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The Salsomaggiore structure (Northwestern Apennine foothills, Italy): a Messinian mountain front shaped by mass-wasting products / Artoni, Andrea; Papani, Giovanni; Rizzini, Francesca; Calderoni, M.; Bernini, Massimo; Argnani, A.; Roveri, Marco; Rossi, M.; Rogledi, S.; Gennari, Rocco. - In: GEOACTA. - ISSN 1721-8039. - 3:(2004), pp. 107-128.

Availability:
This version is available at: 11381/1443015 since: 2024-12-16T14:47:22Z

Publisher:

Published
DOI:

GeoActa, vol. 3, 2004, pp. 107-127, Bologna

The Salsomaggiore structure (Northwestern Apennine foothills, Italy): a Messinian mountain front shaped by mass-wasting products

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Abstract

The Salsomaggiore structure is a tectonic window that exposes the Langhian-Serravallian foredeep units in a thrust-related and overturned anticline surrounded by the allochthonous Mesozoic-Paleogene Ligurian units and by remnants of Eocene-Messinian epiligurian deposits. The late Messinian succession, deposited after the Messinian evaporative event, shows a characteristic onlap against the Salsomaggiore structure and rests above an erosional unconformity that truncates both foredeep and allochthonous units. The tectonic and depositional setting of the Salsomaggiore structure, representative of the Northwestern Apennine foothill, was reached during the intra-Messinian phase, a tectonic phase of major reorganisation of the Northern Apenninic chain.

New surface and subsurface data suggest that the allochthonous units moved north of the present day Salsomaggiore anticline immediately after the early Messinian evaporative event, and formed the Messinian mountain front of Northwestern Apennines. The allochthonous units, preserving a clear tectonic imprint, show also evidence of large-scale slided masses, suggesting that they were emplaced by mass-wasting processes. These processes, shaping the topographic surface of the allochthonous units, were triggered by the contemporaneous uplift of the underlying foredeep units and by mutate climate conditions that enhanced an overall base-level rise. In fact, after the evaporative event, the widespread occurrence of fluvio-deltaic deposits testifies a wetter and rainy climate. Similar intra-Messinian mass-wasting products are widespread along the whole Northwestern Apennine foothills, suggesting that the Northern Apennines Messinian mountain front was dominated by mass-wasting processes.

Keywords: Foreland, Mountain front, Messinian, Stratigraphy, Mass-wasting.

Introduction

In the Northwestern Apennine foothills of Italy, the Salsomaggiore structure is part of the Emilia sector of the Apennine orogenic-wedge, which has its most external fronts buried under the Po Plain (Fig. 1). The Salsomaggiore structure has long been studied by various Authors for the occurrence of natural resources, mainly hydrocarbon and curative waters (Anelli, 1913; Anelli, 1923; Redini, 1943; Pelosio, 1957; Finetti, 1958; Papani, 1999). But most important, the Salsomaggiore structure is representative of the tectono-stratigraphic frame of Northwestern Apennine foothills. In fact, this is the only structure where Miocene foredeep deposits crop out beneath the allochthonous units (Fig. 1), and the late Messinian-early Pliocene deposits, above an erosional and angular unconformity, seal both allochthonous and foredeep units (Fig. 2). This unconformity surface has been recently and, according to us, erroneously interpreted as a tectonic contact (Cerrina Ferroni et al., 2002).

The Salsomaggiore structure is a tectonic window, defined by the Salsomaggiore anticline, surrounded by allochthonous units consisting of Ligurian units, the epiligurian succession and the intra-Messinian chaotic unit (IMCU from now on) (Fig. 2). The Salsomaggiore anticline is a thrust-related, north-east vergent and overturned fold (Zanzucchi, 2000) that coincides with the inner flank of the Tabiano-Cortemaggiore wedge-top basin; the outer flank of this wedge-top basin is the Cortemaggiore front (Figs. 3 and 4). The Salsomaggiore and Cortemaggiore fronts started to uplift and create a relief during the Messinian (Zanzucchi, 1982; Rizzini, 2000; Argnani et al., 2003; Rizzini et al., 2004). Almost simultaneously,

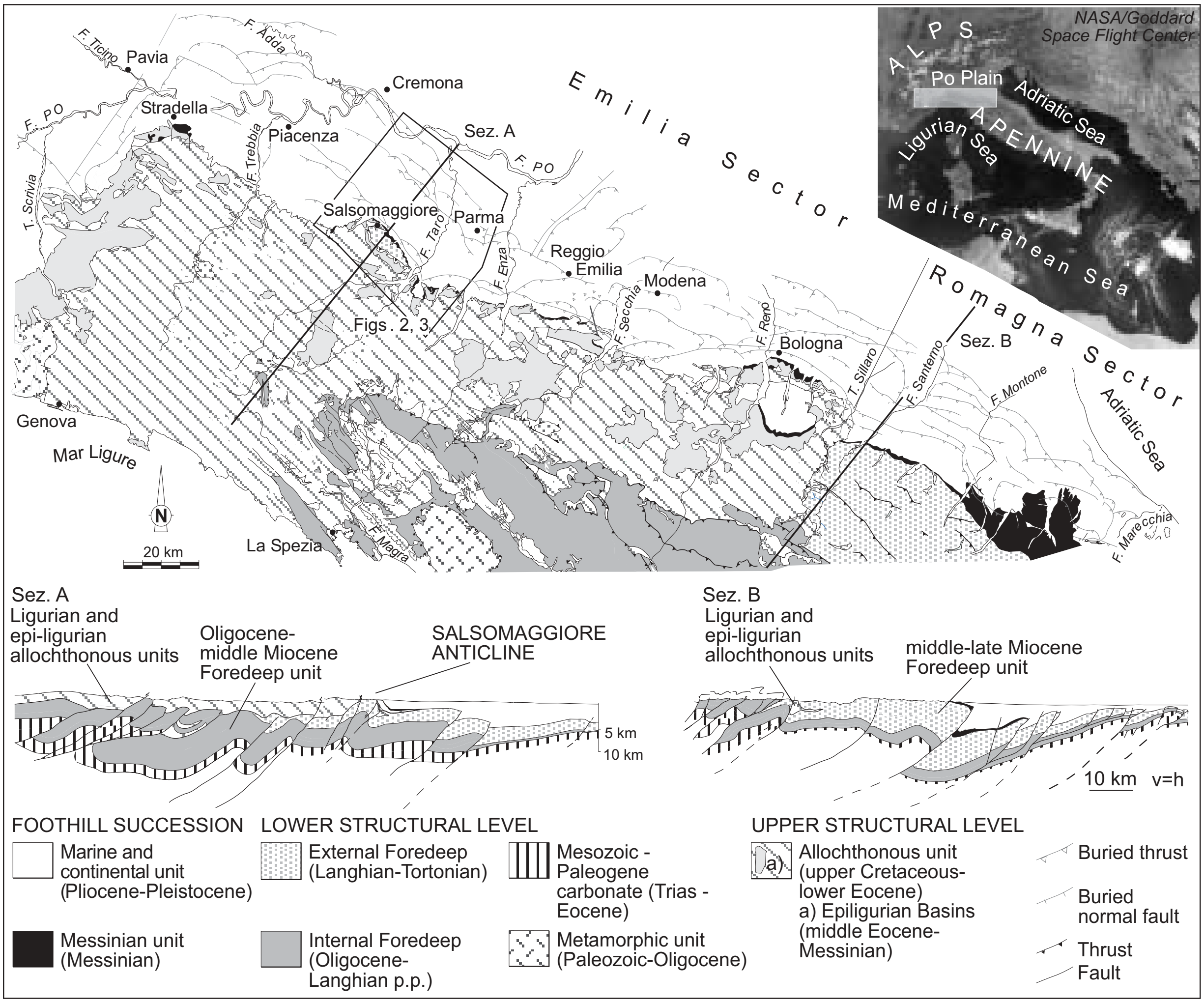

Fig. 1 - simplified geological map of the Northwestern Apennines (modified after Boccaletti and Zanzucchi, 1982; Bigi and Scandone, 1991; Bernini et al., 1997). The map shows the two structural levels framing the Northern Apenninic chain and the Messinian deposits along the Northwestern Apennine foothill. Two cross sections, A and B, show the along margin variability in the vertical stacking of the two structural levels. The Salsomaggiore area is detailed in Fig. 2 and Fig. 3.

the advancing allochthonous units reached and overrode the Salsomaggiore anticline; the Messinian mountain front was then created. During the more recent Pliocene-Pleistocene tectonic phases, this mountain front was reactivated; the Salsomaggiore anticline was amplified, the northern anticline limb steepened (Rizzini, 2000; Argnani et al., 2003; Rizzini et al., 2004) and folded together with the overlying allochthonous units (Fig. 4).

In this context, the present day Salsomaggiore structure can be considered an exposed and relatively well-preserved portion of the Messinian mountain front that was created by the intra-Messinian tectonic phase of the Northern Apennine.

The main aim of this study is to characterise the depositional and deformational events of this ancient mountain front during and following the intra-Messinian tectonic pulse, when the Salsomaggiore structure was created and the Apennine chain suffered radical changes.

Geological framework

The Northwestern Apennine fold-and-thrust belt (Fig. 1) is characterised by two distinct

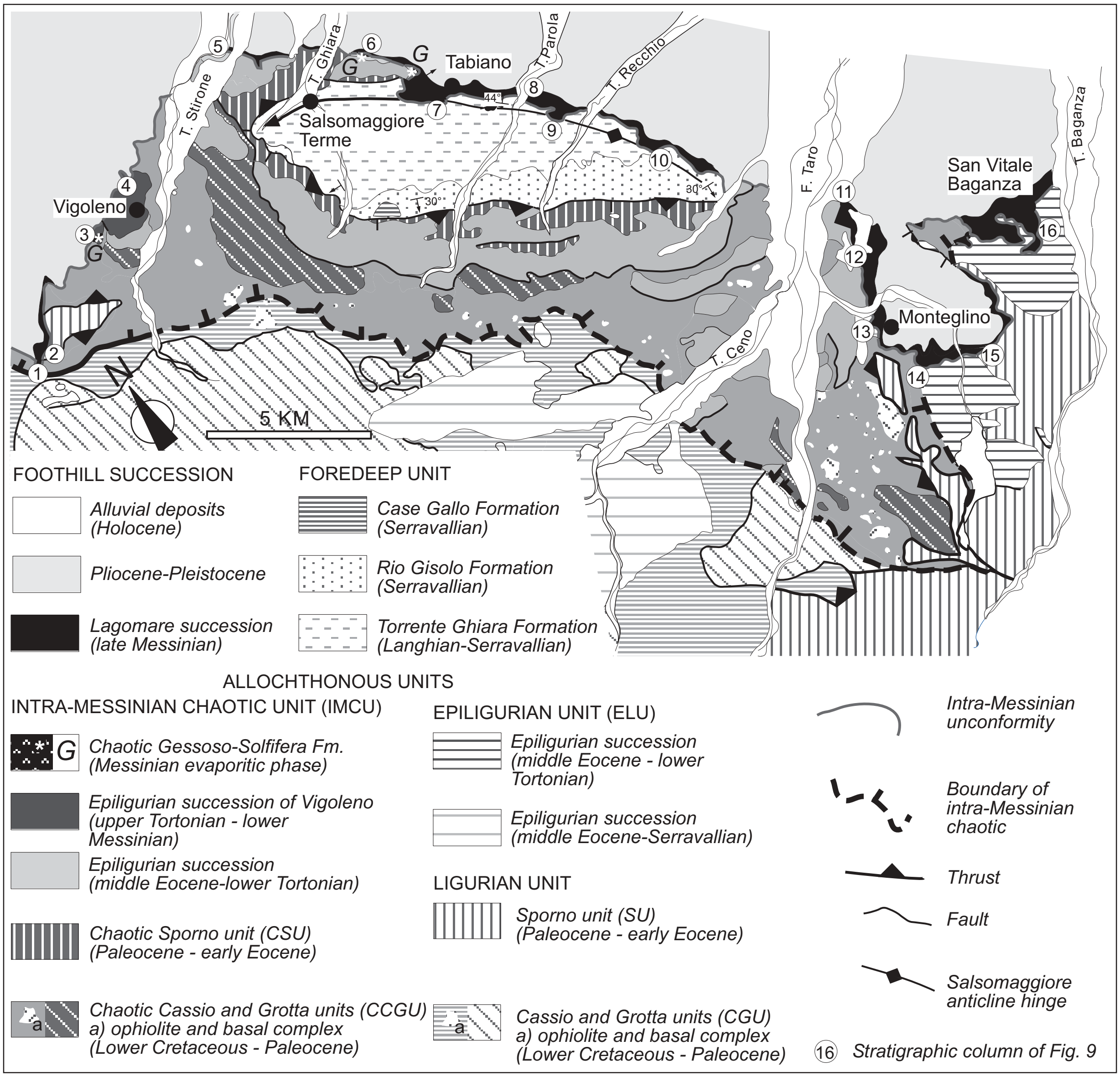

Fig. 2 - simplified geological map of the Salsomaggiore structure, a tectonic window formed by foredeep units (lower structural level) overridden by allochthonous units (upper structural level) of Ligurian, epi-Ligurian units and intra-Messinian Chaotic Unit (IMCU) (modified after Istituto di Geologia di Parma, 1966; Servizio Geologico d'Italia - Regione Emilia Romagna Zanzucchi (ed.) F. 198 Bardi, 1999). In the upper structural level, two Ligurian tectonic units, Cassio-Grotta (CGU) and Sporno (SU), are distinguished. The southern boundary of the IMCU coincides with the Chaotic Cassio-Grotta Unit (CCGU); see text for discussion. The circled numbers are the locations of measured sections used to construct the stratigraphic panel of Fig. 9.

structural levels, whose leading-edges propagated toward N-NE and were associated to a foreland basin that developed since Oligocene to the present (Ricci Lucchi, 1986; Boccaletti et al., 1990; Argnani and Ricci Lucchi, 2001). The upper structural level is made by the accreted Ligurian units; Mesozoic oceanic and forearc deposits derived from the closure of the Ligure-Piemontese ocean and its continental margins (Abbate et al., 1970; Boccaletti et al., 1971; Elter, 1975; Marroni et al., 2002). On top of the Ligurian units, the epiligurian wedge-top basins are characterised by a middle Eocene-early Messinian epiligurian succession made up of tectonically-controlled turbiditic and slope deposits, passing upward to shelfal and, locally, to shallow-water primary

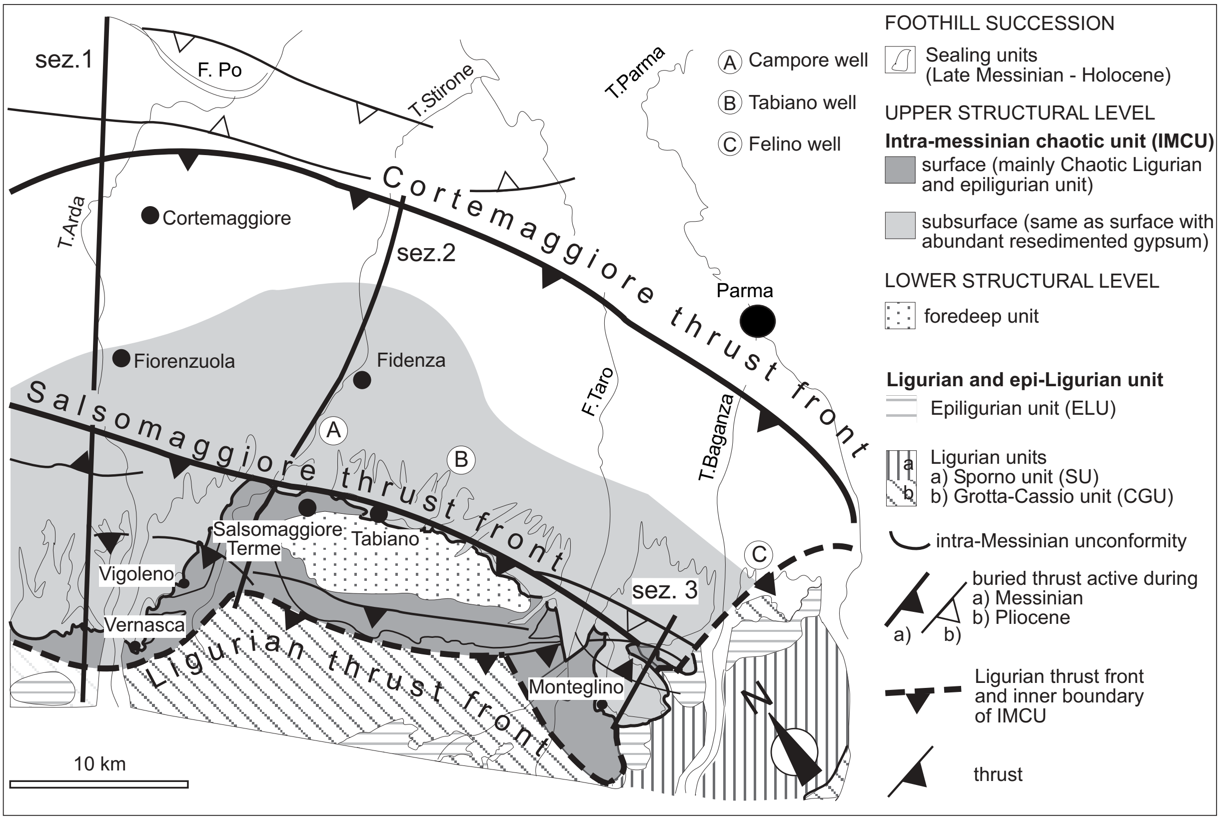

Fig. 3 - structural map of the Salsomaggiore area integrating surface and subsurface data (modified after Rizzini, 2000; Argnani et al., 2003). The three main thrust fronts are shown. The Ligurian thrust front is complicated by the uncertain boundary of the IMCU (dashed line). This boundary separates the Ligurian/epi-Ligurian unit from the Chaotic Ligurian/epi-Ligurian units; see text for details. Sez. 1, sez. 2 and sez. 3 are the traces of the seismic lines interpreted in Fig. 4. Circled capital letters are the location of wells correlated in Fig. 7.

evaporitic deposits (Ricci Lucchi, 1986; Papani et al., 1987; Boccaletti et al., 1990; Amorosi et al., 1993; Mutti et al., 1995; Ottria et al., 2001). The upper structural level overrides on top of the foredeep units (Fig. 1), and the detachment surface becomes younger from the internal to external areas of the Apenninic chain (Pini, 1999).

The lower structural level, folded and segmented by thrusts that involve the Palaeozoic basement (Buness and Giese, 1990), consists of a Mesozoic to Paleogene carbonate succession (Fig. 1), above which Oligocene to Recent foredeep deposits record a number of major and tectonically-controlled depositional sequences (Ricci Lucchi, 1986; Amorosi, 1992; Argnani and Ricci Lucchi, 2001). Coeval depositional sequences are reported to infill the epiligurian wedge-top basins. The Northwestern Apennine foothills can be considered a buried front (Morley, 1986), because the two structural levels and the more external thrust fronts are now buried by a thick succession of late Messinian-Pleistocene deposits thickening toward the Po Plain (Pieri and Groppi, 1981) (Fig. 1, sections A and B).

At present, the Northwestern Apennine foothills can be subdivided in two sectors, according to the vertical stack of the above mentioned structural levels (Fig. 1): the Emilia sector and the Romagna sector. In the Emilia sector, as far as Sillaro River, the allochthonous units are present and overlie the Langhian-Serravallian foredeep deposits outcropping in the Salsomaggiore structure (Figs. 1 and 2). In this sector, the two structural levels were superposed during the intra-Messinian phase, as suggested in previous works (Iaccarino and Papani, 1979; Ricci Lucchi et al., 1982; Argnani et al., 2003; Rizzini et al., 2004), and Messinian evaporitic deposits appear in epiligurian basins of limited extensions.

In the Romagna sector of the Northwestern Apennine foothills, Langhian-Tortonian foredeep deposits of the Marnoso-arenacea Formation are

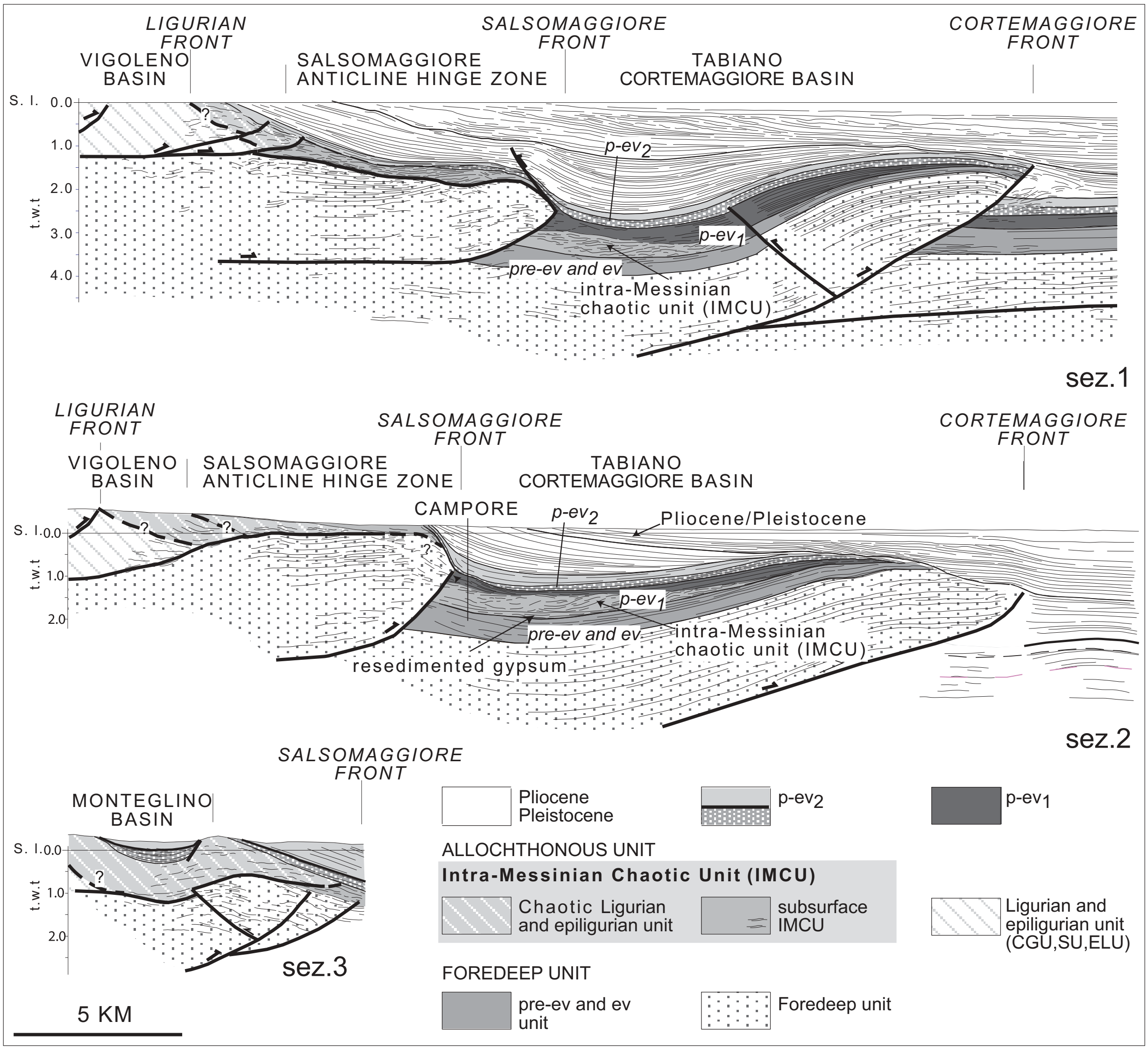

Fig. 4 - line drawings of the seismic reflection profiles integrating surface and subsurface data. Location of the section is in Fig. 3. Messinian stratigraphy is referred to as in Fig. 5.

exposed. They form an arcuate fold-and-thrust system (Capozzi et al., 1991) that started to develop since Miocene time (Ricci Lucchi et al., 1982; Ricci Lucchi, 1986; Mutti et al., 2002). The progressive accretion of the foredeep deposits at the southern margin of Po Plain produced a coeval restriction and shallowing of the basin, up to the precipitation of primary evaporites (Roveri et al., 2003) in the "Vena del Gesso" Basin (Vai and Ricci Lucchi, 1976). Primary evaporites, deposited on the structural highs, laterally pass to resedimented evaporites, and likely to euxinic deposits in the deeper and confined basins; it is during the intra-Messinian phase that the resedimented evaporites spread over most of the deeper basins (Ricci Lucchi, 1975; Roveri et al., 1998; Manzi, 2001; Roveri et al., 2001; 2003). In the Romagna sector, the allochthonous units never reached the present day Northern Apennine foothill (Fig. 1), and Messinian evaporitic deposits lay directly above the foredeep deposits of the lower structural level; the two structural levels are superposed about 30 km south of the present day Northern Apennine foothill (Fig. 1), and are sealed by Serravallian foredeep deposits (Pini, 1999; Mutti et al., 2002; Lucente and Pini, 2003). The allochthonous units appear again in the Marecchia valley (Fig. 1), but there is no evidence of them between Sillaro and Marecchia rivers; thus, the Romagna sector of the Northwestern Apennine can not be interpreted as a large tectonic window, as suggested by Cerrina Ferroni et al. (2002).

In the Emilia sector (Fig. 2), the external fronts are formed by three thrust-related folds that, according to Argnani et al. (2003), are named from the most southern and internal (Fig. 3): Ligurian front, Salsomaggiore front, and Cortemaggiore front.

The Ligurian front is part of the upper structural level, while the Salsomaggiore and Cortemaggiore fronts, bounding the Tabiano-Cortemaggiore wedge-top basin (Fig. 4), belong to the lower structural level (Fig. 1). These fronts were active during the Messinian (Argnani et al., 2003; Rizzini et al., 2004) and started to be sealed by the late Messinian post-evaporitic deposits, being completely sealed by Pliocene-Pleistocene deposits.

All along the Northwestern Apennine foothills, the late Messinian post-evaporitic succession, marking a relative quiescent phase after the intra-Messinian tectonic phase (Iaccarino and Papani, 1979; Ricci Lucchi et al., 1982), seals both structural levels framing the Apennine chain (Gelati et al., 1987; Roveri et al., 1998; 2001). Thus, the mountain fronts and wedge-top basins of Northwestern Apennine, created during the intra-Messinian phase, are preserved immediately beneath the late Messinian succession.

Messinian stratigraphy of the Apennine foreland basin

The Messinian stratigraphy of the Apennine foreland basin has been recently framed in a chronostratigraphic scheme that takes into account the structural evolution of this basin and propose a geologic-stratigraphic model (Roveri et al., 2001; Ricci Lucchi et al., 2002; Rossi et al., 2002) derived from previous works (Gelati et al., 1987; Bassetti et al., 1994; Manzi, 1997; Roveri et al., 1998; Bassetti, 2000) (Fig. 5). The chronostratigraphic scheme was achieved through modern and integrated stratigraphic techniques, including physical stratigraphy, sequence stratigraphy, seismostratigraphy, magnetostratigraphy, astrociclostratigraphy, biostratigraphy, and radiometric dating. Apart from the significant improvement in attributing a numerical dating to the Messinian events (Vai, 1997; Krijgsman et al., 1999a), these integrated methodologies allowed to recognise and trace the depositional events across different paleo-environments that are strongly controlled by the structural evolution of the foreland basin itself. In the recent chronostratigraphic scheme, the intra-Messinian phase generated important structural and depositional changes that created the intra-Messinian unconformity (*lm1* in Fig. 5), recognised all along the Apenninic margin (Iaccarino and Papani, 1979; Ricci Lucchi et al., 1982; Ori et al., 1991; Roveri et al., 2001; Rossi et al., 2002; Artoni, 2003b). These structural changes have been recently underscored also at the scale of the entire Mediterranean area (Mantovani et al., 1997).

After the main Messinian evaporative event, which is testified by shallow-water evaporites occurring in most part of the Mediterranean area (Ricci Lucchi, 1975; Vai and Ricci Lucchi, 1976; Hsü et al., 1977; Krijgsman et al., 1999b; Roveri et al., 2001; 2003) and coeval deeper-water euxinic deposits (Roveri et al., 2001), clastic gypsum facies became predominant and formed chaotic horizons and sheet-like tabular turbiditic bodies (Ricci Lucchi, 1973) that are widespread in the whole Apenninic foredeep. In the past, these gypsum-bearing clastic units were, in lithostratigraphic terms, included in the Gessoso-Solfifera Formation. In the recently revised Messinian stratigraphy, clastic, chaotic and resedimented gypsum are considered to postdate, in part or totally, the main evaporitic phase (Fig. 5). Therefore, the gypsum-clastic facies mark the inception of redeposition processes, and are the deeper-basin physical expression of the intra-Messinian unconformity (Gelati et al., 1987; Roveri et al., 2001; Ricci Lucchi et al., 2002; Artoni, 2003b). The intra-Messinian tectonic phase is also characterised by widespread tectonic deformation (Rizzini and Dondi, 1980; Gelati et al., 1987; Roveri et al., 2001), with subsequent depocenter migrations (Ori et al., 1991; Artoni, 2003b), collapse of basin margins and formation of erosional surfaces. In fact, the intra-Messinian unconformity is both erosive and angular, clearly suggesting its main tectonic nature.

Above the intra-Messinian unconformity, the lm1 unconformity (Fig. 5), and the resedimented gypsum with chaotic units, a thick pile of siliciclastic deposits of variable thickness is observed.

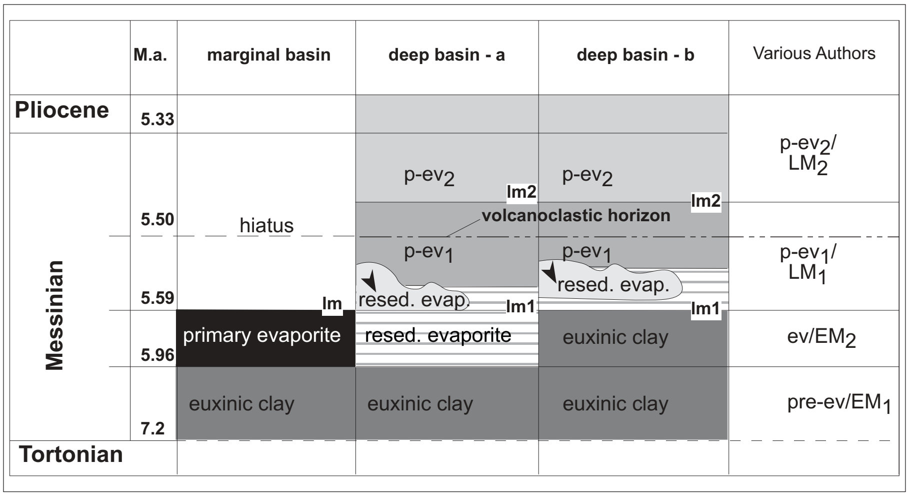

Fig. 5 - stratigraphic sheme of Messinian events in the Apennine foreland basin (after Gelati et al., 1987; Roveri et al., 2001; Rossi et al., 2002).

These siliciclastic deposits are part of the post-evaporitic succession, which has been recently subdivided in $p\text{-}ev_1$ and $p\text{-}ev_2$ units based on physical stratigraphy criteria, including detection of bounding regional-scale unconformities and facies architecture (Bassetti et al., 1994; Manzi, 1997; Roveri et al., 1998; 2001; Rossi et al., 2002).

The $p\text{-}ev_1$ unit, composed by sandstone and clay wedges of shelfal deposits with a regressive trend, is preserved close to the marginal area of the mountain front (Roveri et al., 2001), while turbiditic sandstones occur in deeper basins (Ricci Lucchi et al., 2002; Rossi et al., 2002; Artoni, 2003b).

The $p\text{-}ev_1$ unit is overlain, locally unconformably, by the $p\text{-}ev_2$ unit (Roveri et al., 1998; 2001), or *LM2* (Gelati et al., 1987; Rossi et al., 2002). The depositional characters of the $p\text{-}ev_2$, locally overlying the intra-Messinian unconformity, are clearly distinguishable in the field and have been described in detail by Roveri et al. (1998) and Bassetti (2000). This unit preserves two types of deposits: 1) coarse-grained sandstones and conglomerates, related to small-medium size fluvio-deltaic systems, passing basinwards to a shallow and confined shelf dominated by hyperpicnal flows generated by flood events; 2) micritic limestones, the “colombacci”, generally within claystone and silts in lacustrine environments.

In the whole Apenninic foreland basin the $p\text{-}ev_1$ and $p\text{-}ev_2$ units seal the mountain fronts after the intra-Messinian phase (Iaccarino and Papani, 1979; Ricci Lucchi et al., 1982; Rossi and Rogledi, 1988; Roveri et al., 1998; Rossi et al., 2002; Artoni, 2003b). They mark important paleo-hydrological changes that bring to the appearance of freshwater deposits with fauna of Paratethyan domain (Roveri et al., 1998; 2001; Bassetti, 2000; Ricci Lucchi et al., 2002; Bassetti et al., 2003). These units record an important palaeo-environmental change in the Mediterranean sea, which from a restricted and evaporitic basin becomes a large lake (Lago-mare of Cita et al., 1978) with periodical salinity changes (Roveri et al., 2001). These paleoenvironmental changes were associated to a climate change that, from arid, became wetter and more rainy during the deposition of the post-evaporitic deposits (Roveri et al., 2001).

Allochthonous units emplaced during the Intra-Messinian phase

In the Salsomaggiore area, the intra-Messinian phase coincides with the advancement of the allochthonous units through both thrusting and mass-wasting processes.

The allochthonous units bordering the Salsomaggiore anticline (Fig. 2) overlie the foredeep units (Figs. 2 and 4) and extend to the north as far as the Tabiano-Cortemaggiore basin (Fig. 3). Within the allochthonous units, the Ligurian/epi-Ligurian units and the IMCU can be distinguished

(Fig. 4). They show a complex internal organisation, which is also inherited from pre-Messinian deformation phases.

The Ligurian/epi-Ligurian units

Four tectonic units of regional extension form the Ligurian units in the Emilia sector of Northwestern Apennine; three of them, Cassio, Grotta and Sporno units, crop out in the Salsomaggiore area (Servizio Geologico d'Italia - Regione Emilia Romagna Zanzucchi (ed.) F. 198 Bardi, 1999; Calderoni, 2001) (Fig. 2). In Figure 2 the Cassio and Grotta units are grouped together due to their similarities.

The Cassio-Grotta tectonic unit (CGU)

The Cassio-Grotta unit (CGU from now on) belongs to the External Ligurian units of the Northern Apennine (Elter, 1975; Marroni et al., 2001; 2002); it derives from a Mesozoic domain located at the transition between the oceanic crust of the Ligure-Piemontese ocean and the continental crust of the Adria continental margin. It is interpreted to record the opening and closure of the Ligure-Piemontese ocean since Jurassic to Eocene, and represents a Cretaceous-Paleogene accretionary prism (Boccaletti et al., 1971; Treves, 1984; 1996; Marroni et al., 2001; 2002). In the basal portion of the Cassio-Grotta unit, a sedimentary and tectonic complex (*Complessi di base* of the Authors) consists of brecciated clays and/or tectonic melange that contain eterometric blocks of mudstone, marly limestone, and of oceanic, continental and subcontinental crust (Montanini and Tribuzio, 2001). These crustal rocks were accreted together with pelagic and hemipelagic ocean sediments not younger than the Cenomanian (Marroni et al., 2001; 2002), and form a tectonic melange with pervasive shear zones.

A higher tectonic slice, belonging to the CGU and thoroughly deformed by brittle and ductile deformations, is made up of deep-sea siliciclastic turbiditic deposits of Cenomanian-Santonian age, tectonically encased on top by the Cenomanian-Campanian deep-basin varicoloured emipelagic clay and slaty clay. This higher tectonic melange contains blocks of lower crust (Montanini and Tribuzio, 2001), whilst remnants of the older Jurassic-Cretaceous ocean floor are rare (Zanzucchi, 2000; Marroni et al., 2001; 2002).

The uppermost sub-unit of the CGU is made up of calcareous-marly Helmintoid Flysch (Campanian-Maastrichtian), with local upward transition to Paleogene clay-dominated deposits.

The recognisable structural order, the widespread occurrence of tectonic contacts, shear zones and folding suggest that the CGU is a tectonosome (Pini, 1999); thus, it originated by "pure" tectonic processes affecting the Mesozoic rocks, more or less intensively depending on their multi-layered character, and creating a typical block-in-matrix fabric (Bettelli and Vannucchi, 2003).

The Sporno tectonic unit (SU)

The Sporno tectonic unit (SU from now on) is tectonically the lowest Ligurian unit. This unit is entirely made up of calcareous and calcareous-marly turbidites with a basal bio-calcarenitic division deposited in a deep-sea environment (Sporno flysch, Selandian to Lutetian, in Zanzucchi, 2000).

In the study area and east of River Taro (Fig. 2), this unit is well exposed and overthrusted by the CGU (Fig. 2). In this area, the SU is made up of three stratigraphic members; these show a progressive upward increase of marly deposits (Zanzucchi, 2000) before deposition of the epi-ligurian succession (Fig. 2). Faulting and decametric isoclinal folds are pervasive within this turbiditic deposits, suggesting its tectonosome nature (Pini, 1999).

West of River Taro (Fig. 2), the SU lays in tectonic contact above the foredeep unit, but has a severe internal chaotic organization and can be included in the IMCU (Calderoni, 2001).

The epi-Ligurian units (ELU)

The epi-ligurian units (ELU from now on) are sedimentary units ranging in age from middle Eocene to late Pliocene (Ricci Lucchi, 1986; 1987; Boccaletti et al., 1990; Amorosi et al., 1993; Mutti et al., 1995; Ottria et al., 2001). In the Salsomaggiore area, they consist of deep-water turbiditic deposits that evolve upward to slope and shelfal environments, up to coastal and shallow marine. The ELU unconformably overlie the Ligurian tectonic units and are deposited in tectonically controlled wedge-top basins. The many unconformities occurring in the ELU record major advancing phases of the Ligurian units and testify that the ELU were deposited on a mobile

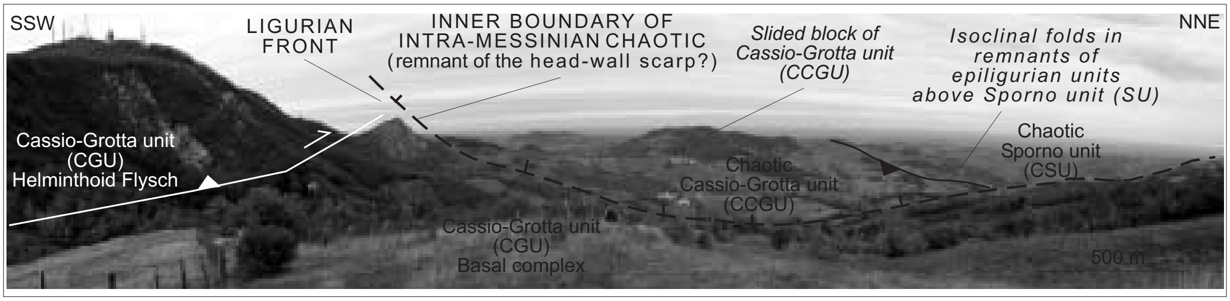

Fig. 6 - view of the Intra-Messinian Chaotic Unit (IMCU) and the possible head-wall scarps eroding the tectonic stack of the Ligurian units along the T. Ghiara. (CGU: Cassio-Grotta tectonic Unit; SU: Sporno tectonic Unit; CCGU: Chaotic Cassio-Grotta tectonic Unit; CSU: Chaotic Sporno tectonic Unit)

and unstable substratum, which was also prone to generate olistostromes (Papani, 1963; Zanzucchi, 1982).

The most recent ELU, located in more external positions (Fig. 2), are now remnants within the IMCU. In particular, the Vigoleno basin (Fig. 2) records shallow-water pre-evaporitic (upper Tortonian-lower Messinian - Miculan, 1992) and primary evaporitic deposits. These external basins testify one of the last advancement of the Ligurian units before the intra-Messinian tectonic phase, when they were dismembered.

The Intra-Messinian Chaotic Unit (IMCU)

The area bordering the Salsomaggiore anticline, both in surface and sub-surface, is characterised by a complex of chaotic deposits that are here attributed to the IMCU. Within the IMCU, five component units can be distinguished, reflecting the dominant deposits or the tectonic units from which they derive (Fig. 2). These are: 1) chaotic Cassio-Grotta unit (CCGU from now on); 2) chaotic Sporno unit (CSU from now on); 3) remnants of middle Eocene-lower Tortonian epiligurian succession; 4) remnants of upper Tortonian-lower Messinian epiligurian succession (Vigoleno basin); 5) chaotic Gessoso-Solfifera. The five units have always unclear and uncertain contacts, which might be tectonic, stratigraphic or tectonized stratigraphic. The uncertainty in defining the nature of the contacts is a distinctive character of the IMCU. The IMCU shows a chaotic and disorganized character also at the mapping scale (Fig. 2), where it appears as a puzzle of different and heterogeneous units.

The CCGU is mainly made by the *Complessi di base,* varicoloured complex and kilometric slices of Helminthoid Flysch; the latter, lacking certain contacts with the surrounding complexes, appears as large slices inside a chaotic tectonic melange (Figs. 2 and 6). These characters are better shown in the external part of the Cassio-Grotta tectonic unit, which also contains remnants of middle Eocene-lower Tortonian ELU. Thus, this portion has been included into the IMCU (Fig. 2).

West of River Taro and SW of Salsomaggiore anticline (Fig. 2), the units attributed to the Sporno tectonic unit (Zanzucchi, 2000) are characterised by a clay complex that supports eterometric blocks of bioclastic limestone and litoarenite. This complex derives from the disruption of Paleogene turbiditic and slope deposits, and is named Chaotic Sporno Unit (CSU) (Figs. 2 and 6). Carbonate and sandstone megaboulders form a chaotic unit that locally contains remnants of early to late Miocene deposits derived from the ELU (Fig. 2).

The ELU, which are tightly folded inside the IMCU, are subdivided according to the preserved portion of the epi-ligurian succession; the remnants are named (Fig. 2) epiligurian succession (middle Eocene-lower Tortonian) and epiligurian succession of Vigoleno basin (upper Tortonian-lower Messinian). All around the Vigoleno basin, a chaotic mass, a possible submarine slide within the epi-Liguran basin (Papani, 1967; Zanzucchi, 1982), is made up of Paleogene to Messinian blocks floating in a clay matrix made of Cretaceous rocks (Calderoni, 2001).

In outcrops of limited extension, selenitic gypsum with crystals in a disordered orientation of growth and in clay matrix can be observed. This texture suggests resedimentation after deposition and represents the chaotic Gessoso-Solfifera (Iaccarino and Papani, 1979; Calderoni, 2001). At

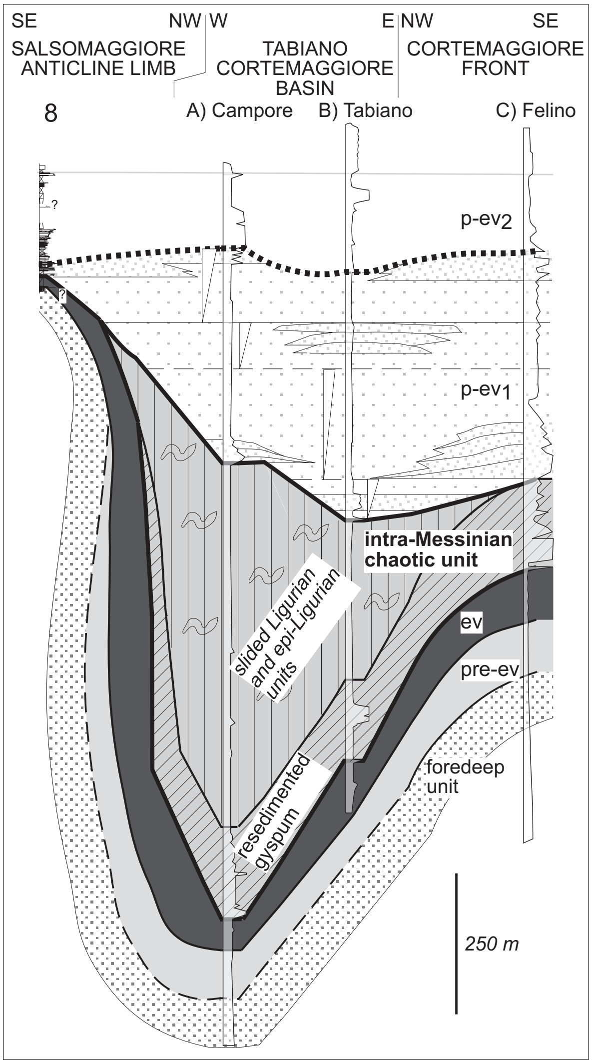

Fig. 7 - stratigraphic cross-section derived by the integration of revised exploration wells (Ghielmi et al., 1998) and the T. Parola section (Artoni, 2003a). The curves associated to the wells are spontaneous potential logs. Location of the wells and stratigraphic log are in Figures 2 and 3. Pre-ev: sandstone turbidites and emipelagic marl; ev: euxinic shale; p-ev$_1$: sandstone and clay of shelfal deposits; p-ev$_2$: sandstone and conglomerate of fluvio-deltaic systems.

present, this unit appears in tectonic contact with the surrounding "chaotic" Ligurian/epi-Ligurian units and can be considered olistolites in the IMCU (Calderoni, 2001). Olistolites of primary gypsum are always found associated to Ligurian/epi-Ligurian units which can be considered their original substratum.

The intra-Messinian chaotic unit in subsurface

The outcropping IMCU can be traced into subsurface, NE of the Salsomaggiore anticline (Figs. 3, 4), in the Tabiano-Cortemaggiore basin. Here, the IMCU can be vertically subdivided in two portions (Figs. 4 and 7). The lower portion is made of resedimented gypsum blocks and gypsum debris flows. These types of chaotic gypsum bodies are also known from studies in the Tabiano area (Papani, 1999), and crop out east of the study area in the Reggio Emilia and Modena areas (Barbacini et al., 2002; Rossi et al., 2002). The upper portion of the IMCU shows a repetition of rocks with ages ranging from Cretaceous to Tortonian. These are fragments and slices of Ligurian and epiligurian units derived from the Cassio-Grotta and Sporno tectonic units.

The seismic reflection lines (Fig. 4) show a chaotic body that, based on internal geometries, can be separated in two adjacent sectors (Fig. 8). A SW sector, between the Salsomaggiore anticline crest and the Ligurian front, which is characterised by extension (Fig. 8). A NE and more external sector, from the Salsomaggiore anticline crest to NE, which shows clear compressive structures, corresponding to a stack of small-scale thrusts forming an embricate fan (already described in Rossi et al., 2002) (Fig. 8).

The Intra-Messinian Chaotic Unit as a complex slided mass

The characters and the internal geometry of the IMCU are typical of a slided mass not much different from subaerial landslides and any other mass sliding on a slope. The two sectors recognized on seismic lines (Figs. 4, 8) correspond to the denudational and translational area (SE sector) and the accumulative area (NE sector) of a landslide. The chaotic features observed in the field and the widespread disruption of the tectonic stack of Ligurian/epi-Ligurian units form a complex body moving and accreting to the north. The slided mass derives from the leading edge of the NE advancing Ligurian/epi-Ligurian units, which were eroded by gravitational processes to form the chaotic Cassio-Grotta unit (CCGU), the chaotic Sporno unit (CSU), the various remnants of epiligurian succession and the chaotic Gessoso-solfifera. The head wall scarp of the slide cannot be clearly defined. Probably, it is a multiple scarp, partially eroded; a remnant of the head wall scarp can be located at the sharp morphologic change from rough to smooth topography SE of Salso-

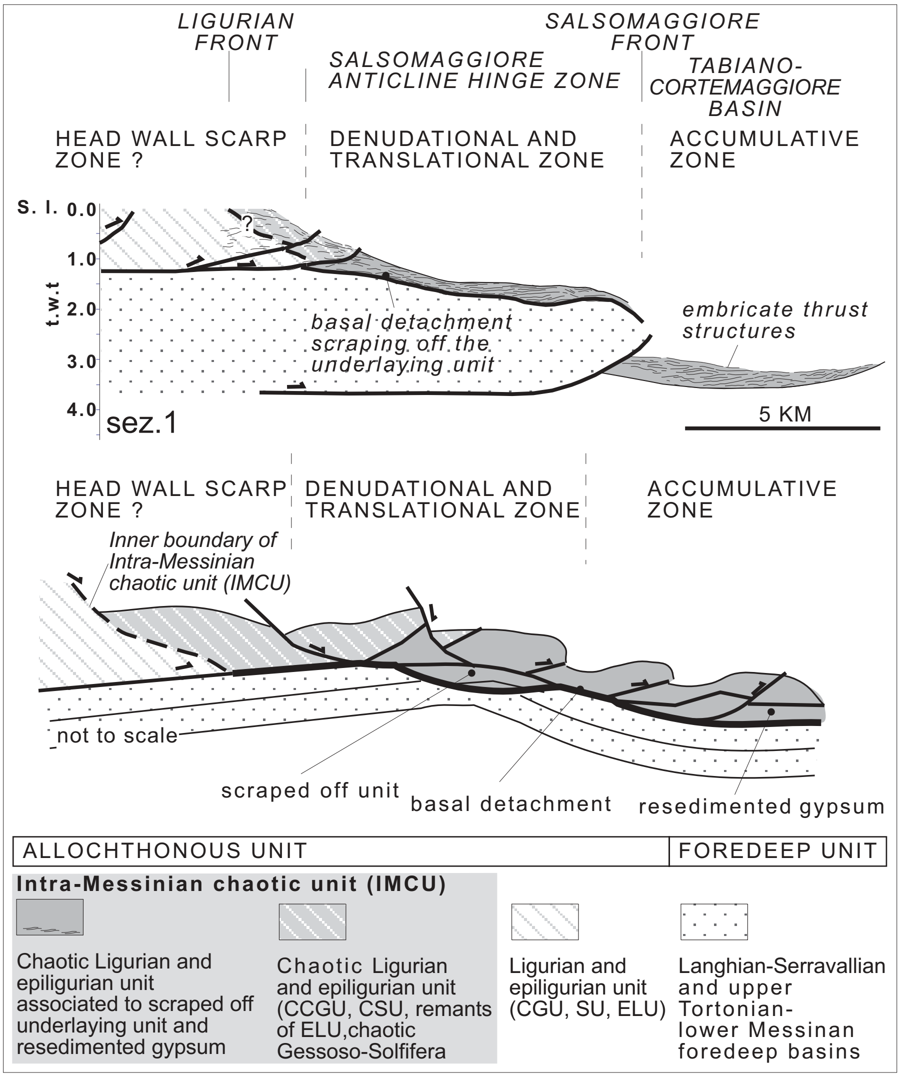

Fig. 8 - the IMCU, subdivided in sectors with different internal units and deformational structures; the section 1 of Fig. 4 is taken as an example. The sectors correspond to internal divisions of slided masses similar to subaerial landslides. See text for details.

maggiore anticline (Figs. 6 and 8). The blocks departing from the scarp and dismembering the Cassio-Grotta and Sporno units were rotating and translating to the north. Before, the uppermost evaporitic deposits of the epi-ligurian unit were resedimented to form the debris flows and/or rock-falls (olistolites) which are found either in surface and sub-surface.

Considering that primary shallow-water and resedimented evaporites are preserved in the epiligurian basins on top of the Ligurian units, the Cassio-Grotta and Sporno tectonic units should have been partly emerged during the Messinian evaporative event. Thus, the sliding mass was connecting shallow-water to deep-water environments, and was translating on the subaqueous and tectonically-controlled slope formed by the Salsomaggiore anticline. The basal detachment of the sliding masses has a flat-and-ramp geometry (Figs. 4 and 8), similar to submarine slides described in Lucente and Pini (2003). The ramps are cutting off the underlying foredeep units, as it can be observed close to the crest of the Salsomaggiore anticline; therefore, the down-cutting ramp scraped off the resedimented gypsum, which thus was accreted to the advancing sliding bodies (Fig. 8). The sliding and accreted masses were finally accumulating against the outer flank of the deeper Tabiano-Cortemaggiore wedge-top basin, the inner flank of the Cortemaggiore thrust front,

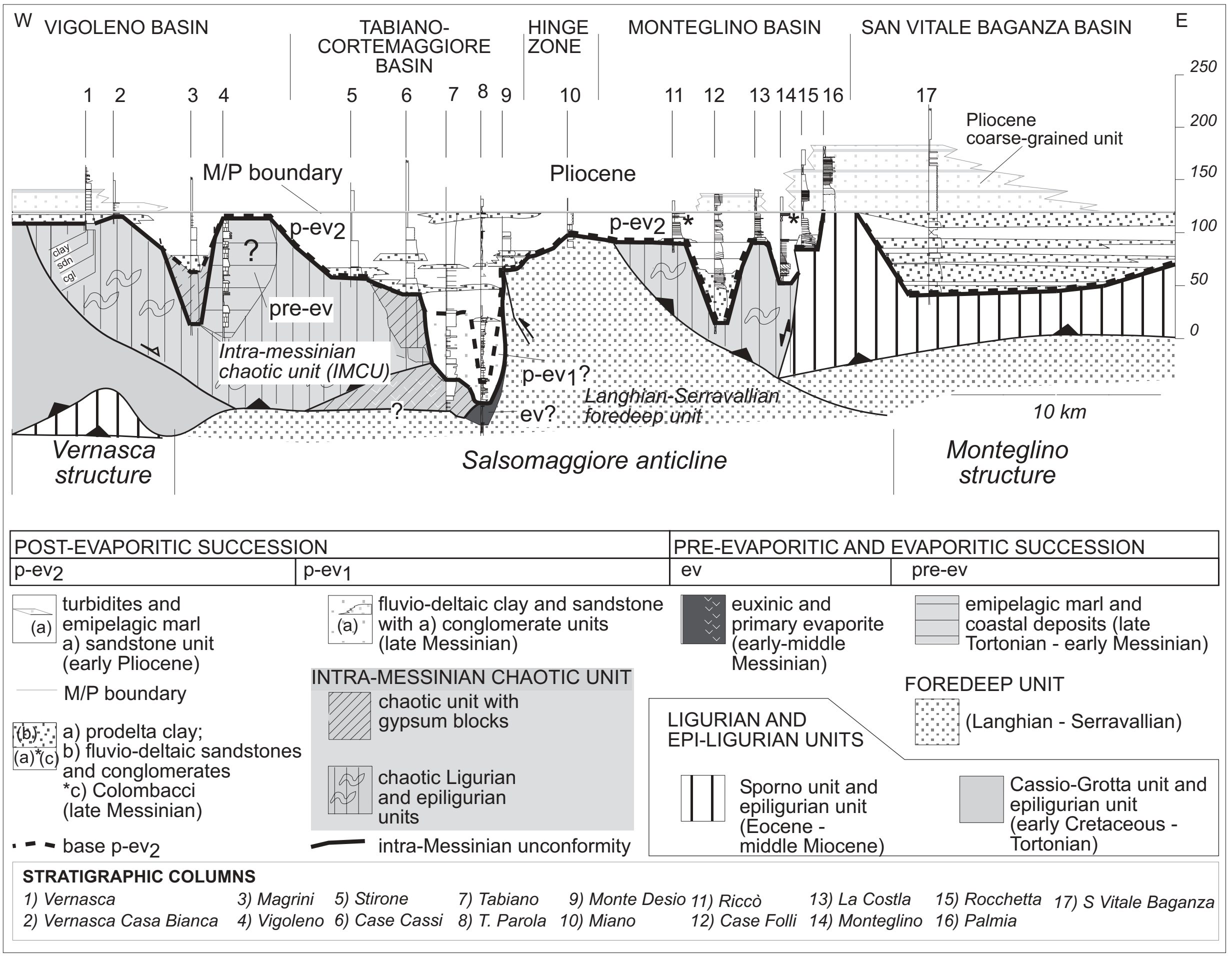

Fig. 9 - stratigraphic cross section of the Messinian deposits bordering the Salsomaggiore structure. The locations of the single stratigraphic column are in Fig. 2. The stratigraphic panel is derived from outcropping data (Medioli and Zanzucchi, 1963; Iaccarino and Papani, 1979; Artoni, 2003a; Gennari, 2003). The datum plane for the correlation is the Miocene-Pliocene boundary, considered as a flat surface at time of deposition.

where the embricate fan was formed (Fig. 8). Because of that, the IMCU should be considered a multiple and composite slide. At present, the slided masses form a body ten kilometers wide and about 200 meters thick in the accumulative zone (Figs. 4 and 8); it borders all around the Salsomaggiore anticline giving an estimated total volume of 70 km^3 (Figs. 3 and 4).

Timing of emplacement of the Intra-Messinian Chaotic Unit

In order to constrain the timing of emplacement of the IMCU, a new stratigraphic panel (Fig. 9) has been built by integrating published measured sections (Medioli and Zanzucchi, 1963; Iaccarino and Papani, 1979), revised stratigraphic sections (Artoni, 2003a, b; Gennari, 2003) and a revised stratigraphy of subsurface data, based on exploration wells (Fig. 7) and seismic lines (Ghielmi et al., 1998; Rossi et al., 2002). The stratigraphic cross-sections show the Messinian events that are comparable to those of the Apennine foreland (Fig. 5).

In the Tabiano-Cortemaggiore wedge-top basin, above the Tortonian emipelagic marls and turbidites, euxinic shales associated to marly and gypsum levels lay beneath the IMCU (Figs. 4, 7 and 9). These euxinic shales are attributed to the *ev* unit (Ghielmi et al., 1998; Roveri et al., 2001) and are correlated to the probable euxinic deposits cropping out on the northern limb of the Salsomaggiore anticline (Artoni, 2003a). These data suggest that euxinic deposits, coeval to the Messinian evaporative event, are distributed over an area extending from the Tabiano-Cortemaggiore basin to the northern limb of the Salsomaggiore anticline. At the same time, shallow-water primary evaporites were deposited in the epiligurian basins. The depositional area of the euxinic unit and the primary gypsum, respectively overlying the foredeep deposits and the allochthonous units, indicate that the evaporitic unit unconformably overlie the Messinian mountain front.

After this euxinic/evaporitic event, the IMCU was emplaced and then sealed by the siliciclastic deposits of *p-ev*$_1$ unit (Figs. 2, 3 and 4). On a regional scale, the end of the evaporitic event is dated at 5.6 M.a., and the overlying *p-ev*$_1$ siliciclastic deposits contain a volcanoclastic marker bed dated at 5.5 M.a (Odin et al., 1997). The volcanoclastic bed does not outcrop in the study area, but *p-ev*$_1$ unit in the subsurface is defined by the appearance of fluvio-deltaic deposits and the inception of Lago-mare succession. These dates imply that the Salsomaggiore structure was completely modified in less than 100,000 years by the emplacement of the IMCU. However, the emplacement of slided mass can be considered "instantaneous" in terms of geologic time.

Factors controlling the emplacement of the Intra-Messinian Chaotic Unit

The driving mechanisms, tectonic *versus* gravitational, for the emplacement of the allochthonous units of the Northern Apennines have long been discussed. Recent detailed studies made it possible to precise that both mechanisms coexist (Conti and Gelmini, 1994; Pini, 1999; Marroni et al., 2002; Bettelli and Vannucchi, 2003; Lucente and Pini, 2003; Artoni et al., 2004). In the case of the IMCU, preserving characters of slided masses, the effects of gravitational mechanisms certainly predominate.

In order to unravel the factors triggering the emplacement of the slided masses, it is reasonable to start from the factors controlling the emplacement of recent landslides, because the IMCU likely departed from subaerial areas.

Holocene mass movements, even with catastrophic characters, are generally triggered by a) oversteepening of mountain fronts (Hermanns et al., 2001; Strecker et al., 2003), b) periods of increased run-off and humid climate (Matthews et al., 1997; Trauth et al., 2000) that supply large amounts of water to slopes or c) earthquakes (Papatheodorou and Ferentinos, 1997). At least the first two factors were certainly coexisting during the emplacement of the IMCU (Fig. 10); the third factor cannot be excluded.

The advancement of the allochthounous units and their tectonic stacking created higher relief of the Ligurian/epi-Ligurian wedge. The relief was also increased by tectonic uplift of the underlying Salsomaggiore anticline (Fig. 10b). In fact, the denudational and translational areas of the slided masses are located close to the crest zone of the Salsomaggiore anticline (Figs. 4 and 8). Almost similarly, the thrust-related folds affecting the underlying Oligocene-Miocene foredeep deposits (Fig. 1) and located SW of the Salsomaggiore anticline contributed to the uplift of the allochthonous units (Fig. 10b). Thus, the relief was steepened by the coeval advancement of the Ligurian/epi-Ligurian units and by the uplift of underlying fold-and-thrust structures. In addition, it should be considered that the rheology of the uplifted units, in particular the basal complex of the Ligurian units, were prone to slide. Because of the steepened relief and the rheological characters of the rocks, the topmost sediments were eroded. The erosion of evaporitic deposits from the epi-ligurian basin formed the gypsum debris flows and olistolites. But, the most impressive consequence of the steepened slopes is the sliding of km-sized masses derived from Ligurian/epi-Ligurian units dismembered by rotational and translational movements (Figs. 6 and 8). These mass-wasting products were preferentially originated at the external and laterally unconfined portions of the Ligurian/epi-Ligurian units.

Concerning climate as a possible controlling factor, recent studies in the Apenninic and Mediterranean area envisage climatic and hydrological change at the transition from early to late Messinian (Krijgsman et al., 1999b; Roveri et al., 2001). The sedimentary successions record a change from hyperhaline to hypohaline waters that might correspond to a change from arid and evaporative to wetter and rainy weather conditions (Figs. 10a, b). The fluvio-deltaic deposits in post-evaporitic units are the evidence of an overall intensification of floods events in a wetter climate. Increased and more concentrated run-off enhanced and triggered the gravitational slope processes that disrupted the emerged portions of the Ligurian/epi-ligurian

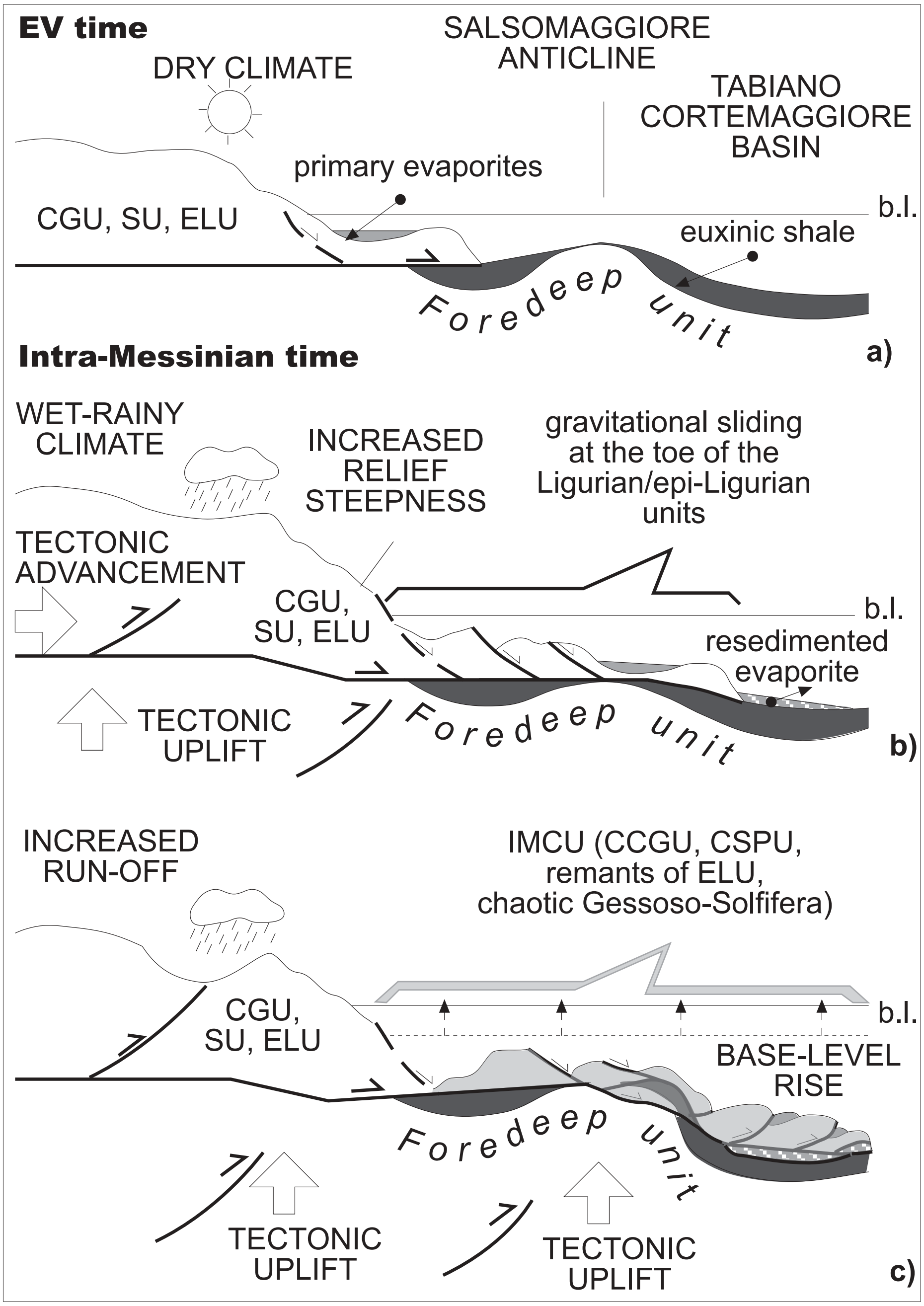

Fig. 10 - emplacement of the allochthonous units during the intra-Messinian phase in the Salsomaggiore area and formation of the Salsomaggiore structure. The mechanisms and the factors controlling the allochthonous emplacement are emphasised at different times: a) during the evaporitic event, ev unit; b) and c) during the intra-Messinian phase. See text for discussion. (CGU: Cassio-Grotta tectonic Unit; SU: Sporno tectonic Unit; ELU: epi-Ligurian unit; IMCU: intra-Messinian chaotic unit; CCGU: Chaotic Cassio-Grotta tectonic Unit; CSU: Chaotic Sporno tectonic Unit)

units. As a further consequence of the increased water supply, the base level of the Tabiano-Cortemaggiore wedge-top basin rose; thus, the IMCU, already partly submerged, was progressively drowned at increasing water depths and was shaped by subaqueous mass-wasting processes (Fig. 10c).

Another mechanism triggering gravity-driven mass movement, that should be investigated furthermore in the Salsomaggiore area, is fluid escaping and deforming throughout the sedimentary cover. These fluids coming up to the surface are associated to diapiric structures, such as mud mounds, mud volcanoes, seeps, dikes, sills and chimneys. The sources for the fluids are generally gas hydrates horizons (MacDonald et al., 2003) or overpressured detachment zones in accretionary prisms (Brown and Westbrook, 1988; Camerlenghi et al., 1995). In the Salsomaggiore area, large-scale fossil diapiric structures have not been found, so far; however, there are many evidences of cold seepage related to hydrocarbon venting, with typical mono-specific faunal assemblages and carbonates precipitates (Lucina limestone) in mounded shape (Iaccarino and Papani, 1979; Piola, 2003). Similar deposits are known from various sites along the Apennine foothills (Ricci Lucchi et al., 1982; Terzi, 1993; Conti et al., 2003) and in recent accretionary prism (Diaz-del-Rio et al., 2003). Recently, they have been associated to fluid expulsion in various structural setting (Conti and Fontana, 2002; Dela Pierre et al., 2002; Conti et al., 2003). In foredeep basins and along structural features, the gas hydrate contribution to fluid vents is considered more likely because of the favourable conditions for hydrates dissociation (Conti et al., 2004; Gubertini and Fontana, 2004). In addition, diapirism associated to hydrocarbon vents is related with significant base-level drops (Henriet and Meniert, 1998) and can form large-scale chaotic masses; base-level fall is a direct consequence of the allochthonous advancement and thrust front uplift during the intra-Messinian phase.

The salsomaggiore structure during the Intra-Messinian phase

To better understand and appreciate the significant depositional and structural changes that occurred to the Salsomaggiore structure during the intra-Messinian phase, it is necessary to depict its evolution since the evaporitic event (Fig. 11).

During the evaporitic stage, the Salsomaggiore anticline was located north of the allochthonous wedge, and formed an obstacle to the advancement of the Ligurian/epi-ligurian units (Fig. 11a) (Argnani et al., 2003; Rizzini et al., 2004). The two structural levels, framing the Northwestern Apennine (Fig. 1), were already present but not yet superposed in the Salsomaggiore area. The position reached by the Ligurian/epi-Ligurian units during this stage is related to a Tortonian tectonic phase recorded in the whole Apennine (Patacca et al., 1990), and recorded by the epi-Ligurian deposits in the study area. This morpho-structural framework is related to a paleo-bathymetric profile that becomes deeper from SW to NE, as recorded by the *ev* unit. In fact, primary gypsum deposits are preserved in patchy and discontinuous outcrops at the top of the epi-ligurian succession. Coeval euxinic deposits occur in the deeper Tabiano-Cortemaggiore basin (Fig. 7), where they are located beneath the IMCU (Ghielmi et al., 1998). It is here suggested that euxinic deposits existed also in confined basins located between the toe of the Ligurian/epi-Ligurian units and the Salsomaggiore anticline hinge (Fig. 11a). At present, these basins are not preserved because buried underneath the allochthonous units or accreted to and translated with the IMCU during its emplacement.

The tectonic processes that occurred during the intra-Messinian phase radically modified the Salsomaggiore structure. The complex structural changes can be sketched in two steps (Fig. 11b,c). The first step coincides with the tectonic advancement of the Ligurian/epi-Ligurian wedge that passed over the hinge zone of the Salsomaggiore anticline (Fig. 11b). The northward advancement of the Ligurian/epi-Ligurian units, favoured by the uplift of more internal folds and thrusts affecting the underlying foredeep units, generated instabilities at the paleo-topographic surface. Therefore, erosion was enhanced and gravitational slides were favoured. The evaporitic basins were dismembered and evaporitic deposits were resedimented (Fig. 11b) to form the gypsum-bearing unit at the base of the IMCU (Fig. 7). One of these evaporitic basins, completely destroyed, is the Campore basin in Fig. 11b. The second step is more catastrophic, and produced the largest gravitational mass movement. It resulted from the uplift of Salsomaggiore anticline, which pushed upward and forced the toe of the previously advanced Ligurian/epi-Ligurian wedge to slide toward the north. Gravitational masses were preferentially departing from the Salsomaggiore anticline hinge zone (Figs. 4 and 8) and slided above the euxinic clay and resedimented gypsum, which both behaved as preferential detachment levels. The sliding masses partly scraped off the detachment horizons and the older foredeep units (Figs. 8 and 11c).

At the beginning, the emplacement of the

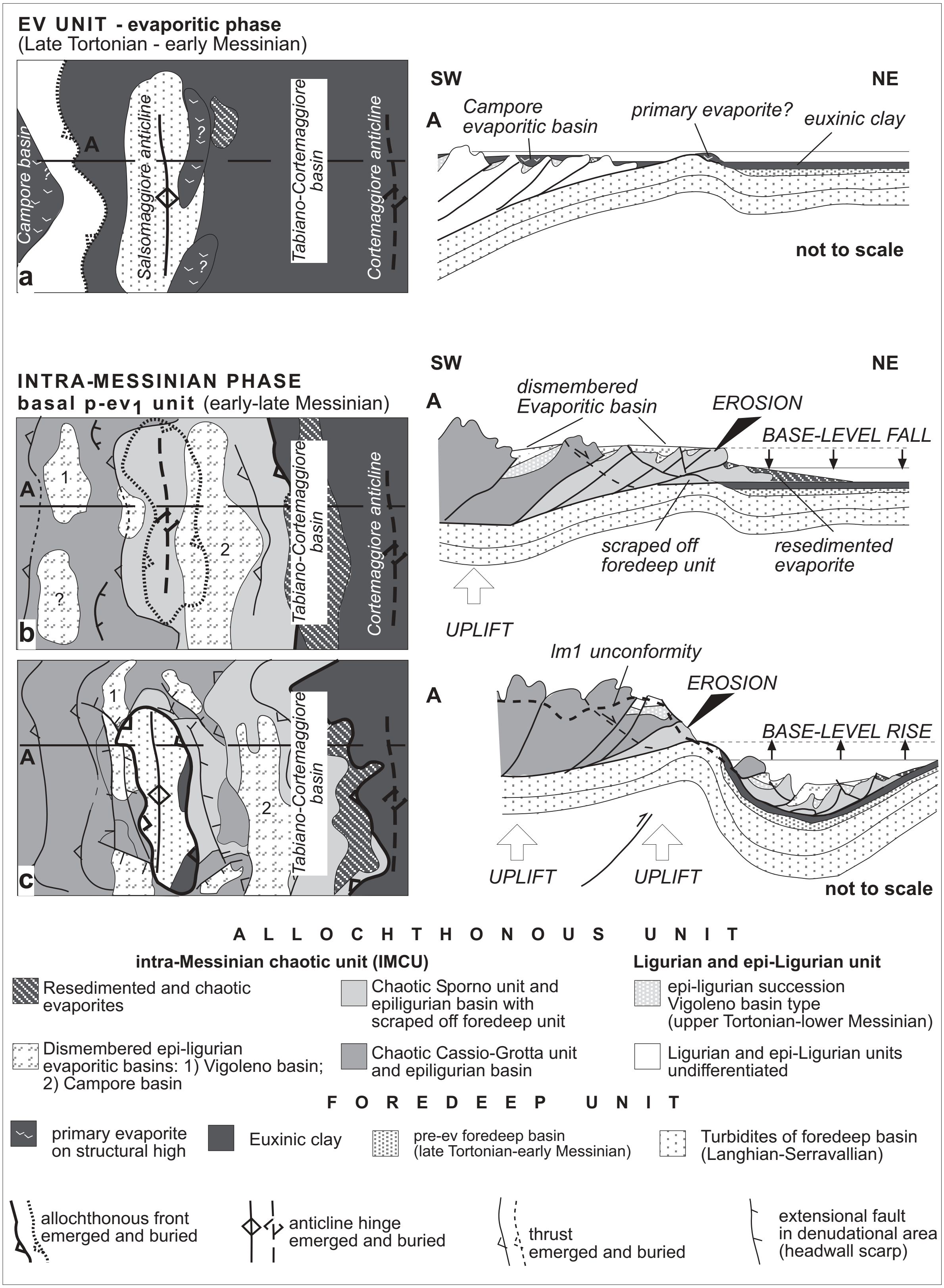

Fig. 11 - sketched palaeogeographic maps and cross-sections showing the tectono-stratigraphic evolution of the Salsomaggiore structure during the early Messinian and the intra-Messinian phase. See text for details and discussion.

IMCU was coupled with a relative falling of base-level. This enhanced erosion and brought up to the surface the foredeep units, already uplifted and close to the Salsomaggiore anticline hinge (Fig. 11c). Then, the increased run-offs and water supply caused the base-level to rise; fluvio-deltaic deposits sealed the newly created topographic surface which exposed the Ligurian/epi-Ligurian units, the IMCU and the exhumed foredeep units. The IMCU was progressively drowned in late Messinian time and completely sealed in early Pliocene time.

Discussion and open questions

The above reconstruction of the Salsomaggiore structure in early Messinian and during the intra-Messinian phase is partially hampered by ambiguous data, hard to constrain. These data and their implications for the reconstruction are hereafter briefly discussed.

The occurrence of an euxinic or evaporitic level, belonging to the *ev* unit, on top and behind the Salsomaggiore anticline hinge, either in surface or subsurface, is not yet demonstrated. Thus, during the Messinian evaporative event, the Salsomaggiore anticline hinge could have been: i) an intra-basinal high with no deposition, possibly undergoing erosion; ii) a buried anticline capped on top by the allochthonous units emplaced during the Tortonian, as suggested by Ruggieri (1956) and discussed in Piola (2003). In the first hypothesis, during the intra-Messinian phase, the Ligurian/epi-Ligurian units moved along a surface that, above the anticline culminations, might have been subaerial or at very shallow-water depth (Fig. 11a). This hypothesis implies a Messinian unconformity older than the intra-Messinian unconformity, which might coincide with the base of ev or EM units (Gelati et al., 1987; Roveri et al., 2001); future studies should find it on a wider regional scale. This first hypothesis implies also that the Ligurian/epi-Ligurian units had translated a relatively longer distance to reach the Tabiano-Cortemaggiore basin. In fact, in the second hypothesis the Ligurian/epi-Ligurian units were closer to the Tabiano-Cortemaggiore basin, because they had already reached the southern flank of this basin during Tortonian.

The first hypothesis has been preferred here because of the probable euxinic level, coeval to the evaporative event, found on the northern limb of Salsomaggiore anticline along the Parola River (Fig. 2) (Artoni, 2003a).

Whichever solution will be demonstrated true, the timing of emplacement of the IMCU in the Tabiano-Cortemaggiore basin should not change; in fact, the IMCU reached this basin during the intra-Messinian phase only (Fig. 11c). What could change is the position of the leading edge of the allochthonous units during the *ev* event.

Another question is the detailed areal distribution of the IMCU in the outcropping area. Studies that address this question could be carried out in a very small area at the northern termination of the Salsomaggiore anticline (Calderoni, 2001). Similar tectono-stratigraphic studies extended on a wider area will allow to better place a precise boundary between the Ligurian/epi-Ligurian units and the IMCU. This boundary is particularly debated where it crosses units that have acquired a chaotic organization in pre-Messinian tectonic phases, e.g. the basal complex in the Ligurian units or submarine landslides of epi-Ligurian basins.

Chaotic masses similar to the IMCU, here described, occur all along the Northwestern Apennine foothills, as already known (Gelati et al., 1987) and recently mapped (Rizzini, 2000; Barbacini, 2001; Argnani et al., 2003; Rizzini et al., 2004). However, they are not described in sufficient detail to unravel their emplacement modality. In the present study, it is suggested that they derive from gravitational processes triggered by the combined action of tectonics and climatic factors. Future studies might better clarify the role of diapiric processes related to fluid escapes, as it has been recently evidenced in coeval deposits of Piemonte region (Dela Pierre et al., 2002) and along the Northwestern Apennine foothills (Conti and Fontana, 2002; Conti et al., 2003; 2004).

Conclusions

The Salsomaggiore structure preserves the depositional and structural record of the intra-Messinian tectonic phase in the Emilia sector of the Northwestern Apennines. During this phase a new and more external mountain front was created. The new Messinian mountain front was formed by the advancement of the allochthonous units that, prosecuting their translation toward north, overrode on top of the Salsomaggiore anticline.

The allochthonous units are subdivided in: i)

Ligurian/epi-Ligurian units, which show an ordered stack of tectonic slices and/or stratigraphic successions, and ii) intra-Messinian chaotic unit (IMCU), which contains fragments of Ligurian/epi-Ligurian units with a complex internal organization very similar to subaerial landslides and any mass sliding on a slope.

The mobilisation of slided masses to form the IMCU was triggered by tectonics and climate. In fact, the intra-Messinian tectonic phase produced widespread tectonic deformation and uplift. The deepest and more internal structural levels of the Northern Apenninic chain were shortened and uplifted, while the frontal structures of this chain propagated north of the Salsomaggiore anticline. The generalized shortening and uplift increased the relief steepness and induced the advancement of the Ligurian/epi-Ligurian units which, at their external toe, were dismembered by mass-wasting phenomena.

The intra-Messinian tectonic phase is also associated to important palaeo-hydrological and palaeo-climatic changes, recognized at the Mediterranean scale. After a period characterized by intense evaporation, preceding the intra-Messinian phase, wetter and more rainy climate conditions characterised the post-evaporitic or Lagomare succession. The climate changes are testified by the diffusion of fluvio-deltaic deposits related to repeated flood events. The increased run-offs and the associated base-level rise supplied a great amount of water that enhanced mass-wasting processes on both subaerial and subaqueous reliefs.

Another mechanism, triggering gravity-driven mass movements, is the fluid expulsions that, in recent accretionary prisms, is related to overpressures of fluids trapped in the sediments. Specifically, in the Salsomaggiore structure there are evidences, not yet studied in as much details as in other part of the Northwestern Appennine foothills, of the occurrence of fluids derived from dissociation of gas hydrates.

Intra-Messinian slided/"chaotic" masses occur all along the Northwestern Apennine foothills. They suggest that the Messinian mountain front of Northwestern Apennines was dominated by mass-wasting processes. Integrated studies of these chaotic masses might precise their variability within different structural settings and might better constrain their emplacement mechanisms.

Because the intra-Messinian phase is characterised by a tectonic paroxysm and climate changes in the whole Mediterranean area, it is worth to investigate the occurrence of similar and coeval mass-wasting products in other palaeogeographic settings.

Acknowledgements

This paper is the result of multidisciplinary studies of the Messinian stage in the Salsomaggiore Terme area (COFIN 2000 – Coordinator F. Ricci Lucchi; COFIN 2003 – Coordinator M. Roveri; Terme di Tabiano-Università degli Studi di Parma – Coordinator G. Papani). The above studies and research were also supported by E.N.I.-Agip S.p.a.. ENI-Agip S.p.a. and Terme di Tabiano are kindly thanked for the support and the permission to publish their subsurface data. S. Iaccarino is thanked for the micropalaeontolgical analyses. G.A. Pini is thanked for fruitful discussions. The reviews of S. Milli and A. Amorosi were greatly appreciated.

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