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Growth processes and melange formation in the southern Apennines accretionary wedge

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ABSTRACT

The Southern Apennines owe their present geometry to the subduction of an Apulian continental lithospheric slab and are thus best interpreted as an accretionary wedge. Southward, the Apenninic thrust front branches on to the still active Ionian wedge, which is related to the present Calabro-Sicilian subduction. The interpretation of conventional seismic reflection profiles and exploration wells, combined with geologic field studies (biostratigraphy and structural geology), provide constraints for a geodynamic model for the post-Messinian growth of the Apenninic prism. Our model for the Apennines is a good analogy for submerged oceanic accretionary prisms; in both instances features such as out-of-sequence thrusts, underplating and duplexes are viewed as processes to explain the thickening of accretionary wedges.

Syntectonic terrigenous deposits have accumulated in the synclines developed above the flats of Pliocene thrust faults. These depocenters represent piggy-back basins. Younger accretion at the eastern border of the accretionary wedge has led to a progressive uplifting and tilting of the already-emplaced thrust sheets, including a continuous westward migration of the depocenters in the piggy-back basins during Pliocene and early Quaternary times. A contrary west-to-east migration of the depocenters locally occurred where preexisting flats of Pliocene thrust faults have been refolded rather than only being rotated.

Dewatering processes and effects of overpressures on undercompacted sediment deformations can also be studied in the southern Apennines. Melanges and broken formations form an important component of the trench, apparently restricted to the base of tectonic nappes.

Listric normal faults are a major structural element which preserves, in combination with the erosion of topographic highs and resedimentation in the piggy-back basins, a uniform geometric shape (critical taper) for the prism. The age and location of these distensive or gravitational effects are also discussed.

1. Introduction

The southern Apennines consist of a currently emerged accretionary wedge developed in Neogene times above a west-dipping subducted slab of the Apulian continental lithosphere (Fig. 1). Combined field studies and interpretation of subsurface data (exploration wells and seismic reflection profiles) helped us to make a complete and up-to-date regional synthesis of a large portion of southern Italy from the Adriatic coast to the Tyrrhenian Sea, between the Maïella fold (Abbruzzi) in the north, to the Gulf of Tarento in the south (Fig. 2). This regional synthesis, published elsewhere [1] deals with biostratigraphic, paleogeographic as well as structural aspects. The timing of the foreland bending is closely constrained by the progressive infills of the foredeep basin by syntectonic deposits, which were later accreted into the Apenninic wedge as a result of the eastward migration of the deformational front through time. Folding and thrusting are also precisely dated thanks to the synchronous sedimentation occurring in the piggy-back basins.

Like in a companion paper published recently on Sicily [2], we shall use here the unique regional data set of the southern Apennines to analyze the various processes involved in the growth of a recent and well-exposed accretionary wedge, and we shall focus on the thematic aspects that can be applied to other but less accessible and submerged accretionary prisms [3–7].

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2. Regional geological background

If we exclude the uppermost nappes of the tectonic pile which represent remnants either of the European continental plate (Calabride) or of the neo-Tethyan oceanic domain (Liguride), all the tectonostratigraphic units now exposed in the southern Apennines derive from the Mesozoic paleomargin of Apulia (Adria), a continental fragment linked to the African lithospheric plate (Fig. 1 and 2). Effectively, recent geodynamic reconstructions of the western Mediterranean point out that after an early stage of oceanic subduction (Late Cretaceous to Paleogene), the complete closure of the neo-Tethyan oceanic domain in Aquitanian times achieved the suture between Europe and Africa in this area, which lead to the overthrusting of the Calabride basement units and of the Liguride ophiolitic units on to the African margin [8]. This collisional event was coeval with rifting in northern Europe, rotation of the Corsican-Sardinian continental block, and the opening of the Provençal basin [9].

Fig. 1. Crustal thicknesses and Moho geometry in the peri-Tyrrhenian area. (A) Moho depth (km below sea level) beneath the Tyrrhenian Sea [29,30]. (B) Apulian Moho and depth of the Benioff Zone [10,30].

As the African-European convergence still progressed in Neogene times, surficial shortening was accommodated by a pervasive subduction of the Apulian continental lithosphere beneath the Eo-Apenninic orogenic belt. In addition to the early Apenninic flexural basin, piggy-back basins also developed on top of the Liguride unit and underwent some Langhian to Tortonian sedimentation. Nonetheless, the main deformations and shortening related to the Apulian continental subduction appear to be Messinian to Pliocene in age [1], and are even still active southward in the Calabrian arc [10,11]. This youngest compressive evolution of the Apenninic orogenic belt is thus exactly synchronous with the opening of a back-arc oceanic domain in the Tyrrhenian Sea, as attested to by the recent results of ODP leg 107 [12,13].

According to their Mesozoic lithologic and biostratigraphic contents, all the various tectonostratigraphic units that built the southern Apenninic accretionary wedge and its foreland derive from three major paleogeographic domains on the Apulian continental margin, each characterized by platform, basinal or even locally transitional affinities [14–20]. From east to west, we have distinguished (Figs. 2 and 3):

(1) An eastern platform domain made up of 4 to 7 km of Mesozoic limestones lying conformably on Permian volcanoclastic deposits (Fig. 3A). This sequence represents the preorogenic sedimentary cover of the foreland from the Adriatic Sea to the foredeep and crops out in Puglia and Gargano (Fig. 2). Westward, it dips progressively beneath the nappes and is also involved in the folds and thrusts of the overthrust belt, where it is deeply buried underneath more allochthonous basinal units (Fig. 3B and C).

(2) A central basinal domain, referenced here as the Bradano allochthon, effectively constitutes the main component of the Bradano trough (a local name for the southern Apenninic foredeep basin) infill. It can be differentiated as two complementary lithostratigraphic units (Fig. 3B and C): (i) a 2 km thick pile of Mesozoic chert and cherty limestone, known as the Lagonegro unit,

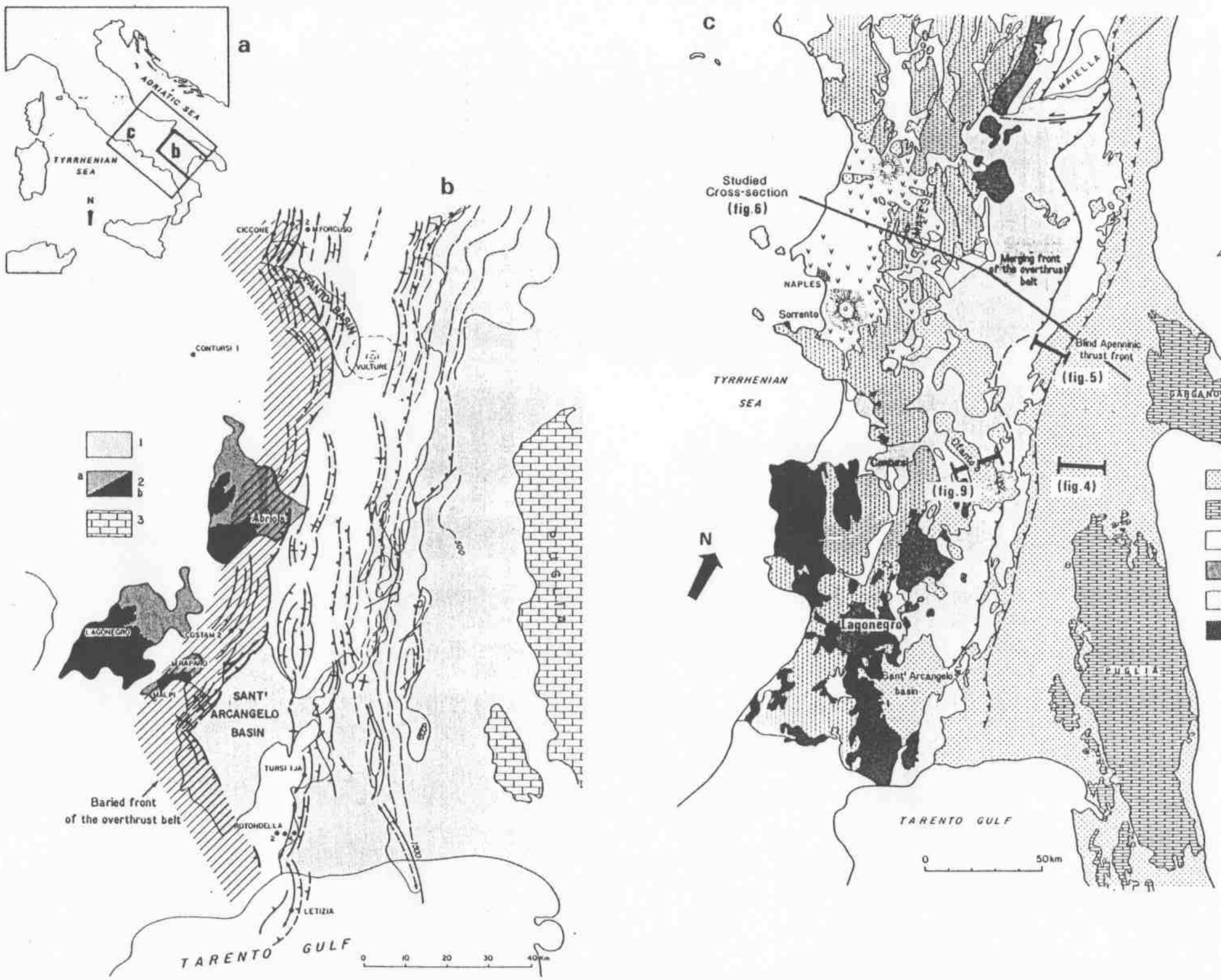

Fig. 2. (a) Index map of Italy. (b) Surface structural map of the southern Apennine showing the main tectonostratigraphic units. *1*, Plio-Quaternary foredeep and piggy-back deposits, *2*, Outcrops of the Lagonegro-Molise Mesozoic basinal sequence, outlining the major nappe anticlines; *3* Mesozoic limestone of the eastern platform. (c) Subsurface structural map of the southern Apennine at the top of the Mesozoic limestone units. In white, Quaternary (volcanics are noted by v). *1*, Messinian to Pliocene syntectonic deposits, *2*, eastern platform; *3* and *4*, Lagonegro-Molise basin (*3*—Cenozoic; *4*—Mesozoic); *5*—Western platform; *6*, Liguride ophiolitic unit.

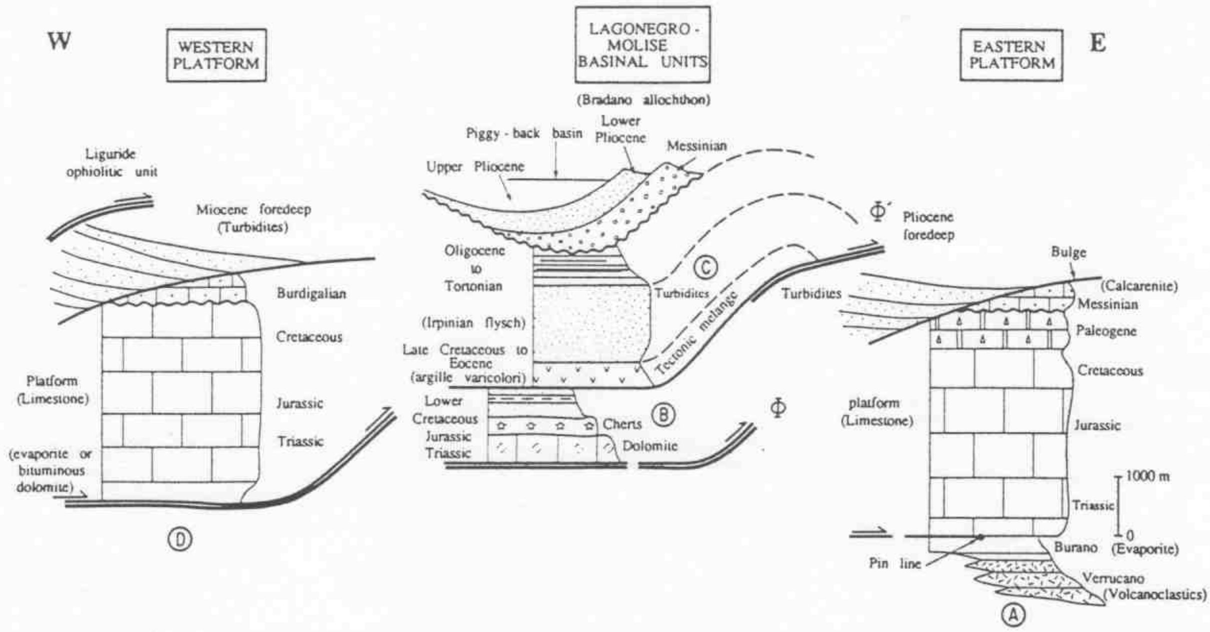

Fig. 3. Synthetic lithostratigraphic columns of the main tectonostratigraphic units. Two types of tectonic contacts are distinguished: (1) major thrust faults separating distinct stratigraphic units (double line) and (2) detachment horizons in the stratigraphic sequence (single line). A, B, C and D refer to the text.

which ranges from Late Triassic to Early Cretaceous age and lies conformably on Triassic dolomite (Fig. 3B); (ii) Late Cretaceous to Eocene "argille varicolori" and Oligocene to Tortonian Irpinian flysch (Fig. 3C), which form dismembered units of the Molise area, with plastic deformations and melanges or broken formations, and which probably represent the currently detached cover of the Lagonegro unit.

(3) A western platform domain made up of Mesozoic limestones similar to those on the eastern platform, and which currently constitutes the uppermost nappe in a large part of the southern Apennines (Figs. 2 and 3D).

Note that, except for the first domain, no Paleozoic basement is encountered at the surface level or in exploration wells. All the exposed nappes are detached on Triassic evaporite or bituminous dolomite, or else on younger decollement levels.

Subsidence related to deflection of the underthrust lithosphere by the advancing orogenic wedge was diachronous along the cross section studied. Due to an eastward migration of the deformation, the western pre-Neogene domain subsided first in the Apennines foredeep and was already accreted and uplifted into the Apenninic wedge at the time when the eastern domain initiated its own subsidence evolution. The timing of the subsidence is well defined for the platform domains, where shallow-water limestones were progressively replaced by more pelagic marly limestones and deep-water turbidites. The timing of the thrusting and accretion of each specific unit in the wedge is less precise. It can be defined either in the autochthon by the occurrence of reworked materials in the foredeep basin (olistoliths or olistostromes) or in the allochthon by unconformities and fan-shaped sedimentation in the piggy-back basins. The western platform started to subside in the south in Langhian-Serravalian times (marly limestones), was then covered by Tortonian flysch, and thus was not tectonized until Late Tortonian nor Messinian times. To the north, the first flysch to occur on top of the platform carbonates of the Abbruzzi Mountains is no older than the Messinian (Montagna Grande, Fig. 2, [18,21,22]).

The eastern platform started to subside in the west in Messinian times (Contursi well, [23]) but only in the Lower Pliocene farther eastward. Most thrusting and shortening occurred recently, in Messinian to Pliocene times, as established by data from the Contursi well, which encountered Messinian evaporites underneath allochthonous units, near the Tyrrhenian coast (Fig. 2c). In addition to the post-Messinian infill in the foredeep basin, syntectonic Pliocene beds were deposited on top of the allochthon in the synclines overlying the flats of the Apenninic thrusts, giving rise to piggy-back basins in the Ofanto or Sant' Arcangelo areas (Figs. 2 and 3).

Uplifting of the belt occurred only very recently. The occurrence of Calabrian marine sediments at 600 m elevation in the Sant'Arcangelo piggy-back basin to the south (Fig. 2c) attests to the amount and high velocity of vertical movements. Besides deep thermal and isostatic readjustments, the compression itself (with deep-seated duplexes or basement involved thrusting) can account for the uplift observed. On the contrary, distension and normal faulting located at the rear of the prism account for the thinning of the uppermost units, and locally, to the tectonic denudation of deeper horizons. Effectively, normal faults are well documented only along the Tyrrhenian side of the Apennines, and were active since the Late Pliocene or early Pleistocene [24,25], thus synchronous with thrust-sheet emplacements farther east.

3. Southern Apenninic accretionary wedge and Apulian continental lithosphere subduction

Kinematic reconstructions help us understand the evolution of the orogenic belts surrounding the Apulian indenter (i.e., the Alps, the Dinarides and the Apennines). The present geometry of the Apennines thus results from Neogene deformations along the western margin of Apulia as a consequence of the northward convergence of Africa against Europe. Published refraction data show a progressive thickening of the crust from the Adriatic foreland toward the southern Apennine, where a 50 km thick crustal root is inferred ([10], Fig. 1b). This thickening of the crust is a clear expression of the west-dipping subduction of the Apulian continental lithosphere beneath the Apenninic orogenic belt [1,26–28]. Southward, the Apenninic thrust front branches onto the still active Ionian wedge, which is related to the present Calabro-Sicilian subduction [16]. Focal earthquake mechanisms evince a Benioff plane down to 450 km beneath the Tyrrhenian coast ([10,11,29], Fig. 4), which marks the location of the subducted lithospheric slab.

A 10 km thick post-Messinian oceanic crust exists west of the Apennines ([30], Fig. 1A). This oceanic crust is interpreted as the result of back-arc distension which occurred simultaneously with major compressive deformation and shortening in the southern Apennines [12].

All the different Mesozoic lithostratigraphic units now involved in the southern Apennines (i.e., western platform, Lagonegro-Molise basin and eastern platform, Figs. 2 and 3) are aspects of an ancient continental paleogeography comprising the western margin of Apulia. The amount of E–W shortening calculated by section balancing from the thin-skinned deformations of the sedimentary cover is at least 150 km. It is only partially compensated for at depth by the thickening of the crustal basement as indicated by the geome-

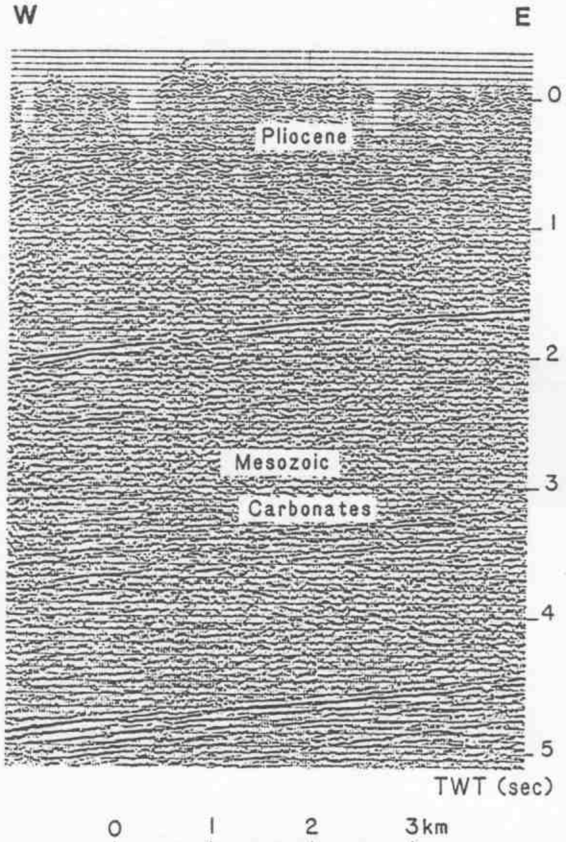

Fig. 4. Seismic reflection line in the Puglia foreland. Note the strong markers at 2 and 5 s TWT, which represent the top and bottom of the Mesozoic platform carbonate.

try of the Moho [28]. This discrepancy observed between the amounts of shortening of the cover and of the basement in the Apennines is probably one of the best documented expressions of the subduction of a continental lithospheric slab (Fig. 1).

Since different Mesozoic paleogeographic domains, either platforms or basin, existed along the Apulian margin, the resulting tectonostratigraphic units of the Apennines exhibit distinct deformation styles, depending upon their preexisting lithologic architecture. The principal decollement levels (Fig. 3) are represented by either evaporitic, argillitic or bituminous dolomitic levels of Triassic ages beneath the younger platform limestone and Lagonegro-Molise pelagic formations, whereas the upper part of the basinal sequence delaminates along Late Cretaceous to Eocene argillitic horizons (the so-called "argille varicolori"). This "argille varicolori" unit forms a major component of the Bradano or the Lagonegro-Molise allochthon, an extensive chaotic domain made up of plastically deformed materials, which almost entirely fill the southern Apenninic foredeep.

Earlier attempts to interpret the Apennines as an accretionary wedge formed during the subduction of first oceanic then continental lithosphere concerned areas farther to the north [31], where the Mesozoic paleogeography was much simpler (lack of differentiated platforms and interdigitized basins). As a whole, the present geometry of the Apennines thus reflects the interaction of superimposed tectonics on either brittle or plastic materials. Isostatic uplifting, related to the Apulian continental subduction provides here an onshore opportunity to study the active deformational processes involved in an accretionary prism, and to compare them with the many other accretionary prisms in the oceanic domain, which are generally submerged.

4. Surface and subsurface constraints used to compile a regional cross section

Property seismic reflection lines and exploration wells are plentiful in the undeformed foreland (Adriatic Sea) and along the Apenninic foredeep basin. Nevertheless, subsurface data rapidly become scarce westward, and only a few traverses can be studied with a complete set of seismic lines across the entire orogenic belt, from the Adriatic coast to the Tyrrhenian Sea. Therefore, we shall focus the following discussion on a specific line which crosses the southern Apennines from Gargano to Capua (Fig. 2).

The seismic lines have been calibrated using both surface and well data. A special effort has been devoted to the location of the main thrust fronts in the smooth topography of the Bradano-Molise area. The top of the Mesozoic eastern platform carbonates constitutes a strong reflector that can be followed from the autochthon (east of the Apenninic thrust front, Fig. 4) to the deepest parts of the foredeep basin, even when it is deeply buried beneath the allochthon (Fig. 5). Farther west, similar markers are found at shallower depths. Recent wells (Benevento 1, Fig. 2) have proved that they also belong to the eastern platform domain, which is largely involved there in the compressive structures of a buried overthrust belt (Fig. 6).

Most of the seismic lines have not been processed deeper than 6 s TWT (two-way times), and, except along the eastern side of the foredeep, the data are of very poor quality beneath the top marker of the platform carbonates. Therefore, the internal structure of the overthrust belt is currently conjectural and has been drawn here using the technique of cross-section balancing. Nonetheless, very local deep seismic profiles (9 s TWT) have proved that pre-Triassic sequences, either sedimentary Paleozoic strata or crystalline basement, were involved in the deformation ([28], Fig. 6).

The internal geometry of the allochthon, especially the connection between the surface trace of the thrust faults and their root zones in the buried overthrust belt, has been determined using markers imaged locally by seismic. Surficial structures such as nappes, anticlines and piggy-back basins were also useful, as we shall see later, in locating the ramps and the flats of the youngest thrust faults [32].

5. Growth processes in the southern Apenninic accretionary wedge

Even though Apenninic deformations are mainly confined to the accretionary wedge (upper plate), some incipient structures also occur in the

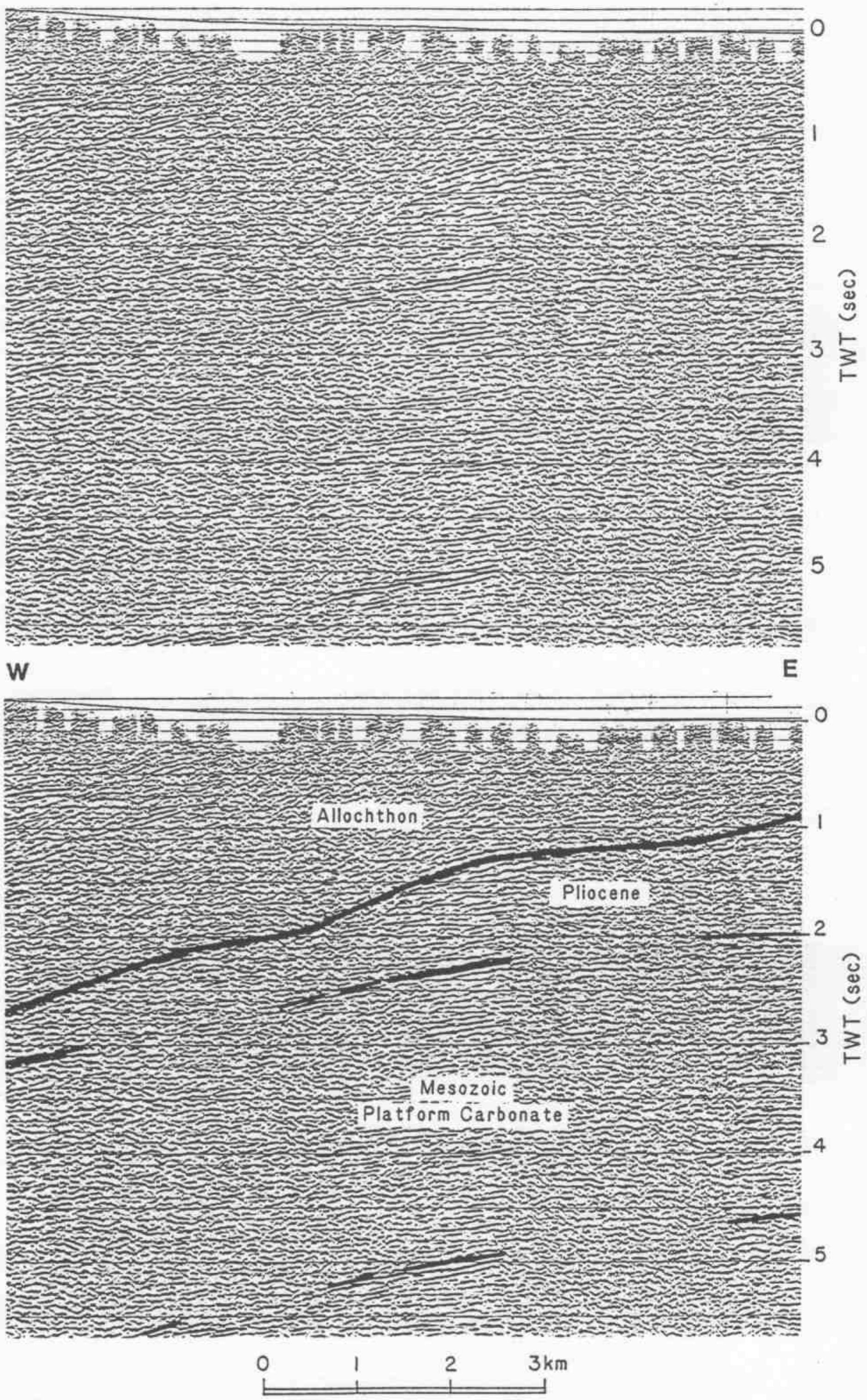

Fig. 5. Seismic reflection line in the Bradano trough. Note the occurrence of an undeformed *Pliocene* sequence (Pl) beneath the *Allochthon* (A). The flexture of the Adria plate is outlined by the west-dipping reflectors of the Mesozoic autochthonous platform carbonates.

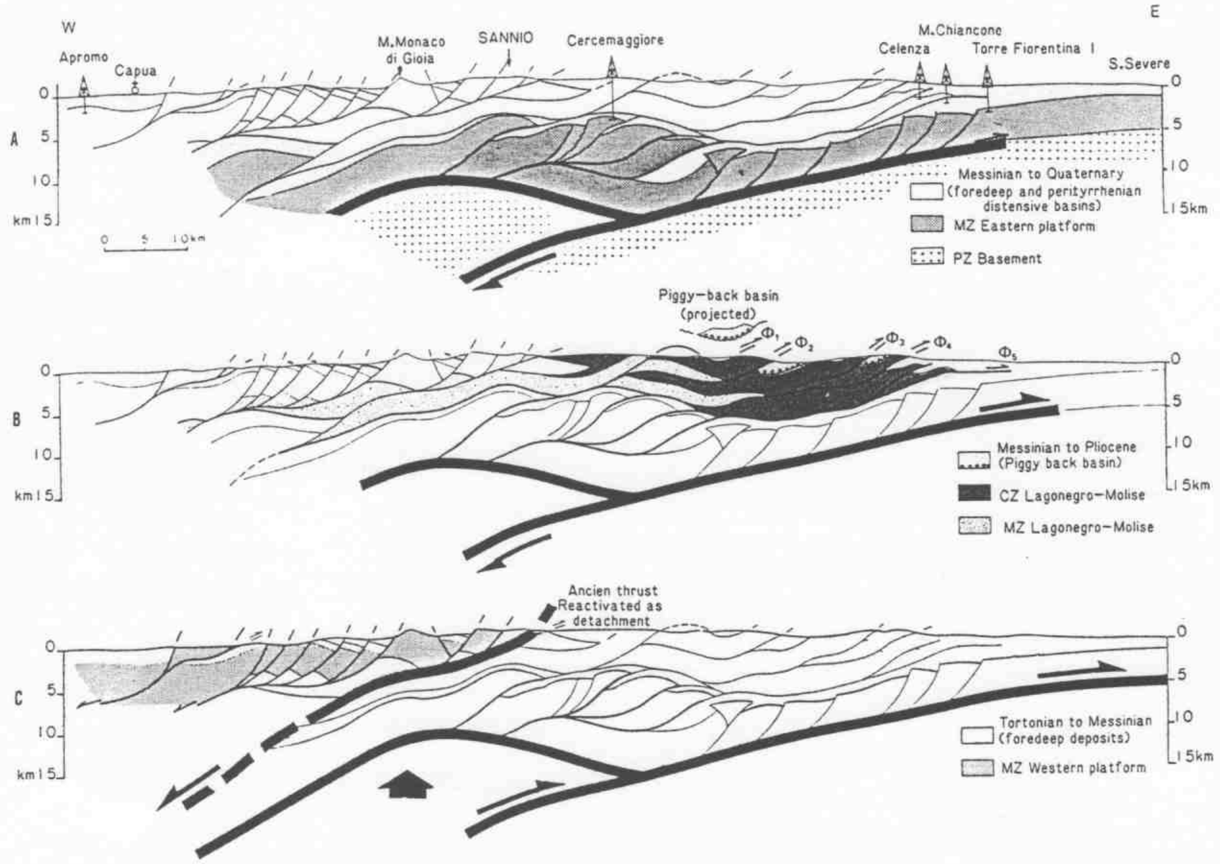

Fig. 6. Geological section across the southern Apennine. (A) Structural style of the eastern platform domain. The Mesozoic platform limestones are involved in the bending of the foreland and are progressively underthrust beneath the allochthon. Farther west, they are accreted to the prism and form a buried overthrust belt. The basement is also rapidly involved in the deformation. (B) Structural style of the Lagonegro-Molise allochthonous unit. Note that folding and thrusting of the para-autochthonous eastern platform affect the geometry of previously emplaced nappes. (C) Structural style of the western platform. Note that early Apenninic thrust faults were reactivated as normal faults at the rear of the prism.

autochthonous foreland, i.e., on the outer wall of the foredeep. In the foreland, the Mesozoic platform carbonates form elongated outcrops from Gargano in the north to the Puglia Peninsula in the south, between the Adriatic Sea and the Bradano trough (Fig. 2). This wide arch has recently been interpreted as the flexural bulge developed on the Apulian plate in response to the load of the Apenninic belt [27]. West of the bulge, the Apulian lithospheric flexure helps to create the foredeep basin (Bradano trough) and is outlined by the upper and lower limits of the Mesozoic Puglian platform carbonate which correspond, on the seismic lines (Figs. 4 and 5), to two strong reflectors: the upper one at the boundary with the Pliocene, and the lower one at the top of Permo-Triassic volcanoclastic rocks. Between these two markers, the thickness of the Mesozoic carbonates (a transparent sequence on the seismic lines), may vary from 2 to 3 s TWT, i.e., 4 to 7 km, depending on whether Upper Cretaceous beds are still present or were eroded during Paleogene times. These horizons, which can be followed on the seismic lines even beneath the allochthon (Fig. 5), run parallel to the bending of the Moho deduced from refraction data (Figs. 1 and 6). From a narrower view point, Lower Pliocene extrados normal faults locally define tilted blocks west of the bulge (Fig. 6). Nevertheless, in response to a younger eastward progression of the compressional front, some of these normal faults were partially or totally inverted during Late Pliocene or even Quaternary times, giving rise to wide anticlinal structures which affect both the autochthonous carbonates and the overlying Bradano allochthon (Fig. 6), especially southward near the Gulf of Tarento (i.e., in the Tursi or Santa Lucia structures, where the platform carbonates have been reached by deep exploration wells, Fig. 2).

Specific portions of the eastern platform and related flysch cover were overthrust by the Bradano allochthon at a time when they were still part of the flexured autochthon. Incorporated later into the accretionary wedge itself (Figs. 2c and 6), these platformal fragments nowadays form a buried overthrust belt, which can be interpreted as the result of successive crustal duplexing. These duplexes were themselves responsible for the remobilization of the already tectonized Bradanic allochthon, in which they produced nappe anticlines (above the neoformed ramps) and klippen (nappe synclines above the new flats, Fig. 7). High-angular discrepancy exists between the overthrust belt fold axis and the orientation of the Puglian inverted structures, which are usually parallel to the foredeep's outer wall. Major bending affects the trends of the overthrust belt, especially near Ciccone and Monte Alpi (Fig. 2c). This

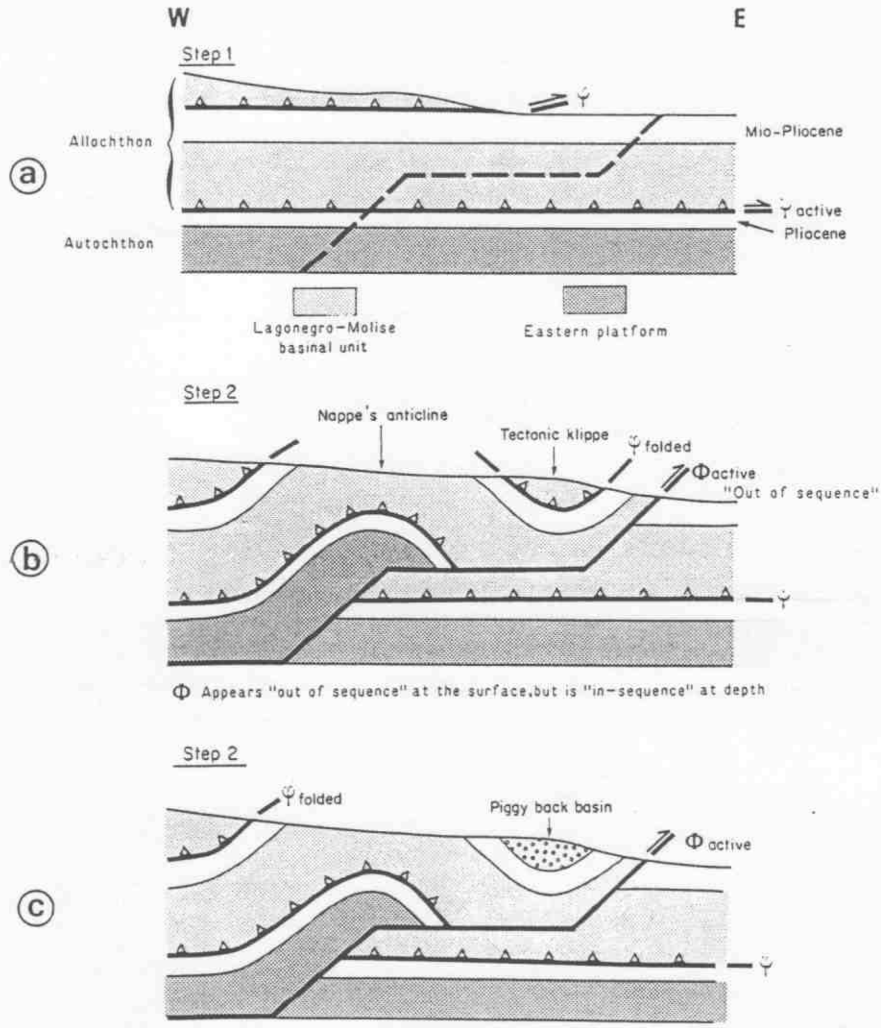

Fig. 7. Diagram illustrating the "out-of-sequence" paradox. The recent in-sequence involvement of deeper horizons in the wedge (i.e., fragments of the eastern platform) induces "out-of-sequence" structures at the surface. Nappe anticlines, klippen and piggy-back basins lie respectively above ramps and flats of the young thrust faults. (a) Intermediate geometry before shortening of the eastern platform at a time when the allochthon was already emplaced; (b) and (c) present geometry with location of tectonic klippen (b) and piggy-back basins (c) that relate to underlying flat.

thus suggests a large amount of shortening between the allochthonous platform duplexes and the autochthonous Puglian foreland, and this compares closely in the north to the Maiella fold (Fig. 2b), a tectonic window which exposes at the surface a fragment of the external Puglian domain underneath the "argille varicolori" allochthon.

West of the Apenninic thrust front, the Pliocene thrust faults that merge from the buried overthrust belt progressively crosscut shallower portions of the accretionary wedge (Bradano allochthon) and are thus responsible for a major part of its thickening, inducing the tectonic superposition of identical stratigraphic sections. In-sequence facing the deformation of the para-autochthon (eastern platform), these young faults locally crosscut older thrusts and may appear out-of-sequence from the surface (Fig. 7). Surface structures of the Bradanic allochthon define the buried geometry of these young thrust planes; nappe anticlines are linked to ramps, whereas synclines, klippen (Fig. 7b) or piggy-back basins (Fig. 7c) appear above the flats. As the deformation continuously progressed toward the outer zones, more units were successively underthrust and added to the accretionary wedge at its eastern border. This eastward migration of accretion led to a progressive uplifting and tilting of the already emplaced thrust sheets; this process was also responsible for the progressive deformation of piggy-back basins (Figs. 3, 8 and 9). Good examples are provided by the Sant' Arcangelo or Ofanto

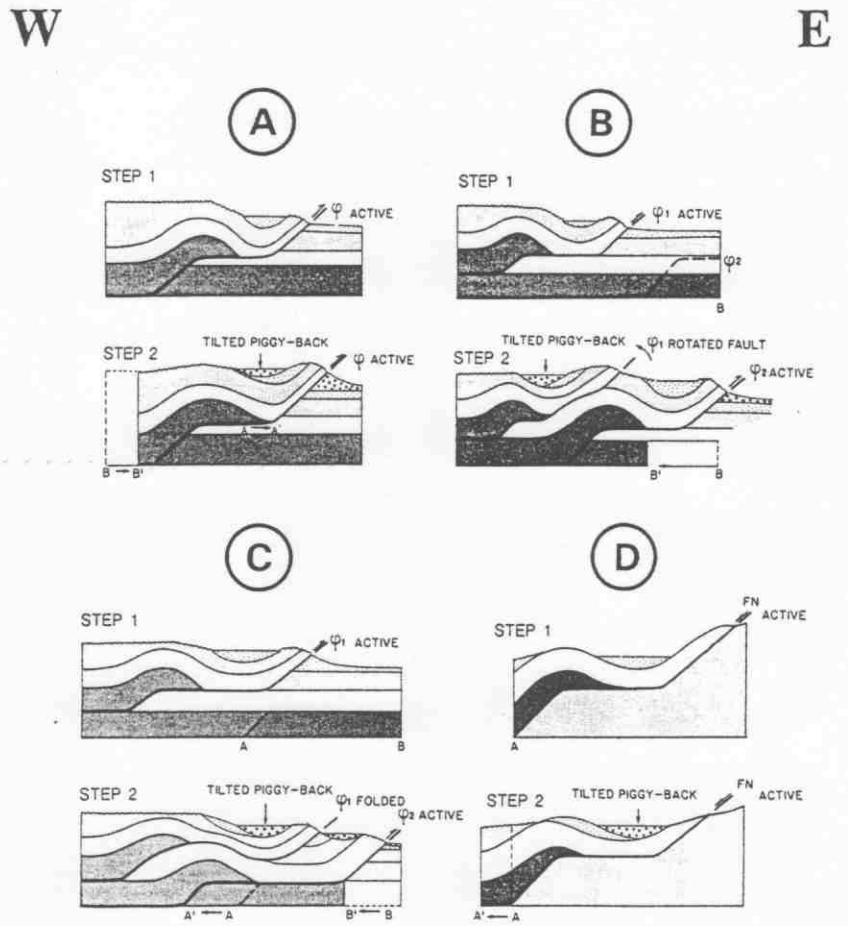

Fig. 8. Diagram showing the various deformations observed in the southern Apenninic compressive piggy-back basins. (A) migration of the depocenters in relation to the progressive emplacement of a single thrust. (B) migration of the depocenters in relation to recent accretion at the toe of the prism, with tilting and rotation of ancient thrust planes. (C) migration of the depocenters in relation to recent accretion at the sole of the prism ("underplating"), with folding of ancient thrust planes. (D) migration of the depocenters in distensive peri-Tyrrhenian piggy-back basins during reactivation as detachments of ancient Apenninic thrust faults.

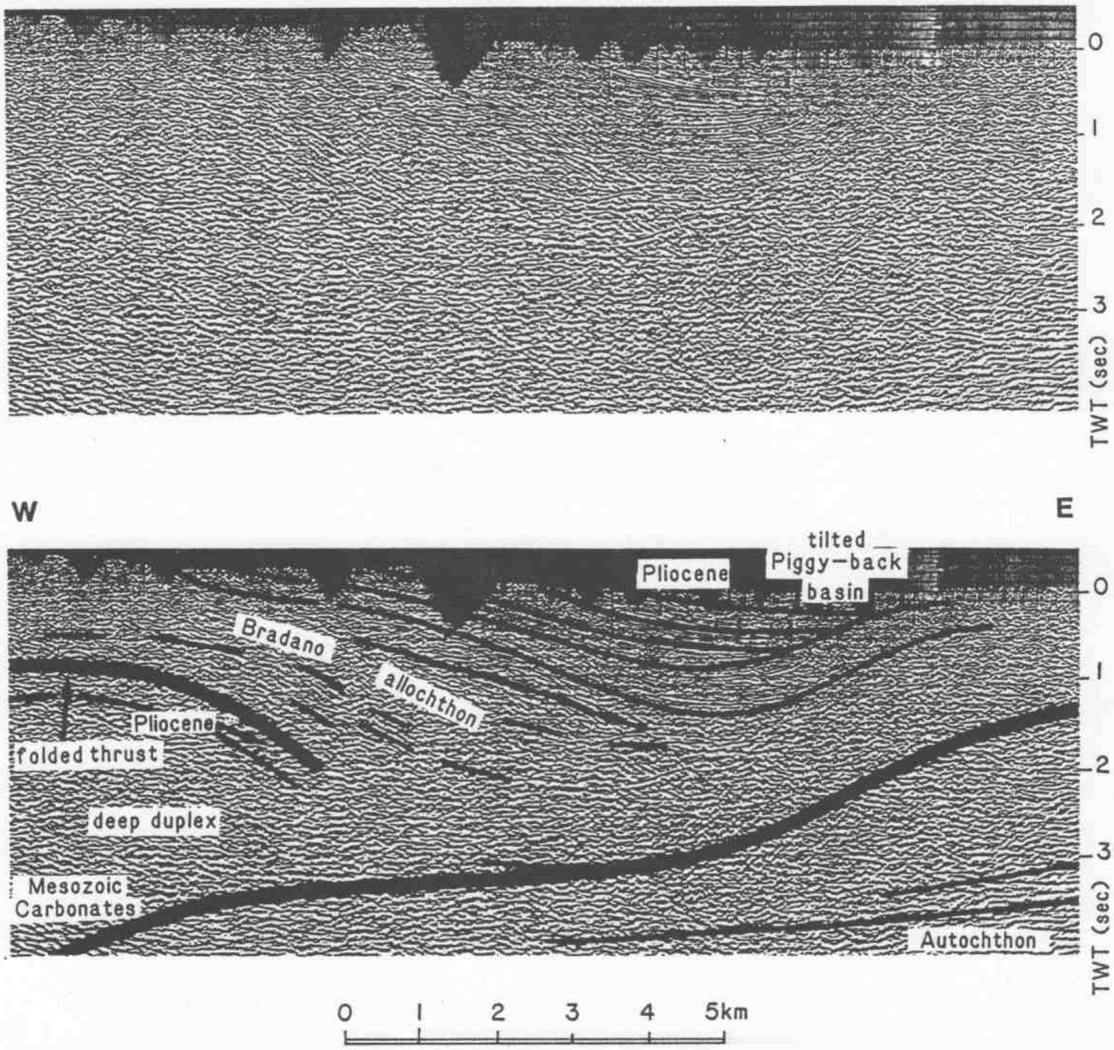

Fig. 9. Seismic reflection line across the Ofanto piggy-back basin. Note the eastward migration of the depocenters in relation to recent accretion at the rear of the prism ("underplating" with folding of ancient thrust planes).

basins (Fig. 2c). Furthermore, in each piggy-back basin, depocenters migrated continuously from east to west, in Pliocene and early Quaternary times, as a result of the progressive tilting of the basin with on-going accretion below the eastern front of the prism (Fig. 8A and B). A contrary west-to-east migration of the basin axis occurs locally where preexisting flats of the Pliocene thrust faults have been refolded rather than being only rotated (Figs. 8C and 9).

The thickening of the crust observed beneath the southern Apennines shows that the basement was involved in the deformation. Unlike thin-skinned models proposed elsewhere [20,33,34], the basal detachment of the accretionary wedge cannot be drawn with a constant flat or gentle westward dip as far west as the Tyrrhenian coast. On the contrary, the basal decollement must dip steeply beneath the Apennines in order to join the Benioff plane and should thus progressively involve deeper basement levels. In the southern part of the Bradano trough (Calvera area), relatively deep reflection data (down to 9 s TWT) have recently been recorded, which clearly image basement involved structures in the eastern platform (Fig. 6).

As deformation continuously progressed eastward, deeper structural levels in the west were also progressively involved in the tectonics. They can be compared with underplating phenomena proposed in submarine accretionary wedges. Recent thrust planes emerging from the deepest detachment levels crosscut shallower ancient structures (Figs. 6 and 7). Usually recognized from the surface as appearing to be "out-of-sequence-thrusts", they effectively participate in the accretionary wedge's growth [35]. Because these structures are continuations of deeper-level thrusts that are linked to shallower thrusts to the east and result from deep-seated duplexing, the concepts of an "out-of-sequence" thrusting event and underplating are related but not independent.

Unlike conditions that have been described in many active prisms [3], no shallow backthrusting has been demonstrated along the southern Apenninic thrust front. Nonetheless, local wedging may occur between the western platform and the Bradano allochthon (Fig. 6). Effectively, due to the early pre-Messinian inversion of the Lagonegro-Molise basin and to the resulting delamination of the Tertiary sedimentary infill, plastic "argille varicolori" and related allochthonous materials emplaced both eastward on the foreland, and westward on the western platform, but well before its Mesozoic substratum itself was involved in the Apenninic accretionary wedge. Nonetheless, this is more a unique form of extrusion tectonics rather than a specific phase of backthrusting. A frontal backthrust has also been proposed [33] to account for the present east-dipping geometry of the Plio-Quaternary molassic beds which lie along most of the Bradano allochthon. This geometry appears local because the contacts between the molassic deposits and the allochthon are usually depositional. Alternatively, this geometry is more likely the surface expression of the most recent outer ramp anticline developed above a frontal blind thrust (Figs. 2 and 6).

6. Role of fluids in the accretionary wedge: melange formation and dewatering processes

Fluid circulations in accretionary wedges have recently elicited increasing scientific interest.

Examples of ancient deformations are exposed in the melanges and broken formations of the southern Apenninic accretionary wedge. Best expressed in the Bradano allochthon, they can be interpreted as the result of similar fluid-related processes, which were active at a time when the prism was still submerged. The Cenozoic depositional history of the Lagonegro-Molise basin led to the preservation of undercompacted Late Cretaceous to Eocene red and green argillites (the "argille varicolori") at the bottom of a thick Oligocene to Neogene turbiditic sequence [1]. Dewatering of the basinal sediments was not completed until after they were incorporated into the Apenninic wedge. Similar to modern accretionary prisms, a part of the interstitial fluids was expelled along major thrustplanes, whereas the remaining water circulated in the extensive turbiditic sandstone reservoirs of the allochthon. Direct evidence of this ancient fluid circulation is confirmed by two sets of observations:

(1) Mud diapirs have frequently been imaged by seismic reflection profiles in Plio-Quaternary sediments that lie above the Apenninic frontal thrust, either north of Gargano, or in the Gulf of Tarento. These mud diapirs result from the expulsion of fluids that traveled along the accretionary wedge's basal decollement.

(2) The spatial relations and the internal structure of the melanges and broken formations are best explained as the result of a tectonic shearing occurring at the base of the Bradano allochthon during a phase when the melange matrix was emplaced in overpressured conditions. These chaotic formations are indeed restricted to the neighborhood of main thrust soles. Even though the Apenninic melange and broken formations were emplaced during a compressive tectonic event, extensional boudinage and open fractures are the only microstructures preserved in the blocks of hard rocks (knockers) (Fig. 10). They thus attest to high fluid pressures, which are necessary to explain the lack of preferential σ_1 orientation during the deformation (no stylolith has ever been observed in limestone knockers). Moreover, the argillitic matrix of the melange is itself slightly sheared ("argille scagliose"), which may explain its contemporaneous dewatering. The water expelled from the undercompacted pelitic matrix would thus have provided the fluids required to explain the brittle deformation of the interbedded hard rocks. The occurrence of such an overpressured sole at the base of allochthons would have greatly facilitated tectonic transport, and this

Fig. 10. Open fractures related to high fluid pressures in hard-rock knockers inbedded in the sheared argillitic matrix of the melange ("argille varicolori").

would probably explain the lack of any penetrative deformation in the underlying sediments of the lower plate. Individual melange belts are commonly several hundred meters thick above the underlying thrust planes of the Bradano allochthon, but, because of shearing, the initial thickness of the undercompacted argillitic levels ("argille varicolori") is poorly defined.

7. Gravity processes in the accretionary wedge

The southern Apenninic accretionary wedge reflects superimposed tectonics, expressed by the reactivation or deformation of earlier structures. Mechanical models have been proposed to explain the progressive geometric evolution of a tectonic wedge, specifying the role of both out-of-sequence thrusts and backthrusts [3,36] as well as the role of extensional faulting [37] to preserve the critical taper of a Coulomb wedge.

Despite this, the only superficial out-of-sequence thrusts observed in the Apennines appear in fact in the right sequence when seen in the context of the deeper basement structural level. Such a conclusion could probably be extended to most other accretionary wedges and be in part connected with "underplating". Moreover, no clear shallow backthrust has ever been defined in the Bradano allochthon. On the contrary, probably as a consequence of its crustal root and uplift above sea level, erosion, gravity sliding and normal faulting appear to be major parameters which control the morphologic balance of the Apenninic wedge. The Apennines are characterized by synchronous distensive and compressive deformations. Compression occurs along the active toe of the prism and at deeper levels to the west along the basal decollement of the allochthon. Compression probably results from frictions along the up-

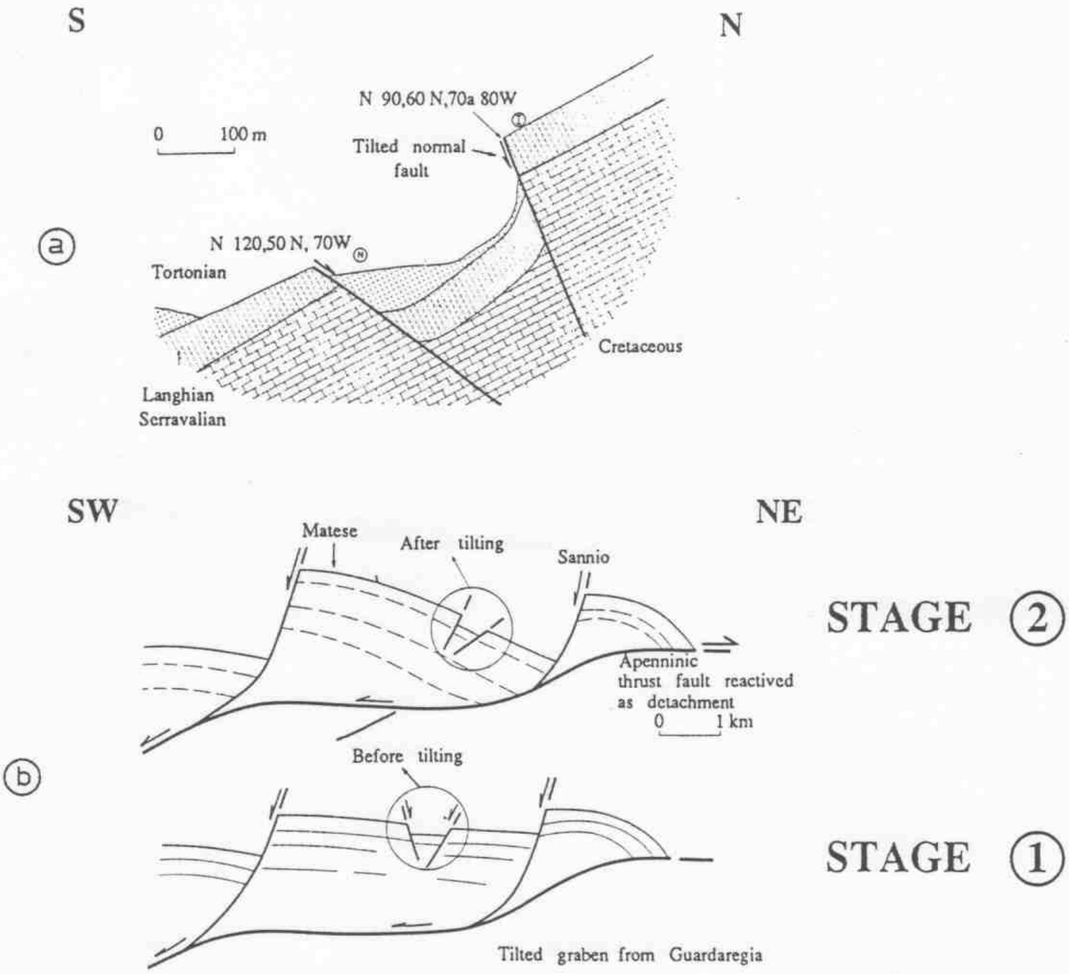

Fig. 11. Rotated normal faults and tilted graben of Guardaregia (western platform, Matese area, see Fig. 1 for location). Due to a shallow detachment level, fragments of the western platform are affected by large rotations. Note the apparent reverse fault, which in fact represents a rotated normal fault. (a) geological section; (b) the two evolutive stages (normal faulting and later rotation).

per surface of the underthrusted lower plate (Benioff plane), as evinced by focal mechanisms. On the contrary, distension occurs preferentially in the surficial parts of the western allochthons, from the highest elevated parts of the belt to the Tyrrhenian Sea (Fig. 5). A distensional mechanism accounts for the shallow seismicity observed at present in the Apennines [38–40]. These peri-Tyrrhenian normal faults thus help to extend and thin the crust but also result in part of the gravitational readjustments between the high Apennines (2.5 km above sea level) and the deep Tyrrhenian Sea floor (3.5 km below sea level).

Thus main normal faults are usually west or southwest facing, with steeply dipping planes at the surface level (between 60 and 80°). Block rotations involving carbonate strata attest to relatively shallow levels of detachment (Fig. 11). Seismic reflection data confirm the listric nature of these faults. The normal faults progressively flatten out at depth where they join ancient west-dipping east-verging thrust planes (Figs. 6 and 11). Early structural models of the Abbruzzi Mountains tentatively interpreted these spectacular normal faults found at the rear of main anticlines (Maïella, Morone, Fig. 2b) as features that were synchronous with compressive folding and with the deposition of flysch strata. More recently, however, precise timing analyses have shown these three sets of events to be diachronous [25]. The flysch represents foredeep deposition; folding and thrusting occurred later when the lower plate was incorporated in the accretionary wedge; and, finally, normal faulting occurred only after the thrusts had been uplifted.

Like during the compression, Plio-Quaternary syntectonic deposits infill distensional piggy-back basins located above the flats of the main detachment faults (Fig. 8D). Shifts in these distensional basin's axes help us decipher the precise timing of peri-Tyrrhenian normal faulting, which was coeval with compression farther east.

8. Conclusions

As in modern submerged prisms, fluid circulations and dewatering processes were probably major phenomena in the Apenninic wedge. The main shortening and deformation thus appear to be preferentially located near overpressured horizons. Compressional and distensional stress regimes have been concomittant through time in the distinct parts of the wedge: (a) the compressional deformations are essentially located along the sole thrust of the prism (which branches at depth on the Benioff plane); and (b) the distensive deformations occur above the thickened crustal roots (areas of major uplift). Various processes have been proposed to account for the growth of submerged accretionary prisms and for them to maintain their critical taper. They include: (1) accretion at the toe, with the progressive tilting of ancient thrust sheets; (2) underplating; (3) out-of-sequence thrusting; and (4) sedimentation in the slope basins. This onshore study confirms the major incidence of toe accretion in the growth processes of a tectonic wedge and shows that underplating and out-of-sequence thrusting are two phenomena related to deep-seated duplexes. We indeed consider these terms as misnomers just because they result from in-sequence thrusting at depth, with a jump between two distinct decollement levels.

The deep mechanisms which help to decouple the prism from the subducted plate cannot be imaged here without deep seismic. As opposed to a submerged prism, the Apenninic wedge does not show any major shallow backthrusting related to a cryptic backstop. Noneless, we infer that a physical connection still occurs between the Apenninic frontal thrusts and the synchronous peri-Tyrrhenian listric faults (Fig. 12). A regional backshear motion is effectively required to balance at depth the basement shortening, and a crustal backstop probably also exists beneath the Apennines as in other accretionary wedges. Westward motion along the roof thrust of this basement indenter is nevertheless entirely transferred to the basal detachment of the peri-Tyrrhenian listric faults, which mask at the surface the deeper backthrusting mechanisms. In addition to these reverse faults and to synchronous sedimentation in the piggy-back basins, normal faults at the rear of the wedge are an other parameter which maintain the critical taper of the Apenninic accretionary wedge and are thus the principal structures that distinguish this uplifted and emerged prism from submerged ones. Unlike the models proposed earlier [37], the normal faults of the Apennines do not face the subduction trough and do not help

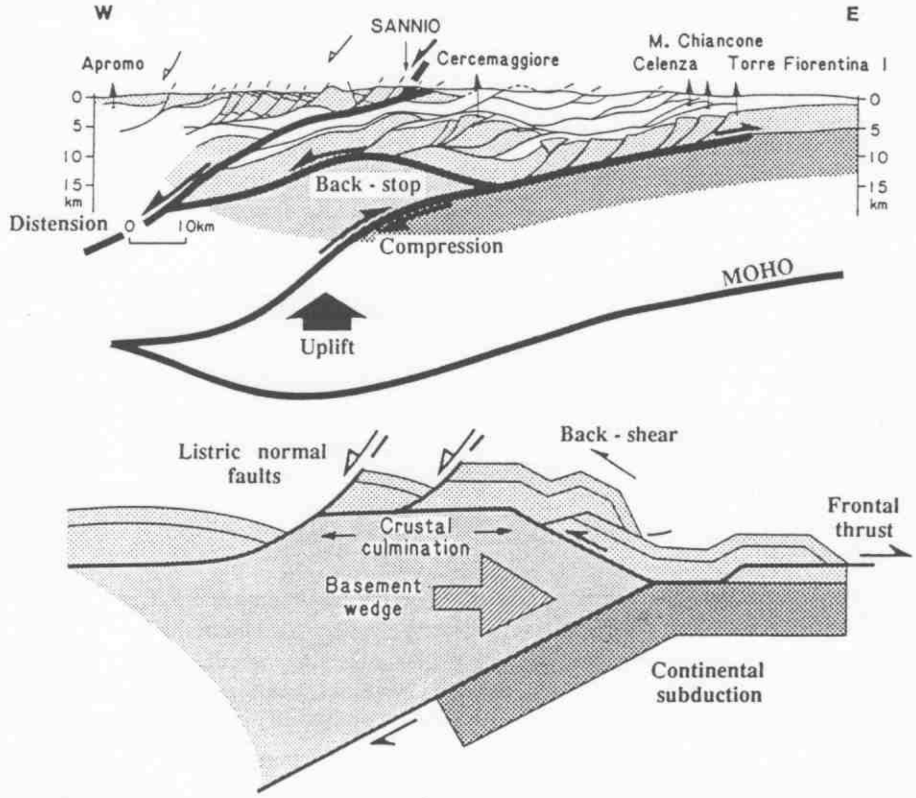

Fig. 12. The Apenninic basement backstop, and the connection between peri-Tyrrhenian listric faults and the Apenninic frontal thrusts. Note that the inferred deep basement shortening is only partially balanced in the cover by the frontal thrusts. A regional backshear motion is thus required at the roof of a deep crustal wedge, but is masked at a surface level by the synchronous peri-Tyrrhenian listric faults that branch on this major detachment.

extend the wedge toward the foreland. On the contrary, they progressively peel off the inner zones of the belt and participate in the "collapse" of a previously thickened continental crust [41]. Probably directly related to the opening of the Tyrrhenian sea, these faults contribute effectively in filling " the hole" represented by the Sea formed, and as a whole, the rear part of the wedge is extending westwards.

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