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Late Cenozoic subduction complex of Sicily

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Abstract—Besides remnants of Hercynian deformations in the Peloritani nappe and of pre-Oligocene Alpine structures in the Troiani nappe, most compressive structures observed in the Sicilian accretionary wedge result from the late Cenozoic (Tortonian to Present) continental subduction of the Apulia (Iblei) block, and are thus synchronous with distensive structures related to the opening of the Tyrrhenian Sea. Syntectonic deposits fill southward-migrating foredeeps in a sequential fashion, and the dating of these deposits helps to constrain the timing of deformation. Similarly, Plio-Quaternary sediments, eroded from the accreted units, rest on top of the allochthon in either compressive piggy-back depressions or extensional basins. The age and configuration of these overlap deposits constrain our reconstructions of the subsurface geometry of the underlying peri-Tyrrhenian detachment faults or S-verging thrust-faults. Post-depositional erosion, normal faulting and syntectonic filling of basins contribute to maintaining the critical taper of the prism, whose geometry is continuously altered owing to frontal accretion, underplating and isostatic uplift.

INTRODUCTION

Active subduction complexes are generally submerged in the deepest parts of the world oceans; therefore, most of our knowledge comes from indirect means such as refraction and reflection seismic data, bore hole cores and cuttings, and in rare instances of direct observations from submersibles. Ancient subduction complexes are widely exposed in orogenic belts, especially around the Pacific (e.g. parts of the Torlesse Formation of New Zealand, Shimanto complex of Japan, Chugach Formation of Alaska, Franciscan complex of California; Ernst, 1970, Hsü 1973, Cowan 1974, Uyeda *et al.* 1974, Howell 1980, Moore *et al.* 1983, Kodama & Taira 1984, Bishop *et al.* 1985). Nonetheless, the initial geometry or internal structures of such complexes are often obliterated by post-accretion tectonics and effects of metamorphism. In addition, erosion has usually removed all the syntectonic deposits that were deposited during the deformation, and their loss further inhibits any precise study of the timing of deformation within the subduction prism. The subduction complex of Sicily is now emerged and because most of the deformation occurred in Pliocene and Quaternary times it provides an opportunity to observe first hand the growing processes of a subduction prism and the genesis of tectonic melanges.

OVERALL STRUCTURE

Sicily is part of a continuous late Cenozoic orogenic belt, which includes mainland Italy (Calabria and the Apennines) and the north part of Africa (Maghrebides) (Amodio-Morelli *et al.* 1976, Boullin 1984, Bouillin *et al.* 1986) (Fig. 1). Most of the island lies above a well-defined Benioff plane that remains seismically active across the entire Calabrian arc. Earthquake hypocenters define a N-dipping subduction plane that extends at least 400 km into the asthenosphere (Gasparini *et al.* 1982, Ciaranfi *et al.* 1983, Boccaletti *et al.* 1984). Calc-alkaline volcanism, related to this N-dipping Benioff plane, exists north of Sicily in the Eolian Islands (Barberi *et al.* 1973, 1974b) (Fig. 1).

The descending plate, which is subducted to the north underneath the Tyrrhenian Sea, is part of the northern African continental lithospheric plate. Loading by allochthonous thrust sheets that make up the accretionary prism help the descending continental plate to flex. Thus, the southeastern part of Sicily (Ragusa Plateau) corresponds to the emerged part of the lithospheric bulge, and the flexural basin (foredeep) crops out between the slightly deformed foreland and the accretionary prism (Barberi *et al.* 1974a, Grandjacquet & Mascle 1978, Scandone 1979, Carbone *et al.* 1982, Broquet *et al.* 1984) (Fig. 2).

The over-riding plate that makes up most of Sicily represents a post-Miocene accretionary prism related to the continental subduction; locally, these young deformations are superposed on older Alpine structures. Syntectonic Pliocene deposits crop out in thrust-related piggy-back depressions as well as in extensional basins. These basinal strata provide data constraining interpretations for the structural evolution of the prism. Besides clear Plio-Quaternary compressive structures (folds and

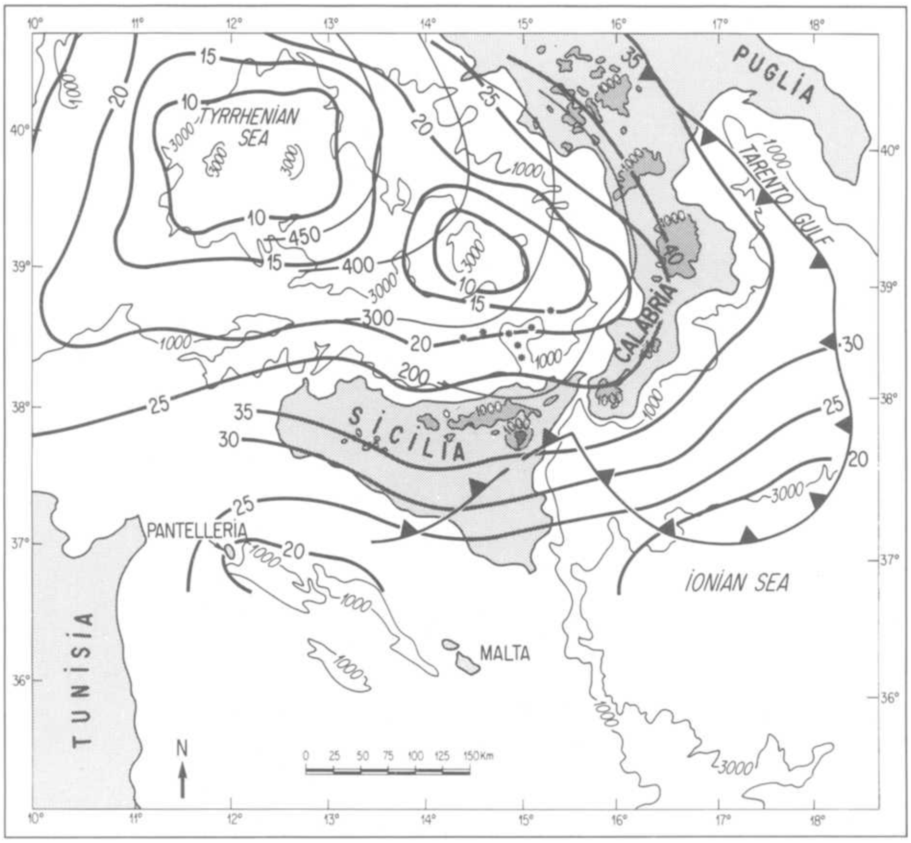

Fig. 1. Crustal thicknesses and physiography of Sicily and neighbouring areas (modified from Gasparini *et al.* 1982, Rehault *et al.* 1987). Thickest lines are depths (km) to Moho; smoothly traced thinner lines are depth (km) to top of Benioff zone; irregularly traced thinner lines are bathymetric contours (m).

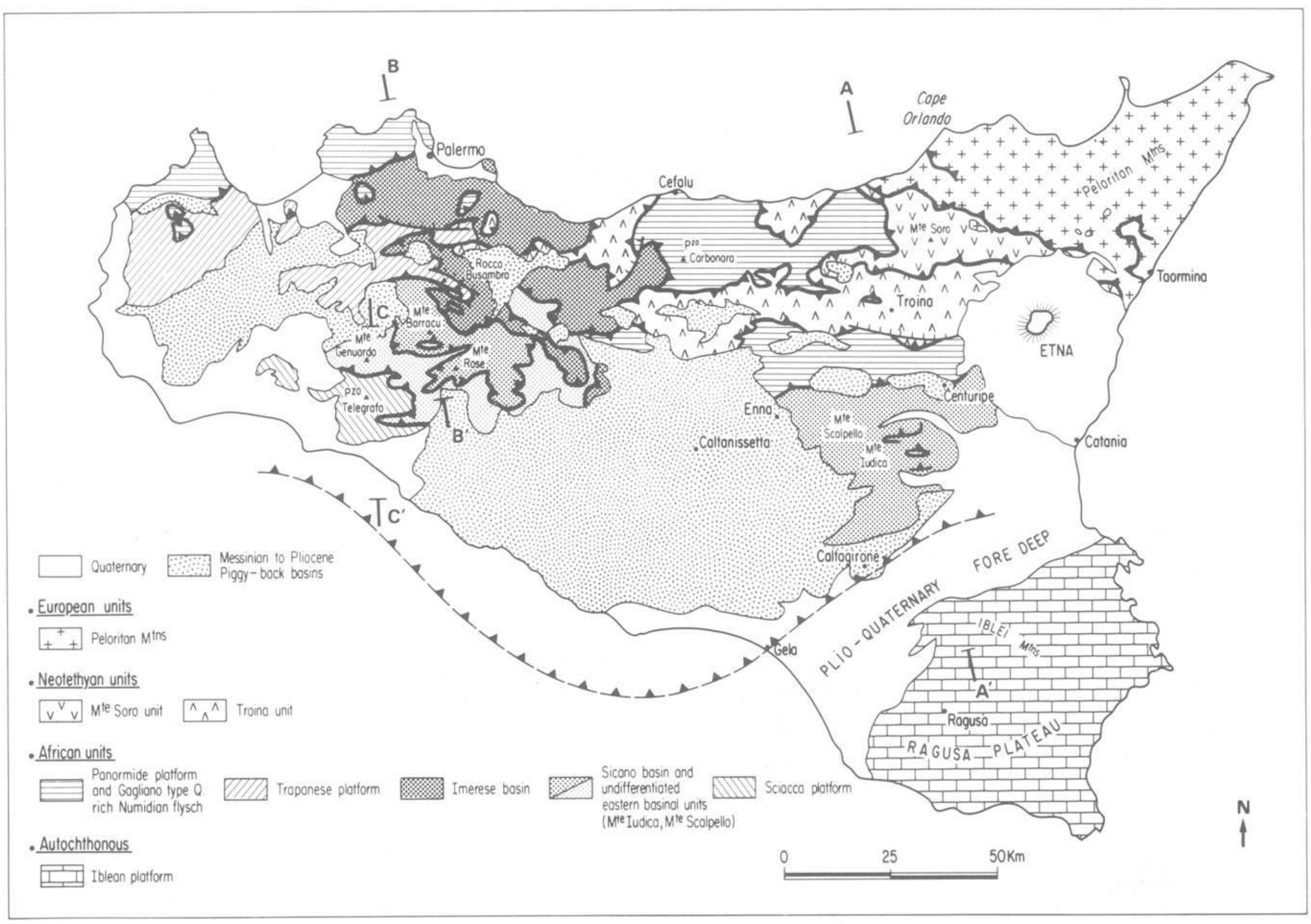

Fig. 2. Structural map of Sicily, modified from Amodio-Morelli *et al.* 1976, Mascle 1979 and Catalano & D'Argenio 1982.

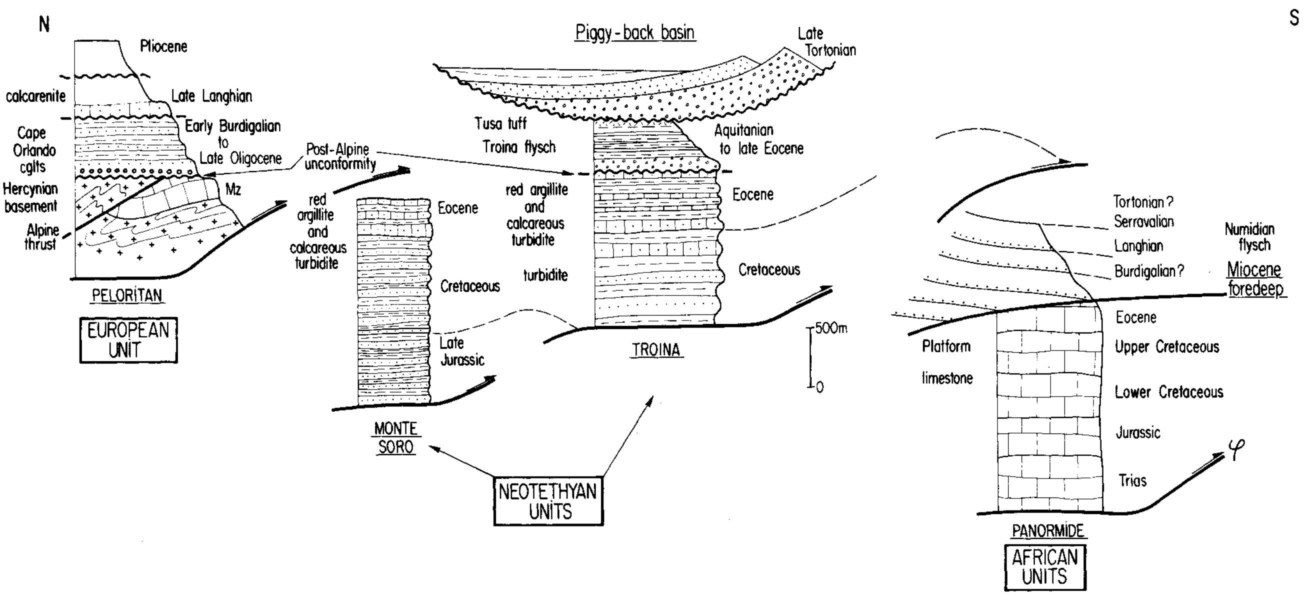

Fig. 3. Lithostratigraphic columns of the European, Neo-Tethyan and African units.

thrusts), synchronous normal faults are numerous in the northern part of the island (Catalano *et al.* 1981). The geometry of the prism maintains a critical taper (Davis *et al.* 1983) by compensating the effects of convergence (accretion at the toe of the prism or duplexing and underplating in the inner parts of the prism) with distensional or flattening features (thinning by erosion and normal faulting).

TERRANES

The tectonostratigraphic terranes of Sicily represent three distinct paleogeographic domains of the Mesozoic Neo-Tethyan realm; included are fragments of the two (European and African) conjugate continental margins, and fragments of the intermediate ocean (Fig. 3).

African terrane

The Mesozoic paleomargin of Africa has been deformed in the Cenozoic. Parts of the margin probably have been subducted beneath the Tyrrhenian Sea, other portions are incorporated in the Sicily subduction complex, whereas an important fragment (Ragusa plateau) is still attached to the craton and constitutes the emerged foreland. This tectonic setting is similar to that of the Apennines (Royden *et al.* 1987, Casero *et al.* 1988, Moretti & Royden 1988, Roure *et al.* 1988); in both areas the African (Apulian) margin comprises thick carbonate platforms, representing carbonate shoals, and packages of cherty limestone and cherts represent intervening deeper-water basins (Broquet 1968, 1970a,b, Mascle 1970, 1979, Catalano & D'Argenio 1978, 1982). These basins resulted from thinning of the crust during a phase of intra-continental rifting in late Triassic and early Jurassic time (Wood 1981, Miconnet 1983, 1988, Di Stefano & Gullo 1987). No oceanic crust is known to exist beneath these basins (Imerese basin in Sicily, a correlative setting of the Lagonegro basin in the Apennines). The allochthonous sedimentary units are inferred to be detached from older strata along an intra-Triassic décollement.

Within the fold and thrust belt of Sicily, we recognize: (i) a southern platform domain (Iblean), now exposed in the Ragusa plateau (Patacca *et al.* 1979); (ii) a basinal domain; and (iii) a northern platform domain.

The stratigraphic relations in the southern platform domain are well known owing to the abundance of exploration wells (Fig. 3). Included in this sequence is a thick shallow-water Triassic to Lower Jurassic carbonate unit that includes the organic-rich Streppenosa Formation, a source rock for the oil (Pieri & Mattavelli 1986). Shallow-water conditions and possibly episodes of subaerial exposure are indicated in the higher parts of the stratigraphic sequence, demonstrated by Upper Cretaceous bauxitic horizons and rudistid reefs, Cenozoic subaerial volcaniclastics and Quaternary calcarenites. Cenozoic lithofacies suggest highly diversified environments of deposition that include deeper water settings (Scaglia) on the northern and eastern border of the plateau (Patacca *et al.* 1979). The extension of the platform facies to the north beneath the allochthonous mass of the accretionary prism remains conjectural because of the inferred presence of transitional facies. This contrasts with the southern Apennines, where exploration wells have recognized fragments of the lower platform accreted by underplating at the base of the subduction complex (Casero *et al.* 1988, Roure *et al.* 1988).

The basinal domain (Imerese) is now entirely allochthonous and only exposed in tectonic windows beneath the upper platform unit or below Neogene turbidite overlap sequences. Besides questionable Permian beds described locally in the west (Mascle & Termier 1970, Mascle 1979), these basinal units comprise Triassic

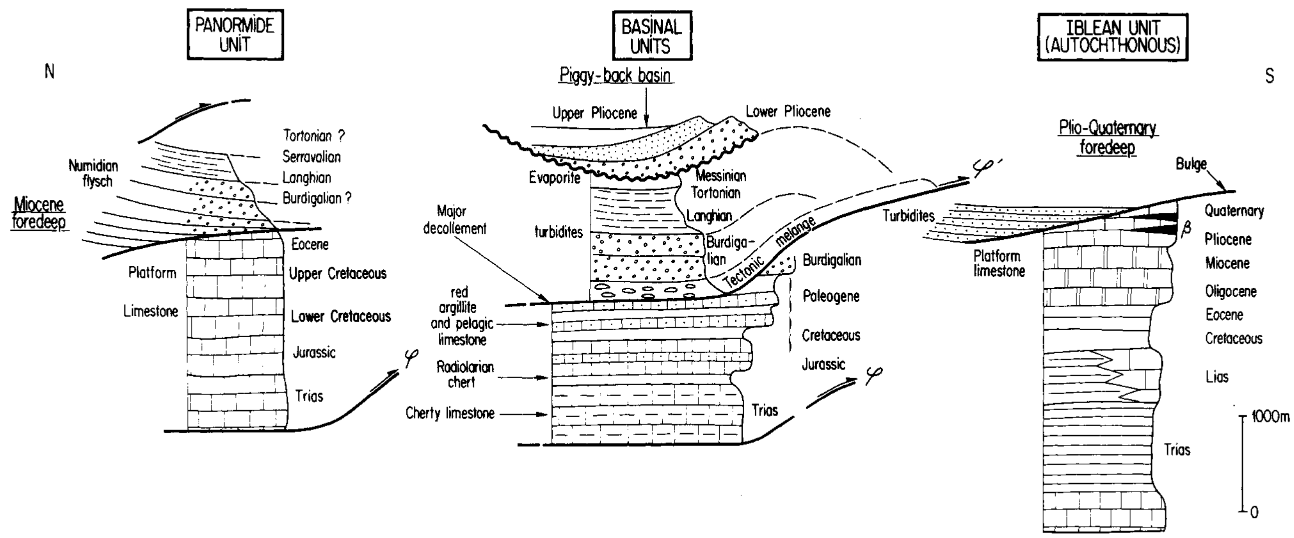

Fig. 4 Lithostratigraphic columns of the African (Panormide, Imerese and Iblean) units.

cherty limestone and Jurassic to Cretaceous radiolarian chert that are overlain by pelagic (Scaglia type) limestone or red and green Paleogene argillite (Lentini 1974, Catalano & D'Argenio 1982). The Sicilian basinal units, as with the Lagonegro units of the southern Apennines, have lost their Neogene sedimentary cover, owing to tectonic detachment along a décollement level within Upper Cretaceous to Paleogene argillites (Fig. 4). The Neogene terrigenous part of the basinal sequence (Burdigalian to Messinian) constitutes an independent allochthonous nappe. The basal tectonic melange (level of detachment) is often referred to as the "argille varicolore" and was previously interpreted as an olistostrome (Rigo 1957, Broquet 1970b, Broquet *et al.* 1984).

The northern platform domain (Panormides) is well exposed in the northwestern part of Sicily. Made of Mesozoic and Paleogene platform limestone, the stratigraphic units of the Panormides are overlain by a Neogene (late Aquitanian or Burdigalian) thick terrigenous sequence (Wezel 1966, 1970, Courme & Mascle 1988). These terrigenous strata are older than similar strata found to the south where Burdigalian to Messinian strata overlie the basinal sequences, and Plio-Quaternary strata lie above the northern border of the Ragusa plateau (Magne *et al.* 1972, Grasso *et al.* 1982, Broquet *et al.* 1984).

Neo-Tethyan terrane(s)

Tectonically overlying the northern platform domain of the African terrane are stratigraphic units, best exposed around Troïna or in the Monte Soro area, made up of an Upper Cretaceous and Paleocene-to-Eocene pelagic sequence, including Scaglia-like limestones, red argillites and terrigenous flysch. Isolated patches of Lower Cretaceous calcareous beds (Aptian) also have been described (Duée 1969, Andreieff *et al.* 1977). The absence of pre-late Jurassic beds, unlike the African intracontinental basinal units, characterizes these paleo-oceanic sequences. An important feature of these units is the occurrence of a major unconformity between Eocene and older beds and an Oligocene quartz-rich terrigenous sequence which includes pebble to boulder sized granitic clasts. We infer this to be evidence of an Alpine (pre-Oligocene) tectonic disturbance (Caire & Truillet 1963, Ogniben 1970, Guerrera & Wezel 1974, Loiacono & Puglisi 1983): if correct, this basinal domain is isolated paleogeographically from the units of the African terrane.

Despite the absence of ophiolite units in Sicily, the inferred Neo-Tethyan pelagic sequences clearly show close affinities with the Liguride units of the southern Apennines (Cilento flysch, Amodio-Morelli *et al.* 1976, Boccaletti *et al.* 1985), and the Ligurides are known to include ophiolitic melange. Thus, we infer an oceanic paleogeographic setting (Neo-Tethys) for these basinal units.

European terrane

The structurally highest terrane is a crystalline nappe occupying the northeastern corner of Sicily (Peloritani Mountains). These fragments of Paleozoic metamorphic rock, including isolated horizons of Mesozoic carbonate sedimentary cover, are inferred to be fragments of European basement (Figs. 2 and 3). Like the Neo-Tethyan oceanic unit, this continental terrane is unconformably overlain by Oligocene terrigenous strata (Capo d'Orlando flysch, Caire & Truillet 1963, Courme & Mascle 1988), and therefore, both units seem to have been affected by Alpine deformations.

TIMING OF THE NEOGENE DEFORMATIONS

Except for the European and Neo-Tethyan units, which were already partially tectonized during the pre-Oligocene deformations, the present architecture of the Sicilian subduction complex reflects Neogene continental subduction of the African margin. The subduction of this continental lithosphere followed the final closing of all remnants of the Neo-Tethys Ocean. The A-type subduction associated with the modern structural domain of Sicily began after a collision event involving a portion of the southern flank of the European plate and the African (Apulian) margin. This collision occurred in the early Miocene (Aquitanian–early Burdigalian) (Rehault 1981, Roure *et al.* 1988). The configuration of subduction associated with this tectonic event was N-dipping and the Sicilian subduction complex subsequently has migrated progressively southward, involving successively different paleogeographic domains (platforms or basins) of the African margin.

The age relations of this southward-advancing thrust front are well constrained by a number of lines of evidence. (1) The age of the first deep-water flysch deposited on top of previously shallow-water carbonate platforms outlines the subsidence of the foreland and the migration of the fore-deep (flexural basin) at the front of the growing and southward advancing allochthon. Whereas Aquitanian (?) or Burdigalian strata (Numidian flysch) overlie the Panormides platform, the first turbidites to reach the Iblean platform are no older than Middle Pliocene. (2) The age of the first unconformable syntectonic deposits of the piggy-back basins post-dates the accretion of underlying allochthonous units in the subduction complex. Internal unconformities and shifts in the basin axes indicate ongoing deformations from the toe of the accretionary prism to deeper levels beneath older deformed sections (Roure *et al.* 1988).

Besides the Oligocene flysch (Capo d'Orlando or Troïna Formations), which relates to the Alpine orogenic event, the first piggy-back deposits are Serravalian on the European and Neo-Tethys units, and no older than Tortonian on the Panormides or the internal parts of the Imerese. To the south, close to the deformation front, the oldest unconformity in the allochthon is younger, usually Middle Pliocene (Fig. 3 and 4).

The red and green argillites ("argille varicolore") in the African basinal units previously have been interpreted as olistostromal deposits sourced from internal nappes (Rigo 1957, Broquet *et al.* 1984). We now believe that the "argille varicolore" units are tectonic melanges that outline décollement or thrust planes along which the Neogene basinal sequences have been detached from a Mesozoic to Paleogene substratum (Roure *et al.* 1988). The contacts between these rocks and the overlying terrigenous sequence are thus tectonic and cannot be used to date deformational events. Immediately beneath these thrust planes the strata become progressively younger to the south and this indicates a southward propagation of successive thrust ramps (Fig. 4). Tectonic melange overlies pre-Burdigalian beds in the north and Tortonian or even Pliocene beds in the south; the main deformation is as young as Quaternary in southern Sicily, and not Burdigalian as previously reported (Broquet 1970a, Mascle 1979, Channel *et al.* 1986). Thus, our stratigraphic study in the Sicily subduction complex provides evidence for recent deformation of the African units. The first accretion of the basinal units is no older than Tortonian, and most of the observed shortening is Plio-Quaternary in time, thus synchronous with the opening of the Tyrrhenian Sea, where the rifting began in the Tortonian (Sardinian margin, Rehault *et al.* 1987) and oceanic crust first formed in late Pliocene-Quaternary (Kastens *et al.* 1987).

GEOMETRIC EVOLUTION OF THE SUBDUCTION COMPLEX

The growth processes of a subduction complex are clearly expressed in the presently emergent accretionary prism of Sicily. Deformation progressively moved southward, younger flysch deposits of the foredeep have been successively accreted into the allochthonous mass of the accretionary prism. Beneath the present thrust front, a blind thrust is required to explain the steep S-dipping attitude of the Calabrian (Quaternary) flysch deposits of the foredeep (Fig. 5–7).

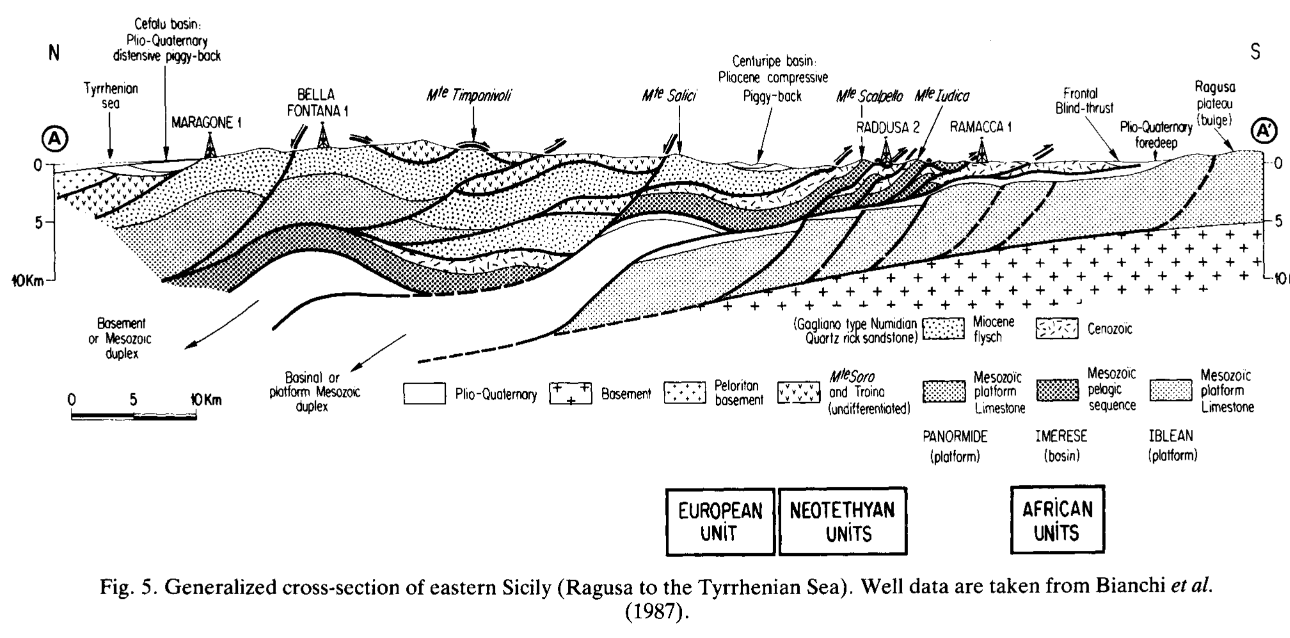

Fig. 5. Generalized cross-section of eastern Sicily (Ragusa to the Tyrrhenian Sea). Well data are taken from Bianchi *et al.* (1987).

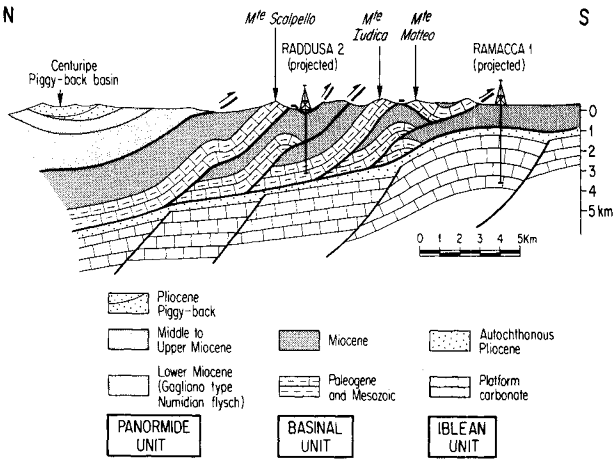

Fig. 6 Piggy-back basin and nappe anticlines: the Centuripe–Mte Judica–Mte Scalpello section. Geometry based on well data, taken from Bianchi *et al.* (1987), and our mapping of stratigraphic and structural relations.

Underthrusting of more external materials at the toe of the prism included a tilting and folding of ancient thrusts, which therefore constitute nappe anticlines above younger ramps (Fig. 5). The frontal thrust is at a shallow horizon, but N-dipping thrust planes extend to deeper levels of décollement within the Mesozoic sequence: high-level nappe anticlines involving the Imerese or Panormides units, probably are related to underplating; that is, accretion of Mesozoic or basement rocks into the subduction complex far north of the deformational front (Figs. 6 and 7).

Because young unconsolidated sediments were overthrust, dewatering processes have played an important role in the tectonic development of the accretionary prism. Thrust surfaces are mainly tectonic melanges, 100 or 200 m thick, with an argillitic matrix displaying incipient cleavage. Hard rock fragments (knockers), encased in this matrix, are cut by open fractures that are locally filled with hydrothermal materials, for example, opal. High fluid pressures help explain these features and circulation of the fluids restricted to specific horizons led to particular levels of décollement. The transition between fault zones, characterized by melange, and the undeformed allochthon is always sharp, and most of the allochthonous sequences, except along faults, remain structurally coherent.

As a result of the subduction of continental lithosphere, a thick crustal root has accumulated beneath the Sicilian subduction complex, as expressed by the Moho geometry (Fig. 1). This presumed root could account for the rapid uplift of the island, as indicated by the occurrence along the northern coast of shallow marine Pliocene and Quaternary beds at elevations as high as 800 m. Additionally, heat migrating laterally away from the loci of rifting in the Tyrrhenian Sea could also contribute to the youthful and rapid uplift along the flank region, including Sicily, of this sea (Chi-yuen Wang written communication 1988).

N-dipping normal faults of Pliocene and Quaternary age are well developed along the northern part of Sicily, from the crest of the island to the Tyrrhenian coast, and similar features exist offshore (Catalano *et al.* 1981). Synchronous with the opening of the Tyrrhenian Sea, normal faulting provides a means to maintain the critical taper of the subduction complex in order to help balance the consequences of frontal accretion, underplating, erosion and uplift which are continuously altering the prism's geometry.

CONCLUSION

Despite a slow rate of plate convergence (less than 1 cm yr^{-1}) between the Eurasia and Africa continental plates, features such as arc magmatism, back-arc rifting, and a forearc basin and accretionary prism are well developed in the environs of Sicily. The fold and thrust belt north of the Ragusa platform is a young, essentially active, accretionary prism. Continental subduction, possibly augmented by elevated heat flow stemming

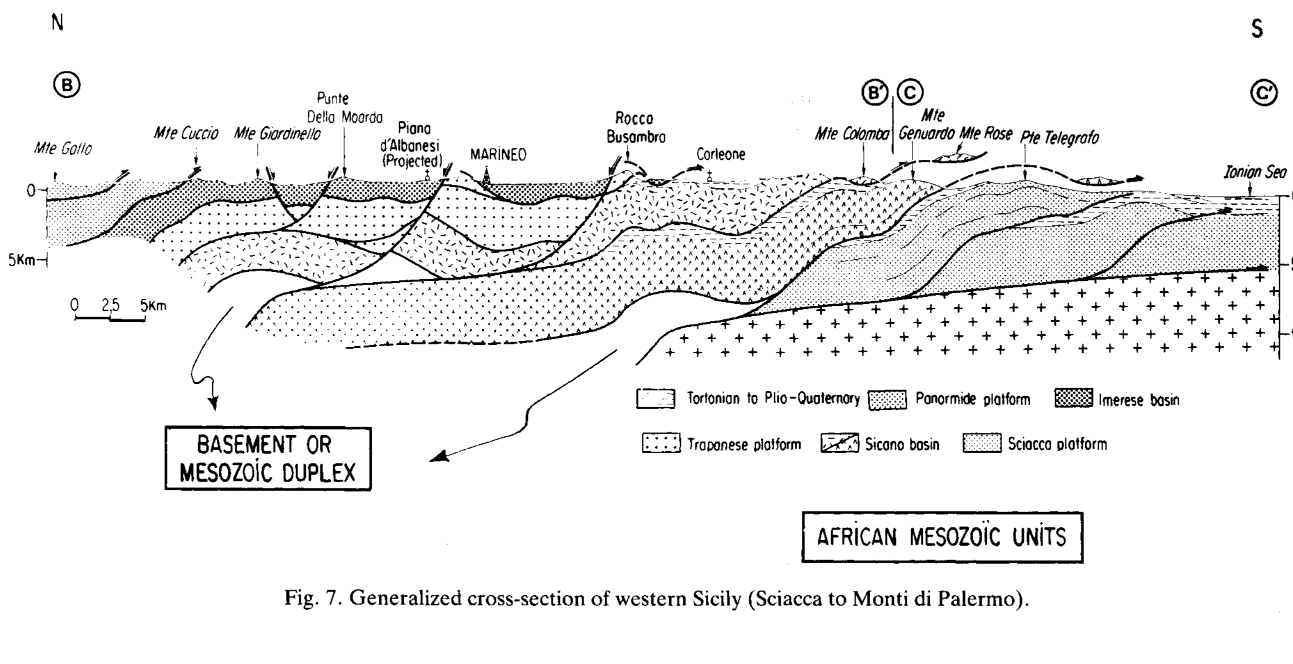

Fig. 7. Generalized cross-section of western Sicily (Sciacca to Monti di Palermo).

from rifting in the Tyrrhenian Sea, accounts for the rapid uplift of the island. A characteristic tectonic feature of the island is compressional thrusting in the frontal area of the accretionary prism contemporaneous with distensional normal faulting in the rearward area of the accretionary prism. These seemingly contradictory stress regimes result from the rapid uplift of the island which places the accretionary prism into a supercritical taper. Normal faulting and erosion distend the prism, thereby preserving a critical taper during episodes of S-verging frontal thrusting and regional uplift.

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