Syn-depositional emplacement of the Liguride allochthon in the Miocene foredeep of the Western Romagna Apennines

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ABSTRACT

In Western Romagna, a segment of the "Sillaro Line" has been mapped in detail. The stratigraphic and tectonic analyses of field data have been framed in a regional-scale study of the tectono-sedimentary relationships, the structural styles and the deformation chronology of the Romagna Apennines. The syn-depositional trajectory of the Liguride overthrust has been reconstructed by retro-deformation, and a specific stratigraphic scheme has been elaborated for the Visignano slump-olistostrome. The conclusive interpretations have been summarized in an evolutionary picture of the Liguride overthrust, which correlates the emplacement, the re-mobilization and the tectonic displacement of the main submarine landslides with the allochthon advancement into the middle Miocene Apennine foredeep.

AIMS

This paper focuses at the middle Miocene evolution of the Western Romagna Apennines, by exploring the relationships between the Liguride overthrust and the local foredeep deposition. The methodologic key-points of the proposed investigation are the following ones:
- detailed mapping of stratigraphic and tectonic field data;
- cross-section recognition of deformation styles and relative deformation chronology;
- regional-scale discrimination between syn-depositional and post-depositional tectonics;
- retro-deformation of the Liguride overthrust in map and cross-section;
- stratigraphic analysis of slump-olistostromes, slid from the Liguride frontal slope to the foredeep basin plain;
- integrate reconstruction of the foredeep inner slope evolution in the study area.

KEYWORDS

Outer Northern Apennines, Sillaro Line, Liguride overthrust, Oligo-Miocene foredeep, Marnoso-arenacea Fm, slump, olistostrome, deformation style, deformation chronology, tectono-sedimentary evolution.

RIASSUNTO

In Romagna occidentale è stato rilevato in dettaglio un tratto della "Linea del Sillaro". L'analisi stratigrafica e tettonica dei dati di campagna è stata inquadrata in uno studio regionale dei rapporti tra tettonica e sedimentazione, dell'assetto strutturale e della cronologia deformativa dell'Appennino romagnolo. La traiettoria sin-sedimentaria del sovrascorrimento Liguride è stata ricostruita mediante retro-deformazione, e uno specifico schema stratigrafico è stato elaborato per lo slump-olistostroma di Visignano. Le interpretazioni conclusive sono state riassunte in un quadro evolutivo del sovrascorrimento Liguride che correla la messa in posto, la rimobilizzazione e la dislocazione tettonica delle frane sottomarine con l'avanzamento dell'alloctono nell'avanfossa appenninica medio-miocenica.

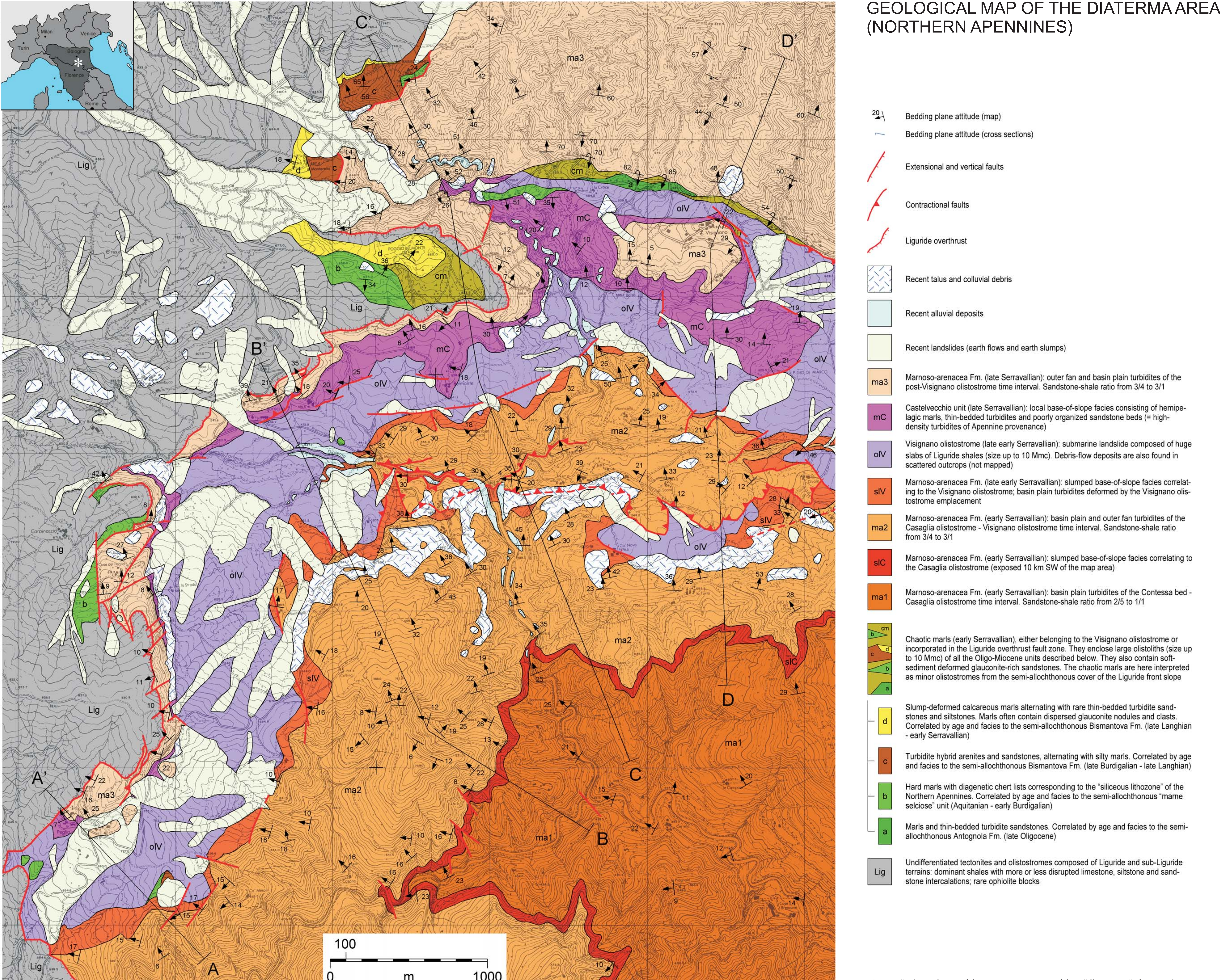


Fig. 1 - *Geological map of the Diaterma segment of the "Sillano Line", from Peglio to Visiganno.*

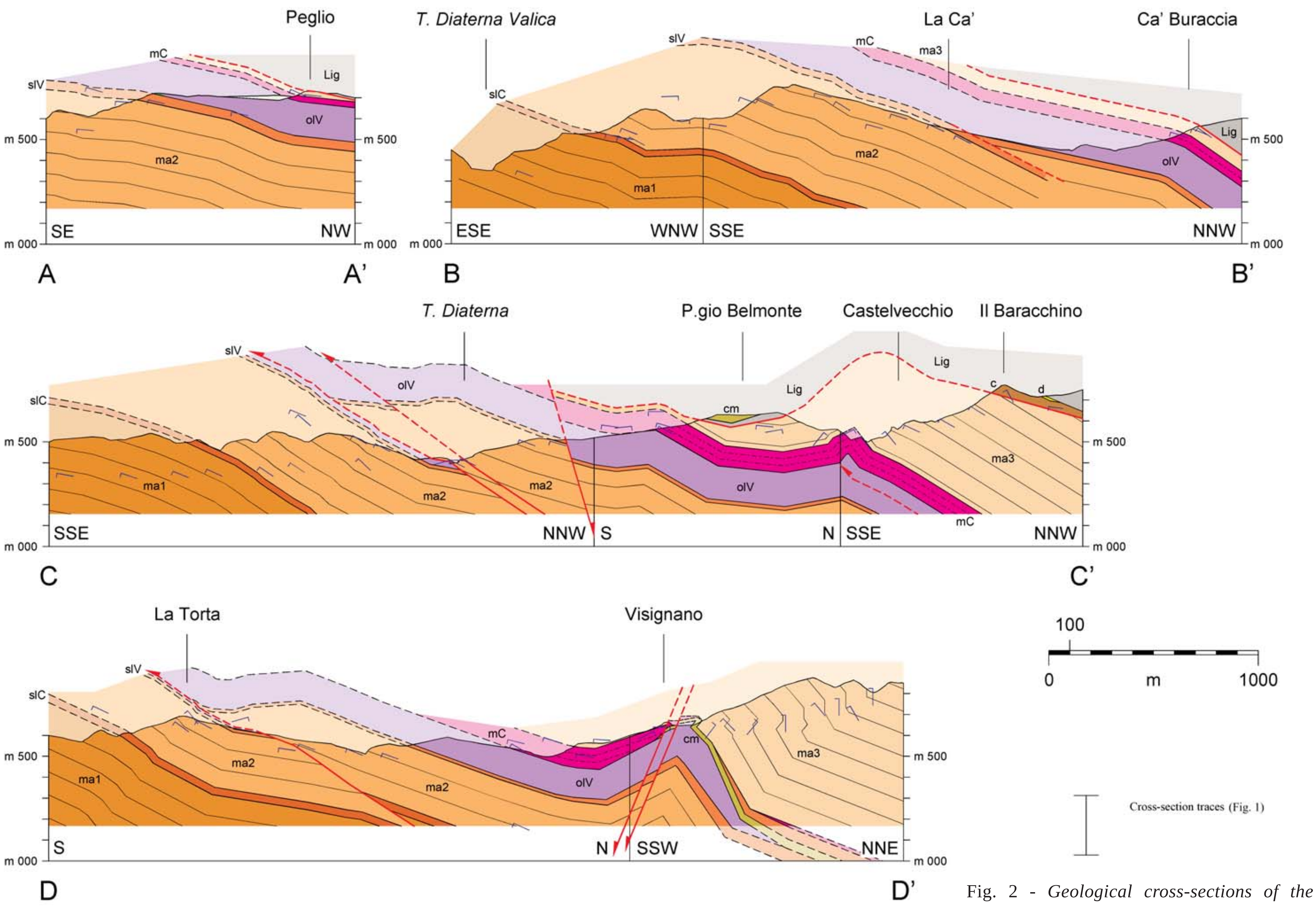


Fig. 2 - *Geological cross-sections of the Peglio-Visignano area. See traces in Fig. 1.*

GEOLOGICAL SETTING

The "Sillaro Line" is the map boundary between the allochthonous terrains of the Emilia Apennines and the palaeo-autochthonous succession of the Romagna Apennines (Barchi *et alii*, 2001; Bortolotti *et alii*, 2001; Bruni, 1973; Dallan Nardi & Nardi, 1974; De Jager, 1979). The Sillaro Line goes from Tuscany to the Po Plain border of the chain, where it merges with the Emilia Apennine front by a complex bundle of arc-shaped obliquethrust-faults (Castellarin & Pini, 1989).
Where the allochthon is in contact with the Oligo-Miocene foredeep succession, the Sillaro Line can be regarded as the intersection line between the primary Liguride overthrust and the topographic surface (Ten Haaf, 1986; Landuzzi, 1994). As a matter of fact, post-Miocene reactivation have not substantially modified the original geometry of that contact zone.

GEOLOGICAL FRAMEWORK

In the study area, the Diaterna segment of the Sillaro Line has been chosen as an example of the geometric and stratigraphic relationships between the Liguride overthrust and the deposition of the Marnoso-arenacea Fm. (hereinafter MA). These relationships have been made more complex by a huge submarine landslide (the Visignano slump-olistostrome), which foreran the allochthon advancement into the Apennine foredeep basin plain. The first investigations were carried out by realizing a detailed geological map (Fig. 1), based upon the field recognition of stratigraphic units and tectonic elements.
The stratigraphic units of the study area belong to three different palaeogeographic domains: allochthon, semi-allochthon and palaeo-autochthon.
Liguride and sub-Liguride allochthonous units are shown as a single colour in all illustrations, as their differentiation was too complex for the purposes of this paper (more details in Bettelli & Panini, 1992). The allochthonous units mainly consist of shale tectonites ("*Argille scagliose*" *Auct*.: name history in Cowan & Pini, 2001), which can enclose: (a) rare blocks from the Ligurian-Piedmont ocean crust (ophiolites, radiolarites and pelagic limestones of Late Jurassic age); (b) tectonic slabs derived from siliciclastic and calcareous turbidite successions (Cretaceous - Middle Eocene); (c) olistostromes related to the accretion stages of the allochthon evolution.

The semi-allochthonous succession
A number of chaotic marl bodies have been identified within the Liguride overthrust fault zone, probably belonging to larger olistostromes yet to be mapped (see also Bettelli & Panini, 1992; Verdastri, 1998; Pignone, 1999). The Oligo-Miocene marl and sandstone olistoliths enclosed in those chaotic bodies can be correlated in terms of lithology, structural position and age with the semi-allochthonous succession of Eastern Emilia (review in Bettelli *et alii*, 1989). The olistolith facies regularly indicate deposition on a submarine slope, with sporadic high-density turbidites from the outer shelf. Slumping structures are common, but are overprinted in places by tectonic deformations induced by the Liguride overthrust.

The palaeo-autochthonous succession
This consists of the MA of the outer Northern Apennine foredeep (Ricci Lucchi, 1975). All subdivisions of the MA are defined here on the basis of lithostratigraphic markers. The only marker horizons that crop out in the study area are two basin-scale submarine landslides, named after the villages of Casaglia and Visignano (Bruni, 1973; de Jager, 1979; Lucente, 2002). Each landslide is composed of an intra-basinal body called "slump", and an extra-basinal body called "olistostrome". The Casaglia olistostrome crops out 10 km SW of the study area, and only the corresponding slump can be found on the reported geological map (Fig. 1). The Visignano olistostrome crops out throughout the study area, while the corresponding slump extends from Visignano to Valmaggiore, 8 km to the NE. Near Visignano, the olistostrome encloses chaotic marl bodies almost identical to those occurring within the Liguride overthrust fault-zone. Outside the study area, similar bodies are scattered within the Visignano-Valmaggiore slump, from the Santerno Valley floor to the Senio Valley sides.
The sedimentary cover of the Visignano olistostrome consists of a peculiar marl and sandstone succession, known as the Castelvecchio unit. Outside the olistostrome zone, the Castelvecchio unit is laterally replaced by a basin plain MA.
The tectonic structure of the study area is characterized by an overall plunge to the NW, that

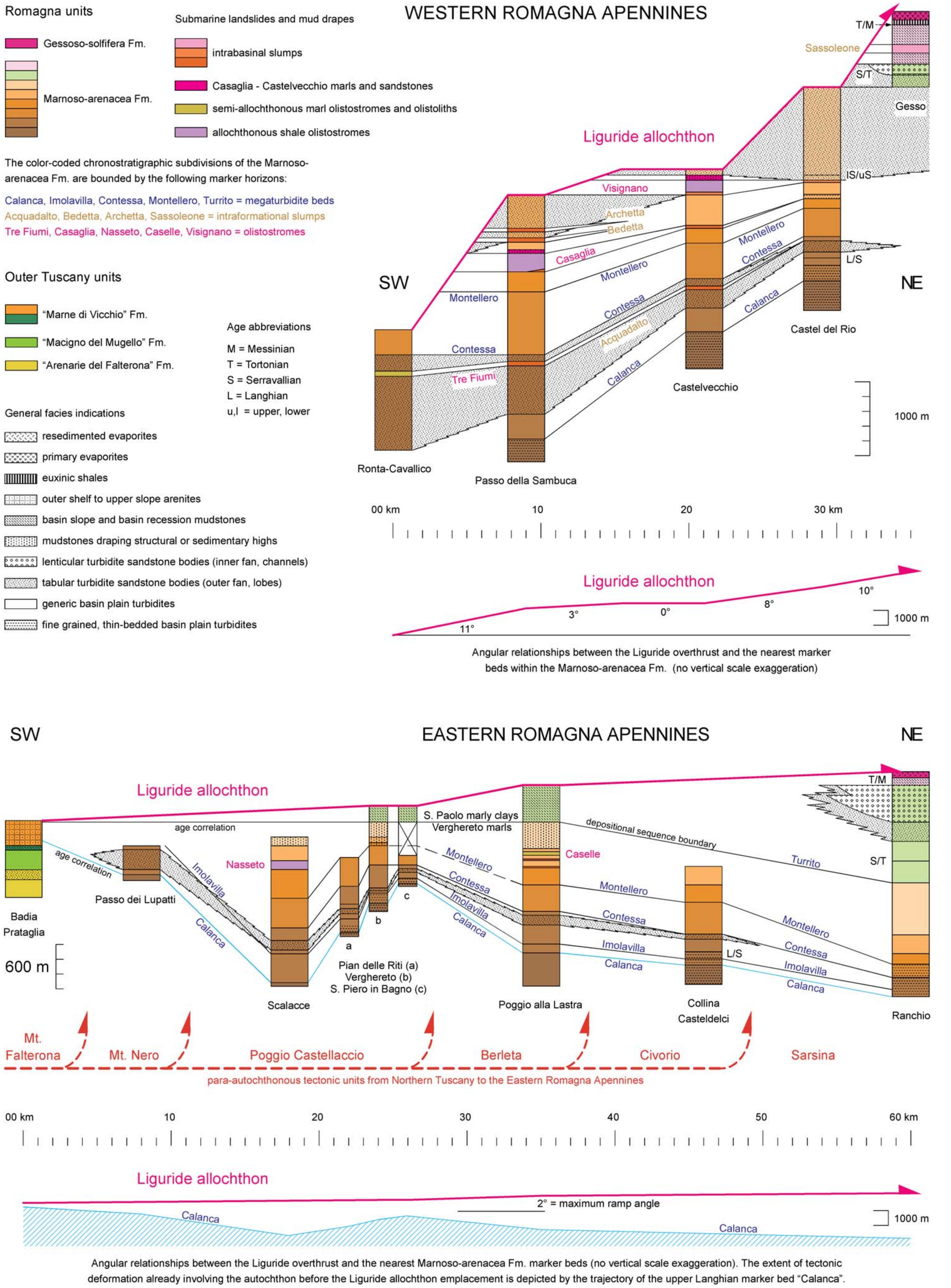


Fig. 3 - *Stratigraphic schemes of the Romagna Apennines. The study area is framed within a regional-scale picture of the relationships between the Liguride allochthon and the Miocene foredeep of the Romagna Apennines. The individual columns have been partly compiled from literature data (*MARTELLI*, 1994), and partly reconstructed by means of cross-sections drawn from published and unpublished geologic maps (*LANDUZZI*, 1994; *VERDASTRI*, 1998). Horizontal distances have been restored to sin-depositional conditions on the basis of shortening estimates carried out on published cross-sections of the whole Romagna Apennines (*BARCHI *et alii*, 2001).*

makes possible a "down-the-plunge" view of the geological map. This kind of observation allows an easy recognition of the deformation styles. It also helps to determine a relative deformation timing, on the base of cross-cutting relationships between tectonic elements.

The following main tectonic features, in chronological order, were found in the study area. (1) A Liguride overthrust, which covers progressively younger palaeo-autochthonous units from SW to NE. The staircase trajectory of the overthrust is composed of a ramp SW of Peglio, a flat from Peglio to Poggio Belmonte, and again a ramp NNE of Poggio Belmonte. (2a) Apennine folds (Diaterna anticline, Poggio Belmonte syncline, Castelvecchio anticline), which involve the MA and the Liguride allochthon as well. (2b) SSW-verging Apennine thrust faults, which affect the N side of the Diaterna anticline (Molino, Bordignano, Divole). (3) A large-scale tilting responsible for the overall plunge to the NW. (4) Extensional faults (Carpinaccio, Belmonte, Casalino, etc.), that offset any other tectonic element.

The "down-the-plunge" observation of the geological map gives a first idea of the cross-section configuration of the whole study area. This overall view helped the authors choose the best traces for the reported cross-section set (Fig. 2). All sections have been defined using the "kink" interpolation technique, which is most suitable to the angular folding style of the MA.

Quantitative results have been obtained about the following subjects.

(a) Thickness of the stratigraphic units. The overall MA succession thins from the SW to the NE. The Liguride body of the Visignano olistostrome is thickest between Peglio and Ca' Buraccia (cross-sections A, B, C). To the ENE, the same body is progressively replaced by extra-basinal chaotic marls and the intra-basinal Visignano Valmaggiore slump (cross-section D). The Castelvecchio unit is thickest from Ca' Buraccia to Belmonte (cross-sections B, C), and rapidly pinches out near Visignano (cross-section D).

(b) Angular relationships between the Liguride overthrust and the MA bedding planes. A well-constrained 18° ramp is shown in cross-section C, from Poggio Belmonte to Il Baracchino.

(c) Sub-surface geometry of the post-deposi-

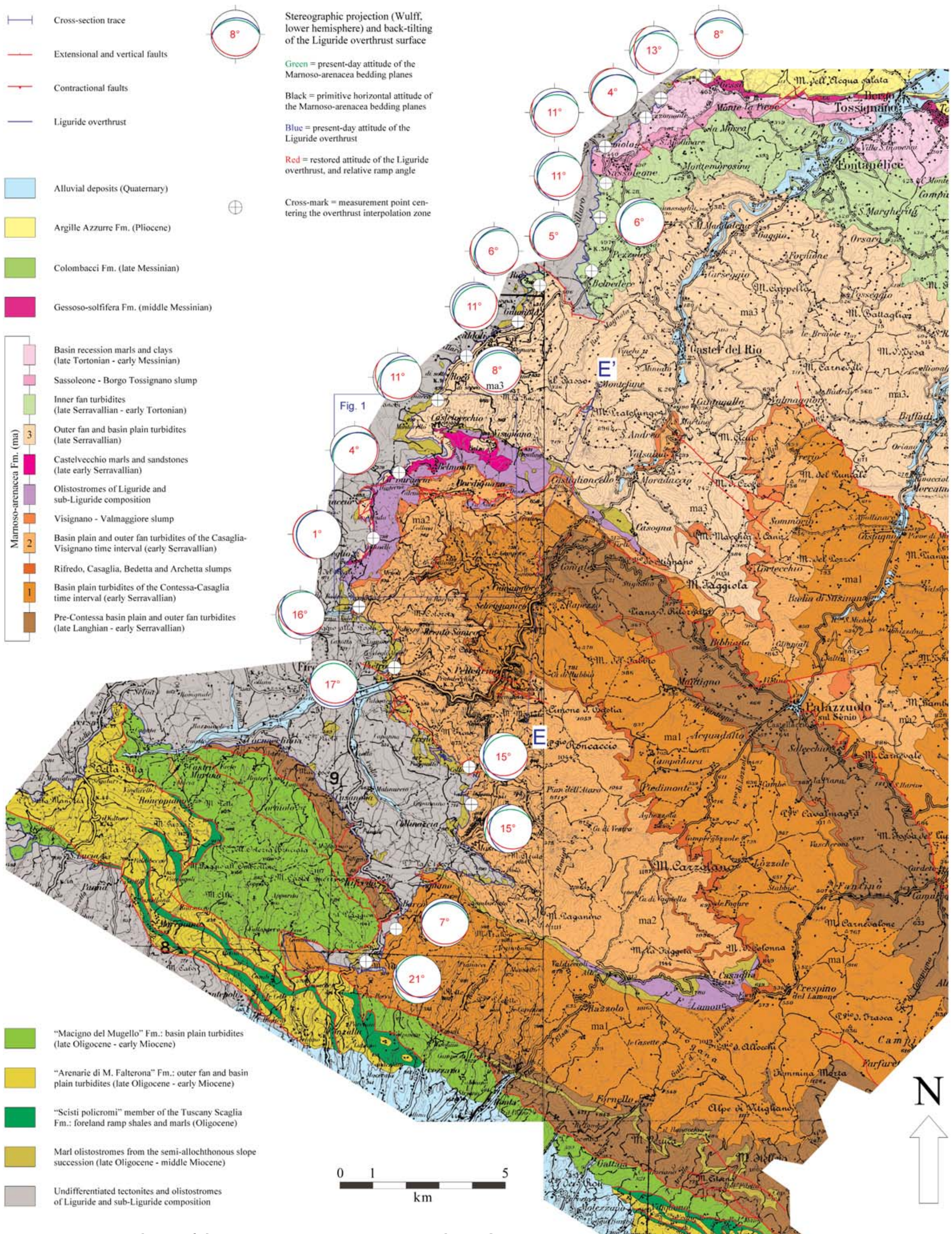
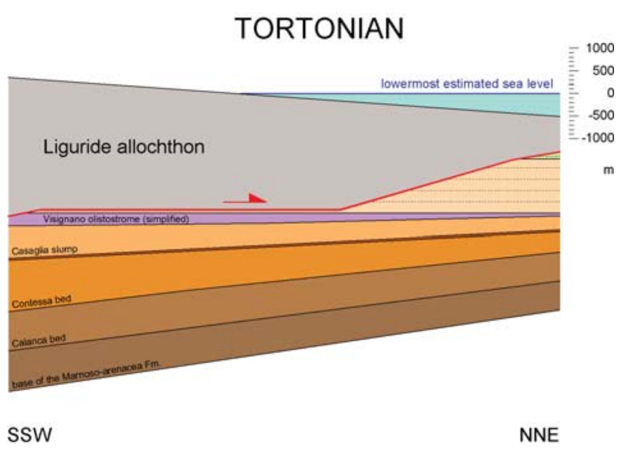


Fig. 4 - *Tectonic scheme of the Western Romagna Apennines. The study area (blue square) is framed within a comprehensive view of the Sillaro Line, i.e. the Liguride overthrust on the outer Tuscany and Romagna structural domains. The scheme has been constructed by assemblage and partial re-interpretation of published and unpublished geological maps* (Cremonini & Elmi, *1971;* Landuzzi, *1992, 1994;* Landuzzi & Bernagozzi, *in progr.;* Verdastri, *1998). Stratigraphic subdivisions are mainly based upon time intervals bounded by litho-stratigraphic marker horizons.*



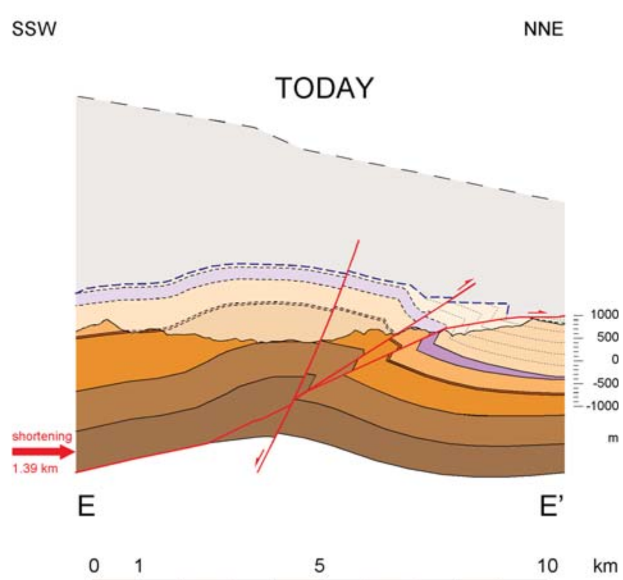


Fig. 5 - *Retro-deformed and present-day cross-sections of the Diaterna anticline. The sin-depositional Liguride overthrust fault is folded by a post-depositional polyphase anticline.*

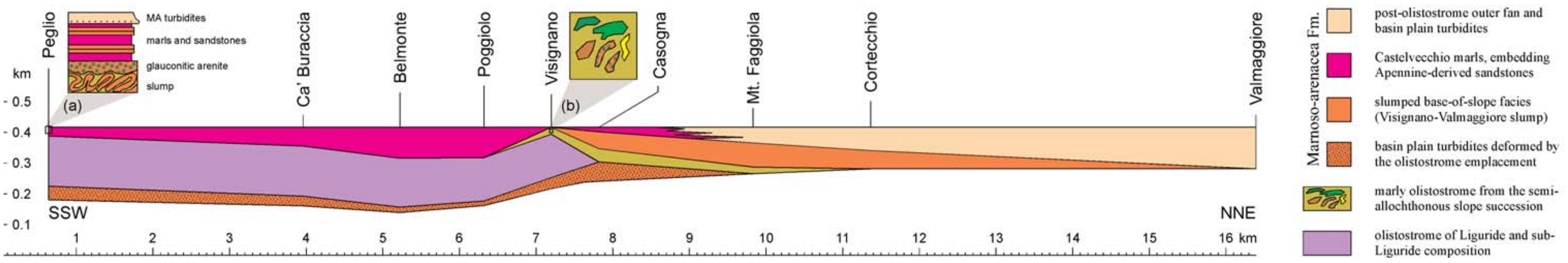


Fig. 6 - *Stratigraphic scheme of the Visignano olistostrome. It has been obtained from correlation of elementary columns measured on the detailed geologic cross-sections (Fig. 2). Horizontal distances have been restored to sin-depositional conditions by bi-dimensional retro-deformation. The two enlarged pictures focus at: (a) Apennine-derived slumps and high-density turbidites within the Castelvecchio unit; (b) chaotic marls enclosing olistoliths from the semi-allochthonous succession..*

tional structures. The Apennine folds and the SSW-verging thrust-faults are related to contractional deformation over shallow detachment levels (cross-sections B, C, D). Folds can derive from fault-bend as well as fault-propagation processes (cross-sections C, D). The maximum offset of thrust-faults is 700 m (cross-section C). The maximum offset extensional fault is 80 m (cross-section C).

The Liguride overthrust

Stratigraphic schemes of the Romagna Apennines (fig. 3) have been realized in order to provide a regional-scale picture of the relationships between the Liguride overthrust and the autochthon turbidite deposition. From NW to SE, these relationships change remarkably, reflecting variations in structure and subsidence of the foredeep basin.

In Western Romagna the MA is a single clastic wedge, whose turbidite deposition has been tectonically "closed" by the allochthon emplacement (RICCI LUCCHI, 1975, 1987). In Eastern Romagna the MA is composed of two clastic wedges, reflecting the progressive separation of a large satellite basin from the main foredeep.

That basin was bounded to the N by a less subsiding zone known as "Verghereto high", where turbidite deposition has been drastically reduced before the allochthon emplacement. The overall time-transgressive trajectory of the Liguride overthrust indicates that throughout the Romagna Apennines the allochthon advancement was in competition with autochthon sedimentation (DE JAGER, 1979). Nevertheless, the angular relationships between the Liguride overthrust and the MA bedding planes change remarkably from the NW to the SE. In Western Romagna, the Liguride overthrust trajectory is mainly composed of strongly inclined ramps: this means that the allochthon was advancing directly into the foredeep depocentre zone, in competition with high autochthon deposition rates. In Eastern Romagna, the Liguride overthrust trajectory is mainly composed of slightly inclined ramps: this means that the allochthon was advancing over autochthonous units already involved in deformation, and subject to lower deposition rates.

The sin-depositional trajectory of the Liguride overthrust has been deeply modified by Late Miocene and Quaternary tectonic overprints, that can be best discriminated in a tectonic scheme of the Western Romagna Apennines (Fig. 4). In spite of the large size of the mapped area, most fold axes regularly dip to the NW, allowing once again a clear down-the-plunge view of the overall tectonic structure.

In a chronological order, the following main tectonic features of the Western Romagna Apennines were found.

(1) A Liguride overthrust, time-transgressive over the outer Tuscan units and the Romagna units as well. The relative ages of the autochthonous units between the Passo della Futa and the Giogo di Scarperia indicate that the allochthon started thrusting over the MA before the Late Langhian.

(2a) Tuscan thrusts, detached in the upper part of the Scaglia Fm., and involved in very complex imbrications. Near the Giogo di Scarperia, these Tuscan units have thrust by no less than 5 km over Romagna units already covered with the Liguride allochthon. That displacement, representing the last stage in the evolution of the Tuscan front, occurred during the Late Langhian - Early Pliocene time interval. This is one of the best examples of how Apennine thrusts could help re-activate the Liguride overthrust.

(2b) Romagna thrusts, that detached near the base of the MA and developed by fault-propagation folding. The most important of these is the Poggio Castellaccio unit (DE JAGER, 1979), whose front terminates to the NW in the study area. The Apennine folds and thrusts reported in the detailed geological map (Fig. 1) are all genetically related to the development of the Poggio Castellaccio front. The post-depositional character of the same front is very clear between Moscheta and Poggio Belmonte, where the Liguride allochthon has been re-folded by the Diaterna anticline. The relative age of the Romagna thrusts is constrained to the Early Messinian - Early Pliocene time interval, but their activity probably reached a climax in the Early Messinian.

(3) A regional-scale tilting to the NW of the Western Romagna structure, depending on a large tectonic culmination in the central Romagna Apennines, which started growing in Tortonian times and remained active up to date. The culmination uplift was accelerated in Plio-Quaternary times, during the transition from the building stage to the exhumation stage of the Apennine belt.

(4) Active longitudinal and transverse extensional faults, overprinted on the previous contractional structure. These are best represented in the Mugello basin (Panna, Ronta, Gattaia, Villore), but also affect the study area.

Fig. 7 - *The Castelvecchio unit in the lower part of the Peglio succession (on the right): a slump of thin-bedded and fine-grained turbidites is flattened out by a thick bed of graded and structure-less arenite (marked in green). That arenite is characterised by an uncommon abundance of clastic glauconite, and also contains limestone and shale clasts. The succession above is composed of marls alternating with flat-parallel sandstone beds. Some of the latter can be common MA turbidites (Bouma Tc-e). The other sandstone beds are coarser-grained, structureless and frequently amalgamated. At a closer view, they are characterised by strongly heterometric grain size, with abundant matrix and scarce cement. As a rule, their composition includes limestone, shale and glauconite clasts. In a broad sense, such sandstone beds can be interpreted as high-density turbidites fed by Apennine sources, but petrographic analyses are needed to more precisely define their provenance.*

Fig. 8 - *The thickest section of the Castelvecchio unit, near Ca' Buraccia (on the left). Grey marls embed cyclically organized sequences of light grey sandstone beds. Those beds, derived from high-density turbidites of Apennine provenance, indicate that the Castelvecchio unit was not a "mud drape" covering a still-standing submarine relief, but the sedimentary fill of a subsiding depression on top of the Visignano olistostrome. The evolution of that small-scale satellite basin has been controlled by sin-depositional folding, due to a combination of regional foredeep subsidence and local olistostrome re-mobilization..*

Fig. 9 - *Near Visignano: vertical stratigraphic boundary between some chaotic marls of the Visignano olistostrome and the subsequent MA. The chaotic marls enclose upper Oligocene, Lower Miocene and Middle Miocene olistoliths. Most Lower Miocene olistoliths are represented by hard marls with local chert lists. Many Middle Miocene olistoliths are represented by soft-sediment deformed arenites (marked in green), very rich in glauconite and similar to those shown in Fig. 7. The chaotic marl body can be interpreted as a glided slab of the base-of-slope succession, marking the toe of the Visignano olistostrome.*

Fig. 10 - *Near Visignano: detail of the chaotic marls shown in Fig. 9. An olistolith of hard Lower Burdigalian marls is enclosed in softer Lower Serravallian marls.*

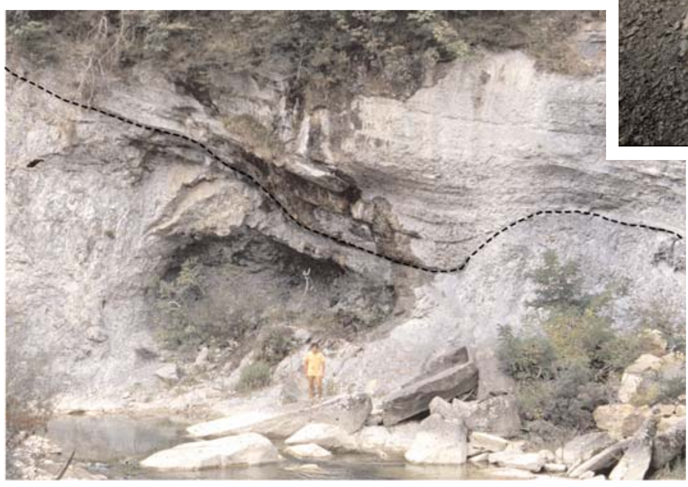


Fig. 11 - *Left bank of the Santerno river bed: a lens-shaped marl body belonging to the Castelvecchio unit has filled a local depression on top of the Visignano olistostrome. The chaotic marls underneath are similar to those shown in Figs. 9 and 10. This outcrop can be seen as a small-scale analog of the whole Castelvecchio unit in the Visignano "olistostrome-top basin".*

During the Quaternary exhumation of the Apennine belt, extensional faults propagated almost to the Po Plain border, testifying to a radical change in the deformation style of the whole Tuscany-Romagna Apennines (ZATTIN *et alii*, 2000; BARCHI *et alii*, 2001).
In the tectonic scheme of the Western Romagna Apennines, the Sillaro Line appears as a deformed and tilted sector of the Liguride overthrust. In order to reconstruct the sin-depositional trajectory of the same overthrust, some of the field data selected for the compilation of the tectonic scheme were also used to perform a retro-deformation procedure based upon stereographic projection (Fig. 4).
The Liguride overthrust was retro-deformed according to the following steps.
(a) Recognition of the less faulted zones of the overthrust surface.
(b) Selection of sub-zones typified by sinuous intersections between the overthrust surface and the topographic relief.
(c) Determination of the present-day attitude of the Liguride overthrust, using a three-point interpolation method.
(d) Determination of the dominant attitude of the MA bedding planes. (e) Stereographic projection of both attitudes.
(f) Tilting of the projected data, in order to restore the MA bedding planes to their sin-depositional horizontal attitude.
As shown by the stereograms reported in Fig. 4, the retro-deformed Liguride overthrust mainly dips to the SSW. This determination suggests that in Langhian and Serravallian times the Liguride front substantially had an "Apennine" trend. Therefore, during the same time interval the allochthon extent over the MA should have been much larger than the present one (ZATTIN *et alii*, 2000; discussion in LUCENTE *et alii*, 2002).
The reconstructed dip angles of the Liguride overthrust accurately depict the overall ramp attitude of its trajectory. The only zone where a 5 km-long flat is found is within the study area, between Peglio and Poggio Belmonte.
Another reconstruction of the sin-depositional trajectory of the Liguride overthrust was obtained from bi-dimensional retro-deformation of the Diaterna anticline, in a cross-section nearly parallel to the original overthrust dip (Fig. 5; trace in Fig. 4).
The present-day cross-section E depicts the Diaterna anticline as a post-depositional fold, mostly controlled by the propagation of the Poggio Castellaccio thrust-front. The retro-deformed cross-section E shows the regular shape of the MA clastic wedge, and a probable profile of the Liguride allochthon. The allochthon thickness has been estimated by apatite fission track analyses of the MA sandstones (ZATTIN *et alii*, 2000).

The Visignano olistostrome

In order to produce a stratigraphic scheme of the Visignano slump-olistostrome (Fig. 6), five elementary columns were measured on the cross-sections A, B, C, D (Fig. 2), and another four were directly drawn from maps. All column sites were then projected on the cross-section E (Fig. 5), which was subsequently retro-deformed. In this way, the horizontal distances between column sites were restored to their sin-depositional values. Eventually, the Castelvecchio unit top was chosen as a datum plane, and the stratigraphic columns were connected one to each other using correlation lines.
The submarine landslide of Visignano is composed of an intra-basinal body called "slump", and an extra-basinal body called "olistostrome". Upon closer examination, the slump can be split in two parts:
(a) the basin plain turbidites extending from Peglio to Visignano, which were deformed by the olistostrome impact on the foredeep basin floor;
(b) the hemipelagic marls and thin-bedded turbidites extending from Visignano to Valmaggiore, which have slumped from a base-of-slope environment.
The olistostrome is mostly composed of Cretaceous-Eocene shale slabs, commonly showing the typical scaly fabric of the Liguride tectonites. Debris flow deposits are sporadic, and the overall olistostrome structure suggests a block-gliding movement. The distal-upper part of the olistostrome is composed of chaotic marl bodies enclosing Oligo-Miocene marl and sandstone olistoliths (Figs. 6, insert a, 9 and 10). The chaotic structure of those bodies would have formed by slumping previous to the olistostrome motion, since the marls did not mix with Liguride shales.
The Castelvecchio unit is a marl succession rich in sandstones of probable Apennine provenance, which filled-up a subsiding depression located on top of the Visignano olistostrome (Figs. 6, inserts a and b, 7 and 8). The boundary between the Castelvecchio unit and the subsequent MA testifies to the sedimentary flattening out of the sea-bottom relief created by the olistostrome emplacement and re-mobilization (Figs. 9 and 11).

SYN-DEPOSITIONAL ADVANCEMENT OF THE LIGURIDE ALLOCHTHON

The stratigraphic schemes of the Western Romagna Apennines and the Visignano slump - olistostrome were used as references for the cross-section reconstruction of the Liguride overthrust evolution in the study area (Fig. 12). The slumped units have been led back to their original sites on the basis of their present-day relative positions. According to bi-dimensional retro-deformation rules, all cross-section areas were kept, and thickness was also maintained for block-glided units.
On the basis of the evolutionary scheme shown in Fig. 12, the following conclusions can be drawn:

Stage 1

(a) During the Late Burdigalian - Early Messinian evolution of the Northern Apennine foredeep, a condensed semi-allochthon succession covered the allochthon front slope, in heteropic boundary with the MA of the foredeep succession.
(b) Because of the tectonic activity of the Liguride overthrust, frequent slumps and high-density turbidites were released from the outer shelf and the upper slope onto the base-of-slope environment. Some of those gravitational deposits were supplied by semi-allochthonous units older than the actual MA.
(c) During calm intervals, the gravitational deposits were draped by marly facies of the MA.

Stage 2

Near the end of the Early Serravallian, the

Visignano olistostrome detached from the Liguride core of the allochthon front slope and moved into the basin, where it was forerun by a huge slump fed by the base-of-slope succession. The olistostrome motion was essentially driven by block-gliding processes that allowed the slid units to preserve their relative order, as well as part of their original structure. The slump-olistostrome advanced 16 km over the foredeep basin floor, and kept moving until temporary stability conditions were recovered in its detachment area.

Stage 3

Because of a continuous relative motion between allochthon and autochthon, the critical stability of the submarine slope was subject to frequent perturbations, restarting the olistostrome advancement each time. As a consequence, the olistostrome foot thrusted over the adjoining slump and was involved in gentle fault-bend folding. The interplay between local folding and regional subsidence gave rise to a small “olistostrome-top basin”, separated from the foredeep by the relative uplift of the olistostrome foot. This peculiar satellite basin has been filled by a base-of-slope succession (Castelvecchio unit), characterised by repeated slumps and high-density turbidites from the semi-allochthonous units. Apennine-derived gravitational deposits also occur in normal foredeep facies close to the Liguride overthrust (BRUNI, 1973; VERDASTRI, 1998), but are most frequent in the Castelvecchio unit. This concentration mainly depends on the active separation between the olistostrome top basin and the foredeep, and was probably enforced by sediment funnelling down the olistostrome detachment scarp.

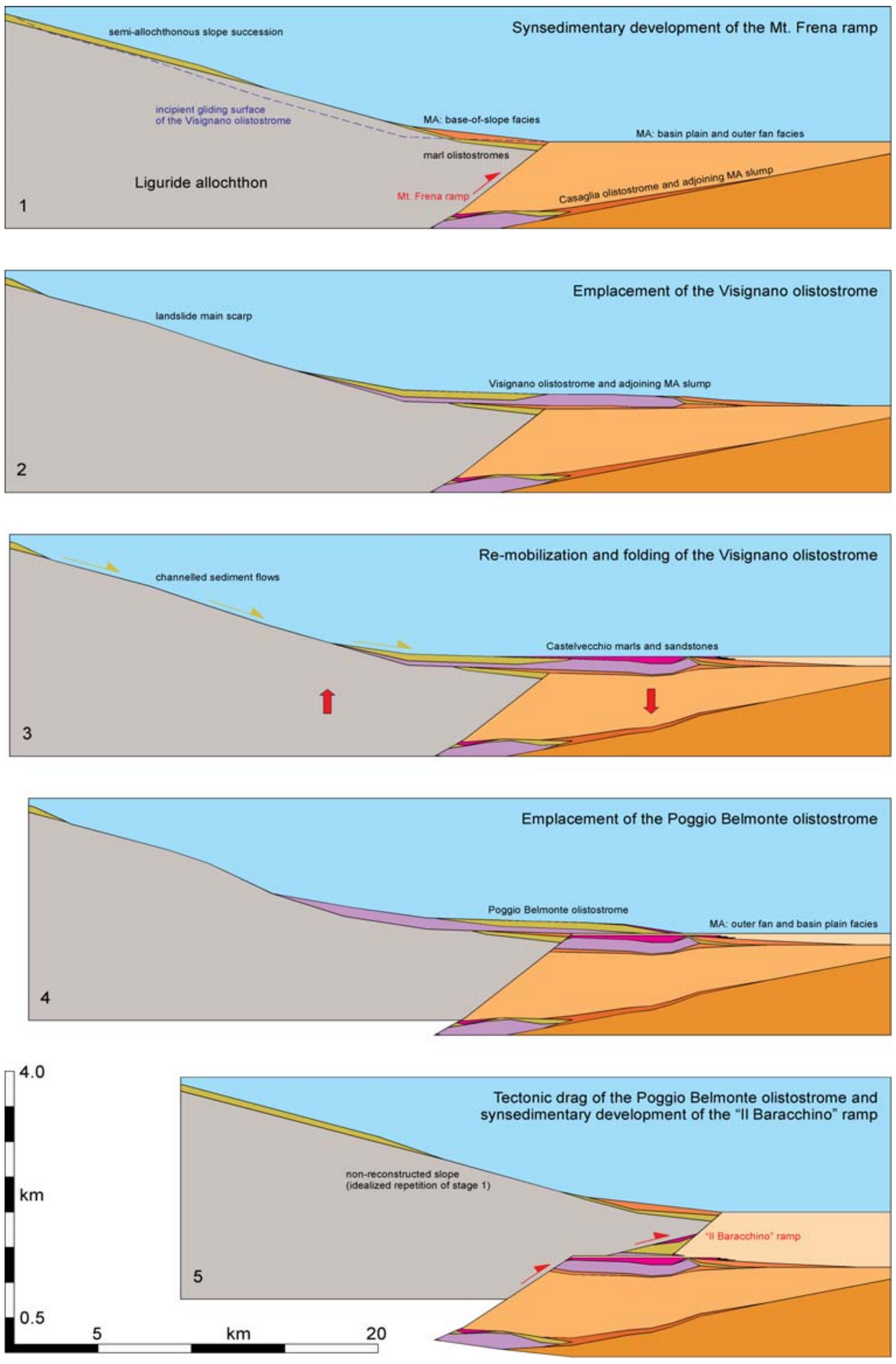


Fig. 12 - *Cross-section reconstruction of the Liguride overthrust evolution. This cartoon frames the Casaglia, Visignano and Poggio Belmonte olistostromes in the Serravallian evolution of the Liguride overthrust. Reference data have been drawn from the stratigraphic scheme of the Western Romagna Apennines (Fig. 3), the retro-deformed cross-section of the Diaterna anticline (Fig. 5), and most of all the stratigraphic scheme of the Visignano olistostrome (Fig. 6). By analogy to present-day submarine slopes, a 4° angle was used to constrain the allochthon front slope during stages 1 and 5. When construction was complete, the vertical size of all cross-sections has been quadruplicated.*

Stages 4 and 5

Not all olistostromes coming from the allochthon front have preserved their stratigraphic relationships to the MA. In many cases, olistostromes were dragged forward by the allochthon advancement before they could be ultimately buried by foredeep turbidites. The best example of such an “extreme re-mobilization” is provided by the Poggio Belmonte olistostrome, whose emplacement and subsequent tectonic drag explains the 5 km-long flat that interrupts the overall ramp trajectory of the Liguride overthrust in the study area. At a larger scale, the common occurrence of chaotic Oligo-Miocene marls within the Liguride overthrust zone seems to indicate an almost continuous “olistostrome carpet”, tectonically interposed between autochthon and allochthon.

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