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Structural evolution of the Lucanian Apennines, southern Italy

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Abstract—In this paper we present a study of an entire segment of the Southern Apennines of Italy, extending from the Pollino mountain range to the south, to the Agri Valley to the north, in which all the units of the chain are represented. Combining regional information with detailed structural data obtained from the different tectonic units forming the orogenic belt, the structure as well as the tectonic evolution of this portion of the orogenic belt are proposed.

The overall architecture of this segment of the Southern Apennines mountain chain represents the result of a complete orogenic cycle in which oceanic subduction, syn-collisional and post-collisional events are well recorded. Structurally, this segment of the orogenic belt exhibits two distinct structural levels, separated by a major detachment surface (the sole thrust of the Accretionary wedge), that occur at the surface in the allochthonous nappes and at depth in the Adria continental margin. The upper level is characterized by an imbricated fan system affecting the allochthonous terranes emplaced during oceanic subduction and the first stages of continent–continent collision. The lower level is represented by a duplex geometry that has developed in the post-collisional stage, during evolution of the foreland migrating thrust system, involving the carbonate platform–basin system of the Adria block. During the last stages of the mountain building process, when the foreland thrust migration was locked by the thickening of the colliding continental crusts, the Southern Apennines were thus affected by a severe strike-slip tectonics that dissects the entire mountain belt deeply modifying the previous thrust geometry.

INTRODUCTION

The Southern Apennines are part of the central Mediterranean orogenic belt and are made up of a pile of nappes derived from the deformation of different Mesozoic–Cenozoic domains as the result of the Late Cretaceous–Quaternary convergence between the African and European plates. The Mesozoic oceanic lithosphere of the Neotethys domain was subducted beneath the European continental margin causing, first, the closure of large portions of the oceanic basin and then the continent–continent collision. Post-collisional processes generated foreland-migrating thrust and fold belts along the African continental palaeomargin, whereas subduction of remnants of the oceanic lithosphere (Ionian basin) developed arc-shaped structures (Calabrian arc) with associated extensional basins (Tyrrhenian basin) at the rear of the mountain belts (Dewey *et al.*, 1989; Ben Avraham *et al.*, 1990; Boccaletti *et al.*, 1990; Monaco and Tortorici, 1995).

The Lucanian Apennines, which are located at the northern border of the Calabrian arc where the innermost crystalline units are piled up (Fig. 1), are made up of different tectonostratigraphic units deriving from the deformation of the oceanic realm of the Neotethys and of the Adria continental margin. The frontal part of the orogenic belt overthrust the foreland–foredeep system represented, at present, by the Apulian platform and by the Bradano trough, whereas the inner portion of the chain is affected by normal faults which bound large tectonic depression filled by Upper Pleistocene–Holocene deposits (Hippolyte *et al.*, 1995).

The crustal structure of this portion of the orogenic belt is defined by a Moho discontinuity that reaches a depth of 40–45 km along the chain axis and progressively rises up to 25–30 km beneath the foreland domain (Boccaletti *et al.*, 1990). The mountain belt is also characterized by negative Bouguer anomalies (Morelli *et al.*, 1975), indicating the occurrence of deep-seated low-density bodies probably related to sedimentary nappes.

Presently the Lucanian Apennines represent a major boundary between two distinct extensional domains: the Southern Apennines and the Siculo–Calabrian rift zone. These domains are, in fact, characterized by active normal faulting that generates earthquakes with magnitudes reaching $7 > \mathbf{M} \geq 6$ in the Southern Apennines and $\mathbf{M} \geq 7$ in the Siculo–Calabrian zone. These relate to different extension directions, NE–SW and ESE–WSW, respectively (Anderson and Jackson, 1987; Westaway, 1993; Tortorici *et al.*, 1995; Monaco *et al.*, 1997).

The Lucanian Apennines are the only segment of the Southern Apennines where a complete section of

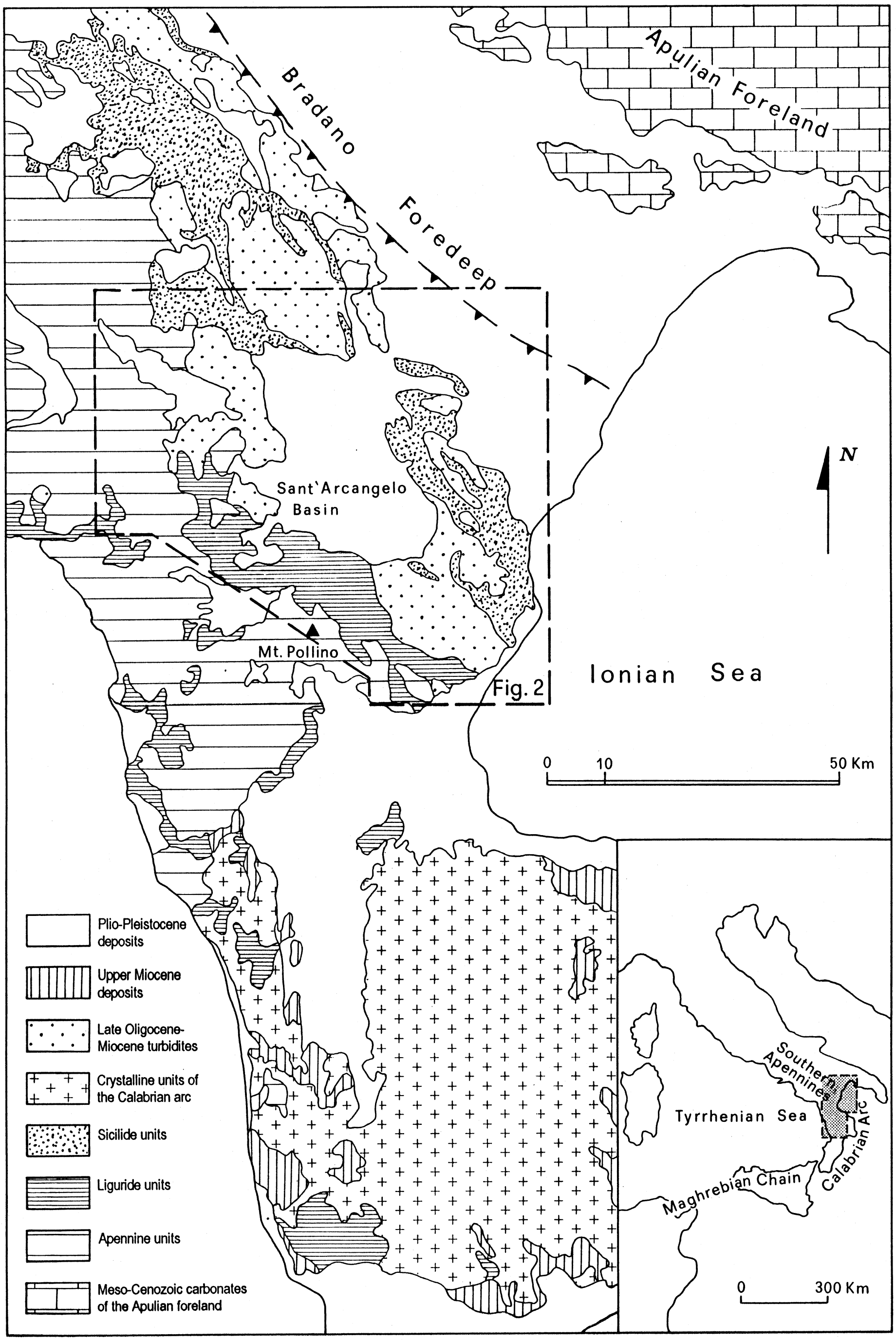

Fig. 1. Schematic structural map of the Southern Apennines. The line with triangles indicates the frontal thrust of the Apennine chain. Inset shows the position in Italy.

the orogenic belt is exposed. For this reason they have always been considered a key area for reconstructing the whole deformation history and for understanding the mountain building processes that occurred in the Southern Apennines. In order to explain the tectonic evolution of this area, that in recent years has also represented an important target for oil exploration, different studies have been carried out by many authors (Selli, 1962; Ogniben, 1969, 1985; D'Argenio *et al.*, 1973; Mostardini and Merlini, 1986; Endignoux *et al.*, 1989; Patacca *et al.*, 1990; Marsella *et al.*, 1995; Lentini *et al.*, 1996). These studies, mainly based on stratigraphic data and facies analysis of the different tectonostratigraphic units without being constrained by detailed structural data, do not provide information on the deformation processes and on the geometry and sequence of the different sets of structures formed at different crustal depths. Many structural works in the Southern Apennines have addressed aspects concerning the evolution of thrusting (Knott, 1987; Cello *et al.*, 1989; Monaco *et al.*, 1991; Hippolyte *et al.*, 1994, 1995; Monaco and Tortorici, 1995), strike-slip tec-

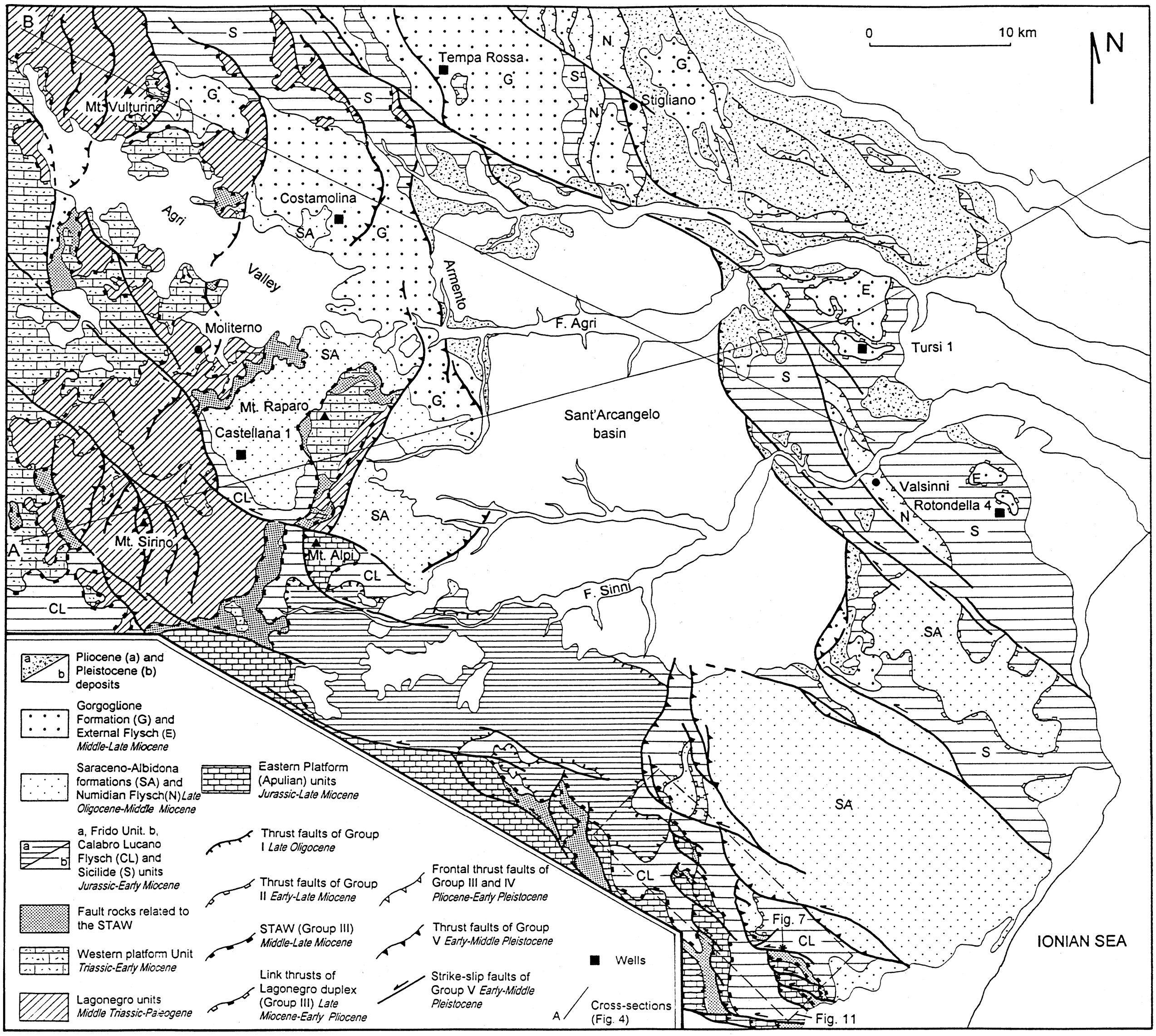

Fig. 2. Structural map of the Lucanian Apennines (location in Fig. 1).

tonics (Ghisetti and Vezzani, 1983; Monaco and Tansi, 1992; Monaco, 1993; Catalano *et al.*, 1993) and orogen-parallel extensional tectonics (Oldow *et al.*, 1993; Ferranti *et al.*, 1996).

In this paper we present a study of a complete segment of the Lucanian Apennines extending from the Pollino mountain range to the south, to the Agri Valley in the north, in which all the units of the chain are represented. The aim of this study, which combines regional information with detailed structural data, is to describe the geology and the structure of the Lucanian Apennines and to develop a tectonic model for this segment of the Southern Apennines. The study is mostly based on detailed field work carried out in key areas, the consequent reinterpretation of published geological maps (Ghisetti and Vezzani, 1983; Carbone *et al.*, 1991; Monaco *et al.*, 1994a; Servizio Geologico d'Italia, 1965, 1968, 1969, 1970a,b), on detailed structural analyses that define the geometric relations between the different sets of structures and on structural interpretations of well logs and seismic lines, including seismic reflection profiles of British Gas Rimi S.p.A., not in the public domain.

GEOLOGICAL SETTING

The overall structure of the Lucanian Apennines (Fig. 2) is characterized by two main structural levels: (i) an upper level represented by a multilayer tectonic complex made of allochthonous nappes (Apennine chain) belonging to the Neotethyan domain (Liguride and Sicilide complexes); and (ii) a lower level, represented by the eastern portion of the Adria block (Apulian platform), forming the Apulian belt and the western portion of the Adria block (Panormide and Lagonegro units). These two levels are separated by a well-documented major shear zone (Cello *et al.*, 1989)

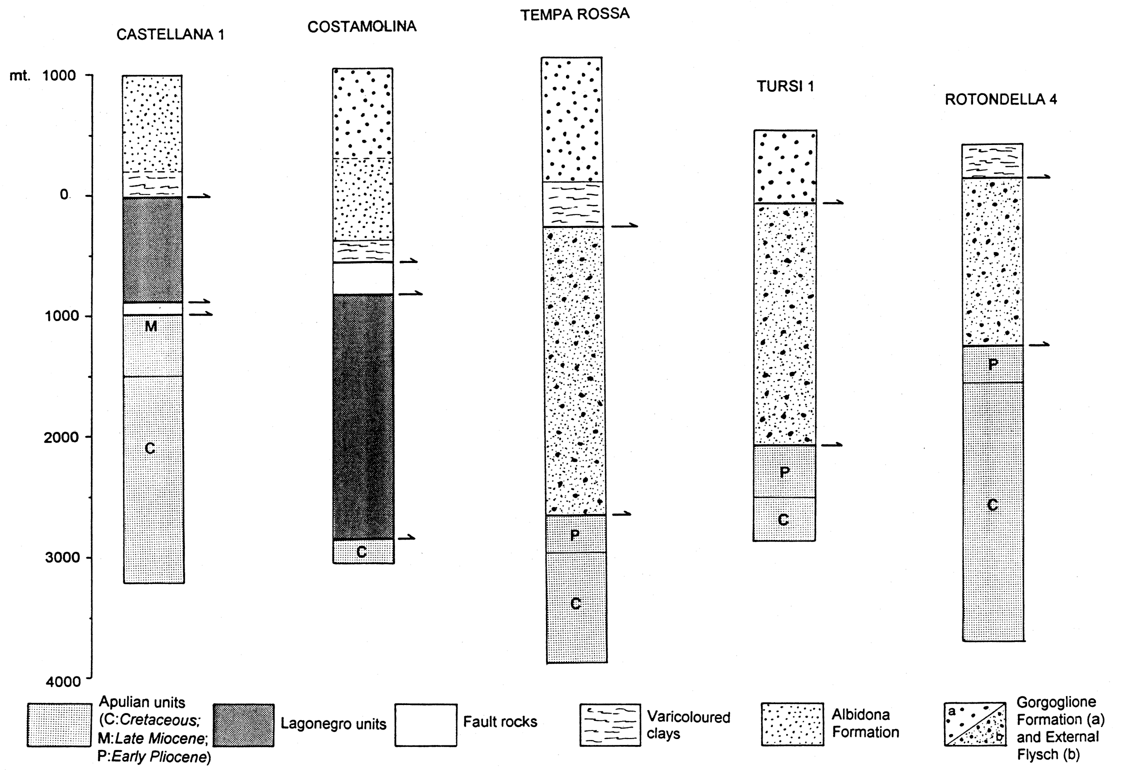

Fig. 3. Well log interpretations showing deep-seated structures of the Lucanian Apennines. Data from Mostardini and Merlini (1986), Schlumberger (1987), D'Andrea *et al.* (1993) and Lentini *et al.* (1996) (location in Fig. 2).

which, along the external front of the Apennine chain, develops above the Lower Pliocene–Lower Pleistocene deposits of the Apulian platform (AGIP, 1977; Mostardini and Merlini, 1986; Cello *et al.*, 1987, 1989; Catalano *et al.*, 1993; Monaco and Tortorici, 1994). On top of the allochthonous terranes are Plio–Pleistocene basins developed during the last phases of the thrust belt foreland migration.

Adria block tectonostratigraphic units

Apulian units. These units form the buried backbone of the Lucanian thrust belt and derive from deformation of the eastern portion of the carbonate platform of the Adria block (Apulian platform). This carbonate level, extending continuously beneath the major shear zone at a depth deeper than 2000 m, has been well identified by the seismic lines and well logs extensively carried out in this region for oil exploration (AGIP, 1977; Mostardini and Merlini, 1986; D'Andrea *et al.*, 1993).

The sedimentary cover of the Apulian domain is made up of Mesozoic–Cenozoic peritidal–pelagic carbonate platform sediments which unconformably rest above a thick Permian–Middle Triassic siliciclastic sequence (Puglia and Gargano 1 wells) which in turn cover a low-grade metamorphic basement (Gargano 1 well). In the Lucanian Apennines the Apulian carbonates, as derived from the analysis of the available well logs (Fig. 3) of Castellana 1, Tempa Rossa (D'Andrea *et al.*, 1993; Lentini *et al.*, 1996), Costamolina (Mostardini and Merlini, 1986; Schlumberger, 1987), Tursi 1 (Mostardini and Merlini, 1986) and Rotondella 4 wells, are made up of Cretaceous–Palaeogene limestones and Lower–Middle Miocene biocalcarenites covered by Miocene–Lower Pliocene terrigenous foredeep sediments. In this region Apulian carbonates are thought to crop out (Fig. 2) as tectonic wedges (e.g. Mt Alpi and Pollino region) extruded through the allochthonous terranes of the upper level of the chain by Pleistocene strike-slip related thrusts (Catalano *et al.*, 1993; Monaco, 1993).

Lagonegro units. These units crop out in a tectonic window exposed because of the structural culmination of Mt Sirino (Fig. 2). They lie tectonically above the Miocene–Pliocene sequences of the Apulian units and consist of two superposed nappes (Lagonegro I and Lagonegro II of Scandone, 1967, 1972) characterized by well-defined successions that reflect different portions of the primary basin and derive from the deformation of a western carbonate basinal domain of the Adria block. The sediments range in age from Middle Triassic to Early Tertiary, and are made up of a Middle Triassic sequence (Monte Facito Formation) of shallow-water terrigenous sediments including lens-shaped bodies of reefoidal massive limestones (Scandone, 1967, 1972; Ogniben, 1969). This sequence is covered by Upper Triassic–Lower Jurassic cherty limestones containing resedimented calcarenites and calcirudites grading upwards to Middle–Upper Jurassic

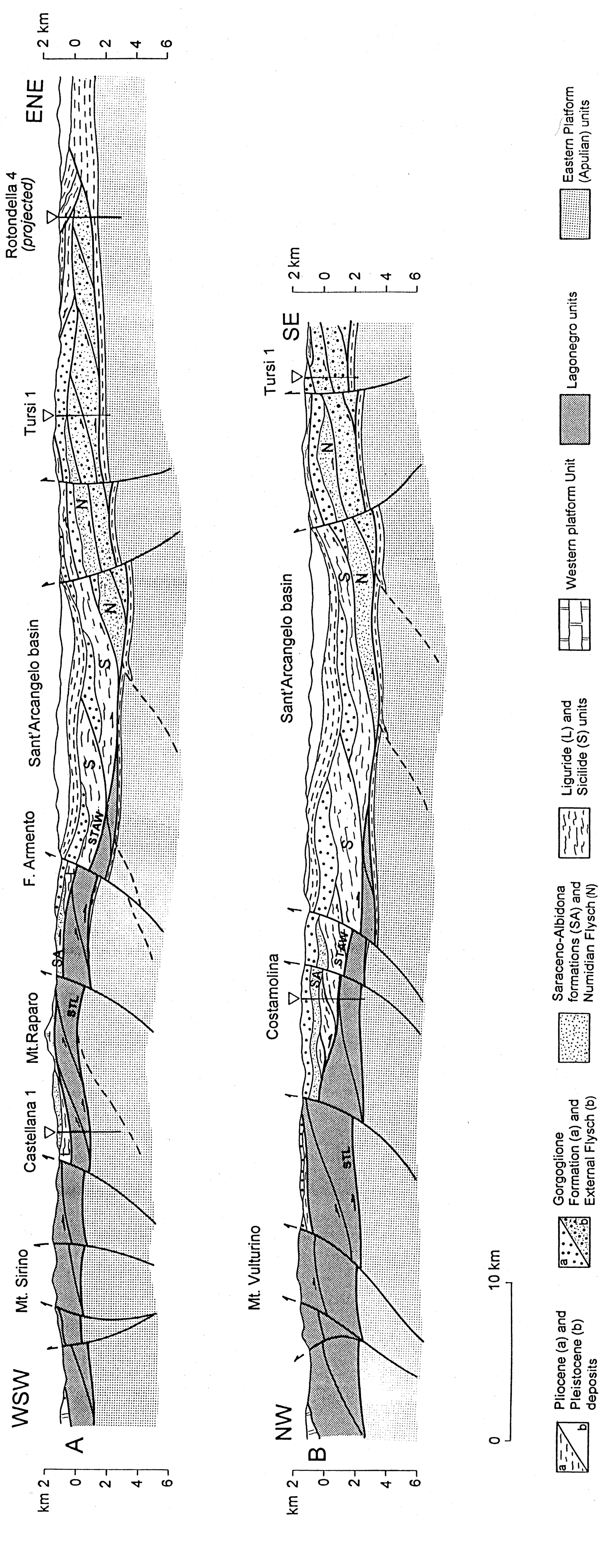

Fig. 4. Cross-sections through the Lucanian Apennines (location in Fig. 2).

polychrome radiolarites with intercalations of graded calcarenites. These sediments are capped by a turbiditic Cretaceous sequence (Galestri Formation) and by Upper Cretaceous–Lower Miocene siliceous argillites, varicoloured cherts, calcirudites, graded calcarenites and quartz-rich sandstones.

Western platform unit. This tectonostratigraphic unit corresponds to the Panormide units of Ogniben (1969) and to the Campano–Lucana platform of D'Argenio *et al.* (1973), and represents the westernmost portion of the Adria block. Tectonically overlying the Lagonegro sediments, it is stratigraphically made up of several hundred metres of Upper Triassic–Palaeogene platform carbonates capped by Lower–Middle Miocene biocalcarenites (Cerchiara Formation of Selli, 1957) and terrigenous turbitides (Bifurto Formation of Selli, 1957). The base of this unit is made of highly fractured dolomites and dolomitic limestones, and is characterized by pervasive cataclastic texture. It is assumed to derive from the shear deformation of different portions of this carbonate succession.

Neotethyan tectonostratigraphic units

These units, located above the main detachment surface separating the two horizons of the Lucanian Apennines, constitute as a whole the allochthonous nappes of the multilayer tectonic complex of the Southern Apennines mountain belt. They are represented by three main groups of terranes. Two of these, known as the Liguride and Sicilide complexes (Ogniben, 1969), derive from oceanic and/or thinned continental crustal domains, thus representing a remnant of an accretionary wedge developed during oceanic subduction (Ogniben, 1985; Cello *et al.*, 1989; Monaco and Tortorici, 1995). The third group is represented by three main turbiditic successions that show primary sedimentary relations with the Liguride and Sicilide terranes, and have been interpreted as the infilling of fore-arc and trench basins developed both above and in front of the accretionary prism (Monaco and Tortorici, 1995).

Sicilide units. These terranes crop out extensively along the frontal part of the Lucanian Apennines (Fig. 2) and constitute a remnant of the toe of the accretionary wedge. They are made up of several thrust sheets of Upper Cretaceous–Oligocene pelagic sediments (highly cataclastic varicoloured clays and marly clays) showing characteristics of mélange, with associated Upper Oligocene–Lower Miocene volcaniclastic turbidites.

Liguride units. In the Lucanian Apennines the terranes of the Liguride units, which as a whole represent the remnants of the innermost and deepest portions of the Neotethyan accretionary wedge, can be subdivided into two main groups. The first group includes the ophiolite-bearing un-metamorphosed terranes corresponding to the Calabro–Lucano Flysch unit (Monaco *et al.*, 1991), whereas, the second group corresponds to the Frido unit of Amodio-Morelli *et al.* (1976) and is made up of the ophiolite-bearing metamorphosed terranes (Fig. 2).

The Calabro–Lucano Flysch unit is represented by a broken formation (*sensu* Hsu, 1968) tectonically dismembered into several thrust sheets. The succession comprises a Cretaceous–Oligocene (?) horizon with pelitic matrix containing blocks of ophiolites and remnants of Upper Jurassic–Lower Cretaceous sedimentary rocks, Cretaceous–Middle Eocene black shales and Upper Oligocene volcaniclastic turbidites (Monaco and Tortorici, 1995 and references therein).

The Frido unit represents the uppermost tectonic unit of the Liguride Complex. It overthrusts the Calabro–Lucano Flysch unit, and is made up of metamorphosed and polydeformed terranes containing blocks of oceanic and continental type rocks. This unit consists of metamorphased shales and limestones, marbles containing relics of aragonite (Vezzani, 1969; Spadea, 1976), and calcschists containing Early Oligocene microfauna (Bonardi *et al.*, 1993). The meta-ophiolites show in places HP–LT metamorphism mineral assemblages overprinted by a greenschist-facies metamorphism (De Roever, 1972; Spadea, 1976, 1979; Lanzafame *et al.*, 1979; Beccaluva *et al.*, 1982; Monaco *et al.*, 1991).

Fore-arc and trench basin turbidites. These sediments are made up of two major successions corresponding to the Numidian Flysch and to the Saraceno and Albidona formations which show primary relations with the accretionary wedge terranes and have been interpreted as sediments infilling trench and fore-arc basins, respectively (Monaco and Tortorici, 1995).

The Numidian Flysch is represented by a 700 m thick Lower (Aquitanian)–Middle (Langhian) Miocene turbiditic quartz-rich sequence, sandwiched between different varicoloured clay thrust sheets of the Sicilide units along the frontal portion of the thrust belt (Fig. 2).

The Saraceno Formation usually outcrops as thrust sheets tectonically overlain by the Calabro Lucano Flysch unit. Its original relationships with the ophiolite-bearing terranes are only visible in a few places where it unconformably overlies the Calabro–Lucano Flysch unit (Fig. 2). It is represented by an Upper Oligocene–Lower (Aquitanian) Miocene (according to Monaco and Tortorici, 1995) calcareous turbiditic sequence, containing siliciclastic levels at the top deriving from the unroofing of the accretionary wedge terranes (Critelli, 1991; Monaco and Tortorici, 1995).

The Albidona Formation is represented by 800 m thick, Lower (Burdigalian)–Middle (Langhian) Miocene (Bonardi *et al.*, 1985), siliciclastic turbidites containing conglomerate beds with boulders of continental basement rocks, ophiolites (metabasalts, serpentinites), andesite and rhyodacite volcanics (Lanzafame *et al.*, 1977).

Suture-related basins turbidites

These successions, represented by the Gorgoglione Formation and by the External Flysch, lie unconformably over the previously different imbricated accretionary thrust sheets of the accretionary wedge terranes and fore-arc and trench basin turbidites. The Gorgoglione Formation is represented by a thick (more than 1000 m at the surface) Middle (Langhian)–Upper (Tortonian) Miocene (Boenzi and Ciaranfi, 1970) quartz–felspathic turbiditic sequence. The External Flysch is made up of Middle (Langhian)–Upper (Tortonian) Miocene (Ogniben, 1969) calcareous turbiditic sequences cropping out along the frontal part of the chain (Fig. 2), where it is tectonically covered by the accretionary wedge terranes of the Sicilide units and the Numidian Flysch forming, altogether, an imbricated stack over the Pliocene sediments of the Apulian platform.

Thrust top basin sequences

These sediments are made up of two major Plio-Pleistocene successions (Vezzani, 1967), separated by a regional unconformity, which represent the infilling of the Sant'Arcangelo Basin, a basin developed above the different tectonic units of the chain (Fig. 2). The first succession consists of 1300 m thick Middle–Upper Pliocene marine terrigenous deposits, while the second is 1600 m of Lower–Middle Pleistocene marine sediments grading upwards into a coarse-grained fluviatile–deltaic sequence (Vezzani, 1966, 1967).

STRUCTURES

The tectonic units cropping out in the Lucanian Apennines display several sets of structures that record a complex deformation history which led to the building of the Southern Apenninic chain. Based on structural geometry and overprinting relationships, five main groups of structures related to the different stages of the tectonic evolution of this portion of the orogenic belt have been recognized. We consider that the overall architecture of this portion of the Lucanian Apennines to have resulted from five phases of superposed structures related to a forelandward migrating thrust and fold system (I–IV) and to subsequent strike-slip tectonics (V) described below. Two deep geological transects are also presented (Fig. 4) to illustrate the major structures belonging to the different groups of structures. The cross-sections were originally constructed at a 1:25,000 scale, integrating surface geological and structural data resulting from field survey with the available deep well logs and seismic reflection lines. The orientations of the cross-sections have been chosen as those best suited to describe the geometry of the major structures related to both systems. Cross-section A is approximately parallel to the transport direction of the thrust and fold system, whereas profile B is

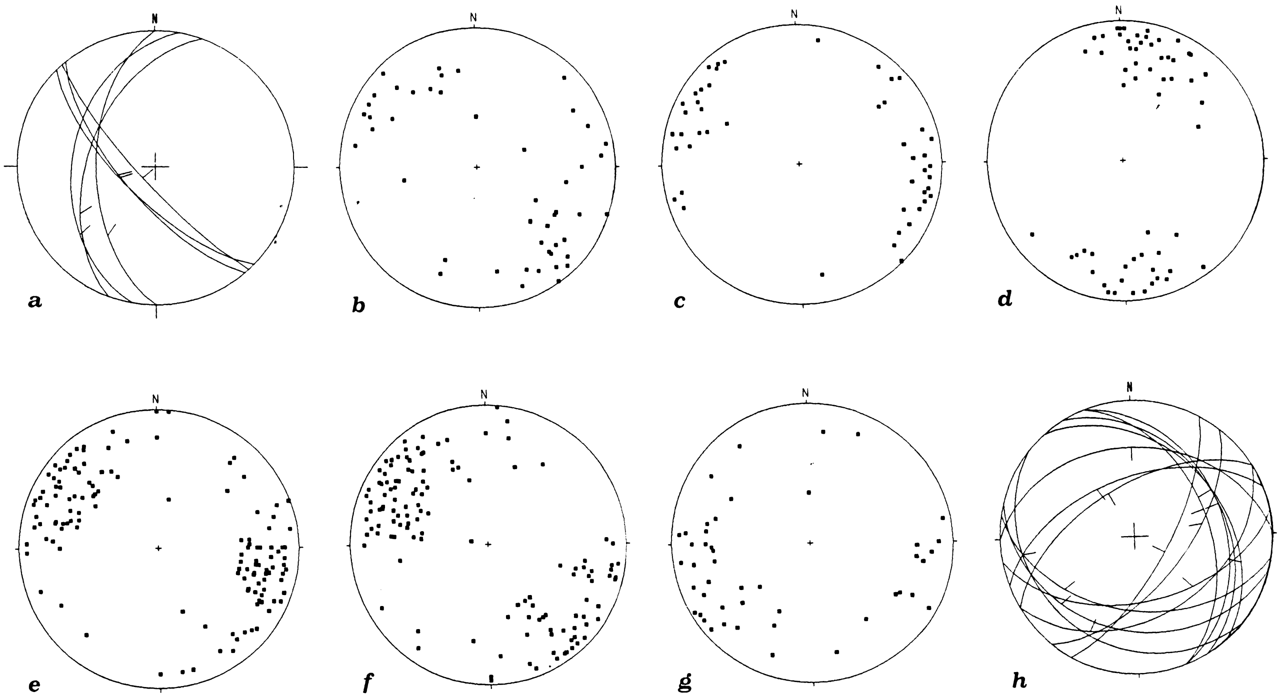

Fig. 5. Lower-hemisphere equal-area projections of Group I structures from the Calabro–Lucano Flysch, varicoloured clays (a & b) and Frido units (c–h). (a) Attitude of major T_{Ia} thrust planes and associated slickensides; (b) & (c) F_{Ib} fold axes; (d) L_{Ib} stretching lineations; (e) F_{Ic} fold axes; (f) L_{Ic} crenulation lineations; (g) L_{Id} stretching lineations; (h) attitude of major T_{Ie} thrust planes and associated slickensides. Data after Monaco and Tortorici, 1995.

normal to the major contractional structures activated by the strike-slip tectonics.

Group I structures

The structures of this group were developed during the construction of the accretionary wedge during the oceanic subduction and the early stages of the continent–continent collision. The structures are considered the result of a non-coaxial progressive deformation with five main tectonic events developed at different times and at different structural levels (Monaco, 1992; Monaco and Tortorici, 1995).

The earlier structures of this group are those related to the tectonic inclusion of oceanic slices and blocks and to the formation of tectonic mélanges in the different units (Frido and Calabro–Lucano Flysch units) of the Liguride Complex and of the varicoloured clays of the Sicilide Complex. During this event, blocks of ophiolites and continental-type rocks (gneiss and amphibolites) were included within the shale sequence of the Frido unit. In the gneissic rocks relics of mortar-type structures evolving to a cataclastic–mylonitic foliation (S_m) are recognizable (Cirrincione and Monaco, 1996). In the Calabro–Lucano Flysch unit and in the Sicilide terranes, this deformation is marked by the development of mélange characterized by internal thrusting (T_{Ia}) and by the formation of intrastratal duplexes and asymmetric boudins (Lister and Snoke, 1984) indicating a present-day N–NE direction of transport (Fig. 5a).

In the Frido unit, the tectonic mélange formation was followed by the development of a pervasive tectonic foliation (S_{Ib}) affecting both the matrix (phyllites and calcschists) and blocks (metabasites and gneisses). This planar fabric is characterized by the occurrence of glaucophane, lawsonite and occasionally aragonite in both metabasites and gneisses blocks and in the calcschists. A roughly NNE–SSW-oriented mineral stretching lineation (L_{Ib}) is locally observed on the schistosity surfaces that are affected by rootless isoclinal intrafolial folds (F_{Ib}), mostly showing WNW–ESE oriented fold axes (Fig. 5c & d).

Centimetric to metric, asymmetric and NE-verging isoclinal folds (F_{Ib}) with axes showing a NW–SE orientation (Fig. 5b) have also been observed in both the Calabro–Lucano Flysch unit as well as in the varicoloured clays of the Sicilide Complex. These structures in the main fold-hinge zones are accompanied by a cm-spaced cleavage (S_{Ib}) which in turn forms well-developed pencil structures. Folding most probably developed during the imbrication, as well as the overthrusting (T_{Ib}) of the Calabro–Lucano Flysch unit above the Sicilide terranes, which led to the formation of the different tectonic slices that presently characterize these units.

In the Frido unit rocks the earlier S_{Ib} foliation is deformed by centimetre- to metre-sized, asymmetric NNE-verging folds (F_{Ic}) with NW–SE-trending axes (Fig. 5e). Crenulation cleavage (S_{Ic}) is well developed in the hinge zones of major F_{Ic} folds, giving rise (Fig. 5f) to a NW–SE-trending S_{Ib}-foliation–crenulation intersection lineations (L_{Ic}).

The Frido unit also exhibits a set of structures developed in the brittle–ductile transition. These are represented by shear zones (T_{Id}) which gave rise to the several thrust sheets characterizing this tectonic unit. The shear zones are marked by cataclastic belts superimposed on the S_{Ib} foliation. Asymmetric foliation boudinage, evolving to a typical mélange (Platt and Vissers, 1980; Fisher and Byrne, 1987; Needham and Mackenzie, 1988) characterized by block in matrix structures (Silver and Beutner, 1980; Raymond, 1984), is developed along the major shear zones, where extensional faults with associated stretching lineations (L_{Id}) are found (Fig. 5g). This event was followed, at shallow crustal levels, by the overthrusting of the whole Frido unit on top of the unmetamorphosed terranes of the Calabro–Lucano Flysch unit. This overthrust (T_{Ie}), with associated regional asymmetrical large folds (F_{Ie}) which deform all the previous structures, is marked by the occurrence of cataclasite bands of variable thicknesses and by slickensides showing a present-day NE tectonic transport direction (Fig. 5h).

Group II structures

The structures of Group II are those post-dating the uplift of the Frido unit during the early stage of the continent–continent collision. This group includes the structures that deform the primary sedimentary relationships between the mélange terranes of the accretionary wedge (Liguride and Sicilide allochthonous terranes) and their Oligocene–Miocene turbiditic covers, forming the different thrust sheets characterizing the allochthonous terranes of the Lucanian Apennines.

These structures are represented by NE-migrating thrust faults (T_{II}) which, from southwest to northeast, bring the Calabro–Lucano Flysch unit above the sediments of Saraceno–Albidona formations (Sinni Valley) and the varicoloured clays of the Sicilide Complex on top of Numidian Flysch (Figs 2 & 4). Towards the northeast, thrust faults (Fig. 6a & b) give rise to the duplication of thrust sheets formed by varicoloured clays with its sedimentary cover of Gorgoglione Formation and the overthrusting of the latter on top of the External Flysch (Figs 2 & 4). The major thrusts are accompanied by flexural folding (F_{II}) which defines NW–SE-trending, overturned to recumbent ramp anticlines and footwall synclines. These flexural folds are accompanied by mostly NW–SE-oriented asymmetric parasitic folds (Fig. 6c & d) in the limbs, and symmetric folds in the hinge regions. In the Saraceno Formation parasitic folds mainly show a chevron geometry with typical associated structures resulting from dilation in the hinge regions (saddle reef), and flow of

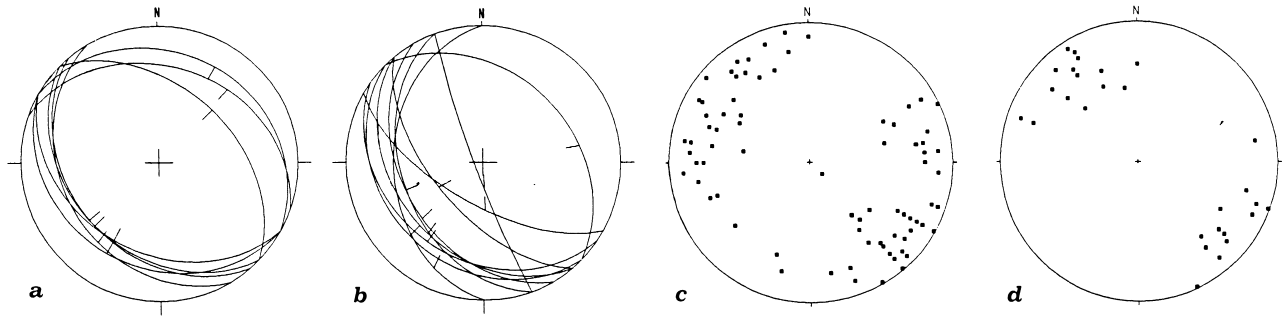

Fig. 6. Lower-hemisphere equal-area projections of Group II structures. (a) & (b) Attitude of major T_{II} thrust planes and associated slickensides (ticks) occurring in the Saraceno-Albidona and Gorgoglione formations; (c) & (d) F_{II} fold axes occurring in the Saraceno-Albidona formations (after Monaco and Tortorici, 1995).

incompetent material from the limbs to the hinge zones and hinge collapse. Asymmetric kink folds with steep SW-dipping axial surfaces are also associated with this deformation event in the rocks of the Saraceno Formation. Along the major thrust planes, small-scale duplexes and slickensides indicating a general NE–NNE transport direction can be observed (Fig. 6a & b).

Group III structures

This group includes all the structures related to the large-scale overthrusting process which led to the tectonic superposition of the whole accretionary wedge (Liguride and Sicilide terranes) and the related Oligocene–Miocene terrigenous sediments on top of the carbonate domains belonging to the Mesozoic palaeomargin of Adria block (western platform, Lagonegro and Apulian units). The most important structure of this group is thus represented by the main sole thrust of the accretionary wedge (STAW) which separates the allochthonous terranes from the underlying carbonate units. In this group are also included the structures that affect the different portions of the Adria block giving rise, beneath the STAW, to the formation of duplex geometry characterizing the western platform and Lagonegro units and the Apulian belt.

Sole thrust of the accretionary wedge (STAW). The STAW is represented by a sub-horizontal shear zone (T_{III}) of regional extent (Fig. 2). As shown by the interpretation of several seismic profiles and by well log analyses (Mostardini and Merlini, 1986; Cello *et al.*, 1987, 1989), it mainly occurs at depth but locally crops out due to the effects of extensive Pleistocene strike-slip tectonics (cf. Group V structures below).

At the surface (Fig. 2) the STAW is well exposed in the Lagonegro region, where it brings the Frido and the Calabro–Lucano Flysch units, with the overlying sediments of the Saraceno and Albidona formations (Moliterno–Mt Alpi area), and the varicoloured clays of the Sicilide Complex and the terrigenous sequences of the Gorgoglione Formation (Agri Valley), into contact with the Lagonegro units. In the Pollino mountain range and at Mt Alpi the STAW superposes the different tectonic elements of the Liguride Complex directly onto the carbonate platform units probably belonging to the Apulian belt (Monaco *et al.*, 1994a,b).

The shear zone is up to about 200 m thick, and consists of a silty–marly clay matrix containing exotic blocks of metric to kilometric size (Fig. 7), forming a 'collisional tectonic mélange'. The blocks consist of metamorphic rocks belonging to the Frido unit (Pollino area, Sinni and Agri valleys); ophiolites (Pollino area, Sinni and Agri valleys); gneisses and amphibolites (Pollino area); elements of the Calabro–Lucano Flysch unit and of the Saraceno and Albidona formations (Pollino area, Sinni and Agri valleys, Mt Raparo area); shales, calesiltites and marly limestones of the Sicilide Complex (Pollino area); Numidian-type quartzarenites (Pollino area); cherty limestones and varicoloured shales of the Lagonegro units (Mt Raparo area); highly cataclastic Cretaceous and Paleogene platform carbonates (Mt Raparo area, Agri and Sinni valleys, Pollino area); Lower Miocene biocalcarenites of the Cerchiara Formation and conglomerates and marls of the Bifurto Formation. The whole of this level can thus be interpreted as being a shear zone containing exotic elements belonging to both the allochthonous units of the hangingwall and to the carbonate units (western platform, Lagonegro and Apulian units) of the footwall.

Different structures developed within the STAW depend on the lithologies involved in the deformation. Pelitic rocks are mainly affected by synthetic shear surfaces localized along bands parallel to the main shear zone boundaries, with isolated lithons elongated in the SW–NE direction of transport. Alternations of competent and incompetent layers are either affected by NE-verging fold structures (F_{III}) or by boudinage of the competent layers, as well as by minor synthetic shear planes (Fig. 8). NE dipping shear bands often developed within the main shear zone indicating a top-to-the-northeast sense of shear. Blocks of competent rocks (limestones, ophiolites and gneisses) are usually highly fractured and are affected by boudinage and by synthethic shear planes which define lithons elongated

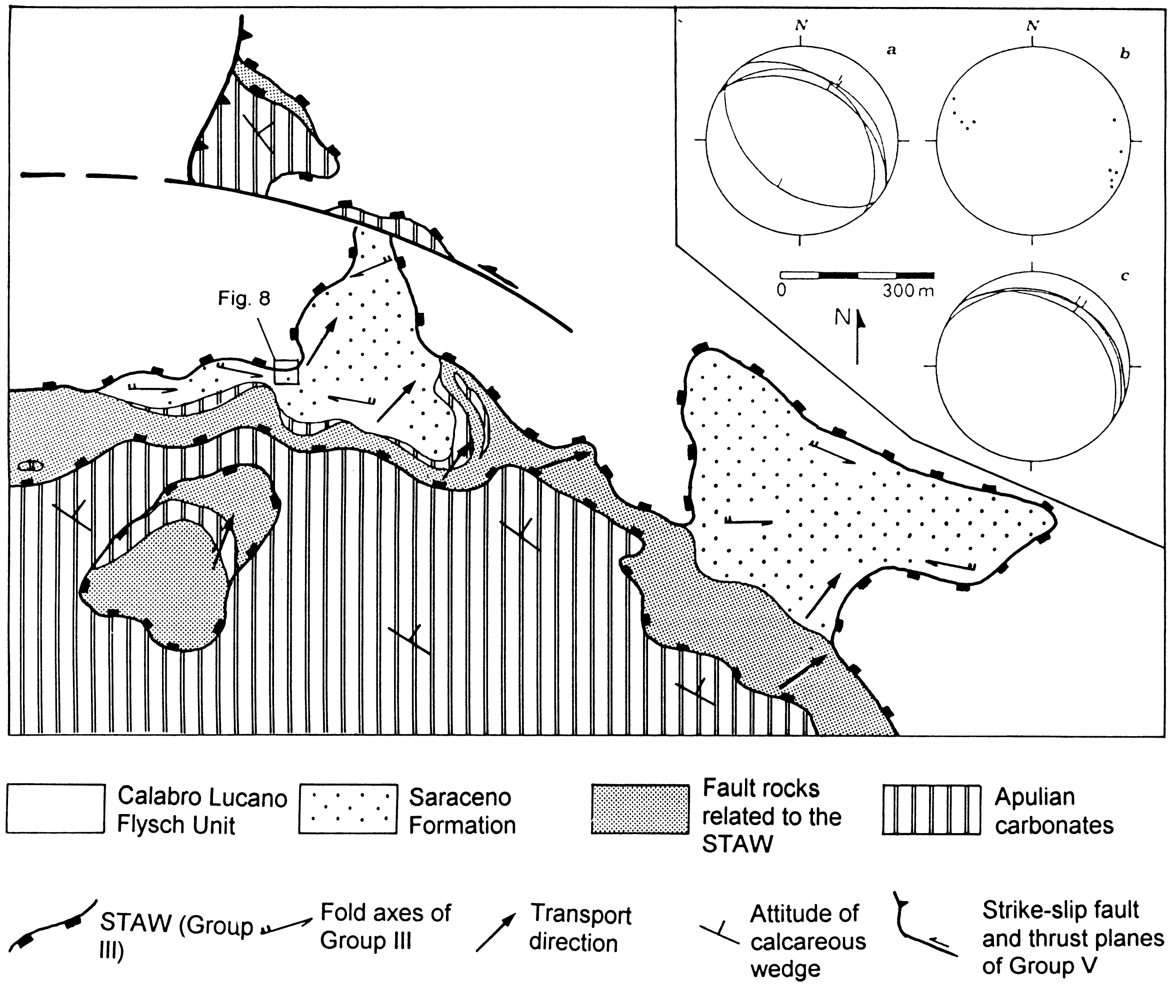

Fig. 7. Geological sketch map showing the structural features of the sole thrust of the accretionary wedge (STAW) in the Pollino region (for location see Fig. 2). Inset shows lower-hemisphere equal area projections of the structures characterizing the STAW. (a) and (c) show the attitude of major shear planes and associated slickensides occurring in the calcareous blocks and in the Saraceno deposits, respectively; and (b) shows the fold axes affecting the blocks of the Saraceno Formation.

in the NE direction. Kinematic data derived from the analysis of shear bands, minor duplex structures, fold geometry and slickensides surfaces with striae indicate a general NE transport direction, as shown in Figs 7 and 8.

At a certain depth the STAW is clearly recognizable by the analysis of well logs. In the Castellana 1 and Costamolina wells, the STAW brings the Saraceno and Albidona formations onto the Cretaceous sediments belonging to the Lagonegro units, whereas in the Tempa Rossa, Rotondella 4 wells, different tectonic elements of the Liguride and Sicilide terranes are directly superposed above the Upper Miocene foredeep sediments (External Flysch) of the Apulian domain (Fig. 3). In places, the shear zone is marked by a recognizable cataclastic zone that is several hundreds metres thick and contains blocks of platform carbonates (Costamolina well).

Lagonegro duplex. These units crop out at the surface, in the Mt Sirino–Lagonegro region extending southwards up to the Sinni Valley. Moreover, it must be noted that in the Pollino region, south of the Sinni Valley, sediments belonging to the Lagonegro succession have never been found either at the surface (Monaco *et al.*, 1994a) or at depth (see well logs in Fig. 3).

The analysis of the available well logs shows that the Lagonegro units form a large-scale NE-pinching lens-shaped level at depths, between the allochthonous accretionary wedge terranes and the Apulian carbonates. This geometry suggests that the Lagonegro units, as a whole, represent a duplex of regional extent (Fig. 4) developed between the STAW, which represents the roof thrust, and a shear zone that brings the Lagonegro sequences above the different stratigraphic horizons (from Late Cretaceous to Pliocene) of the Apulian domain, representing the sole thrust of the Lagonegro duplex (STL). The STL is only recognizable at a depth through the analysis of well logs (Castellana and Costamolina wells) and seismic reflection lines (Mostardini and Merlini, 1986), and is usually defined by the occurrence of a horizon formed

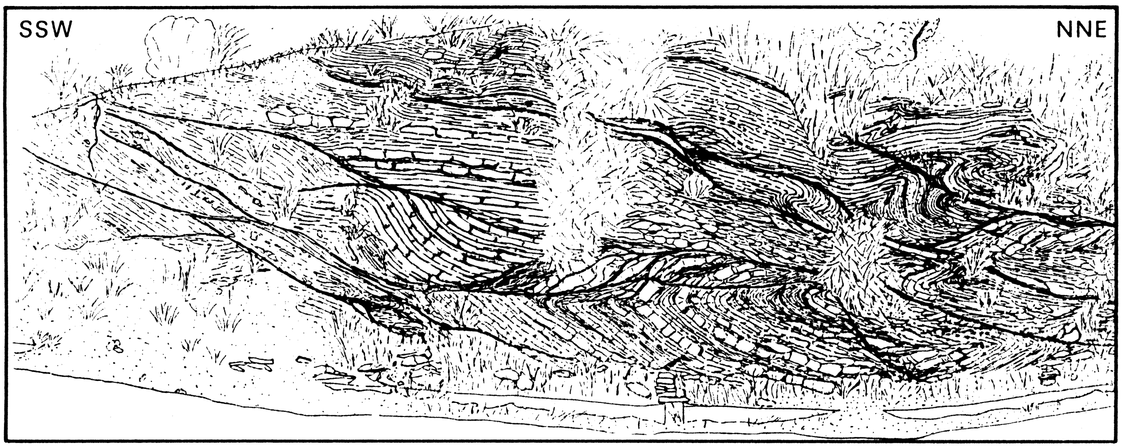

Fig. 8. Drawing showing the structural pattern characterized by a set of synthetic shear planes with associated tight folds affecting a lens-shaped block of Saraceno Formation included within the STAW (location in Fig. 7). Transport direction is roughly parallel to the section.

by Middle Miocene sediments interpreted to have undergone a large shear from southwest to northeast, involving both the terrigenous cover of the inner portion of the Apulian carbonates and the frontal thrust sheets of the External Flysch. Well log analysis shows, moreover, that along the STL the Apulian carbonates are usually brecciated with associated thin levels of red clays which might be interpreted as being a gouge zone (Castellana and Costamolina wells).

At the surface branch points between link thrusts separating the different horses of the duplex, that include the Western platform units in the uppermost horses, and the STAW are well exposed in the Moliterno area and in the Agri Valley.

Thrust faults (T_{IIIa}) separating the different horses of the Lagonegro succession usually bring Triassic sediments above the Cretaceous sequence. They are characterized (Mazzoli, 1992) by shear planes developed within a pelitic matrix that contains asymmetric lithons of calcarenites and micaceous sandstones indicating a present-day NE–NNE direction of transport. Thrusting, usually accompanied by flexural folding, developed in the deep diagenetic zone without reaching anchimetamorphic conditions (Mazzoli, 1993). The major folds (F_{IIIa}), which show axes mostly oriented along a NW–SE direction (Fig. 9a), are usually subhorizontal to recumbent and are accompanied by metric-scale parasitic folds showing typical symmetric (*M*) or NE-verging asymmetric (*S* or *Z*) shapes depending on their structural position. Striations and mineral fibre lineations oriented at high angles to hinges occur along bedding surfaces in the Upper Triassic cherty limestones and in the Jurassic cherts. Veins of quartz and calcite in limestones and radiolarites, together with the occurrence of interstratal duplexes (Tanner, 1989), indicate a component of interlayer slip during folding.

The uppermost horses of this duplex structure are represented by the western platform carbonates which overthrust the Lagonegro sediments in the Agri Valley to the west of the Moliterno–Mt Vulturino area (Fig. 2). The tectonic contact is marked by a 100–200 m thick level of highly cataclastic dolomites which derive from the deformation of different stratigraphic levels of this carbonate succession. Minor duplex horizons, shear bands, calcite shear veins fibres, and slickensides on polished thrust surfaces indicate an overthrusting direction to the northeast (Fig. 9b).

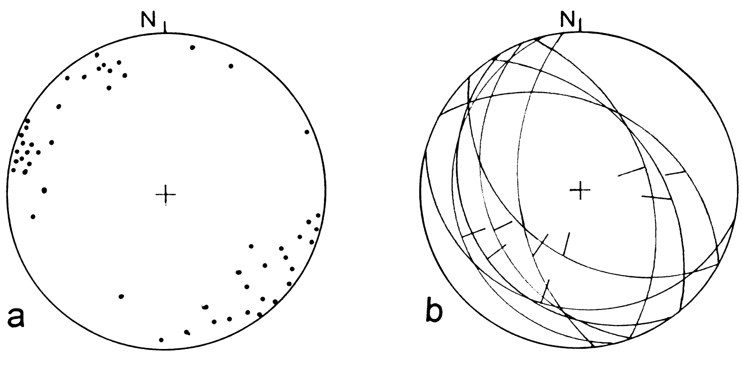

Fig. 9. Lower-hemisphere equal-area projections of: (a) F_{IIIa} fold axes affecting the Lagonegro succession; and (b) the attitude of major T_{IIIa} thrust planes and associated slickensides occurring along the main tectonic contact between the western platform carbonates and the Lagonegro units.

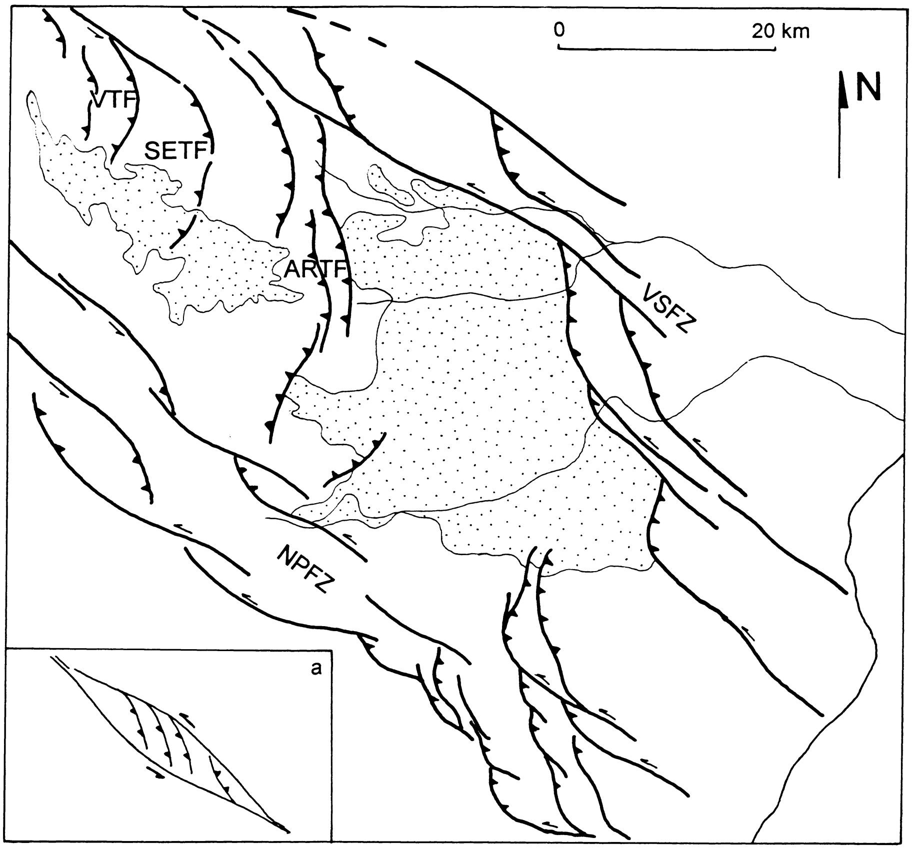

Fig. 10. Schematic structural map showing the overall pattern of the left-lateral strike-slip system affecting the Lucanian thrust belt (same area of Fig. 2). Note the large push-up area that develops between the North Pollino fault zone (NPFZ) and the Valsinni Stigliano fault zone (VSFZ), and bounds the Plio–Pleistocene Sant'Arcangelo Basin (dotted area). Inset shows kinematic interpretation of a contractional duplex in a left-lateral strike-slip system (after Woodcock and Fisher, 1986).

Frontal thrusts. In this group of structures the frontal thrusts of the chain that form northeastwards the outer ridge of the Sant'Arcangelo Basin (i.e. Valsinni–Stigliano ridge) are also included (Fig. 2). These thrust faults (T_{IIIb}) affect the frontal slices of the thrust belt and the External Flysch which are overthrust above the Lower Pliocene foreland sediments (Fig. 4). T_{IIIb} thrusts are also recognizable at depth in the Tempa Rossa, Tursi 1 and Rotondella 4 wells (Fig. 3).

Group IV structures

The structures of this group are represented by large antiforms that deform all the structures belonging to Groups I–III. These structures show NW–SE-trending axes and, characterized by kilometric length, affect all the tectonic units of the chain. The major antiforms (F_{IV}) are well exposed in the Agri Valley where they affect the varicoloured clays and the Gorgoglione Formation, along the southwestern border of the Sant'Arcangelo basin where these structures deform the STAW and the overlying Albidona Formation forming an antiform showing the hinge zone in the Mt Raparo area, and along the Sinni Valley where the metamorphosed terranes of the Frido Unit are involved (Fig. 2). Kilometric large F_{IV} antiforms also affect the Upper Pliocene–Lower Pleistocene sediments of Sant'Arcangelo Basin.

These structures represent the surface response for the occurrence of spaced deep-seated ramp anticlines affecting the buried Apulian platform carbonates as shown both in the geological profiles, derived from the analysis of deep seismic lines (Mostardini and Merlini, 1986; Casero *et al.*, 1988; Hippolyte *et al.*, 1994), as well as in the available seismic lines (see fig. 8 in Hippolyte *et al.* 1994). The occurrence of these ramp anticlines that affect the top of the buried Apulian carbonates implies that a main deeper detachment must have developed, probably located at the boundary between the basement and the Apulian sediments. In the seismic line reported in Hippolyte *et al.* (1994), this could be represented by sub-horizontal reflections approximately located at 4 s, assumed to coincide with the sole thrust of the Southern Apennines orogenic belt (STSA) defining a duplex structure developed within the carbonate Apulian carbonates, as suggested by Cello *et al.* (1989). Thrust faults (T_{IV}) affecting the Upper Pliocene–Lower Pleistocene sediments at the front of the thrust belt could represent frontal thrusts along which the displacement occurring at depth on the STSA are transferred at the surface.

Group V structures

These structures, superimposed onto all pre-existing structures described above in Groups I–IV, are related to the development of a system of WNW–ESE-trending left-lateral strike-slip fault zones. These affect the previous thrust belt, both carbonate substratum and overlying allochthonous units, and dissect the entire Southern Apennines mountain chain (Monaco and Tansi, 1992; Catalano *et al.*, 1993). The fault zones are characterized by the occurrence of several right-hand en échelon, left-lateral fault segments (Ft_V). The horizontal movements occurring along the different fault segments are accommodated by thrusts (T_V) and folds (F_V) that modify the pre-existing tectonic layering that forms the grain of the Southern Apennines thrust belt. In the Lucanian Apennines this strike-slip fault system is made of two major fault zones that showing an overall right-hand en échelon arrangement gives rise in the overlapping area to the development of impressive contractional imbricated structures (Fig. 10). This area, defined to the south by the North Pollino fault zone (Catalano *et al.*, 1993) and to the north by the Stigliano–Valsinni fault zone (Catalano *et al.*, 1993), is located between the Sinni and the Agri valleys including the Plio–Pleistocene Sant'Arcangelo Basin.

The North Pollino fault zone (NPFZ) extends (Fig. 11) from the Lagonegro–Mt Sirino area to the northeastern border of the Pollino mountain range, reaching the Ionian coast, where it affects Lower–Middle Pleistocene sediments which are strongly deformed along the fault planes (Catalano *et al.*, 1993). T_V thrusts and associated F_V folds, striking from NNE–SSW to N–S, develop in the overlapping portions located between different en échelon fault segments (push-up structures) or at the tip of the major fault segments forming large trailing contractional imbricated fans (Woodcock and Fisher, 1986). A large push-up structure (Figs 2 & 10) is present in the Mt Sirino area where, along the Cogliandrino Valley, a series of W-dipping, NNE–SSW- to N–S-striking thrust faults bring the Lagonegro units above the STAW. Thrust-related folds, with axes oriented along a NE–SW to N–S direction, deform the pre-existing Group III fold structures with a high angle giving rise to an overall dome and basin geometry (Mazzoli, 1992). It is worth noting that the occurrence in the Lagonegro region of two sets of folds with axes oriented along NW–SE and NNE–SSW directions, respectively, has been known since the last century (De Lorenzo, 1896).

Trailing contractional imbricated fans are, indeed, well developed along the northwestern tips of the major right-hand en échelon left-lateral strike-slip fault segments, which extend from the Mt Alpi region to the Ionian coast. These contractional structures give rise to the occurrence of several large carbonate wedges which are pushed-up through the allochthonous terranes of the Liguride units (Fig. 11). These ridges, mostly formed by Upper Cretaceous rudistid limestone covered by Lower–Middle Miocene biocalcarenites and calcareous turbidites, are bounded southward by sub-vertical WNW–ESE-trending strike-slip faults (strike ranging between 090° N and 130°) with well-preserved sub-horizontal slickensides (pitch ranging between 10° and 20° towards the east), showing a left-lateral component of motion (Fig. 12). At the north-

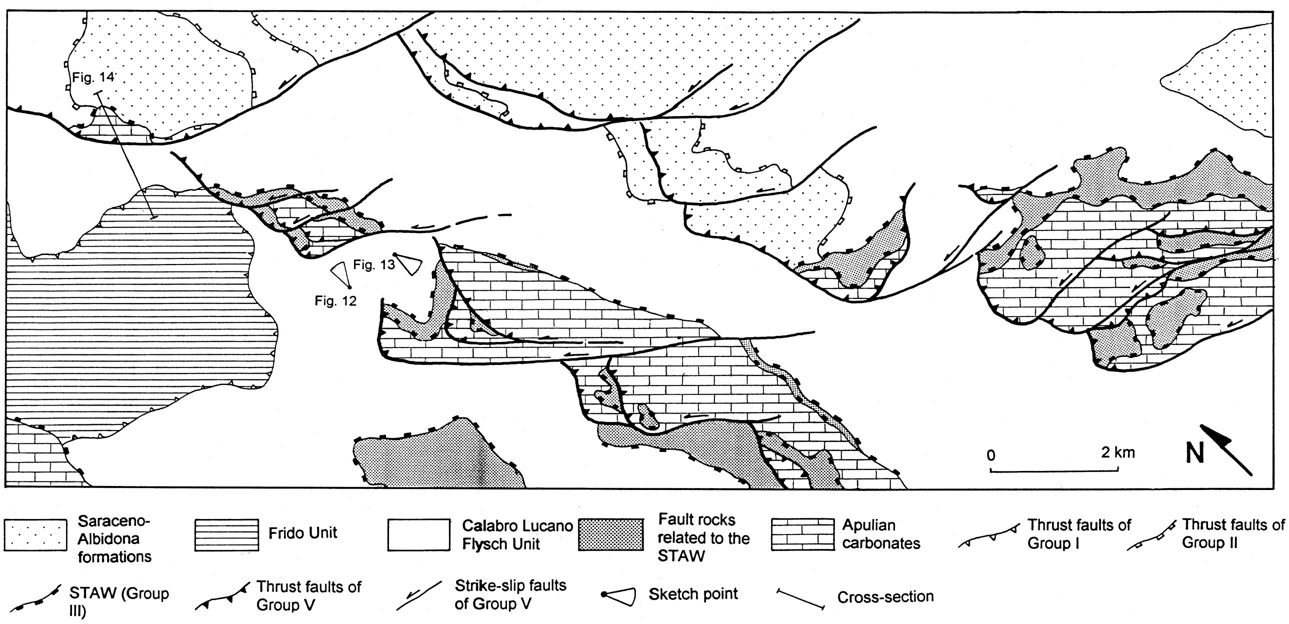

Fig. 11. Structural sketch map of the southern part of the NPFZ (location in Fig. 2).

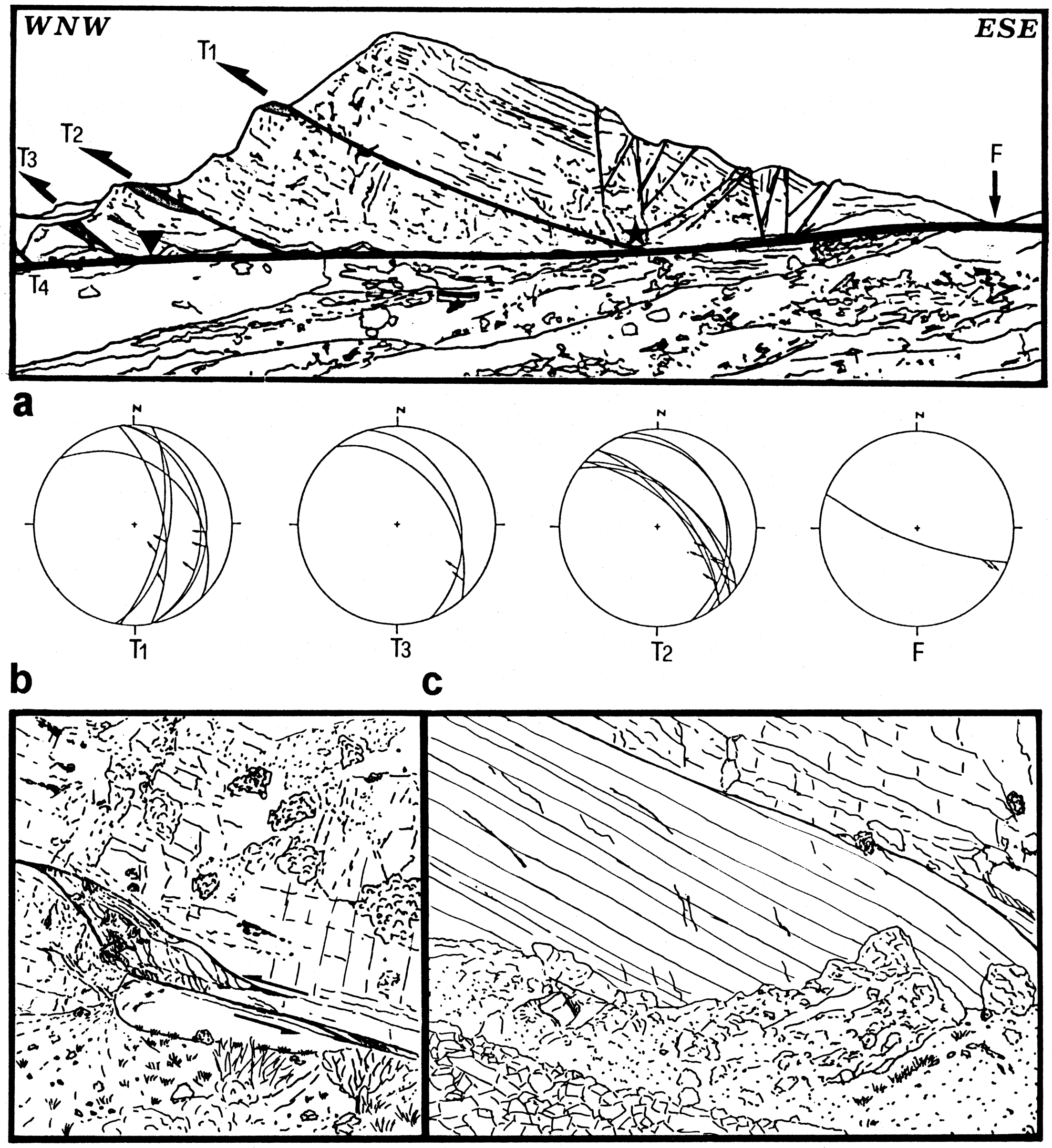

Fig. 12. (a) View of the S-facing wall of the carbonate wedge of La Falconara (for location see Fig. 11) showing the NW-verging thrust faults (T_{1-4}) accommodating the horizontal component of motion occurring along the left-lateral strike-slip fault (*F*) along which the wedge was extruded. Lower-hemisphere equal-area projections show the attitude of fault planes and associated slickensides related to the T_{1-3} main thrusts and the *F* strike-slip border fault. (b) Sketch illustrating a flat–ramp geometry occurring along T_1 thrust (star in a). (c) Sub-horizontal slickensides characterizing the strike-slip border fault (triangle in a).

western tips of the strike-slip master fault segments, NNE–SSW- to N–S-trending thrust ramps, with associated ramp anticlines, have resulted in the extrusion of the carbonate wedges (Fig. 13). This makes it possible to observe the shear zone which marks the STAW (see Group III structures above) and the geometric relations between the different groups of structures (Fig. 14).

Trailing contractional imbricated fans also developed at the northwestern tips of the strike-slip fault segments of the Valsinni–Stigliano fault zone (VSFZ). These occur running from the Valsinni village area towards the northwest, and affect the northeastern border of the Sant'Arcangelo Basin (Fig. 10). Along these structures the frontal slices of the Sicilide terranes together with the Miocene turbidites (Numidian Flysch, External Flysch and Gorgoglione Formation) overthrust the Plio–Pleistocene sediments of the Sant'Arcangelo Basin westwards (Figs 2 & 4). Convex-upwards oblique thrust planes showing a left-lateral component of motion splay out from the main strike-slip fault segments, producing asymmetric positive flower structures.

The overlap developing between the NPFZ and the VSFZ, located in the Agri Valley, is characterized by the occurrence of several roughly N–S- to NNE–SSW-

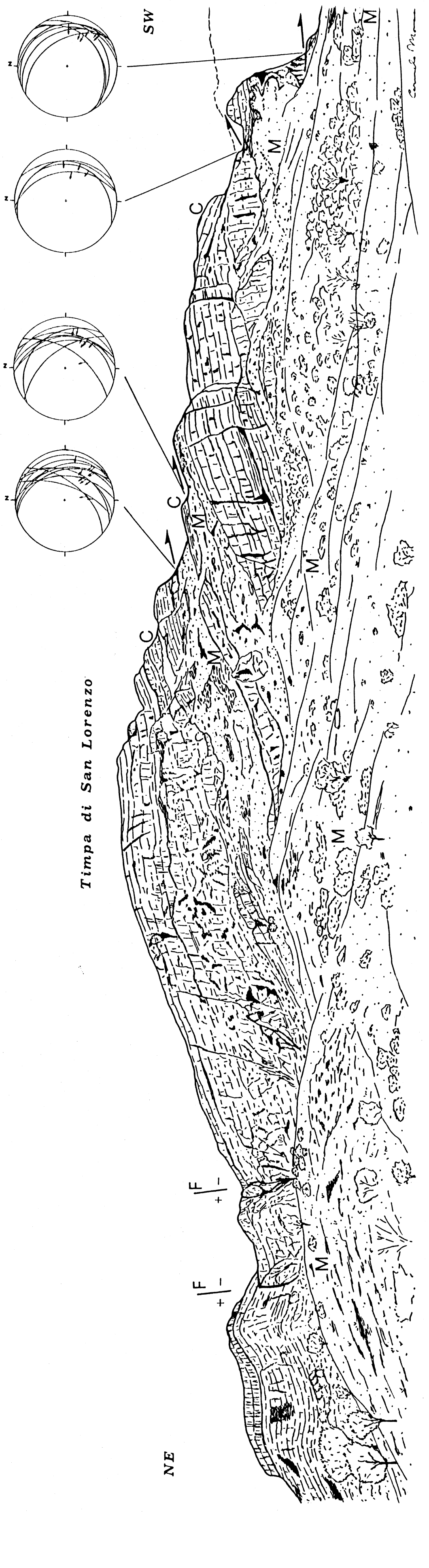

Fig. 13. View of the northwest front of the imbricated thrust system that accommodates the horizontal component of motion of Ft_V left-lateral strike-slip fault and affects the Apulian carbonates (C) and the fault rocks (M) related to the STAW. Lower-hemisphere equal-area projections show the attitude of fault planes and associated slickensides occurring along the main T_V thrust faults (location in Fig. 11).

oriented arc-shaped thrust faults, with an eastward facing convexity, that splay out from the the VSFZ affecting the Middle Pliocene–Pleistocene sediments of the western border of the Sant'Arcangelo Basin (Fig. 10). The main structures developed within this zone are represented by the Mt Vulturino (VTF), Mt Sant'Enoc (SETF) and Armento–Mt Raparo (ARTF) thrust faults (Fig. 10).

The VTF and the SETF are represented by N–S-trending thrust propagation folds which bring the Lagonegro units above the allochthonous Sicilide terranes and the terrigenous sequences of the Gorgoglione Formation (Fig. 2). F_V folds deform the F_{IIIa} folds with a high angle, giving rise (e.g. at Mt Vulturino) to the development of type 1 vs type 2 interference patterns of Ramsay (1967).

The ARTF (Figs 2 & 10) runs along the western border of Sant'Arcangelo Basin and, along its northern branch, brings the varicoloured clays of the Sicilide units with the Middle–Late Miocene turbiditic cover of the Gorgoglione Formation, above Middle–Upper Pliocene sediments. The thrust fault is accompanied by a ramp anticline affecting the Gorgoglione Formation, and by a footwall syncline deforming the Middle–Upper Pliocene deposits. From the village of Armento to the Agri River, the thrust fault is sealed by the uppermost conglomerate sediments of the Lower–Middle Pleistocene sequence of the Sant'Arcangelo Basin (Figs 2 & 10). To the south this structure assumes progressively a NNE–SSW trend, also affecting the Lower–Middle Pleistocene sequence, while in its southernmost edge it is sealed by Middle Pleistocene conglomerates. In this area the Lower Pleistocene sands are affected by a large and open anticline with a NNE–SSW trending axis, which is interpreted as a fault-tip fold related to the blind thrusting of the Armento structure. Southwards, around the village of Carbone, the Armento thrust fault still crops out bringing the Albidona Formation above the Lower Pleistocene sands (Figs 2 & 10).

Near the Agri River from the NNW–SSE branch of the ARTF a major NNE–SSW-trending, W-dipping thrust fault (Mt Raparo branch) splays out. This structure runs along the eastern slope of Mt Raparo and affects the whole pile of nappes. It displaces the large NW–SE-trending antiform belonging to the structures of the Group IV described above, and makes it possible to observe the shear zone characterizing the STAW in the uplifted hangingwall (Figs 2 & 10).

TIMING OF DEFORMATION

The Group I structures include all those features related to the building of the Liguride and Sicilide accretionary complex by a progressive shear deformation that occurred during oceanic subduction, and also those structures affecting the accretionary wedge

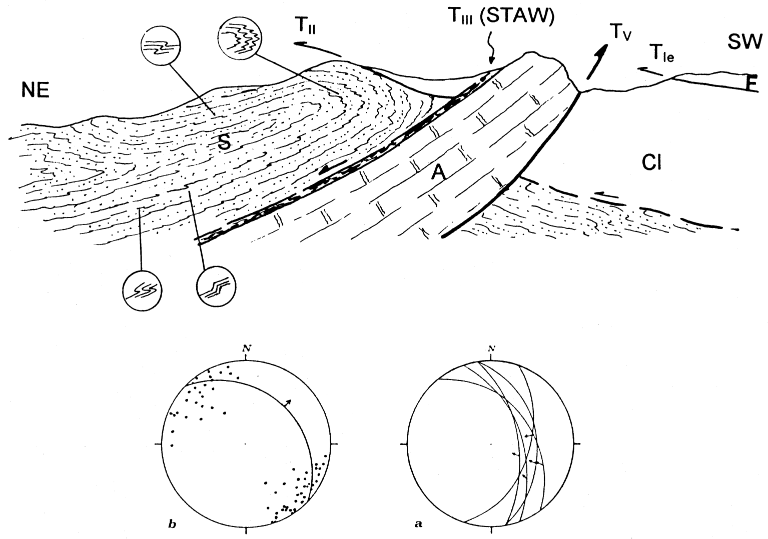

Fig. 14. Cross-section (for location see Fig. 11) showing the geometric relations between the different groups of structures. Lower-hemisphere equal-area projections show: (a) the attitude of fault planes and associated slickensides related to the main T_V thrust along which the Apulian carbonates (A) are overthrust above the Calabro–Lucano Flysch (Cl) and Frido (F) units; and (b) the F_{III} fold axes affecting the Saraceno Formation (S) along the STAW whose attitude and relative slickensides are also reported.

during the earliest stages of continental collision. Early Oligocene microfauna found in the calcschists of the Frido Unit (Bonardi *et al.*, 1993), together with the occurrence of fragments of metamorphic rocks and metabasites belonging to the Liguride Complex terranes in the lithoarenitic sandstones of the Upper Oligocene–Lower Miocene Saraceno Formation stratigraphically overlying the accretionary wedge terranes, imply that HP–LT metamorphism of the Frido unit and its uplift with consequent emplacement onto the Calabro–Lucano Flysch unit occurred during the Late Oligocene (Monaco and Tortorici, 1995).

The earliest structures, related to the tectonic inclusions of oceanic slices and blocks and to the formation of tectonic mélanges, however originated between the Late Cretaceous, at the beginning of the onset of the Africa–Europe convergence (Dewey *et al.*, 1989), and the Early Oligocene.

The Group II structures that developed during continent–continent collision affect both the accretionary wedge terranes and its Upper Oligocene–Upper Miocene (Lower Tortonian) turbiditic cover, thus implying an age ranging from the Early to Late Miocene. During this time lapse the overthrust of the whole accretionary wedge above the innermost portions of the Adria block began, probably with the early development of the STAW.

The structures of Group III are related to the development of the STAW which separates the allochthonous terranes from the underlying carbonate units of the Adria domain, also including the link thrusts that define the different horses of Lagonegro and Western platform units, and the frontal splays of the whole thrust system.

The youngest sequences represented in the blocks embedded within the STAW's shear zone are made of Middle Miocene (Langhian) sediments of the Numidian Flysch. Samples from silty–clay matrix characterizing the shear zone collected between Mt Raparo and Pollino area yield nannofossils and foraminifera assemblages, referable to Middle Miocene (mostly Langhian and subordinately Serravallian) age. Moreover, in the study area, the STAW develops above the Upper Miocene (Castellana 1 well) sedimentary cover of the Apulian carbonates (see Fig. 3), thus implying that the STAW developed during the Middle–Late Miocene.

Following the propagation of the STAW, above the nappes forming the hangingwall, a large sedimentary basin (Sant'Arcangelo Basin) was formed, infilled by an almost 3000 m thick Lower Pliocene–Lower Pleistocene pile of sediments. This suggests the occurrence of a huge ridge located along the western border of the Sant'Arcangelo Basin, the unroofing of which gave rise to the supply of the sedimentary materials for the basin infilling. We suggest that this ridge was the result of the western platform–Lagonegro duplexing which was accompanied by an antiformal deformation of its roof thrust, with consequent uplift of the accretionary wedge terranes which were completely dismantled. This implies that duplex deformation occurred between Late Miocene (Messinian) and Early Pliocene times. The T_{IIIb} frontal thrusts, which affect the Lower Pliocene sediments, developed during Middle Pliocene times.

The structures belonging to Group IV are related to the duplexing of the buried Apulian carbonates. The large F_{IV} folds referable to this group of structures affect the Upper Pliocene–Lower Pleistocene sediments of the Sant'Arcangelo Basin, which show thickness variations and angular unconformities around folds indicating that this folding was active during the sedimentation of Lower Pleistocene sediments (Hippolyte *et al.*, 1994). The regional unconformity separating the Middle–Upper Pliocene sequence from the Lower–Middle Pleistocene sediments of the Sant'Arcangelo Basin probably represents the surface response to the folding of the roof thrust bounding the buried duplex structure that developed within the Apulian carbonates. This implies that the duplexing of the Apulian carbonates occurred between Late Pliocene and Early Pleistocene times, during which also the T_{IV} thrust faults developed at the front of the thrust system.

The strike-slip related structures of Group V offset the Lower Pleistocene sediments of the Sant'Arcangelo basin and, southeastwards, those of the Ionian coast (Catalano *et al.*, 1993; Monaco and Tortorici, 1994). They are sutured by the Middle–Upper Pleistocene deposits of the southwestern margin of the Sant'Arcangelo Basin. These structures may therefore be ascribed to an Early–Middle Pleistocene deformation event.

DISCUSSION AND CONCLUSIONS

The geological features exposed along the lines shown in Fig. 4, combined with the structural pattern characterizing the Lucanian Apennines and with the timing of deformation, allow us to reconstruct the main stages of the evolutionary history of this portion of the African continental margin from the early rifting processes to the post-collisional events.

The first evidence of the occurrence of sedimentary basins in this area is represented by Middle Triassic deposits, when rifting processes produced normal faulting which dissected the continental areas giving rise to basin formation. In that period the continental margins of the African plate, where platform carbonate sedimentation occurred, began to be outlined. The platform margin was dissected by elongated troughs, probably related to the activity of basin border faults, which penetrated within the carbonate platform domain. The region thus assumed a configuration defined by a large peritidal platform dismembered by a series of half-grabens which mark pelagic basins (*sensu* Santantonio, 1994) where the Lagonegro successions were deposited. According to Santantonio's model, the Lagonegro Basin was therefore bordered by a large carbonate platform (eastern or Apulian platform) towards the continental areas, and by a minor platform domain (western platform) developed on the crests of rotated hangingwall blocks, towards the rifted areas (Fig. 15). Block tilting of large hangingwall blocks created carbonate ramps that were the source area of the gravity flow deposits that, by infilling the half-grabens, characterize the whole Lagonegro succession. The lack of the Lagonegro successions south of the Sinni Valley strongly suggest that these extensional basins did not propagate towards the present south.

During Middle Jurassic–Early Cretaceous times the continental crust continued to be thinned while the oceanic lithosphere was produced, creating the Neotethyan domain where the pelagic successions of the Sicilide and Liguride Complexes developed. The Adria block was therefore outlined preserving along its passive margin the Triassic–Jurassic architecture without any significant changes (western platform, Lagonegro basin and eastern or Apulian platform).

During Late Cretaceous–Late Oligocene times the subduction of the Neotethys oceanic domain beneath the European (Corsica–Sardinia) continental margin produced the growth of an accretionary wedge remnants of which are represented by the Calabro–Lucano Flysch unit and the Frido unit, and by the varicoloured clay mélange of the Sicilide Complex. During this period the earliest structures of Group I developed. At the end of this stage the Frido unit terranes underwent a HP–LT subduction metamorphic event.

In the Late Oligocene, after the closure of the oceanic realm, continent–continent collision between the Corsica–Sardinia and the Adria margins started, causing the uplift of the metamorphosed Frido unit. Structural and petrological data (Monaco *et al.*, 1991; Monaco and Tortorici, 1995) strongly suggest that the emplacement of the Frido unit over the inner portion of the accretionary wedge (Calabro–Lucano Flysch unit) occurred by duplexing along a major crustal shear zone, according to the model of Silver *et al.* (1985) for the exhumation of HP–LT rock assemblages. During this period, small slope basins were filled by volcaniclastic and wedge-derived detritus (volcaniclastic turbidites).

In Late Oligocene–Early Miocene times (Fig. 16), collisional processes were responsible for complete emplacement of the Frido unit over the Calabro–Lucano Flysch unit. The inner portion of the wedge was deformed by the earliest structures of Group II and large perched basins developed, to be filled with terrigenous turbidites (Saraceno–Albidona formations) deriving from the unroofing of the continental margin and from the inner portion of the accretionary wedge. Volcaniclastic turbidites (Tufiti di Tusa and/or Corleto Perticara Formation) together with the Numidian Flysch fed by the African continent, were deposited onto the lower slope of the wedge filling new perched basins and reaching the trench.

During Middle–Late Miocene (Fig. 16), the complete continent–continent collision was responsible for the deformation of the whole accretionary wedge (whose earlier thrust structures were reactivated) and for the strong uplift of the innermost elements of the chain (e.g. the crystalline nappes of the Corsica–Sardinia margin). Large episutural basins filled by thick turbiditic sequences (Gorgoglione Formation)

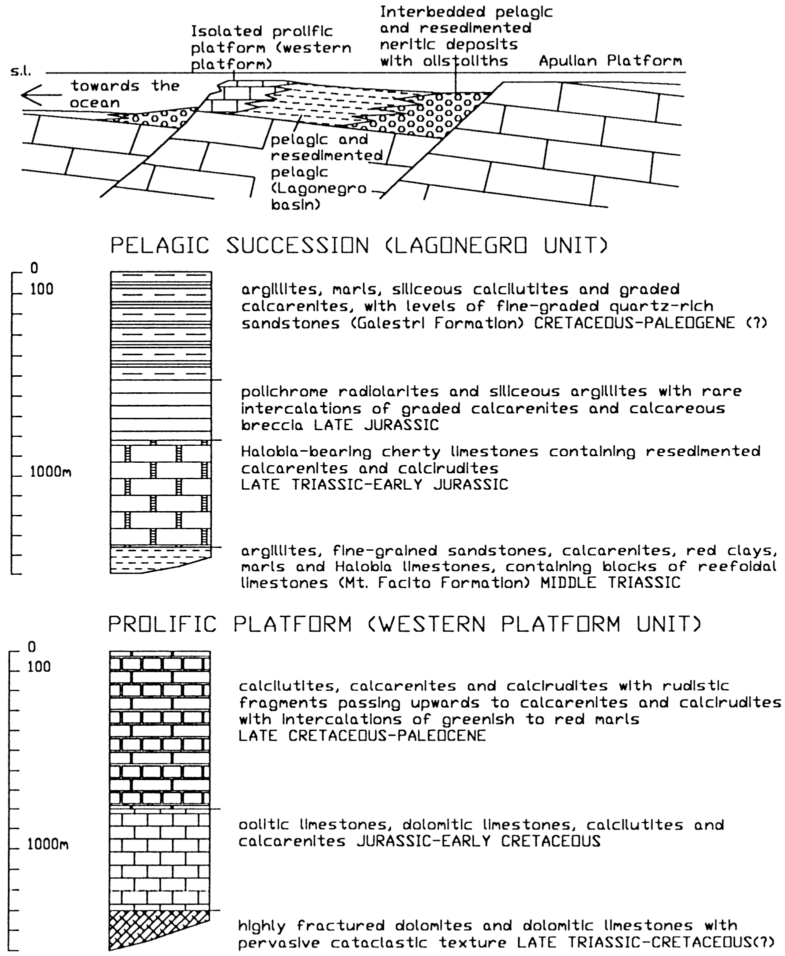

Fig. 15. Palaeotectonic scheme showing the pelagic carbonate platform and basin distribution of the Adria continental paleomargin during Triassic–Palaeogene (after Santantonio, 1994).

developed above the deformed accretionary wedge complex. During this stage the whole accretionary prism was tectonically emplaced, along a major sole thrust (STAW), on the westernmost portions of the continental margin of Adria block whose flexure formed the foredeep trough where the turbiditic sedimentation of the External Flysch occurred.

From Late Miocene to Early Pleistocene, the ongoing continental collision caused the complete emplacement of the accretionary wedge onto the continental margin of Adria block. The allochthonous terranes overthrust the different domains of the western platform, the Lagonegro Basin and the eastern (Apulian) platform along the STAW. During the first stage of this event the STAW (structures of Group III) propagated above the carbonate ramps of the western border of Lagonegro basin reactivating the pre-existing hinterland-dipping (oceanwards) normal faults. During this inversion tectonic process thrust faults propagated downwards to the main shear zone (STAW) in the footwall of pre-existing normal faults (Schonborn and Schumacher, 1994). Slices of the highest portions of carbonate ramps were thus detached and involved within fault rocks characterizing the STAW which continued to propagate towards the foreland above the Miocene horizons of the western platform and Lagonegro domains, reaching its eastern hinterland-dipping normal border faults.

In Late Miocene–Early Pliocene (Fig. 16), thrust migration propagated downwards along a deeper shear zone (STL) developing along the Triassic sediments of the western platform and Lagonegro domains. A large duplex structure formed by horses of Triassic–Miocene western platform and Lagonegro successions thus developed between the STL, representing the sole thrust, and the STAW which assumed, at that time, the role of the roof thrust. Duplexing was accompanied by an antiformal deformation of the roof thrust giving rise to the growth of a large ridge affecting the overlying allochthonous terranes. At the frontal part of the system, thrust propagation gave rise to the imbrication of the previously detached Oligocene–Miocene sediments forming the outer ridge of Sant'Arcangelo Basin. The latter, therefore, represents a thrust-top basin filled by sediments derived by the unroofing of the ridge related to the duplexing of the western platform–Lagonegro domains. From Early to Late Pliocene the thrust system propagated towards

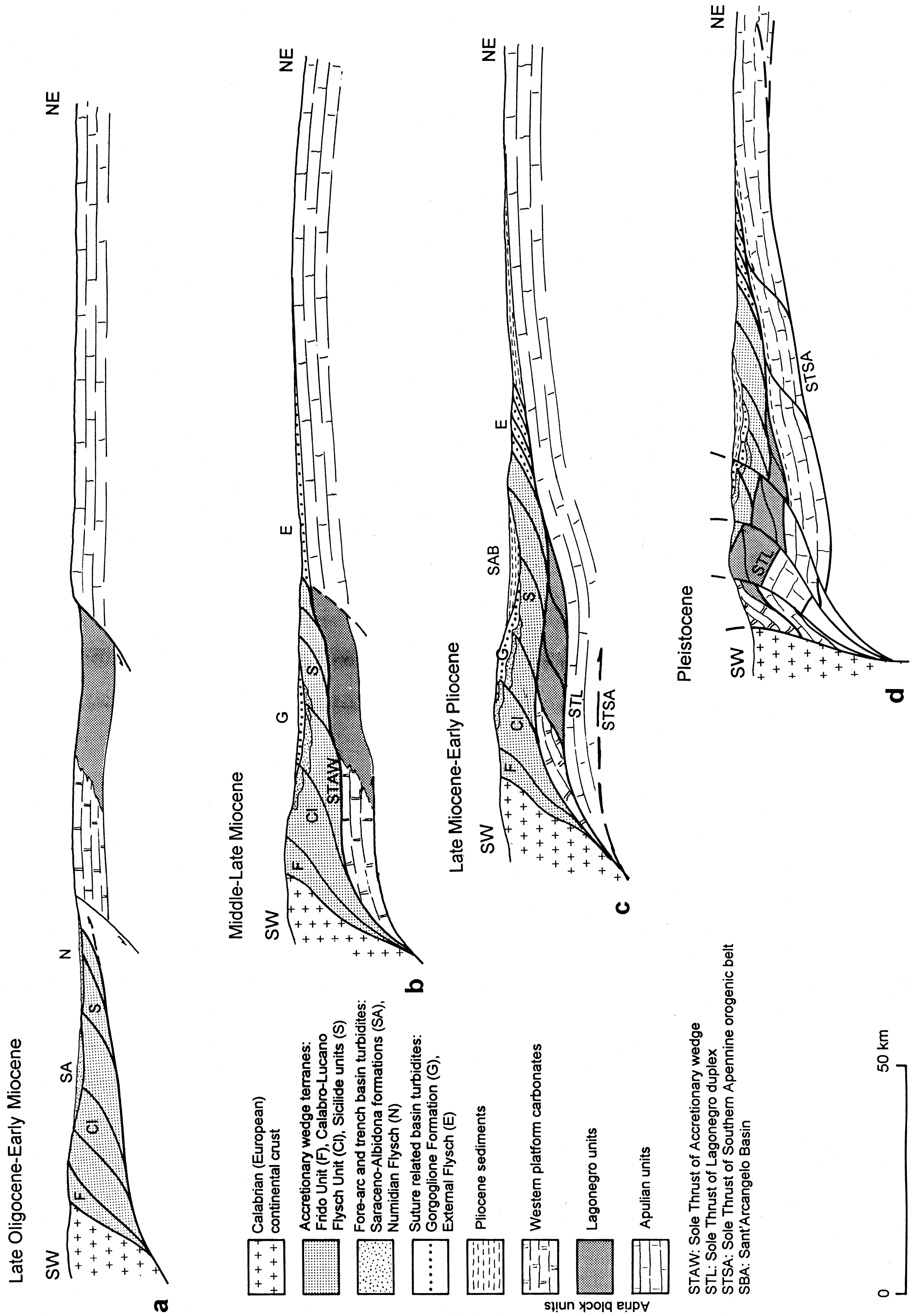

Fig. 16. Cartoon showing the different stages of development of the Lucanian Apennines from Late Oligocene–Early Miocene to Pleistocene.

the foreland involving the foredeep Pliocene deposits of the eastern (Apulian) platform passively carrying the Sant'Arcangelo Basin. During Late Pliocene–Early Pleistocene, foreland propagation thrust tectonics involved the buried platform developing a deep sole thrust (STSA) along the Triassic horizon of the Apulian carbonates. In the inner portion of the thrust belt the platform succession, confined between the STSA and the well-defined roof thrust separating the External Flysch from the Pliocene Apulian sediments, was deformed with a duplex geometry whereas at the frontal part of the belt thrust ramps were stacked (Fig. 16). This stage of deformation is marked by the Upper Pliocene unconformity that separates the two main sedimentary sequences of the Sant'Arcangelo Basin (see stratigraphy above).

From Early to Middle Pleistocene (Fig. 16) the forelandward thrust migration was inhibited by the thickening of the colliding continental crusts, and strike-slip tectonics became the principal mode of deformation. Strike-slip faults with associated thrusts and folds (structures of Group V) affected the entire mountain belt deforming the pre-existing thrust geometry.

The overall architecture of the Lucanian Apennines points out that this segment of the Southern Apennines mountain chain represents the result of a complete orogenic cycle in which oceanic subduction, syn-collisional and post-collisional events are well recorded. Structurally, this segment of the orogenic belt exhibits two distinct structural levels, separated by a major detachment surface (STAW), that occur at the surface in the allochthonous nappes and at depth in the Adria continental margin. The upper level is characterized by an imbricate fan system affecting the allochthonous terranes emplaced during the oceanic subduction and the first stages of continent–continent collision. The lower level is represented by a multiduplex geometry, involving the carbonate platform–basin system of the Adria block, that has developed in the post-collisional stage, during the evolution of the foreland migrating thrust system.

The occurrence of large nappes of allochtonous terranes deriving from the subduction of oceanic lithosphere and the development of strike-slip tectonics during the last stages of the mountain building processes, make it very difficult to estimate the amount of shortening in this segment of the Southern Apennines. However, the overthrust of the Lagonegro units and the accretionary wedge terranes above the Upper Miocene sediments of the Apulian platform, detected in the Castellana 1 well, suggests a minimum amount of shortening of about 50 km since Late Miocene times.

Our study points out, moreover, that orogen-parallel extension on systems of low-angle normal faults and orogen-orthogonal extension on crustal high-angle normal faults, as proposed by Oldow *et al.* (1993) and Ferranti *et al.* (1996), did not play a relevant role in the tectonic evolution of this segment of the Lucanian Apennines. In this portion of the chain, strike-slip tectonics is the principal mode of deformation during the Quaternary, thus implying that this area may represent a large transfer zone between the extensional domains of the Southern Apennines and the Siculo–Calabrian rift zone.

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