bedded and amalgamated sandstones and chaotic, metre-thick, slumped units are present. The unit has a slightly lenticular geometry and pinches-out depositionally towards SE. **Middle Burdigalian (MNN3b)**.

Slope or base-of-slope non-channelized sandstone lobe confined on the SE side by a growing anticline.

5.11.7. Gottasecca Sandstone (Gs)

Thick- to very thick-bedded, mostly amalgamated, turbidite sandstones and minor intercalations of alternating sandstones and mudstones with sandstone/mudstone ratio >1. **Middle Burdigalian (MNN3b?)**.

Slope or base-of-slope deposits probably channelized.

5.12. PRATOLUNGO FORMATION (PL)

The Pratolungo Fm is a wedge-shaped unit, only represented in the area extended from the Caliogna Valley to the Borbera Valley where it is truncated by the pre-Langhian angular unconformity. It shows maximum thickness in eastern area (some hundreds of metres between Carrosio and Arquata Scrivia) and thins out rapidly, up to 10-20 m, to the west, where it is strongly condensed. Basal glaucarenitic transgressive deposits (the Visone Glaucony and Lerma Glaucony) are overlain by whitish, delicately bioturbated hemipelagic marls or marly limestones, in thin to medium layers, commonly interstratified in the lower part with graded and planar-laminated layers of resedimented fine glauconitic quartz sandstone/siltstone rich in planktonic foraminifers. Minor turbidite mudstones rarely underlain by thin divisions of fine-grained siliciclastic sandstone are interbedded, mainly in thicker successions. The unit includes three members, the Visone Glaucony and the time equivalent Lerma Glaucony, both occurring in the lowermost part of the unit, and a sandy turbidite member (Costa Montada Sandstone). **Middle Burdigalian (MNN3a p.p.-MNN3b p.p.)**.

Hemipelagic slope and basinal deposits.

5.12.1. Visone Glaucony (GV)

The unit, ca. 2m thick, conformably overlies without apparent gap the Visone Limestone in the Acqui-Visone area, where the transition is accompanied by a drastic reduction of the shallow-water bioclasts and a rapid increase in planktonic foraminifers; conversely, near Monte Capriolo the unit lies with sharp, apparently conformable contact on a reduced thickness of the Montechiaro d'Acqui Fm or unconformably on the Rocchetta Fm (Fig. 22b). The unit consists of fine-grained hybrid glauconitic arenites and fine-grained glaucarenites grading upwards into siltstones. It shows an upward-fining trend associated with a decrease in authigenic glauconitic content and is heavily bioturbated. It is very rich in calcareous nannofossils and both planktonic and benthic foraminifers, commonly glauconitized, and is time-equivalent to the transgressive Lerma Glaucony. **Middle Burdigalian (MNN3a p.p.)**.

Condensed outer ramp deposits.

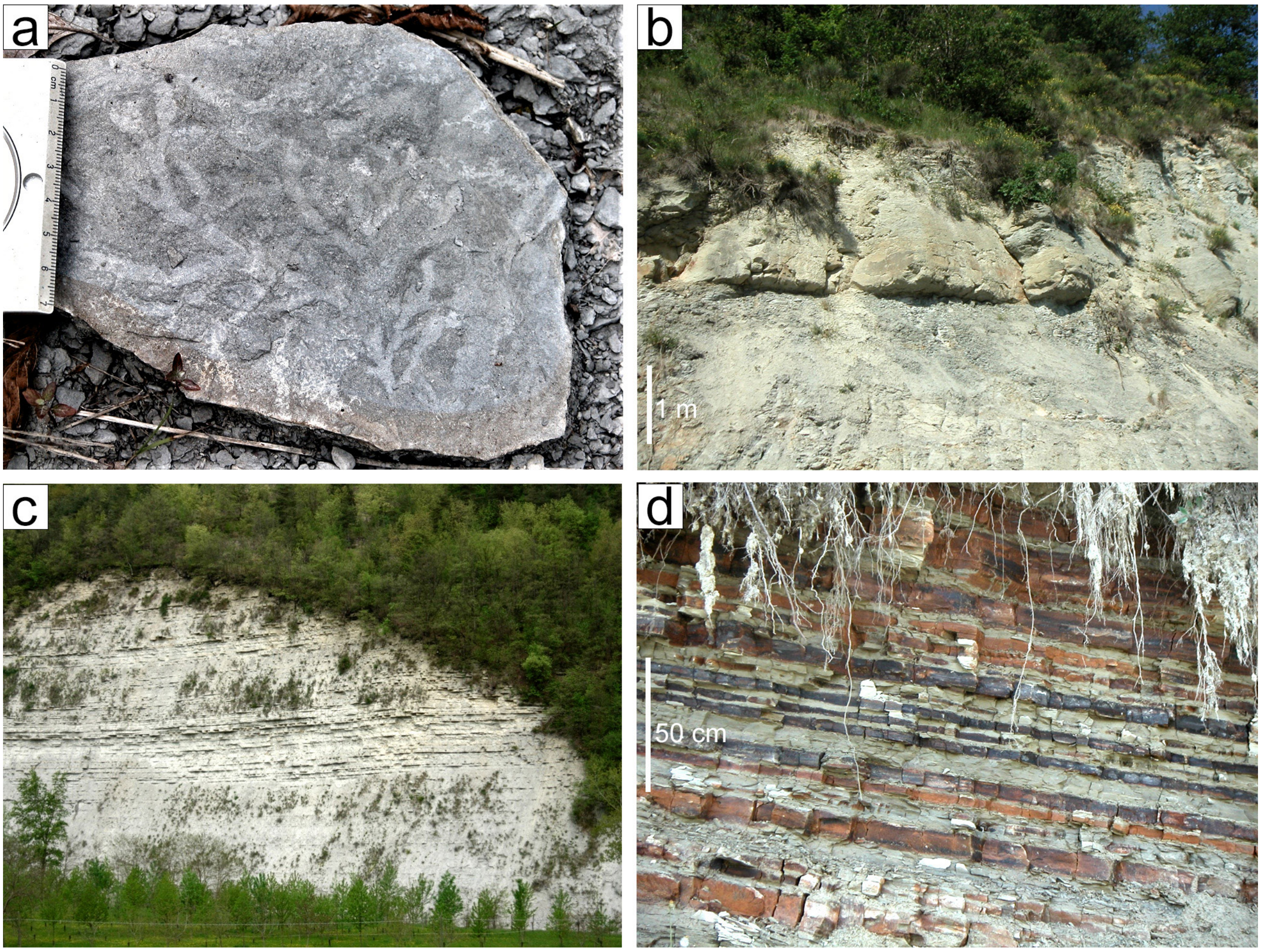

Fig. 22 - a) *Thalassinoides* on bed surface of Rio della Torre Lower Sandstone. (Rio della Torre Valley, W of C. Terrerosse). b) Visone Glaucony unconformably lying on marls of the Rocchetta Fm and grading upwards to marls of the Pratolungo Fm. Road Acqui-Ponzone, W of C. Battitassa (M. Capriolo). From the Explanatory Notes of the 1:50000 Geologic Sheet Acqui Terme (courtesy of A. d'Atri). c) Cortemilia Fm (inferred lobes). N of Pezzolo (Uzzone Valley). d) T. Lemme Siliceous Lithozone (LS2). NW of the village of Terzo.

5.12.2. Lerma Glaucony (GL)

This unit is laterally equivalent to the Visone Glaucony. It extends from the Visone Valley to the Borbera Valley with a slight eastward younging diachroneity; in the latter area it is truncated by the pre-Langhian unconformity. The Lerma Glaucony overlies the Rocchetta Fm and the Carrosio Sandstone with a locally prominent angular unconformity marking a large stratigraphic gap. The basal unconformity surface is erosional and draped by a lag of centimetric clasts (fragments of marls, glauconitized clasts, pebbles of serpentinites and granitoid rocks), plant remains of up to decimetric dimensions and shark teeth. From the basal surface firm-ground burrows infilled with the overlying sediment pipe downwards for 10-20 cm. The unit is thoroughly bioturbated and shows upward fining from medium-coarse to fine glaucarenites, accompanied by decrease in glauconitic content. In the Tagliolo Monferrato, Mornese and Vignole Borbera areas the unit shows an expanded stratigraphy, being represented by stratigraphically distinct lithosomes respectively 8, 14 and more than 7.5 meters thick of bioturbated, fine-grained glauconitic sandstones (see Fig. 28). **Middle Burdigalian (MNN3a p.p.)**.

Transgressive condensed lag deposits; local expanded lithosomes are interpreted as storm-influenced lower shorefaces indicating successive steps of the transgression (see section 6.2.3. and figure 28 for detailed description and interpretation).

5.12.3. Costa Montada Sandstone (CM)

The member shows a large-scale lenticular geometry. It consists of resedimented fine sandstones in medium to thick layers, amalgamated or separated by thin pelitic interbeds. **Middle Burdigalian (MNN3a p.p.)**.

Deposits infilling an upper-slope submarine valley.

5.13. CORTEMILIA FORMATION (CO)

The Cortemilia Formation extends in the W-E direction from the Bormida di Millesimo Valley in the Langhe area to the Scrivia Valley in the Alto Monferrato area where it is truncated by the Scrivia Fault. East of this fault the unit was eroded during the formation of the Pre-Langhian unconformity. SW of the mapped area the unit wedges out gradually, up to complete pinching out on the right side of the Belbo Valley near the locality of Bragioli (a few Km outside the study area), showing onlap against the underlying slope and base-of-slope wedge of the Serole Fm (cf. Pl. VIII online). The unit is comprehensive of the Cortemilia, Cremolino and Costa Areasa formations (*auctt.*). It overlies the Serole Fm in the Langhe area and the Pratolungo Formation in the Alto Monferrato area, and is in turn overlain by the T. Lemme Siliceous Lithozone (LS2). The unit consists of medium- to thick-bedded, alternating turbidite sandstones and mudstones with sandstone/mudstone ratio ≥1. In the western sector (Bormida of Millesimo Valley) thick- to very thick-bedded sandstone beds with very high sandstone/mudstone ratio or amalgamated are present in the intermediate and uppermost parts of the formation. In this area sandstone bed packages up to few tens of meters thick are vertically separated by variable thicknesses of thin- to medium-bedded sandstone-mudstone couplets (Fig. 22c). In the eastern sector (Lemme and Scrivia valleys), the formation is characterized by regularly alternating basinal turbidites and hemipelagites (Fig. 23a). The top of the Cortemilia Fm in the Langhe area almost coincides with the LCO of *H. ampliaperta*, whereas in the Lemme Valley section this bioevent has been found within the T. Lemme Siliceous Lithozone LS2 (Fornaciari and Rio, 1996) (Fig. 23b). **Middle-upper Burdigalian (MNN3b p.p.-MNN4a)**.

Non-channelized outer-fan deposits (depositional lobes) passing to basin plain deposits in the eastern sector.

5.14. T. LEMME SILICEOUS LITHOZONE (LS2)

The T. Lemme Siliceous Lithozone (**LS2**) is a regional key unit, like the other siliceous lithozones (Fig. 22d). It extends in the SW-NE direction from the Bormida Valley of Millesimo (Cortemilia area) to the Scrivia Valley, where it is truncated by the pre-Langhian unconformity. The unit shows maximum thickness (about 350 m) in the Lemme valley area, with a progressive thinning out westwards. In the eastern area (type section in the Lemme Valley) the unit consists of partly silicified intervals, 2-8 m thick, alternating with intervals of similar thickness of marls interbedded with turbidites. The partly silicified intervals consist of beds 5-20 cm thick, of delicately bioturbated and homogeneous, hard and tightly cemented, fine to coarse, light grey/whitish siltstones, turning yellowish or brown-reddish on weathered surfaces. These beds break tipically into parallelepiped-shaped pieces; their fossil content is represented by *Bathysiphon*, otoliths, pteropods, thin-shelled bivalves, and planktonic foraminifers. The hard silstone beds rhythmically alternate with interbeds of poorly cemented, diffusely bioturbated, grey to dark-grey mudstones. The marly/turbiditic intervals consist of faintly stratified to massive, or in places scaly, grey-whitish, bioturbated hemipelagic marls with pteropods, *Eudolium*, *Aturia aturi* and *Teredo*, associated with subordinate grey turbiditic pelites and rare medium- to thick-bedded, fine-grained, graded and planar-laminated sandy turbidites with sandstone/pelite ratio <<1, locally rich in plant remains and *Ditrupa*. West of the Orba Valley the unit subdivides into more condensed sub-units of decametric thickness, respectively named Bubbio Siliceous Lithozone (**LS2a**) and Morsasco Siliceous Lithozone (**LS2b**). The Bubbio Siliceous Lithozone can be traced up to the Bormida di Millesimo Valley, where it closes owing to erosion. The Morsasco Siliceous Lithozone (**LS2b**), in turn, subdivides, W of the Bormida Valley, into two more sub-units, separated by about 20 metres of hemipelagic marls, respectively named Monastero Bormida Siliceous Lithozone (**LS2b1**) and Quartino Siliceous Lithozone (**LS2b2**). These sub-units can be traced up to the surroundings of the village of Vesime, where they wedge out. The Bubbio Siliceous Lithozone (**LS2a**) is located atop the Cortemilia Formation. The Morsasco Siliceous Lithosone (**LS2b**) and the laterally equivalent couple of **LS2b1** and **LS2b2** units are located atop the S. Sebastiano Sandstone and respectively the Bubbio Tongue of the Cassinasco Formation. All the sub-units consist of hard, laminated, whitish siltstones, weathering to brown-reddish, with variable silica content, rhythmically alternating with mudstones. *Bathysiphon*, pteropods and otoliths are common. **Uppermost Burdigalian-lower Langhian (MNN4a p.p.-MNN 5a p.p.)**.

Slope deposits grading westwards to base-of-slope deposits, both probably linked to peculiar oceanographic conditions favourable to the biosiliceous production.

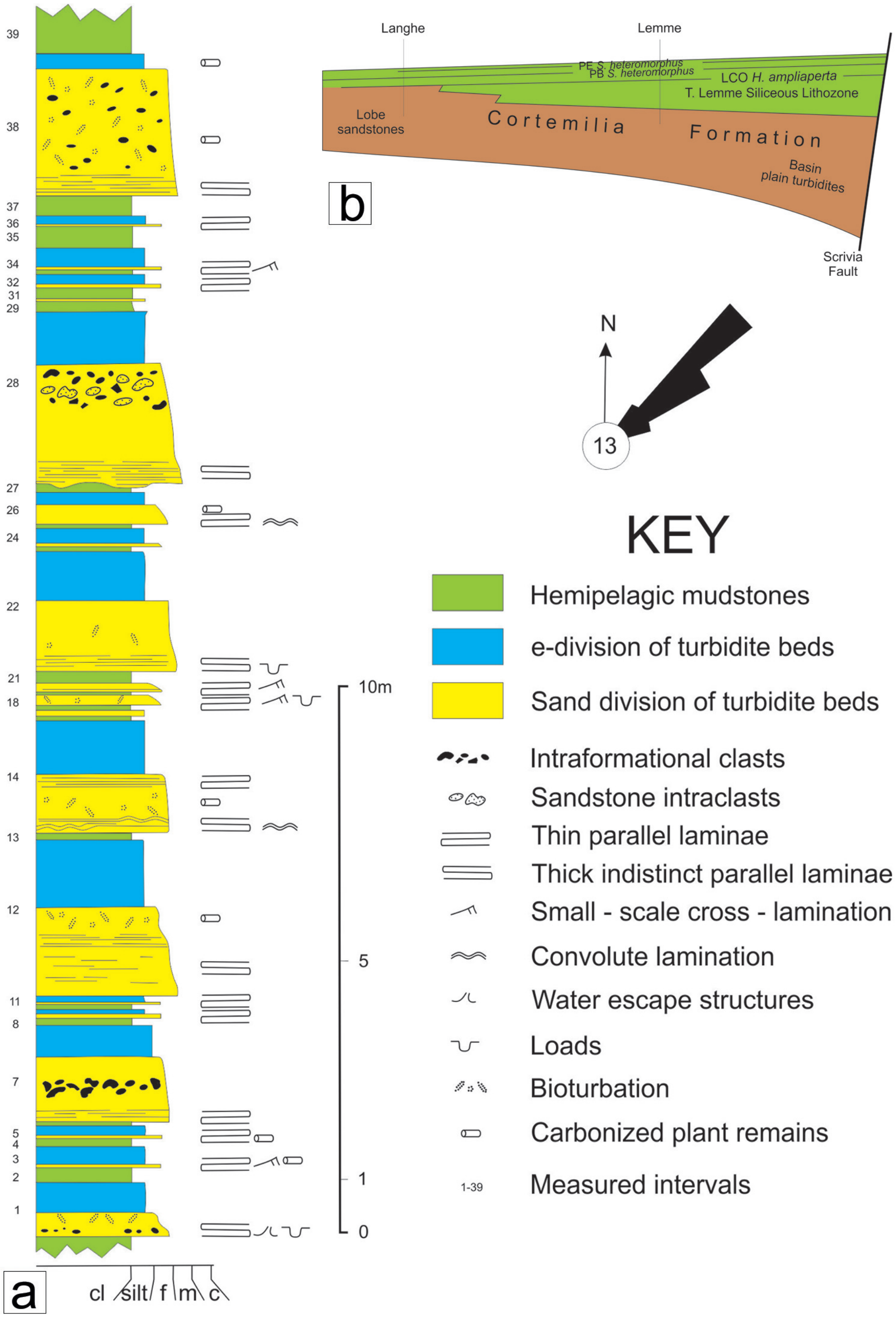

Fig. 23 - a) Facies sample in the Cortemilia Fm (T. Lemme section). b) Scheme showing the lateral relationships between the upper part of the Cortemilia Fm and the LS2 Siliceous Lithozone.

5.15. CASSINASCO FORMATION (CA)

In the study area the formation shows a large-scale wedge-shaped geometry, with maximum thickness to the SW (not less than 3 km) and a progressive thinning out toward NE. Beds of this unit are bundled to form tabular sandstone intervals up to several tens of meters thick, separated by variably thick intervals of medium- to thick-bedded sandstone-mudstone turbidites. The formation shows onlap againt the pelitic wedge of the Cessole Formation and that of the Murazzano Fm (Borgomale Tongue). To the NE the formation subdivides into two sub-units, respectively named Montabone Tongue (**Ca-LM**) and Bubbio Tongue (**Ca-LB**), the former onlapping against the wedge of the Cessole Formation, the latter bounded at the base by the Bubbio Siliceous Lithozone (**LS2a**) and at the top by the Morsasco Siliceous Lithozone (**LS2b**) (Pls. I and II). SW of the study area, the formation shows onlap against the Serole and Murazzano sedimentary wedges, and subdivides into two main sub-units, the Feisoglio Tongue (**Ca-LF**) and the Camo Tongue (**Ca-LC**), both wedging out SW-wards (Pl. VIII online). Between the valleys of T. Bormida and T. Orba the formation comprises, in the lowermost part, a broadly lenticular sandstone member named San Sebastiano Sandstone (**Ca-SS**) time-equivalent of the Bubbio Tongue. The unit consists of thick- to very thick-bedded turbidite sandstones, amalgamated or interbedded with thin mudstones, and, subordinately, medium- to thick-bedded sandstone-mudstone turbidites with sandstone/mudstone ratio ≥1 (Fig. 24 a,b). **Lower Langhian-lower Tortonian (MNN4b p.p.-MNN8)**.

Oversupplied outer fan deposits

5.16. MARCHESINI SILICEOUS LITHOZONE (LS3)

Hard laminated siltstones with variable silica content, rhythmically alternating with marls, in layers 5 to 15 cm thick. **Serravallian (MNN6b)**.

Basinal deposits linked to conditions of reduced siliciclastic input and of favoured biosiliceous production.

5.17. MURAZZANO FORMATION (MZ)

5.17.1. Borgomale Tongue (Mz1)

Compact homogeneous marls, delicately bioturbated, indistinctly stratified, interbedded with rare, centimetric to decimetric turbidite layers of fine-grained, graded and

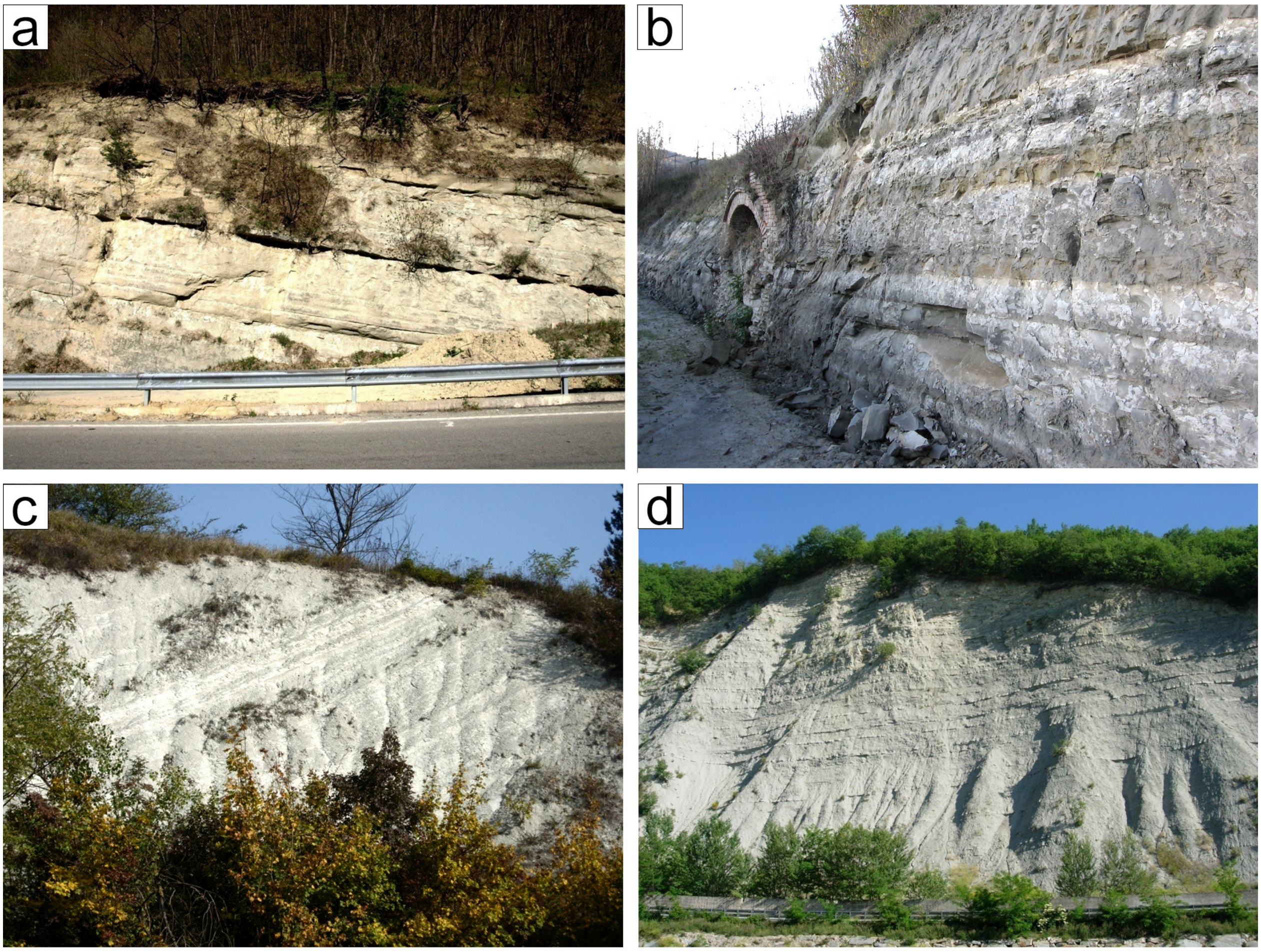

Fig. 24 - a), b) Cassinasco Formation. a) Thick to amalgamated strata. Road Cassinasco-Bubbio. b) Alternating medium-bedded sandstones and mudstones. Locality Rio Campolungo. From the Explanatory Notes of Acqui Terme 1:50000 Geologic sheet (courtesy of A. d'Atri). c), d) Cessole Formation. c) Gavi Siltstone Mb. Near Gavi. d) Morsasco Mudstone and Sandstone Mb (near the village of Cessole).

laminated sandstones. In the study area the formation is a sedimentary wedge pinching out NE-wards within the Cassinasco Formation. At the base the Borgomale Tongue is bounded by the Marchesini Siliceous Lithozone (**LS3**); at the top it is onlapped by the Camo Tongue of the Cassinasco Fm. About 10 Km SW of the study area, near the type-locality, the Murazzano Formation thickens considerably due to the progressive pinch out of the overlying Camo Tongue of the Cassinasco Formation (Pl. VIII online). **Serravallian (MNN6b-?MNN7 p.p.)**.

Hemipelagic slope to base-of-slope deposits.

5.18. CESSOLE FORMATION

The formation can be traced in the W-E direction from the Bormida di Millesimo Valley to the Borbera Valley. It forms a sedimentary wedge ("Cessole wedge") gradually thinning out westwards and closing near Vesime (Bormida di Millesimo Valley). East of the Scrivia Valley, the formation pinches out gradually eastwards, reducing to a few tens of metres near the Villalvernia-Varzi Line and shows onlap and unconformable angular relationships with the underlying Cortemilia, Pratolungo and Rocchetta formations. The unit comprises two members laterally and vertically passing into one another, named Gavi Siltstone and Morsasco Mudstone and Sandstone. **Middle-upper Langhian (MNN 5a p.p.-MNN 5b p.p.)**.

Shoreface to shelf and prodelta deposits (Gavi Siltstone) grading laterally and downslope basinwards into delta-slope deposits (Morsasco Mudstone and Sandstone).

5.18.1. Morsasco Mudstone and Sandstone (Ms)

Mudstones interbedded with fine to very fine turbidite sandstones and siltstones, showing variable sandstone/mudstone ratio (Fig. 24d). The sandy divisions of turbidites, typically of yellow colour, are generally 3-30 cm thick, graded and laminated, with planar-parallel laminae and common small-scale cross-laminae forming single or multiple ripple trains with high angles of climb. Hyperpycnal layers are probably common besides turbidites. Concentrations of small bioclasts are common at the base, and abundant minute plant remains along the laminae. Mudstone layers are generally 10-30 cm thick, dark-grey coloured, delicately bioturbated and contain fragments of thin-shelled bivalves and pteropods. To the west, in proximity of the closure of the Cessole Fm wedge, a plurimetric interval of thick-bedded turbidite sandstones with sandstone/pelite ratio >>1 is present in the middle part of the unit and turbidites with sandstone divisions 20-50 cm thick in the upper part.

Delta-slope deposits forming a sedimentary wedge prograding toward WSW.

5.18.2. Gavi Siltstone (Ga)

W of the Scrivia Valley, bioturbated siltstones/fine sandstones alternate with whitish silty marls in medium to thin layers, showing poorly distinct stratification (Fig. 24c). Macrofaunas are represented by echinoids, pteropods, and sparse bivalves. East of Scrivia Valley, where the unit lies on a substratum of variable age with angular unconformity, a transgressive lag is followed first by ~20 m of hummocky and planar-laminated sandstones, then siltstones with interbeds of medium- to thick-bedded, fine- to medium-grained sandstones with normal grading or planar lamination and abundant plant remains (e.g. Sorli section, Pl. XII).

Shelf deposits, with transgressive shoreface deposits in the basal part (eastern sector), grading upwards into regressive prodelta mudstones.

5.19. SERRAVALLE SANDSTONE (SV)

Fine- to very coarse-grained hybrid arenites, pebbly sandstones, conglomerates and siltstones. The hybrid arenites contain abundant bioclasts, including bryozoans (dominant), brachiopods, coralline algae, bivalves, gastropods, annelids, and planktonic and benthic foraminifers. The basal contact with the Cessole Formation is always sharp, erosional, associated with a firm-ground ichno-assemblage, and marked by abrupt increase in grain size, being covered by discontinuous layers of bioclastic coarse and microconglomeratic arenites. In the easternmost area (north-eastern part of the T. Borbera Valley) the contact corresponds to a very low-angle angular unconformity. The top contact with the siltstones and sandstones of the the Malvino Sandstone is generally sharp; in the Scrivia Valley, near Stazzano, it corresponds to an erosional discontinuity overlain by slumped deposits of the Malvino Sandstone rich in rhodoliths. Three facies associations can be distinguished: 1) in the eastern area (Borbera Valley) the lower part of the formation consists of plurimetric intervals (up to 10-15 m thick) of medium to thick sandstone layers with tabular geometry, alternating with similarly thick intervals of bioturbated fine sandstones, coarse siltstones and mudstones. The sandstone beds are graded, with planar and hummocky-type lamination, and associated with rare cross-laminated sets (sandwaves). In the upper part (Costa delle Bolle area) an erosionally-based, broadly lenticular body of kilometric extent is present, consisting of resedimented sandstones in thick to very thick, mostly amalgamated beds (Fig. 25a); 2) in the central area, particularly the Scrivia Valley, the dominant facies is represented by sets of hybrid arenites with medium to large-scale cross-lamination (sandwaves), occurring both as single isolated sets (locally form sets) and cosets (Fig. 25b), cyclically alternating in the lower part of the succession with intervals of bioturbated mudstones with planktonic foraminifers. In the upper part the cross-laminated cosets become dominant, with increasing thickness upsection. In association: sandstone layers either graded, or with planar to hummocky lamination (storm layers); 3) in the western area, west of the Scrivia Valley, and up to the Orba Valley, the lower part of the formation consists of medium- to very coarse-grained, resedimented and locally conglomeratic, thick to very thick sandstone layers, graded or graded-

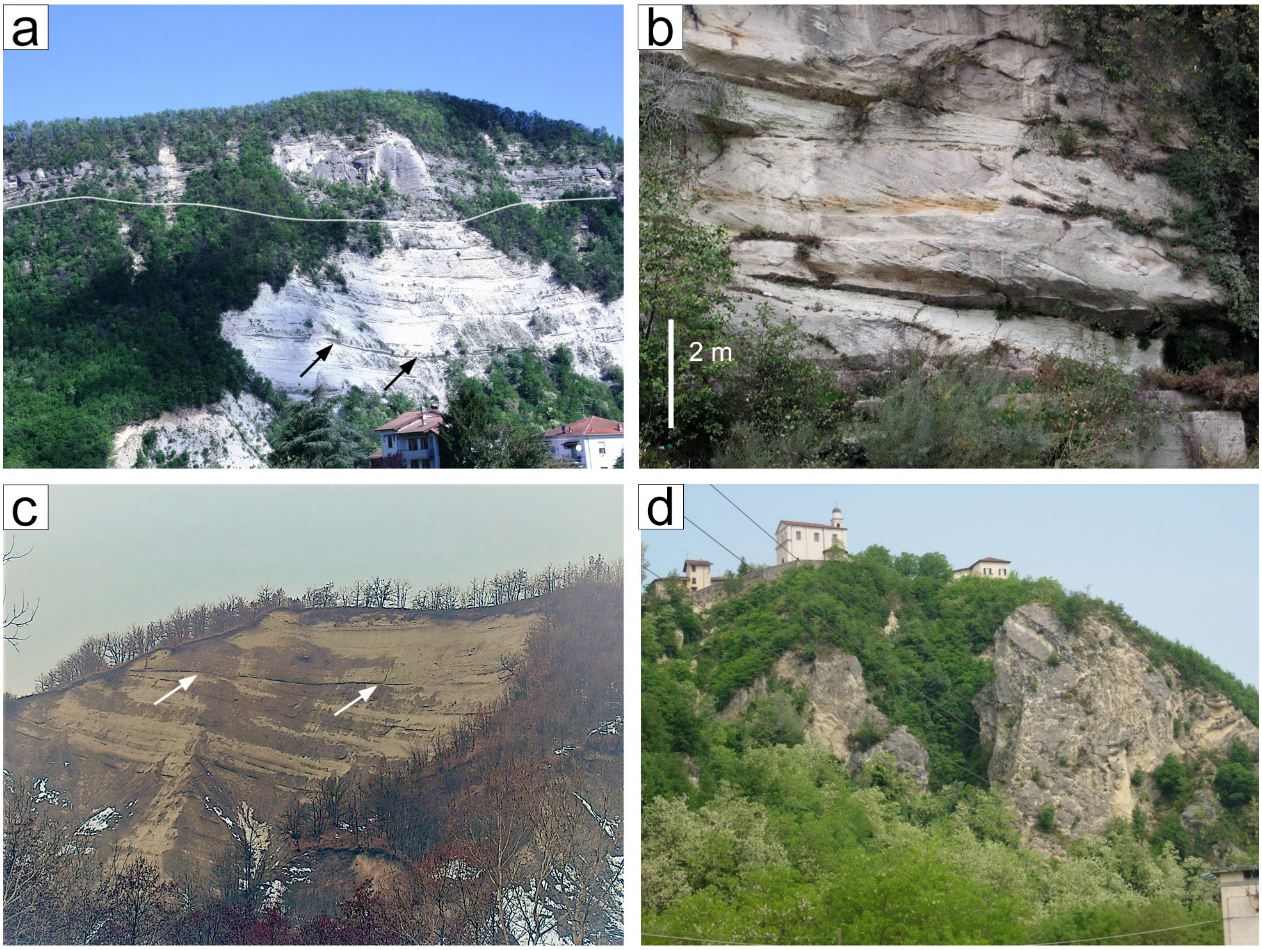

Fig. 25 - a), b) Serravalle Sandstone. a) Panoramic view of Costa delle Bolle (Borbera Valley). The contact between the Gavi Siltstone member of the Cessole Fm and the Serravalle Sandstone is arrowed; the prominent massive sandstones in the upper part of the scarp are inferred to represent an incised valley fill (base highlighted by white line). b) Sandwave coset showing unidirectional cross-bedding. Along the Scrivia River near Serravalle Scrivia. c) Slump scar (arrows) at the transition between the Malvino Sandstones and S. Agata Fossili Marl (NW of S. Andrea). d) Rocca Grimalda Chaotic Complex with olistoliths and blocks of Serravalle Sandstone. Scarp below the village of Rocca Grimalda.

to-laminated, commonly amalgamated, with even large pelitic intraclasts, interbedded with rare medium-scale cross-laminated sets (sandwaves). In association: thin- to medium-bedded, medium- to fine-grained sandstones and thoroughly bioturbated mudstones. The upper part is dominated by medium-scale cross-laminated sets of hybrid, medium- to coarse-grained sandstones (sandwaves). **Serravallian (MNN5b p.p.-MNN7 p.p.)**.

Tractive shelf deposits (sandwaves) associated with storm layers and outer-shelf mudstones in the central type-area, interfinger westwards with coarse-grained, resedimented fan-delta front deposits partly reworked by tractive flows (sandwaves), and eastwards with storm-dominated shelf deposits, locally reworked by tractive flows (sandwaves), passing upwards to resedimented deposits confined within a broad shelf incised valley. The basal contact of the formation is the record of a forced regression.

5.20. MALVINO FORMATION

The formation includes two members passing laterally into one another: Malvino Sandstone and Masseria Boschetto Sandstone and Mudstone; the latter encases three conglomerate units (Masseria Baiardo Conglomerate, Bocca d'Asino Conglomerates and Vargo Conglomerate) confined in a half-graben bounded to the East by the listric normal intra-Tortonian Vargo Fault and shows maximum thickness in the eastern part of the graben infill, against the bounding synsedimentary fault.

5.20.1. Malvino Sandstone (Ml)

Bioturbated fine-grained sandstones and siltstones with poorly distinct stratification, passing, with gradual increase in grain size, to coarse sandstones W of the Scrivia Valley. Fossil remains consist of gastropods, bivalves, echinoids, corals and plant fragments. Multiple coalesced slump scars of pluri-hectometric lateral extent are present in the S. Andrea area, at the transition to the overlying S. Agata Fossili Marl (Clari and Ghibaudo, 1979) (Fig. 25c). Large-scale slumped masses consisting of rhodolithic calcirudites passing upwards to fine sandstones and siltstones locally overlie the contact with the underlying Serravalle Sandstone (Stazzano in the Scrivia Valley). In the Vargo area the member interfingers with thin-bedded turbidites (Masseria Boschetto Sandstone and Mudstone). **Tortonian p.p.**

Outer shelf deposits.

5.20.2. Masseria Boschetto Sandstone and Mudstone (Mbo)

Alternating, medium-bedded, fine-grained turbidite sandstones and mudstones. The unit grades laterally westwards to the Malvino Sandstone and encases the three above-mentioned resedimented conglomeratic units. **Tortonian p.p**.

Fan-delta slope resedimented deposits.

5.20.3. Masseria Baiardo Conglomerate (MBa)

Thick-bedded, resedimented conglomerates with sandy matrix and channelized geometry. **Tortonian p.p**.

Fan-delta slope resedimented deposits.

5.20.4. Bocca d'Asino Conglomerate (BA)

Thick-bedded, resedimented conglomerates with sandy matrix and channelized geometry. The conglomerates contain rhodoliths, bored pebbles and, locally, abundant resedimented shallow-water macrofauna. **Tortonian p.p**.

Fan-delta slope resedimented deposits.

5.20.5. Vargo Conglomerate (Vr)

Thick-bedded, resedimented conglomerates with sandy matrix and channelized geometry. **Tortonian p.p.**

Fan-delta slope resedimented deposits.

5.21. ROCCA GRIMALDA CHAOTIC COMPLEX (RG)

Chaotic unit (diamicton) characterized by a sandy-pelitic matrix including olistoliths of up to hectometric size (Fig. 25d). The matrix (**RG1**) contains clasts of variable size (Fig. 26b), particularly pebble- to boulder-sized clasts of the Serravalle Sandstone and Cessole Fm.

Locally the lower part of the complex contains metric clasts of intensely folded siliceous sediments of

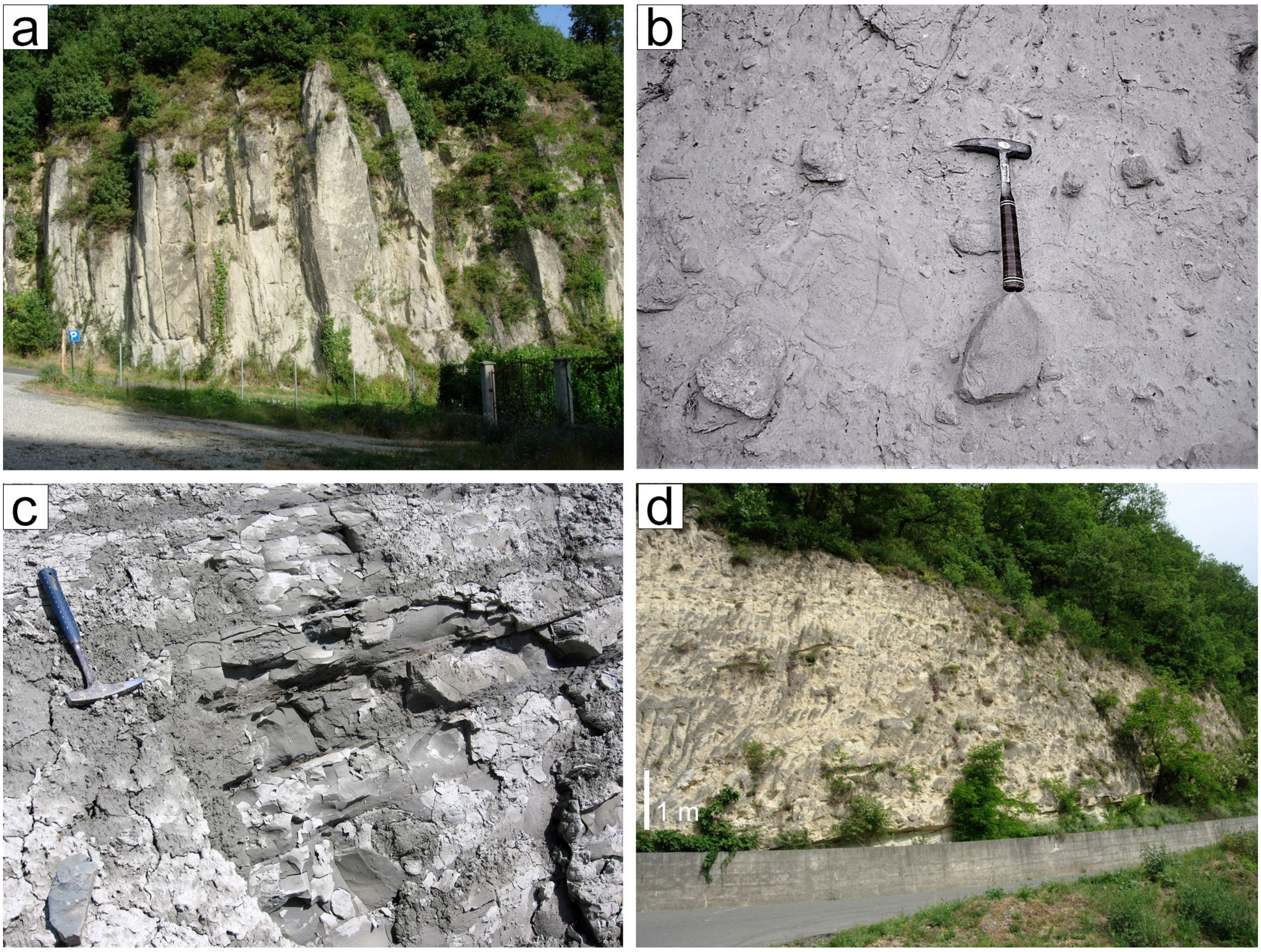

Fig. 26 - a), b) Rocca Grimalda Chaotic Complex. a) Giant olistolith of Serravalle Sandstone. Near Rocca Grimalda. b) Chaotic facies RG1 (diamicton). Road to Rocca Arcate. c) Sant'Agata Fossili Marl. Railway station of Alice Bel Colle. (From the Explanatory Notes of the 1:50000 Acqui Terme Geological Sheet, courtesy of A. d'Atri). d) Orsara Bormida Calcarenite (member of Sant'Agata Fossili Marl) with decimetric to metric clasts of lithified biocalcirudites and marly and diatomaceous intraclasts. The substrate of the body, visible behind the wall, is represented by diatomaceous marls. NNE of the village of Orsara Bormida.

the underlying Morsasco Siliceous Lithozone. Larger olistoliths, of up to hectometric size, are present at the top of the unit (RG2, RG3). **RG2**: boulders and slabs of the Serravalle Sandstone (Fig. 26a) characterized by thick cross-beds associated with graded or graded-laminated and bioturbated layers, locally (Rocca Grimalda) deformed into decametric folds. **RG3**: hectometric slab with preserved stratigraphy of bioturbated coarse siltstones of the Cessole Fm (**RG3a**) grading upwards to the Serravalle Sandstone represented by medium- and fine-grained bioturbated hybrid sandstones in layers 10-20 cm thick, interbedded with siltstones (**RG3b**).

Estimated maximum thickness of the Rocca Grimalda Chaotic Complex is 150 m. The basal contact is marked by the truncation of the underlying sedimentary succession, due to gravity emplacement. From W to E the unit is overlain by onlap first by the turbidites of the Cassinasco Formation and then by the resedimented deposits of the Orsara Bormida Calcarenite. **Lower Tortonian**.

Chaotic deposits emplaced by gravity-driven mass movement. RG1: matrix derived from the breakdown during downslope translation of semi-consolidated successions of shelf sandstones/siltstones, and slope mudstones respectively belonging to the Serravalle Sandstone and Cessole Fm. RG2: assemblage of olistoliths mainly representing portions of shelf successions of the Serravalle Sandstone. RG3: large-scale olistolith formed by upper slope deposits of the Cessole Fm (RG3a) grading to outer shelf deposits of the Serravalle Sandstone (RG3b) and representing a detached slab of the platform-margin succession.

5.22. S. AGATA FOSSILI MARL (SAF)

Grey bioturbated homogeneous marls (Fig. 26c) interbedded in the uppermost part with blackish laminated pelitic intervals and in the lowermost part with pluridecimetric diatomaceous intervals and siliceous laminites containing abundant fish scales and plant remains (e.g beneath the Orsara Bormida Calcarenite (sect. 6.2.8.). In the Ripa dello Zolfo area (N of S. Agata Fossili), methane-derived carbonate blocks occur in the upper part of the unit (Dela Pierre et al., 2010). In the Strevi-Orsara Bormida area, the formation is characterized in the lowermost part by a bioclastic member named Orsara Bormida Calcarenite (**OB**) (Fig. 26d), and, in the middle part (Stazzano area), a sandstone-conglomerate member named Villa Monti Conglomerate (**VM**). **Tortonian p.p.-lower Messinian (MNN8-MNN11)**.

Hemipelagic slope deposits encasing two channelized bodies.

5.22.1. Orsara Bormida Calcarenite (OB)

Unit with overall large-scale lenticular geometry mostly made up of resedimented thick- to very thick-bedded biocalcirudites and biocalcarenites, interlayered with metric intervals of diatomaceous and dolomitic marls and spongolitic sandstones (Strevi-Orsara Bormida area). The unit is composite, consisting of at least three bodies characterized by upward-fining and thinning trends. Typically, each body consists in the lower part of plurimetric layers of graded biocalcirudites and biocalcarenites with decimetric to metric clasts of lithified biocalcirudites and marly and diatomaceous intraclasts up to 1-2 metres in size, embedded in a poorly cemented calcarenitic matrix (Fig. 26d). The upper part consists of biocalcirudites and biocalcarenites richly fossiliferous (bivalves, gastropods, bryozoans, coralline algae, fragments and spines of echinoids, minor fragments of solitary corals, annelids, benthic foraminifers), in tabular, thick to very thick strata, graded or graded to planar-laminated. **Tortonian p.p.**

Resedimented channelized deposits sourced from nearby carbonate ramps.

5.22.2. Villa Monti Conglomerate (VM)

Resedimented conglomerates and sandstones in thick to very thick and amalgamated beds. The unit has a lenticular geometry. **Tortonian p.p.**

Slope channel-fill deposits.

5.23. GESSOSO-SOLFIFERA GROUP

5.23.1. Sant'Alosio Conglomerate (SA)

Resedimented conglomerates and sandstones (three stacked lenticular bodies) (**SA1**) up to some tens of metres thick, associated with graded sandstones and chaotic intervals with blocks of biogenic limestone and graded biocalcarenite (**SA2**). The bodies appear encased in the lower Messinian upper part of the Sant'Agata Fossili Marl near the localities "Il Poggeto" and "S. Alosio", East of the Scrivia Valley and contain up to decimetric clasts of micritic limestone and quartzite. In the S. Alosio locality, a more favourable exposure allows the recognition of a lithologically complex body with strongly lenticular geometry, with lateral extent of about 800m and thickness of 100-120m. The lower part consists of erosionally-based medium to thick layers of graded to laminated sandstone, encasing conglomerate lenses 20-30m thick. The upper part is dominated by chaotic facies with fragments and blocks of bioconstructed limestone with coralline algae and *Halimeda*, locally associated with decimetric layers of graded calcarenite, whereas the uppermost part is dominated by clasts of methane-derived limestone. **Upper Messinian**.

Infill of an incised subaqueous valley.

5.23.2. Valle Versa Chaotic Complex (VV)

Chaotic complex (diamicton) with decimetric to hectometric blocks embedded in a matrix of clayey marls with brecciated texture. The blocks consist of selenitic gypsum, dolostone and vacuolar dolomitic limestone, *Lucina*-bearing micritic limestone, and polygenic carbonate breccias. In the Acqui Terme area up to hectometric slabs of non-consolidated Sant'Agata Fossili Marl and Cessole Formation are associated. The decametric to hectometric boulders of selenitic gypsum have been mapped only in the Cassano Spinola-

Villalvernia area (**Ge**). **Upper Messinian**.

Gravity-emplaced mass deposits.

5.23.3. Cassano Spinola Conglomerate (CS)

In the type-locality: thick-bedded conglomerates and subordinate sandstones **(CS1)** interbedded with grey laminated marls with brackish faunas and local, thin- to medium-bedded, silty-sandy intervals **(CS2)** (Pl. XII and sect. 6.2.9.). In the Acqui Terme area: alternating medium- to thick-bedded, graded or structureless sandstone layers and centimetric-decimetric mudstone interbeds; local pelitic intervals with fresh- to brackish-water gastropods (*Theodoxus* sp., *Congeria* sp.). Local lenticular sandstone-conglomerate bodies of decametric thickness and hectometric to kilometric lateral extent, not individually mapped (**CS**). **Upper Messinian**.

Fan-delta and lagoonal deposits.

5.24. BLUE MUDSTONE (ARGILLE AZZURRE) (AA)

Homogeneous grey-blue marl with indistinct stratification, containing bivalves, gastropods, echinoids, pteropods, benthic and planktonic foraminifers (*Sphaeroidinellopsis seminulina* in the lower part, *Globorotalia margaritae* and *G. puncticulata*). Locally, at the base, metric-scale resedimented conglomerates with pelitic matrix (Acqui Terme area), and yellow bioturbated sand (Villalvernia area). **Zanclean (MP11-MP14a)**.

Outer shelf and upper slope hemipelagic deposits.

6. DEPOSITIONAL SETTING

6.1. SUMMARY OF THE DEPOSITIONAL SYSTEMS

A brief summary of the depositional systems involved in the various TPB units is presented (Fig. 3).

The Pianfolco Formation (Upper Eocene? Lower Rupelian?) may be attributed to the infill of a small intramontane basin tectonized in a time pre-dating the deposition of the Molare Sandstone. The Savignone Conglomerate (lower Rupelian) is interpreted as a composite Gilbert-type fan-delta system infilling a structural depression. The Molare Fm (middle Rupelian) is characterized by highly varied facies associations: from coalescing alluvial fans in the Borgo, Cartosio and Albareto grabens, to composite Gilbert-delta and fan-delta slope deposits in the Lerma and Borlasca grabens respectively, to channelized (locally canyon-fill), and non-channelized resedimented deposits of a fan-delta slope environment in the Lemmi-Spinti Graben. The Rocchetta Fm (uppermost middle Rupelian -Chattian), is mostly made up of slope and base-of-slope hemipelagic deposits containing several bodies of resedimented sandstones and conglomerates.

The Montechiaro d'Acqui Siliceous Lithozone (LS1, Aquitanian) is regarded as consisting of hemipelagic, basin-wide deposits linked to conditions of reduced siliciclastic input, and of favoured biosiliceous production, which enclose, in the Langhe Sub-basin, turbidite units infilling small intra-slope basins. The Visone Limestone (lower Burdigalian) is regarded as a carbonate ramp with a heterozoan assemblage. The Montechiaro d'Acqui Fm (uppermost Aquitanian-lower Burdigalian) is mostly hemipelagic and contains bodies of generally coarse-grained resedimented siliciclastic deposits, commonly rich in bioclasts and biosomata. The Visone and Lerma Glaucony (middle Burdigalian) are regarded as transgressive deposits. The Serole Fm (middle Burdigalian) is attributed to a prodelta slope setting (possibly channel-levee system) and the coeval hemipelagic and fine-turbiditic Pratolungo Fm to a slope to base-of-slope setting. Bodies of siliciclastic turbidites are encased in both formations. The Cortemilia Fm (middle-upper Burdigalian) is represented in western area by lobe deposits of an outer-fan environment, passing eastwards to basin-plain turbidites. The deposits of the T. Lemme Siliceous Lithozone (LS2, uppermost Burdigalian-lower Langhian) interfinger with turbidites and represent hemipelagic, basin-wide, slope to base-of-slope deposits linked to conditions favourable to biosiliceous production. The Cessole Fm (middle-upper Langhian) is interpreted as a westward offlapping, clinoform wedge made up of shelf/prodelta deposits (Gavi Siltstone) grading downdip into delta slope deposits (Morsasco Mudstone and Sandstone); E of Scrivia Fault, where the unit onlaps against the uplifted and tilted substrate with angular basal unconformity, it comprises transgressive shoreface deposits in the lowermost part. West of the Scrivia Valley the clinoformed part is thought to represent highstand and falling-stage deposits. The Serravalle Sandstone (Serravallian), laid down on the Alto Monferrato High, shows sharp and erosional basal contact thought to record a forced-regression, and consists, in the central area of the high, of a shelf association of tractive hybrid arenites (sandwaves) and storm layers, alternating with outer-shelf mudstones; it interfingers westwards (Orba valley) with coarse-grained, fan-delta slope resedimented deposits and eastwards (Borbera Valley) with predominant shelf sandstones sharply overlain by resedimented deposits confined within a broad shelf incised valley. The Malvino Fm (Tortonian p.p.) consists of outer-shelf deposits locally associated with large-scale slumped masses. In the Vargo area the formation interfingers with sandy turbidites encasing channelized resedimented conglomerates as infill of a half-graben.

The Cassinasco Fm (Langhian-lower Tortonian) consists of oversupplied outer fan deposits. The Roccagrimalda Chaotic Complex (lower Tortonian), is composed of chaotic deposits (diamicton) emplaced by a gravity-driven mass wasting event. The S. Agata Fossili Marl (Tortonian-lower Messinian) consists of hemipelagic slope deposits encasing channelized bodies. The Gessoso-Solfifera Group (upper Messinian) includes the infill of an incised subaqueous valley (Sant'Alosio Conglomerate), a complex of gravity-driven mass deposits bounded at the base by a deeply incised erosional surface (Valle Versa Chaotic Complex) and an upper Messinian unconformably-based fan-delta complex consisting of coarse deposits interfingering with lagoonal mudstones (Cassano Spinola Conglomerate). The subsequent Zanclean succession is characterized by outer shelf and upper slope hemipelagic deposits (Blue Mudstone).

6.2. SELECTED CASES OF SEDIMENTOLOGICAL CONCERN AND REPRESENTATIVE SECTIONS

In this section selected units having more appeal for the sedimentology and stratal organization, and/or role played in the geologic evolution of the study area, are described in more detail, mainly with reference to measured sections. In the following, the focus is particularly on the units represented in the central and eastern TPB, since the sedimentological context of the units cropping out in the Langhe area has been widely treated in a previous paper (Ghibaudo et al., 2014).

6.2.1. The environmental settings of turbidite bodies

The resedimented sandstone and sandstone-conglomerate bodies encased at various levels within fine-grained sediments of Rupelian to early Messinian age may be referred to a range of depositional settings, based on their external geometry, internal organization and structural context: they range from slope and base-of-slope, simple to stacked channels (e.g. the Rodini Sandstone, Brovida Sandstone, Molino di Mombaldone lower Sandstone, Case Poggi Calcarenite), to units confined within structurally-generated depressions of the submarine topography (e.g. the Ovrano, Rio della Torre units), to sediments infilling submarine valleys (e.g. the Piantivello Sandstone, Rocca Crovaglia Sandstone), or true canyons (e.g. the Mogliavacca Sandstone, Lerma Conglomerate), or submarine half-grabens (e.g. the Noceto Sandstone, Pian Bruno Calcarenite, C. Mazzurini Sandstone, Cassinelle Sandstone), or simple to coalescing slump-scars (e.g. Molino di Mombaldone middle and upper Sandstone, Bric Torrione Sandstone).

Larger and particularly coarser-grained bodies, specifically those encased in the Rocchetta Fm, commonly consist of vertical and lateral stacking of multiple fining-upward channel elements associated to overbank deposits.

With specific reference to the Rocchetta Fm, four types of turbidite bodies may be distinguished, based on the geometry and dimensions:

1) Lenticular channelized sandstone bodies of small to intermediate dimensions, with comparatively low width/thickness ratio (thickness in the order of tens of metres and lateral extent ranging from 350 m to about 1 km in direction roughly transverse to paleocurrents).

2) Sandstone bodies with broadly lenticular geometry, moderate to large dimensions and higher width/thickness ratio (thickness ranging from a few tens to hundreds of metres and lateral extent from 1-2 Km to 10 km).

3) Sandstone bodies with wedge-shaped geometry bounded by growth faults.

4) Sandstone bodies with approximately tabular geometry (thickness of a few tens of metres and lateral extent ranging from 1.9 Km to 3.4 km).

The overall organization of turbidite units encased in the Rocchetta Fm is generally characterized by up-stratigraphy decrease in the basal erosional relief and increase in width/thickness ratio of individual bodies, inferred to indicate transition from upper slope to base-of-slope setting.

Some lenticular, coarse-grained channel bodies encased in the mudstones of the Rocchetta Fm show evidence of lateral accretion (Figs. 8a; 15 a,b; 27 a,b). They have been particularly observed in the Mioglia brachysyncline, near the village of Frascheto (see also Mutti and Normark, 1991; Mutti et al., 2002; Tinterri and Civa, 2014); in this area laterally accreted bodies 1-5m thick and 100-300 m wide display sharp, scoured base and consist of coarse, poorly sorted, hybrid and locally pebbly sandstones. These channel units show distinct lateral accretion surfaces and are bounded above and below by the thin-bedded muddy deposits of the Rocchetta Fm. Flute marks at the base of the bodies indicate flow normal to the dip of the accretion surfaces. The beds involved in the accretionary pattern show distinctive grain size increase downdip, with coarsest facies near the basal erosional surface of the body. We share the interpretation given by Mutti et al. (2002), who refer these bodies to a depositional context of small meandering channels incised in the Rocchetta slope muds. It is suggested that the ability to build laterally migrating point bars is a characteristic attribute of dense, coarse-textured turbidity flows active in slope meandering channels cut in a muddy substrate.

Some layers within turbidite bodies (e.g. in Brovida Sandstone and Mogliavacca Sandstone bodies; Figs. 9c, 11d) show repeated grain-size changes leading to a thin-bedded rhythm of fine-grained sandstone and mudstone/siltstone, with common intrasequence small-scale erosional contacts. This pattern is thought to indicate waxing and waning flow energy and suggests pulsating, long-lived, hyperpycnal flows subject to cyclic changes in the rate of fallout (e.g. Zavala and Pan, 2018).

6.2.2. The siliceous horizons of the TPB succession

The siliceous deposits occurring at several levels in the TPB succession, interpreted as slope or base-of-slope hemipelagites originally rich in biosiliceous component, represent marker horizons on regional scale.

An interaction of several processes in the genesis of siliceous horizons is suggested by the interbedding of different types of deposits, including hemipelagites, siliceous laminites, turbidites, and planar- to ripple-laminated fine-grained sandstone to siltstone layers with common mud drapes, inferred to represent hyperpycnites. Characteristic is the abundance of plant remains and the presence of fossils indicative of an offshore, deep-water setting. The regional extent of the siliceous horizons is probably linked to a generalized increase in organic productivity, favouring basinwide blooms of siliceous phytoplankton (Amorosi et al., 1995). It is tought that

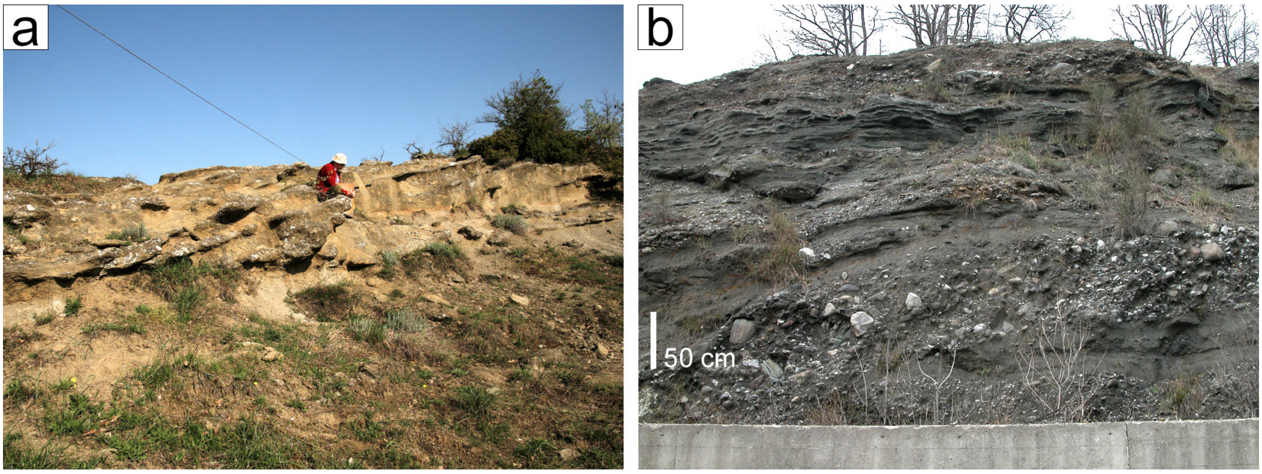

Fig. 27 - Examples of coarse-textured channelized bodies encased in the slope mudstones of the Rocchetta Fm, showing inclined bedding inferred to result from lateral accretion. a) Mioglia area, N of the village of Frascheto. b) Piana Crixia Conglomerate. Locality Ciazze, N of Piana Crixia.

oceanographic conditions favourable to the biosiliceous production may relate to climate-induced changes in marine conditions. Specifically, periodic increases in freshwater runoff from nearby land areas may have led to dilution of the upper water column by freshwater input; the resulting salinity stratification of the water column resulted in poorly oxygenated or temporary anoxic bottom water conditions (e.g. Rossignol-Strick, 1983; Mangini and Schlosser, 1986). Increased continental runoff also would have added land-derived organic matter and dissolved nutrients to the sea, leading to enhaced siliceous plankton productivity.

6.2.3. The transgression recorded by the Visone and Lerma Glaucony

The Visone Glaucony and the Lerma Glaucony form a single transgressive unit which can be traced on the whole extent of the Alto Monferrato High, although presenting a variety of facies, thickness, vertical stratigraphic organization, and types of contacts with the substrate (Pls. I and II; Fig. 28a).

The Visone Glaucony

In the Acqui Terme-Visone area the Visone Glaucony rests on the ramp carbonates of the Visone Limestone with non-erosional, conformable contact and has quite constant thickness of about 2 m. The upper contact with the marls of the Pratolungo Fm is transitional. The unit consists of thoroughly bioturbated fine glaucarenites with muddy matrix passing upwards to muddy glauconitic silts. The sandy fraction consists of glauconitic grains, planktonic foraminifers, and, very subordinately, siliciclastic and shelf bioclastic grains and rare autigenic phosphatic grains. Glauconite is present either as more or less evolved grains developed on an unrecognizable substrate or as infilling of internal cells of planktonic foraminifers. The discontinuity of outcrops prevents complete understanding of large-scale stratigraphical relationships and geometry of the unit. At the outcrop scale the Visone Glaucony shows a tabular geometry with maximum extent of some hundreds of metres.

The Lerma Glaucony

East of Acqui Terme-Visone area the Visone Glaucony laterally grades into the Lerma Glaucony, which overlaps the depositional pinchout of the underlying foramol Visone Limestone, and rests unconformably on the marls of the Rocchetta Fm, except in the Carrosio area, where it overlies the Carrosio Sandstone. Correlated sections are presented in figure 28a, aimed at showing the stratigraphic organization of the Lerma Glaucony. Regionally this unit is mostly represented by a tabular blanket 1-1.5 m thick, consisting of hybrid skeletal glaucarenites passing upwards to muddy, thoroughly bioturbated fine glaucarenites; however, in three areas it shows a more expanded stratigraphy, as will be detailed below. The base of the Lerma Glaucony is an erosional unconformity representing a variable hiatus of several million years (d'Atri, 1990b). The contact with the underlying slope marls of the Rocchetta Formation is an angular unconformity at angles ranging from a few degrees to 30°-35°. The unconformity surface is floored by a discontinuous lag consisting of medium- to coarse-grained glaucarenites with scattered extrabasinal and intrabasinal pebbles commonly glauconitized. Extrabasinal clasts of serpentinites and granitic rocks associated with marly lithoclasts eroded from the underlying Rocchetta Formation are present. Fossils contained in the lag include echinoids, oysters, bryozoans, colonies of encrusting corals, rhodoliths, fragmented and whole bivalves, among which thick-shelled oysters, *Amussium* and *Pycnodonte*, and shark teeth. Large wood fragments, up to 20 cm long, commonly bored by *Teredo,* are commonly associated. Large burrows infilled with glauconitic material pipe downwards from the unconformity surface for up to 30 cm. They are regarded

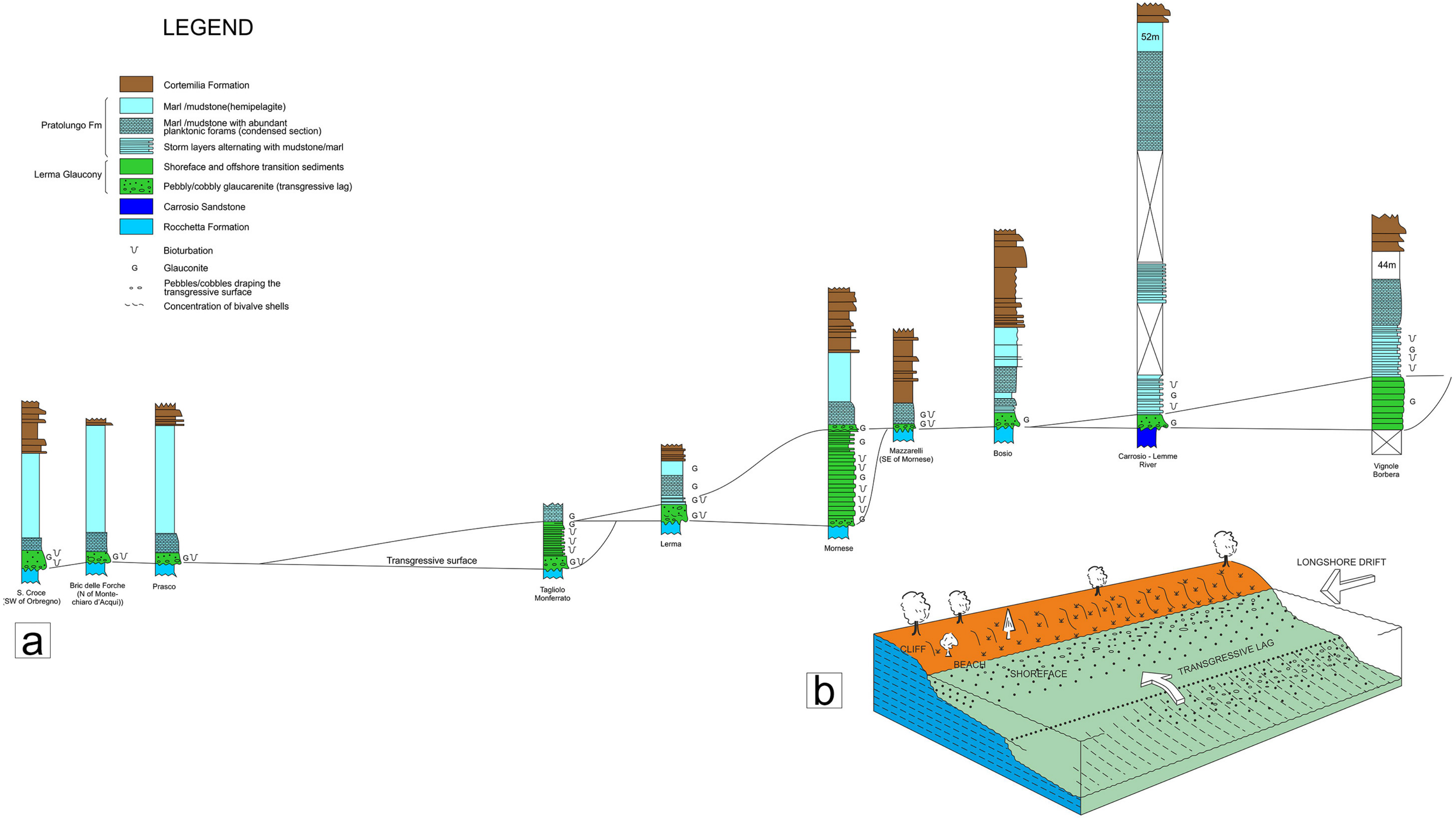

Fig. 28 - a) Cross-correlation among Lerma Glaucony sections. b) Model of stepped transgression. Inspired by Pattison and Walker (1992).

as firm-ground burrows of the *Glossifungites* ichnofacies. The upper contact of the Lerma Glaucony with the marls of the Pratolungo Fm is sharp to transitional in a short space, and conformable.

As noted above, the Lerma Glaucony shows local stratigraphic expansions. Specifically, in the Tagliolo Monferrato, Mornese and Vignole Borbera areas the unit is represented by distinct lithosomes with more complex internal organization respectively 8, 14 and more than 7.5 m thick, forming morphological steps (Fig. 28a). These steps and the related expanded stratigraphy, moreover, appear to be progressively younger from west to east, due to the shift of the transgression in that direction.

The *Tagliolo Monferrato lithosome* reaches a maximum thickness of about 8 metres. Above a quite thick basal fossiliferous lag (1.5 m) covering the unconformable lower contact, the remaining part of the lithosome (6.5 m) consists of a succession of sharp-based and normally graded, somewhat burrowed, very fine-grained muddy glaucarenite beds 10 to 20 cm thick, alternating with subordinate, thoroughly bioturbated silty marls with scattered glauconitic grains. This bed package shows an upward decrease in abundance of the glauconitic fraction from 10-20% to 5-10% and is sharply overlain by hemipelagic marls of the Pratolungo Fm.

The basal surface is interpreted as a ravinement surface and the overlying, fossiliferous coarse lag as a residual transgressive concentration laid down during the shoreface retreat. The remaining part of the unit is interpreted to be laid down in an offshore-transition environment affected by storm events. The sharp transition to the marls of the Pratolungo Fm is considered a flooding surface.

The *Mornese lithosome*, 14 m thick, is better exposed and offers the opportunity of more complete and detailed observations (Fig. 28a). The basal glaucarenitic lag with extra- and intraformational clasts grades upwards into an interval (1) with poorly distinct stratification, 9.7 m thick, consisting of fine- to medium-grained, slightly glauconitic (4-5%) quartz-sandstone layers 10-30 cm thick, alternating with thoroughly bioturbated and sparsely glauconitic (1-2%), very fine-grained sandstone interbeds 10-20 cm thick. The beds are sharp-based, contain glauconitized arenitic intraclasts, mostly in the lower part, and locally show planar-parallel laminae and/or low angle, probably hummocky cross-laminae. Sparse echinoid spines, fragments of serpulids, and small fish teeth are present. The uppermost 1.5 m of this interval consist of fine-grained sandstone homogenized by bioturbation. This interval grades upwards, with fining trend, into a bed package (2) pervasively bioturbated, 3 m thick, of dominant siltstone, with 4-5 layers 10-20 cm thick of very fine-grained, sharp-based sandstone with small intraclasts, and sparse glauconite (2-3% on average, but up to 30 % in the burrow infills). This is abruptly overlain by an interval (3) comprising a layer of scattered extrabasinal pebbles up to 4 cm in diameter, marly glauconitized intraclasts, and rare oyster fragments, grading to 40 cm of bioturbated, very fine sandstone and coarse siltstone; this interval is sharply capped by a firm-ground surface with burrows of the *Glossifungites* ichnofacies, draped by a discontinuous lag of tightly cemented and sometimes bored glauconitized sandstone intraclasts, up to 8 cm in size, and *Teredo*-bored plant remains. This surface is overlain by an upward-fining unit (4), 3.7 m thick, grading from biosiltite with planktonic foraminifers to bioturbated marly biosiltite with glauconite decreasing from 10% to 1%; this in turn grades to homogeneous marls.

The interpreted depositional setting of the interval (1), which overlies the basal transgressive lag, is a lower shoreface below fair-weather wave base with isolated and locally amalgamated storm layers. An offshore-transition environment is inferred for the interval (2), with accumulation below fair-weather wave base and sparse storm events. The composite interval (3) is interpreted to mark resumption of transgression with reworking of part of the underlying deposits into a residual lag. The upward fining unit (4) records a rapid deepening marking the transition to the hemipelagites of the Pratolungo Fm.

The *Vignole Borbera lithosome* crops out for 7.5 m; the real thickness cannot be evaluated, since the base is covered. The succession consists of coarse to very coarse quartz-glaucarenites (5-10% of glauconite) in medium- to thick-bedded and in places amalgamated layers (up to 70 cm), with few thin interbeds of fine to very fine sandstone. The strata are sharp-based, in places normally graded, some of them showing planar/low angle to hummocky laminae, and trains of clay chips in the lower part. The topmost metre is coarser (coarse granule-bearing sandstone), marking a weak upward-coarsening trend. The sandy lithosome is sharply overlain by the Pratolungo Fm, represented first by an interval 8 m thick of alternating thin-bedded and bioturbated marly limestone and siltstone rich in planktonic foraminifers and then hemipelagic marls.

The sandy lithosome is interpreted to reflect the progradation of a storm-influenced lower shoreface. The abrupt basal contact of the Pratolungo Fm is inferred to represent a flooding surface, overlain first by shelf deposits with distal storm layers and then hemipelagites.

Interpretation of the stratigraphic organization

As above noted, in different areas the glauconitic unit presents different facies, thickness and vertical stratigraphic relationships (Fig. 28a). The Acqui-Visone area, located in the westernmost part of the Alto Monferrato High, experienced a non-erosional marine flooding after the deposition of the Visone Limestone, due to the submerged setting of this area. Conversely, in the eastern area of the high the transgression of the Lerma Glaucony occurred on an emerged area and was accompanied by ravinement. A lowstand component to the origin of the discontinuity at the base of this unit is demonstrated by the deep erosion associated with the surface; it is unlikely, in fact, considering the large hiatus, that the substrate could have been eroded only by the ravinement process. The relative sea level must have fallen, leading to emergence and subaerial erosion and removal of all traces of the subaerial exposure, in order to bring the substrate into a position where it could be transgressively ravined.

As above described, the Lerma Glaucony displays a depositional pattern given by a thin blanket of glaucarenite alternating in the direction of advancing transgression with local thicker glaucarenitic bodies with a more complex organization (Fig. 28a). In both cases a ravinement process during shoreface retreat generated a sharp erosion discontinuity at the base. The layer mantling the discontinuity corresponds to a ravinement-reworked lag with ripped mud clasts, whole or fragmented shells, shark teeth, small plant fragments and granule to pebble gravel. None of the shells is in life position and all appear transported. The *Glossifungites* ichnofacies associated with the discontinuity indicates colonization of the firm substrate (firmground) during the depositional hiatus between the eroding event and subsequent deposition.

The sharp-based, thicker lithosomes are interpreted as incised shoreface deposits (e.g., Pattinson and Walker, 1992; Walker and Bergman, 1993; Bergman, 1994; MacEachern et al., 1999), namely sharp-based shoreface sandstones interpreted to rest upon transgressive surfaces of erosion incised into underlying deposits. These sand bodies are interpreted to have been produced during minor stillstand phases punctuating an overall relative sea level rise and probably reflecting a temporary decrease in the accommodation/sediment ratio.

Pattison and Walker (1992) observed that, if relative sea level rise is punctuated by stillstands, it is probable that incised shorefaces will be formed (Fig. 28b). They observed that each shoreface will be underlain by an erosive surface (the *initial* transgressive surface IT, Walker, 1990) and the shoreface sediments will probably be truncated by a higher erosion surface as transgression continues (the surface of *resumed* transgression RT). The result is the formation of time-transgressive and spatially separated sand bodies with similar sedimentological origin and a link with an overall transgressive event. These incised shorefaces are typically bounded in the landward direction by incisions appearing as asymmetrical steps parallel to the regional strike, steeper on the landward side, and gradually flattening seawards (Pattison and Walker, 1992) (Fig. 28 a,b). The renewed transgression then forms the erosive envelope rising in the landward direction. Thus, during an overall transgression punctuated by stillstands, the successive, diachronous, stepped shorefaces parallel to the regional strike are incised at progressively higher positions concurrently with the landward shift of the transgression (Figs. 28 a,b and 39).

This characteristic geometry is partly interpretative, as it cannot be fully documented in detail in the field, given the discontinuity of the outcrops. However, the Mornese lithosome, which crops out more completely, provides the most useful information, as it shows to be capped by an unconfomity surface interpreted to reflect the erosional removal of the upper part of the lithosome during the resumption of the transgression, with reworking of shoreface deposits into a transgressive lag. The thin, sharp-based blanket of glaucarenite covering the substrate in the more extensive intervening areas between the sand lithosomes are thought to represent the record of rapid progress of the transgression during phases of enhanced rates of relative sea-level rise. The observed stratigraphic organization can be explained in conclusion as the result of fluctuations of relative sea level during an overall transgression punctuated by episodes of relative stillstand when the incised shorefaces were formed. The latter can be regarded as parasequences bounded by discontinuity surfaces.

6.2.4. The Pratolungo Fm, Cortemilia Fm, and T. Lemme siliceous lithozone (LS2)

Carrosio-Lemme, Vignole Borbera and E Piota-Vallescura sections

The Carrosio-Lemme section (Pl. IX), measured along the T. Lemme Valley, illustrates a stratigraphic interval from the top of the Carrosio Sandstone, through the Lerma Glaucony, the Pratolungo Fm and the Cortemilia Fm, to the T. Lemme Siliceous Lithozone (LS2); the Vignole Borbera section (Pl. XI) depicts an interval comprising the Lerma Glaucony, the Pratolungo Fm and the lowermost part of the Cortemilia Fm; the E Piota (Vallescura) section (NNE of the village of Lerma) (Pl. X) represents an interval including most part of the T. Lemme Siliceous Lithozone (LS2) and the lowermost part of the Cessole Fm.

The *Lerma Glaucony* in the Carrosio-Lemme section overlies the delta-front deposits of the Carrosio Sandstone by means of an erosional unconformity. The base of the unit is a ravinement surface draped by a transgressive lag consisting of fine to medium-coarse bioturbated glaucarenites with centimetric clasts (intraclasts, glauconitized clasts, clasts of serpentinites and granitoid rocks), plant remains and shark teeth. A description of the Lerma Glaucony in the Vignole Borbera area is given above (section 6.2.3.).

The *Pratolungo Formation* has been measured in both Carrosio-Lemme (Pl. IX) and Vignole Borbera (Pl. XI) sections. Above the transgressive glaucarenites of the Lerma Glaucony, a lower metric interval of the sharp-based Pratolungo Fm is represented by alternating silty marl and thin-bedded hybrid arenites (where the carbonate fraction is mostly given by planktonic foraminifers). The following interval is dominated by a characteristic facies represented by graded and planar-laminated fine glauconitic quartz-arenites/siltstones rich in planktonic foraminifers, associated with hemipelagic marls, and interbedded with scattered thin- to very thin-bedded grey siliciclastic fine-grained turbidite sandstones with sparse glauconite. In the more expanded Carrosio-Lemme section this facies is interstratified with an interval of delicately bioturbated hemipelagic marls with otoliths and sparse glauconite.

The Pratolungo Fm grades into the upper Burdigalian succession of siliciclastic turbidites of the *Cortemilia Fm*. In the Lemme Valley section the formation (local name: Costa Areasa Fm) crops out with a measured thickness of about 600 m (Pl. IX). The turbidites mostly consist of sandstone-mudstone couplets with sand/mud ratio ≤1, alternating with marly hemipelagites (Fig. 23a). The turbidite couplets range in thickness from 0.1 to more than 3m, with an average of 1.5 m. The beds are tabular, bounded by strictly panar-parallel stratal surfaces. The sandy division is made up of fine to medium-coarse sandstones, with a predominance of medium and fine grain sizes, and shows distribution grading and planar laminae to ripple cross laminae. The pelitic interval consists of homogeneous, grey silty mudstone, generally thicker than the sandy interval. Bouma sequences are incomplete, of the type Tb-e, Tb/e, Tc-e, Td-e, Te. Paleoflow direction indicated by common basal sole marks was consistently NE-wards (Pl. IX). In association, rare thick to very thick layers (max 3.2 m), are characterized by lack of Bouma sequences and presence of thick and poorly distinct planar-parallel laminae, and local water escape structures (dish, pillars). The turbidite beds show quite irregular thickness and fail to show any cyclical organization. The hemipelagites occur as layers a few cm to a few tens of cm thick, regularly present at the top of turbidite beds, and can be easily differentiated from the grey to dark grey pelitic "e" divisions of the turbidites for their different colour. They consist of homogeneous and compact, variably calcareous marls, slightly silty, with conchoidal fracture and light brown colour weathering to whitish, and are commonly affected by intense bioturbation. Macrofossils, locally common, are represented by pteropods, small bivalves and echinoids.

The following unit, i.e. the *T. Lemme Siliceous Lithozone (LS2)*, is a key unit of regional importance in the TPB. It shows maximum thickness (about 350 m) in the Lemme valley area (the type-area), with a progressive thinning out westwards. In the Lemme valley the unit consists of (1) bedsets made up of rhythmically alternating siliceous and muddy layers, irregularly interstratified with (2) bed packages of muddy hemipelagites associated with sparse turbidites. The (1) bedsets, 2-8 m thick, consist of beds 5-20 cm thick of delicately bioturbated and homogeneous, hard, fine to coarse and partly silicified siltstones with *Bathysiphon*, otoliths, pteropods, thin-shelled bivalves and planktonic foraminifers, rhythmically alternating with poorly cemented, diffusely bioturbated, grey to dark grey mudstone layers. The (2) intervals consist of faintly stratified to massive, bioturbated hemipelagites with pteropods, *Eudolium*, *Aturia aturi*, *Bathysiphon* and *Teredo*, associated with subordinate grey turbiditic pelites and rare medium- to thick-bedded, fine-grained, graded and planar-laminated sandy turbidites with sandstone/pelite ratio <<1, locally rich in plant remains and *Ditrupa*. In the area N of Mornese (near C. Valponasca), ripple trains in both siliceous facies and associated thin-bedded turbidites within the LS2 unit show paleoflow toward 300°.

As noted in the biostratigraphical section, the lower part of the LS2 siliceous lithozone in the Lemme valley area is apparently coeval to the upper part of the Cortemilia Fm of western TPB, indicating facies change in W-E direction, and maximum thickness of the LS2 unit in proximity of the Scrivia Fault (Fig. 23b).

Interpretation

Both Carrosio-Lemme and Vignole Borbera sections highlight an extremely fast platform drowning episode, documenting the transition from the Lerma Glaucony, which in both areas is transgressive on an emerged substrate, through a thin interval of outer-shelf deposits with inferred distal storm layers, to the rapidly deepening Pratolungo Fm, rich in planktonic foraminifers, interpreted as indicative of a slope hemipelagic depositional setting. The quartz-glaucarenites with planktonic foraminifers are interpreted as derived from cannibalization and resedimentation of the transgressive glauconitic sands after the drowning event.

The Cortemilia turbidites of the Lemme Valley area are regarded as representing a basin plain facies association (see also Galbiati, 1976 and Andreoni et al., 1981). The predominance of Bouma sequences indicates flows of relatively low concentration, whereas the rare presence of thick and poorly distinct planar-parallel laminae, associated in places to water escape structures (dish, pillars) are interpreted to reflect relatively more concentrated flows experiencing a liquefaction stage just prior to the deposition (Walker, 1978).

The T. Lemme siliceous lithozone (LS2) is inferred to be laid down in a slope setting. The siliceous deposits are thought to represent hemipelagites originally rich in biosiliceous component (diatoms, radiolarians), transformed during the diagenesis through dissolution of the opaline skeletal remains and precipitation of crypto-crystalline silica (Einsele, 2000, and references therein). The composition of this unit is probably linked to a generalized increase in organic productivity, possibly linked, as above proposed, to increased continental runoff adding land-derived organic matter and dissolved nutrients to the sea, and leading to enhanced siliceous plankton productivity (e.g. Baumgartner, 2013; Celestino et al., 2017). The internal cyclicity represented by alternating siliceous (1) and marly (2) intervals is interpreted as the expression of a high-frequency cyclicity in a slope environment (Ghibaudo et al., 2014), possibly linked to an orbital control.

In the Vallescura section, NNE of the village of Lerma (Pl. X) the LS2 Lithozone is comparable to the Lemme Valley section in internal organization and facies association.

The T. Bormida di Millesimo section (S of Vesime)

(Pl. XI) shows the transition from the upper part of the Cortemilia Fm to the LS2a Bubbio Siliceous Lithozone located at the base of the Bubbio Tongue of the Cassinasco Fm. *The Cortemilia Fm* shows more proximal (presumably lobe) facies association compared to the basin-plain turbidites of the Lemme Valley area. The sandy divisions of the turbidite layers range in grain size from very fine to medium sand and show sharp, sometimes scoured, and locally burrowed base (in places *Paleodictyon*), common normal grading and planar-parallel lamination (predominant Tb/e sequences); several sand divisions show an apparently biphasic nature, with a laminated lower part displaying evidence of traction plus fallout deposition, and a homogeneous and structureless slurry mud-rich upper part, sometimes with subtle thick lamination. Plant remains, sometimes bored by *Teredinidae*, and aligned mudstone intraclasts, locally large, are common; unidirectional structures, like flute and groove casts, indicate paleoflow mostly directed E-wards, or ENE-wards. The hemipelagites are moderately to poorly represented in association with the turbidites and consist of light-grey, massive, delicately bioturbated mudstones, generally 5-15 cm thick.

The *LS2 Siliceous Lithozone* in this section, like in most part of the Langhe Sub-Basin, shows a somewhat different facies association with respect to the LS2 successions located more to the east, like those of the E Piota (Vallescura) and Lemme-Carrosio sections. This facies association has been separated by d'Atri et al. (in press) from their Siliceous Mb of the Montechiaro d'Acqui Fm and regarded as a different formation (Bistagno Fm). This lithozone is made up of thin-bedded, variably silicified intervals up to 8 m thick of sparsely bioturbated couplets of silt layers and marly hemipelagites, interbedded with thin- to medium-bedded turbidite packages up to 13 m thick. In the former intervals, 2-10 cm thick sharp-based siltstone layers with millimetric parallel to ripple drift lamination, or dark-grey pelite layers sometimes underlain by a few discontinuous silty laminae with micro-loaded and micro-erosional base, grade transitionally into light-grey and delicately bioturbated, homogeneous marly hemipelagites. Associated fossil remains are represented by otoliths, pteropods, thin-shelled bivalves, and plant remains, sometimes bored by *Teredinidae*.

Parallel-laminated layers are more diffusely present in this facies association, compared to that of eastern area. This may reflect a deeper-water setting with more frequent episodes of anaerobic bottom conditions

6.2.5. The Morsasco Mudstone and Sandstone Mb of the Cessole Fm

Piota - C. Setteventi section

The Piota-Case Setteventi section illustrates the transition from the T. Lemme Siliceous Lithozone LS2 to the lower part of the *Morsasco Mudstone and Sandstone (MMS) Mb of the Cessole Fm* (PL. XI). The latter, although poorly and incompletely cropping out, shows some of the typical sedimentological features of the MMS, including the grain size ranging from fine to very fine sand to silt, and presence of multiple ripple trains and internal mud drapes, suggesting that the beds may partly represent hyperpycnites. The sparse faunal elements, such as pteropods and thin-shelled bivalves, indicate a relatively deep-water environment which is consistent, together with the other features and the stratigraphic relationships with the Gavi Siltstone Mb of the Cessole Fm, with the interpretation of the unit as consisting of delta-slope deposits forming a clinoformed wedge prograding toward WSW.

6.2.6. The coalescing slump scars at the base of the Serole Formation

The transition between the Montechiaro d'Acqui Fm and the overlying thin-bedded turbidites of the Serole Fm is characterized in the Langhe area by multiple slump scars; these form local erosional discontinuities particularly in the Bric Torrione, C. Rocchino, Denice and Uzzone Valley areas, with the partial or total removal of the marls of the Montechiaro d'Acqui Fm (Pls. I and II; Fig. 41) (see also Ghibaudo et al., 2014). Except for the Bric Torrione scar, clearly evidenced by a lenticular sandstone body (Bric Torrione Sandstone) confined in the lower part the scar, the other surfaces are more subtle, as the outcrops do not allow detailed observations, so that their presence can only be inferred from local reductions in thickness, or total absence, of the underlying marls of the Montechiaro d'Acqui Fm. The Bric Torrione scar has a width of about 1.5 km and an estimated maximum depth of 80 m. It completely removes the underlying Piantivello unit and the Montechiaro d'Acqui Fm. The scar infill is made up of the turbidites of the Bric Torrione Sandstone in the lower part and the Serole Fm in the upper part (Ghibaudo et al., 2014). The C. Rocchino and Denice composite scars have an estimated depth of a few tens of metres and a lateral extent of several hundreds of metres (Ghibaudo et al., 2014). The Uzzone Valley coalescing scar is a plurikilometric feature some tens of metres deep, removing most part of the Montechiaro d'Acqui Fm, and locally leading to the superposition of the Serole Fm on the Siliceous Lithozone LS1c. The large areal extent of this surface and local variations in thickness of the marls of the Montechiaro d'Acqui Fm suggest an origin by slump scar coalescence.

Interpretation

Reactivation of the Uzzone Valley Fault System at the end of deposition of the Montechiaro d'Acqui Fm is thought to have triggered gravity destabilization of the slope, resulting in the generation of simple and multiple slump scars. However, accumulations of slumped sheets were not observed, suggesting that the sediment removal may have taken place by multiple liquefied mud flows in poorly consolidated sediments, rather than by large mass failure.

6.2.7. The Gavi Siltstone MB of the Cessole Fm and the Serravalle Sandstone

Scrivia Valley section

The Scrivia Valley section (Pl. XIII), located in the area where the historical stratotype of the Serravallian was established (Vervloet, 1966), illustrates the stratigraphic interval including the uppermost part of LS2, the Gavi Siltstone, the Serravalle Sandstone, and the lowermost part of the Malvino Formation.

The uppermost part of the *LS2 unit* is represented by hard, homogeneous and bioturbated coarse siliceous siltstones in thin to medium beds (10-20 cm), regularly alternating with homogeneous, bioturbated marly layers 10-50 cm thick, with *Bathysiphon*.

The *Cessole Formation*, directly overlying the LS2 unit, is represented by the *Gavi Siltstone* member, since the Morsasco Mudstone and Sandstone Mb developed west of the Scrivia Valley as a prograding delta slope (Pls. I and II). The lower part of the Gavi Siltstone, ca. 100 m thick, is represented by quite uniform, pervasively bioturbated silty mudstone; the stratification is poorly distinct, barely evidenced by thin interbeds of blackish pelites 1-2 cm thick, spaced every 1.5-2 m. The faunal content is represented by pteropods, *Bathysiphon*, otoliths, local echinoids and solitary corals, and the trace fossils by *Zoophycos*, *Phycosiphon* and common tubes. The following interval, up to the top of the Gavi Siltstone (about 300 m), is characterized by an organization into small-scale cycles 10-20 m thick, showing a slight trend coarsening upwards. Individual cycles display in the lower part indistinctly stratified and delicately bioturbated homogeneous muddy siltstones with rare interbeds of dark "e"-type pelites 1-2 cm thick; in the upper part a gradual transition occurs into bioturbated siltstones with poorly distinct strata (10-40 cm) highlighted by the interbedding of thin layers of blackish pelite 2-3 cm thick, usually underlain by thin unidirectional ripple form sets (h: 2-10 mm) in coarse siltstones or fine sandstones. Rare beds of bioturbated sandstone, ranging from very fine to medium-grained, sometimes finely bioclastic, 5-30 cm thick, with sharp base, local normal grading, and planar lamination occur in this interval. The siltstones in the upper part of the cycles commonly contain carbonized vegetal remains up to 2-3 cm in length, locally bored by *Teredo*. Within this interval an overall regressive trend is manifested by upward increase in cycle thickness and slight overall coarsening trend. The regressive trend in the Gavi Silstones is also shown by the upward change in the macrofossil assemblages, represented in the lower part by *Eudolium*, *Aturia*, *Clio pedemontana*, *Nucula* and rare solitary corals; these taxa become progressively rarer upwards, and eventually disappear. Among the ichnofossils, *Zoophycos* is ubiquitous, whereas *Phycosiphon* occurs only in the upper part of the succession.

The deposits are interpreted to reflect prodelta influences, and to evolve with regressive trend from an upper slope to outer shelf setting. The intercalated thin layers of blackish pelites and/or small-scale couplets of rippled form sets overlain by dark pelite (respectively "e" divisions and small Bouma Tc-e sequences) are interpreted to represent deposition from diluted turbidity currents, or hyperpycnal flows, or distal storm-driven flows.

The transition to the *Serravalle Sandstone* is sharp and characterized by firm ground with *Glossifungites* ichnofacies and abrupt increase in grain size; the basal surface is covered by discontinuous, lenticular, scour-based layers of hybrid coarse and microconglomeratic arenites with rhodoliths, locally abundant intraclasts, and sparse small exotic pebbles.

Hybrid sandstones are a typical component of the formation: they contain an important coeval carbonate fraction, consisting of bioclasts of various organisms, such as bryozoans, bivalves, gastropods, annelids, brachiopods, echinoids and coralline algae.

In the lower part of the Serravalle Sandstone cropping out in the Scrivia Valley a cross section has been constructed by correlating by the method of walking out 16 stratigraphic sections measured on an almost continuous outcrop long about 800 m, located some hundreds of metres south of the town of Serravalle Scrivia in the type area of the formation (Pl. XIV). The overall thickness measured is around 200 m. The following facies can be identified.

Facies 1: bioturbated siltstones and shales

Homogeneous, bioturbated siltstones and very fine sandstones with grey to light blue colour, containing planktonic and benthic foraminifers; the ichnofossil assemblage includes *Phycosiphon*, *Teichicnus*, sparse echinoid burrows, and small common tubes. This facies shows thicknesses ranging from some centimetres to few metres. The sediments of facies 1 represent the lowest energy deposits of the facies association.

Facies 2: graded-to-laminated slightly bioclastic, coarse to fine sandstone beds, amalgamated or interbedded with facies 1

The layers show lateral continuity of some hundreds of meters, erosional lower contacts, graded-to-laminated internal structure, and transitional upper contacts. The top few centimetres of finer-grained beds are usually intensely bioturbated. Lamination is mostly planar, locally of hummocky type. Coarser-grained beds are thicker and characterized by lower lateral continuity, locally lenticular geometry with scoured base, and common concentrations of angular or slightly rounded intraformational clasts of facies 1 with dimensions of up to 30 cm. The external and internal characteristics of the beds point to a rapid introduction of sand in the quiet depositional environment of facies 1 by decelerating flows during high-energy events.

Facies 3: cross-bedded sandstones

This facies is represented by simple and compound medium- to coarse-grained, hybrid cross-bedded sandstone units.

Subfacies 3a - Simple cross-bedded sandstone sets (Pl. XIV). They are characterized by a lower flat and slightly erosional base and a wavy to planar top, and show thicknesses of up to 3-4 m. In places these cross-bedded sets preserve, with minor modifications, the original depositional wavy outline (true form sets) with wavelenghts of up to 60-70 m, thus showing the geometry and internal structures typical of bedforms generated by the migration of a single train of sandwaves. Internal structures are represented by only one set of unidirectional, medium- to large-scale cross-laminae with angular to tangential lower contacts. The tops of the sandwaves were commonly subjected to erosion due to high-energy flows involved in the genesis of facies 2, either as bypassing currents producing sheet erosion, or as scouring followed by deposition. In some cases, the facies 2 infill is localized in the trough between two adjacent sandwaves (Fig. 29d; Pl. XIV).

The bioturbation is very common and, without exceptions, is concentrated along the surfaces of individual laminae (Fig. 29b) and on the tops of the bed forms. Groups of higly bioturbated laminae commonly alternate with non-bioturbated laminae. Particularly intense bioturbation, sometimes associated with a composition richer in carbonate fraction, typifies the last-formed lamina (Pl. XIV). The bioturbation is identified as *Macaronichnus-Ophiomorpha* ichnofabric.

Subfacies 3b - Compound cross-bedded sandstone cosets (Fig. 29 a,d). These bodies show thicknesses ranging from 2 to 29 m and consist of stacked sets ranging in thickness from 30 cm to 1.5 m, made up of unidirectional cross laminae and bounded by gently dipping erosional surfaces. Reactivation surfaces are locally seen at the transition between superimposed sets. Even in this case many burrows are concentrated along individual laminae.

Facies 4: coarse-grained facies linked to gravity-driven processes of resedimentation.

The above described facies are typical of the area of Serravalle Scrivia, whereas in the western area of the Alto

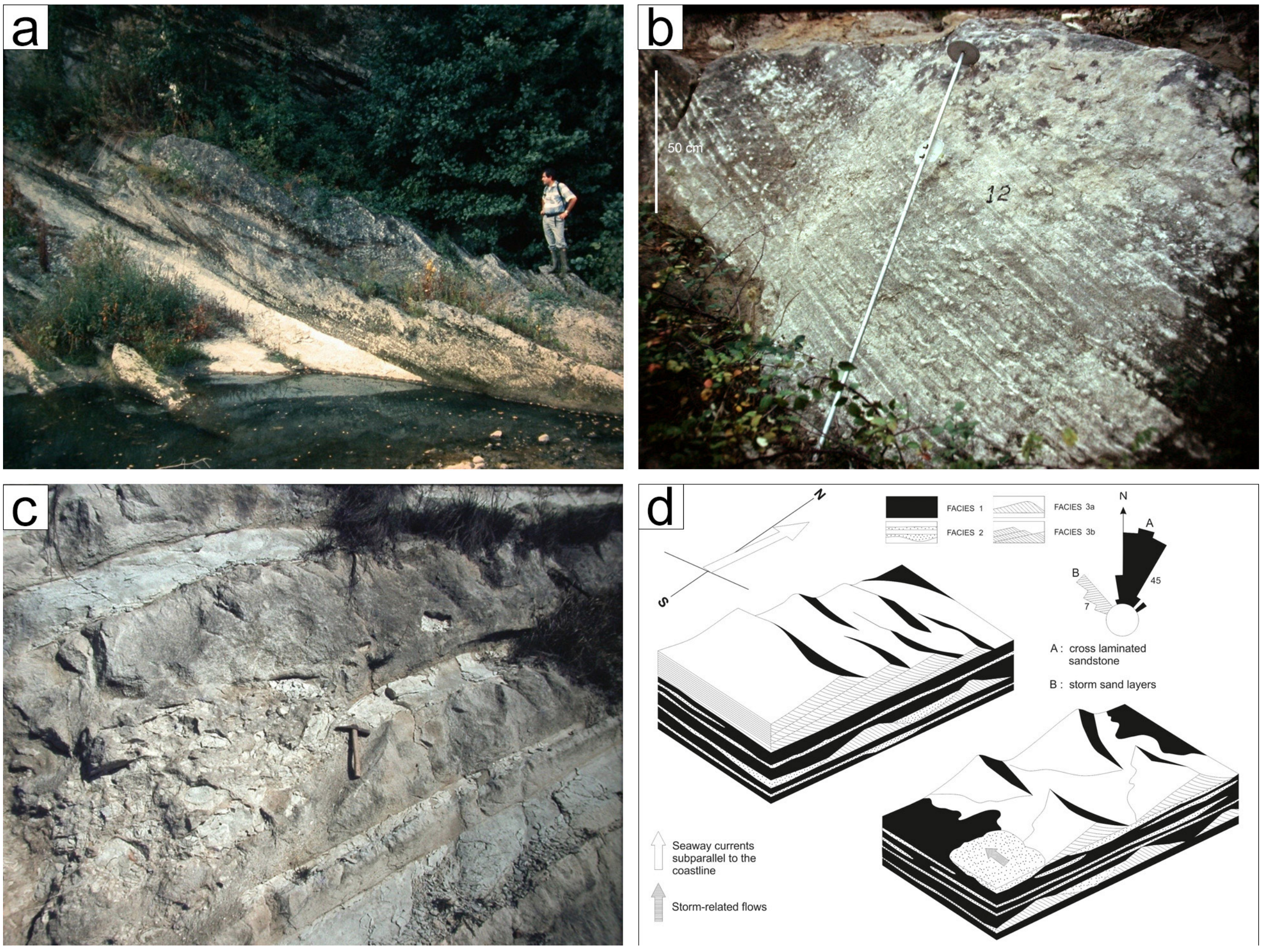

Fig. 29 - Serravalle Sandstone. a) sandwave coset (subfacies 3b) showing unidirectional cross-bedding and tangential cross-laminae. Bank of the Scrivia River near Serravalle Scrivia. b) Detail of a cross-bedded sandwave showing *Macaronichnus-Ophiomorpha* ichnofabric. Bank of the Scrivia River near Serravalle Scrivia. c) Thick hybrid sandstone layer showing large mudstone clasts. d) Scheme of interaction between traction currents involved in the alongshore migration of sandwaves and ephemeral storm-induced flows. The current rose illustrates the divergence of the two type of flows.

Monferrato High, particularly west of the village of Gavi, they are commonly interbedded with facies 4. This consists of polymictic, structureless or normally graded pebble to cobble conglomerates, rarely with sparse boulders, with variable amount of sand matrix and commonly erosional bases. Beds are up to 2 m thick and commonly contain mud intraclasts up to 40 cm in length. This facies is generally associated with massive or roughly graded-bedded, very coarse to medium-grained hybrid arenites, locally containing granules to small pebbles, in beds up to 2m thick commonly with large mud intraclasts (Fig. 29c) and deeply erosional base. Rare antidune structures and scour infills capped by backset-bedding indicate the local occurrence of supercritical flows and hydraulic jumps. The observed features point to deposits laid down from mass flows ranging from high-concentration turbidity flows to debris flows. These gravity-flow deposits are interbedded with the tractive, cross-stratified facies.

The Serravalle Sandstone shows a tendency to an organization into small-scale sequences. Within the area of the Alto Monferrato High, two type of sequences may be identified: in the Scrivia Valley, where the depositional setting was quite sheltered from important terrigenous input, the sequences are expressed by alternating intervals of siltstone rich in planktonic foraminifers and hybrid arenites as storm layers and/or sandwaves; conversely, in the western area, more subject to fan-delta influx, an organization locally occurs into upward-fining small-scale sequences dominated by resedimented, coarse-grained, locally mass-flow terrigenous deposits in the lower part, grading upwards into sets/cosets of sandwaves.

In the Borbera Valley an erosionally-based, broadly lenticular body of kilometric extent is present in the upper part of the formation (Costa delle Bolle area), consisting of resedimented sandstones in thick to very thick, mostly amalgamated beds.

Interpretation

The abrupt basal surface of the Serravalle Sandstone is interpreted to result from forced regression recording an event of significant relative sea-level drop. The fine-grained sediments of facies 1 were presumably transported in suspension and settled from the water column in a low-energy setting. Facies 2 is regarded as the product of storm-driven flows (Fig. 29d; Pl. XIV). The lenticular, coarser-grained layers of this facies suggest the intervention of stronger and channelized storm-driven flows, poweful enough to erode the shelf bottom, while the finer-grained, thinner, and more tabular beds could represent more distal deposition by unconfined, sheet-like flows in areas located in front and laterally to the storm channels.

The facies 3 represents sandwaves subject to periodic migration in a shelf environment. The *Macaronichnus-Ophiomorpha* ichnofabric is known as typical of offshore tidal shelf sandwave facies (e.g. Pollard et al., 1993). A particularly intense bioturbation, sometimes associated with a composition richer in carbonate fraction, typifies the last-formed lamina of the sandwave, marking the abandonment stage (Pl. XIV). The subfacies 3a results from the migration of single sandwaves, whereas facies 3b is interpreted to be linked to a setting characterized by large sand supply and active sedimentation, where the sandwaves could climb on the stoss side of the downcurrent ones, thus forming sand ridges.

The coarse deposits laid down by gravity-driven processes (facies 4) are thought to reflect episodic fan-delta influx.

The erosionally-based, broadly lenticular body of kilometric extent present in the upper part of the formation in the Borbera Valley (Costa delle Bolle area), is thought to represent the infill of a broad shelf incised valley, recording an event of significant relative sea-level drop during the sedimentation of the Serravalle Sandstone.

The evidence stemming from the facies analysis suggests a depositional setting characterized by an interaction between ephemeral storm-driven flows, and more continuous tractive flows producing sandwave trains (e.g. Le Bot and Trentesaux, 2004). This setting is illustrated by the Figure 29d and is supported by the paleocurrent rose highlighting a 60° difference in paleocurrent direction between storm-driven flows and the mean direction of sandwave migration. These processes, which are preponderant in the Serravalle Scrivia area, interacted with fan-delta-related mass flows, particularly in the western area of the Alto Monferrato High.

Migration of the sandwaves in a shelf environment was periodic: during high-energy periods the sandwaves migrated rapidly dowcurrent, while during longer periods of low energy, they were quiescent, and their surface was bioturbated by benthic organisms. The genesis of the sandwave field is interpreted to reflect a paleogeographic setting characterized by deposition occurring in a seaway where strait conditions occurred (e.g. Longhitano et al., 2012; Longhitano, 2013, and references therein). In general, narrowing of a seaway connecting marine basins with opposite tidal phases could lead to tidal current amplification (tidal straits of Longhitano, 2013), occurring independently from the tidal regime of the basins connected by the seaway. Commonly a single direction of sand-wave migration sub-parallel to the coastline is predominant. In the studied example the seaway was probably bounded by Alpine and proto-Apenninic emerged areas. Its narrowing and consequent activation of strong currents, may have resulted from an episode of sea-level drop, possibly enhanced by tectonics, as attested by the evidence of forced regression at the base of the formation. The narrowing may have been accompanied by a tidal resonance effect enhancing the energy of flows. Although the sandwave trains are ultimately controlled by strait-related tidal current amplification, some typical features of tidal deposits, such as tidal bundles and double mud drapes, are lacking, as expected in the case of tidal deposits in shelf settings. This contrasts with examples illustrated by Longhitano (2013, 2018), who reports the presence of these structures.

Interbedded fan-delta deposits dispersed approximately NW-wards were sourced from uplifted areas subject to intense denudation located SE of the Alto Monferrato High; they were accumulated in a shelf area with arcuate coastline (Casnedi, 1983) belonging in our opinion to the margin of the Alessandria Basin, where they underwent reworking by tractive flows to form sandwave trains and local sand ridges. Coarse sediment input from the strait margin is regarded by Longhitano (2013) as a common distinctive element of the tidal-strait facies association. He defined as “strait-margin zone” an emerged area commonly tectonically active capable to generate huge flux of clastic sediments as debris-falls and debris flows descending perpendicularly to the seaway axis, where tidal currents can rework them into sandwaves.

The importance of the coeval carbonate fraction suggests that somewhere in the shelf area a carbonate factory was active, from which carbonate debris, mixed with a fan-delta-related terrigenous fraction, was transported and deposited both by ephemeral storm-driven flows and more continuous, tidal-related tractive flows.

A high-frequency orbital control, possibly implying small-scale eustatic fluctuations, may be envisaged in the generation of high-frequency sequences, especially those identified in the Scrivia Valley area, with mudstones rich in planktonic foraminifers alternating with sandwaves. On the other hand, a climatic control may be involved in the case of upward fining sequences consisting of fan-delta front deposits capped by sandwaves: it may be suggested that periods of massive introduction of terrigenous deposits were followed by periods of remission of the terrigenous influx, during which tractive reworking of previous deposits and mixing with a carbonate fraction could occur.

The Sorli section

The Sorli section (NE of the village of Albarasca, T. Borbera Valley) (Pl. XII) illustrates the *Gavi Siltstone Member of the Cessole Fm* in the eastern sector of the TPB, NE of the Scrivia Valley, where this member of the Cessole Formation lies with angular basal unconformity on the substrate, which was tilted, uplifted and eroded as a result of the Langhian tectonics (see below and Fig. 42b). The basal contact of the unit changes from conformable in the Scrivia Valley area to increasingly unconformable NE-wards with evidence of enlarging gap amplitude, and eventually transgressive onlap on emerged substrate starting from the Sorli area.

The lowermost part of the local succession, unconformably lying on the Oligocene Variano Sandstone, is represented by an interval characterized by ca. 2 m of mudstone with ripple trains, bioturbated by meniscus-burrows; this interval is truncated by an erosional surface marked by firm-ground with associated *Glossifungites* ichnofacies, in turn draped by pebbly glauconitic sandstone with clasts of limestones, gneissic rocks, ophiolites, chert, sandstone intraclasts derived from the underlying substrate, and shark teeth. This basal lag is followed first by trough cross-bedded sand and then by a succession ~60 m thick, consisting of packages of very fine thoroughly bioturbated sandstone interbedded with thin- to medium-bedded layers of fine sandstone showing local planar-parallel or hummocky lamination, or with isolated sandwaves (level 21-22), alternating with intervals of bioturbated siltstone to silty mudstone.

Interpretation

The lowermost part of the section is interpreted as a typical transgressive interval laid down on an emerged surface; the thin muddy interval overlying the basal unconformity is regarded as the record of a brief lagoonal episode, in turn truncated by a ravinement surface. An organization into parasequences can be identified in the following marine succession, consisting of a range of deposits including upper shoreface cross-bedded sand, lower shoreface and offshore-transition bioturbated fine sand with inferred storm layers, and shelf mudstones.

6.2.8. The Malvino Sandstone and Sant’Agata Fossili Marl (Fig. 30)

T. Lemme and Rio Mazzapiedi sections

A detailed section including the Malvino Sandstone and the Sant’Agata Fossili Marl has been measured in the Lemme Valley and has been complemented with observations along the Rio Mazzapiedi Valley, East of the Scrivia Valley (Fig. 30).

The *Malvino Sandstone* in this area is 35 m thick and consists of a succession of generally structureless, fine to very fine, grey silty sandstone and siltstone, overlying the Serravalle Sandstone. Bioturbation is pervasive, with tubes up to 3-4 cm in diameter. The stratification is poorly distinct, marked by alternating thin- to medium-bedded layers of fine-grained sandstone, with basal clear-cut and top transitional contacts, and siltstone interbeds of similar thickness. Common carbonized plant debris is associated with *in situ* fossils, such as corals, gastropods, otoliths and foraminifers, indicating a circalittoral environment (Robba, 1968). Rare, poorly persistent layers of medium-grained to granule-bearing sandstone 5-50 cm thick are interbedded at various levels of the succession.

East of the Scrivia valley this member thickens to up to 250 m, maintaining the same lithology. In the Vargo area the above lithologies interfinger with sandy turbidites encasing channelized resedimented fossiliferous sandstone-conglomerate deposits infilling a half graben bounded by a synsedimentary listric fault (the Vargo Fault). The uppermost part of the formation is commonly affected by slumping phenomena (see also Vervloet, 1966) and locally (S. Andrea area) by extensive, multiple slump scars (Clari and Ghibaudo, 1979).

Interpretation

Faunal assemblages and sedimentological features,

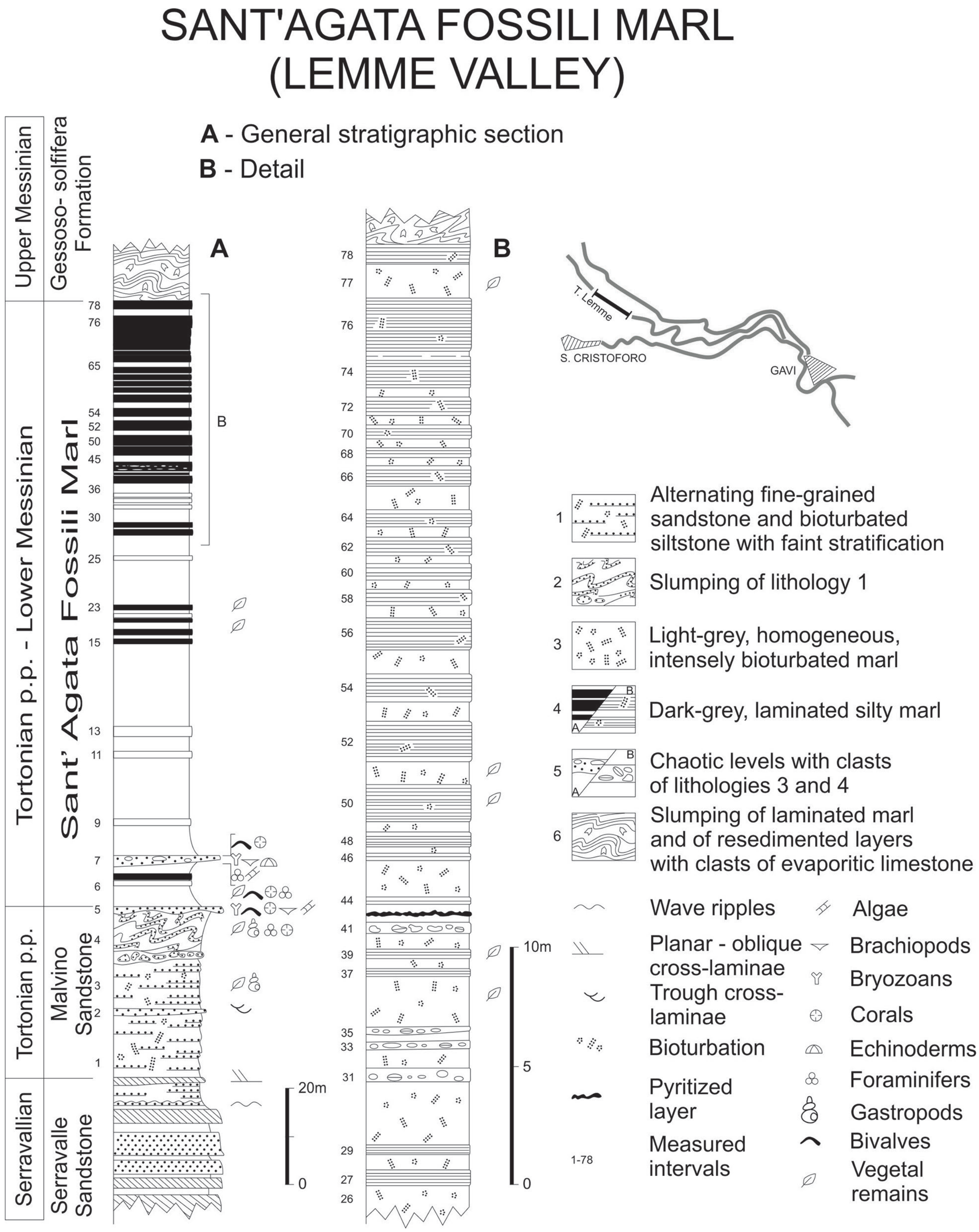

Fig. 30 - a) Log of the Sant'Agata Fossili section in the T. Lemme Valley. b) Detail of the upper part.

such as the fine-grained sandstone beds interpreted as storm layers, alternating with bioturbated mudstone, allow the attribution of the Malvino Sandstone to an outer shelf setting subject to delta influences. The resedimented, mass-flow coarse deposits of the Vargo area suggest a nearby fan-delta source. The pervasive gravity destabilization effects, such as slumping and slump scars at the top of the Malvino Sandstone suggest a general tectonic tilting with steepening of depositional gradients (Clari and Ghibaudo, 1979).

The outer-shelf Malvino Sandstone is sharply overlain by the *S. Agata Fossili Marl*, which is 94 m thick in the

Lemme Valley. In this area the formation shows favourable exposures and a more complete stratigraphic succession, whereas elsewhere a large part of the unit is eroded by the intra-Messinian unconformity. Three facies have been identified: muddy bioturbated facies, muddy laminated facies and chaotic facies (Fig. 30).

The muddy bioturbated facies

The muddy bioturbated facies is represented by grey, homogeneous, slightly silty hemipelagic marl, commonly rich in plant remains. An intense bioturbation completely obliterates any primary physical structure. A benthic fauna, generally sparse and even rare in the lower part of the unit (levels 8-42), is represented, in order of decreasing abundance, by gastropods, bivalves, scafopods, solitary corals, otoliths, cirripeds, chitonids, echinoids. Benthic macrofaunal assemblages (Sampò, pers. comm.) can be referred to the *Dentalium radula* paleo-community in the lower part (levels 8-42), and the *Sorgenfreispira moronii* paleo-community in the upper part (levels 43-78) (Pavia, pers. comm.; Robba, 1968), both indicating an upper bathyal environment.

The muddy laminated facies

The muddy laminated facies consists of grey-blackish silty mudstone layers 0.2 to 2m thick, characterized by thin and delicate parallel lamination due to the varved rhythm of thin millimetric silty laminae alternating with shaly laminae (Fig. 30). Bioturbation, as well as benthic macro- and microfauna, are completely missing. The microfauna in this facies consists almost exclusively of planktonic foraminifers.

The muddy laminated facies alternates with the homogeneous bioturbated facies, with contacts either sharp or rapidly transitional by means of increase of the bioturbation intensity in a short space. Worth noting is the local presence of thin (0.5-1 cm) levels of iron sulphide concretions. Figure 30 shows that the laminated layers are progressively thicker and more common upwards becoming preponderant in the uppermost, lower Messinian part of the succession.

The chaotic facies

The chaotic facies is represented by layers 0.2 to 1.2 m thick, locally interbedded with the other facies and predominantly occuring in the lower and intermediate intervals of the S. Agata Fossili Marl. Angular to sub-rounded intraformational clasts, 1 to 15-20 cm in diameter, of the two facies described above are chaotically embedded in a homogeneous marly matrix forming 30-50% of the volume. The lower and upper contacts of the layers are generally sharp and slightly irregular.

Interpretation

The Sant' Agata Fossili Marl appears to consist of bathyal hemipelagites. The sharp transition from the Malvino Sandstone to the marls highlights a very rapid drowning event, heralded, as noted above, by pervasive gravity destabilization effects at the top of the Malvino Sandstone.

A slope setting prone to destabilization is confirmed by the presence of chaotic levels with intraformational clasts, interpreted as the product of intrabasinal debris flows, probably resulting from the dismembering and chaoticization of slumped masses in the last phase of their downslope translation.

Particularly significant is the rhythm of alternating bioturbated marls with benthic faunas and blackish laminites devoid of any benthic faunal element. The varved lamination is probably seasonal, with silty laminae reflecting a seasonal increase in suspended fine terrigenous input. The rhythm is attributed to cyclic variations of oxygen content at the sea bottom in a situation of progressive confinement of the depositional environment at the Tortonian-Messinian transition and during the early Messinian (Ghibaudo et al., 1985; Dela Pierre et al., 2010). As above outlined, this is linked with the specific paleogeography which was established in the Mediterranean since the late Tortonian. The progressive isolation of this sea from the world ocean led to important changes in the water circulation and deep-water ventilation. The occurrence of periodic bottom water anoxia alternating with intervals of bottom oxygenation is generally referred to short-term climatic fluctuations induced by the precession astronomical cycles (e.g. Hilgen and Krijgsman, 1999). Orbital-forced variations in climate are thought to be involved (Krijgsman et al., 1995; Hilgen et al., 1995). Laminites coincide with periods of wet climate and precession minima; bioturbated marl with dryer periods and precession maxima. It is commonly envisaged that enhanced runoff from the land during the wet periods increases the transport of siliciclastics and land-derived organic material towards the basin (Schenau et al., 1999). At the same time, the large fresh-water input causes water stratification and shoaling of the pycnocline, so that nutrients become concentrated in the photic zone (Rossignol-Strick, 1983). The high productivity combined with the water stratification causes restriction of deep-water ventilation resulting in oxygen depletion and preservation of organic material (Mangini and Schlosser, 1986). The fact that the laminites become preponderant in the uppermost, lower Messinian part of the Sant'Agata Fossili Marl suggests more and more restricted and oxygen-poor conditions at the transition to the salinity crisis of the Messinian.

6.2.9. The Cassano Spinola Conglomerate (Pl. XII)

C. Pian delle Botte and Scrivia R. sections

The Cassano Spinola Conglomerate belongs to the upper part of the Messinian post-evaporitic interval. Its base is a subaerial surface, deeply erosional into the substrate (Pls. I, VII online; Fig. 3), locally reaching the S. Agata Fossili Marl, and in places appearing as angular unconformity. As a result of the erosional contact, and of the irregular top surface of the underlying Valle Versa Chaotic Complex, the formation shows large thickness changes even over small distances. The thickness in the area located East of the Scrivia Valley, where the formation is quite well exposed, is about 550 m; to the West, it ranges from 70 m (N of Orsara Bormida) to 300 m (Alice Bel Colle). The overall trend is coarsening upwards.

Two sample sections have been measured; they are represented in the stratigraphic log of plate XII as vertically stacked segments separated by ca. 150-200 m of deposits, not represented in the log. The first segment has been measured in the lower part of the succession (on the right bank of the Scrivia River, near C. Pian della Botte, ca. 1 km West of Monterosso) and the second in the upper part of the succession (ca. 1 km downstream of the first, near the bridge of the S.S. 35 connecting Serravalle Scrivia with Cassano Spinola).

The main body of the unit, occurring in the SW area, is made up of coarse-grained facies, whereas, to the NE, it subdivides into a fringe of alternating sandstone-conglomerate tongues and pelitic intervals. The tongues may reach a thickness of 20-30 m, and a lateral extent ranging from some tens of metres to 6 km (e.g. the Ricaldone body); in places where conglomerates lie on mudstones, their contact is generally sharp and erosional. In the lower part of the formation the clast composition is dominated by sedimentary rocks, such as sandstones, micritic limestones, marly limestones, biocalcarenites and rare ophiolites; these are replaced in the upper part by abundant clasts of greenstones such as amphibolites, prasinites, ophicalcites, serpentinites, eclogites, gabbroic rocks, associated to recycled conglomerates.

Facies description and interpretation are mainly from Ghibaudo et al. (1985).

Facies 1

Coarse-grained conglomerates (cobbles and boulders), clast supported, with sandy-pelitic matrix, disorganized or poorly organized, in thick to very thick, irregular beds with faintly developed normal or rarely inverse grading. Conglomerate beds grade commonly upwards, with sharp or transitional contact, to discontinuous layers of moderately sorted coarse to granule sandstone lenses with crude planar lamination.

Facies 2

Poorly to moderately organized pebble-cobble conglomerates with sand matrix, better sorted than facies 1, with faint to moderately developed grading and clast imbrication, occurring in thick to very thick beds (50-150 cm) showing lenticular geometry in sections transverse to paleocurrents and weakly erosional basal contact. They commonly grade upwards into decimetre-thick layers of coarse to granule sandstone or microconglomerate, homogeneous to crudely planar-laminated, with trains of small pebbles parallel to the stratification.

Facies 3

Medium-grained to microconglomeratic sandstone with thick and poorly developed planar-parallel laminae and/or medium-scale cross laminae, alternating with thin pebble layers. Tabular geometry with good lateral persistence.

Facies 4

Medium- to very coarse-grained, locally microconglomeratic sandstone showing normal grading and sometimes planar-parallel lamination, in layers 15-100 cm thick, amalgamated, or more commonly with mudstone interbeds variably thick (some cm to some tens of cm) with sparse *Planorbis*. Sandstone beds show tabular geometry with sharp or locally small-scale erosional basal contact and contain worn oyster fragments.

Facies 5

Mud-supported disorganized conglomerates, some tens of decimetres to 1.5 m thick, pinching out within surrounding mudstones and associated with other resedimented deposits.

Facies 6

Dark-grey, silty mudstones with common plant remains, either homogeneous, or showing a varve-like rhythmic pattern formed by mudstone laminae or thin layers, closely interbedded with millimetric to centimetric, sharp-based laminae or layers of silt to fine sand, sometimes graded and locally showing small-scale current ripples; wavy/convolute lamination is locally observed. Fresh- to brackish-water sparse fauna is represented by *Saccoia, Melanopsis*, *Theodoxus* sp., indicating affinity with the well-known “Strati a Congerie” of the so-called “Lago Mare”.

Paleocurrents

A total of 21 paleoflow measurements, from clast imbrication and subordinately medium-scale cross bedding indicates a quite dispersed pattern showing a preferential transport direction toward NW.

Internal architecture

The succession appears to be organized into megasequences. The main conglomerate body cropping out in the SW area is made up of facies 1, 2, and subordinately 3, vertically organized, at least in the middle-upper part of the succession, into three megasequences fining upwards. In the north-eastern area the formation shows a predominant organization into symmetrical megasequences, with a lower upward-coarsening part, where facies 2 and 3 occur at the top of a succession of facies 6 to 4, and an upper part with upward-fining trend. In the NE sector, where the formation subdivides into a fringe of alternating coarse and fine intervals, small-scale, upward coarsening cycles are locally observed. These consist of homogeneous marly siltstones incorporating with upward increasing abundance layers of medium-fine sandstone 15-30 cm thick with planar-parallel lamination and commonly wave ripples at the top, grading in the upper part to fluvial deposits.

Interpretation

Facies 1: subaerial debris flow units, capped by waning-stage deposits, typically occurring in the proximal part of alluvial fans. Facies 2: Stream-flow deposits linked to main and secondary channels crossing the fan intermediate parts, mostly generated by the accretion of sandy-gravelly longitudinal bars. Similar deposits are described by numerous authors (e.g. Gloppen and Steel, 1981 cum bibl.). Facies 3: Sheet-flow deposits laid down by a network of very shallow braided systems separated by low-relief bars in the distal reaches of the fans (e.g. Bull, 1972). Facies 4: turbidites laid down in a body of still water, probably linked to fluvial floods encroaching on a water body. Facies 5: subaqueous debris flow deposits. Facies 6: deposition by settling of fines in a fresh to brackish (probably lagoonal) body of water, with periodic influx of diluted turbulent suspensions (possible hyperpycnal flows) linked to minor or distal floods.

The overall trend of the Cassano Spinola Conglomerate is coarsening upwards, reflecting the progradational pattern of the fan-delta system into a lagoonal-lacustrine body of water. The megasequences occurring in the main conglomerate body cropping out in the SW area are characteristic of the proximal, entirely subaerial part of the system. On the other hand, those occurring in the NE area record the fringing-out, distal part of the system interfingering with the adjoining water body.

Several authors agree in considering that the fan to fan-delta megasequences reflect a tectonic control (e.g. Steel and Wilson, 1975; Steel et al., 1977; Heward, 1978; Gloppen and Steel, 1981). The upward-fining, entirely subaerial megasequences of the proximal part should reflect phases of rapid uplift followed by the progressive denudation and retreat of source areas (Steel and Wilson, 1975), whereas the symmetrical megasequences of the distal parts of the fan-delta system should reflect first the progradationl stage as a response of source area uplift, then source area retreat leading to progressive reduction of the coarse terrigenous input. The upward change in the clast composition reflects the progressive denudation of source areas.

The smaller-scale cycles typical of the NE portion of the fan-delta system record periodic submergences by lagoonal to lacustrine water bodies and probably represent climate-controlled small-scale progradational cycles.

7. TECTONO-STRATIGRAPHIC EVOLUTION OF THE STUDY AREA

7.1. INTRODUCTION

This section aims at illustrating the tectono-stratigraphic evolution of the area. Only qualitative structural data are presented, since a detailed structural analysis is out of the focus of this work. These data, however, integrated with the stratigraphic and sedimentological aspects of the succession, provide significant constraints on the geologic evolution of the basin.

The cross-section of Plate II summarizes the geometries, structural setting and the latero-vertical relationships of lithostratigraphic units. It is on average oriented SW-NE (Fig. 1), i.e. roughly perpendicular to the average dip direction of the succession. In the Langhe area the Chattian-Burdigalian lithostratigraphic units cropping out in the Bormida di Spigno Valley have been projected on the plane of the cross section. The cross section of Plate II is intended to focus on the stratigraphic architecture of the basin fill, and to primarily show the effects of the extensional block faulting; for sake of clarity of the representation, it does not highlight the effects of the compressional and transpressional deformation episodes.

As noted above, plate VI (online) shows the map at 1:75000 scale supplemented with the specific denominations of the structural elements, whereas Plate VII (online) shows the areal distribution of the structural elements and the main unconformities.

The Oligo-Miocene stratigraphic succession dips, on average, to NW and NNW, defining a regional homocline. The dip angles of the beds predominantly vary between 8° and 12°. The structural elements that characterize the study area consist predominantly of high-angle fault systems, some large-scale listric faults and, less commonly, small- to medium-scale folds and thrusts. Most folds are inferred to be fault-related. The most important structure is the approximately E-W-striking Villalvernia-Varzi line, which during the Oligocene-early Miocene acted repeatedly as a strike-slip fault separating the Borbera-Grue area from the Apennines (e.g., Di Giulio and Galbiati, 1995; Felletti, 2002). Faults within the basin show two main directions: NNW-SSE to NW-SE and E-W to ENE-WSW.

A structural partition of the TPB, anticipated to some extent since the early Oligocene (Rossi et al., 2009), became fully developed in the late Oligocene-Aquitanian, when, according to Gelati and Gnaccolini (1998), the following paleogeographic domains from west to east were differentiated: the Monregalese High, the Langhe Sub-basin, the Alto Monferrato High and the Scrivia-Borbera Trough (our Borbera-Grue Sub-basin).

The distribution of the structural elements is not uniform. A look to the geologic map (Pls. I and VII online) highlights a remarkable differentiation: from the Cremolino-Ovada zone to the eastern margin of the study area the tectonic architecture is relatively simple, characterized by a horst and graben structure linked to NNW-SSE striking faults active during the mid-Rupelian stretching stage. Sealing of most faults by the Lerma Glaucony is evident in this area. Conversely, the central and western areas show a remarkably denser network of faults. In particular, the area located between Ovada and Malvicino, corresponding to the strongly positive Alto Monferrato High, displays a prominent fault system oriented around the E-W direction, overprinting the former Rupelian extensional system. In the central area a NW-SE oriented system appears, that becomes diffusely present in the Langhe Sub-basin; moreover, the lineaments striking on average E-W in the central area gradually change to a predominant ENE-WSW direction in the Langhe area.

7.2. PRIABONIAN TO EARLY RUPELIAN EVENTS IN THE EASTERN TPB AREA

7.2.1. Stratigraphy

The geologic history of the Tertiary Piedmont Basin began with a Priabonian to early Rupelian stage of evolution with peculiar characteristics affecting a limited area of the future TPB, namely the Borbera-Grue sector. In order to have a complete picture of the succession of events involving the whole TPB basin, it is necessary to give a brief hint on this early part of the history, although most of the involved area has not been the subject of a field survey.

Deposits of Priabonian-early Rupelian age pre-dating the deposition of the Molare Formation are only preserved in the eastern part of the TPB (Fig. 31), whereas they are missing elsewhere in the TPB, except for localized and limited continental deposits (Pianfolco Formation). In the eastern TPB the Priabonian to lower Rupelian succession lies unconformably on the Monte Antola Formation and internal Ligurian units and is comparable to that of the adjacent north-Apenninic area. It is briefly described here using the names of formational units of the 1: 50000 Geological Sheet Cabella Ligure (2014), namely the Monte Piano Formation, Dernice Formation, Grue Formation, Rio Trebbio Sandstone, and Monte Rivalta and Val Borbera members of the Savignone Conglomerate. We will refer to this group of units as Ranzano Allogroup, regarded as representative of a peculiar palaeogeographic and palaeotectonic setting (see below). This designation is close to that adopted by most authors (e.g. Di Giulio and Galbiati, 1995; Martelli et al., 1998; Cibin et al., 2001) (Fig. 31).

The Monte Piano Marl, the oldest unit of the Ranzano Allogroup (Priabonian, MNP18-MNP19 p.p.) lies unconformably on the Ligurian substrate deformed by the Meso-alpine tectonics and is attributed to a lower to middle bathyal marine environment (Mancin and Pirini, 2002).

The Dernice Formation (Priabonian, MNP19 p.p.-MNP21a p.p.; Catanzariti et al., 1997), corresponds to the Pizzo d’Oca Unit of Mutti et al. (1995) and Bernardeschi (2009), and consists of coarse- to fine-grained turbidites characterized by European and/or Insubric crust-derived detritus (B petrofacies of Cibin, 1993). This unit shows discontinuous areal extent and highly variable thickness from a maximum of 200 m to zero, and its lower limit is a sharp unconformable contact with the Monte Piano Marl.

The Grue Fm (Priabonian-lowermost Rupelian, MNP21a p.p.-MNP21b) is a turbidite unit characterized by remarkably lenticular geometries with rapid lateral pinchout and erosional base.

The Rio Trebbio Sandstone (lower Rupelian, MNP22 p.p.) consists of fossiliferous and bioturbated shelf sandstones and shows evidence of cannibalization of former deposits and abrupt regression (Cavanna et al., 1989; Di Giulio 1990; Mutti et al., 1995; Dela Pierre et al., 2003).

The coarse-grained deposits of the Monte Rivalta Member of Savignone Conglomerate (lower Rupelian, MNP22 p.p.) are attributed by Marroni et al. (2014) to prograding deltaic systems fed by hyperconcentrated flows. The Val Borbera Member of the Savignone Conglomerate (lower Rupelian, MNP22 p.p.) is a huge conglomerate complex whose thickness estimate varies among authors from 1300 m to 2500 m. It constitutes the infill of a structural depression inferred by Mutti et al. (1995) to be a transtension-related pull-apart basin. This basin was originally bounded by the NNW-trending Merlassino fault at the eastern side and the NW-trending Spinti Fault at the western side; this fault system probably confined also the southern, highly tectonized, conglomerate complex cropping out in the Savignone-Vobbia area. The conglomerates infilling the Borbera trough are compositionally dominated by limestone clasts of the Monte Antola Fm forming the local substrate of the succession. Di Biase (1998) and Marroni et al. (2014) considered the Borbera conglomerates a foreset-bedded prograding system. Rather than a single body, the complex is probably a tectonically controlled multiple system of stacked Gilbert-type delta bodies with high-gradient clinoforms of upward increasing height (Figs. 4c, 32). The delta complex was probably fed by hyperconcentrated flows originated by catastrophic floods from emerged, tectonically active areas, characterized by high-relief topography, subject to active erosion. The direction of progradation is difficult to define, given the intense tectonization of the conglomerates; considering that the present-day W or NW dip of the conglomerates certainly includes a component of the original primary dip of the foresets, an approximately north-westerly progradation can be supposed. In the lower part of this unit Gelati and Gnaccolini (1978) documented transgressive horizons, whereas the middle-upper part shows evidence of gravity-driven hyperconcentrated flows.

During the above delineated Priabonian to early Rupelian stage of TPB evolution, evidence of a sill at the location of the future VV Line separating the TPB and north-Apenninic depositional areas is lacking (Di Giulio and Galbiati, 1995; Mutti et al., 1995 with references therein).

Elsewhere in the TPB, possibly coeval sediments are those forming the continental-lacustrine complex of the Pianfolco Formation, cropping out in a very limited area.

7.2.2. Tectonic evolution

The succession of the Ranzano Allogroup was laid down in a setting controlled by an intense and prolonged synsedimentary tectonics, as indicated by several unconformities and angular discordances bounding the various units and sealing repeated deformations (Di

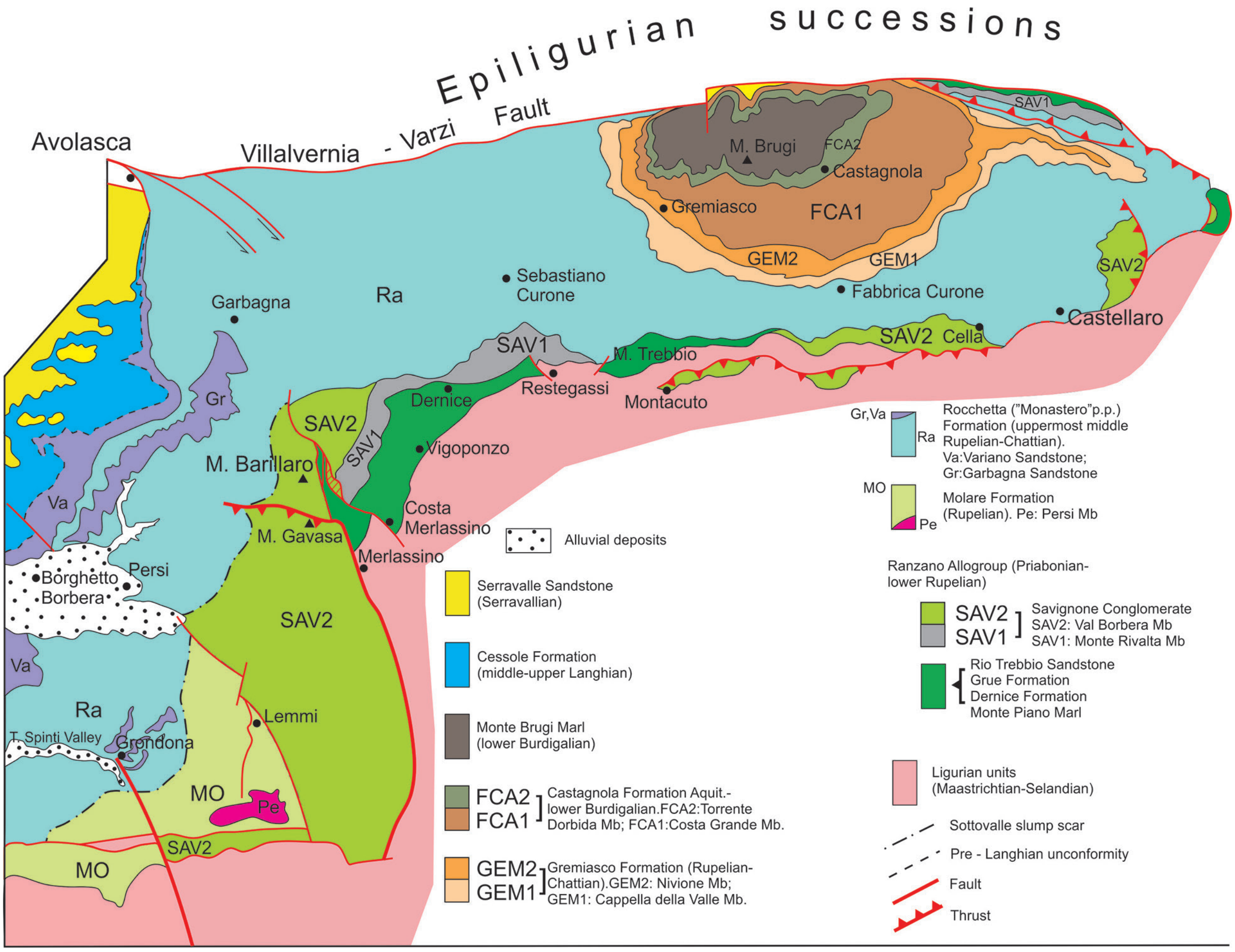

Fig. 31 - Schematic geological map of the eastern part of the TPB. Sources: 1: 100.000 Geological sheets Voghera and Rapallo, Fossati et al. (1988), Cavalli (1988), Trivioli (1990), Di Biase (1998), Bernardeschi, (2009), 1:50000 Geogical Sheet Cabella Ligure (2014), Festa et al. (2015), and, to a limited extent, our field survey data.

Giulio, 1991; Trivioli, 1990; Bernardeschi, 2009). The diagrammatic reconstruction presented by Bernardeschi (2009), suggests, for the entire succession, the persistence of pulsating strike-slip tectonics.

The transition from hemipelagic Monte Piano Marl to turbiditic sedimentation of the Dernice Fm is also recorded in the Epiligurian succession of N-Apennines, and in the succession of Western Alps (Marnes Bleues-Grès d'Annot) (Mutti et al., 1995; Bernardeschi, 2009). Bernardeschi (2009) argued that, during the deposition of the Pizzo d'Oca unit (corresponding to the Dernice Fm), high-angle extensional faults with strike-slip component began to form, leading to the delineation of highly subsiding depocentres. The succession including the Monte Piano Marl, Dernice Fm, and Grue Fm, was described by Di Giulio (1991) as deformed in several places by pluridecametric, locally overturned folds, and bounded at the top by an angular unconformity. Antiformal, north-verging folds with axes directed ENE-WSW are present within the units of the Ranzano Allogroup predating the Val Borbera Member in the areas of Dernice, Mt. Rivalta and Case Poldini with decreasing deformation effects upward in the succession (Trivioli, 1990). Bernardeschi (2009) stressed the importance of a repeatedly activated lineament, the Merlassino Fault, which created accommodation space for the adjacent succession of the Val Borbera Member of the Savignone Conglomerate. The angular unconformity at the base of this member is regarded by Mutti et al. (1995) as the record of an important tectonic and sedimentary break, indicated as Phase Ligure II of presumed late Priabonian or eo-Rupelian age, responsible for the creation of structural highs formed by rocks of the Monte Antola Fm, whose denudation fed the Savignone fan-delta systems. Specifically, Mutti et al. (1995) suggested that the contact zone between the Monte Antola Fm and the Voltri Group is to be considered the lateral ramp of a northward verging upthrust of the Voltri Group onto the western part of the Mount Antola Fm with its cover, as a result of transpression along the Sestri-Voltaggio Line during the Phase Ligure II. This proposal is shared by Miletto and Polino (1992), Polino et al. (2007), Capponi et al. (2009), and Vercesi et al. (2014). In our opinion the uncovering and exposure to erosion of the Voltri Massif postdates the deposition of the Savignone Conglomerate. We share the Vignaroli et al. (2009) contention that the exhumation of High-Pressure (HP) metamorphic units of the Voltri Massif and their exposure to erosion results from extensional detachments associated with normal faulting which can be placed at ~30 Ma, in the early Rupelian, during a phase of crustal stretching which affected the whole TPB (see below) and was concomitant with the deposition of Molare Conglomerate. In our opinion, the phase Ligure II may be regarded as a stage of wrench tectonics preceding and accompanying the deposition of the Val Borbera Member of the Savignone Conglomerate. This contention is supported by the huge space creation involved in the generation of the structural depression which rapidly accommodated the spectacularly thick succession of conglomerates, and the presumably concomitant dramatic relief created by the uplift of the Antola High. Structural measurements performed by Trivioli (1990) at several sites within the Val Borbera Member yielded strain ellipsoids compatible with a deformation typical of transcurrent zones. This author specifically observed that in several points the pebbles of the conglomerate show open fractures infilled with matrix, suggesting early deformation in a stage preceding the lithification of the conglomerate (Fig. 32).

Proof of tectonic deformation during the deposition of the upper part of the Val Borbera Mb of the Savignone Conglomerate is given by the fact that the Costa Merlassino Fault is sealed by the late stage conglomerates, with evidence of reverse faulting associated to a component of dextral transpression (Trivioli, 1990), as attested by the splays indicated in the Cabella Ligure Geologic Sheet. Moreover, the change in composition of the uppermost conglomerates, which include increasing amounts of ophiolitic detritus, indicates a change in the source areas, suggesting uplift of the western block (possibly along the Scrivia Fault). An evolution is suggested, expressed first by a transtensional regime concomitant with the opening of the Val Borbera structural depression (as suggested by Mutti et al., 1995) and with the deposition of the conglomerates, then by transpression in the latest stage of the infill.

In western TPB, the geological map of the Pianfolco area published by Charrier et al. (1964) shows high-angle, probably transcurrent faults oriented NNW-SSE crossing the Brecce della Costa di Cravara and sealed with angular unconformity by the overlying marine sandstones of the Molare Fm. The precise age of this tectonics remains indeterminate, being only fixed its priority with respect to the Molare Sandstone.

In conclusion, we believe that the observed stratigraphic context and the repeated internal unconformities of the Ranzano Allogroup are indicative of a virtual continuum of deformation throughout the succession, with predominance of strike-slip tectonics.

7.3. THE MID-RUPELIAN EXTENSIONAL BLOCK-FAULTING

An important stretching phase occurred in the middle Rupelian, during which the eastern and western sectors evolved jointly, although still with significant differences. Block faulting with approximately E-W direction of extension (in present-day coordinates) displaced the pre-Cenozoic basement and controlled the sedimentation of the Molare Conglomerate. Crustal stretching resulted in intense vertical mobility leading to the dissection of the substrate into differentially subsiding blocks as horst and grabens bounded by normal high-angle faults deep-seated in the metamorphic basement (Mutti et al., 1995, 2002; Maino et al., 2013; Ghibaudo et al., 2014) (Pls. I and II; Fig. 32). The structural depressions accommodated a rapidly accumulating succession mostly consisting of conglomerates. A clastic contribution from the Voltri Massif is supported by compositional data (Gnaccolini, 1974) and is compatible with the hypothesis of the exhumation of this massif as a result of an extensional episode (Vignaroli et al., 2009), synchronous with the early stages of the TPB sedimentation.

The involved, primarily normal faults are mostly oriented NNW-SSE in the central-eastern area (Pl. VI online). The most representative among them, in this area, are, from east to west, the Lemmi, Spinti, Scrivia, Lemme, Sestri-Voltaggio, C. Robella, S. Lucia, and Rio Granozza faults, bounding the Lemmi-Spinti, Borlasca, Lerma, and Albareto grabens. In western TPB (Langhe area) the involved faults are mostly oriented NW-SE and include the Malvicino and C. Foglino faults bounding the Cartosio Graben, and the Case Tone and Rio Ammogliazza faults bounding the Borgo graben. Major structural elements include, from E to W, the Cabella Ligure Horst, the Lemmi-Spinti Graben, the Scrivia Horst, the Borlasca Graben, the Voltaggio Horst, the Lerma Graben, the Belforte Horst, the Albareto Graben, the Acqui Terme Horst, the Cartosio Graben, the Spigno Monferrato Horst, the Borgo Graben and the Rocchetta Cairo Horst (Pls. I and II). Listric normal motion accompanying the graben opening can be locally identified (Fig. 33a). The block faulting in the TPB area was accompanied to the S by the uplift of the basement of Ligurian Alps (Fig. 33 b,c).

The first palaeogeographical differentiation within the TPB may date to this stage. The embryonic delineation of the Alto Monferrato High (Rossi et al., 2009; Mosca et al., 2009) is indicated by the reduced thickness of the Molare Fm in the Prasco, Cavatore, Ponzone, Cimaferle and Bandita areas, compared to the area of the future Langhe Sub-basin, and the area located East of Belforte Monferrato (Pl. I).

The coarse-grained deposits of the Molare Formation infilling the lows imply unroofing and denudation of a quite rugged, block-faulted topography. Uplift of basement rocks in southern source areas during the deposition of the conglomerates resulted in internal and progressive unconformities in the sedimentary succession (Fig. 33 b,c). The strong tectonic control led to large variability in thickness and composition of the deposits, the latter mostly reflecting the local substrate (e.g. Mutti et al., 1995, 1996, 2002). Gelati and Gnaccolini (2003) argued that provenance of the Molare conglomerate was from

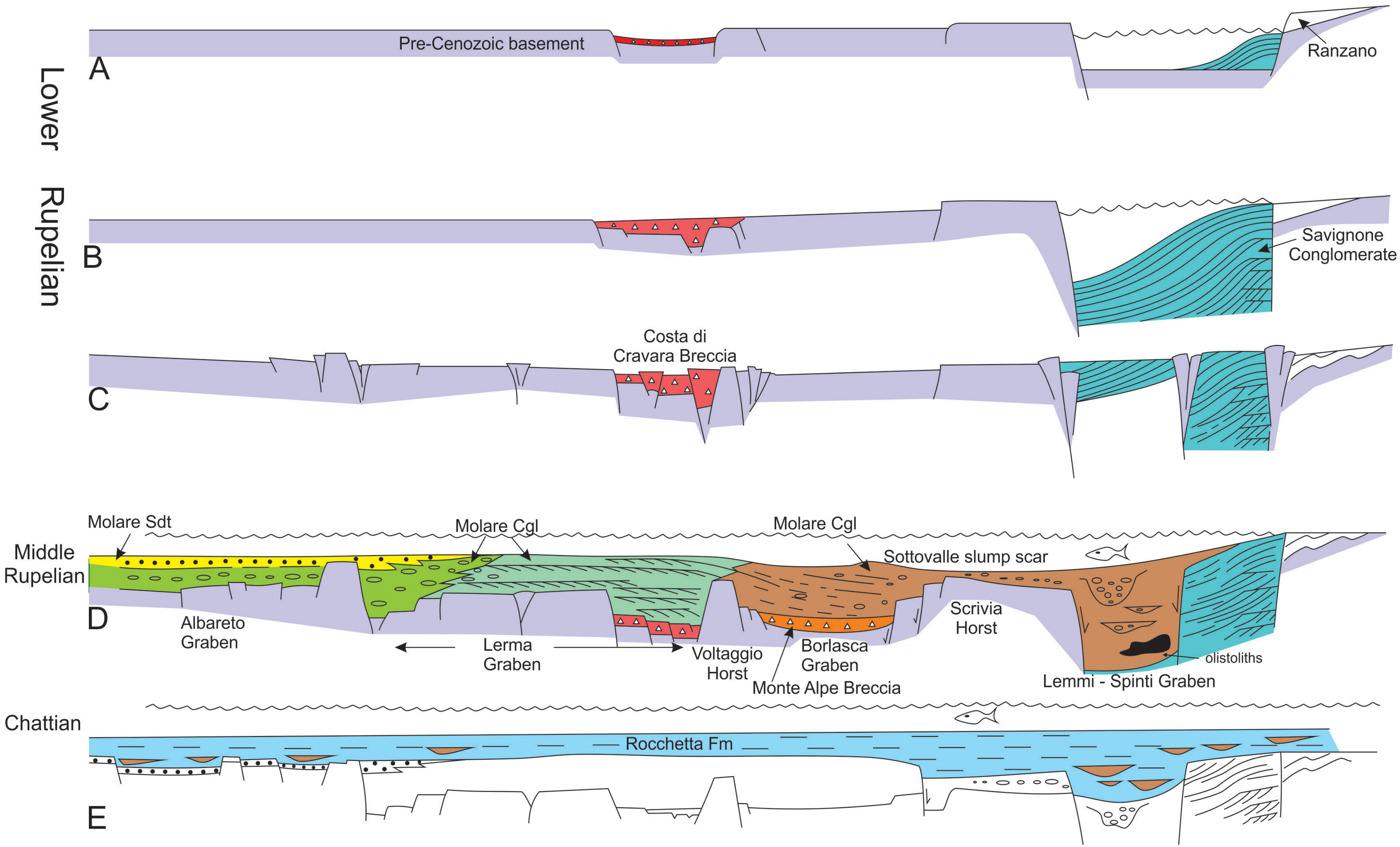

Fig. 32 - Schematic reconstruction of the tectono-sedimentary evolution of the TPB from the early Rupelian to the late Chattian. Note specifically that the Savignone Conglomerate and the Molare Conglomerate are regarded as the record of successive sedimentary stages separated by tectonic deformation, and that the latter graben-infilling unit is characterized by westward younging and change in facies associations from deep-water turbiditic to deltaic to continental.

rocks represented in the highlands located in the present-day area of Ligurian Alps (Briançonnais succession and Voltri Group). Paleoflow approximately NE-wards to N-wards (in the present-day coordinates) was confirmed by our observations of clast imbrications (Fig. 33).

The extensional strain apparently affected the TPB as a sort of wave shifting diachronously from the east to the west, with a change in the dimensions of the generated structural troughs and thickness of the related infills (Fig. 3). In the eastern TPB the structural depressions are slightly older and deeper than the western troughs. Moreover, significant changes in facies associations can be observed in the East-West direction. A fan-delta slope setting in eastern areas changes westwards first into a deltaic depositional context, and then into a continental setting dominated by catastrophic flooding. The Lemmi-Spinti Graben in the Borbera-Grue area was generated by the activation of the Lemmi Fault and re-activation of the Spinti Fault, leading to the rapid downwarping and dramatic drowning of a tectonic block formerly seat of deposition of Savignone Conglomerate. Deep-water coarse-grained resedimented Molare deposits infilling the graben show marked facies change with respect to the Savignone Conglomerate. Rapid tectonic subsidence and creation of tectonic scarps are testified by the accumulation, in the lower part of the graben infill, of gravity-emplaced olistoliths and olistostromes which typify a lithozone named Persi Member in the Geologic Sheet Cabella Ligure (Persi Lithozone in our lithostratigraphy). Importantly, this lithozone and the overlying deposits of the Molare Fm (Monastero Fm in Trivioli, 1990) include detritus derived from the denudation of Penninic high pressure-low-temperature metamorphic units (Cortesogno and Haccard, 1984; Martelli et al., 1998; Di Biase and Pandolfi, 1999; Cibin et al., 2001; Vignaroli et al., 2008; Bernardeschi, 2009).

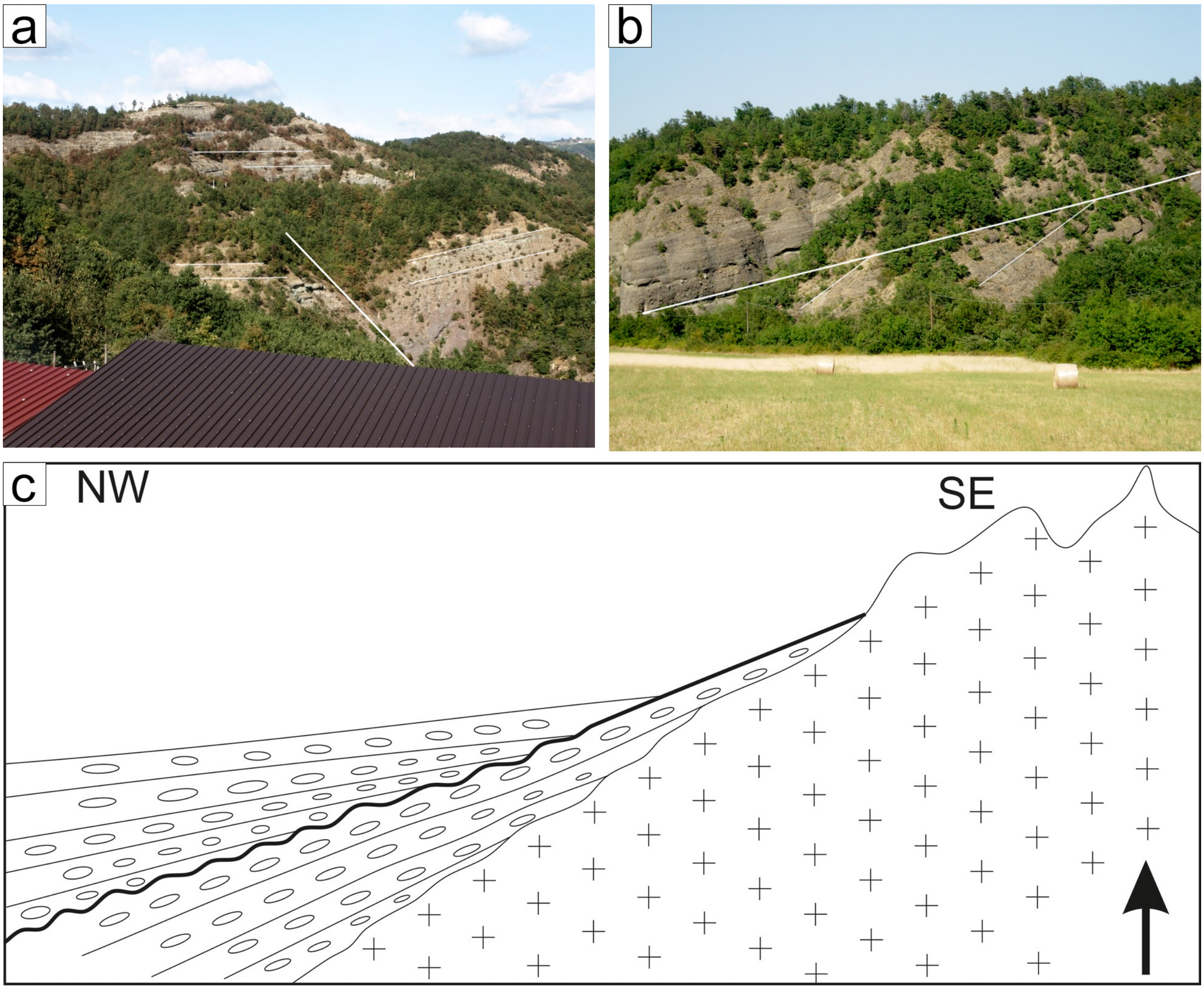

Fig. 33 - Structural elements inferred to be linked to the phase of middle Rupelian crustal stretching. a) Listric synsedimentary growth fault in the continental Molare Conglomerate (stratification highlighted by white lines). Near C. Ramale (NW of Monteacuto). b) Synsedimentary angular unconformity in Molare Conglomerate interpreted as growth structure linked to uplift of the basement (out of the photo, to the right). Right bank of the Orba River, in front of Castel Cerreto. c) Uplift of basement rocks in southern source areas of the Molare Conglomerate results in internal and progressive unconformities in the sedimentary succession (drawn from a photo; SW of Albareto, near C. del Signore).

Minor amounts of clasts from HP rocks are indeed reported also in the Pianfolco Fm (Charrier et al., 1964; Carrapa et al., 2004) and in the Savignone Conglomerate (Carrapa et al., 2004), indicating that the exhumation, although rapid, was progressive, with uplift and erosion first of upper crustal levels and then of deeper units of the orogenic wedge. After the mass wasting episode recorded by the Persi Mb, the Lemmi-Spinti Graben accommodated impressive accumulations of turbidite sandstones and disorganized conglomerates in an inferred fan-delta slope to base-of-slope depositional environment, as infill of channels and, near the village of Sasso, a large-scale submarine erosional feature accommodating coarse conglomerates, interpreted as large canyon carved in the slope. West of the Lemmi-Spinti Graben, the Borlasca graben was infilled by fan-delta front conglomerates grading upwards to fan-delta slope deposits, and, further westwards, the Lerma graben was invaded by stacked wedges of Gilbert-type deltas. Large olistoliths present in the lower part of the Lerma graben infill (upper valley of Rio Roverno) are possibly coeval to the gravity-driven accumulations of the Persi Member. The Lerma and Borlasca grabens were initially separated; after the burial of the intervening Voltaggio Horst, they became part of a wider depression which accommodated the uppermost 300 metres of the local succession. Further westwards, the shallower and younger Albareto, Cartosio and Borgo grabens were essentially infilled with continental deposits linked to coalescing alluvial fans and subordinately braided streams and scree processes linked to denudation of fault scarps; nearby uplifting catchment areas of rugged relief were subject to high rates of denudation and high-gradient transfer zones (Mutti et al., 1996).

7.4. THE MID-RUPELIAN STRATIGRAPHY AND TECTONICS

After the deposition of the Molare Conglomerate the western TPB and part of the Alto Monferrato High were flooded by transgressive marine shelf sands (the Molare Sandstone) (Pls. I and II) linked to a storm-dominated fan-delta depositional system and characterized by storm layers, episodic hyperpycnites and local coarse fan-delta front deposits. The transgressive deposits covered first the continental conglomerates infilling the structural depressions, such as the Albareto, Cartosio and Borgo grabens, and then the adjacent horsts, where they were laid down directly on the pre-Cenozoic basement (Fig. 32) with development of typical rocky shore monomictic boulder conglomerates (e.g. on the Spigno Monferrato Horst). Flooding on emerged landscapes led to the development of a prominent ravinement surface covered by a transgressive heterometric and discontinuous lag up to some metres thick of well-rounded pebbles to boulders derived from the local substrate (Fig. 6b). The coarse transgressive lag possibly correlates eastwards with the San Rocco horizon described by Gnaccolini (1978) in the Lerma-Lemme Valley area, where it is intercalated in a succession of fan-delta conglomerates.

The shelf sandstones pass laterally eastwards into time-equivalent coarse fan-delta deposits of the Lerma area, and, farther eastwards, into fan-delta slope deposits of the Borlasca and Lemmi-Spinti grabens (Figs. 3, 32). Like the Molare Conglomerate, the Molare Sandstone as well is regarded as a diachronous unit, with increasingly younger ages toward the south-western margin of the basin (Lorenz, 1969; Rossi et al., 2009).

An important synsedimentary tectonic episode, characterized by the first activation of the VV Line (VV Line hereafter) in a left-lateral strike-slip regime (Di Giulio and Galbiati, 1995), took place in the late middle Rupelian. In the easternmost sector of the TPB this tectonic phase is recorded by important transpressional and contractional structures, linked to the pronounced restraining bend of the VV Line, which turns there from E-W to NW-SE direction; as a result, the area became a favourable location for compressional and contractional stress due to left-lateral motion along the line (Phase Ligure III of Mutti et al., 1995; Di Giulio and Galbiati, 1995). Di Giulio and Galbiati (1995) noted that N-ward overturned folds deform their sequences S1 and S2 (respectively upper Priabonian and lower Rupelian in age, both belonging to the Ranzano Allogroup), and the basal part of sequence S3 (middle-upper Rupelian). Contractional structures include the *ca.* E-W trending, north-verging major thrust developed between Montacuto and Castellaro, bringing the Ligurian substrate to overthrust the deposits of the TPB, the E-W trending Monte Trebbio syncline, which deforms the Dernice Fm and the Rio Trebbio Sandstone, and the large syncline involving the Savignone Conglomerate (Gelati and Gnaccolini, 1978; Trivioli, 1990; Bernardeschi, 2009; Marroni et al., 2014). Mutti et al. (1995) stressed that this deformation led in eastern TPB to internal unconformities, and inversion by dextral transpression of the former extensional NNW-striking system, such as the Merlassino Fault. This deformation, documented by tilting and folding the Priabonian-early Rupelian part of the succession, is testified by the important, in places angular, unconformity dated to the Rupelian Zone MNP 23 (Marroni et al., 2014) at the base of the "Monastero Formation" (mostly corresponding to our Rocchetta Fm). However, the deformation apparently continued in the earliest stages of deposition of this unit, as indicated by the fact that it also affected the basal unconformity surface and the lowermost part of the overlying deposits (Di Giulio and Galbiati, 1995). In the area of the Cabella Ligure Geologic Sheet, the deposits below the unconformity are mostly represented by the Savignone Conglomerate and Ranzano allogroup, as the Molare Fm is almost absent there; therefore, the gap is wider than in the adjoining area close at hand to the West, i.e. the Lemmi-Spinti Graben, where the Molare Fm is well represented. In the latter area the position of the unconformity was indicated by Trivioli (1990) to occur between his Monastero 1 unit (mostly corresponding to our Molare Fm) and his Monastero 2 unit (mostly corresponding to the lower part of our Rocchetta Fm).

In the central-western TPB the inferred effects of this tectonics are represented by growth faulting in the Molare Sandstone, leading to contrasts in sediment thickness, and mass wasting episodes (see below). Tectonic activity apparently continued in the earliest stages of deposition of the Rocchetta Fm even in this area, as indicated, for instance, by the low-angle unconformities present in the lowermost part of the formation, suggesting the onset of the growth of the NW-striking Mioglia flexure (Fig. 34 a,b).

Growth faults in the central-western TPB belong to three groups (Pl. VI online): a first group, more numerous, includes faults striking WNW-ESE (ranging from N60W to N68 W), among which the Rio Carpenaro, Rio Pietra N and Rio Pietra S (Mioglia area), and the C. Foglino Fault (near Cartosio); thickness contrasts due to growth faulting are particularly apparent across the faults of the WNW-ESE system in the eastern Mioglia area. A second group includes faults striking ENE-WSW to E-W, among which the Madonna della Bruceta F. (W of Grognardo), the C. Cappeletta F. (N of Bandita) and Bric Uvi Fault (N of Cimaferle). Inferred breakdown of scarps linked to these faults led to emplacement of breccias and olistoliths in the marine shelf sandstones of the Molare Fm (Pls. I and VI online; Fig. 35). The above mentioned two groups of faults behaved mostly as left-lateral lineaments and may be regarded as synthetic Riedel shears; the third group of faults, striking NW-SE and characterized by normal motion, includes the Montaldo F. and the Piana F., both bounding the Piana Crixia graben and active in the earliest stage of deposition of the Rocchetta Fm. The confinement of the Piana Crixia body within this graben, forming a narrow, fault-bounded depocenter, suggests a complex tectonic dissection of the submarine topography. The three groups of structures are consistent with a regime of left-lateral motion along an approximately E-W master lineament, concurrent with NW-SE direction of extension (in present-day coordinates) (Fig. 35).

An inferred pure left-lateral strike-slip regime occurred in this stage in most part of the TPB, with the exception of the easternmost area, where the presence of a restraining bend of the VV Line resulted in oblique slip with localized effects of sinistral transpression and contraction. As will be detailed below, this tectonics conceivably led to the conversion of the TPB in a left-stepover, pull-apart basin between the overlapping fault strands represented by the ca. E-W striking VV Line and the WNW-ESE Stura Fault. The central-western area of the TPB characterized by denser fault concentration is interpreted as a sort of transfer zone developed during the Rupelian tectonics as a result of strain accumulation in the area of overlap of the left stepping system of the Villalvernia-Varzi Line to the NE and the Stura Fault to the SW.

7.5. THE LATE RUPELIAN-CHATTIAN DROWNING STAGE

7.5.1. General features

Since the latest middle Rupelian a regional drowning event, accompanied by acceleration of tectonic subsidence, and certainly enhanced by the eustatic strong sea level rise of the TB1.1 cycle (Miller et al., 1998), was recorded by deposition of the hemipelagic mudstones of the Rocchetta Fm (uppermost middle Rupelian - Chattian), occurred in a progressively deeper-water slope and base-of-slope setting. The hemipelagic mudstones locally alternate with thin-bedded turbidites laid down by dilute turbidity flows or with hyperpycnites, and encase coarse-grained turbidite bodies of variable dimensions, the older of which being at least partly fed from cannibalization of the Molare Conglomerate (Mutti et al., 1995).

The thickness of the Rocchetta Fm is strongly variable (Pls. I and II); it is estimated in the order of 1000 m in the Turpino and Rocchetta Cairo depocentres of the Langhe Sub-basin, and 1200 m in the Borbera-Grue Sub-basin; on the other hand, it is significantly reduced in the central TPB from the T. Erro Fault to the Lemme Fault, namely in the area of the Alto Monferrato High, a paleo-structural

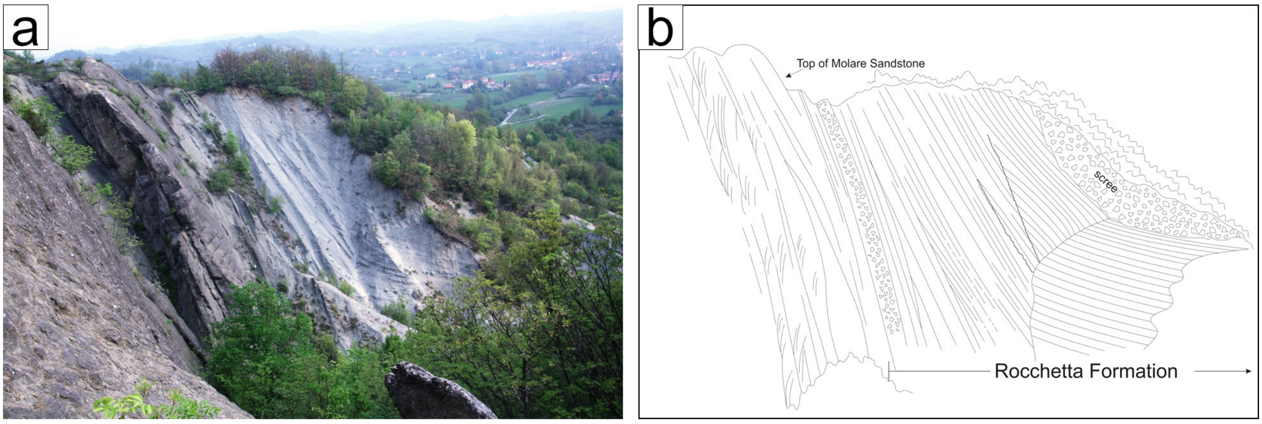

Fig. 34 - The Mioglia flexure W of Rocca di Crena. a) Earlier stage of deformation (inferred mid-Rupelian in age) is indicated by internal angular unconformities in the marls of the lowermost part of the Rocchetta Fm. The subsequent main deformation of the flexure is attributed to the transpressional episode of inferred early Aquitanian age. b) Drawing from the photo. Note the mouth bar sequence in the uppermost part of the Molare Sandstone.

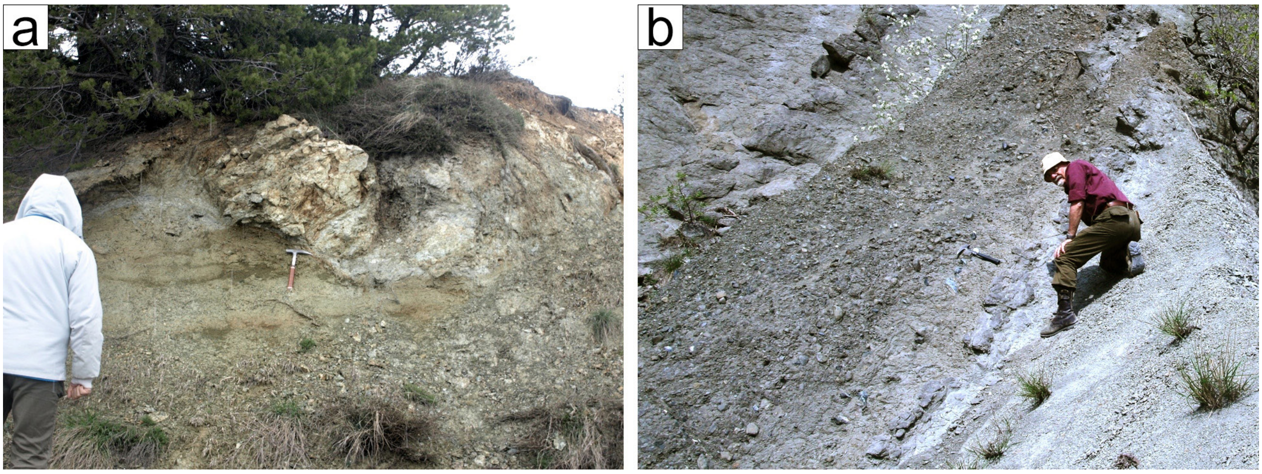

Fig. 35 - a) Breccias and olistoliths in the Molare Sandstone near C. Battaglino (Cartosio SE). b) Breccia layer in the upturned lowermost part of the Rocchetta Fm involved in the Mioglia flexure (SSE of the locality Campo di Pretto).

element already in existence as embryonic structure during the deposition of the Molare Conglomerate, but mostly developed after the deposition of the Rocchetta Fm, i.e. during the main, Chattian-Aquitanian transpressional stage of the TPB evolution (see below).

Several volcanic ash layers interbedded with the marls of the Rocchetta Fm (d'Atri and Tateo, 1994) are extremely useful as marker beds providing timelines for long-distance correlations within the TPB.

Many slope and base-of-slope turbidite sandstone and conglomerate bodies of variable dimensions are encased in the formation, particularly in the more subsiding Langhe and Borbera-Grue sub-basins, where they show a gradual upward change in geometry, with an overall trend of increasing width/thickness ratio reflecting a transition from upper slope to base-of-slope settings. The bodies cover a wide range of genetic typologies, from simple or stacked channels, to infills of submarine valleys, to units confined within depressions bounded by growth faults, to infills of simple or coalescing slump-scars of variable scale. Larger bodies appear composed of multilateral and multistorey, mutually intersecting channel elements together with overbank deposits (Figs. 9a, 10a, 11c). A special case is that of channelized bodies showing evidence of lateral accretion, an organization particularly identified in several examples of coarse-textured channel fills (Figs. 8 a,b; 15 a,b; 27).

Persisting slope instability during the deposition of the Rocchetta Fm is indicated by the abundance of slump scars (Fig. 7a) and slump-emplaced masses throughout the TPB. In the eastern TPB gradient steepening led to collapse of the former deltaic deposits with development of a large erosional unconformity identified as a composite slump scar of plurikilometric extent (the Sottovalle slump scar) which testifies the removal of important volumes of the underlying deposits in the Borlasca and Lemmi-Spinti areas. Further NE-wards, in the easternmost TPB, the gap is even larger, with the Rocchetta Fm (Monastero Fm of the Cabella Ligure Geologic Sheet) overlying the Savignone Conglomerate with an unconformable and locally angular contact. Stocchi et al. (1992) recognized in the Borbera-Grue area a large polyphasic erosional feature, interpreted as a large-scale and composite slump scar at the base of the Chattian Gremiasco unit which includes both muddy hemipelagic units and a complex of nested lenticular channelized bodies encased in them. The authors attributed the formation of the scar to the gravity-destabilization resulting from tectonic tilting of the basin margin particularly during the deposition of the upper part of the Rocchetta Fm (late Chattian); they noted the dimensional disproportion between the erosional depressions and the turbidite bodies, suggesting that the turbidity flows passively infilled previously formed coalesced slump scars produced by the remobilization of important sediment volumes. High tectonic mobility and gravity instability are also documented on the northern side of the VV Line, where they are recorded by an olistostromic mélange, the "Brecce argillose della Val Tiepido-Canossa" *auct.* encased in the Antognola Fm, which is coeval to the Rocchetta Fm (e.g. Panini et al., 2004). These broad effects of gravity destabilization are probably coeval to the composite slump scar of Molino di Mombaldone area (Pls. I, II; Fig. 36) in the Langhe Sub-basin, a large-scale feature about 1 km wide and up to 150 m deep, whose formation was probably preceded by a gentle tilting of the substrate; Ghibaudo et al. (2014) suggested that the composite scar evolved into a submarine canyon/slope valley system (Fig. 36).

The Rocchetta Formation is overlain by a siliceous and hemipelagic lithozone, the Montechiaro d'Acqui Siliceous Lithozone (LS1), attributed to the Aquitanian (Zones MNN1c-MNN1d p.p.), and representing a marker horizon on regional scale, useful for basinwide correlations (Schüttenhelm, 1976; d'Atri, 1990a; Gelati and Gnaccolini, 1998; Fava, 2001; Mutti et al., 2002; Ghibaudo et al., 2014).

In the following, various aspects of sedimentation in the different sectors of the TPB are treated.

Fig. 36 - Detail of the large-scale Mombaldone slump scar and subsequent infill. The sandstone package at the base (Molino di Mombaldone lower unit) has been gently tilted by synsedimentary tectonics before the generation of the slump scar. Meander of the Bormida River, N of the village of Mombaldone.

7.5.2. The Borbera-Grue Sub-basin

Several medium-scale conglomerate and sandstone bodies with limited lateral persistence are present in the lower-middle part of the Rocchetta Fm, whereas in the upper part large plurikilometric lenticular sandstone bodies, namely the Garbagna Sandstone and the Variano Sandstone (Pls. I and II), the latter correlated with part of the Gremiasco Fm by Cavanna et al. (1989), are interpreted as wide submarine valley fills.

Clear indication of a confinement effect of a northern submarine ridge corresponding in position to the VV Line (Di Giulio and Galbiati, 1995) is provided by the turbidite bodies located S of the line, specifically those of the composite Gremiasco Fm (*sensu* Cabella Ligure Geologic Sheet), which are shown by Di Giulio and Galbiati (1995) to pinch out northwards close to the VV Line; the confinement effect is confirmed by the main paleocurrent directions, which show an overall rotation of flow directions from W-E to NW-SE in the easternmost part of the basin, following a trend paralleling that of the VV Line (Di Giulio and Galbiati, 1995). Moreover, in a study of sandstone composition Martelli et al. (1993) documented that, since the drowning stage, the TPB and the Epiligurian Apennine successions evolved separately. Together with sedimentological evidence, this indicates that a morphologic-tectonic boundary has arisen, most probably corresponding in position to the VV Line (Di Giulio and Galbiati, 1995). Moreover, the complex internal architecture of the Gremiasco turbidite system records periods of intense basin-modifying structural deformation during sedimentation (Ibbeken, 1978; Mutti et al., 2002, and references therein), highlighted by spectacular onlap terminations against synsedimentary fault scarps and large-scale submarine truncations.

7.5.3. The Alto Monferrato High

Isolated turbidite bodies encased in the Rocchetta Fm sparsely occur on the Alto Monferrato High (larger ones occurring in the areas of Cassinelle, Ovada, Lerma, Ponzone), but do not show thicknesses and stacking patterns comparable to those of the Langhe and Borbera-Grue sub-basins.

The role of synsedimentary tectonics in creating accommodation space is specifically suggested by the geometry of the Cassinelle body, which is viewed as the infill of a structural depression bounded to the west by the NW-striking Castellamare Fault (Pl. I, II; Fig. 14d); similarly, the Ponzone channelized body was emplaced in a structural low bounded to the West by the synsedimentary NNW- trending segment of the Chiappino Fault.

7.5.4. The Langhe Sub-basin

In western TPB the tectonic collapse was a true platform-drowning event, marked by a very rapid, although conformable, transition from the shelf setting of the Molare Sandstone to deep-water slope sedimentation. The significant acceleration of subsidence rate in this area is clearly highlighted by the subsidence curves presented for the Millesimo and Dego areas by Carrapa (2002) and Carrapa et al. (2003).

The turbidite bodies encased in the Rocchetta Fm in the Langhe Sub-basin have been treated in detail in Ghibaudo et al. (2014). Here they are only briefly mentioned. The overall trend of upward increasing width/thickness ratio is manifested by the change in geometry, the lower bodies appearing as the infill of a large canyon (the Mogliavacca-Brovida system), and upper ones (e.g. Cobarello body) progressively tending to a sheet-like geometry. The larger turbidite bodies encased in the Rocchetta Fm (Mogliavacca, Brovida, Cobarello and Noceto sandstone bodies) are mostly concentrated in the Rocchetta Cairo Depocentre (Ghibaudo et al., 2014). The largest and youngest body, i.e. the Noceto unit, appears as the infill a pluri-kilometric half-graben bounded by the listric Rio Girosa growth fault (Ghibaudo et al., 2014).

The Chattian turbidite bodies (e.g. the Budroni System, Cazzola and Fornaciari 1990, and the Noceto body) were mainly fed from NW, except in the SW area (e.g., Cengio System, Felletti and Bersezio 2010), where sediment flux was from the south-western basin margin. The paleocurrent pattern indicates regional E- or ESE-dipping palaeo-slopes (in present day coordinates). A suggestion that the turbidite system extended at least onto, and probably beyond, the present-day Ligurian Alps comes from reconnaissance field work in the Sassello basin-remnant located on the Ligurian Alps, where the local Oligocene stratigraphy (Lorenz, 1969) is found to be quite comparable to the lower succession of the Langhe Sub-basin, with Molare continental and shelfal sandstones passing upwards to some tens of metres of muddy sediments (Rocchetta Fm) encasing packages of turbidite beds.

7.5.5. The tectonic context

We propose that during the deposition of the Rocchetta Fm an inversion of motion occurred along the VV Line, with change into right-lateral transtension. Support for this change of motion is provided by the structural setting of the eastern TPB (Fig. 37). Here, NW-striking left-lateral oblique-slip lineaments accommodated increased thickness of the Rocchetta Fm in contiguous compartments (Fig. 37). Specifically, the Scrivia Fault shows opposed throw with respect to the former motion which created space for the Molare Conglomerate SW of the fault; indeed, the fault created accommodation NE of

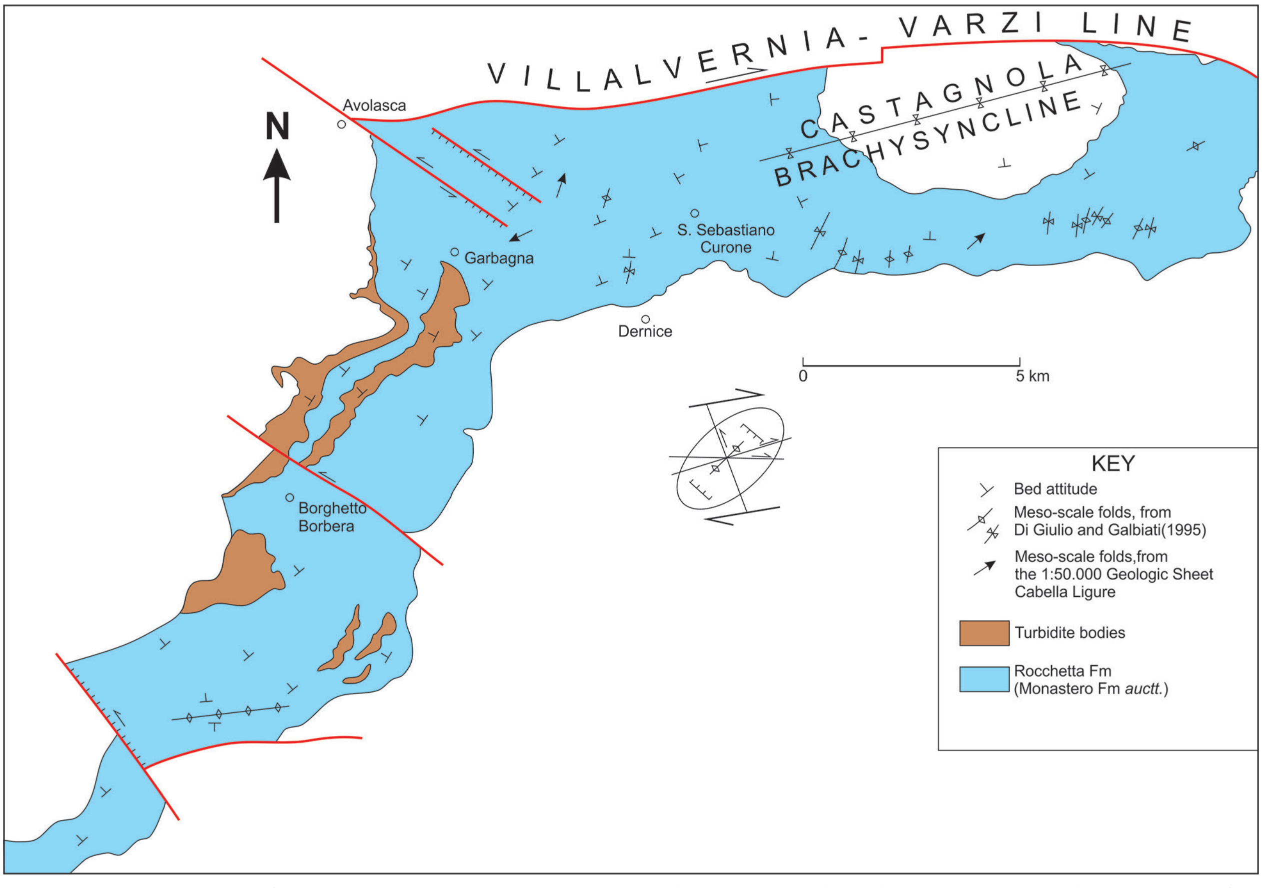

Fig. 37 - Structural setting of the eastern TPB suggesting a right-lateral transtension along the VV Line during the deposition of the Rocchetta Fm, i.e. in a stage predating the main sinistral transpressional motion of late Chattian-Aquitanian.

this line for the Rocchetta Fm, which reaches an estimated thickness of 1200 m, contrasting with the thickness of 150 m in the adjacent Lemme area, SW of the line. Moreover, two NW-striking oblique-slip sinistral faults located SE of Avolasca near the VV Line allowed anomalous thickness of the marls of the Rocchetta Fm to accumulate between the northern terminations of the bodies of the Variano Sandstone and the Garbagna Sandstone (Fig. 37). The axis orientation of folds generated during Rocchetta time with respect to the VV Line provides further evidence. Specifically, the Castagnola brachysyncline shows ENE-WSW axis orientation, at angle with the VV Line. Its synsedimentary growth is suggested by plenty of gravity destabization events during the deposition of the Rocchetta Fm, and by some indications of stratal convergence of this unit on the eastern side of the syncline. Moreover, Di Giulio and Galbiati (1995) reported in the upper part of their sequence S3 (corresponding to our Rocchetta Fm and to Monastero Fm of the Sheet Cabella Ligure) the presence, South of the VV Line, of arrays of irregular meso-scale folds with axes trending NE-SW, NNE-SSW and N-S, having little continuity (Fig. 37). They considered them alternatively as tectonic or slump-related features; noting that the folds are very disordered, with changeable axes attitude and locally passing to chaotically textured masses, they were inclined to regard them as slump-related features implying synsedimentary changes in the depositional paleo-slope linked to the concomitant motion of the VV Line; conversely, Marroni et al. (2014 and Geologic Sheet 1:50000 Cabella Ligure) regard them as tectonic deformations. In our opinion both origins are plausible.

In western TPB two normal listric, approximately N60W-striking faults, the Rio Girosa and the Vico faults bounding respectively the Noceto Half-graben and the Turpino Depocentre of the Rocchetta Fm are attributed to this tectonic stage. NW-striking faults (ranging from N35W to N60W) include the La Costa Fault, active during the deposition of the Mogliavacca Sandstone, the Castellammare F. bounding the Cassinelle Half-graben, the Colombara F. (Fig. 38b), the R. Granozza F., the Castello di Casareggio F., the Scrivia F., the Lemmi F. and the Avolasca faults. These groups of structures are though to represent either normal faults or left-lateral antithetic shears with oblique-slip motion, consistent with a context of right-lateral transtension affecting the whole TPB. Local meso-scale folds with axes approximately striking ENE-WSW are probably related to sinistral strike slip motion along NW-SE faults (e.g. Fig. 38a).

This tectonic episode may correspond to the event A described by Federico et al. (2014) in the Voltri Unit, which includes faults fitting a right-lateral transtensional scenario.

7.6. THE TRANSPRESSIONAL EVENT

7.6.1. Tectonic setting

A major turnover occurred throughout the TPB in the late Chattian-Aquitanian, with change of transtension into sinistral transpressional tectonics. This major tectonic episode occurred in a stress field implying a framework of a regional NE-SW trending direction of compression (Capponi and Crispini, 2002; Carrapa et al., 2003a, Capponi et al., 2009; Federico et al., 2009; Maino et al., 2013; Federico et al., 2014), and represents the acme of strike-slip tectonic mobility. It is recorded by meso- and large-scale folds commonly linked to transpressional faults, thrusts, and inversion of previous extensional and transtensional structures. In the eastern TPB Di Giulio and Galbiati (1995) demonstrated that the most important impulse of left-lateral transpressional motion along the VV Line occurred during this event, renewing the uplift of a structural ridge grossly fitting the direction of the line. In proximity of the restraining bend of the easternmost segment of the VV Line, transpression was particularly intense, documented by the deformation of the Chattian Gremiasco Fm (“Nevione Structure” of Ibbeken, 1978), which generated tight folds with E-W axes and tendency to southward overturning. The deformation in this area was dated to the transition Chattian-Aquitanian by Di Giulio and Galbiati (1995) or to the late Chattian (Zone MNN1a) by the Geologic Sheet Cabella Ligure. Some diachroneity is thought to exist in E-W direction, with transpression in the eastern TPB being slightly older than in western TPB. Indeed, in the Valle Uzzone area a system of *en échelon* NE-striking decametric folds deformed the lower Aquitanian Poggiolo Fm as left stepover system between the ENE-striking S. Ilario and Rio Porcavio faults belonging to the Valle Uzzone fault system (Pls. I, VI and VII online). The deformations are sealed by the overlying middle Aquitanian siliceous lithozone LS1b, allowing, therefore, to date the transpressional effects to the early Aquitanian in this area (Ghibaudo et al., 2014).

The ENE-WSW to E-W fault system sub-parallel to the VV Line, already active during the previous tectonic event of the late middle Rupelian was strongly reactivated with sinistral motion, particularly in the central area of the basin. This dominant structural direction was associated with a secondary lineament, mostly oriented NNW-SSE to NW-SE, along which a reactivation in dextral transpression of former extensional or transtensional faults took place. This system may have played a critical role in the development of the Alto Monferrato High as a strongly positive structure with respect to the adjacent sub-basins, leading to partial emergence (Fig. 39). The margins of the high appear to be marked in this stage by the Scrivia Fault on the eastern side and the NNW-SSE T. Erro-Sassello-S. Giustina-Celle Ligure composite lineament on the western side. Dextral transpression along the NNW-SSE to NW-SE fault system is supported by an array of *en échelon* NW-striking meso-scale folds in the Sassello basin area, clearly highlighted by Lorenz (1969). A similar transpressional context was probably that of the Gorini tectonic complex (described as “Grognardo thrust zone” by Piana et al., 2006). It may be reasonably stated, therefore, that several compressional structures present in the TPB, such as folds, inverse faults (Fig. 40

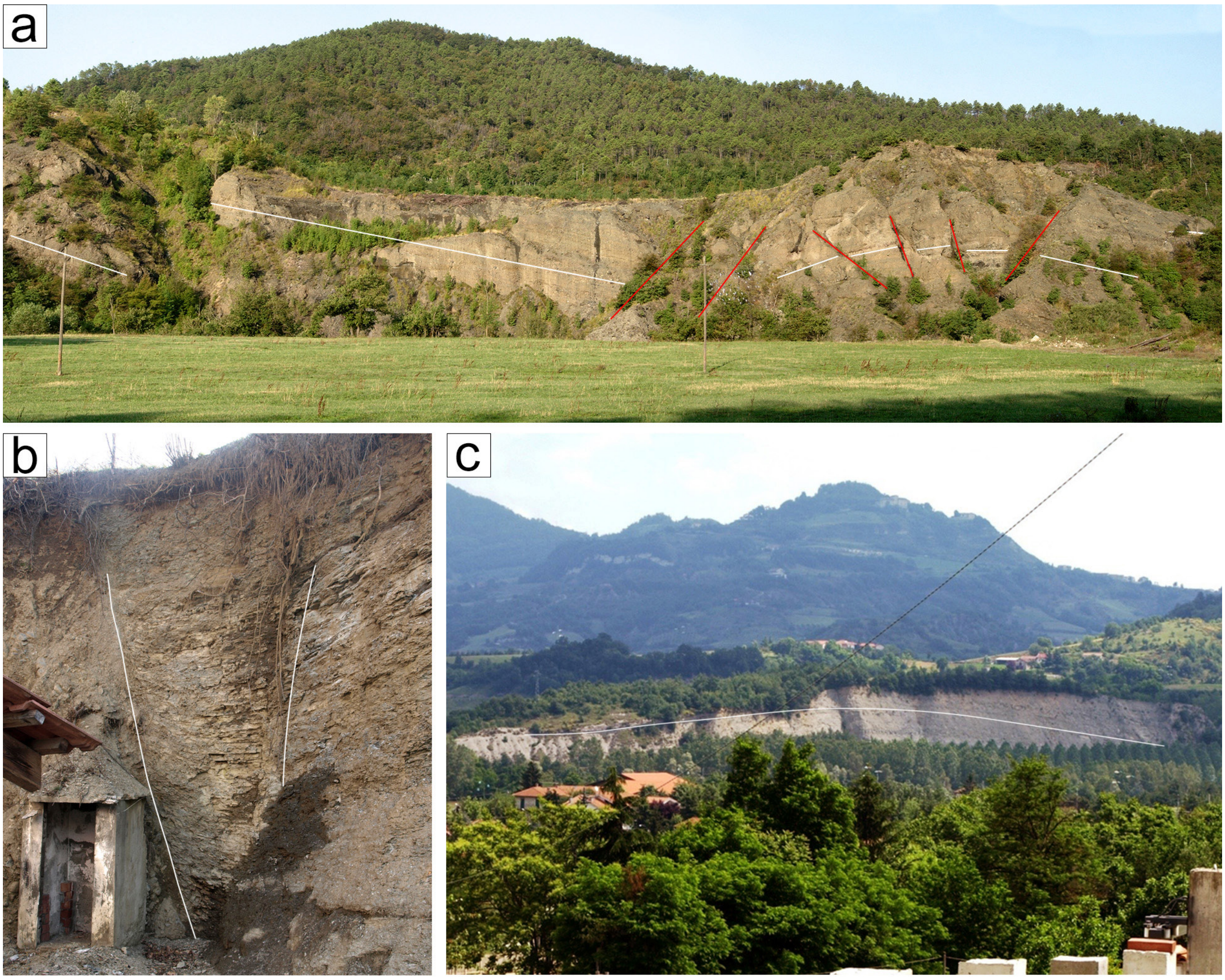

Fig. 38 - a) and b) Structural elements inferred to have been generated during the Late Rupelian-Chattian transtensional stage. a) Meso-scale faulted folds (stratification highlighted by white lines) with axes striking ca. ENE-WSW in the Molare Conglomerate, probably related to sinistral strike slip motion along the NW-SE Rio Granozza Fault. Left bank of Granozza creek, W of houses of spot height 219 (SE of the village of Molare). b) NW-striking Colombara Fault, N of Cartosio, interpreted as transtension-related structure. c) Meso-scale anticline in the Rocchetta Fm, with axis striking ca. NNW-SSE, belonging to an *en echelon* belt linked to the N55W Malvicino Fault and inferred to result from left-lateral motion along this lineament during the early Aquitanian transpressional stage. South of the hill 260 m high, E of Molino di Mombaldone.

a,b) and thrusts, represent the effects of transpressional deformation in a framework of NE-SW direction of compression. Examples are the thrusts striking NE- to N-NE described by Spagnolo et al. (2007), Federico et al. (2009) and Crispini et al. (2009) in the eastern Voltri Group, in association with dextral transpression along the Sestri Voltaggio Lineament, and the *en echelon* meso-scale folds with axes striking NNW-SSE associated with the N55W Malvicino Fault (western TPB) (Figs. 38c, 39, 40).

Other thrusts attributed to this tectonics may be regarded as purely compressional structures. Thrusts with NNE- to ENE-ward vergence were reported by Pasquarè (1968), Capponi and Giammarino (1982), Bernini and Zecca (1990), Hoogerduijn Strating et al. (1991), d'Atri et al. (1997), Piana et al. (1997, 2006), Capponi et al. (1999 a,b, 2001), Mosca et al. (2009), and Federico et al. (2014). The Mioglia flexure, regarded as the surface expression of an ENE- to NE-verging blind thrust is thought to belong to this group (Bernini and Zecca, 1990) (Fig. 34 a,b). The adjoining brachysyncline to the East of the flexure and the gentle anticline to the West are both part of the structure (Pl. I).

7.6.2. Stratigraphic effects

Stratigraphic gaps of variable amplitude bear witness of the important late Chattian-Aquitanian tectonics (d'Atri, 1990a; Dela Pierre et al., 1995; Piana et al., 1997; Molli et al., 2010). In the western part of the Alto Monferrato High (Acqui Terme-Visone area) a large gap encompassing the LS1 unit and the upper part of the Rocchetta Fm marks the angular unconformity at the base of the lower Burdigalian ramp carbonates of the Visone Limestone (d'Atri, 1990a; Dela Pierre et al., 1995; Laubscher, 2010) (Figs. 3, 39). East of Acqui Terme, up to the Carrosio

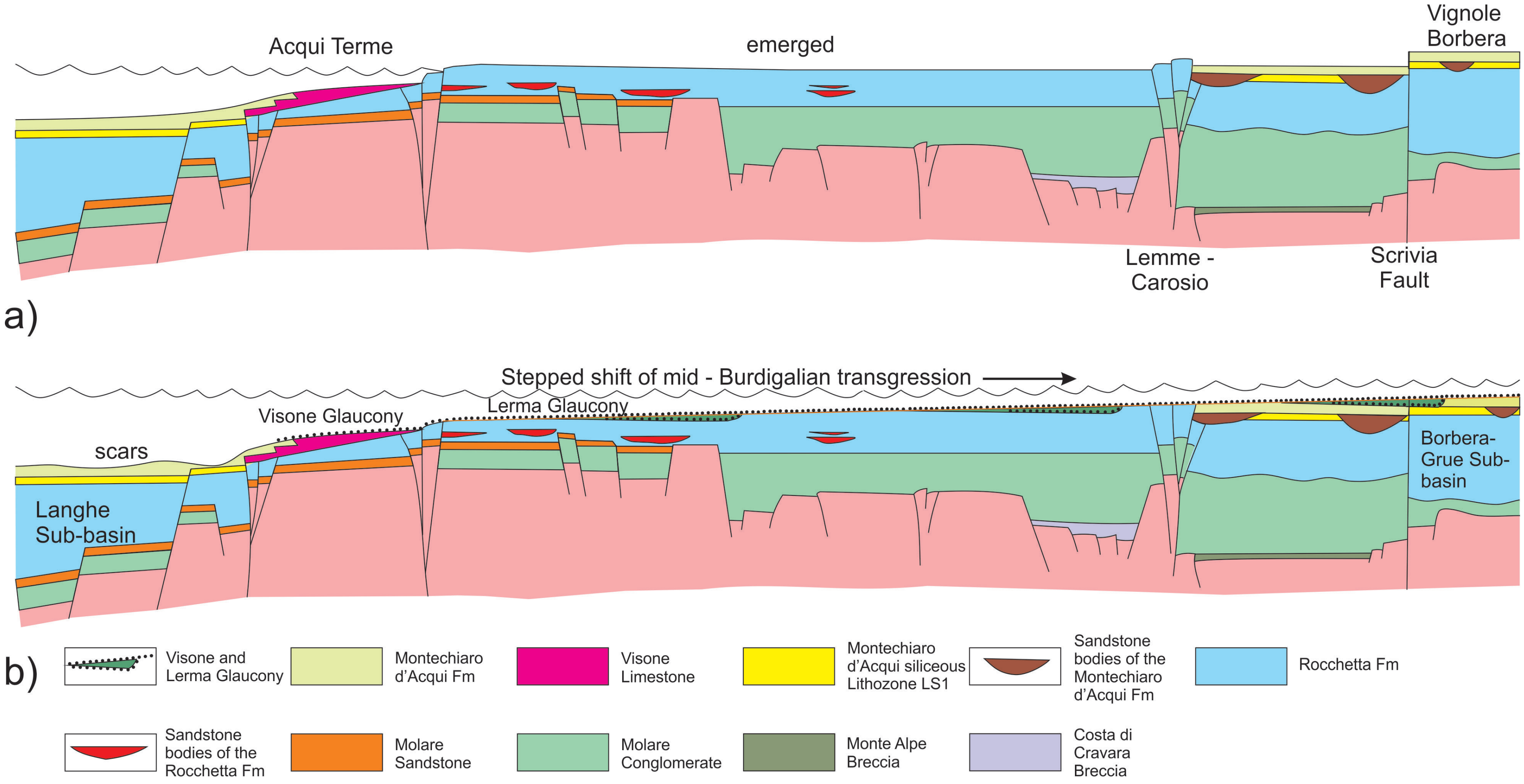

Fig. 39 - Tentative and schematic reconstruction of the Aquitanian-early Burdigalian paleogeography of the central TPB area. Transpressional tectonics leading to strong uplift of the Alto Monferrato High (upper picture) was followed by the middle Burdigalian stepped transgression (lower picture).

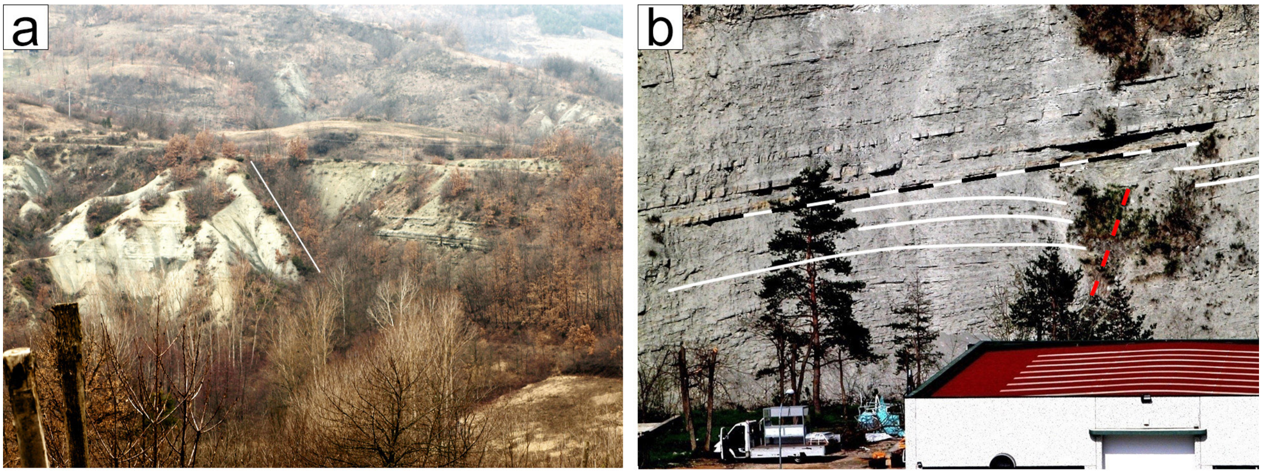

Fig. 40 - Structural elements inferred to have been generated during the transpressional stage. a) NW-striking C. Fallabrini inverse fault putting the Molare Sandstone in contact with the Rocchetta Fm. (E of C. Bagola, near spot height 295.5, NE of Valosio). b) Inverse fault and related fold within the Poggiolo Fm, unconformably sealed at the top by younger undeformed strata of the same formation (large scarp in front of the village of Uzzone, in the Uzzone Valley).

area, a larger gap, accompanied in several places by an angular discordance of up to 30°-35°, marks the unconformable contact between the Rocchetta Fm and the middle Burdigalian transgressive Lerma Glaucony. In this area the latter unit is bounded at the base by a ravinement surface, documenting emergence during late Aquitanian-early Burdigalian times, in contrast with the western part of the Alto Monferrato High (Acqui Terme area) that remained submerged. As above observed, a lowstand component to the origin of the discontinuity at the base of the Lerma Glaucony is demonstrated by the deep erosion associated with the unconformity surface; it is unlikely, in fact, considering the large hiatus, that the substrate could have been eroded only by the ravinement process. The relative sea level must have fallen, leading to emergence, subaerial erosion and removal of all traces of the subaerial exposure, in order to bring the substrate into a position where it could be transgressively ravined.

The formations missing in the gap, namely the LS1 siliceous horizon and Montechiaro d'Acqui Fm, reappear east of Carrosio, up to Vignole Borbera. Further NE-wards, in the Val Borbera area, the discontinuity is cumulated with the angular unconformity at the base of the Langhian shelf deposits of Cessole Fm, with a truncation of the complete Burdigalian succession. In the easternmost Borbera-Grue (Castagnola area) a gap of apparently small amplitude accompanies the angular unconformity between the deformed Gremiasco Fm (Chattian) and the onlapping Costa Grande Mb of the Castagnola Fm, whose basal deposits are referred to the Aquitanian by Di Giulio and Galbiati (1995) or to the latest Chattian - zone MNN1a- by the Cabella Ligure Geologic Sheet. West of the Alto Monferrato High, the gap becomes gradually smaller in the sector located between the Caliogna and the Erro valleys (d'Atri et al., in press), to finally disappear or be of minimum amplitude in the Uzzone valley area (Ghibaudo et al., 2014).

7.7. THE AQUITANIAN-EARLY BURDIGALIAN TECTONIC MOBILITY AND STRATIGRAPHIC ARCHITECTURE

7.7.1. Tectonic setting

Wrench tectonics continued in the Aquitanian to early Burdigalian times, repeatedly modifying basin geometry. This led to marked variability in thickness, facies distribution, paleocurrent pattern, and composition of the sediments of this age, and to contemporaneous development of a complex submarine topography of narrow subsiding areas and high-standing blocks (Fig. 41).

The E-W to ENE-WSW fault system was apparently active with extensional or transtensional motion, locally creating accommodation space for the Montechiaro d'Acqui Fm. Examples are the arcuate C. di Mano Fault, S of which the marls of this formation are significantly thicker, and the C. Mazzurini Half-graben, genetically controlled by the E-W subvertical Pian dei Buri growth fault (Pl. VI online) (Gelati and Gnaccolini, 1998; see also Ghibaudo et al., 2014 for details).

In western TPB the NE-SW Uzzone Valley lineaments acted as growth faults during the deposition of the Montechiaro d'Acqui Fm, determining the birth of intrabasinal highs and subsiding troughs; these acted as depocentres, accommodating thick Aquitanian-lower Burdigalian deposits, with several turbidite units encased in the hemipelagic marls of the Montechiaro d'Acqui Formation (Pls. I, II; Fig. 41). Tectonic control is highlighted in this area by location of successive turbidite sandstone bodies and trend of paleocurrents (Ghibaudo et al., 2014). In the late stage of deposition of the Montechiaro d'Acqui Fm some evidence exists of weak resumption of compressional or transpressional deformation. This led to the growth of some gentle, large-scale NE-SW folds (radius of hundreds of meters) near the head of the Rio della Torre Valley, which deformed the

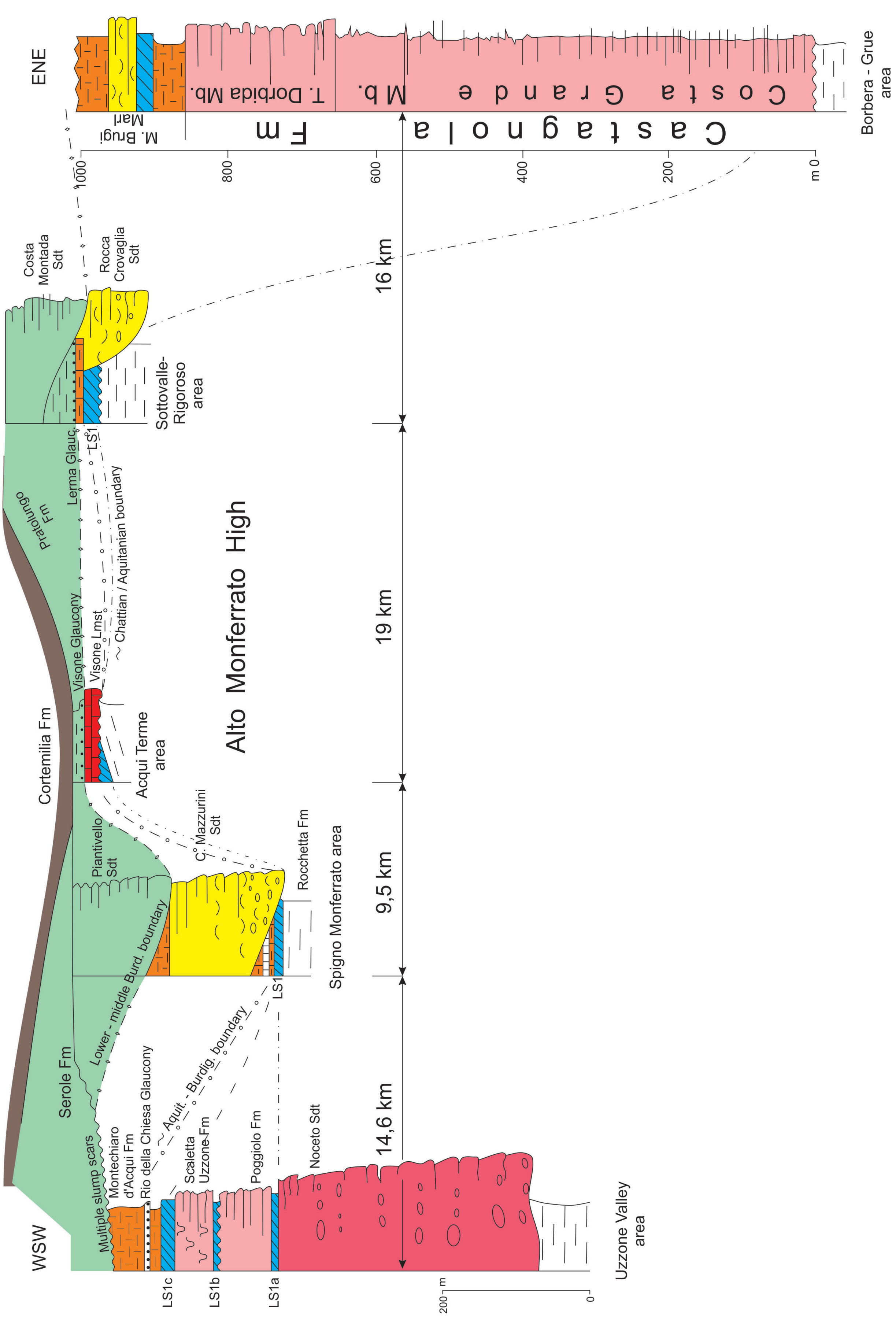

Fig. 41 - E-W cross section to schematically show the Aquitanian-Burdigalian stratigraphy across the TPB, and persistence of the Alto Monferrato High during the Aquitanian-early Burdigalian times.

Montechiaro d'Acqui Fm without affecting the younger Serole Fm, and to the partial structural inversion of the Noceto Half-Graben by means of dextral motion along the NE-SW C. Villara Fault, generating a medium-scale anticline on the left side of the Rio Pescritta, called "Rio Pescritta Anticline" (Ghibaudo et al., 2014).

In the easternmost TPB, the Castagnola brachysyncline was infilled with the thick Aquitanian to lower Burdigalian turbidite succession of the Castagnola Fm (comprising the Costa Grande Mb, up to 650 m thick, mostly consisting of pelitic-sandy turbidites, and the overlying Torrente Dorbida Mb, ~200 metri thick, composed of medium-bedded turbidites), and the younger (lower Burdigalian) M. Brugi Marl. The geometry of the stratal onlaps of the turbidites is slightly divergent near the margins of the Castagnola basin (Stocchi et al., 1992), suggesting that the brachysyncline had been subjected to a gentle accentuation in the early Burdigalian times by late movements along the VV Line. The mild deformation of the oldest turbidite lithosome deposited in the Castagnola basin (Felletti, 2002) may be referred to this motion.

7.7.2. Stratigraphy

Facies, stratal pattern and paleocurrent directions of the Castagnola turbidites indicate that the deposition occurred in a ponded, structurally confined basin-plain environment (Andreoni et al., 1981; Cavanna et al., 1989; Stocchi et al., 1992; Di Giulio and Galbiati, 1995). Palaeocurrents are relatively uniform with an average orientation toward ENE, and local opposite directions suggesting an effect of rebound of flows against the NE margin of the basin (Stocchi et al., 1992).

The unit of M. Brugi Marl (referred to the lower Burdigalian foraminiferal zone MFN5 by Mancin and Pirini, 2002), up to 200 m thick, forms the nucleus of the Castagnola brachysyncline. It is composed of three members, of which the lower (particularly thick) and the upper are rich in siliceous deposits, whereas the intermediate is made up of turbidites locally with abundant bioclasts and larger foraminifers (Labesse, 1966; Tateo et al., 1995). The M. Brugi unit is regarded as time- and facies-equivalent of the Montechiaro d'Acqui Formation, which in western TPB locally contains in the uppermost part a package of alternating marly and siliceous layers (Fig. 19c) (not represented in the enclosed geological map). The M. Brugi unit may correlate with the Aramengo-Marmorito unit of the Monferrato area, consisting of lower Burdigalian diatomites and diatomacous marls (Polino et al., 1995), and with the lower Burdigalian Pteropod Marl containing silica-rich sediments (Clari et al., 1995); in the Epiligurian and north-Apenninic successions it corresponds to the Contignaco (Mancin and Pirini, 2001). The intermediate member of the M. Brugi Marl is thought to correlate with similar lower Burdigalian bioclastic-rich units diffused throughout the TPB (e.g. the C. Mazzurini and Rocca Crovaglia Sandstone, see below).

After the uplift and development into a strongly positive structure, the Alto Monferrato High was flooded in the western part by the lower Burdigalian ramp carbonates of the unconformably-based Visone Limestone which consists of two minor sequences separated by an unconformity draped by a coarse transgressive lag (d'Atri, 1990 a,b). On the Alto Monferrato High the carbonate unit grades laterally offshore to outer-shelf marls of the Montechiaro d'Acqui Fm; conversely, in the Langhe Sub-basin, it grades into considerably thicker hemipelagic slope marls of the same formation, which cover a time span slightly wider than that expressed by the Visone Limestone, extending downwards into the late Aquitanian (Zone MNN 2a pp.) and upwards into the lower part of the Burdigalian Zone MNN 3a.

In the whole TPB, but particularly in the Langhe Sub-basin, bodies of mixed composition consisting of resedimented carbonates (mainly made up of rhodoliths, rhodalgal detritus and larger foraminifers), associated with coarse-grained siliciclastic deposits (commonly conglomerates) and variable glauconitic content, are encased in the marls of the Montechiaro d'Acqui Fm, and inferred to derive from the destabilization and cannibalization of one or more carbonate ramp(s) of uncertain position. These bodies include: i) in the Langhe area the Case Mazzurini body and minor units of resedimented glauconitic sandstones and rhodalgal calcarenites (e.g. the Case Mevie Calcarenite, Case Poggi Calcarenite, and Pian Bruno Calcarenite); ii) in the Alto Monferrato area the Chiappino Sandstone; iii) in eastern TPB the Rocca Crovaglia Sandstone (Fig. 21), and the bioclastic-rich resediments associated to the Monte Brugi Marl. Resedimented deposits of similar composition are also recorded in the San Michele Member of the Monferrato area (Falletti, 1994). The coarse-grained siliciclastic component associated to the bioclastic fraction highlights the concomitant activation of important terrigenous inputs, particularly from the western basin margin. An important uplift of probable tectonic origin is recorded in the Monregalese area, where upper Oligocene hemipelagic and resedimented deposits are abruptly overlain by an Aquitanian to lower Burdigalian coarse-grained coastal wedge and fluvial deposits (Casnedi and Mosna, 1970; Casnedi 1971; Rossi et al., 2009). Mutti et al. (1995), argued that this coarse-grained sediment input results from the activation of new sources represented by basement and cover of Brianzonese units, and marks a change with respect to former units, Molare to Noceto, whose source rocks belong to the Voltri Group and Montenotte-Erro-Tobbio Sheet.

7.8. THE TURNOVER OF THE MIDDLE-LATE BURDIGALIAN

An important drowning event, accompanied by a major change in basin physiography, occurred in the middle Burdigalian, as a response to dramatic increase in subsidence rate and accommodation space creation (Dela Pierre et al., 1995; Rossi et al., 2009; Molli et al., 2010). Seismic profiles (Rossi et al., 2009; Mosca et al., 2009) indicate that the middle-upper Burdigalian turbidite system of the Cortemilia Fm formed a thick asymmetric wedge lapping out northwards against the backlimb of an important uplifting structure. This structure may be identified as the surface expression of the growing deep-seated "Front of the Alpine Axial Sector" (AXF) a north-verging thrust illustrated by Mosca et al. (2009) and Rossi et al. (2009) and formerly outlined by Polino et al. (1995), accommodating the northward displacement of buried elements of the axial Alpine belt. As will be detailed below, the first delineation of the AXF structure could have occurred in the middle Burdigalian.

The Alto Monferrato High was affected in this stage by a sudden event of platform drowning. In the western part of this high (Acqui-Visone area) the carbonate ramp of the lower Burdigalian Visone Limestone was rapidly flooded without apparent discontinuity by a transgressive glauconitic unit rich in planktonic foraminifers, the Visone Glaucony (Pl. I, Fig. 39). From the Acqui-Visone area the transgression backstepped eastwards with slight diachroneity on previously emerged areas of the eastern part of the Alto Monferrato High, generating the Lerma Glaucony. This unit overlies, through an unconformable ravinement contact draped by a coarse lag and locally accompanied by angular discordance, substrates of variable age ranging from the Rocchetta Fm (maximum gap) to the Carrosio Sandstone (Figs. 28, 39, 41). As discussed in more detail in the section on depositional setting (Fig. 28), the eastward progression of the transgression on the emerged landscape is highlighted by the geometry and stratal architecture of the Lerma Glaucony; this unit shows regionally a tabular, blanket-like geometry, with local stratigraphic expansions interpreted as successive, stepped shoreface lithosomes inferred to have been laid down during minor stillstand phases punctuating an overall relative sea level rise. Further eastwards the Lerma Glaucony overlies the Montechiaro d'Acqui Fm and can be traced eastwards up to the Borbera Valley, where it is truncated by the pre-Langhian angular unconformity.

The transgressive deposits grade with rapid deepening trend into hemipelagites of the mid-Burdigalian Pratolungo Fm (biozones MNN3a and MNN3b), interpreted as slope deposits. Characteristic resedimented glaucarenites present in the lower part of this unit probably derived from the cannibalization of the transgressive glauconitic deposits after the drowning event. Locally, in the Alto Monferrato (Ponzone-Chiappino area) the transgressive deposits and the Pratolungo Fm are missing and the Montechiaro d'Acqui Fm are unconformably overlain by the Cortemilia Fm (Fig. 42a). On the other hand, starting from the Carrosio area, the marls of the Pratolungo Fm show rapid eastward increase in thickness.

In the Langhe Sub-basin large-scale erosional discontinuities, interpreted as coalescing slump scars, led to partial or total removal of the Montechiaro d'Acqui Fm (Pl. I and Figs. 3, 39, 41). In this area the deposits coeval to the Pratolungo Fm are represented by the Serole Fm, a pelitic succession with thin-bedded turbidites and associated sandstone bodies inferred to record the NE-ward progradation of a prodelta slope wedge. This is regarded as the distal expression of eastward prograding fluvio-deltaic prisms, whose source areas were identified by Rossi et al. (2009) in the uplifted western margin of the TPB (Saluzzese and Monregalese areas). Several turbidite sandstone bodies of hectometric to kilometric scale, possibly made up of channel-levee deposits, are present in the lowermost part of the Pratolungo Fm (Costa Montada Sandstone), and at the base of the Serole Fm, where they locally occur as infill of slump scars removing part of the underlying Montechiaro d'Acqui Fm, (e.g. the Bric Torrione Sandstone), or as infill of a large base-of-slope valley (Piantivello Sandstone).

Both the Serole and Pratolungo units were followed by basinwide deposition of a thick turbidite succession (Cortemilia Fm, middle-upper Burdigalian). This unit

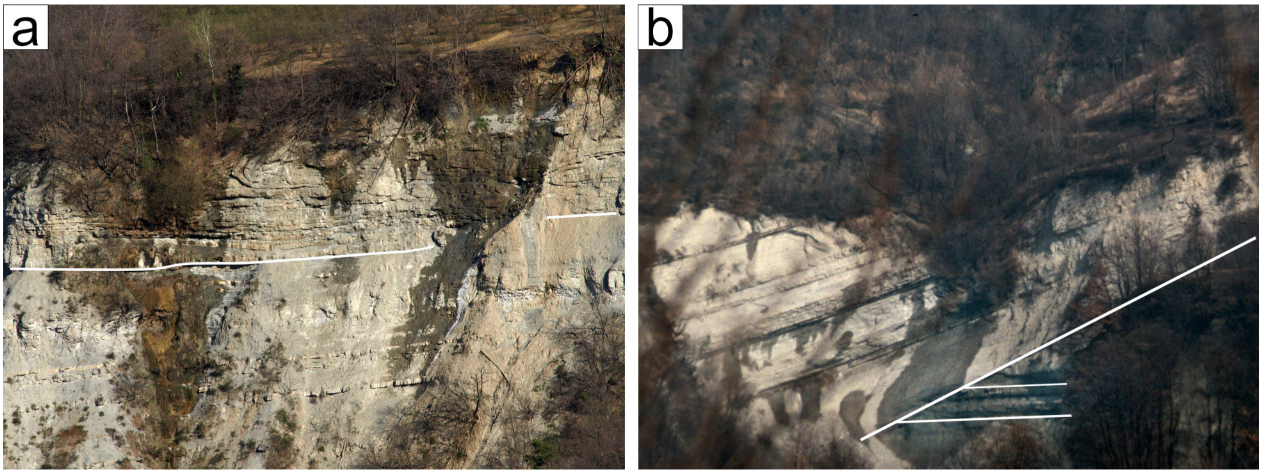

Fig. 42 - a) Unconformable contact between the Montechiaro d'Acqui Fm and the Cortemilia Fm. Note the slump folds in the latter unit. W of Chiappino (S of C. Rossa). b) Angular unconformity between the Chattian Variano Sandstone and the Langhian Gavi Siltstone Mb of the Cessole Fm. Borbera Valley, NW of Borghetto Borbera.

is known with local names, such as Cortemilia Fm in the western sector of the TPB, Cremolino Fm in the central part, and Costa Areasa Fm in the eastern area (e.g. Geological Sheets 81 Ceva, and 83 Genova of the 1:100000 "Carta Geologica d'Italia"). For sake of simplicity we adopted the inclusive formational name of Cortemilia Fm. The local names reflect different facies associations passing into one another: as observed by Mutti et al. (2002), an intergradation exists from inferred lobe turbidites in the western TPB (Fig. 22c) to basin plain turbidites to the East, the latter best represented in the Lemme Valley area (Fig. 23 and Pl. IX). The formation is a thick, volumetrically important, highly efficient turbidite system covering a wide area as a result of important enlargement of the basin and shows lateral onlap against basin margins and structural highs, as shown by seismic sections (Rossi et al., 2009). The large volume of terrigenous sediments stored in this unit suggests a substantial uplift and strong erosion of the West-Alpine source area (Mutti et al., 2002).

The Langhe Sub-basin became in this stage the main depocentre of the TPB, characterized by dramatic increase in subsidence rate and maximum space creation (Gelati et al., 1993; Dela Pierre et al., 1995; Rossi et al., 2009; Mosca et al., 2009; Molli et al., 2010). Carrapa et al. (2003a) could highlight by means of subsidence curves an important acceleration of subsidence between 17.5 Ma and 15.5 Ma, with the most subsiding depocentre persistently coinciding with the central part of the Langhe basinal area (Dego, Spigno). Gelati et al. (1993) calculated an average sedimentation rate of 10 cm/kyr, reaching 30 cm/kyr in depocentral areas. The base of the Cortemilia turbidite system is a conformable surface in the study area but appears as a regional unconformity in the seismic lines (Mosca et al., 2009). Physiography, general architecture, and paleocurrent pattern are significantly more regular when compared to the older, late Oligocene to early Burdigalian turbidite successions, characterized by confined, structurally-controlled basins and abrupt lateral changes in thickness and facies associations, due to the pervasive control by strike-slip tectonics (Gelati et al., 1993; Piana and Dela Pierre, 2000; Ghibaudo et al., 2014).

7.9. THE LANGHIAN BASIN REORGANIZATION

A major basin reorganization occurred in the Langhian fosterd by thrust-related uplift of the southern margin of the TPB, as well as rise and NW-ward tilting of the Borbera-Grue sector accompanied by downwarping and remarkable subsidence in the Langhe Sub-basin, still accommodating thick turbidite deposits (Pls. I, II), and concurrent birth of the subsiding Alessandria Basin. A significant change in the sandstone composition at the transition from Cortemilia to Cassinasco turbidites was documented (Gelati and Gnaccolini, 2003), specifically a sharp decrease in the percentage of serpentinite fragments.

The uplift of the Borbera-Grue area and birth of the Alessandria Basin were accompanied by the onset of deformation of the upper Cenozoic stratigraphic succession in the area located between the Alto Monferrato High and the Borbera-Grue area, with progressive curvature to NNE of stratal directions. The tilting and rise of the Borbera-Grue area is testified by an erosional and angular unconformity of eastward increasing importance at the base of the middle-upper Langhian Cessole Fm, truncating the upper Burdigalian basin-plain turbidites and the underlying stratigraphy down to the Oligocene Variano unit (Ghibaudo et al., 1985; Gelati and Falletti, 1996; Mutti et al., 2002) (Fig. 42b). Above the unconformity the middle-upper Langhian Cessole Fm is inferred to form a progradational sedimentary wedge (Pl. II) which can be traced from the Borbera-Grue area, where the unit is represented by transgressive to highstand shelf to prodelta deposits of the Gavi Siltstone, to the West (Fig. 24c, Pl. XII), with development, beyond the Scrivia Valley and up to the Vesime area (Bormida di Millesimo Valley), of a wedge of highstand to falling stage deposits including delta-slope downlapping clinoforms of the Morsasco Mudstone and Sandstone (Fig. 24d, Pl. II). In the easternmost area (e.g. Sorli section: Pl. XII) the unit shows evidence of basal ravinement on an emerged landscape, whereas in the Langhe area the distal part of the wedge is onlapped by turbidites of the Cassinasco Fm (Mutti et al., 2002) (Pl. I, II). Presence of fine-grained inferred hyperpycnites in both members of the formation is worth noting.

Carbonate shelf deposits, represented by biocalcarenites and biocalcirudites, sometimes hybrid, re-appear in places in the marginal parts of the TPB, namely in the Finale Ligure area, represented by the Langhian-Serravallian Calcare di Finale (Gelati and Gnaccolini, 1988; Brandano et al., 2015), and in the Monferrato, where the uppermost Burdigalian-lower Langhian Tonengo calcarenite (Zone N8, Bicchi et al., 1994) unconformably seals with uniform draping different tectono-stratigraphic units (Clari et al., 1995).

7.10. SERRAVALLIAN

In Serravallian times, the Alto Monferrato area persisted as submarine high, with development of a shelf sandwave complex of hybrid arenites interfingering with fan-delta deposits (Serravalle Sandstone) (Ghibaudo, 1984; Caprara et al., 1985). Evidence of forced regression at the base of this unit is provided by a discontinuity surface recognized from the Lemme Valley to the east, characterized by firm-ground with *Glossifungites* ichnofacies, covered by thick, coarse-grained and scour-based layers of hybrid sandstone with abundant skeletal debris and outsize mudstone clasts. The depositional setting of the Serravalle Sandstone (Fig. 29, Pls. XIII and XIV; see more details on depositional setting in the section 6.2.7.) was characterized by an interaction between three types of flows: i) cross-shore ephemeral storm-driven flows, ii) along-shore unidirectional tractive flows producing a field of migrating bioclast-rich sandwaves and sand ridges on the shelf, and iii) fan-delta-related mass flows emplacing coarse siliciclastic deposits. The former two processes are preponderant in the Serravalle Scrivia area, whereas the interaction with fan-delta deposits is particularly clear in the western area of the Alto Monferrato High. A forced regression in the upper part of the unit is recorded by a broad erosional discontinuity at the base of a shelf incised valley (Borbera Valley area) infilled with fan-delta resedimented deposits (Fig. 25a).

Paleocurrent pattern of the fan-delta deposits suggests that a source area subject to intense denudation was located SE of the Alto Monferrato High (Gelati and Gnaccolini, 2003; Bertotti and Mosca, 2009). This is supported by the conclusions of Caprara et al. (1985), who noted that the detrital modes of Serravalle Sandstone are close to those of the clastic Tertiary formations of Apennines, contrasting with the composition of the coeval Cassinasco turbidites which indicates a provenance from the Alpine chain, possibly the Penninic nappes of the Maritime Alps.

The trend of the paleo-coastline and inner shelf during the deposition of the Serravalle Sandstone was reconstructed by Casnedi (1983) as having a curved pattern, corresponding in our opinion to the south-eastern arcuate margin of the Alessandria Basin. The average dip azimuths of sandwave unidirectional cross-bedding are approximately normal to the mean direction of dispersal of fan-delta deposits, suggesting a roughly alongshore migration of the bedforms. The genesis of the sandwave field is inferred to reflect a paleogeographic setting with deposition occurring within a seaway bounded by Alpine and proto-Apenninic emerged areas, and probably connecting marine basins with opposite tidal phases, so that tidal current amplification could be produced; the sandwaves are thus interpreted as the typical element of a "tidal strait facies association" (Longhitano, 2013), with the associated fan-delta deposits sourced from uplifted areas representing a "strait-margin zone" .

The abrupt downward shift at the base of the Serravalle Sandstone correlates in time with a reactivation of turbidite sedimentation in the highly subsiding Langhe depocentre, where the thick Cassinasco Fm shows eastward onlap relationships with the distal part of the Cessole wedge (Pls. I, II). The NE- to ENE-ward average direction of the turbidite paleocurrents (Gnaccolini, 1968; Gelati and Gnaccolini, 2003) is thought to coincide with the tectonic-controlled orientation of the basin axis.

An important forced regression, believed to have had a composite eustatic and tectonic nature, affected the TPB Basin in the late Serravallian, recorded in the upper part of the Serravallian Sandstone by the development of an incised submarine valley (Borbera Valley area, Fig. 25a) and increased input of fan-delta coarse-grained deposits. Indeed, a regional contractional tectonics affected the TPB in late Serravallian times (Falletti et al., 1995). Evidence can be found in the Langhe area west of Acqui Terme, where the lower part of the Cassinasco Fm was affected by strike-slip tectonics along a system of sub-vertical NW- and WNW-trending faults which do not continue in the upper part of the formation. A similar system was reported by Festa et al. (2015) in the Borbera-Grue area, where the deposition of the late Serravallian-lower Messinian succession was controlled by NW-striking sinistral faults of the Sarizzola Fault Zone cross-cutting the western segment of the Villalvernia-Varzi Fault Zone (Festa et al., 2015).

The activity of a conjugate NE-SW and NW-SE trending structural system suggests the predominance of a N-S compressional regime in this stage, consistent with the tectonic regime established since the middle-late Burdigalian.

7.11. TORTONIAN-EARLY MESSINIAN

During the deposition of the Tortonian-lower Messinian Malvino and Sant'Agata Fossili formations, persisting N-S compression was accompanied by the activation of an E-W extensional regime achieved by means of a a conjugate system of NW-SE, N-S, and NNE-SSW normal faults, leading to an incipient rifting stage. This tectonics was accompanied by regional gravity destabilization with emplacement of mass-flow deposits and chaotic slumps, especially in the central-eastern TPB.

A system of NNE-SSW to N-S normal faults offset the Serravalle Sandstone west of the Scrivia Valley creating a series of small half-grabens accommodating the deposits of the Malvino Fm (Pl. I). Concomitantly, in the Vargo area, east of the Scrivia Valley, a large-scale half-graben, bounded by the listric NW-SE Vargo Fault (east of Scrivia Valley) (Ghibaudo et al., 1985) accommodated lenticular bodies of resedimented fossiliferous sandy conglomerates of the Malvino Fm (Pls. I, II). These coarse-grained deposits are attributed by Mutti et al. (2002) to highly immature mixed depositional systems developed directly seaward of fan-deltas active on the southern margin of the basin following a phase of dramatic tectonic oversteepening and uplift. The Vargo Fault worked in concomitance with the reactivation of the NW-striking Sarizzola fault zone, set in motion since the late Serravallian, and showing evidence of left-lateral movements (Festa et al., 2015). Presumably in the same time span the western margin of the Alto Monferrato High collapsed by means of the activation of a step-like system of probably NNW-striking extensional faults causing gravity destabilization and emplacement of a chaotic complex including giant olistoliths of Serravalle Sandstone and of the underlying Cessole Fm in the Rocca Grimalda area (Pls. I, II, Figs. 25d, 26 a,b) (Caprara et al., 1985; Complesso caotico di Rocca Grimalda in d'Atri et al., 2014).

Basinward progradation of flood-dominated fluvio-deltaic systems from uplifted marginal areas led to progressive narrowing of depocentres accommodating sand-prone thick-bedded oversupplied turbidite systems (upper part of the Cassinasco Fm) (Rossi et al., 2009; Mosca et al., 2009) (Pls. II, VIII online).

The transition between the Malvino Fm and the hemipelagic outer-shelf to slope deposits of the S. Agata Fossili Marl (Fig. 26c) marks a period of general and rapid drowning and basin homogenization, coinciding with the deactivation of the Cassinasco turbidite system. In the area near S. Alosio (eastern TPB) multiple intraformational unconformities were generated by coalescing slump scars (Fig. 25c) of pluri-hectometric extent (Clari and Ghibaudo, 1979). Gravity destabilization of coeval carbonate platforms during the sedimentation of the lower part of S. Agata Fossili Marl led to the emplacement of resedimented biocalcarenites (the Orsara Bormida body and another small body in the Scrivia Valley) (Fig. 26d).

The S. Agata Fossili Marl includes packages of diatomaceous laminites recording periods of anoxic sedimentation in a progressively restricted environment. This trend, together with a significant deepening, continued in the early Messinian (Fig. 30), with hemipelagic deposits interbedded with turbidite sandstones, the former consisting of burrowed blue-gray silty marls alternating with laminated euxinic mudstones; this pattern suggests cyclic variations of oxygen content at the sea bottom linked to progressive confinement of the depositional environment, preluding to the subsequent salinity crisis (Ghibaudo et al., 1985; Dela Pierre et al., 2010) (Fig. 30; see more details on depositional setting in the section 6.2.8.).

7.12. LATE MESSINIAN-PLIO-QUATERNARY

The evaporitic deposits (Nizza Monferrato Member) that elsewhere in the TPB overlie the upper member of Sant'Agata Fossili, are missing in the surveyed area, being cannibalized together with pre-evaporitic deposits and resedimented in the upper Messinian Valle Versa Chaotic Complex (*sensu* Dela Pierre et al., 2003) (Pl. I, Fig. 3) and in the Sant'Alosio Conglomerate (eastern TPB), a lenticular body of channelized sandstones and conglomerates encased in the upper part of the Sant'Agata Fossili Marl (Ghibaudo et al., 1985; Festa et al., 2015) (Pl. I), and possibly confined in a half graben bounded on the NE side by a NW-striking fault. The deposits of the Valle Versa Chaotic Complex, laid down by gravity-driven mass flow processes, include a wide spectrum of clast sizes up to large olistoliths, and are bounded at the base by the intra-Messinian unconformity, an erosional surface in places deeply incised into the substrate (Pl. I, Fig. 3), reflecting an important tectonics linked to the resumption of polyphasic north-verging thrusting. The chaotic deposits, having a wide occurrence in the TPB, are also a typical feature of the whole Apenninic margin in both outcrop and subsurface (Rossi et al., 2002). Dela Pierre et al. (2007) pointed out that they result from different evolutionary stages, including first faulting, then gravity sliding, and eventually diapiric rising triggered by methane-rich fluids in overpressure conditions which pierced the former units.

The synsedimentary tectonics played a role even in the latest Messinian, as demonstrated by the unconformity at the base of the Cassano-Spinola Conglomerate. This continental and brackish-water aggradational unit, time-equivalent of the Lago Mare deposits of the Mediterranean area, shows important thickness changes due to the local infilling of irregular morphological depressions at the top of the Valle Versa Chaotic Complex (d'Atri et al., 2014).

Intense deformations continued in the Plio-Pleistocene, particularly shaping the frontal arcs (Laubscher et al., 1992; Piana, 2000; Piana and Dela Pierre, 2000; Dela Pierre et al., 2007; Mosca et al., 2009; Festa, 2011); conversely, the sedimentary succession of the Langhe basin was translated northwards in a passive way, without suffering significant shortening and deformation (Piana and Polino, 1995). In concomitance with active northward thrusting, a general northward tilting and uplift of the TPB Oligo-Miocene succession started from the late Miocene (Forcella et al., 1999; Barbieri et al., 2003), resulting in the final Plio-Pleistocene exhumation of the TPB.

7.13. THE UNCONFORMITIES IN THE TERTIARY PIEDMONT BASIN

Omitting to consider the early evolution of the eastern TPB, major identified tectonic-driven unconformities (Pl. VII online and Fig. 3), above the middle Rupelian nonconformity at the contact between the pre-Cenozoic basement and the Molare Conglomerate, are located: between the Molare Fm and Rocchetta (= Monastero) Fm (uppermost middle Rupelian), notably in the easternmost TPB area; at the base of the lower Burdigalian Visone Fm; at the base of the middle Burdigalian Lerma Glaucony; at the base of the Langhian Cessole Fm in eastern area; in the upper part of the Serravallian Serravalle Sandstone; at the base of the Tortonian Malvino Fm; at the base of the intra-Messinian Valle Versa Chaotic Complex and of the upper Messinian Cassano Spinola Conglomerate. In the Rupelian to Langhian part of the TPB succession these discontinuities are typically more prominent in the eastern part of the basin, suggesting a critical influence of the dynamics of the Apenninic orogen on the evolution of the TPB; this link may also explain the contextual E-W diachroneity of sedimentary and tectonic events with westward younging trend (Fig. 3).

8. GEOLOGIC EVOLUTION OF THE STUDY AREA IN A REGIONAL FRAMEWORK

8.1. EARLY STAGE OF TPB EVOLUTION

The early geologic history of the TPB is mostly recorded in the eastern TPB prior to the start of the generalized TPB sedimentation. Its reconstruction is briefly delineated here, although several aspects remain uncertain.

^{40}Ar/^{39}Ar datings of metamorphic rocks in the Voltri Massif and of clasts from the TPB suggest the following metamorphic evolution (Federico et al., 2005): an eclogite peak in early Eocene, at ca. 49-43 Ma (between ~50 and ~34 Ma according to Vignaroli et al., 2010, their D_1-M_1 stage) is followed by retrogressive overprinting, first of blueschist facies in middle Eocene at ca. 43-40 Ma and then of greenschist facies in early Oligocene at ca. 33 Ma (D_2-M_2 stage of Vignaroli et al., 2010, assigned to the 33-35 Ma time interval). The D_2-M_2 stage overlaps with a main regional denudation episode and onset of the TPB sedimentation (Bertotti et al., 2006). The exhumation scenario proposed by Vignaroli et al. (2010) in the Alps-Apennines junction area during the Tertiary involves a two-stage process, evolving from synorogenic to postorogenic contexts. Early synorogenic exhumation from eclogitic and blueschist facies conditions (middle Eocene) occurred within the subduction zone and was driven, according to Vignaroli et al. (2010), by the circulation path imposed at depth by transpressional kinematics at the convergent plate boundaries. The synorogenic exhumation was then followed by an early Oligocene postorogenic exhumation stage in an extensional regime concomitant with crustal thinning and opening of back-arc basins (Vignaroli et al., 2010).

The Priabonian to lower Rupelian succession of the eastern TPB preceding the post-orogenic exhumation is the sedimentary record of a peculiar tectonic and palaeogeographic behaviour with respect to the western part of the basin (Langhe and alto Monferrato), as confirmed by the independence of the subsidence and palaeothermal history (Bersezio and Peraldo, 2003). The translation of the Adria plate during the middle to late Eocene occurred along a major transcurrent, originally NE-trending sinistral lineament, now oriented approximately N-S, roughly following the older Alpine suture belt and running along the eastern margin of the Corsica-Sardinia block at the boundary between the Iberian and Adriatic plates, in a setting of oblique convergence (Dewey et al., 1989; Laubscher et al., 1992; Marroni and Pandolfi, 2003; Lacombe and Jolivet, 2005; Ford et al., 2006; Molli et al., 2006; Vignaroli et al., 2008, 2010; Argnani 2009; Handy et al., 2010; Dumont et al., 2012; Maino et al., 2013; Treves and Nirta, 2014; Principi and Treves, 2014). This left-lateral strike-slip lineament is believed to be a major crustal discontinuity playing a major role in the northward displacement of Adria, particularly during the Eocene (Treves and Nirta, 2014; Principi and Treves, 2014; Marroni et al., 2016). Following the proposal of Vignaroli et al. (2008, 2010) a double-sided middle Eocene subduction (ablative subduction of Tao and O'Connell, 1992; see also Roda et al., 2010) occurred in Corsica and Ligurian Alps, linking a northern branch, where a portion of Adria was overriding the European crust along the Alpine arc, with a southern branch where a portion of Adria was subducting westwards under Iberia (Apennines).

Vignaroli et al. (2008) pointed out that the general northward motion of the Adria with respect to the Eurasia appears to be nearly parallel to the strike of the two trenches; they considered that the deep strike-slip deformation in the subduction system is the possible mechanism to bury oceanic and continental rocks at great depths and to induce their subsequent early exhumation. According to Vignaroli et al. (2010) sinistral transpressional strike-slip motion at the boundary between the two plates was the geodynamic setting of the middle Eocene syn-orogenic exhumation of the Voltri Massif HP complex. This scenario is supported by the presence in the eastern Corsica of middle Eocene submarine mass wasting episode (Puccinelli et al., 2012) with deep erosion of a large relief inferred to have created along a major sinistral transpressional lineament, with generation of sedimentary mélanges (Massari and Dieni, 2014). Moreover, evidence was found of transpression along the main tectonic lineaments in the area of the Alps-Apennine junction during the late Eocene-early Oligocene northward displacement of the Adria plate, such as the Ottone-Levanto Line (Cerrina Feroni et al., 2002, 2004; Hobbs et al., 2014; Marroni et al., 2016) and the Sestri-Voltaggio Lineament (Mutti et al., 1995; Ogata, 2010; Marroni et al., 2016). It is worth noting that Laubscher et al. (1992) showed a possible continuation of the above-mentioned sinistral lineament running along the eastern margin of the Corsica-Sardinia block into the Ottone-Levanto Line. This finds support in the proposal of Elter and Marroni (1991) and Marroni and Treves (1998), that important sinistral strike-slip motions occurred in pre-Oligocene times along this line. Moreover, Hobbs et al. (2014) and Marroni et al. (2016) suggested that this line, one of the most important structural elements that played a fundamental role in the geodynamic evolution of the Northern Apennines at its junction with the Western Alps, acted as sinistral traspressional shear zone in the late Eocene-early Oligocene times during the northward displacement of the Adria plate. It was correlated with other lines of the Alpine-Apennine system, such as the the Sestri-Voltaggio line and the Central Corsica shear zone. In the Marroni et al. (2016) interpretation, all these tectonic lineaments developed during collisional tectonics, resulting in both east- and westward thrusting of the internal zone of the Alpine-Apennine system onto the continental margin domains, coeval with the northward displacement of the Adria plate.

Within this geodynamic context, left-lateral transcurrent motion is believed to have been active since at least the Priabonian, possibly also since Bartonian in north-Apenninic area and in the eastern TPB (Ogata, 2010; Vignaroli et al., 2010). Lineaments possibly involved, in addition to the Ottone-Levanto Line were the Sestri-Voltaggio Line (Haccard 1975; Cortesogno and Haccard 1979) and the Scrivia Fault. The latter lineament during this stage is believed to have represented a major geologic boundary between the eastern and western TPB, the former acting as depocentre dominated by deep-marine and shelfal clastic sediments (our Ranzano Allogroup) in the late Eocene to earliest Rupelian and the latter probably behaving as emerged land at this time.

We suggest that in the middle to late Eocene a setting of strike-slip-controlled high tectonic mobility generated small but rapidly subsiding, highly confined and migrating depocentres in the eastern TPB (ponded mini-basins of Tinterri et al., 2017), with geometry and dimensions variable through time, highly unstable source areas, and infills mostly represented by low-efficiency turbidite systems, characterized by progressive angular unconformities (i.e. growth stratal pattern), and onlap against basin margins, the latter being subject to syn-sedimentary uplift (Papani, 1990; Ogata, 2010). The structural depression which accommodated the Savignone Conglomerate was interpreted as transtensional pull-apart basin by Mutti et al. (1995). A similar interpretation as strike-slip basins may be extended to the coeval highly subsiding, confined troughs hosting the Val Pessola Member in the northern Apennines (cf. Martelli et al., 1998; Mancin and Pirini 2001; Cibin et al., 2003). Considering the unconformities punctuating the succession and the context of high tectonic mobility, we suggest that all the above outlined small depocentres are small-scale strike-slip basins subject to alternating transtensional and transpressional strain conditions, developed in the eastern TPB and in the adjacent northern Apennines. A comparison is instructive with the Corsica Basin infill, where seismic data presented by Mauffret et al. (1999) indicate a stratigraphic succession wholly similar to that cored in in the Martina 1 and Mimosa 1 wells (Cornamusini and Pascucci, 2014), where highly deformed lower to middle Eocene sediments are unconformably overlain by weakly deformed Rupelian deposits; in our opinion the hypothesis of a tectonic setting comparable to that of the coeval successions of eastern TPB and northern Apennines is attractive. The latter two areas were not yet separated from one another as differentiated geologic domains at this time (Papani, 1990; Mutti et al., 1995; Cibin et al., 2001; Ogata, 2010). The middle-late Eocene left-lateral motion at the plate boundary, also involving the above-mentioned lineaments, presumably inhibited the migration of the North-Apenninic orogenic front, as supported by the lacking development in this stage of known Apenninic foredeep and associated sedimentary prisms, as stressed by Mutti et al. (1995). The sedimentary succession laid down during this stage in the eastern TPB on top of the Alpine edifice may be defined as *episutural* (Biella et al., 1988; Polino et al., 1990; Schumacher and Laubscher, 1996; Biella et al., 1997; Schmid and Kissling, 2000), corresponding to the term "epimesoalpine" proposed by Mutti et al. (1995), and implying that the depositional area included in a unique paleogeographic domain the TPB and the northern Apennines, not yet differentiated at this time. On the other hand, the term *Epiligurian* (Ricci Lucchi and Ori, 1985), is appropriate in our opinion for the younger deposits laid down in N-Apenninic satellite basins after the onset of retreat of the Apenninic subduction.

8.2. MID-RUPELIAN CRUSTAL STRETCHING (~33-31 MA)

A major geodynamic change occurred in the Mediterranean region starting from ca. 33 Ma, marked by reorganization of plate movements (Stampfli et al., 2002) from a regionally compressional subduction coeval with the formation of Alpine mountain belts, to crustal stretching and thinning (Jolivet et al., 2008), associated with a thermal perturbation and magmatism. The turnover was concomitant with slowing of Africa-Eurasia convergence and beginning of eastward retreat of the Apennine slab, accompanied by onset of backarc rifting in the Liguro-Provençal area (Vignaroli et al., 2010 with references therein). Vignaroli et al. (2008, 2010) argued that a major tectonic unroofing stage due to E-W crustal stretching affected the Voltri massif since ca. 33 Ma (early Rupelian), achieved along low-angle top-to-the-W, ductile-to-brittle extensional detachment systems (see also Hoogerdujing Strating, 1994) associated with normal faulting. This is described by the authors as post-orogenic exhumation, considered to have taken place in a brittle-dominated environment, after the middle Eocene synorogenic early exhumation from eclogitic and blueschist facies conditions. The involved processes led to exhumation of the deep, metamorphic units of the Mesoalpine prism in the footwall of a regional-scale extensional shear (Carminati et al., 1998; Jolivet et al., 2003, 2008; Federico et al., 2005; Doglioni et al., 2005; Vignaroli, 2006; Vignaroli et al., 2008, 2010; Bernardeschi, 2009; Beltrando et al., 2010; Maino et al., 2013).

The geologic evolution in this stage was no longer restricted to the eastern TPB: it became a common history for the whole TPB, where the extensional regime, related to a general E-W direction of maximum extension, led to block faulting and differentiation of the topography into a system of horst and graben bounded by normal faults. As noted by Vignaroli et al. (2008) and Maino et al. (2013), the main E-W directed extension in the TPB is orogen-parallel and kinematically compatible with the coeval extension and rifting generated by the onset of the opening of the Liguro-Provençal basin. The post-orogenic exhumation in the TPB overlapped with the main regional denudation episode following the uplift, which resulted in the Rupelian generalized coarse-grained sedimentation (Bertotti et al., 2006; Vignaroli et al., 2010). This contrasts with the underfilled Rupelian sedimentation which occurred in nearby areas (e.g. the marl-dominated sedimentation of the Chiasso Group in the Lombardian Southern Alps) and implied deep erosion of a rugged topography with significant relief within the TPB. As noted by Maino et al. (2013), the Molare Conglomerate records the dismantling of the rapidly exhuming orogen associated with moderate subsidence rate in the structural depressions; this episode corresponds to their F1 extensional stage identified in the south-western TPB.

The above outlined E-W differentiation of environmental settings during the deposition of the Molare Formation, with westward change from turbiditic, through deltaic, to continental conditions in a system of grabens showing average westward decrease in subsidence rate, can be reasonably interpreted in the context of the onset of back-arc extension in the rear of the initially migrating North-Apenninic front; this supports the contention that the onset of retreat of the Apenninic slab occurred during the early Oligocene, as suggested by Faccenna et al. (2004), Rosenbaum and Lister (2004), and Vignaroli et al. (2010). Since then, a differentiation began to occur between the geologic context of the TPB and that of the Epiligurian domain of northern Apennines.

The abundance of detritus derived from HP rocks in the sedimentary succession of the Molare Fm is the record of the ongoing denudation of uplifted Penninic high pressure-low-temperature metamorphic units of the Mesoalpine prism (i.e. the Voltri Group), as a result of post-orogenic exhumation. This can be documented in a characteristic olistolith-bearing lithozone present in the eastern TPB in the lowermost part of the Molare Formation, i.e. the Persi Member of the 1:50000 Geologic Sheet Cabella Ligure (di Biase and Pandolfi, 1999; Bernardeschi, 2009) (our Persi Lithozone). Mutti et al. (1995) pointed out that the Persi Member may correlate with the unconformity-based Specchio unit of the adjacent Northern Apennines, a thick, chaotic, and olistolith-bearing body derived from the cannibalization of underlying platform and slope deposits and forming a gravity-emplaced mass at the base of the Varano de' Melegari Member, dated at ~32-29 Ma according to Martelli et al. (1998). The latter is the first unit containing a significant fraction of clasts derived from HP rocks of the Penninic units (Cibin et al., 2001), and therefore can correlate with the Molare Fm of the TPB. The major intra-Rupelian regional unconformity between the underlying Val Pessola Mb and the middle-upper Rupelian Varano de Melegari Mb, is believed to mark an important palaeogeographic change (Martelli et al., 1998; Cibin et al., 2001), comparable to that occurred in eastern TPB at the transition from the Ranzano Allogroup to the Molare Conglomerate.

During the Priabonian (ca. 35 Ma) convergence between Adria and Europe slowed down (1.5 to 1.3 cm yr^{-1} or less), due to increase in the forces resisting further subduction at the onset of continent-continent collision in the Alps, with entry of buoyant European continental margin into the subduction zone (Jolivet et al., 2000). This geodynamic setting eventually led to tearing of the European slab beneath the Alps (von Blanckenburg and Davies, 1995; Davies and von Blanckenburg, 1995). Although there is not consensus about the date of the slab tearing (e.g. Handy et al., 2010 and references therein), most authors have favoured a post-collisional breakoff occurred around the Eocene/Oligocene boundary (e.g. Stampfli et al., 1998). Handy et al. (2014) suggested that after the onset of tearing beneath the Alps in the Priabonian (35 Ma), the slab tear propagated westwards, joining the Ligurian area by the Rupelian. We share this proposal, and believe that, in concomitance with the slowing down of the convergence between the Adria and Europa plates, the propagation of the slab tear in the Ligurian area concurred in creating favourable conditions for the onset of active retreat of the Apenninic slab since ca. 32 Ma.

We believe that the migration of the Apenninic accretionary wedge in presence of still consumable, negatively buoyant oceanic lithosphere in the eastern Ligurian Ocean started since the early Oligocene, resulting in the the first development at this time of an Apenninic foredeep. This is supported by the assumption that the Aveto succession (32 Ma) represents the record of the first development of a subaqueous proto-apenninic wedge, as supported by the presence of ophiolitic fragments in the debris flow deposits at the top of the succession, indicating that the sedimentation was stopped by the tectonic emplacement of the Liguride Units in the early Oligocene (Catanzariti et al., 2003).

The early Oligocene onset of migration of the N-Apenninic front (Faccenna et al., 2004; Rosenbaum and Lister, 2004; Vignaroli et al., 2010), led in turn to the beginning of back-arc extension and related rifting in the rear of retreating eastern Ligurian slab (e.g. Séranne, 1999; Dèzes et al., 2004). The ensuing Gulf of Lion-Provençal rifting marks the onset of opening, at ca. 32 Ma, of the Ligure-Provençal backarc basin in the wake of retreating Adria subduction (Vanossi et al., 1994; Mutti et al., 1995; Gelati and Gnaccolini, 1998; Séranne, 1999; Rollet et al., 2002; Speranza et al., 2002; Dèzes et al., 2004; Vignaroli et al., 2008; Vignaroli et al., 2009; Beltrando et al., 2010; Ghibaudo et al., 2014; Handy et al., 2015). Within this geodynamic framework, the Rupelian rifts of the TPB may be interpreted as backarc structural features formed in the rear of retreating eastern Ligurian slab, in a geodynamic context comparable to that of the Gulf of Lion - Provençal rifting. The main E-W directed extension in the TPB is kinematically compatible with the coeval extension generated at the onset of the opening of the Liguro-Provençal basin. The postorogenic exhumation of HP rocks in this stage should therefore have occurred in a context of plate divergence (e.g. Liao et al., 2018). The rifting propagates westwards with a certain diachroneity. Indeed, TPB grabens show progressive westward opening and significant decrease in subsidence rate and thickness of infilling deposits in that direction (Fig. 3); moreover, TPB rifting was essentially middle Rupelian in age, whereas the Liguro-Provençal backarc rifting occurred later, namely since the late Rupelian, ~30 Ma (Rollet et al., 2002; Dèzes et al., 2004), and ended in the Aquitanian, ~21 Ma (Rollet et al., 2002). The diachroneity is thought to reflect the role of the Apenninic subduction as the primary cause of rifting.

8.3. THE LATE MIDDLE RUPELIAN SINISTRAL STRIKE-SLIP TECTONICS AND ONSET OF ADRIATIC INDENTER TRANSLATION (~30.5 MA)

An episode of probably near-pure sinistral strike-slip tectonics on regional scale occurred in the late middle Rupelian. This is regarded as reflecting the onset of the NW-ward indentation of the rigid continental core of the Adriatic microplate (i.e., the Adriatic Indenter, AI) into the Alpine orogenic edifice, a motion accommodating Africa-Europe convergence and occurring by means of a regional left-lateral transfer zone (see also Ford et al., 2006 and Dumont et al., 2011). We postulate that sinistral shear became manifest in this stage in the intervening area between master faults represented by the VV Line and a major lineament bounding the TPB to the south, previously indicated by Laubscher (1971) as Ligurian fault zone and corresponding in our opinion with the Stura fault zone. The Stura fault system (indicated by us as "Stura Fault" hereafter, for sake of simplicity), whose importance was stressed by Ricou and Siddans (1986), Giglia et al. (1996) and Bigot-Cormier et al. (2006) among others, was first documented by Ricou (1981) and Lefèbvre (1983) along the so-called "Couloir de la Stura". It comprises the "Stura couloir", the "Cicatrice del Preit" and the "Limone-Viozene" fault zones (Ricou, 1981; Lefèvre, 1983; Musso et al., 2009; Piana et al., 2009, 2011). Giglia et al., 1996 could establish that sinistral strike-slip displacement along this composite lineament affected the Mesozoic-lower Oligocene succession that rests on the NE boundary of the Argentera Massif. Bertok et al. (2011) demonstrated that the Stura fault zone, affected by synsedimentary tectonics since the middle-late Jurassic, was re-activated since the early Oligocene as a regional sinistral transfer zone (the "Ligurian transfer zone" of the authors; the "Ligurian Sinistral Transfer" - LST - of d'Atri et al., 2016). We believe that the sinistral motion was nearly pure strike slip in this stage, due to near parallelism between the above mentioned lineaments and the direction of sinistral shear produced by the NW-ward translation of the AI, and we propose that the regional left-lateral transfer zone activated between the overlapping fault strands corresponding to the VV Line and Stura Fault resulted in the conversion of the TPB into a left-stepover strike-slip basin (Ghibaudo et al., 2014). In this assumption we follow the opinion of Laubscher (2010), who interpreted the TPB (his Langhe Basin) as a strike-slip basin formed concurrently with the left-slip motion along the VV Line and similar in extent and in origin to the basins originated along the Caribbean strike-slip system. Formerly, Dela Pierre et al. (1995) suggested that the strongly subsiding upper Oligocene Langhe Basin is a pull-apart basin resulting from strike-slip activity.

Due to the inferred partly overlapping master faults (VV Line and Stura Fault), the resulting pull-apart basin should be characterized by a rhomboidal shape (Corti and Dooley, 2015). The western and eastern boundaries of the basin are not easy to identify. The western boundary may be represented by a NNE lineament passing near Mondovì, on the prosecution of a similarly oriented fault crossing the basement to the south. The eastern boundary is more difficult to identify: its correspondence with the Sestri Voltaggio fault system may be postulated.

During the westward migration of the AI, the TPB and adjoining areas experienced strain partitioning between strike slip at the northern and southern sides of the indenter and compression at its front. This resulted in severe and repeated refolding, WNW-directed thrusting and S- to SE-directed backfolding of Penninic units in the Western Alps (Handy et al., 2015; Beucher et al., 2017); on the other hand, in the inner side of the Western Alps, this tectonics generated SE-verging Alpine backthrusts in the Saluzzese area accompanied by development of pensile basins on them, and deep-seated high-angle faults in the Monregalese area of the TPB and its westerly subsurface continuation (Rossi et al., 2009; Mosca et al., 2009). In the area between Cuneo and Bagnasco seismic data presented by Mosca et al. (2009) illustrate a roughly E-W to WSW-ENE striking lineament with flower geometries, controlling the development of km-scale sub-basins; in our opinion this lineament may belong to the Stura fault system.

8.4. THE LATE RUPELIAN-CHATTIAN DROWNING STAGE (~30-24 MA)

A large-scale basin reorganization in the TPB is recorded in the latest middle Rupelian by an event of regional collapse and rapid drowning. The late middle Rupelian conversion of the TPB into a stepover, pull-apart basin, which occurred in a context of regional left-lateral strike-slip faulting, was followed by dramatic acceleration of subsidence, recorded by a drastic change in sedimentation, particularly evident in western TPB, where it led to a true platform drowning event, probably enhanced by the important eustatic sea-level rise of the Rupelian TB1.1 cycle (Miller et al. 1998). This episode led to basinwide deposition of slope hemipelagites (Rocchetta Fm), encasing bodies of coarse-grained resedimented deposits, particularly important in the Langhe and Borbera-Grue depocentres. The high subsidence rate which accompanied the rapid drowning of the TPB finds a support in the conclusions reached by Bertotti et al. (2006), who could establish, by means of apatite (U-Th)/He and fission track thermochronology data, that, after rapid Eocene to early Oligocene exhumation (Carrapa et al., 2003), the belt corresponding to the outcropping basement-TPB contact in the area of the present Ligurian Alps experienced >4 km of subsidence from 30 to 26 Ma.

Concomitantly with drowning in the basin, an important phase of uplift in the west-Alpine area is indirectly reflected by the coarse-grained turbiditic sedimentation in the Rocchetta Fm, particularly in the Langhe area, presumably fed from western fan-delta systems, indicating high denudation rates of the west-Alpine axial sector (Rossi et al., 2009).

We assume that an episode of inversion of movement occurred along the VV Line with respect to the former left-lateral motion, with activation of a right-lateral transtensional regime in the TPB during the deposition of the Rocchetta Fm (Fig. 37). In the TPB this tectonic episode may correspond to the event A described by Federico et al. (2014) in the Voltri Unit, including faults fitting a right-lateral transtensional scenario. The left-lateral motion along the VV Line may be genetically linked with the sinistral transtension of unknown magnitude postulated by Laubscher (2010) to have occurred along the Periadriatic Line in a stage predating the major event of late Oligocene-early Miocene transpression and related Adria indentation. The geodynamic context of this event of dextral transtension is not clear. It may be supposed that a provisional demise of the WNW translation of the Adriatic Indenter and change into regional transtension have been generated by an acceleration of SE-ward subduction of the downgoing Apennine slab, concurrently with slowing down of the Africa-Europe convergence in the Chattian.

The role of the VV Line as element of separation between the TPB and Epiligurian Apennine succession, resulting in a separate evolution of the two domains, is documented by the compositional study of sandstone encased in the Antognola Fm (Martelli et al., 1993). Moreover, Cibin et al. (2001) stressed that the base of the Antognola Marl marks a significant step of Penninic source widening, and a major tectonic reorganization. Di Giulio and Galbiati (1995) argued that all the above elements indicate the rise of a morphologic-tectonic boundary most probably corresponding to the VV Line. Changes in the depositional paleo-slope linked to tectonic-driven deformations of the substrate are indicated by diffuse effects of gravity destabilization both in the Langhe and Borbera-Grue sub-basins, such as multiple large-scale slump scars and local mass wasting which accompanied the deposition of the Rocchetta Fm.

A genetic analogy is proposed between the TPB and the Corsica Basin, which developed in a comparable geologic setting in the wake of the Apenninic front (Ghibaudo et al., 2014). This basin contains over 5 km thick Oligo-Miocene sedimentary fill (Mauffret and Contrucci, 1999; Mauffret et al., 1999), and is interpreted as a rhomboidal pull-apart basin grown during an Oligocene-early Miocene transtensional regime on an oblique convergent margin, in the wake of the Apenninic front (Mauffret et al., 1999). It should have developed before or during the opening of the Ligure-Provençal Basin, concurrently with the Oligocene collapse of the Alpine Corsica belt and strike-slip motion along the plate boundary (see also Daniel et al., 1996; Mauffret and Contrucci, 1999; Argnani, 2002). It may also be proposed that this basin accommodated the distal deposits of the Chattian turbidite system of the TBP (Ghibaudo et al., 2014). Indeed, this turbidite complex most probably extended onto, and possibly beyond, the present-day uplifted Ligurian Alps, joining an area of the present-day northern Tyrrhenian Sea located in internal position with respect to the Macigno Basin and possibly corresponding to the Corsica Basin (Ghibaudo et al., 2014).

8.5. THE MAIN PHASE OF THE ADRIATIC INDENTER TRANSLATION (~24-22 MA)

The change in the direction of motion of the Adriatic Indenter (AI) with respect to Europe from NW-ward to WNW-ward (Schmid and Kissling, 2000; Handy et al., 2010) resulted in conditions of oblique convergence and increased collisional coupling (Schmid and Kissling, 2000; Ziegler et al., 2002), whose effects are recorded in a large part of the Mediterranean area in the Aquitanian (Edel et al., 2001, and references therein). The increased coupling led to the switch from transtensional to generalized transpressional regime in the TPB, accompanied by local inversion of formerly active lineaments.

This event took place in our opinion concurrently with the first entrance into subduction of Adriatic continental crust in northern Apennines as a result of the late Oligocene-early Miocene collision linked to overriding of the Corsica-Sardinia block on the Adriatic continental margin, after the brief early-middle Oligocene stage of consumption of residual oceanic crust. It is worth noting that this event, involving the collision of the Briançonnais microplate with the Apulia continental margin, was accompanied by transpressional tectonics in Sardinia and southwestern Corsica (Carmignani et al, 2004 and references therein), thought to be coeval with the transpressional tectonics which affected the TPB.

The main phase of sinistral transpression along the VV Line dates to the late Oligocene/early Miocene (Elter and Pertusati, 1973; Pieri and Groppi, 1981; Laubscher et al., 1992; Schumacher and Laubscher, 1996). Laubscher (1991), Laubscher et al. (1992) and Schumacher and Laubscher (1996) established that this main transpressional lineament acted as a sinistral transfer fault zone and, operating together with dextral transpression along the Insubric Line at the northern boundary of the Adria Indenter, accomplished the convergence of Adria and Europe by underthrust of the Adriatic Indenter (AI) under the Western Alps and, to the east, under the Ligurian Alps along the Ottone-Levanto zone (their Insubric-Helvetic phase of Alpine orogeny). The left-lateral motion along the VV Line led to the emplacement of the Monferrato Apenninic units carried piggy-back westwards along this lineament on top of the AI (Laubscher et al., 1992; Schumacher and Laubscher, 1996). We share this reconstruction implying the crucial role played by the VV Line in this stage. The amount of left-slip resulting from the westward transportation of the Appenninic nappes to the north of the Ligurian Alps was estimated by the above authors in excess of 100 km, perhaps as much as 140 km. We argued that transpression along the VV Line occurred slightly earlier in the eastern part of this lineament; a similar E-W diachroneity was observed by Laubscher (2010) for the Insubric Line.

The transpressional motion induced uplift of the belt surrounding the VV Line, as highlighted by subsurface data, particularly the NE-SW seismic line passing through the Quargnento well bored at the NE margin of the Alessandria basin (Rossi et al., 2009; Mosca et al., 2009). This seismic line shows a positive structure bounded on the northern side by a NE-verging thrust inferred to correspond in position to the westward prolongation in the subsurface of the VV Line; on the backlimb of the structure, two stacked, southward prograding Visone-type clinoform wedges appear to have been tilted southwards, and onlapped by subparallel reflectors of middle Burdigalian to Langhian deposits. In our opinion, a structural high promoting the settling of a shallow-water carbonate ramp in the early Burdigalian was created by transpressional motion along the VV Line; subsequently, northward compression converted this lineament into a north-verging thrust, and caused southward tilting of the carbonate deposits, as indicated by the marine onlap of the middle Burdigalian-Langhian turbiditic succession against the tilted carbonate ramp at the backlimb of the structure.

The progressive indentation of the rigid continental core of the Adriatic microplate (i.e., the AI) into the Alpine orogenic wedge contributed to the oroclinal bending of the Western Alps (Schmid et al., 1989; Schmid and Kissling, 2000; Collombet et al., 2002, Handy et al., 2010). Moreover, the westward migration of the AI during the late Oligocene-early Miocene implied strain partitioning between transpressional strike slip along the VV Line and Insubric Lineament on one hand, and, on the other hand, WNW-directed thrusting and S- to SE-directed backfolding along the Penninic Front in the Western Alps (Handy et al., 2015), as well as SE-verging backthrusts in the internal side of the West-Alpine arc (Giglia et al., 1996; Schumacher and Laubscher, 1996; Mosca, 2006; Spagnolo et al., 2007; Maffione et al., 2008; Capponi et al., 2009; Malusà et al., 2009; Mosca et al., 2009; Molli et al., 2010; Handy et al., 2015). Specifically, on the internal side of the Western Alps, seismic lines reveal E- to SE-verging backthrusts driving the juxtaposition of substrate over the TPB sedimentary successions during Oligocene to early Miocene times (Saluzzese area: Rossi et al., 2009; Mosca et al., 2009). This tectonics was concomitant with the back-folding and backthrusting which affected the western part of the Southern Alps, with vergence towards the Po plain (Giglia et al., 1996).

The indentation of Adria is known moreover to have been accompanied by the main morphogenetic phase of the Alps (Pfiffner et al., 2002; Garzanti and Malusà, 2008; Beltrando et al., 2010), with rapid generation of topographic relief. Indeed, there is evidence of generalized coarse sedimentation in various areas of TPB, and in western south-Alpine domain as well as northern Apennines in late Chattian-Aquitanian times. Worth reminding are the Aramengo-Marmorito formations in western Monferrato (Bonci et al., 1990), fed by emerged source areas S of the Monferrato (Clari et al., 1995), and the Gonfolite of the Adriatic foredeep, regarded as the proximal depositional area of the Macigno (Lorenz, 1984; Gelati et al., 1988; Garzanti and Malusà, 2008). Denudation of a rapidly uplifting area near the southern margin of the TPB in a span of time from 26 to 20 Ma (late Chattian-Aquitanian) was inferred by Bertotti et al. (2006).

The important morphogenetic phase was accompanied by the significant change in sediment composition within the TPB, as stressed by Carrapa (2002), who highlighted that the formerly active lower Oligocene sources, dominantly located in the area of Ligurian Alps/Voltri Group, gradually moved to the West-Alpine area. High denudation rates of the West-Alpine axial sector from late Oligocene onwards, linked to important uplift, resulted in eastward shedding of huge volumes of coarse-textured sediments via fan-delta systems, prograding eastwards from the western margin of the TPB (the Saluzzese-Monregalese belt, Rossi et al., 2009). In fact, since the end of early Oligocene and until part of the Burdigalian the source areas were located to the NW and SW with respect to the basin (Gelati and Gnaccolini, 1980; Cazzola et al., 1981; Cazzola and Rigazio, 1983; Cazzola and Sgavetti, 1984; Cazzola and Fornaciari, 1990; Gelati et al., 1993; Gnaccolini et al., 1998; Gelati and Gnaccolini, 1998; Gelati et al., 2010).

8.6. THE MAIN COUNTER-CLOCKWISE ROTATIONS (~20-18 MA)

Counter-clockwise rotation of the Adriatic Indenter (AI) mainly occurred during the Burdigalian, since about 20 Ma (Bauve et al., 2014), around an eulerian pole located near Torino (Cheloni et al., 2003; Delacou et al., 2008). The rotation was accommodated by dextral motion along the Insubric Line, the PFT (Penninic Front), and the Jausiers-Tinée-Saorge-Taggia - Bersezio fault system (Collombet et al., 2002; Sanchez et al., 2010; Rolland et al., 2012; Bauve et al., 2014 and references therein).

The internal Alps suffered nonhomogeneous counterclockwise rotations ranging from 27° to 117° with remarkable southward increase of rotation angles (Collombet et al., 2002), probably reflecting the concomitant enhancement of the curvature of the West-Alpine arc. On the other hand, the CCW rotation angle of the Adriatic Plate was estimated to be in the order of 20-25° by Collombet et al. (2002), and of about 25° by Márton et al. (2017). Maffione et al. (2008, 2010) demonstrated that in the early to middle Miocene the TPB underwent a rotation of ca. 50° counterclockwise with respect to Africa, a value remarkably higher than the rotation angles reported for the Adriatic Plate, suggesting a largely independent behavior. Maffione et al. (2008) could establish that the TPB rotation took place in concomitance with the drift and very fast counterclockwise rotation of the Corsica-Sardinia microplate, with comparable timing and magnitude, and concluded that the two domains were joined together at that time and behaved as a unique block.

The counter-clockwise rotation of the Corsica-Sardinia microplate (Maffione et al., 2008) is known to have been accompanied by oceanic spreading and generation of the central oceanic portion of the Ligure-Provençal basin as a back-arc basin in the wake of the south-eastward roll-back of the Apennines-Maghrebides subduction (Rehault et al., 1984; Vigliotti and Langenheim, 1995; Doglioni et al., 1997; Gueguen et al., 1998; Speranza et al., 2002; Faccenna et al., 2002; Rollet et al., 2002; Gattacceca et al., 2007; Cherchi et al., 2008; Carminati et al., 2012). Gattacceca et al. (2007) established that approximately 30° of rotation occurred between 20.5 and 18 Ma, that is mostly during the Burdigalian.

Taking inspiration from the reconstruction presented by Laubscher (1991), Laubscher et al. (1992), Perotti et al. (1994), and Maffione et al. (2008), it is suggested that a Sardinia-Corsica-Liguria block, including the TPB [("the young Ligurian plate" of Kissling et al. (2012)], came into existence as a unique microplate following the rotation occurred SE of the Ligurian Sea collapse. The present-

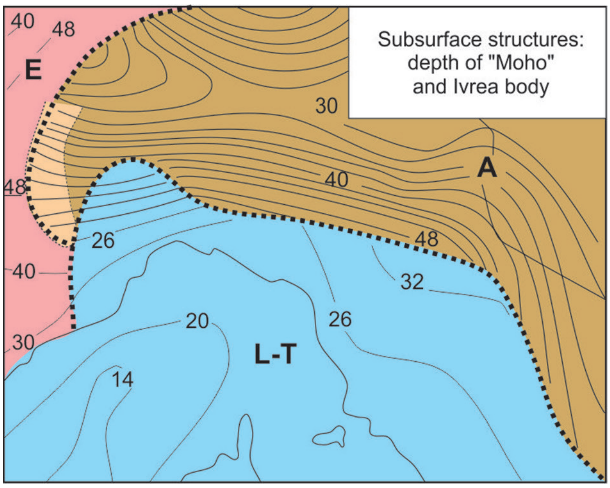

Fig. 43 - Crustal thickness in the Alps-Apennines junction area (contour interval of 2 km), depth of Moho, and Ivrea body. Dashed lines: boundaries between European (E), Adriatic (A) and Ligurian-Tyrrhenian plates (L-T). From Molli et al., 2010 (references therein).

day Moho architecture and geometry of the Moho discontinuities shows high complexity in the area of the Alps-Apennines junction, as indicated by the geophysical data (e.g. Ziegler and Dèzes, 2005) (Fig. 43). It is tempting to attribute this configuration mainly to the effects of the Burdigalian rotation, regarded as playing a critical role in fixing the boundaries of "the young Ligurian plate" interposed between the European and Adria plates. The northern boundary of this "young Ligurian plate" should have had an arcuate geometry, which prefigured that of the front of the AXF crustal structure (see below), whose emplacement may have initiated in concomitance with the TPB rotation, with main development in the middle-late Burdigalian and Langhian.

8.7. THE TECTONIC TRANSLATION TOWARD THE PADAN FOREDEEP

8.7.1. The late Burdigalian revolution (~17 Ma)

A major morphostructural reorganization affected the "young Ligurian microplate" and adjoining areas since the late Burdigalian and led to important changes in the rates of accommodation and sediment flux. This reorganization is thought to relate to the beginning of delamination and retreat of the Apenninic margin and inferred concomitant onset of underplating in the western part of the northern Apennines and TPB area. After the late Oligocene-early Miocene continental collision between the Corsica-Sardinia Block and Adriatic continental margin (Carmignani and Kligfield, 1990), the northern Apennines evolved as a retreating margin, due to rollback of the downgoing Adriatic slab and delamination of subducted continental crust (Reutter et al., 1980; Royden et al., 1987; Doglioni, 1991; Royden, 1993; Carmignani et al., 1995; van der Meulen et al., 1998, 1999; Mauffret and Contrucci, 1999; Lucente and Speranza, 2001; Di Giulio et al., 2013; see Molli, 2008 for an updated review). The beginning of delamination and retreat of the northern Apenninic margin is regarded as a major turnover in the style of Adria subduction (Doglioni, 1991; Serri et al., 1993; Molli, 2008). Chiarabba et al. (2014) argued that the nature of this process beneath the northern Apennines is not uniform along strike. Active penetration of the detachment into the Adria lithosphere (delamination-retreat mechanism) seems to be evident in the south-eastern sector of northern Apennines, whereas penetration of the detachment in the north-western sector seems to have arrested, or to have experienced greater resistance, thereby leading to deep crustal underplating (Chiarabba et al., 2014). We may reasonably infer that the underplating dynamics also involves the area located to the west of the north-western sector of Northern Apennines, namely the TPB. Useful indications on the time of activation of underplating process in the TPB are provided in our opinion by the NE-SW seismic line passing through the Quargnento well in the NE margin of the Alessandria basin (Rossi et al., 2009; Mosca et al., 2009). This seismic line highlights a major, deep-seated, NE-verging thrust, inferred to have been generated following reactivation in compression of the VV Line as discussed preliminarily above in section 8.5.; the thrust backlimb is onlapped by middle- to upper Burdigalian sediments, thus allowing the identification of the time of tectonic emplacement. We suggest that this major structure represents the evidence in the sedimentary cover of the "Front of the Alpine Axial Sector" (AXF), a deep-seated thrust recently illustrated by Mosca et al. (2009) and Rossi et al. (2009) and formerly outlined by Polino et al. (1995), which accommodated the displacement of buried elements of the axial Alpine belt (Mosca et al., 2009; Molli et al., 2010). The thrust is a major unexposed medium- to low-angle arcuate fault zone extending westwards until the Saluzzo area and marking in the subsurface the present-day Alps-Apennine junction (Mosca et al., 2009). Considering the stratigraphic evidence of the middle-late Burdigalian time of the AXF emplacement, it is reasoned that the separation of the two sectors of respectively underplating and delamination retreat outlined by Chiarabba et al. (2014) may date back to this time. This assumption finds support in the general attribution to the Burdigalian of the onset of the delamination process. Indeed, the related extension in the rear of the northern Apennines is indicated by the middle Burdigalian drowning event in Sardinia (Cherchi et al., 2008), the birth since the Burdigalian of strongly subsiding basins in Corsica (e.g., Saint Florent, Francardo, and Aleria basins) (Jolivet et al., 1990; Pandeli and Principi, 2007; Carminati et al., 2012) and the onset of rifting between the Corsica margin and the Elba Island (Carmignani et al., 1995; Mauffret et al., 1999; Zarki Jakni et al., 2004).

As noted above, the arcuate belt corresponding to the front of the AXF may have been first delineated in concomitance with the rotation of the TPB and related individualization of the "young Ligurian Plate". Therefore, the emplacement of the AXF was probably prompted by the event of rotation of the Sardinia-Corsica-Liguria microplate. The dramatic acceleration of subsidence in the TPB, coinciding with the onset of basinwide turbiditic deposition probably relates to the onset of emplacement of this structure, which created the space for the thick asymmetric wedge of Cortemilia turbidites pinching out northwards against the baclimb of the structure. This may explain the confinement of the Cortemilia turbidites (Gnaccolini, 1968), preventing their extension in the Epiligurian area. On the other hand, the remarkable southward increase in thickness of the Cortemilia turbidite system is thought to imply the concurrent activation of out-of-sequence thrusts near the southern margin of the TPB.

The onset of emplacement of the "Front of the Alpine axial Sector" is believed to have resulted in the flexural bending of the Adriatic crust, which in turn led to the spreading of the Apenninic foredeep into the western Padan domain (Biella et al., 1997), as recognized by Roure et al. (1989), who calibrated the substrate of the foredeep, represented by the Gonfolite, as Burdigalian.

The middle-late Burdigalian in the TPB may be therefore regarded as a critical turning point marking the involvement of the TPB area in the deformation of the Padan fronts (Laubscher et al., 1992; Dalla et al., 1992; Castellarin, 1994; Piana and Polino, 1995; Dela Pierre et al., 1995; Schumacher and Laubscher, 1996; Piana and Dela Pierre, 2000; Mosca et al., 2009; Rossi et al., 2009). This turnover marks the change of the TPB Basin into a perisutural basin (Mosca et al., 2009). It is worth noting that the northward thrusting did not significantly involve the sedimentary cover of the TPB which was almost passively translated northwards (Piana and Polino, 1995).

8.7.2. The Langhian basin reorganization

An important tectonic and paleogeographic reorganization took place during the Langhian.

After the middle-late Burdigalian space creation, which controlled the geometry of the Cortemilia asymmetric wedge onlapping northwards against the AXF structure, the further deformation of the Alpine Axial Sector, with development of a large-scale crustal antiform (Falletti et al., 1995; Mosca et al., 2009), led to basin inversion and northward tilting of the Cortemilia turbidite wedge; as a result, deposition of Langhian turbidites occurred with onlap and stratal convergence against the tilted upper Burdigalian turbidite wedge, as evidenced by seismic data (Rossi et al., 2009; Mosca et al., 2009). North of the large-scale antiform, a linked crustal synform with a shape arcuate in plan created the space for the Savigliano and Alessandria basins, with axis oriented SSW-NNE in the former and E-W in the latter; the large-scale crustal structure was attributed by Carrapa (2002) and Bertotti and Mosca (2009) to the generation of a lithospheric crustal fold with a width in the order of 30-60 km, in response to the build-up of collision-related intraplate compressional stresses.

The propagation of the crustal antiform was accompanied by a pronounced uplift of the basin margins, including i) the area located east of the Scrivia Valley (the Borbera-Grue sector), probably as a result of the onset of development of the Emilian arc laterally bounded by the Voghera sinistral transfer fault; ii) the western basin margin, as proved by the presence of a coarse-textured progradational coastal wedge of Langhian-Serravallian age in the subsurface of the Saluzzese region (Rossi et al., 2009); iii) the southern margin of the basin, probably affected by out-of-sequence thrusts.

The Borbera-Grue area underwent a true basin inversion, as testified by an erosional unconformity of NE-ward increasing importance truncating upper Burdigalian basin-plain turbidites and older deposits tilted toward WNW (Ghibaudo et al., 1985; Gelati and Falletti, 1996; Mutti et al., 2002) (Pls. II and VII online, Fig. 3). The northward migration of the Emilian arc bounded by the Voghera lateral ramp is also recorded in the Voghera Apennines by a basinwide unconformity sealing the Epiligurian succession at the base of the Monte Vallassa Sandstone and in the northern Apennines by the unconformity at the base of the Bismantova shelf deposits (Amorosi et al., 1996; Cibin et al., 2001; Catanzariti et al., 2002). This discontinuity can relate with a major step of the migration of the Ligurian Units onto the Northern Apennine foredeep, and represents the beginning of a new middle-upper Miocene sedimentary cycle (Molli et al., 2010).

The birth of Alessandria and Savigliano basins was accompanied by shift of major turbidite depocentres toward them (Falletti et al., 1995; Mutti et al., 2002; Mosca, 2006; Mosca et al., 2009; Molli et al., 2010). These mutually linked events are regarded as effects of the continuation of underplating process.

Abundance of detrital input from Western Alps in the turbidites of the Langhe Sub-basin implies denudation and erosion of continental crust of the Alpine Axial Sector (e.g. Dora Maira) (Rossi et al., 2009). Seismic lines presented by these authors indicate that the Cortemilia and Cassinasco Formations represent two distinct turbidite systems, being separated by a major discontinuity generated by a phase of basin reorganization.

The NE-SW structural direction is particularly important in the TPB during the Langhian (Gnaccolini, 1989; Gelati and Gnaccolini, 2003). It is displayed by the orientation of the axis of the Langhe Sub-basin, the paleocurrent pattern of Cassinasco turbidites, and the Voghera lateral ramp and its SW-ward prosecution, which controlled the eastern margin of the Alessandria basin (Mosca et al., 2009). Specifically, the role played by the Voghera lateral ramp as releasing lineament allowing larger advancement of the Emilia arc of the Apennines with respect to the Monferrato arc is worth of concern in the Langhian evolution of the TPB. This lineament corresponds to the Volpedo-Valle Salimbene Fault

(VVS) of Laubscher et al. (1992), regarded by them as a deep-seated lithospheric fault. Laubscher et al. (1992) argued that this lineament developed as normal fault with large offset during the Oligo-Miocene "Toscanide phase" and was reactivated during the Plio-Pleistocene, when it formed a rigid transverse boundary for the post-Messinian Padanide orogenic wedge forced to follow the fault as a sinistral transfer lineament. Specifically, the authors concluded that a deep Moho patch SE of the Volpedo-Valle Salimbene (VVS) Fault may be a relic of the Padanide subduction; in their map of figure 9 drawn from Buness et al. (1990), depicting the pattern of the Moho depth in the Ligurian knot, they stressed the importance of a Moho discontinuity with a trend approximately corresponding to the VVS Fault. In our opinion, a first, important left-lateral transfer motion along this fault occurred already in Langhian times, an assumption supported by profile B in Laubscher et al. (1992: their Fig. 7a) and the seismic section 3' in Cassano et al. (1986), both indicating a significant increase in thickness of the middle Miocene deposits in proximity of the fault. In this perspective, it may be conjectured that the Voghera lateral ramp had in the Langhian the role of sinistral crustal lineament linked to a segmentation of the lithosphere at depth. We interpret this lineament as evidence for incipient lithosphere tearing, separating zones subject to different downgoing rates of the Apennines slab. This represents perhaps the north-westernmost example of lithospheric segmentation beneath the Apenninic chain which separated domains undergoing contrasting styles of lithospheric deformation, following the model illustrated by Rosenbaum and Agostinetti (2015).

8.7.3. Serravallian

During the Serravallian a major impulse was given to the development of the outer thrust system propagating toward the Padan foredeep (e.g. d'Atri and Piana, 2002; d'Atri et al., 2002). North-verging thrusts progressively reached the Torino Hill sector during the late Serravallian (Festa et al., 2005; Mosca et al., 2009), and involved the Ligurian units of the Monferrato arc and their SE-prosecution hidden in the subsurface. In the TPB the effects of the late Serravallian tectonics may be represented by the upper Serravallian unconformity observed in the Borbera Valley, marked by concurrent significant increase in coarse sediment input.

Thrust-related uplift of the southern margin of the TPB associated with northward tilting led to the further northward shift of the turbidite depocentres. Moreover, seismic lines highlight an unconformity-based upper Serravallian turbidite wedge showing onlap and stratal convergence against the southern uplifted margin (d'Atri et al., in press). Gravity instability due to basinward tilting led to the emplacement of decametric olistoliths and slumps (Murazzano Fm) derived from the collapse of previous shelf edge deltas (Rossi, 2017).

The contraction episode was accompanied by significant increment of subsidence in the Alessandria Basin, as highlighted in seismic lines by convergent onlaps of the reflectors against the basin margins.

Tectonic-driven uplift of the south-eastern margin of the basin led to the emergence of a large area, whose erosion products fed a N- to NW-ward prograding coarse fan-delta complex encroaching on the Alto Monferrato High; the related siliciclastic deposits mixed with an important bioclastic component in the Serravalle Sandstone (Gelati and Gnaccolini, 2003). The sandwave field of this unit is interpreted as a typical "strait facies" laid down in a seaway between the paleo-Alps and the above-mentioned southern emerged territory. A seaway existing in this area was envisaged by the palaeogeographic reconstructions of Rögl (1998); it is believed to have connected marine basins characterized by opposition of tidal phase and subject therefore to strong currents leading to the migration of sandwave trains (e.g. Longhitano et al., 2012 and references therein).

Uplift and slope margin outbuilding led to progressive reduction of the extent of basin depocentres (Rossi et al., 2009; Rossi, 2017). Specifically, coarse-grained coastal wedges fed from the Briançonnais basement and Argentera Massif of the Alpine domain, and now buried in the subsurface, prograded basinwards from the western margin (Rossi et al., 2009).

The Serravallian structural pattern is believed to have controlled the ENE- to NE-directed axis of the Langhe Sub-basin at that time, as well as the settling of the carbonate platform of Finale Ligure to the South (Gelati and Gnaccolini, 2003).

Langhian and Serravallian thrust propagation was particularly intense in the northern Apennines (Boccaletti et al., 1990; Conti and Gelmini, 1994; Gelati and Gnaccolini, 2003). Specifically, the overthrust of the Ligurian units over the Langhian deposits of the "Bobbio Window" may relate essentially to the Serravallian "tectonic crisis" (Gelati and Gnaccolini, 2003). A late Serravallian tectonics in the Epiligurian succession is indicated by an unconformity in the upper part of the Bismantova Group (Cibin et al., 2001).

The Serravallian tectonics can be viewed in the frame of the important, late Langhian to Messinian contraction phase linked to northward fast movement of Adria, named Jura-Lombardic phase by Laubscher (2010), lasting from 14 to 6 Ma. In addition to the important impulse given to the development of the outer thrust system propagating toward the Padan foredeep, this phase resulted in the creation of the Lombardic thrust belt, now largely hidden under the Po plain (Laubscher, 2010), and in the stepping of the Alpine deformation further north-westwards into the north-Alpine foreland, incorporating the western part of the Molasse basin and the Jura mountains into the orogenic wedge (Schmid et al., 2004).

8.7.4. Tortonian-early Messinian

Ongoing N-S contraction during the Tortonian resulted on one hand in the further propagation of the thrust front towards the Padan foredeep, on the other hand in further uplift and concurrent northward tilting of the southern and western basin margins; this led to the northward shift of Savigliano and Alessandria depocentres, which evolved as highly subsiding sub-basins (Molli et al., 2010). This evolution led to the further, progressive narrowing of the sediment accommodation space in the TPB (Rossi et al., 2009). Seismic data highlight the southward onlap and stratigraphic convergence of Tortonian sediment wedges (e.g. d'Atri et al., in press) documenting the important, tectonic-driven uplift and tilting of the southern margin, leading to northward migration and volumetric reduction of depocentral areas (Rossi et al., 2009).

An important point worth stressing is the evidence of E-W extension occurring in the Tortonian concomitantly with continuing N-S contraction. Effects of this extensional tectonics during the deposition of the Malvino Fm are represented by a series of small half-grabens west of the Scrivia Valley, bounded by NNE-SSW to N-S normal faults, and the Vargo half-graben delimited by a NW-striking, presumably listric fault in eastern TPB (Ghibaudo et al., 1985). The Vargo growing trough was infilled with coarse-grained deposits referred by Mutti et al. (2002) to highly immature mixed depositional systems; these developed directly seaward of flood-dominated fan-deltas formed along the southern margin of the basin, following a phase of dramatic tectonic oversteepening and uplift. Extensional tectonics was associated with mass-wasting, which locally generated huge accumulations, such as the olistostromic deposits of the Rocca Grimalda Chaotic Complex, linked to the collapse of the western margin of the Alto Monferrato High.

The onset of basinwide deposition of hemipelagic, outer-shelf to slope Sant'Agata Fossili Marl, like the N-Apenninic Termina Fm, documents a subsequent platform drowning stage thought to reflect a persisting component of extensional tectonics lasting from Tortonian to early Messinian. Continuing gravity instability, probably linked to slope steepening, is recorded at the base of Sant'Agata Fossili Marl by plenty of slump scars (Clari and Ghibaudo, 1979), and in the lowermost part of this unit by the resedimented coarse bioclastic deposits of the Orsara Bormida unit, thought to derive from the cannibalization of a carbonate platform settled on a coeval structural high. The extensional episode therefore evolved from localized rifting to a drowning episode which generated bathyal hemipelagites of basinwide extent, locally encasing channelized resedimented coarse-grained deposits.

It is suggested that E-W extension was a far-reaching effect of the coeval E-W extension affecting the Tyrrhenian Basin. The latter began to open in the early middle Tortonian (~10-9 Ma), as indicated by the age of synrift Tortonian sediments in the northern Tyrrhenian Sea (Rosenbaum and Lister, 2004); the process was accompanied by detachment faults and thinning of continental crust in the rear of the Apenninic front, as a direct tectonic response to subduction rollback (Carminati et al., 1998; Mauffret et al., 1999; Rosenbaum and Lister, 2004).

The lower Messinian rhythm of alternating bioturbated marls with benthic faunas and blackish laminites devoid of any benthic faunal element reflects cyclic variations of oxygen content at the sea bottom, a largely known situation in the Mediterranean due to progressive confinement of the depositional environment at the Tortonian-Messinian transition and during the early Messinian.

8.7.5. Late Messinian-Pleistocene

The upper Messinian Valle Versa Chaotic Complex is thought to record the onset of polyphasic thrusting during an important regional phase of deformation which continued in the Pliocene (Piana, 2000; Piana and Dela Pierre, 2000; Dela Pierre et al., 2007; Mosca et al., 2009; Festa, 2011), consistent with the NW- and N-ward movement of the Padanide thrust (*sensu* Laubscher et al., 1992), translated for about 10-20 km (Pieri and Groppi, 1981). The sole of the Padanide thrust transported passively northwards the elements emplaced during the Aquitanian-Burdigalian tectonics, including the VV Line (Laubscher et al., 1992). Moreover, significant advancement of the Emilian arc toward the Padan foredeep occurred by means of large sinistral transfer along the Volpedo-Valle Salimbene Fault acting as lateral ramp of the arc in the Plio-Pleistocene (Laubscher et al., 1992). In this stage Torino Hill and Monferrato were overthrust onto the Po plain foredeep (Festa et al., 2005); conversely, the infill of the Langhe basin was translated northwards in a passive way, without suffering significant shortening and deformation (Piana and Polino, 1995).

A significant acceleration of subsidence rate in both Alessandria and Savigliano depocentres occurred in the Plio-Quaternary, with rapid downwarping since the early Pliocene (Dela Pierre et al., 1995; Mosca, 2006; Bertotti and Mosca, 2009).

In concomitance with active northward thrusting, a general northward tilting and uplift of the Oligo-Miocene succession of the TPB, which started from the late Miocene (Forcella et al., 1999; Barbieri et al., 2003), resulted in the final Plio-Pleistocene exhumation of the TPB infill.

9. CONCLUSIONS

The Tertiary Piedmont Basin (TPB), located at the Alps-Apennines junction, is a polyhistory basin with a complex evolution reflecting the geodynamic reorganization of the central Mediterranean area during Oligo-Miocene times. Important steps of evolution of the TPB and adjoining areas include the birth in the Borbera-Grue area of an episutural composite basin not differentiated from the north-Apenninic domain, the orogenic exhumation of the Mesoalpine prism, the opening of the Liguro-Provençal Basin concurrently with the rollback of the Apenninic subduction and NW- to WNW-ward translation of the Adriatic Indenter, the CCW rotations, and the eventual build-up of collision-related intraplate compressional stresses (Fig. 44).

After the Cretaceous-Eocene collision, a middle-upper Eocene to lowermost Oligocene composite episutural belt including the Borbera-Grue area and the Northern Apennines, not yet differentiated at that time, was originated as a paleogeographic domain located on the northward prosecution of an inferred major crustal

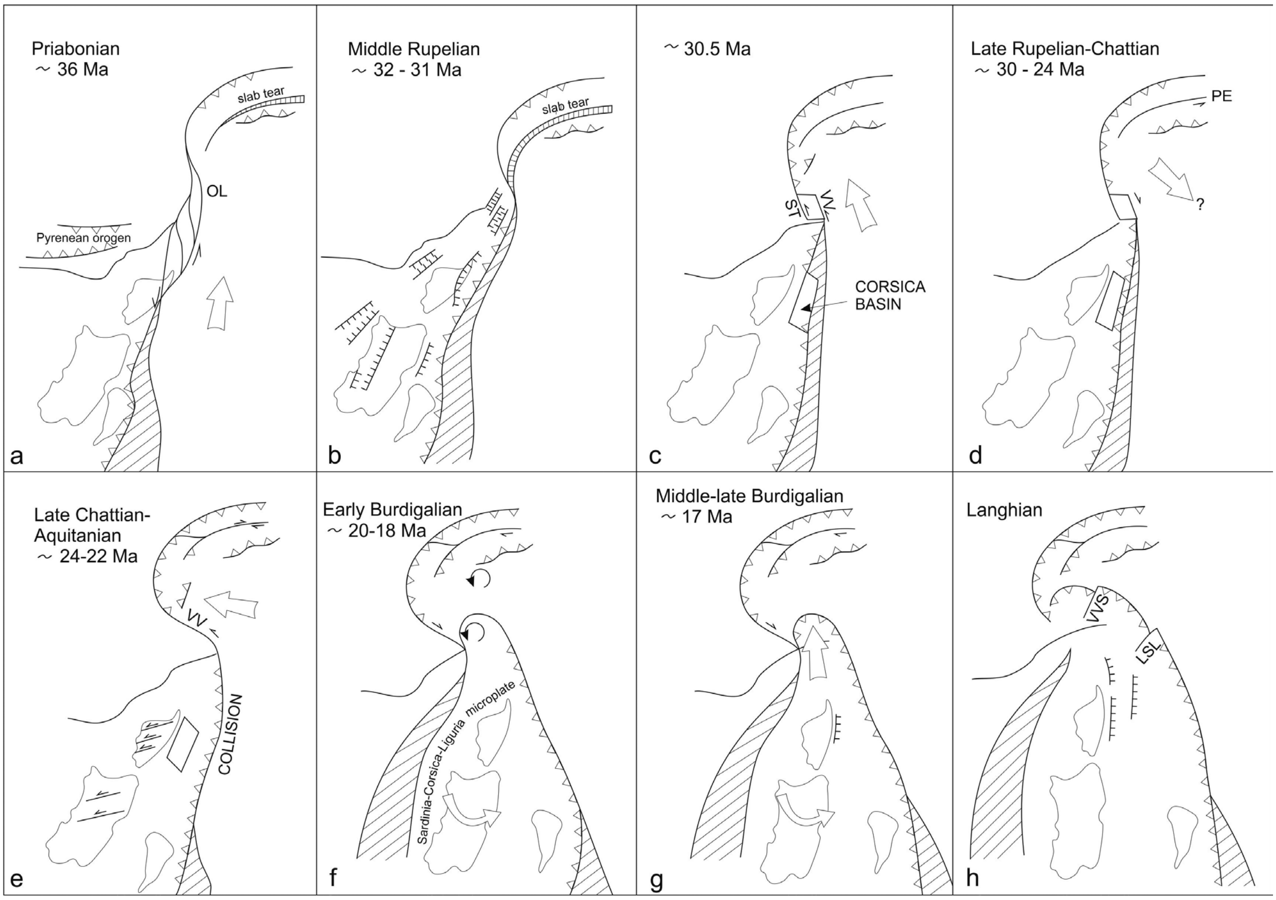

Fig. 44 - Tentative schematic reconstruction of the tectonic evolution of the Tertiary Piedmont Basin (TPB) in a supra-regional framework. a) An episutural composite basin, not yet differentiated from the domain of Northern Apennines, was generated in Priabonian to early Rupelian times in the Borbera-Grue area (eastern TPB) on the northward prosecution of an inferred major left-lateral crustal discontinuity located at the eastern margin of the Corsica-Sardinia block, linked to the northward migration of the Adria Plate and roughly following the older Alpine suture belt. This major discontinuity likely branched out northwards into an array of faults, among which the Ottone-Levanto Line and possibly the Sestri-Voltaggio Line and the Valle Scrivia Fault, responsible, together with associated conjugate faults, for confining small but rapidly subsiding depocentres with geometry and dimensions variable through time, highly unstable source areas, and mostly immature turbiditic sedimentation; OL: Ottone-Levanto Line; b) during the middle Rupelian crustal stretching generated a horst-and-graben topography in the TPB; this rifting stage was linked to the onset of retreat of the N-Apenninic slab, interpreted to have activated following the propagation of the Apine slab tear below the Ligurian Alps; the main direction of extension was orogen-parallel and kinematically compatible with the coeval backarc rifting generated in the Liguro-Provençal area; c) in the late middle Rupelian the onset of NW-ward translation of the Adriatic Indenter (AI) resulted in sinistral pure shear along the left-stepping system of the Villalvernia-Varzi Line (VV) and the Stura Fault (ST), leading to the conversion of TPB into a left stepover pull-apart basin; east of Corsica a similar basin was created (the Corsica Basin); d) tectonic inversion with change to right-lateral transtension, accompanied by a generalized drowning, occurred in the late Rupelian-Chattian; e) in late Chattian-Aquitanian the change in the direction of motion of the Adriatic Indenter with respect to Europe from NW-wards to WNW-wards led to conditions of increased collisional coupling and a generalized left-lateral transpression; f) in the early Burdigalian differential CCW rotation with respect to the Adria Plate led to the birth of a microplate including the TPB + Ligurian area + Corsica-Sardinia block; g) in the middle-late Burdigalian emplacement of the Alpine Axial Front (AXF), a deep-seated, arcuate, north-verging thrust, accommodated the northward displacement of buried elements of the axial Alpine belt (Mosca et al., 2009) in a presumed context of crustal underplating, and led to the involvement of the TPB in the northward thrusting and deformation of the Padan fronts; h) in the Langhian the Alpine Axial Sector was deformed into a large-scale crustal antiform, north of which a linked large-scale synform arcuate in plan created the space for the concomitant development of Savigliano and Alessandria basins in the rear of the thrust front; significant northward advancement of the Emilian arc was promoted by sinistral motion along the NE-SW Voghera transfer fault, inferred to coincide with the lithospheric Volpedo-Valle Salimbene Line (VVS) of Laubscher et al. (1992), and to represent the expression of a sinistral tear of the subduction front; a similar dynamics may have involved at this time the Livorno-Sillaro Line (LSL) (Rosenbaum and Agostinetti, 2015).

discontinuity at the eastern margin of the Corsica-Sardinia block, roughly following the older Alpine suture belt and corresponding to the sinistral transpressional boundary between the obliquely convergent Iberian and Adriatic plates (see also Treves and Nirta, 2014; Principi and Treves, 2014; Marroni et al., 2016) (Fig. 44). This discontinuity is inferred to branch out northwards into an array of strike-slip faults playing the role of confining boundaries of small but rapidly subsiding depocentres with geometry and dimensions variable through time, highly unstable source areas, and mostly immature turbiditic sedimentation. An important step of this early history is the deposition of the Savignone Conglomerate interpreted as large-scale Gilbert-type delta complex prograding into a pull-apart trough subject to extremely high subsidence rate.

A subsequent episode of crustal stretching in the middle Rupelian led to intense vertical mobility along normal high-angle faults, with the generation of a horst and graben topography, and expansion of coarse-grained sedimentation (the Molare Conglomerate) to the whole Tertiary Piedmont Basin (TPB) (Gelati et al., 1993; Mutti et al., 1995; Dela Pierre et al., 1995; Mutti et al., 2002; Vignaroli et al., 2009; Ghibaudo et al., 2014) (Fig. 44). Extensional strain developed in the rear of the nascent Apennines, being genetically related to the onset of rollback of the downgoing Adriatic slab, thought to have been fostered since ca. 32 Ma by the propagation of a slab tear from beneath the Alps into the Ligurian area, and was kinematically compatible with the coeval backarc rifting generated in the Liguro-Provençal area. The crustal stretching was concomitant with post-orogenic exhumation of the Mesoalpine prism (Vignaroli, 2006; Jolivet et al., 2008; Vignaroli et al., 2008, 2009, 2010), as indicated by the abundance of detritus derived from the erosion of Penninic high pressure-low-temperature metamorphic units. The extensional strain affected the TPB as a sort of westward shifting time-transgressive wave, with diachronous propagation of rifting, accompanied by westward decrease in subsidence rate and accommodation space of the generated structural troughs, as well as striking changes in depositional setting of the infilling coarse-grained deposits (Molare Conglomerate) from turbidite-dominated deep-water fan-delta slope in eastern area, to fan-delta front, and, at the western end, continental environments linked to alluvial fans, braided streams and scree denudation processes.

In the late middle Rupelian the extensional regime turned into a left-lateral strike-slip regime with probably pure sinistral motion. Activation of the left-stepping major lineaments represented by the Villalvernia-Varzi (VV Line) to the NE and the Stura fault system to the SW is thought to have lead to the conversion of the TPB into a left-stepover strike-slip basin located between the opposite Alpine and Apenninic subductions (Ghibaudo et al., 2014) (Fig. 44). This evolution is thought to reflect the onset of NW-ward translation of the Adriatic Indenter. Depositional settings in the basin were still differentiated at this time, with persisting deep-water turbiditic sedimentation in the eastern TPB, grading westwards first into a coarse fan-delta system, and then a shoreface to shelf setting (represented by the Molare Sandstone, transgressively overlying the continental Molare Conglomerate). In the easternmost TPB left-lateral motion along the VV Line led to localized important effects of sinistral transpression due to the presence of a pronounced restraining bend of this line, whose direction turns in this area from E-W to NW-SE; here the deformations include folding and local thrusting, as well as fault inversions of formerly active extensional NNW-striking systems, and were sealed by an important unconformity at the base of the Monastero Fm *auctt*. (our Rocchetta Fm) (Phase Ligure III of Mutti et al., 1995). In the central-western TPB growth faulting, as well as accumulation of gravity-emplaced breccias and olistoliths at the foot of fault paleo-escarpments (Toleto and Bandita areas), were activated during the sedimentation of the Molare Sandstone, whereas the onset of the growth of the NW-striking Mioglia flexure in the Langhe area is recorded by unconformities in the lowermost part of the Rocchetta Fm.

A dramatic tectonic and eustatic drowning and accelerated subsidence then affected the TPB since the latest middle Rupelian. This is recorded by a drastic change in sedimentation, which turned from a still E-W differentiated sedimentation pattern to uniform basinwide deposition of slope to base-of-slope hemipelagites of the Rocchetta Fm encasing bodies of coarse-grained resedimented deposits, particularly important in the Langhe and Borbera-Grue depocentres. Structural evidence indicates that during this stage a change occurred into regional-scale right-lateral transtension, accompanied by a temporary inversion of motion along the VV Line. Although already delineated during the deposition of the Molare Fm, the separation the TPB and N-Apennine Epiligurian domains was definitive since the onset of deposition of the Rocchetta Fm. Indeed, the paleocurrent pattern, geometry, and sandstone composition of the turbidite bodies are compatible with the rise at that time of a morphologic-tectonic boundary most probably corresponding in position to the VV Line (Martelli et al., 1993; Di Giulio and Galbiati, 1995).

In the late Chattian-Aquitanian the transtension turned into a main left-lateral transpressional episode. This occurred when the indentation of the Adriatic microplate into the Alpine orogenic edifice changed direction of motion from NW-ward to WNW-ward, resulting in conditions of increased collisional coupling (Schmid and Kissling, 2000; Ziegler et al., 2002; Handy et al., 2010), which led to tectonic escape of the Adriatic Indenter between the Periadriatic dextral Insubric lineament and the sinistral VV Line, as proposed by Schumacher and Laubscher (1996) (Fig. 44). In the TPB sinistral transpression along the VV Line and the sub-parallel E- to ENE-striking fault system was associated with reactivation in dextral transpression of formerly active NNW-SSE to NW-SE fault system. The latter had a critical role in the uplift and partial emergence of the Alto Monferrato High, enhancing its differentiation from the adjacent Langhe and Borbera-Grue sub-basins. A certain westward younging is manifested by the main transpressional episode, which occurred at the transition Chattian-Aquitanian or late Chattian in the eastern TPB, and in the early Aquitanian in western TPB.

Siliceous deposits, occurring at several levels in the Aquitanian to lower Langhian interval of the TPB succession, represent marker horizons on regional scale and are interpreted as slope or base-of-slope hemipelagites originally rich in biosiliceous component due to events of increased organic productivity, favouring basinwide blooms of siliceous phytoplankton.

In the early Burdigalian the Alto Monferrato High was the site of deposition of ramp carbonates and outer shelf marls, whereas in the flanking sub-basins continued a hemipelagic deposition punctuated by the emplacement of several bodies of resedimented, commonly coarse-grained mixed deposits.

In the early Burdigalian a strike-slip regime continued in the TPB mainly as a result of the onset of counterclockwise rotation of the TPB. A paleogeographic differentiation persisted between the Alto Monferrato High and adjacent sub-basins. Strike-slip tectonics is particularly reflected in the stratigraphic architecture of the Uzzone Valley area (Langhe Sub-basin), where a NE-SW growth fault system, active during the deposition of the Montechiaro d'Acqui Fm, determined the birth of intrabasinal highs and minor basins, controlling paleocurrents and location of successive turbidite sandstone bodies (Ghibaudo et al., 2014). Tectonic mobility is also documented by destabilization and cannibalization of carbonate platforms of uncertain location, which generated bodies of mixed composition consisting of resedimented carbonates associated with coarse-grained siliciclastic deposits, locally occurring as infills of structural troughs (e.g. the Case Mazzurini Sandstone) or submarine valleys (e.g. the Rocca Crovaglia Sandstone).

The onset of counterclockwise rotation of the Adriatic Indenter (20 Ma: Bauve et al., 2014) and, concomitantly, of the Corsica-Sardinia block (20.5 Ma: Gattacceca et al., 2007), occurred around the beginning of the Burdigalian. The rotation of the Adriatic indenter involved a composite dextral system, including the Periadriatic (Insubric) Line, the PFT (Penninic Front), and the Jausiers-Tinée-Saorge-Taggia fault system in south-western Alps (Collombet et al., 2002; Sanchez et al., 2010; Rolland et al., 2012; Bauve et al., 2014). CCW rotation of the TPB took place with an angle close to that of the Sardinia-Corsica block (ca. 50° according to Maffione et al. 2008, 2010) and higher than that estimated for the rotation of the Adria indenter (20-25°: Collombet et al., 2002; Márton et al., 2017). This indicates a partly independent behaviour and supports the contention that since the beginning of the Burdigalian the Sardinia-Corsica block and Ligurian area, including the TPB, behaved as a unique microplate located SE of the Ligurian Sea collapse and interposed between the European and Adria plates (see also Kissling et al., 2012) (Fig. 44). We propose that the present-day Moho architecture and crustal discontinuities in the area of the Alps-Apennines junction (e.g. Ziegler and Dèzes, 2005) have been mainly settled during the Burdigalian rotations, inferred to have had a critical role in fixing the boundaries of the Sardinia-Corsica-Liguria microplate (Fig. 43).

A major tectonic reorganization occurred in the TPB since the middle Burdigalian. A transgression occurred with gaps of various amplitude on the deformed substrate of the Alto Monferrato High, where it took place with a characteristic backstepping pattern. Indeed, the transgressive blanket (Lerma Glaucony) displays a depositional pattern given by a sheet-like glaucarenite layer, alternating in the direction of progressing transgression with local thicker glaucarenitic bodies interpreted as incised shoreface deposits produced during minor stillstand phases punctuating an overall relative sea level rise. Then, a dramatic acceleration of subsidence coincided with the deposition of slope deposits of the Pratolungo Fm and laterally equivalent Serole Fm, both grading upwards to a basinwide turbidite system, the Cortemilia Fm. This probably occurred in concomitance with the onset of emplacement of the "Front of the Alpine Axial Sector" (AXF) a deep-seated, arcuate, north-verging thrust accommodating the displacement of buried elements of the axial Alpine belt (Mosca et al., 2009; Rossi et al., 2009; Molli et al., 2010), and probably implying the northward displacement of the northern arcuate boundary of the neoformed Sardinia-Corsica-Liguria microplate (Fig. 44). This tectonic event is thought to mark the onset of northward thrust propagation toward the Padan foredeep and is interpreted to reflect the beginning of a process of underplating. The emplacement of the AXF resulted in the flexural bending of the Adriatic crust, which in turn led to the spreading of the Apenninic foredeep into the western Padan domain, marking therefore the change of the TPB Basin into a perisutural basin.

The subsequent history is one of continuing outward migration of the Padan fronts until recent times. A marked tectonic and paleogeographic reorganization in the TPB took place during the Langhian. The formerly emplaced Alpine Axial sector was deformed into a crustal antiform (Falletti et al., 1995; Mosca et al., 2009), causing the northward tilting of the late Burdigalian Cortemilia turbidite wedge, against which Langhian turbidites onlapped, as shown by seismic data (Mosca et al., 2009; Rossi et al., 2009); to the north of the antiform, a linked large-scale synform arcuate in plan created the space for the concomitant development of Savigliano and Alessandria basins, with axes respectively oriented SSW-NNE and E-W, into which major turbidite depocentres progressively shifted. Concurrently, the Emilian arc began to significantly advance northwards by means of sinistral motion along the the NE-SW Voghera lateral ramp

(Falletti et al., 1995; Mutti et al., 2002; Mosca, 2006). The latter lineament is inferred to coincide with the Volpedo-Valle Salimbene Line of Laubscher et al. (1992), a deep-seated lithospheric fault active in our opinion as sinistral transfer line since the Langhian.The onset of development of the Emilian arc and related transfer motion along the Voghera lateral ramp probably resulted in the westward tilt and uplift of the Borbera-Grue area, where a true basin inversion occurred, as testified by an erosional and angular unconformity truncating progressively older units in north-easterly direction. This discontinuity surface was then flooded with onlapping relationships by shoreface and shelf deposits of the Cessole Formation (middle-upper Langhian), which pass basinwards, beyond the Scrivia Valley, into a westward downlapping prograding wedge of delta front and prodelta slope deposits, in turn later onlapped by the turbidites of the Cassinasco Fm.

The uplift of the Borbera-Grue area and concurrent birth of the subsiding adjacent Alessandria Basin probably led to the deformation of the upper Cenozoic stratigraphic succession, causing a progressive curvature to NNE of stratal directions in the sector located between the Alto Monferrato High and the Borbera-Grue area.

Pronounced Langhian-Serravallian uplift of the western TPB margin is proved by the presence of a coarse-textured progradational coastal wedge in the subsurface of the Saluzzese region (Rossi et al., 2009; Rossi, 2017); moreover, uplift of the southern and south-eastern margins, probably affected by out-of-sequence thrusts, led to progradation on the Alto Monferrato High of a coarse Serravallian fan-delta complex, whose siliciclastic deposits were associated with an important bioclastic component in the Serravalle Sandstone. This unit is characterized by a sandwave field interpreted as a typical "strait facies", probably controlled by tidal current amplification, laid down in a seaway between the paleo-Alps and paleo-Apennines. The depositional setting was typified by an interaction between ephemeral storm-driven flows, and more continuous tractive flows producing sandwave trains, concomitant with the input of coarse fan-delta detritus from the denudation of uplifted south-eastern areas. In the same time span, a thick turbidite succession (the lower part of the Cassinasco Fm) was accommodated in the downwarping Langhe Sub-basin.

Active tectonics is documented by late Serravallian north-verging thrusts reaching the Torino Hill (Festa et al. 2005; Mosca et al., 2009), and NW-striking transcurrent faults in the TPB; a late Serravallian forced regression is recorded by the incision of a shelf valley in the Borbera Valley area coupled with a significant coarsening of terrigenous input. Northward tilting led to northward shift and progressive reduction of the extent of turbidite basin depocentres, as well as southward onlap and stratal convergence of the unconformity-based upper Serravallian turbidite wedge (seismic lines in d'Atri et al., 2014).

Continuing N-S contraction during the Tortonian led to further propagation of the thrust fronts toward the Padan foredeep and further uplift of the basin margins, as well as northward shift and volumetric reduction of the Savigliano and Alessandria basins, which evolved as highly subsiding depocentres (Rossi et al., 2009; Molli et al., 2010). On the other hand, a concomitant important episode of E-W extension and incipient rifting occurred in the central-eastern TPB by the activation of a conjugate system of NW-SE and NNE-SSW faults, which bounded small grabens and half-grabens locally infilled by resedimented coarse-grained deposits (e.g. the Vargo half-graben in the Malvino Fm). The extensional stage was accompanied by persisting gravity instability, expressed by coalescing slump scars and an important mass wasting episode at the western margin of the alto Monferrato High, which generated the Rocca Grimalda Chaotic Complex. A subsequent rapid platform drowning is recorded by the onset of basinwide deposition of hemipelagic, slope deposits of the Sant'Agata Fossili Marl. The extensional strain is interpreted as far-reaching effect of the coeval E-W back-arc extension which affected the Tyrrhenian Basin since ~10-9 Ma (Rosenbaum and Lister, 2004), concomitantly with thinning of continental crust in the rear of the migrating Apenninic front. Progressive confinement of the depositional environment at the Tortonian-Messinian transition and during the early Messinian is linked with the well-known paleogeography established in the Mediterranean since the late Tortonian. A characteristic rhythm, generally interpreted as precession-driven, consisted of alternating bioturbated marls with benthic faunas indicating bottom oxygenation and blackish laminites devoid of any benthic faunal element indicating bottom water anoxia. Two important erosional unconformities mark the base of the intra-Messinian Valle Versa Chaotic Complex and respectivey the base of the upper Messinian fan-delta/lagoonal Cassano Spinola Conglomerate, showing affinity with the well-known "Strati a Congerie" of the "Lago Mare". The latter unit shows an overall trend coarsening upwards, reflecting the tectonic-driven progradation of the fan-delta system into a lagoonal-lacustrine body of water.

The upper Messinian Valle Versa Chaotic Complex is thought to record the onset of polyphasic north-verging thrusting during an important regional phase of deformation which continued in the Pliocene and Pleistocene (Piana, 2000; Piana and Dela Pierre, 2000; Dela Pierre et al., 2007; Mosca et al., 2009; Festa, 2011), leading to a significant outward propagation for the post-Messinian Padanide orogenic wedge, and particularly a significant advancement of the Emilian arc. Regional shortening occurred in concomitance with a significant acceleration of subsidence rate in both Alessandria and Savigliano basins, particularly since the early Pliocene (Dela Pierre et al., 1995; Mosca 2006; Bertotti and Mosca, 2009). On the other hand, the infill of the Langhe basin was translated northwards in a passive way, without suffering significant shortening and deformation (Piana and Polino, 1995).

In concomitance with active northward thrusting, a general northward tilting and uplift of the Oligo-Miocene succession of the TPB started from the late Miocene (Forcella et al., 1999; Barbieri et al., 2003), resulting in the final Plio-Pleistocene exhumation of the TPB basin.

The critical role played by the dynamics of the Apenninic orogen and the translation of the Adriatic Indenter in controlling the geologic evolution of the TPB is clear in the Rupelian to Aquitanian time span. Indeed, in this period most prominent discontinuities were typically generated in the eastern or central-eastern sectors of the TPB, with eastward widening and increasing importance of stratigraphic gaps, whereas they are virtually absent in the western TPB; moreover, an E-W diachroneity can be demonstrated in the sequence of tectonic and stratigraphic events, accompanied by significant lateral changes in facies associations.

As final remarks, we stress the importance of Laubscher's intuition (1991) that the TPB-Liguria should be regarded as part of a complex including the Sardinia-Corsica block, separated from Europe and Iberia by the Ligure-Provençal sea collapse. The analogy of geological evolution between the TPB and the Corsica-Sardinia block is supported by several events in common: the Eocene phase linked to the northward translation of the Adria plate along a major transcurrent sinistral lineament, roughly following the older Alpine suture belt and running along the eastern margin of the Corsica-Sardinia block at the boundary between the obliquely convergent Iberian and Adriatic plates (see also Treves and Nirta, 2014; Principi and Treves, 2014; Marroni et al., 2016); the post-orogenic crustal stretching and extensional collapse concomitant with active eastward retreat of the Apennine slab, leading to the Rupelian unroofing in the TPB by means of extensional detachment systems of the Voltri massif (Vignaroli et al., 2008, 2010) and in Corsica to the early Oligocene reversal of the sense of shear, with east-vergent displacements and exhumation in Green Schist Facies of the deepest HP-LT units (Jolivet et al., 1990; Daniel et al., 1996; Brunet et al., 2000; Pandeli and Principi, 2007; Carminati et al., 2012); the consequent Oligocene rifting in the TPB and in both islands (Cherchi and Montadert, 1982; Sowerbutts and Underhill, 1998; Ferrandini et al., 2003); the formation of the Corsica Basin as a possible pull-apart basin in the wake of the Apenninic front (Mauffret and Contrucci, 1999), like the inferred birth of the TPB as a left-stepover basin; the late Oligocene-early Miocene transpression in both islands (Chabrier and Mascle, 1977; Carmignani et al., 1992, 1995, 2004; Oggiano et al., 1995; Pasci et al., 1998; Sowerbutts and Underhill, 1998; Ferrandini et al., 1999; Mauffret and Contrucci, 1999; Faccenna et al., 2002); the CCW rotation of the TPB behaving as a unique block together with the Corsica-Sardinia massif (Maffione et al., 2008); the turning point in the late Burdigalian-Langhian with onset of a new tectonic cycle connected with the first opening of the northern Tyrrhenian Basin.

Notes

(Note 1) The authors could not find the financial support to print a complete 1:20000 scale geologic map of the entire southern part of the Tertiary Piedmont Basin, so the geology of the basin is presented in the enclosed 1:75000 scale map (Plate I). A geologic map at scale 1:20000 with topography in evidence is available online (Plate III online).

(Note 2) The succession of the TPB is characterized by the presence, at various stratigraphic levels, of siliceous horizons of basinal extent, here defined "siliceous lithozones". These siliceous intervals have the meaning of key horizons and are extremely important for basin-scale correlations. The adopted LS1, LS2, LS3, etc.… notations refer to the different siliceous lithozones of the TPB succession in ascending stratigraphic order. The siliceous lithozones splitting into minor units located atop turbidite formations are indicated by the notations LS1a, LS1b, LS1c, LS2a and LS2b. Where two lower-rank siliceous lithozones join due to the lateral pinch out of intercalated turbidite units, they are indicated in the map by the notations LS1a-b, LS1b-c, etc.…

(Note 3) North of the Villalvernia-Varzi Line, the Antognola Fm (upper Rupelian-early Aquitanian) is time-equivalent of the Rocchetta Fm. The Antognola Fm crops out in the north-western Apennines, lying conformably at the top of the Ranzano Fm or, locally, disconformably at the top the "Ligurian substrate", with variable thickness from a few tens of m up to a maximum of 600 m. The Antognola Fm is bounded at the top by the siliceous deposits of the Contignaco Fm (Aquitanian-early Burdigalian), time-equivalent of the Montechiaro d'Acqui Siliceous Lithozone LS1 of the TPB.

Appendix. Supplementary data

Supplementary data associated with this article can be found in the online version, at the site www.jmes.it.

The online plates include: a geological map of the study area at the scale 1:20000, with the topography in evidence (Plate III); location of the measured sections (Plate IV); geological map at 1:75000 scale supplemented with the specific denominations of the structural elements (Plate VI); structural map of the area presenting the structural elements and the main unconformities (Plate VII); an extended cross section intended to depict the basin organization supplemented with a schematic view of the geology beyond the study area, toward the south-western closure of the basin (Plate VIII).

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