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Peri-Adriatic mélanges, and their evolution in the Tethyan realm

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Abstract

In the peri-Adriatic region, mélanges represent a significant component of the Apennine and Dinaride-Albanide-Hellenide orogenic belts as well as ancient and present day accretionary wedges. Different mélange types in this broad region provide an excellent case study to investigate the mode and nature of main processes (tectonic, sedimentary and diapiric) involved in mélange formation in contrasting geodynamic settings. We present a preliminary subdivision and classification of the peri-Adriatic mélanges based on several years of field studies on chaotic rock bodies, including detailed structural and stratigraphic analyses. Six main categories of mélanges are distinguished on the basis of the processes and geodynamic settings of their formation. These mélange types are spatially and temporally associated with: 1) extensional tectonics, 2) passive margin evolution, 3) strike-slip tectonics, cases, there appears to have been a strong interplay and some overlap between tectonic, sedimentary, and diapiric processes during mélange formation; however, in highly deformed regions it is still possible to distinguish those mélanges that formed in different geodynamic environments and their main processes of formation. This study shows that a strong relationship exists between mélange-forming processes and the paleogeographic settings and conditions of mélange formation. Given the differences in age, geographic location and evolutionary patterns, we document the relative importance of mélanges and broken formations in the tectonic evolution of the peri-Adriatic mountain belts.

Key words: Mélange, olistostromes, broken formation, tectonosomes, mud diapirs, subduction processes, subduction channels, obduction, allochtonous nappes, Apennines, Dinarides-Albanides-Hellenides.

Introduction

In the peri-Adriatic region (Fig. 1), mélanges are common as part of the Apennines and Dinaride-Albanide-Hellenide orogenic belts and accretionary wedges. Their formation and incorporation into these orogenic systems played a significant role in the Mesozoic-Cenozoic tectonic evolution of the central Mediterranean region.

The term “mélange” was first coined by Greenly (1919) to describe a unit of highly disrupted rocks in North Wales (Anglesy Island). After its reintroduction by Hsü (1968), the term mélange has been applied worldwide to indicate chaotic, block-in-matrix rocks. In particular, the term has been used to indicate rock units associated with the subduction of oceanic crust in the circum-Pacific areas, such as the west coast of US, New Zealand, and Japan. Since its application to the circum-Mediterranean region, the term has been applied to different kinds of chaotic rock types containing a wide range of characteristics (see Camerlenghi and Pini, 2009 and references therein), that result from protracted cycles of rifting, drifting, oceanic subduction, continental collision and intracontinental deformation, different from the almost exclusively subduction-related Pacific mélanges. Moreover, the term mélange frequently flanks or substitutes for more traditional terms, such as wildflysch, schistes à blocs, agglomerates, argille scagliose, and olistostromes (see Camerlenghi and Pini, 2009 and references therein). The large majority of these indicate chaotic, mostly block-in-matrix rocks, related to a sedimentary origin, a complex sedimentary-tectonic origin, and/or to mud diapirism (Hsü, 1968, 1973; Abbate et al., 1970; Elter and Trevisan, 1973; Naylor, 1981; Castellarin et al., 1998; Pini, 1999; Festa et al., 2005; Trümpy, 2006; Dela Pierre et al., 2007; Camerlenghi and Pini, 2009).

Therefore, in the circum-Mediterranean mountain chains, the term mélanges has been frequently applied to rock units of sedimentary origins (see below), whereas in the Pacific realm the term has been always considered as related to a tectonic origin (i.e., Meschede et al.,1999; Chang et al., 2000; Wakabayashi, 2004; Ikesawa et al., 2005) with notable exceptions (Williams et al., 1984; Cowan, 1985; Barber et al., 1986; Brandon, 1989; Horton and Rast, 1989; Brown, 1990; Cousineau, 1998; Yamamoto et al., 2000). Notably, some of these, non-Mediterranean exceptions used Mediterranean mélanges as paradigmatic examples (see, e.g, Hsü, 1965; 1974; Cowan, 1985).

In this paper, we describe the mélange occurrence in the Apennine and Dinaride-Albanide-Hellenide mountain belts, both of which are part of the broad Alpine orogenic system. Given the differences in age, geographic location, and evolutionary patterns, we propose a new categorization of these mélanges, taking into account their geodynamic environments and processes of formation. We also document their relative importance in the evolution of these mountain belts and in the Tethyan system.

Contribution of Apenninic geology to the mélange concept

Bianconi (1840) described the mesoscopic scaly texture of block-in-matrix rocks of the Ligurian nappe in the northern Apennines as “argille scagliose” (scaly clays). This term was then progressively extended to all the tectonic, tectono-stratigrahic and sedimentary chaotic rock bodies of the Apennines, also named mélanges (*s.l.)* after Greenly (1919), that are characterized by a block-in-matrix arrangement at the outcrop scale (Signorini, 1946; Azzaroli, 1948; Merla, 1952; Ogniben, 1953; Maxwell, 1959; Elter, 1960). Different chaotic units, including both Jurassic (Ligurian units) ophiolites and Mesozoic-Cenozoic sedimentary successions originally deposited on oceanic and/or continental crust of the Adria microplate (Subligurian, Sicilide, Tuscan, Marche-Umbria, Molise-Sannio, Lagonegro units), were recognized and described in different stratigraphic and structural context of the Apenninic thrust-and-fold belt.

The argille scagliose were considered to be the products of sedimentary processes deformed in response to tectonic events (orogenic landslides; Merla, 1952; Signorini, 1956). Another descriptive term, “argille brecciate” (brecciated clays), was proposed by Ogniben (1953) and Rigo de Righi (1956) to describe the block-in-matrix fabric at the millimeter-to centimeter scale of chaotic sediments in southern Apennines and Sicily. In contrast to argille scagliose, argille brecciate has been interpreted as the product of mass-wasting processes (debris flows and debris avalanches, see Camerlenghi and Pini; 2009 for major details).

Argille scagliose, argille brecciate and chaotic rock bodies with block-in-matrix fabric, recognized as sedimentary bodies within layered coherent sedimentary marine successions, were defined in Sicily as “olistostromes” by Flores (1955; 1956). This term, from the Greek “□□□□□□□□□□” (to slide) and “□□□□□□” (bed), was used to indicate different products of mass-gravitational transport (i.e., Beneo, 1956; Rigo de Righi, 1956; Abbate et al., 1970; 1981; Elter and Trevisan, 1973; Ricci Lucchi, 1975) including block slides (olistoliths), avalanches, debris flows and iper-concentrated flows (Camerlenghi and Pini, 2009). These differ from the argille scagliose on the basis of their brecciated matrix consisting of rounded to angular polymictic millimeter-to centimeter-scale clasts of claystone, random distributed throughout the clayey matrix. The scaly fabric is often present and may overprint but not completely obliterate the brecciated texture (Bettelli and Panini, 1985).

The chaotic appearance of the argille scagliose, argille brecciate and olistostromes in outcrops led to the proliferation of different terms such as Ligurian mélange, chaotic complex, undifferentiated complex, complesso caotico eterogeneo (heterogeneous chaotic complex) or caotico eterogeneo (heterogeneous chaotic) to describe the same chaotic successions in different sectors of the Apennines chain (see, e.g., Abbate and Sagri, 1970).
Some of these terms have been used synonymously with the term olistostrome in regional-scale maps (e.g. Boni et al., 1970, Bellinzona et al., 1971; Boccaletti and Coli, 1982). As a consequence, a conceptual linkage between olistostromes, argille scagliose and other terms that describe rocks with a block-in-matrix fabric has always been improperly maintained or never been excluded (see discussion in Camerlenghi and Pini, 2009 for major details). While the application of these terms in the Apennines was changing, many of these concepts were exported and favorably applied to disrupted rock bodies of different ages exposed in different geodynamic contexts and stratigraphic-structural positions elsewhere (see for example, Hsü, 1965; Raymond, 1984; Cowan, 1985; Orange and Underwood, 1995).

Starting in the 1980s, chaotic rock bodies and disrupted rocks of the Apennines have been distinguished (Bettelli and Panini, 1985, 1987; Castellarin et al., 1986; Castellarin and Pini, 1987; Pini, 1987; Camerlenghi and Pini, 2009 and references therein) into: a) strongly deformed units (tectonosomes or broken formations) displaying a prevailing block-in-matrix fabric, in which part of the same coherent stratigraphic unit can be recognized and mapped; b) sedimentary block-in-matrix rocks (or olistostromes or sedimentary mélanges) related to different mass-wasting sedimentary processes (debris flows and avalanches, sliding-gliding of blocks), with the possible contribution of mud volcanoes and diapirs. These sedimentary bodies have a classic block-in-brecciated-matrix fabric, with the matrix made up of clays supporting millimeter-scale clasts (brecciated matrix, see Swarbick and Naylor, 1980; Abbate et al., 1981 and references in Camerlenghi and Pini, 2009).

Regional setting of the peri-Adriatic region

During late Mesozoic-Cenozoic, the Mediterranean region (Fig. 1) experienced complex subduction and associated collisional events, resulting in the development of different fold-and-thrust belts (Dilek, 2006). The Apennine and Dinaride-Albanide-Hellenide mountain belts are the product of this subduction-collision history and presently are separated by the Apulia-Adriatic foreland.

The Apennines consist of an east-to northeast vergent fold-and-thrust belt developed after the Late Cretaceous – Early Cenozoic closure of the Ligurian ocean (Alpine Tethys) (Fig. 2a) and the convergence between the continental margin of the European plate (Corsica-Sardinia), to the west, and of the Adria microplate (of African affinity), to the east (i.e., Boccaletti et al., 1980; Dewey et al., 1989; Castellarin, 1994;).

During pre-collisional eo- and meso-alpine episodes of convergence (Vai and Castellarin, 1993; Pini, 1999; Vescovi et al., 1999) the Ligurian units, which represent the most internal palegeographic domain (Fig. 2) adjacent to the European passive margin, were deformed and incorporated in the Late Cretaceous - middle Eocene accretionary wedge related to oceanic ("B" type) subduction (i.e., Marroni et al., 2001; Bortolotti et al., 2005). These units are the remnants of the Ligurian ocean (Alpine Tethys) and consist of Mesozoic to lower Tertiary sedimentary successions and subordinate Jurassic ophiolitic rocks (portion of oceanic crust). They represent the more far-travelled units of the Apennine belt and currently occupy the highest structural position in the chain.

In the Northern Apennines, the Ligurian units are the innermost and uppermost units of the Ligurian nappe (Elter, 1975; Bortolotti et al., 2001; Cerrina Feroni et al., 2002) that is represented in a more external and lower position by the Subligurian units. These units originated from the thinned continental margin of the Adria microplate (Figs. 2b, 3 and 4).

In the southern Apennines (Figs. 2 and 6), the Ligurian units (Ligurian complex *sensu* Ogniben, 1969) are classically subdivided into three main units of Upper Jurassic to lower Miocene age (see Bonardi et al., 1988; Patacca and Scandone, 2007 for major details). The two lower units respectively consist of slightly metamorphic rocks (Frido unit) followed by a metapelitic mélange (Episcopia-San Severino mélange *sensu* Patacca and Scandone, 2007) with serpentinite, granulite, amphibolite, granitoid and marble blocks (e.g., Spadea, 1982; Patacca and Scandone, 2007). The uppermost unit is non-metamorphic and consists of pillow basalts overlain by upper Jurassic radiolarites, shales, and quartz arenites (Timpa delle Murge Formation), black shales (Crete nere Formation) and alternating calcareous-siliciclastic turbidites (Saraceno Formation).

The Sicilide units, which also occupy the highest position in the southern Apennine thrust sheet, were originally deposited in a more external Tethyan basin (Figs. 2b) resting on basement of unknown character (thinned continental and/or oceanic crust; i.e. Patacca and Scandone, 2007).

During neo-Alpine deformation (late Oligocene – early Pleistocene) thrust accretion across the Apulia-Adriatic continental margin is shown by the east-northeastward migration of the Ligurian and Subligurian units. In the Northern Apennines, these units, which form a detached thrust sheet, tectonically overlie the Miocene sedimentary succession of Tuscan and Romagna-Marche-Umbria units (Figs. 3 and 4). In the southern Apennines (Figs. 6 and 7), Ligurian and Sicilide units tectonically overlie a complex imbricate orogenic stack consisting of carbonate platform (Lazio-Abruzzi and Campania-Lucania units) and pelagic basins of the Adriatic margin (Molise, Sannio and Lagonegro units).

In both the northern and southern Apennines, the timing of eastward migration and shortening is strongly constrained by the discordant deposition of eastward-younging top-thrust basins (middle-late Eocene – Pliocene, Figs. 1, 5 and 6), known as Epiligurian basins in the northern Apennines (Fig. 5), onto the inner Ligurian, Subligurian and Sicilide units and the outer accretionary wedge of the thrust belt (Ghisetti et al., 2003). Deposition of top-thrust basins and Epiligurian units occurred simultaneously with the east and northeast migration of the thrust-and-fold belt that, as a consequence, strongly controlled the shape and sedimentation of these basins (Ori and Friend, 1984).

Miocene – early Pliocene thrust accretion across the Apulia – Adriatic continental margin was accompanied by Tyrrhenian back-arc extension (i.e., Mazzoli and Helman, 1994).

The northwest-trending Dinaride – Albanide - Hellenide orogenic belt lies to the east of the Apulia-Adriatic foreland (Figs. 1 and 2). It is characterized by a double-vergent structural architecture bounded by west-vergent thrust faults in the external zone (to the west) and east-verging faults in the internal zone (to the east, Fig. 8a) (Dilek, 2006 and reference therein).

The west-directed thrust faults are the result of the Tertiary tectonic collision (Fig. 2b) between the Adria microplate (Apulia-Adriatic foreland) and Eurasia (Pelagonian platform), whereas the east-directed thrust faults are associated with Latest Jurassic-Early Cretaceous ophiolite eplacement (Dilek et al., 2005; Dilek, 2006).

Ophiolites are distributed along a northwest-trending belt (Figs. 1 and 8a) from the Kosovo region in the north, through Albania and Greece, to western Turkey, where they join the Tauride belt (Ghikas, 2007; Dilek et al., 2008; Ghikas et al., this issue). The northwest trending belt formed through the closure of several Tethyan basins during northeastward migration of Gondwana and the opening of the Atlantic Ocean (Dilek et al., 2005; Smith and Rassios, 2003). During the Middle Triassic – Jurassic, the Pindos basin, located at the northern margin of the Neotethys Ocean and bounded by Pelagonia to the east and Apulia to the west, rifted (Dilek et al., 2007; Sharp and Robertson, 2006). Extensive carbonate shelves developed on both of these microcontinents during subsidence along the margins of the basin (Dilek et al. 2005). In the Middle Jurassic (Fig. 2a), the Pindos basin began to close, with the formation of a west-dipping intra-oceanic (Casey and Dewey, 1984) subduction zone. Westward subduction continued until the arrival and partial subduction of Pelagonia (Smith and Rassios, 2003) during the Early Cretaceous (Sharp and Robertson, 2006). This continued until the Tertiary oblique collision of Apulia with Pelagonia, completing the emplacement of the western Dinaride-Albanide-Hellenide ophiolite (Dilek et al. 2007; Ghikas et al., this issue). The collision-induced deformation propagated westward as an oblique convergence between Adria and Eurasia that produced a thin-skinned fold-and-thrust belt, consisting of Eocene-Quaternary sedimentary successions (Fig. 2b). Thus, along the external thrust front of the Dinaride-Albanide-Hellenide mountain belt strain partitioning occurred in and across a broad dextral shear zone in the Balkan Peninsula. This promoted the local collapse of the orogenic belt in well-developed transtensional zones (Dilek and Koçiu, 2004; Dumurdzanov et al., 2005; Dilek, 2006).

Postcollisional magmatism is widespread in the Dinarides and the Hellenides with the occurrence in the northern Greece (Voras mountains) and Macedonia of low-K calc-alcaline volcanic rocks (ca. 5.0-4.0 Ma) and shoshonitic volcanism (ca. 2.5-1.5 Ma) (Pe-Piper and Piper, 2002).

Geodynamic environment and processes of formation of the peri-Adriatic mélanges

The peri-Adriatic region, provides several excellent examples and a complete case history that allow us to consider how mélanges related to different geodynamical situations during the complex geologic history of the eastern Mediterranean, as well as how different processes (tectonic, sedimentary and diapiric) were involved in their formation. Thus, we propose a preliminary subdivision and classification of the peri-Adriatic mélanges. Although many examples are preserved elsewhere in this complex region, the proposed classification scheme only applies to select examples from different sectors of the Apennine and Dinaride-Albanide-Hellenide mountain belts.

1) Extensional tectonics-related mélanges

This group refers exclusively to mélanges that formed from sedimentary, en-mass processes (mass-wasting). Bodies from debris avalanches and flows, single-slide blocks and groups of slide blocks are commonly referred to as megabrecce, olistoliths, and olistolith fields or swarms, respectively (Castellarin, 1972, 1982; Bernoulli, 2001; Camerlenghi and Pini, 2009 and references therein). The most notably examples are the Norian-Jurassic and, in part, Cretaceous megabreccias of the Southern Alps (Castellarin, 1972; Bosellini et al., 1977) and Northern Apennines (see, among many others, Castellarin et al.; 1978, Cecca et al., 1981; Castellarin, 1982; Fazzuoli et al., 1985; Bernoulli, 2001; Galluzzo and Santantonio, 2002) and the Upper Cretaceous megabreccias of the Apulia foreland in Central-Southern Apennines (Maiella, Gargano and Adriatic off-shore; see Bernoulli, 2001 and reference therein; Fig. 6). Other examples include the megabreccias and olistoliths of the Cretaceous Calcirudite a Rudiste Fm. in the Gran Sasso area (i.e., Ghisetti and Vezzani, 1986; Ghisetti and Vezzani, 1998; Bernoulli, 2001; Fig. 6). In each case, the mélanges are deposited in pelagic limestones. They have an intrabasinal composition, and their main sources are the already cemented carbonate platform rocks (frequently slightly older than the age of deposition of bodies), with some contribution of contemporaneous, slumped pelagic limestones.

In the Western Hellenides, the Upper Triassic-Lower Jurassic Agios Nicolas Formation. (see Naylor and Harle, 1976) consists of pebbly mudstones and boulders deposited by debris flows and sliding into the shale basins, triggered by extensional faulting during rifting. The mudstone matrix contains pebbles, cobbles, and boulders of sandstone (arenite and wacke) derived from the Pelagonian hinterland (Ghikas et al, this issue). A comparable example is the proto-Advella mélange, emplaced by gravitational-movement on the eastern margin of the pre-Apulian foreland (see Ghikas et al., this issue).

Sedimentary bodies associated with extension are thought to be related to either 1) normal faults dissecting and controlling the margins of carbonate platforms (Castellarin, 1972, 1982; Eberli, 1987; Accordi and Carbone, 1988; Eberli et al., 1993; Vecsei, 1991, 1998; Bosellini et al., 1993; De Alteris and Aiello; 1993; Graziano, 2000; Rusciadelli, 2005) during and after rifting (Naylor and Harle, 1976; Fazzuoli et al., 1985; Marchegiani et al., 1999; Bernoulli, 2001), or 2) the geometry of the carbonate platform margin (scalloped margins, see Bosellini, 1998).

2) Passive margin (?)-related mélanges

Passive margins instability may trigger the progressive deformation of basin slopes, such as in the case of the carbonate and siliciclastic fine-grained turbidites and mudstones of the Early Cretaceous Palombini Shales (locally defined Ronchi argillites), which constitutes the lowest horizon of the stratigraphic succession of the Modino mass-wasting complex (Modino "basal" complex, De Libero, 1998; Pini et al., 2004; Fig. 4). The Ronchi argillites were deformed at various degrees, from in-situ folding and boudinage to slump-slide structures, evolving down flow to cohesive debris flows. The latter led to complete stratal disruption and development of a block-in matrix fabric. Sediments were deformed when poorly or non-consolidated and show plastic deformation of clasts with enhanced fluidal structures of the matrix (Pini et al., 2004; Camerlenghi and Pini, 2009).

Similar examples are described in the Othris Mountains (in Greece) by Smith et al. (1979). Here, late Jurassic- early Cretaceous radiolarian siltstones were deformed by debris flows and slumping related to instabilities of the passive margin (Smith et al., 1979). The ophiolitic mélange of Albania (Shallo, 1990) also formed during the late Jurassic-early Cretaceous continental margin evolution, due to development of slides triggered by tectonic and sedimentary events.

All of these bodies are mainly monomictic, recycling the sediments of the same formation. The major problem whit this interpretation concerns the triggering mechanism. These deformed bodies are found in the Early Cretaceous, after rifting concluded, and in a passive margin setting at the edge of the thinned Adria continental margin or at the transition to the oceanic realm (see, e.g., De Libero, 1998; Pini et al., 2004). Many processes could have triggered the slides in these situations, as well as the Late Cretaceous to early Tertiary "extensional" olistostromes in the Adria-based units (Tuscan, Umbrian domains). Some possibilities include: 1) tectonic reactivation of extensional Jurassic structures, 2) the influence of pre-existing submarine topography, 3) deep ocean processes, and/or 4) extension throughout the Cretaceous and early Tertiary (Fazzuoli et al., 1985; Montanari et al., 1989; Marchegiani et al., 1999; Bernoulli, 2001). An alternative explanation considers the onset of Early Cretaceous compression related to subduction at the northern edge of the Ligurian ocean, as suggested by some paleogeographic reconstructions (Schettino and Scotese, 2002).

3) **Strike-slip tectonics-related mélanges**

The more classic example in the international literature of the Mediterranean area are the Moni and Arakapas mélange in Cyprus (Robertson, 1977; Krylov et al., 2005). They are mud-rich, block-in-matrix bodies, which are considered to be of both tectonic and sedimentary origin. The Arakapas mélange, (Krylov et al., 2005) is an olistostrome developed along fault scarps during Cenomanian-Campanian strike-slip activity in a fore-arc basin transform zone (Troodos zone). The younger, Tertiary, stage of the Moni mélange (Neo-Moni, Krylov et al., 2005) is a tectonic mélange related to the activity of a transpressional wrench fault, reactivating olistostromes associated with subduction (Robertson, 1977).

In the Northern Apennines, the lower portion of the Eastern Ligurian sedimentary succession, the so-called basal complexes of the Helminthoid flysch (see Abbate et al., 1970; Bortolotti et al., 2001; Marroni et al., 2001; Cerrina Feroni et al., 2002) (Fig. 2b) are characterized by Late Cretaceous cohesive debris flows with a "brecciated" argillaceous matrix (classic olistostromes) mostly sourced in Early Cretaceous Ligurian sediments (Palombini shales). These, in turn, host large-scale (from hundred of meters to several kilometres in length) ophiolitic blocks and continental margin fragments (Marroni et al., 1998). Marroni et al. (2001) interpret these bodies as products of submarine landslides or a portion of the sea floor that was uplifted by synsedimentary transpressive faults, acting in the retroarc basin of the paleo-Apenninic accretionary wedge. Detritial evidence from the oceanic crust has been used as a paleogeographic key in discriminating between "western" and "eastern" External Ligurian units (Marroni et al., 2001).

The lower part of the Messinian mélange, of the northern Tertiary Piedmont Basin (Torino Hill and Monferrato, Figs. 1 and 9), represents another example of strike-slip tectonic mélanges (Festa et al., 2005; Dela Pierre et al., 2007; Festa, 2009). Regional scale wrench-faulting (e.g. Rio Freddo deformation zone *sensu* Piana and Polino, 1995, Fig. 1) dismembered of the previously coherent evaporitic succession and produced a tectonic disrupted unit.

Other comparable examples are exposed along the Villalvernia- Varzi line (Fig. 1), a regional and polyphase deformational zone that juxtaposed the Tertiary Piedmont Basin and the northern Apennines during late Oligocene to late Miocene. Here, strike-slip movements mixed three different chaotic rock bodies (Festa, unpublished data) originally deposited at the base of the Epi-Ligurian units (Calcari di Zebedassi *Auct.*, Upper Cretaceous in age, see Boni et al., 1970) and as olistostromes within the Epi-Ligurian units (lower and upper Miocene olistostromes, Complesso caotico and Complesso caotico indifferenziato *sensu* Boni et al., 1970), thus producing a new strike-slip tectonic mélange.

The Thitonian ophiolitic mélange of Albania (Shallo, 1990; Rassios and Dilek, 2009, Fig. 8) may also have been associated with strike-slip tectonics during the late Jurassic - early Cretaceous. Its general trend and structure crosscut different ophiolitic (i.e. Kashnjet-Gornisique-Kcire) and/or continental margin successions (i.e.

Barmash-Leskovik area). It is characterized by zones of elongated blocks set within an argillitic-foliated matrix (Shallo, 1990).

4) (Oceanic crust) Subduction-related mélanges

These types of mélange could be subdivided on the basis of their formational processes as:

4a - mass-wasting deposits at the wedge front

Mass–wasting deposits are widely abundant in the Bocco Shales, above the Internal Ligurian units (Figs. 4 and 5). These Paleocene (Danian) bodies overlay a complete stratigraphic succession. The lower term is a complete sequence of oceanic crust (Marroni and Pandolfi, 2001). Very thick (hundreds of meters), dismembered slide blocks (olistoliths) are present together with bodies from mud-rich cohesive debris flows (olistostromes), very coarse to coarse turbidites, thin-bedded turbidites, and mudstones. Slide blocks and olistostromes are composed of the same Jurassic ophiolite sequence and the related Late Jurassic to early Paleocene sedimentary sequence, which outcrops below the Bocco Shales. The largest blocks consist of contorted thin-bedded turbidites of the same Bocco Shales, interpreted as slide blocks from a steep slope. According to Marroni and Pandolfi (2001), slide blocks and olistostromes of the Bocco Shales were generated by episodic instability of the front of the Paleocene accretionary wedge due to the subduction of reactivated faults offsetting the oceanic crust and causing relief in the lower plate. In modern subduction systems, subducting sea-mounts and ridges cause slope oversteepening and front-of-wedge instability, resulting in gigantic submarine landslides (e.g., Hikurangi margin, continental margin of New Zealand, Collot et al., 2001; Costarica continental margin, von Heune et al., 2003; Hühnerbach et al., 2005). Mud diapirism, which has been suggested as a triggering mechanism for similar deposits in the Western Alps (Di Giulio, 1992), has been discounted by the lack of diapiric structures (Marroni and Pandolfi, 2001).

The Late Cretaceous pre-flysch successions of the Internal Ligurian (Fig. 5) units are characterized by large scale (several tens of meters thick) mud-rich olistostromes, such as the classic Forcella Pass olistostrome in the Val Lavagna Shales (Bortolotti et al., 2004), that are mainly composed by older, Early Cretaceous rocks (Palombini Shales), and ophiolitic clasts (Abbate et al., 1970). The leading mechanisms of transport and deposition were cohesive debris flows acting on already consolidated, tectonized and disrupted units. These bodies episodically occur as meter to tens of meter thick sedimentary bodies in well-bedded, normal successions. Considering the Late Cretaceous geodynamic setting and the examples of the younger Bocco Shales, the hypothesis of instability of a passive margin (Naylor, 1981) can be rejected (Bortolotti et al., 2004) in favour of instability on a tectonically active slope at the front of the paleo Appenninic accretionary wedge, as suggested by Görler and Reutter (1968), but more definitive conclusions have not have not been reached.

4b - Tectonic mélanges and broken formations

A large number of stratally-disrupted units in the External Ligurian units (Fig. 5) belong to this group, after the so-called basal complexes, chaotic complexes, or argille scagliose of the Northern Apennines have been distinguished in either Epiligurian olistostromes (see Type 6), or stratally disrupted stratigraphic units (broken formation or tectonosomes, Pini, 1987; Bettelli and Panini, 1987; Castellarin and Pini, 1987 and following papers, see references in Pini, 1999 and Camerlenghi and Pini, 2009). The latter, defined as broken formations and tectonosomes formed from the interaction of different subduction-related processes: layer-parallel boudinage in an early stage of subduction by fluid overpressure and lithostatic loading (Bettelli and Vannucchi, 2003), progressive oblate-type boudinage and transposition of sedimentary layers by protracted sheath folding, associated with large scale thrusting (Vannucchi and Bettelli, 2002; Bettelli and Vannucchi, 2003), block stacking by both large scale and mesoscopic–scale duplexing and thrusting (Pini, 1999; Cowan and Pini, 2001).

Due to their progressive deformational origin, the finite style and fabric of these mélanges depends on the rheology of the rocks involved, that is from the mechanical characters of the multilayer, which reflect the main depositional environment and the composition (see Bettelli and Vannucchi, 2003). Different deformational styles within diverse stratigraphic intervals in the same sequence may be, therefore, explained by the rheology of the multilayer, but can also be related to the superposition of different tectonic phases (see Pini, 1999), namely the Upper Cretaceous, eo-alpine phases and the Eocene, meso-alpine, or Ligurian phase (see, among many others, Vai and Castellarin, 1993; Pini, 1999; Vescovi et al., 1999; Daniele and Plesi, 2000; Bortolotti et al., 2001; Marroni et al., 2002; Catanzariti et al., 2007).

Different intensity as of stratal disruption are recognizable in the Northern Apennines broken formations-tectonosomes. The "broken formations" in Fig. 5 are Neocomian to Campanian basal complexes, detached from the Ligurian Helminthoid flysches, that contain structures ranging from contorted, highly-folded and boudinaged beds to complete stratal disruption (Vannucchi and Bettelli, 2002; Bettelli and Vannucchi, 2003 and references therein). The tectonosomes of Pini (1999) correspond to an entire Ligurian-type succession (Fig. 5), ranging in age from Neocomian to lower Eocene (Sillaro-Samoggia structural unit, see Cerrina Feroni et al., 2002), which is more severely deformed, with a prevailing complete stratal disruption (Pini, 1987; 1999, Conti, 1987).

The Frido Formation (late Jurassic – early Cretaceous) of the Ligurian units (Fig. 6-7) is a tectonic mélange that represents the remnants of the outcropping deeper portion of the accretionary wedge of the Southern Apennines. It underwent collision with the Apulia passive margin during the early Miocene (Knot, 1994), producing a series of thrust sheets with different lithological features and metamorphic overprinting that records subduction of oceanic crust and deformation during HPLT metamorphism (Laurita et al., 2009 and reference therein).

In Greece (Vourinos Mountains., see Ghikas et al, this issue) and Albania (Dilek et al., 2005, 2008) meter-to kilometre-scale, exotic blocks of ultramafic rocks and ophiolites are seen in an early Cretaceous sedimentary mélange (i.e., Vourinos sub-ophiolitic mélange) resting on the Pelagonian platform succession (Fig. 8). The Vourinos sub-ophiolitic mélange rests tectonically on the Pelagonian microcontinental margin. Its internal structure and stratigraphy is reminiscent of a block-in-matrix sedimentary mélange representing initially a broken formation that formed in a continental slope-rise setting (Ghikas et al., this issue). However, this mélange was subsequently tectonically incorporated into the Pelagonian margin during the obduction of the Vourinos ophiolite in the Middle Jurassic during which it was pervasively metamorphosed and tectonized.

5) **Collision-related mélanges**.

In the Apennines, no mélanges have been conclusively attributed to this because the timing of the end of subduction and the inception of intracontinental deformation varies greatly throughout paleogeographic extent of the Ligurian ocean (see Marroni and Treves, 1998; Cibin et al., 2001; Cerrina Feroni et al., 2002). The are also multiple interpretations regarding the paleogeographic positions of the diverse Ligurian units (see, e,g., Daniele and Plesi, 2000; Bortolotti et al., 2001; Argnani et al., 2004). The late Eocene olistostromes at the base of the Epiligurian succession (Figs. 4 and 5) above the Ligurian nappe (Type 6c) may represent this type of mélange. The Advella mélange in the Western Hellenides, for example, could represent deformation that has occurred since the Eocene as a result of continental collision (Fig. 8) between the pre-Apulian foreland and Pelagonia (Ghikas et al., this issue). These polygenic mélange, originally emplaced by sedimentary processes (see 1. Extensional tectonic-related mélanges), is characterized by a block-in-matrix fabric with blocks ranging in age from Mid-Triassic to Cretaceous, and was emplaced onto Cretaceous-Eocene shelf and turbidite deposits of pre-Apulia (Kostopoulos, 1988; Jones and Robertson, 1991; Rassios and Moores, 2006). It contains rocks associated not only with the initial rifting of Pelagonia and pre-Apulia, but also with the development of a mature carbonate platform, the deposition of thick shallow-marine turbidite and detrital sequences, and the emplacement of the Pindos ophiolite (Jones and Robertson, 1991; Ghikas et al., this issue).The Avdella mélange, therefore, represents a much more complete history of the Pindos basin than the Vourinos mélange.

6) **Intracontinental deformation, "obduction" related mélanges**

This group is by far the most common type observed in the Peri-Adriatic mélanges. It is related to obduction of the accretionary wedge over the continental crust and of the “oceanic” nappe translation.

6a - Sub-nappe mélanges

6a1- precursory olistostromes

Considered among the classic olistostromes of the Apennines (Abbate et al., 1970, 1981), these sedimentary bodies contain a typical block-in-brecciated-matrix fabric (type A olistostromes), or are aggregates of individual blocks, supported or not supported by a brecciated matrix (Type B and C, respectively, Lucente and Pini, 2003). These bodies were deposited by cohesive debris flows and/or blocks avalanches (Figs. 3 and 10) in migrating foredeep basins (see, for the northern Apennines, Lucente and Pini, 2008). Defined as precursory olistostromes by Elter and Trevisan (1973), these bodies have been described elsewhere at the front of tectonic mélanges, facing lateral or frontal ramps or at the front of accretionary wedges and/or nappe systems (Tuscan, Umbrian, Lazio-Abruzzi and Molise foredeep successions, see, e.g., Abbate et al., 1970, 1981; Sgrosso, 1988; Pescatore et al., 2000; Cowan and Pini, 2001; Pini et al., 2004; Vezzani et al., 2004; 2009; Festa et al., 2006; Lucente and Pini, 2008; Patacca and Scandone, 2007; Camerlenghi and Pini, 2009). In the northern Apennines, olistostromes are present in all stage of the migrating foredeep complex, from the early Oligocene Macigno foredeep to the middle-late Miocene Marnoso-arenacea foredeep, and in the Messinian to Pliocene front-Apenninic deposits (Figs. 3 and 10) (see, e.g., Abbate et al., 1970, 1981; Ricci Lucchi, 1986; Conti, 1987; Ricci Lucchi and Vai, 1994; Cornamusini, 2001; Roveri et al., 2002; Landuzzi, 2004; Lucente and Pini, 2003, 2008). They are the result of the collapse of the wedge front, resedimenting Ligurian and Subligurian rocks and deposits from the wedge-top Epiligurian basins (Lucente and Pini, 2008 and references therein). They are often associated with intrabasinal mass-wasting deposits, consisting of sediments form the margins of the foredeep basins close to the front-of-the-wedge (inner slopes) and the same deposits of the basin plains (Lucente and Pini, 2003, 2008).

In the Central and Southern Apennines, for example, chaotic rock bodies of argille scagliose have been emplaced in the foredeep sediments at the front of tectonic mélange of the Sicilide units (Figs. 6 and 11). These olistostromes, which are interbedded in the different foredeep successions from the inner peri-Tyrrhenian region (upper Tortonian Frosinone Fm., see Cosentino et al., 2002) to the outer peri-Adriatic region of the Matese platform area (Pietraroja Flysch, upper Tortonian – lower Messinian in age, see Sgrosso, 1988; Vezzani et al., 2004, 2009; Festa et al., 2006; Patacca and Scandone, 2007), testify to the eastward migration of the Sicilide units.

Different factors are able to trigger these sediments failures. In fact, earthquakes at active margins, rather than oversteepening slope angles, are the most efficient factor in increasing stresses in weakened sediments and triggering failures (Maltman, 1994; Camerlenghi and Pini, 2009).

6a2 - Olistostromal carpet at the base of a nappe

This group is conceptually related to the previous one, since it comes from the protracted activity of debris flows and avalanches at the front of an advancing nappe or tectonic mélange (Figs. 4 and 11). This coalescent carpet of olistostromes has been recognized at the base of the Ligurian nappe in the Bologna area (Landuzzi, 2004; Pini et al., 2004; Camerlenghi and Pini, 2009) as the lowest part of a system of imbricated stacks of normal bedded units, tectonosomes, tectonic mélanges, and olistostromes at the base of the Ligurian nappe (Pini, 1987, 1993; Bettelli and Panini, 1992; Landuzzi, 2004). This widely extending composite lithosome, see Fig. 5, is directly connected to the precursory olistostromes, as suggested by Lucente and Pini (2008) (Fig. 10), and consists of extrabasinal (Ligurian-Subligurian) and intrabasinal (wedge-top basins, basin margin and foredeep) blocks and bodies.

This olistostromal carpet, some of the related large-scale mass wasting complexes, such as the Modino mass-wasting complex (Figs. 4 and 10), and part of the stack of units at the base of the Ligurian nappe, have been grouped together in the Sestola-Vidiciatico unit and interpreted as an equivalent of a subduction channel by Vannucchi et al. (2008). These two interpretations are not in disagreement. The origin of the Sestola-Vidiciatico unit from submarine landslides at the front of the Ligurian nappe is not excluded, at least in part, by Remitti et al. (2007) and Vannucchi et al. (2008). They do provide examples of tectonized olistostromes. The Sestola-Vidiciatico unit (Fig. 3), or the part coinciding with the olistostromal carpet, is therefore to be considered a mixed tectono-sedimentary mélange, because: 1) the exotic blocks are supplied by mass-wasting episode at the front of the wedge, sourcing rocks from the front of the wedge (Ligurian-Subligurian) and from the wedge-top basins (Epiligurian), and also involving the slope and part of the basin plain, as in the case of Monte Modino complex (Lucente et al., 2006; Lucente and Pini, 2008); and 2) part of the exotic blocks may derived from erosion at the base of the nappe (Vannucchi et al., 2008). These intimate interplay of tectonic and sedimentary processes closely recalls observations from the front of modern convergent wedges during erosion (see, e.g., Choconat et al., 2002; Ranero and von Heune, 2002; von Heune et al., 2003), and confirms the validity of the Sestola-Vidiciatico as a fossil equivalent of a subduction channel, even if it is related to the emplacement of an "oceanic" nappe atop an intracontinental stacking of units, above the continental crust of Adria (Boccaletti et al. 1990; Castellarin et al., 1992; Barchi et al., 2001; Carmignani et al., 2001; Argnani et al. 2003).

The Cretaceous sedimentary mélange exposed in the Othris Mountain (Greece) (see Smith et al., 1979), is a debris flow that was deposited just in front of the advancing ophiolitic thrust sheet. The east-ward displacement of the thrust sheet tectonically deformed the mélange that, located in the lowest part of a system of embricated stack, represented an olistostromal carpet enveloping exotic blocks of ultramafic rocks and ophiolites (up to 200 meters wide).

6a3 - tectonic mélange and tectonic-sedimentary mélanges at a base of a nappe (6a1 plus 6a3)

In other areas of the circum-Mediterranen region, the concentration of olistolithes and olistostromes below the base of allochtonous nappes is emblematic (e.g. Ankara mélange, see Bailey and Mc Callian, 1950, 1953).

In the Central and Southern Apennines (Fig. 6), the Flysch Rosso (late Cretaceous-early Miocene) and the Sicilide argille scagliose (Late Oligocene – Early Miocene) represent notable examples of tectonic-sedimentary mélanges at the base of the Molise units (Figs. 7 and 11) and of the Mt. Moschiaturo Klippe in the

Sannio-Molise region (Vezzani et al., 2004; 2009; Festa et al., 2006). In spite of an intense stratal disruption that led locally to a block-in-matrix fabric, the stratigraphy (alternating varicoloured clayey marls, grey-reddish marls and siliceous calcarenites), can still be recognized and mapped. It is characterized by a structurally-ordered block-in-matrix fabric. In the matrix, pervasive scaly fabric is present and often associated to mesoscale S-C shear zones, defined by centimeter-to decimeter-sized lithons.

The whole internal structure consists of fault-bounded bodies ranging from decimeter (Mt. Moschiaturo)-to kilometer (Molise units) scale. Tectonic shearing, acting at the base of the units, was probably the main factor in disrupting the originally coherent succession. Tectonic loading probably triggered overpressure conditions at the base of the unit, as fluids expelled upwards by the clayey matrix produced brittle deformation in the calcareous interlayers (Festa et al., 2006). Locally upward rising of overpressured and underconsolided sediments and mud diapirs, as is frequently imaged in seismic reflection profiles in Plio-quaternary sediments above the Apenninic frontal thrust, either north of Gargano, or in the Gulf of Taranto, is not excluded (Roure et al.,1991).

6b - intra-nappe mélanges (related to deformation during nappe translation)

These types of mélange are subdivided on the basis of the processes involved in their formation. These types are:

6b1 - Sedimentary

Submarine mass-wasting bodies, dominantly composed of only interbasinal sediments, have been described as olistostromes by Jacobacci (1963), Abbate et al. (1970; 1981) and Elter and Trevisan (1973).

Some notable examples include the Breccia della Renga (Serravallian – Tortonian, see, for example, Cipollari and Cosentino, 1995) at Mt. Simbruini (Fig. 6) and the Brecce di San Massimo (Late Tortonian – Lower Messinian, see Ghisetti and Vezzani, 1998, Fig. 6) at the front of the Matese platform (Central Apennines). These lenticular chaotic rock bodies are composed only of intrabasinal sediments, emplaced by submarine mass-wasting phenomena (i.e., Ghisetti and Vezzani, 1986; Vezzani et al., 2004; 2009; Festa et al., 2006). In southern Apennines, the Gorgoglione Flysch (Langhian – Serravallian) is characterized by channelled polygenetic calcareous conglomerates and sandstones, olistostromes of Liguride and Sicilide units (Sauro and Basento rivers, see Carbone and Lentini, 1990) and calcareous olistoliths (Mt. Carruozzo), up to a kilometer wide (Vezzani et al., 2009) (Fig. 6).

6b2 - Tectonic and/or tecto-sedimentary

The Coscogno mélange in the Northern Apennines is a rather puzzling unit, that has been recognized and mapped by Bettelli et al. (2002). Exhumed intermixed chunks of Ligurian, Epiligurian and Subligurian units comprise this mélange. According to Bettelli et al. (2004), these lithosomes of different paleogeographic origin represent thrust splays with contractional contacts. This mélange should represent a tectonic mélange developed deep inside the Ligurian nappe (Bettelli and Panini, 1992; Capitani, 1993). The exhumation of the mélange, and the involvement of the Epiligurian deposits(?) occurred in the late Oligocene-early Miocene, and has been attributed to either out-of-sequence thrust dissecting the entire Ligurian nappe, transpressional activity along strike-slip faults, or to normal faulting (Capitani, 1993). The scarce continuity of the outcrops does not allow for a determination of the nature of the contacts inside and around the body, so an alternative interpretation of these mélanges, as separated, stacked Ligurian and Subligurian units and subunits that are exposed in a tectonic window, has been proposed (Cerrina Feroni et al., 2002).

The outer accretionary wedge of the central-southern Apennines (Mt. Frentani mélange, Vezzani et al., 2004, 2009; Festa et al., 2006; Torrente Calaggio Fm., Patacca and Scandone, 2007 and the Falda di Metaponto *Auct.* Figs. 6 and 7) is marked by a 10-15 km wide belt of intra-nappe tecto-sedimentary mélange. It consists of a block-in-matrix arrangement with intraformational block coming from Cenozoic Molise units, the Messinian evaporitic succession and late Miocene – lower Pliocene foredeep deposits (Ghisetti et al., 2003; Vezzani et al., 2004, 2009; Festa et al., 2006; Patacca and Scandone, 2007). The blocks range in size from decimeters-to hundred of meters. The matrix mainly consists of brecciated matrix with the locally overprinting of a pervasive scaly cleavage. The emplacement and deformation of these chaotic bodies (Fig. 11) is consistent with slope and debris avalanches at the external frontal thrust that produced mass-gravity deposits during tectonic deformation (Ghisetti et al., 2003). The rapid burial provided by the deposition of the early-middle Pliocene top-thust and foredeep clastic Mutignano successions (late Pliocene – early Pleistocene) could have caused pore-fluid dissipation and promoted the upward rise of overpressured chaotic sediments, exceeding hydrostatic pressure (mud diapirs; diapiric mélange) as suggested by some outcrops north of Atessa (early – late Pliocene). Later deformational stages of the already emplaced mélange are associated with folding and thrusting of the Apulia platform.

6c - Epi-nappe mélanges

These types of mélange are subdivided, based of their formational processes into three categories. These categories are:

6c1 – Sedimentary

One of the most notable examples of this type of mélanges is the Messinian mélange in the episutural Tertiary Piedmont Basin (Figs. 1 and 9). It represents a sedimentary body of mixed rocks, resulting from dismemberment of the originally coherent stratigraphic succession (Dela Pierre et al., 2002; 2007; Irace, 2004; Festa et al., 2005; Irace et al., 2005; Festa, 2009). This succession consisted of pre-evaporitic Tortonian - lower Messinian hemipelagic marls and shallow-water Messinian gypsum deposited in response to the Mediterranean salinity crisis. Despite interpretations (Dela Pierre et al., 2002; 2003; Irace, 2004; Irace et al., 2005) that have related the Messinian mélange (Valle Versa chaotic complex *sensu* Dela Pierre et al., 2002) to gravity-driven phenomena triggered by intra-Messinian tectonics, Festa et al. (2005; 2009), Dela Pierre et al. (2007) and Festa (2009) have shown that Messinian mélange has a more complex stratigraphic and structural arrangement. It is a composite chaotic unit formed from different bodies of mixed rocks from a variety of processes (tectonic, gravitational and diapiric), each of which can be inferred to represent a mélange-forming process. Tectonic disrupted units, gravity-driven sedimentary units and diapiric-disrupted units of mixing rocks (*sensu* Festa, 2009) correspond to type 3 (strike-slip tectonic-related mélange), type 6c1 (epi-nappe sedimentary mélange) and type 6c3 (epi-nappe diapiric mélange), respectively, of this paper.

Several olistostromal bodies characterize the episutural, wedge-top Epiligurian deposits (Figs. 3, 4, 5 and 10) and dominantly consist of mud-rich, block-in-brecciated-matrix deposits related to cohesive debris flows, which may also host large blocks (meters to tens of meter thick) of both well-stratified and stratally-disrupted Ligurian units. Generally speaking, the main components are from previously lithified and deformed External Ligurian units, although blocks and detritus from the contemporaneous and slightly older Epiligurian deposits are also present.

The dimension of the bodies spans from some hundreds of square meters to some tens of square kilometers of areal extent and from few meters to as much as 300-400 meters in thickness (Pini, 1987, 1999). In the largest bodies, thick (some tens of centimeters to several meters) zones of banding and fluidal structures in the matrix at meter to centimeter-scale are present at the base and inside the bodies (Pini, 1999) and display simple shear-related flow structures that geometrically resemble mylonitic fabrics. These thick olistostrome bodies can be, therefore, considered as either stacks of anastomosing smaller bodies (in analogy with examples in Cyprus, see Swarbick and Naylor, 1980), or the result of progressive, multiphase emplacement of large bodies with independent relative motion of discrete masses along shear zones.

Their stratigraphic distribution is almost continuous through the entire Epiligurian stratigraphic record (from late Eocene to Pliocene olistostromes, see, e.g., 1:50.000 Italian Geological Map, Bologna sheet). They seem to be more frequent and more widely distributed at late Eocene base of the Epiligurian succession (Figs. 3, 5 and 10), marked by the Baiso breccias, and the lower Miocene Canossa-Val Tiepido olistostrome (Bettelli et al., 1987). Some, very laterally extended and hundred of meters thick chaotic sedimentary bodies, such as the early Oligocene Specchio megabody, have not been compared with the olistostromes yet, because of a more "coherent" aspect at the outcrop due to the higher abundance of rafting blocks and slabs.

Frequently, the overlaying sediments sink inside the olistostromes, with viscous flow of the block-in-matrix rocks around the "normal" bedded Epiligurian strata, as well as the basal contacts of the olistostrome are almost vertical and seem to "pierce" their substratum of tectonosome units. One possible explanation can be a post-depositional reactivation (as mud- diapirs?) of the olistostromes, induced by their underconsolidated state and high pressure of pore fluids. The magnitude of these phenomena, already suggested for the Bologna foothills (see, e.g., Pini, 1999; Pini et al, 2004) deserves further study.

6c2 - Tecto-sedimentary

Some notable examples are most of the Sicilide units (late Cretaeous – early Miocene) exposed in the Central - Southern Apennines which are mainly emplaced by tectonic and subordinate sedimentary processes. They are well-exposed in the Campobasso sector (Molise, Figs. 6 and 7) where a large (more than thousand km^2) and thick (up to 2000 meters) nappe ("Coltre sannitica" *sensu* Selli, 1962, Sannio unit *sensu* Patacca et al., 1992) tectonically overlies the Molise units (Fig. 7). It consists mainly of a block-in-matrix fabric that lacks total stratal disruption (Vezzani et al., 2004; 2009; Festa et al., 2006). Large blocks (up to few km^2 wide), which preserve the original stratigraphic succession, show preferential distributions that are aligned with main shear zones. The emplacement of this huge nappe is consistent with the tectonic movement above the Apennine thrust sheet from the inner to the outer portions. During this movement, local mass-wasting phenomena and gravitational sliding were triggered by tectonic instability.

6c3 - Diapiric

In some cases, the epi-nappe mélanges are (or are suitable to be) reactivated as diapirs. As previously described (see 6c1), this is documented for the Messinian mélange of the Tertiary Piedmont Basin (Festa et al., 2005; Dela Pierre et al., 2007; Festa, 2009, Figs. 1 and 9). Here, diapiric bodies (up to tens of meter wide) pierce the gravity-driven and tectonically disrupted units of the Messinian mélange, causing their partial reorganization. Loading from deposition of gravity-driven chaotic sediments, the presence of low permeability layers (primary evaporites), and strike-slip faulting may have caused the Messinian mélange to locally reactivate as a diapir (Festa, 2009).

Other comparable examples in different sectors of the Tertiary Piedmont Basin and Northern and Southern Apennines are still being examined (Codegone, Festa and Pini, unpublished data).

Discussion and conclusions

The examples of mélanges described in this paper represent only a few of numerous excellent examples preserved in the peri-Adriatic region. We have proposed a preliminary, subdivision and classification of the peri-Adriatic mélanges, with the perspective of investigating some classical mélange problems. The main problems we have examined are: (1) whether a relationship exists between different types of mélanges and their tectonic paleogeographic settings, and (2) in which geotectonic setting(s) mélanges are most abundant and influential.

Obducted ophiolitic and ophiolite-bearing submarine nappes: The largest number of mélanges occurs at the base of submarine allochthonous nappes, in the examples discussed here and in the other circum-Mediterranean chains (see Camerlenghi and Pini, 2009). Particularly, the most abundant cases are related to ophiolitic or ophiolite-bearing nappes, already obducted, and overriding and moving onto a continental plate and a foreland basin system. The main question regarding this group of mélanges is their origin, specifically regarding the contributions of sedimentary vs. tectonic processes at their onset and evolution. The different methodological approaches and geodynamic visions of various authors have caused several interpretative problems, but most of these sub-nappe mélanges are derived from the interplay of both tectonic and sedimentary processes. Sedimentary mass-wasting processes at the front of the nappes supply a considerable amount of materials to the mélanges throughout their formation and evolution, through the time of nappe translation. This is recorded by the presence of precursory olistostromes in the sedimentary record of migrating foreland basins, at least in the Apennines and the Dinarides-Albanides-Hellenides as described in this paper, in the Alps (wildflysch units, Camerlenghi and Pini, 2009 and references therein) and in Turkey (Camerlenghi and Pini, 2009).
Tectonic processes, however, play a significant role when elements from the base of the nappe are incorporated into the basal mélange through possible frictional-erosional processes (Jurewicz et al., 2007), in a similar way to subduction erosion (von Huene and Ranero, 2003), or to folding-thrusting of the basal contact of the nappe (see Catalano et al., 2007) related to out-of-sequence thrusts (see Castellarin and Pini, 1989).

Mélanges at the base of accretionary prisms and subduction channels: Mélanges associated with subduction of oceanic crust (accretionary wedges) appear to be an entirely quite different situation. The circum-Adriatic, fossil sedimentary mélanges are only concentrated in peculiar situation and along certain stratigraphic horizons (see the example of the Paleocene Bocco Shales of the Internal Ligurian units, Northern Apennines). They do not have an ubiquitous and continuous distribution in time and space through the sedimentary record. Accretionary-wedge-related sedimentary mélanges are therefore not so common, they are outnumbered by the "continental" sub-nappe mélanges, and their volumetric relevance is scarce (see Fig. 5).

This seems to be consistent with the actualistic scenario, suggested by the examples of the Pacific convergent margins. The concentration of mass-wasting bodies in this setting is scarce, and they are very small in comparison to other geodynamical settings, such as passive margins (see discussion in Camerlenghi and Pini, 2009); with the notable exception of the situation of tectonic erosion (see, e.g., Choconat et al., 2002; Ranero and von Heune, 2002; von Heune et al., 2004) and the collapse of front of the wedge due to subduction of relevant lower plate irregularities (seamounts, volcanoes, normal faults, etc., see, e.g., Collot et al., 2001; von Huene et al., 2004; Hühnerbach et al., 2005). The largest fossil mass-wasting deposits are in fact the expression of similar geotectonic situation as evidence by the Bocco Shales (Marroni and Pandolfi, 2001).

In this geodynamical setting the tectonic mélanges should prevail. In the circum-Adriatic chains, several disrupted formation have been recently interpreted as related to subduction processes (Pini, 1999; Vannucchi and Bettelli, 2002; Bettelli and Vannucchi, 2003). However, these rock units are severely to completely disrupted stratigraphic units that always maintain their lithostratigraphic and chronologic identities (broken formations, tectonosomes), and not true mélanges. Broken formations-tectonosome do not contain exotic blocks, and are conceptually more similar to the "normal" bedded, but strongly deformed basal complexes of the Internal Ligurian units and some of the External Ligurian units (Levi et al., 2007). The "normal" bedded basal complexes, moreover, have not been considered as Argille scagliose or mélanges at all, but they display zone of higher stratal disruption (see Levi et al., 2006) comparable with the zone of moderate disruption of the units labelled as "broken formation" in Fig. 5.

Generally speaking, considering the basal complexes of the Ligurian units as a whole and with the only exclusion of the sedimentary mélanges at the base of the External units (Fig. 5), there is a progressive grading in the intensity of stratal disruption between the normal bedded units and the broken formations and tectonosomes.
The only mélanges, referred to as merely tectonic that have been reported in this paper, always show characteristic features that suggest a possible contribution of sedimentary processes in including the exotic blocks or defining certain fabric elements. One can wonder if solely tectonic mélanges can really be found in the circum-Adriatic realm.

Mud-diapiric reactivation of sedimentary and/or tectonic mélanges: Another important point is the existence of mélanges related to mud diapirs and volcanoes. All the examples we describe are related to the reactivation of previously deposited sedimentary and/or tectono-sedimentary mélanges as mud diapirs. Two main points about this group of mélanges can be discussed: do they occur in a particular geodynamic setting, and if so what is the role of this setting in producing mélanges?

The occurrence or rare but well-exposed examples of mud diapirs or minor mud-diapiric phenomena in different geodynamic setting (see, for example, the sub-nappe Flysch Rosso, the intra-nappe Mt. Frentani mélange, the epi-nappe Messinian mélange of the Tertiary Piedmont Basin and the Epiligurian olistostromes) suggests that their formation is not strictly related to a particular setting. On the contrary, fluid overpressure caused by the quick loading provided by deposition of gravity-driven sediments (or olistostromes) or by the emplacement of tectonic nappe, the presence of low-permeable clayey layers and faulting, represent necessary factors to form mud diapirs. These conditions are easily reached in the environment and mechanism in which mélanges form. Moreover, deep seated olistostromes, or water-rich, tectono-sedimentary mélanges are probably the major candidates in supplying mud diapirs, as observed in the Gulf of Cadiz and the Alboran Sea (see Camerlenghi and Pini, 2009 for major details). High pore-fluid content and a very high porosity remain inside mass-wasting deposits long after their emplacement.

Tectonosomes and strongly deformed and dewatered tectonic mélanges should be less prone to generating mud diapirs. However, pseudo-diapiric anticlines and ridges have been tentatively recognized and mapped in the Po-Plain border of the Northern Apennines (Pini, 1987, 1993, 1999) and in the Southern Apennines.

Mélanges, therefore, preserve a complex deformational history due to the superposition of different and often linked processes. During this long history, diapirism can play an important role in re-shaping the mélange bodies, changing and complicating the contacts with the normal, well bedded formations and, basically, in exhuming the mélanges (see the case of Coscogno mélange).

We conclude that tectonic, sedimentary, and diapiric processes commonly work together with often an intimate, mutual interplay and linkage in the formation of mélanges. Yet, it is still possible to distinguish mélanges formed in different geodynamic environments and the main processes of their formation. The different case studies we have examined in the peri-Adriatic region suggest that a close relationship exists between different types of mélanges and their tectonic paleogeographic settings. Moreover, the complex evolutionary history of mélanges, generally involving the superposition of tectonic, sedimentary and diapiric processes and the reactivation of previously-formed mélanges, allow us to better understand the role of mélanges in the complex evolution of the peri-Adriatic orogens and accretionary wedges.

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FIGURE CAPTIONS

Figure 1 – Distribution of main mélanges and broken formations in the peri-Adriatic region. The map has been compiled after a large number of citations quoted in the text and on the basis of the following maps (Bigi et al., 1990; Cerrina Feroni et al., 2002; Vezzani et al., 2009, and various sheets of the 1:50.000 scale Geological Map of Italy).

Figure 2 – Paleogeographic sketch of the Apennines and Dinarides-Albanides-Hellenides at different stages: (A) the Alpine Neo-Tethys during middle-late Jurassic (modified after Dercourt et al.,1986); (B) the paleogeography at the end of the Mesoalpine tectonic phase during Late Eocene – early Oligocene (modified after Castellarin, 1994).

Figure 3 - Structural-stratigraphic diagram of the Northern Apennines showing the main structural units, the lithostratigraphic groups and the paleogeographic domains (modified after Camerlenghi and Pini, 2009). A particularly emphasis is given to the distribution of sedimentary mélanges (olistostromes) and broken formation (tectonosomes). Block letters indicate stratigraphic and paleogeographic names; structural units are in italics.

Figure 4 - Simplified, speculative cross section of the Northern Apennines and the adjoining Po Plain. Liberally based on: Castellarin et al. (1994) and Argnani et al. (2003).

Figure 5 - Geological map of the Northern Apennines showing the main bodies of mélanges described in the text. The map is after Pini (1999) and Lucente and Pini (2008). Main sources for the mélange distribution are in: Boccaletti and Coli, (1982), Pini (1993), Marroni et al. (2001), Marroni and Pandolfi (2001), Bettelli et al. (2002), Cerrina Feroni et al. (2002); various sheets of the 1:50.000 scale Geological Map of Italy.

Figure 6 – Geological-structural map of the Central-Southern Apennines (after Vezzani et al., 2009). Abbreviations indicate the type of mélange described in the text and its location.

Figure 7 – Cross section of the Central-Southern Apennines (after Vezzani et al., 2009) showing the distribution of the main mélanges described in the text. Location in Fig. 6.

Figure 8 – Simplified geological map of Albanide-Hellenide mountain belt showing the distribution of the Mesohellenic ophiolite belt and other major tectonic zones. Cross section showing the distribution of the main mélanges (modified after Rassios and Dilek, 2009).

Figure 9 – Scheme (not in scale) showing the stratigraphic and structural relationships between strike-slip tectonics-related mélanges (3), epi-nappe sedimentary mélanges (6c1) and epi-nappe diapiric mélanges (6c3) in the Torino Hill (Tertiary Piedmont Basin). Modified after Festa (2009).

Figure 10 - Distribution of the large scale mass-wasting complexes, m.w.c., (I to X) in the SW to NE migrating foreland basin system of the Northern Apennines, from late Oligocene to late Miocene. Adapted from Lucente and Pini (2008).

Figure 11 – Schematic cross sections showing the emplacement of the Sicilide units in the Molise-Sannio region, Central-Southern Apennines (modified after Ghisetti et al., 2003*).* During the first tectonic stage (A), Sicilide units represented a tecto-sedimentary epi-nappe mélange (6c2). Slope and debris avalanches at the external frontal thrust (B) of the Sicilide units produced an intra-nappe tecto-sedimentary mélange (6b2). Later tectonic stages (C) deformed the already emplaced mélange.

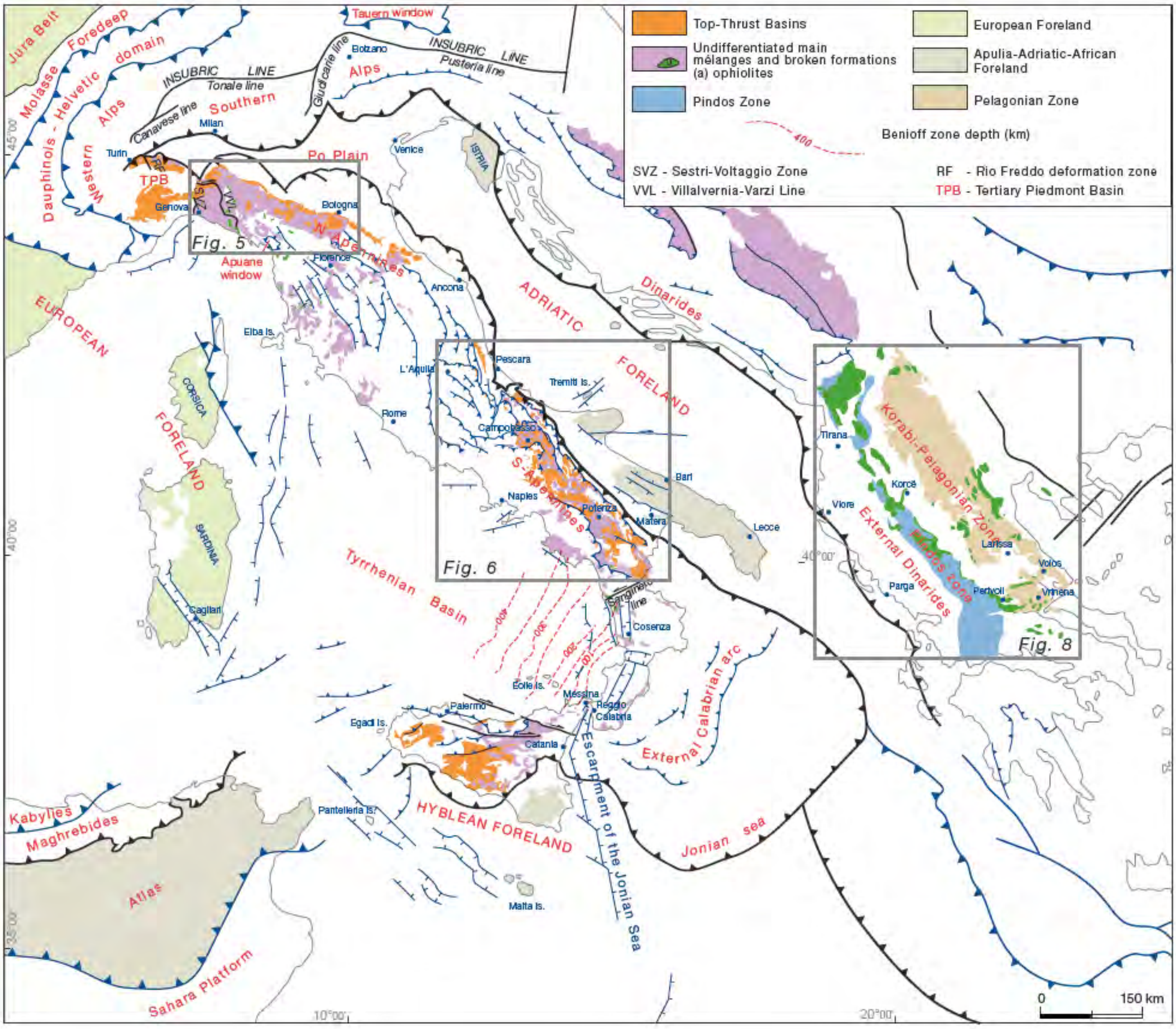


Figure 1

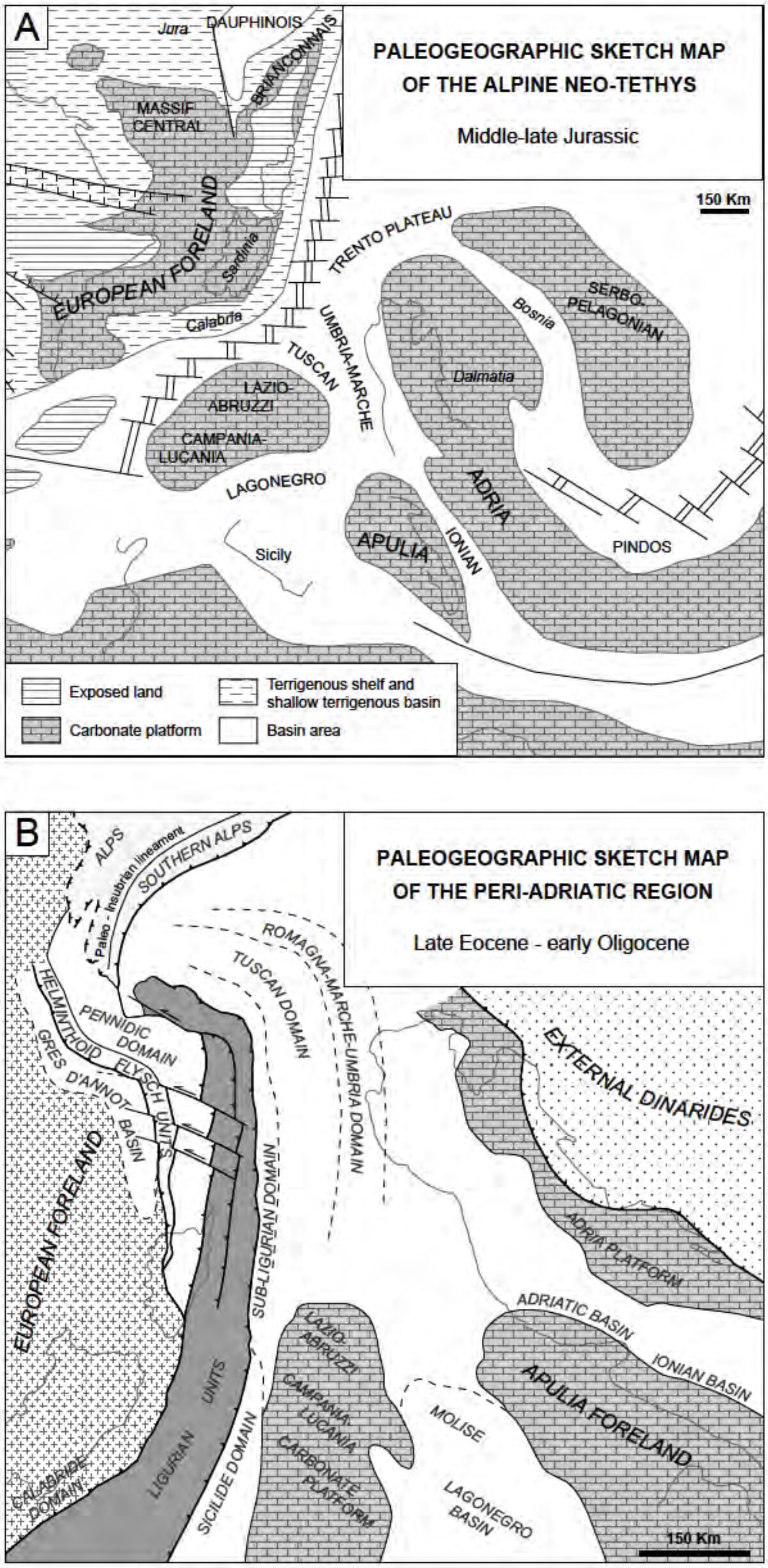
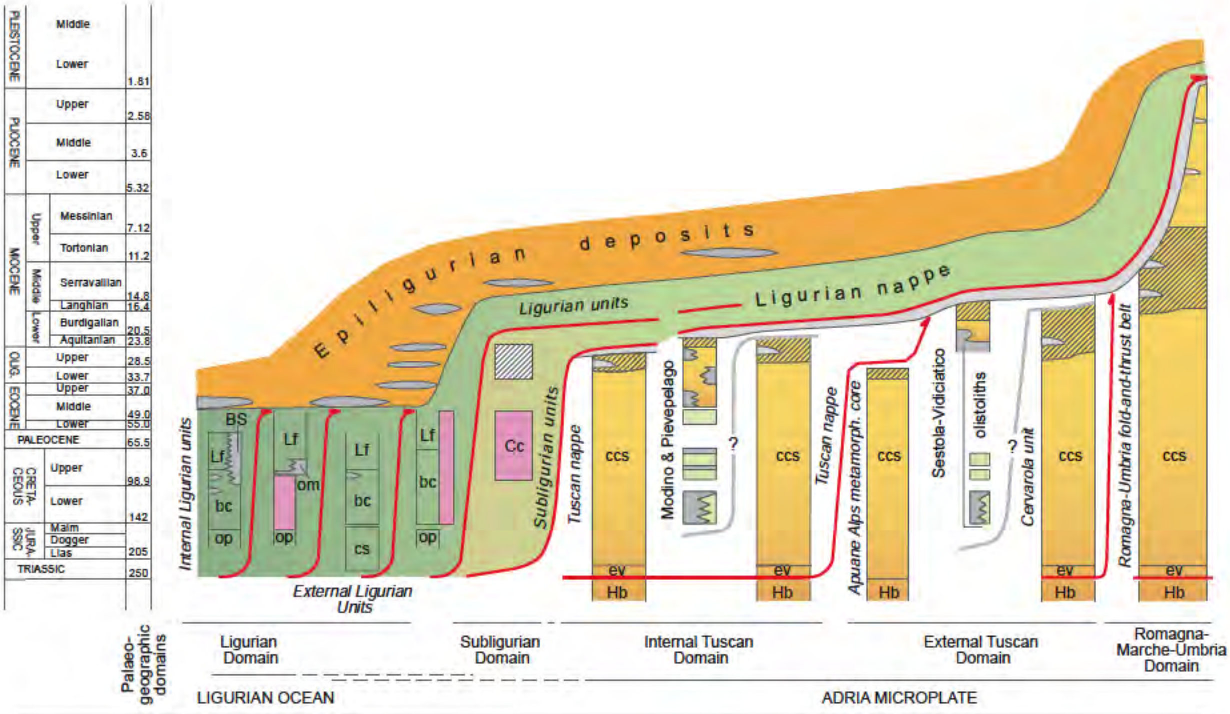

A
PALEOGEOGRAPHIC SKETCH MAP
OF THE ALPINE NEO-TETHYS
Middle-late Jurassic
150 Km
Jura
DAUPHINOIS
BRIANCONNAIS
MASSIF CENTRAL
EUROPEAN FORELAND
Sardinia
Calabria
TRENTO PLATEAU
UMBRIA-MARCHE
TUSCAN
LAZIO-ABRUZZI
CAMPANIA-LUCANIA
LAGONEGRO
Sicily
APULIA
IONIAN
ADRIA
Dalmatia
Bosnia
SERBO-PELAGONIAN
PINDOS
Exposed land
Carbonate platform
Terrigenous shelf and shallow terrigenous basin
Basin area
B
PALEOGEOGRAPHIC SKETCH MAP
OF THE PERI-ADRIATIC REGION
Late Eocene - early Oligocene
ALPS
Paleo - Insubrian lineament
SOUTHERN ALPS
ROMAGNA-MARCHE-UMBRIA DOMAIN
TUSCAN DOMAIN
PENNIDIC DOMAIN
HELMINTHOID FLYSCH UNITS
GRES D'ANNOT BASIN
EUROPEAN FORELAND
SUB-LIGURIAN DOMAIN
LIGURIAN UNITS
SICILIDE DOMAIN
CALABRIDE DOMAIN
LAZIO-ABRUZZI
CAMPANIA-LUCANIA CARBONATE PLATFORM
MOLISE
LAGONEGRO BASIN
EXTERNAL DINARIDES
ADRIA PLATFORM
ADRIATIC BASIN
IONIAN BASIN
APULIA FORELAND
150 Km

Figure 2



BS = Bocco Shales and equivalents
Lf = Ligurian flysches (Helminthoid and Paleocene-Eocene flysches)
om = Casanova and Mt. Ragola complexes (ophiolitic mélanges)
bc = Ligurian pre-flysch successions ("basal complexes")
cs = Triassic-Jurassic substratum from a continental margin (Adria?)
op = ophiolites
Cc = Canetolo complex
ccs = carbonate and carbonate-clastic succession
ev = Triassic evaporites
Hb = Hercinian basament and continental deposits

Stratally disrupted stratigraphic sequences (tectonosomes)
Olistostromes, olistoliths complexes, slide blocks
Precursory olistostromes and olistostromal carpet
Turbiditic infills of foreland basins
Contact of uncertain, debated nature (tectonic vs. sedimentary origin)

Figure 3

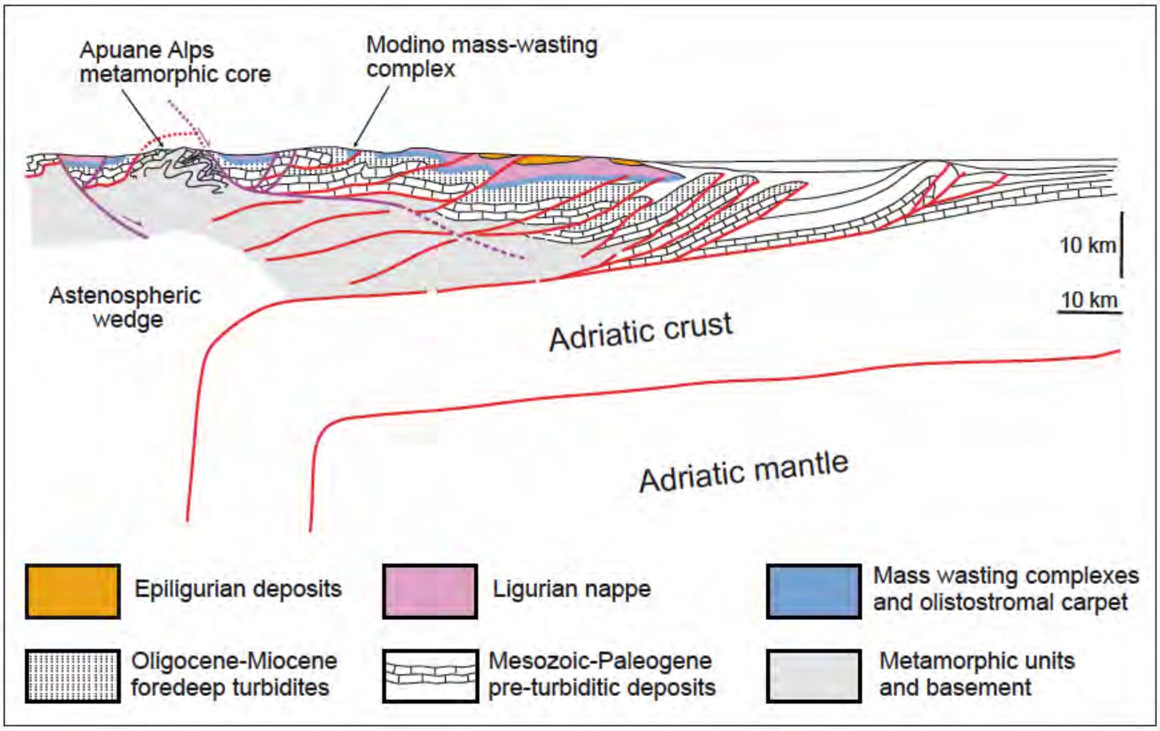
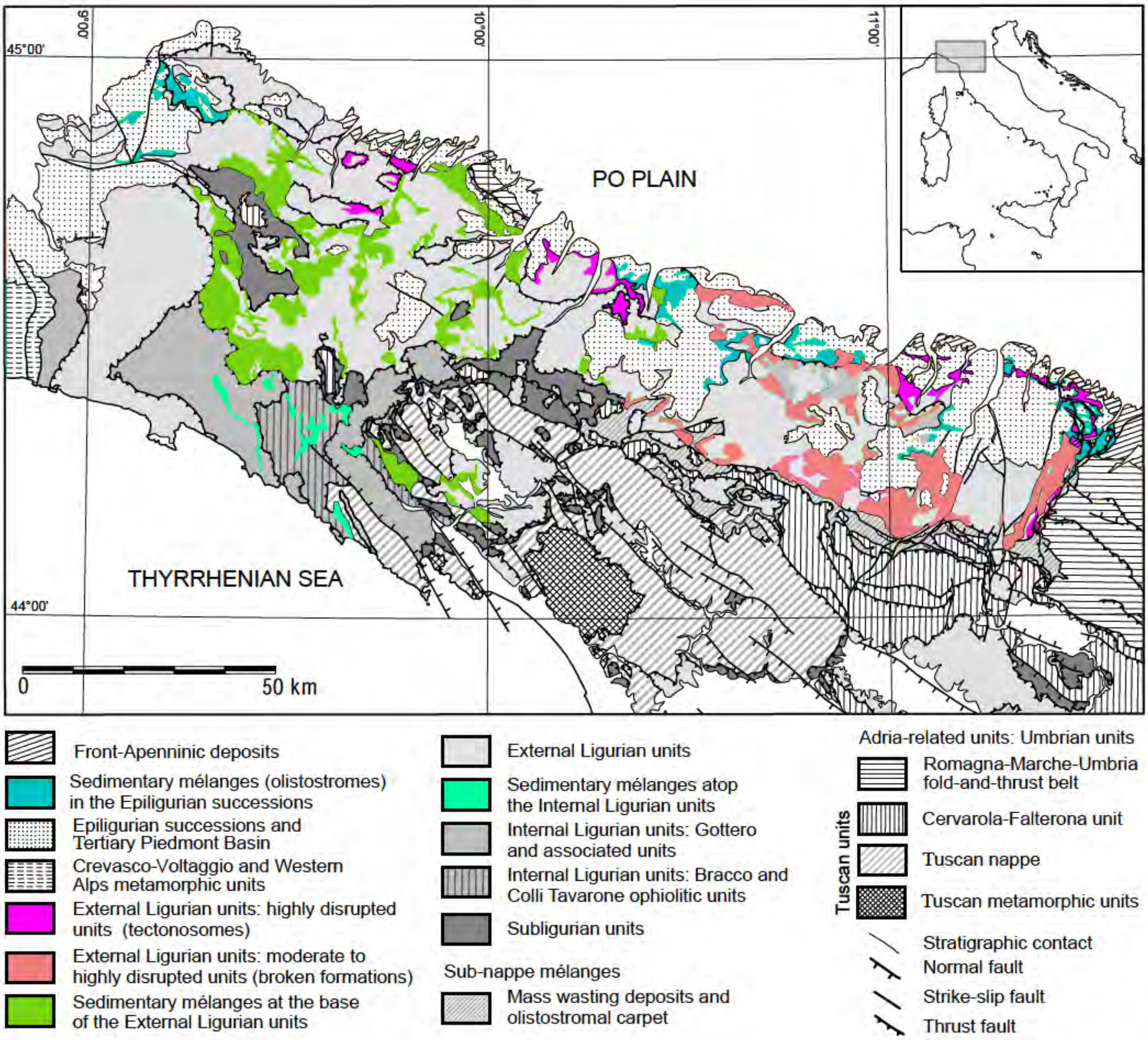

Apuane Alps
metamorphic core
Modino mass-wasting
complex
10 km
10 km
Astenospheric
wedge
Adriatic crust
Adriatic mantle
Epiligurian deposits
Ligurian nappe
Mass wasting complexes
and olistostromal carpet
Oligocene-Miocene
foredeep turbidites
Mesozoic-Paleogene
pre-turbiditic deposits
Metamorphic units
and basement

Figure 4



9°00'
10°00'
11°00'
45°00'
44°00'
PO PLAIN
THYRRHENIAN SEA
0
50 km
Front-Apenninic deposits
Sedimentary mélanges (olistostromes) in the Epiligurian successions
Epiligurian successions and Tertiary Piedmont Basin
Crevasco-Voltaggio and Western Alps metamorphic units
External Ligurian units: highly disrupted units (tectonosomes)
External Ligurian units: moderate to highly disrupted units (broken formations)
Sedimentary mélanges at the base of the External Ligurian units
External Ligurian units
Sedimentary mélanges atop the Internal Ligurian units
Internal Ligurian units: Gottero and associated units
Internal Ligurian units: Bracco and Colli Tavarone ophiolitic units
Subligurian units
Sub-nappe mélanges
Mass wasting deposits and olistostromal carpet
Adria-related units: Umbrian units
Romagna-Marche-Umbria fold-and-thrust belt
Tuscan units
Cervarola-Falterona unit
Tuscan nappe
Tuscan metamorphic units
Stratigraphic contact
Normal fault
Strike-slip fault
Thrust fault

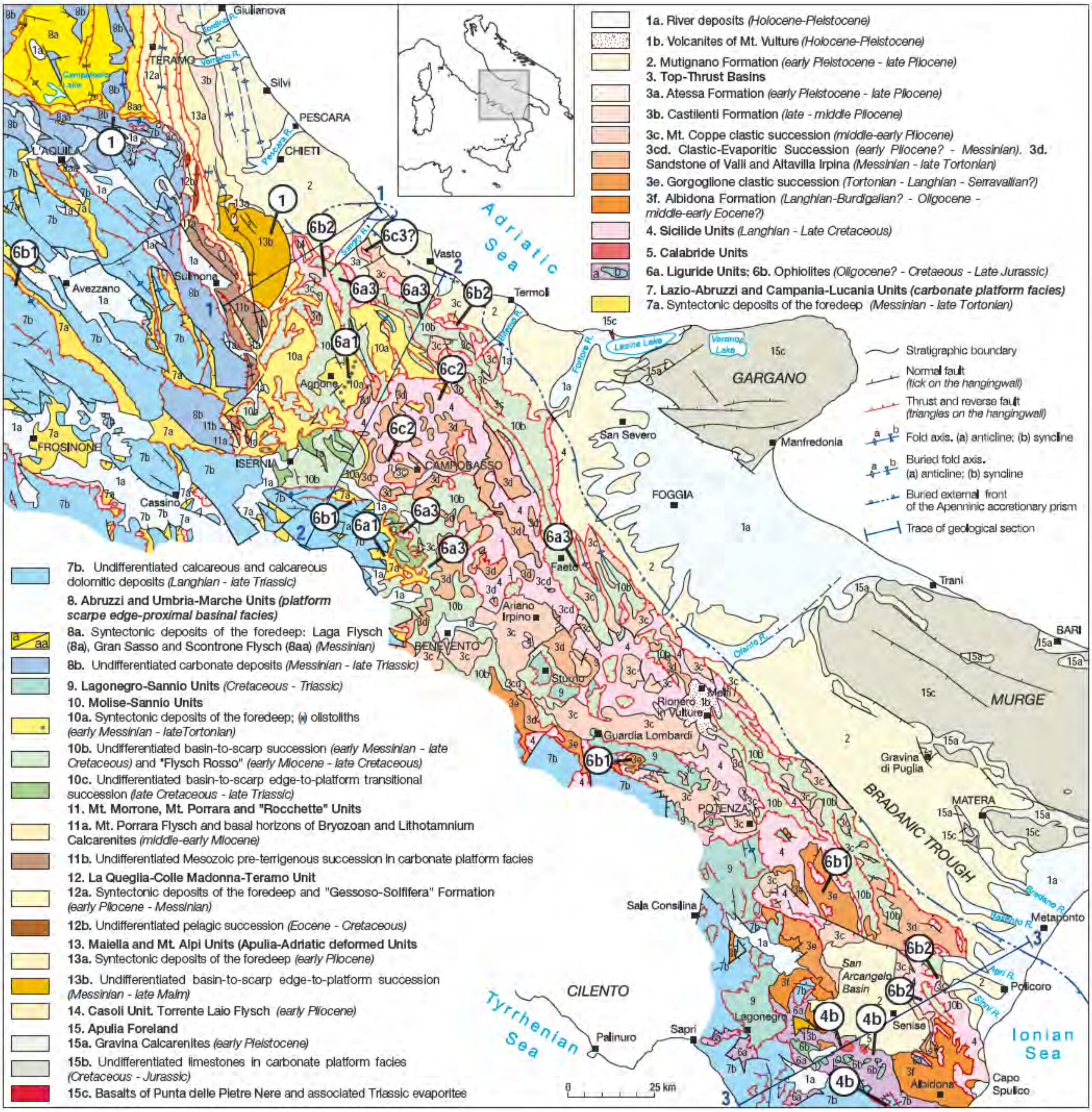
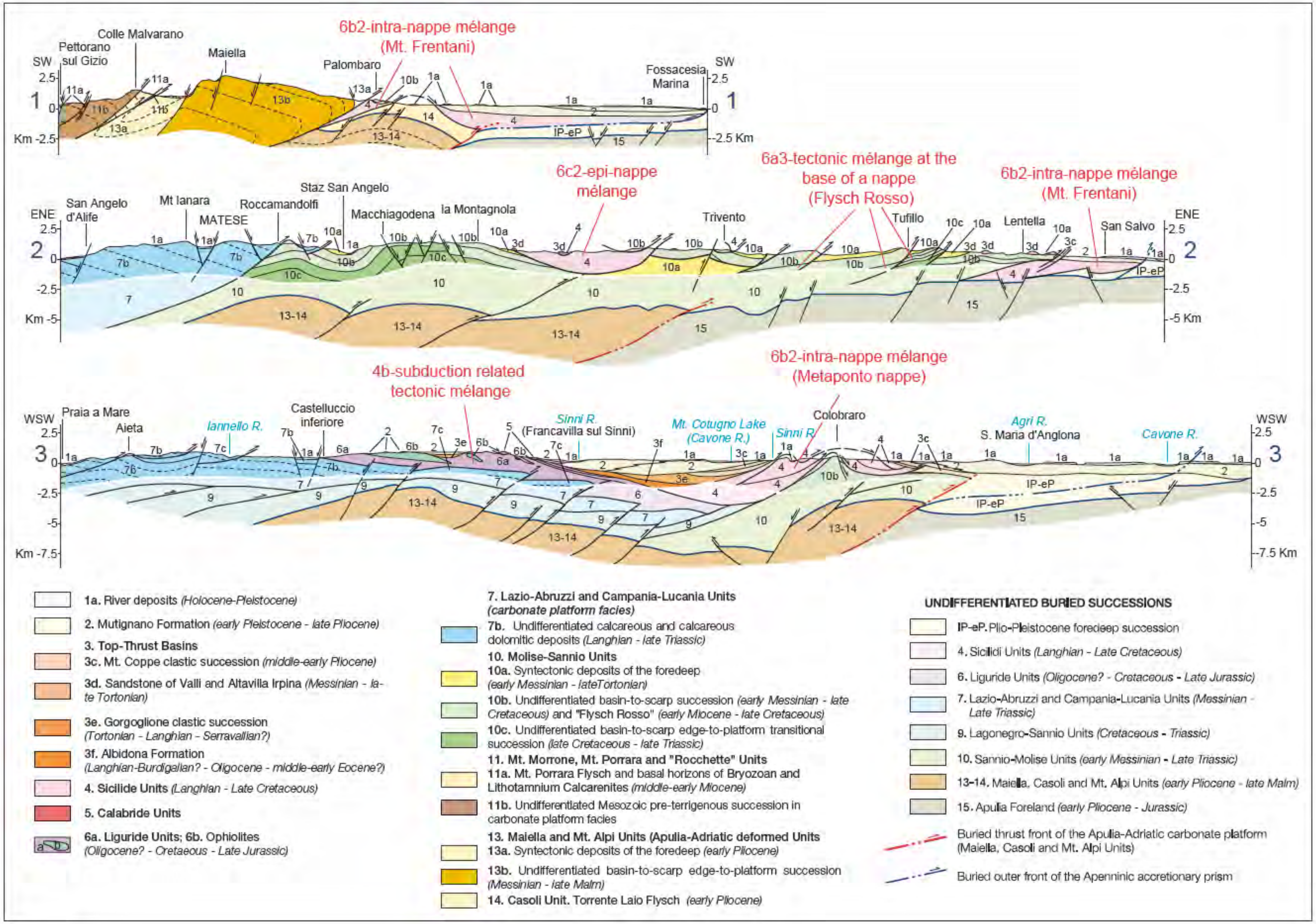

1a. River deposits (Holocene-Pleistocene)
1b. Volcanites of Mt. Vulture (Holocene-Pleistocene)
2. Mutignano Formation (early Pleistocene - late Pliocene)
3. Top-Thrust Basins
3a. Atessa Formation (early Pleistocene - late Pliocene)
3b. Castilenti Formation (late - middle Pliocene)
3c. Mt. Coppe clastic succession (middle-early Pliocene)
3cd. Clastic-Evaporitic Succession (early Pliocene? - Messinian). 3d. Sandstone of Valli and Altavilla Irpina (Messinian - late Tortonian)
3e. Gorgoglione clastic succession (Tortonian - Langhian - Serravallian?)
3f. Albidona Formation (Langhian-Burdigalian? - Oligocene - middle-early Eocene?)
4. Sicilide Units (Langhian - Late Cretaceous)
5. Calabride Units
6a. Liguride Units; 6b. Ophiolites (Oligocene? - Cretaceous - Late Jurassic)
7. Lazio-Abruzzi and Campania-Lucania Units (carbonate platform facies)
7a. Syntectonic deposits of the foredeep (Messinian - late Tortonian)
7b. Undifferentiated calcareous and calcareous dolomitic deposits (Langhian - late Triassic)
8. Abruzzi and Umbria-Marche Units (platform scarpe edge-proximal basinal facies)
8a. Syntectonic deposits of the foredeep: Laga Flysch (8a), Gran Sasso and Scontrone Flysch (8aa) (Messinian)
8b. Undifferentiated carbonate deposits (Messinian - late Triassic)
9. Lagonegro-Sannio Units (Cretaceous - Triassic)
10. Molise-Sannio Units
10a. Syntectonic deposits of the foredeep; olistoliths (early Messinian - late Tortonian)
10b. Undifferentiated basin-to-scarp succession (early Messinian - late Cretaceous) and "Flysch Rosso" (early Miocene - late Cretaceous)
10c. Undifferentiated basin-to-scarp edge-to-platform transitional succession (late Cretaceous - late Triassic)
11. Mt. Morrone, Mt. Porrara and "Rocchette" Units
11a. Mt. Porrara Flysch and basal horizons of Bryozoan and Lithotamnium Calcarenites (middle-early Miocene)
11b. Undifferentiated Mesozoic pre-terrigenous succession in carbonate platform facies
12. La Queglia-Colle Madonna-Teramo Unit
12a. Syntectonic deposits of the foredeep and "Gessoso-Solfifera" Formation (early Pliocene - Messinian)
12b. Undifferentiated pelagic succession (Eocene - Cretaceous)
13. Maiella and Mt. Alpi Units (Apulia-Adriatic deformed Units)
13a. Syntectonic deposits of the foredeep (early Pliocene)
13b. Undifferentiated basin-to-scarp edge-to-platform succession (Messinian - late Malm)
14. Casoli Unit. Torrente Laio Flysch (early Pliocene)
15. Apulia Foreland
15a. Gravina Calcarenites (early Pleistocene)
15b. Undifferentiated limestones in carbonate platform facies (Cretaceous - Jurassic)
15c. Basalts of Punta delle Pietre Nere and associated Triassic evaporites
Stratigraphic boundary
Normal fault (tick on the hangingwall)
Thrust and reverse fault (triangles on the hangingwall)
Fold axis. (a) anticline; (b) syncline
Buried fold axis. (a) anticline; (b) syncline
Buried external front of the Apenninic accretionary prism
Trace of geological section
Adriatic Sea
Tyrrhenian Sea
Ionian Sea
GARGANO
MURGE
BRADANIC TROUGH
CILENTO
Giulianova
TERAMO
Silvi
PESCARA
CHIETI
L'AQUILA
Avezzano
Sulmona
Vasto
Termoli
Agnone
CAMPOBASSO
ISERNIA
FROSINONE
Cassino
San Severo
Manfredonia
FOGGIA
Faeto
Ariano Irpino
BENEVENTO
Sturno
Rionero in Vulture
Melfi
Guardia Lombardi
POTENZA
Trani
BARI
Gravina di Puglia
MATERA
Metaponto
Policoro
Sala Consilina
San Arcangelo Basin
Senise
Lagonegro
Sapri
Palinuro
Albidona
Capo Spulico
Lesina Lake
Varano Lake
Campotosto Lake
0
25 km

Figure 6


6b2-intra-nappe mélange (Mt. Frentani)
Colle Malvarano
Pettorano sul Gizio
Maiella
Palombaro
Fossacesia Marina
SW
Km -2.5
-2.5 Km
6c2-epi-nappe mélange
6a3-tectonic mélange at the base of a nappe (Flysch Rosso)
6b2-intra-nappe mélange (Mt. Frentani)
Staz San Angelo
San Angelo d'Alife
Mt Ianara
MATESE
Roccamandolfi
Macchiagodena
la Montagnola
Trivento
Tufillo
Lentella
San Salvo
ENE
Km -5
-5 Km
4b-subduction related tectonic mélange
6b2-intra-nappe mélange (Metaponto nappe)
Praia a Mare
Aieta
Iannello R.
Castelluccio inferiore
Sinni R.
(Francavilla sul Sinni)
Mt. Cotugno Lake (Cavone R.)
Sinni R.
Colobraro
Agri R.
S. Maria d'Anglona
Cavone R.
WSW
Km -7.5
-7.5 Km
1a. River deposits (Holocene-Pleistocene)
2. Mutignano Formation (early Pleistocene - late Pliocene)
3. Top-Thrust Basins
3c. Mt. Coppe clastic succession (middle-early Pliocene)
3d. Sandstone of Valli and Altavilla Irpina (Messinian - late Tortonian)
3e. Gorgoglione clastic succession (Tortonian - Langhian - Serravallian?)
3f. Albidona Formation (Langhian-Burdigalian? - Oligocene - middle-early Eocene?)
4. Sicilide Units (Langhian - Late Cretaceous)
5. Calabride Units
6a. Liguride Units; 6b. Ophiolites (Oligocene? - Cretaeous - Late Jurassic)
7. Lazio-Abruzzi and Campania-Lucania Units (carbonate platform facies)
7b. Undifferentiated calcareous and calcareous dolomitic deposits (Langhian - late Triassic)
10. Molise-Sannio Units
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10b. Undifferentiated basin-to-scarp succession (early Messinian - late Cretaceous) and "Flysch Rosso" (early Miocene - late Cretaceous)
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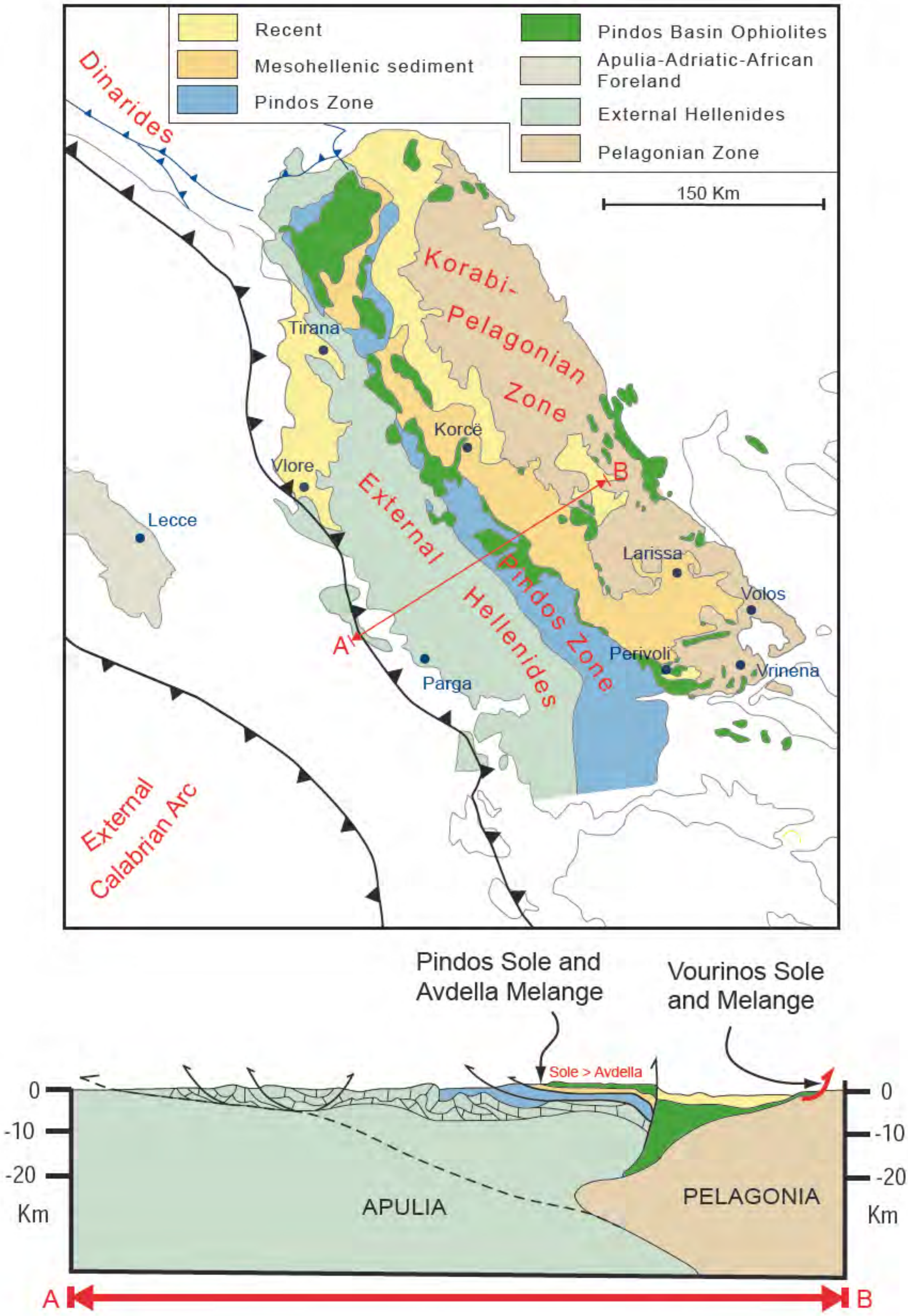
11. Mt. Morrone, Mt. Porrara and "Rocchette" Units
11a. Mt. Porrara Flysch and basal horizons of Bryozoan and Lithotamnium Calcarenites (middle-early Miocene)
11b. Undifferentiated Mesozoic pre-terrigenous succession in carbonate platform facies
13. Maiella and Mt. Alpi Units (Apulia-Adriatic deformed Units
13a. Syntectonic deposits of the foredeep (early Pliocene)
13b. Undifferentiated basin-to-scarp edge-to-platform succession (Messinian - late Malm)
14. Casoli Unit. Torrente Laio Flysch (early Pliocene)
UNDIFFERENTIATED BURIED SUCCESSIONS
IP-eP. Plio-Pleistocene foredeep succession
4. Sicilidi Units (Langhian - Late Cretaceous)
6. Liguride Units (Oligocene? - Cretaceous - Late Jurassic)
7. Lazio-Abruzzi and Campania-Lucania Units (Messinian - Late Triassic)
9. Lagonegro-Sannio Units (Cretaceous - Triassic)
10. Sannio-Molise Units (early Messinian - Late Triassic)
13-14. Maiella, Casoli and Mt. Alpi Units (early Pliocene - late Malm)
15. Apulia Foreland (early Pliocene - Jurassic)
Buried thrust front of the Apulia-Adriatic carbonate platform (Maiella, Casoli and Mt. Alpi Units)
Buried outer front of the Apenninic accretionary prism

Figure 7



Recent
Mesohellenic sediment
Pindos Zone
Pindos Basin Ophiolites
Apulia-Adriatic-African Foreland
External Hellenides
Pelagonian Zone
150 Km
Dinarides
Korabi-Pelagonian Zone
Tirana
Korcë
Vlore
Lecce
External Hellenides
Pindos Zone
Larissa
Volos
Perivoli
Vrinena
Parga
A
B
External Calabrian Arc
Pindos Sole and Avdella Melange
Vourinos Sole and Melange
Sole > Avdella
0
-10
-20
Km
APULIA
PELAGONIA

Figure 8

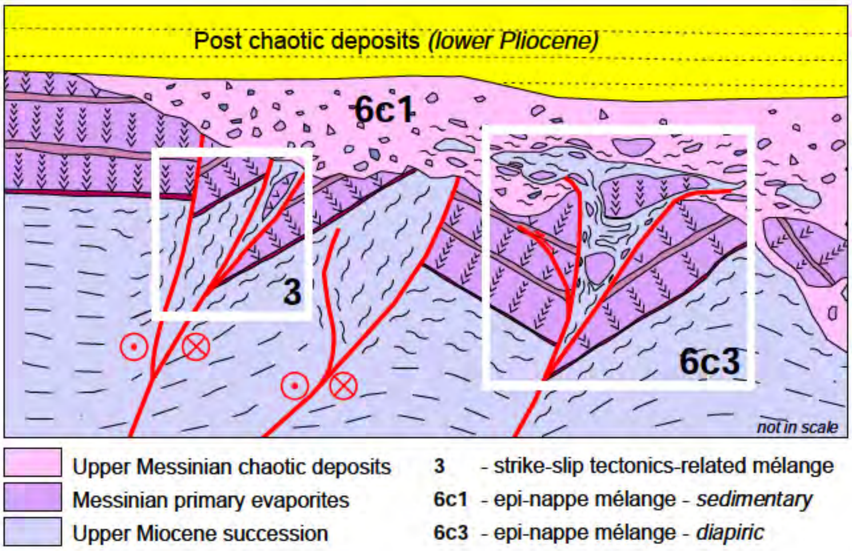
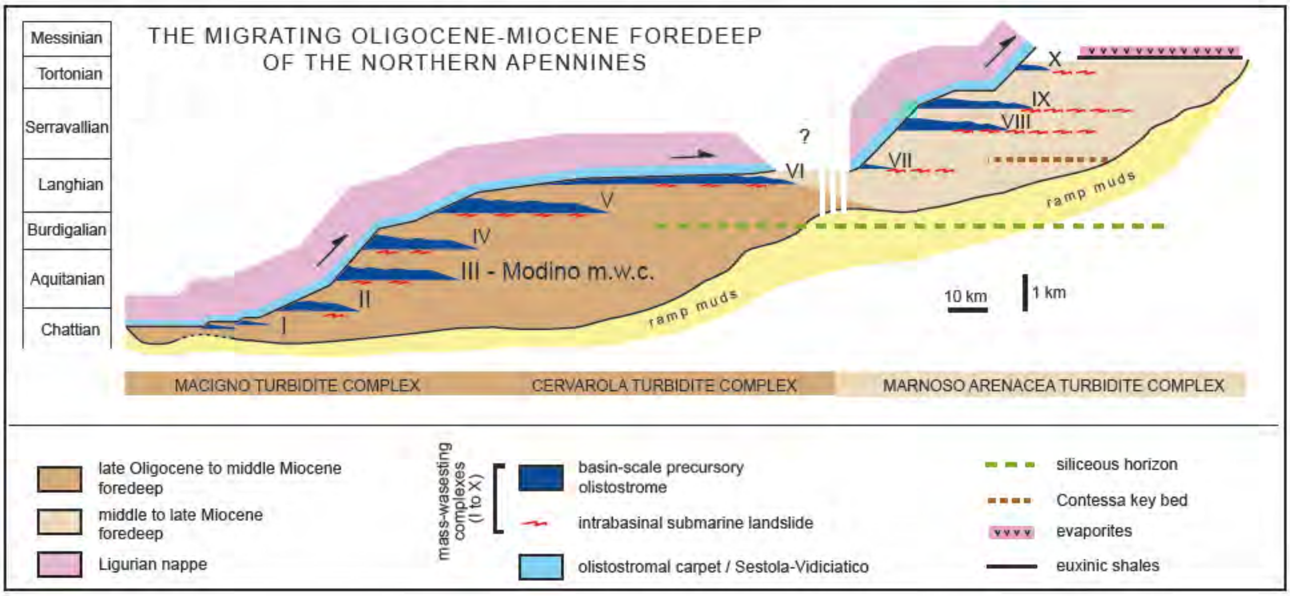

Post chaotic deposits (lower Pliocene)
6c1
3
6c3
not in scale
Upper Messinian chaotic deposits
Messinian primary evaporites
Upper Miocene succession
3 - strike-slip tectonics-related mélange
6c1 - epi-nappe mélange - sedimentary
6c3 - epi-nappe mélange - diapiric

Figure 9



THE MIGRATING OLIGOCENE-MIOCENE FOREDEEP
OF THE NORTHERN APENNINES
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Chattian
I
II
III - Modino m.w.c.
IV
V
VI
?
VII
VIII
IX
X
ramp muds
ramp muds
10 km
1 km
MACIGNO TURBIDITE COMPLEX
CERVAROLA TURBIDITE COMPLEX
MARNOSO ARENACEA TURBIDITE COMPLEX
late Oligocene to middle Miocene foredeep
middle to late Miocene foredeep
Ligurian nappe
mass-wasesting complexes (I to X)
basin-scale precursory olistostrome
intrabasinal submarine landslide
olistostromal carpet / Sestola-Vidiciatico
siliceous horizon
Contessa key bed
evaporites
euxinic shales

Figure 10

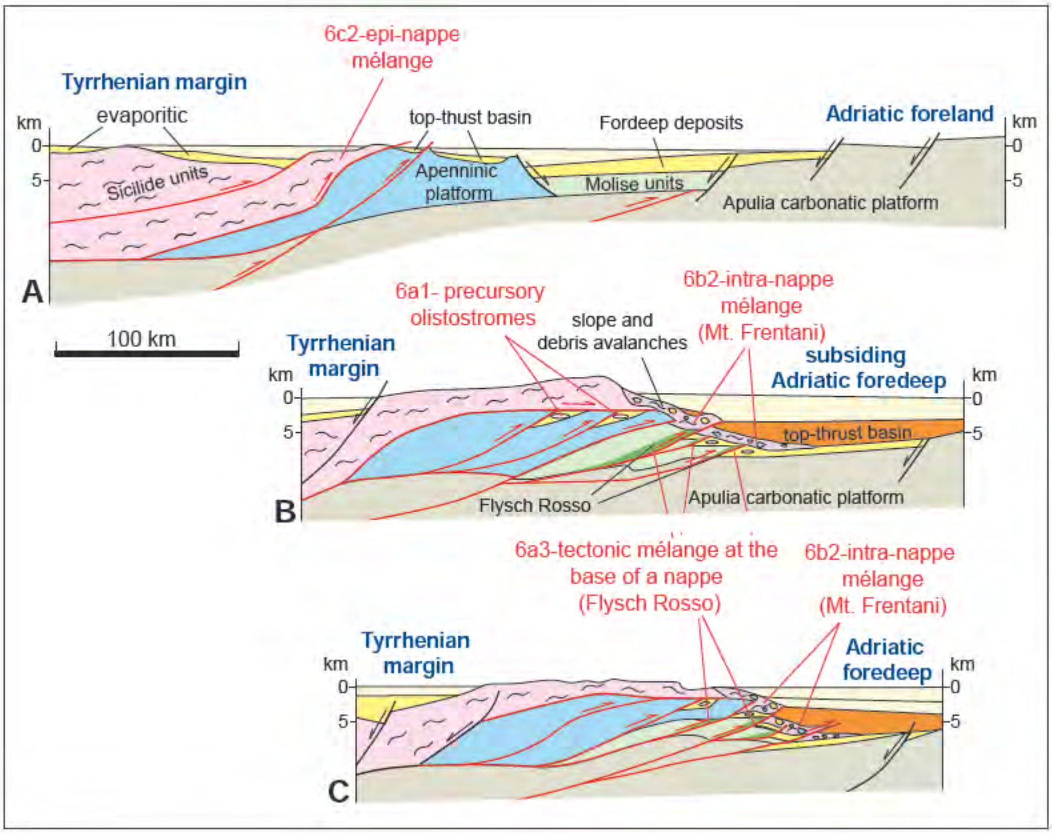

6c2-epi-nappe
mélange
Tyrrhenian margin
km
evaporitic
top-thust basin
Fordeep deposits
Adriatic foreland
km
0
5
Sicilide units
Apenninic
platform
Molise units
Apulia carbonatic platform
A
100 km
6a1- precursory
olistostromes
slope and
debris avalanches
6b2-intra-nappe
mélange
(Mt. Frentani)
Tyrrhenian
margin
subsiding
Adriatic foredeep
top-thrust basin
Flysch Rosso
Apulia carbonatic platform
B
6a3-tectonic mélange at the
base of a nappe
(Flysch Rosso)
6b2-intra-nappe
mélange
(Mt. Frentani)
Tyrrhenian
margin
Adriatic
foredeep
C

Figure 11