Annales Societatis Geologorum Poloniae (2000), vol. 70: 81–98.

EXTENSIONAL TECTONICS DURING MAGHREBIDES CHAIN BUILDING SINCE LATE MIOCENE: EXAMPLES FROM NORTHERN SICILY

Giuseppe GIUNTA, Fabrizio NIGRO & Pietro RENDA

Department of Geology and Geodesy, University of Palermo, Corso Tukory n 131, 90134, Palermo, Italy

Giunta, G., Nigro, F. & Renda, P., 2000. Extensional tectonics during Maghrebides Chain building since late Miocene: examples from Northern Sicily. *Ann. Soc. Geol. Polon.*, 70: 81–98.

Abstract: The Northern Sicilian-Maghrebian Chain courses W–E from the Trapani Mts to the Peloritani Mts and is composed by a set of tectonic units deriving from the Miocene–Pleistocene deformation of the Northern African Continental Margin. Inside it three main geotectonic elements ("external", Sicilide and "Austroalpine") are present and outcrop juxtaposed with a W–E trend. The external element composes the more western Trapani, Palermo and Western Madonie Mts, the Sicilide composes the Eastern Madonie and Nebrodi Mts, while the "Austroalpine" composes the more eastern Peloritani Mts. The orogen shows a culmination in the Trapani Mts and a depression in the Peloritani Mts.

The main plicative stages are relatable to late Oligocene–early Miocene from the more internal sectors, while the deformation of the more external sectors starts from early-middle Miocene.

The Sicilian chain body is re-involved in tectonism since late Tortonian, which persists until the recent time. During this interval, the deformation of the Sicilian Chain continued by activation of fault systems with different displacements.

In the present paper, an important extensional tectonic stage is recognised, starting from the Tortonian; it is supported by structural data and shows through several geological sections across the northern sectors of the Sicilian orogen. This deformation is of exceeded wedge critical taper values, controls the early stages of the Tyrrhenian Basin opening, and is represented by low-angle fault system, producing tectonic omissions in the stratigraphic sequence.

The detachment fault system is subsequently displaced by a complicated grid of Plio-Pleistocene net- and strike-slip fault system that controls the genesis of tectonic depressions in the northern off-shore areas of the Sicilian Chain. This neotectonic system may be reconnect to a W–E trending simple shear system, which controls the more recent Tyrrhenian Basin development.

Key words: extensional tectonics, late Miocene, Tyrrhenian opening.

Manuscript received 2 August 1999, accepted 15 February 2000

INTRODUCTION

In many orogens the regional-scale Tertiary extensional deformation development is often controlled by the presence of pre-existing deformational structures; this has been described in many examples of the external zones or the internal part of the subductional and collisional systems. With respect to the collapse mechanisms that affect the more internal sectors of active margins or of the collisional orogens, there are frequent examples showing evolution of belts of different age conditioned by the development of extensional tectonic structures with different geometrical characters (e.g., Brewer & Smythe, 1984; Hossack, 1984; Cheadle *et al.*, 1987; Constain & Coruh, 1989).

The low-angle extensional systems have frequent regional trends, which run parallel to the pre-existing belt, and develop through the activation of first order flat surfaces, mostly reactivating previous thrust horizons. Minor order listric high-angle faults link along these surfaces, causing widespread tilting of blocks (Jarrige, 1992). The combination of low-angle décollements and high-angle faults give rise to ramp and flat geometries at every scale (Gibbs, 1984a, b, 1989; McClay & Ellis, 1987; Ellis & McClay, 1988).

With regard to the low-angle extensional systems, some well-known examples came from the Basin and Range Province of the North American Cordillera (Anderson, 1971; Davis & Coney, 1979; Howard & John, 1987; Miller & John, 1988; Lister & Davis, 1989; Lucchitta, 1990; Yin & Dunn, 1992; Constenius, 1996), where the existence of very low-angle normal faults has been revealed ("detachment faults"; Davis *et al.*, 1980; Davis, 1983; Davis, 1988; Davis

& Lister, 1988) inside the Cenozoic sedimentary covers (Highly Extended Terrains), producing continental extension and the exhumation of the Palaeozoic metamorphic substrate (core complex).

In the peri-Mediterranean areas, the Neogene extension is in places represented by low-angle fault systems, superimposed on previously deformed belts (e.g., Avigad *et al.*, 1997; Crespo-Blanc, 1995; Martinez-Martinez & Azanon, 1997 and references therein); similar geometries appear also characterising the Jurassic Tethys continental margin (e.g., Froitzheim & Eberli, 1990).

The Apenninic-Maghrebides system represents an arch-shaped orogen located in the Central Mediterranean, affected by stretching in its inner part since late Miocene, related to the Tyrrhenian Basin formation (Malinverno & Ryan, 1986; Patacca *et al.*, 1992). This extensional tectonics is contemporaneous to compression, which moved toward the foreland sector of the belt (Patacca & Scandone, 1989; Giunta, 1991).

Several examples of Neogene extensional deformations are known along the Apenninic chain. These represent the collapse evolution of the more internal zones, coaxial and opposite moving with respect to thrusting (Lavecchia *et al.*, 1995), that have reactivated inherited thrust surfaces. The best known regarding the Apuane Mts core complex genesis (Carmignani & Kligfield, 1990; Carmignani *et al.*, 1994) and the extensional areas of the inner sector of the central-southern Apennines and Calabria (Platt & Compagnoni, 1990; Oldow *et al.*, 1993; Ferranti *et al.*, 1996; Boccaletti & Sani, 1998), both interpreted as the consequence of the Tyrrhenian Basin "opening". Also, Meletti *et al.* (1995) pointed out the main problems connected to the kinematic evolution of the Tyrrhenian-Apenninic Chain couple: particularly, they analyse the relationships between the lithosphere and the astenosphere in the Northern Apennines, in the frame of the roll-back-like mechanism.

In Sicily, similar extensional deformations are poorly known; only Nigro (1998) recognised Plio-Pleistocene low-angle extensional systems, which developed on the Miocene tectonic edifice, while the recognised high-angle dip-slip systems, mostly characterising the Northern Sicily coastal sectors, have been generally ascribed to Plio-Pleistocene tectonism (*i.e.*, Abate *et al.*, 1978).

In the present paper, with the support of field surveys, mesostructural analysis and several geological cross-sections, an important extensional tectonics has been recognised since late Miocene, superimposed on the thrust tectonics of the inner Sicilian-Maghrebides. It is represented by low-angle fault systems with ramp-flat courses, in places producing extended tectonic omissions that have exposed large bands of Permian(?)–Triassic terrains in a younger-on-older configuration, and controlled the sedimentation processes in the internal sector of the constructing orogen. The recognised shallow dipping detachment system on land changes in depth toward the north, where it involves deeper levels of the chain crust. Extensional tectonics is represented by two main stages; the first one, of late Miocene–early Pliocene, gave rise the collapse of the internal sector of the constructing orogen, where clastic and evaporitic sedimentation develops; the second, of late Pliocene–Pleistocene, is expressed by a complicated grid of high-angle normal faults connected to a strike-slip system that controls the evolution of rhegmatic tectonic depressions in the northern mainland and its off-shore areas. The neotectonic system may be attributed to a W–E trending dextral simple shear mechanism, representing the recent evolution of the Tyrrhenian opening.

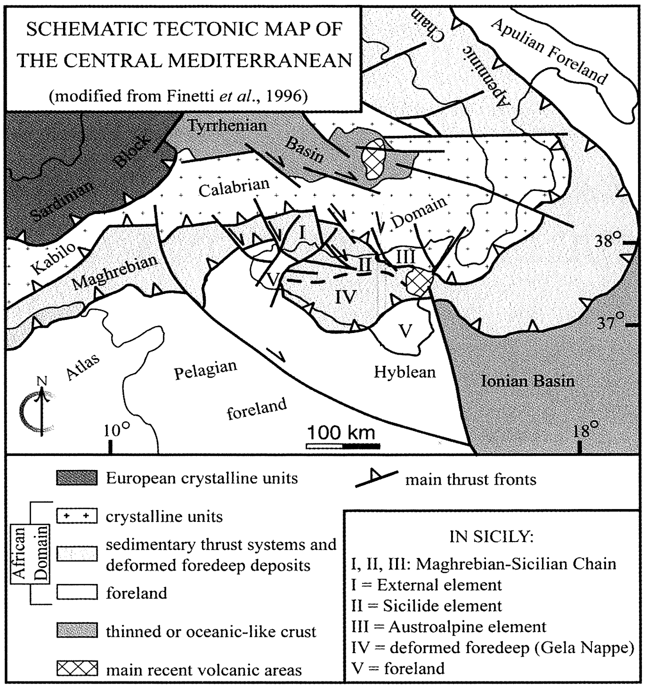

Fig. 1. Schematic tectonic map of the Central Mediterranean

GEOLOGICAL FRAMEWORK

Mainland Sicily, located in the Central Mediterranean, represents a sector of the Maghrebian Chain, in which different structural domains can be distinguished, northward bounded by the Tyrrhenian Sea (Fig. 1).

The chain is overall represented by a W–E trending thrust system progressively emplaced since early Miocene. The kinematic processes are expressed by the progressive foreland migration of foredeep-deformation front couple and of the chain body, composed of thrust and/or plastic nappes which in turn carry piggy-back basins. The gently deformed foreland outcrops in the south-east and westernmost Sicily mainland, and is widely inflected below the Sicilian-Maghrebian thrust system.

The chain front is today located in the Southern Sicily and its off-shore, where late Pleistocene deposits underplate beneath its toe region (so-called Gela Nappe; Beneo, 1961).

The main Maghrebides portion is located in the north-central sectors of the Sicily mainland and is composed of three main kinematic elements: "external", Sicilide and "Austroalpine". These tectonic assemblages, today dismembered and juxtaposed from west to east, belong to the Mesozoic African Margin and are derived from the deformation of different domains and from a more and more clockwise rotation toward the east of the tectonic units during the Tertiary (Giunta, 1991). The "external" element outcrops in Western Sicily, from the Trapani Mts to the Madonie Mts, the Sicilide in the Nebrodi Mts, and the "Austroalpine" in eastern Sicily (Peloritani Mts).

The "external" element is composed of a set of tectonic units, deriving from the deformation of Mesozoic to Tertiary successions, representing pelagic basins interposed between carbonate platforms. The deformation of these successions occurred between Miocene and Pliocene and is expressed by several tectonic units overthrust in ramp-flat and duplex style, progressively emplaced from north to south in a piggy-back sequence. The geometrical position of these units inside the tectonic edifice could reflect the ancient palaeogeography (Giunta & Liguori, 1973; Scandone *et al.*, 1974; Catalano *et al.*, 1978).

From the bottom, the "external" tectonic edifice is composed of (Fig. 2B, D):

– Saccense and/or Trapanese units (up to 1500–2000 m thick), composed of carbonate platform to pelagic carbonatic deposits;

– Imerese and Sicanian units (up to 1500 m thick), composed of pelagic carbonatic deposits. They outcrop in south-western Sicily and are represented by several emergent thrust sheets, in places largely displaced;

– Panormide Units (up to 1500–2000 m thick), composed of carbonate platform deposits;

– Sicilide Units (up to 200–300 m thick), composed of mostly pelagic shales, with internal "chaotic" geometries, discontinuously outcropping between the Trabia Mts and the Madonie Mts.

The Panormide and Imerese successions start above a siliciclastic substratum of Permian(?)–Late Triassic age (Mufara and Lercara fms), representing the bottom of the outcropping Sicilian sedimentary multilayer.

During the Miocene compressional tectonics, foredeep deposits disconformably overlaid the carbonatic substrate (Giunta, 1985); the Oligo-Miocene foredeep deposits over the Imerese, Panormide and Sicilide units are known as the Numidian Flysch. These successions, today in places detached from their substrate, widely outcrop in more southern areas with respect to the Palermo Mts (from the eastern Sicani Mts to the eastern Sicilian-Maghrebides); in these areas the Numidian Flysch represents the outcropping covers of the Imerese and Sicilide imbricate fan (Bianchi *et al.*, 1987). The foredeep deposits of the more external tectonic units (Sicanian and Trapanese) are mostly represented by Serravallian marls.

An arenaceous-conglomeratic succession of the so-called Terravecchia Fm. unconformably outcrops over the early Miocene tectonic edifice. This is generally interpreted as a molassic deposit that post-dates the main "tectonogenetic" stage of the Northern part of the Sicilian-Maghrebides Chain (Broquet, 1968; Mascle, 1979).

The deformations affecting the tectonic edifice since the Pliocene are poorly analysed; they are often represented by net- and strike-slip faults system in the Northern Sicily hinterland, and by net- and dip-slip faults system, mostly characterising its coastal areas. Recently, Nigro (1998), Abate *et al.* (1998a) and Giunta *et al.* (1998) have analysed the neotectonic brittle structures of the Northern Sicily and framed them in a geodynamic context related to the Tyrrhenian Basin development. Particularly, according to Ghisetti & Vezzani (1984), who interpreted the Kumeta and Busambra ridges as two positive flower structures related to Plio-Pleistocene dextral wrench tectonics, Nigro (1998) interpreted these structures as the tectonic upwelling of the underplated Maghrebides foreland, through a deep-seated transpressional fault system related to the Tyrrhenian Basin evolution.

FIELD DATA

In the Northern Sicilian Maghrebides Chain the main geometric characteristics are expressed by a complicated interference pattern related to Miocene thrust tectonics, late Miocene low-angle extensional tectonics and a neotectonic high-angle net- and strike-slip fault system.

Thrust tectonics

Compressional tectonics is represented by several thrust sheets, characterised by frontal ramp anticlines. The general trending of plicative axial surfaces indicates an Africa vergence of the structures. The Miocene thrust surfaces generally dip towards NW in the Palermo Mts and towards the north in the Madonie Mts (Fig. 2D). There are no pop-up structures or back-thrust near the main ramp anticlines.

In the Palermo Mts, Panormide and Imerese foreland vergent thrust sheets largely overthrust on the deformed external shallow substrate through a very low angle flat (Catalano *et al.*, 1998); here, thrust step-up geometries are characterised by a few degrees of dip. Toward the external zones, the Sicanian stack of tectonic units replace the Imerese imbricate fan over the foreland deformed substrate; here the Sicanian stack links along a sole thrust and shows a more highly thrust step-up angle.

The deformed foreland is affected by an emergent thrust system in the more south-western Sicily (Sciacca Mts), where the step-up geometries are characterised by the very high values of dip of the described chain transept. The regional monocline gently dips towards the Sicilian wedge by about 4°.

Low-angle extensional structures

The recognised low-angle extensional fault system affects the Sicilian tectonic edifice between the Palermo and the Western Madonie Mts and is characterised by:

– synthetic and antithetic ramp (listric) and flat geometries, linking along extended flat (detachment faults);

– younger-on-older configuration, represented by the mechanical contact between the Oligo-Miocene Numidian Flysch and the underlying Permian(?)–Late Triassic Mufara Lercara fms, which in turn produces tectonic omissions;

– ramp décollement-like, extensional duplexes and in places roll-over anticline geometries;

– "chaos"-like structure (Wernicke & Burchfiel, 1982).

The detachment fault system mostly inverted previous thrust and high-angle reverse fault surfaces. In places it is sutured by the Terravecchia Fm. molassic deposits and

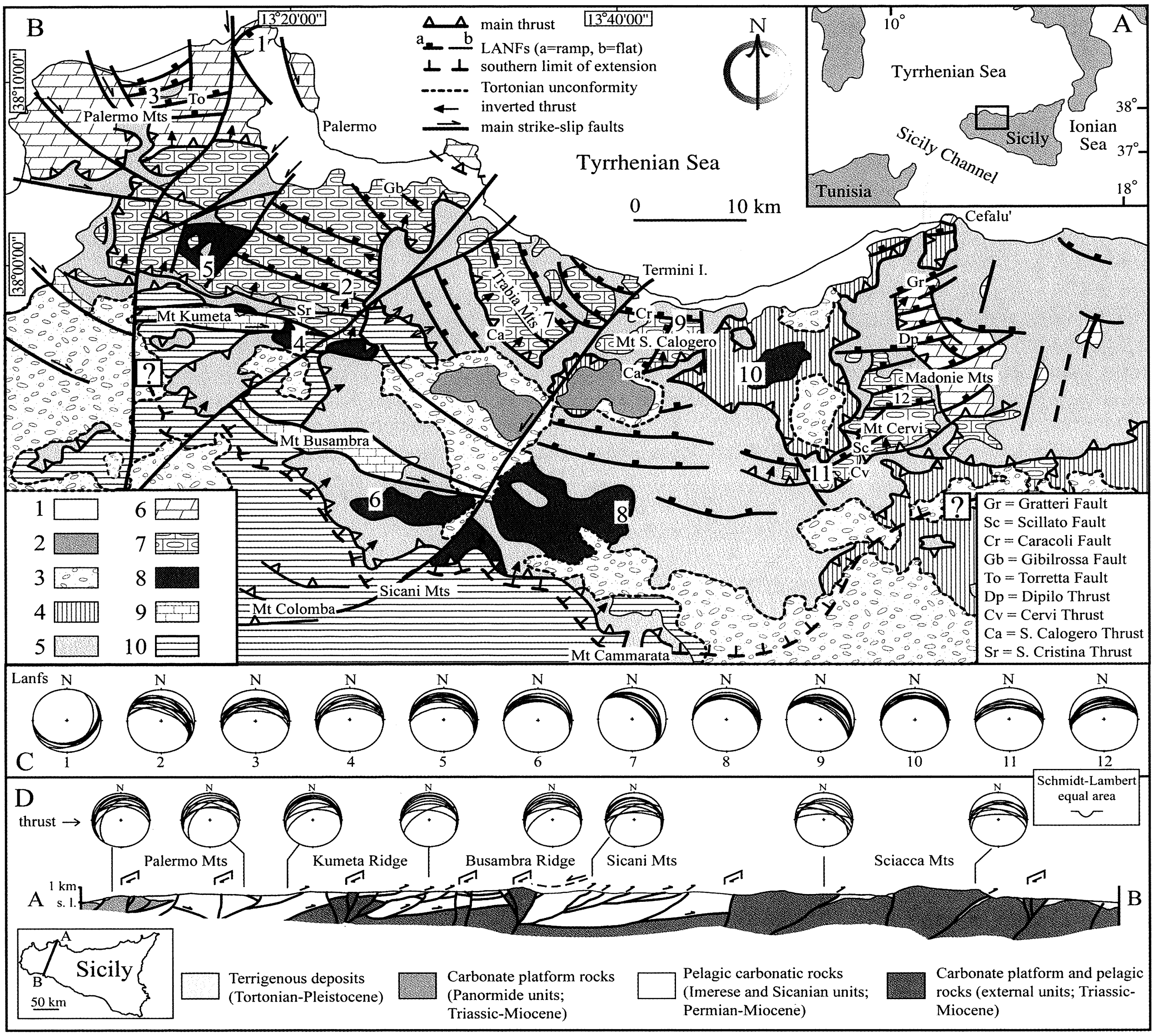

Fig. 2. **A.** Index map of the study area; **B.** Schematic geological map of the Palermo-Madonie Mts. *1* – Plio-Pleistocene deposits; *2* – Messinian to early Pliocene deposits; *3* – Terravecchia Fm. (late Tortonian); *4* – Sicilidi units (Cretaceous–early Tertiary); *5* – Numidian Flysch (late Oligocene–early Miocene); *6* – Panormide units (Triassic–Oligocene); *7* – Imerese units (Triassic–early Oligocene); *8* – Mufara-Lercara fms (Permian–Triassic); *9* – Trapanese units (Triassic–early Miocene); *10* – Sicanian units (Triassic–early Miocene); **C.** Stereonet of mesostructural data regarding the recognized Lanfs system. The sites are shown in Fig. 2B; **D.** Schematic structural section across the Western Sicilian-Maghrebian Chain. For cross section, horizontal scale is equal to vertical

arched by neotectonic positive flower structures.

The limit of the extension outcrops south of the Kumeta, Busambra and Trabia-Termini Imerese Mts (Fig. 2B), with a WNW–ESE trending alignment; the extensional system also shows displacement toward the Cefalù Basin.

The cross-sections of Figs 3 and 4 show several examples of extensional faults systems between the Palermo and Madonie Mts; they have been semi-quantitatively restored, even if the widespread presence of younger strike-slip faults cannot allow us a very well-defined balancement.

The listric course of extensional fault surfaces is also expressed by tilting of blocks, which show a high angle inside the Mesozoic–Tertiary carbonates of Panormide and Imerese tectonic units, and a low angle inside the Numidian Flysch and Mufara-Lercara fms. Fault breccia, mostly along flat surfaces, is commonly present.

Extensional ramp faults in the Palermo Mts (cross sections A-A' to C-C' of Fig. 3) and in the Trabia-Madonie Mts (cross sections D-D' to H–H' of Figs 3 and 4) induced tilting of Jurassic carbonatic blocks of Panormide and Imerese rock bodies and link along the older thrust surfaces (mostly bounding the bottom of the Mufara-Lercara fms). Accentuated of hangingwall tilting is in places revealed by roll-over geometries, as in the northern Palermo Mts (Mt Castellaccio, Fig. 5) or in the Trabia Mts (Mt Famo near Caccamo Village, Fig. 6), where portions of older tectonic units back-

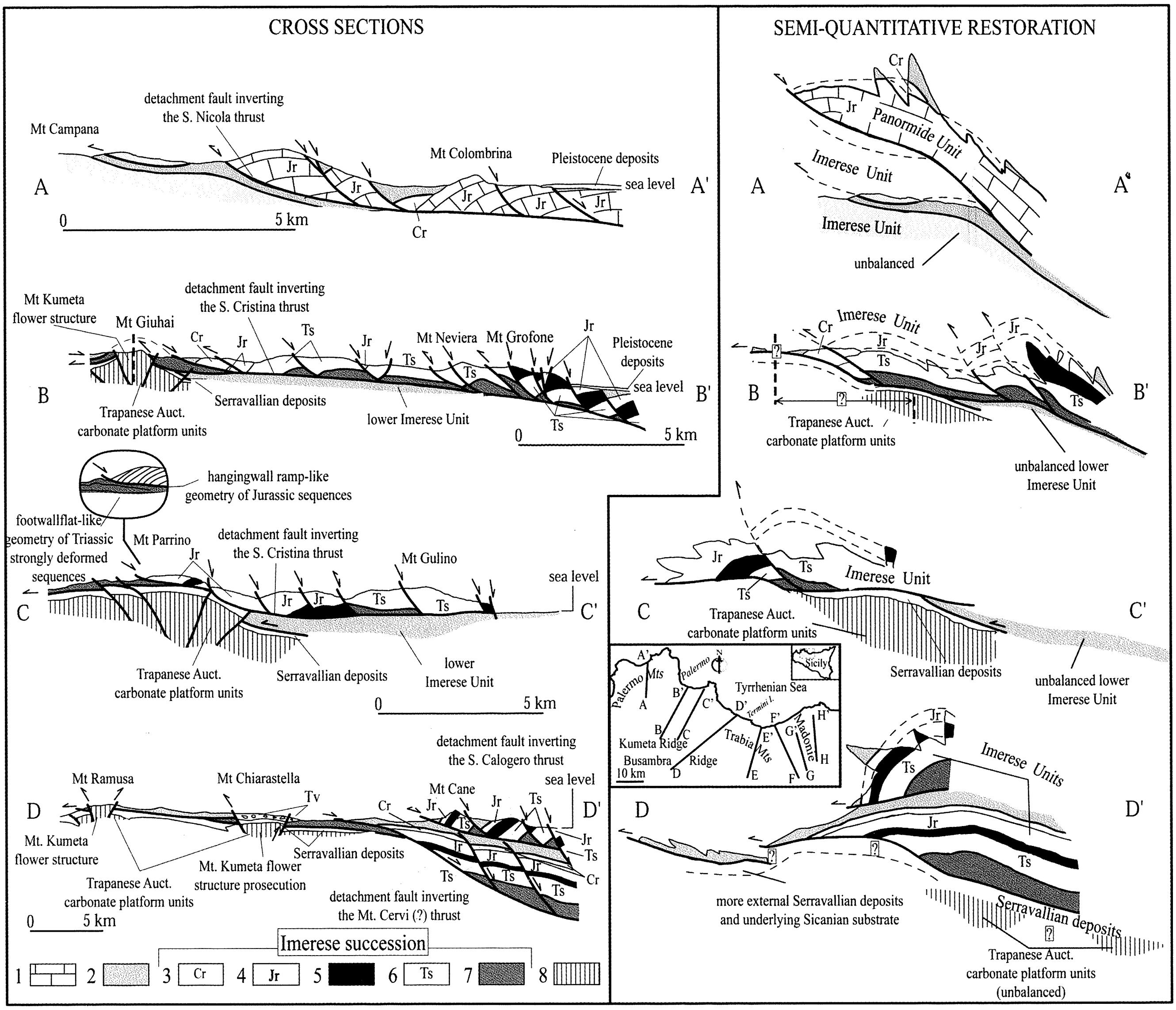

Fig. 3. Schematic geological cross sections of the Palermo-Termini Imerese Mts. *1* – Panormide units (Mesozoic–Tertiary); *2* – Numidian Flysch (late Oligocene–early Miocene). Imerese units: *3* – Cretaceous–Eocene; *4* – Middle-Late Jurassic; *5* – Early Jurassic; *6* – Late Triassic; *7* – Mufara-Lercara fms (Permian–Triassic). *8* – Trapanese units (Mesozoic–Tertiary); *Tv* – Terravecchia Fm. (late Miocene). Cross sections show only the main neotectonic strike-slip structures. Horizontal scale is equal to vertical

slide along thrust surfaces. The occurrence of slickensides and other kinematic indicators reveals that the deformation is characterised by dip- and subordinately net-slip displacements. The trend of these structures have a main peak of frequency towards NW–SE and/or WNW–ESE in the Palermo Mts, swinging to E–W in the Madonie Mts (Fig. 2C). The system overall gently dips toward N–NE, except in the Kumeta and Busambra Mts areas, where transpressional structures identified since the Pliocene (Ruggieri, 1966) have arched the extensional sole.

The listric ramp-flat extensional faults are superimposed onto a tectonic edifice and have inverted the older thrust surfaces. In the Palermo Mts (A-A' cross section of Fig. 3) the extensional flat is located along the previous Panormide S. Nicola Thrust, while in the B-B' and C-C' cross-sections the extensional ramp system links along the Imerese S. Cristina Thrust unit (Fig. 7). It outcrops in the Mt Grofone-Mt Gulino carbonatic massif, which is bounded by two important NE–SW trending neotectonic left transcurrent structures. Reactivation of older fault surfaces is demonstrated by the superposition of variously plunging slickensides in the same fault scarp, as for example along the northern slope of the Kumeta ridge and in the northern Palermo Mts. The inversion of previous thrust surfaces is also recognisable in the more eastern study sector, where the Mt S. Calogero and Mt Cervi thrust (Imerese unit) is reactivated by extensional detachment (cross-sections D-D' to H-H' of Figs 3 and 4).

In the Trabia and Termini Imerese Mts, extensional detachments determinate tectonic omissions in the frontal portions of the inverted older thrust (cross section B-B' to D-D' of Fig. 3), as indicated by tectonic superposition of the

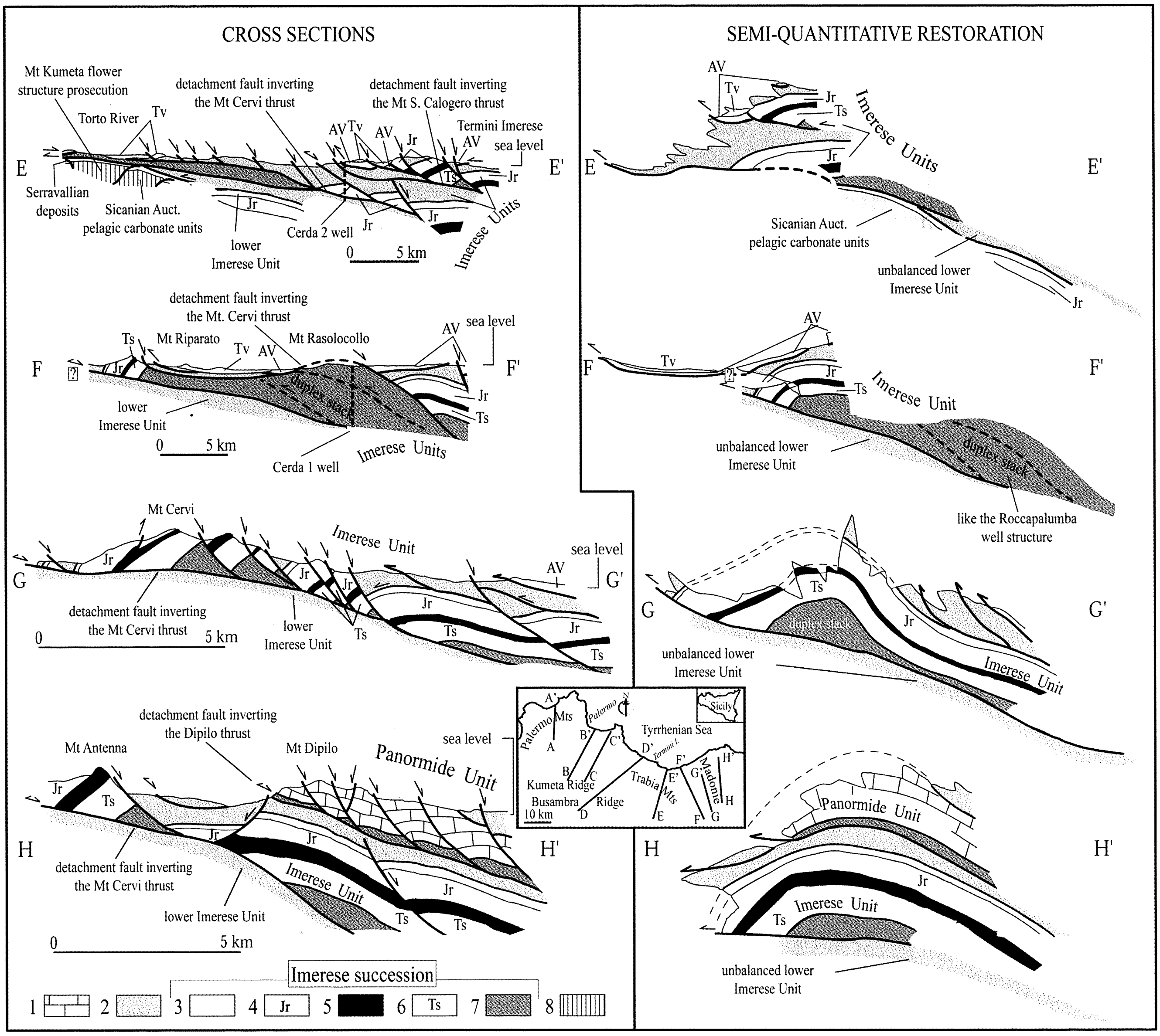

Fig. 4. Schematic geological cross sections of the Palermo-Termini Imerese Mts. *1* – Panormide units (Mesozoic–Tertiary); *2* – Numidian Flysch (late Oligocene–early Miocene). Imerese units: *3* – Cretaceous–Eocene; *4* – Middle-Late Jurassic; *5* – Early Jurassic; *6* – Late Triassic; *7* – Mufara-Lercara Fms (Permian–Triassic). *8* – Sicanian units (Mesozoic–Tertiary); *Tv* – Terravecchia Fm. (late Miocene); *AV* – Sicilidi units (Argille Variegate, Cretaceous–Eocene). Cross sections show only the main neotectonic strike-slip structures. Horizontal scale is equal to vertical

Oligo-Miocene Numidian Flysch over the Permian(?)–Late Triassic Mufara-Lercara fms, in a younger-on-older geometry. The main detachment fault, located between the Numidian Flysch and the Mufara Fm. in the southern part of the D-D' and E-E' cross-sections, becomes deeper in a ramp system in the northern part. Here, below the Imerese rock bodies of the Mt S. Calogero Thrust (found the Trabia Mts), the main detachment fault cross-cuts the Mesozoic carbonates of the Mt Cervi Thrust, recognised through shallow wells and geophysical data (Cusimano & Liguori, 1988). The semi-quantitative restoration of the cross sections of Figs 3 and 4 indicates that the amount of extension in these areas is valued at almost 25–30 kilometres.

An extended detachment is recognised in the Mt Rasolocollo areas (cross-section F-F' of Fig. 4), where the Mufara Fm. is widely covered by Numidian Flysch and Sicilidi units, through an extensional flat surface. Along it, there is a ramp surface (Scillato Fault, Fig. 8) that has displaced the Mt Cervi Thrust ramp anticline link, outcropping in the Caltavuturo area and determining a displacement of more than 2000 m.

Ramp-décollement (Dahlstrom, 1970) is often observed near Mt Parrino; here, the Mufara Fm. supports remnants of Jurassic Imerese succession showing a hangingwall ramp-like geometry (cross-section C-C'). This geometry also characterises the Northern Palermo Mts, inside the carbonatic succession of the Panormidi units (Cape Gallo, Fig. 9), and the southern Trabia Mts (near Vicari, Fig. 10).

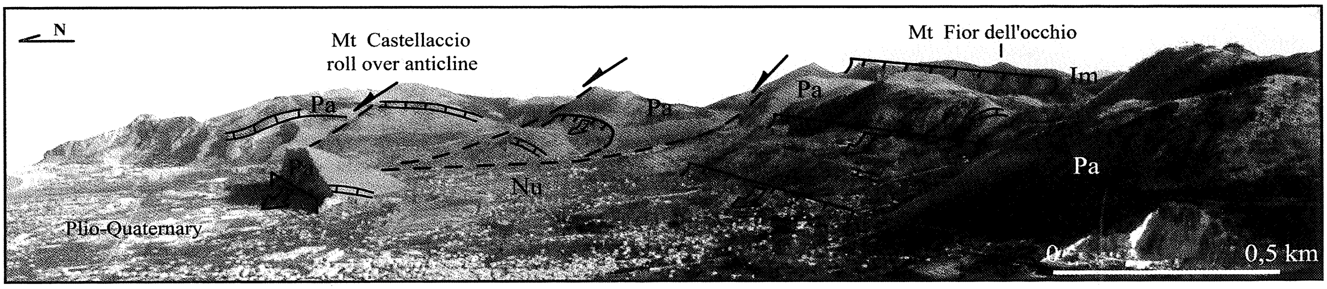

Fig. 5. Panoramic view of the Palermo Mts, showing north-dipping extensional ramps linking along a flat shallow depth located and the roll-over structures of Mt Castellaccio. *Pa* – Panormide unit (Mesozoic–Tertiary); *Im* – Imerese unit (Mesozoic–Tertiary); *Nu* – Numidian Flysch (Late Oligocene–Early Miocene)

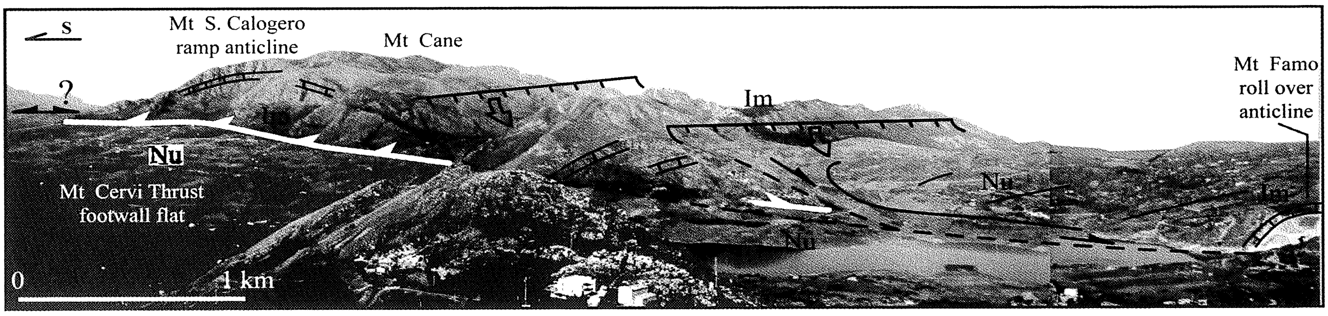

Fig. 6. Panoramic view of the Trabia Mts, showing north-eastern dipping extensional ramp set linking along the previous Mt S. Calogero Thrust and the roll-over structures of Mt Famo. Extension produces the exposure of the geometrically deeper Numidian Flysch of the Mt Cervi Thrust footwall flat in the back of ramp anticline. *Im* – Imerese unit (Mesozoic–Tertiary); *Nu* – Numidian Flysch (Late Oligocene–Early Miocene)

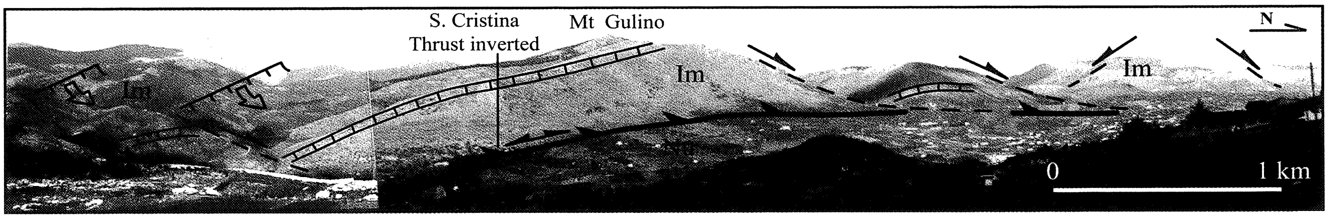

Fig. 7. Panoramic view of the southern Palermo Mts, showing north-eastern dipping extensional ramp set linking along the older S. Cristina Thrust surface. *Im* – Imerese unit (Mesozoic–Tertiary); *Nu* – Numidian Flysch (Late Oligocene–Early Miocene)

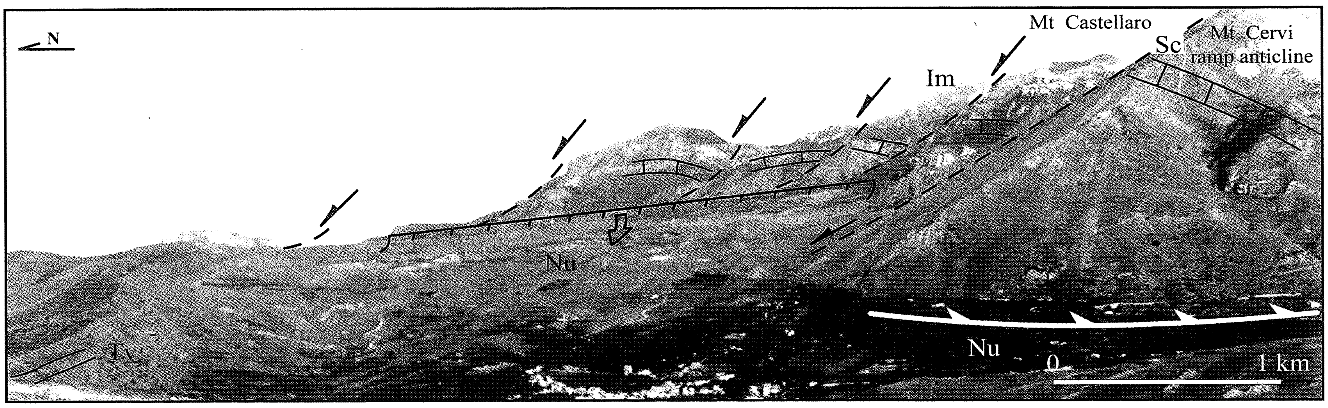

Fig. 8. Panoramic view of the Madonie Mts, showing northern dipping extensional ramp set linking along an older thrust surface. *Tv* – Terravecchia Fm. (Tortonian–Early Messinian); *Nu* – Numidian Flysch (Late Oligocene–Early Miocene) and Sicilide unit (Cretaceous–Tertiary); *Im* – Imerese unit (Mesozoic–Tertiary); *Sc* – Scillato Fault

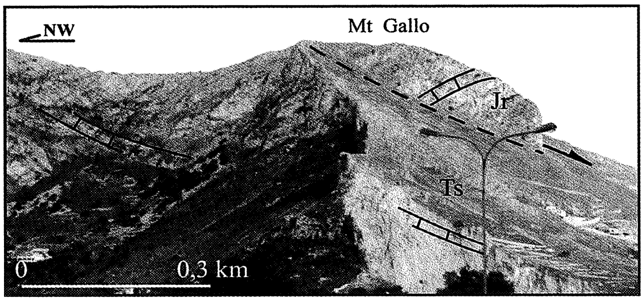

Fig. 9. Mt Gallo décollement ramp inside the Panormide unit. *Ts* – Triassic successions; *Jr* – Jurassic successions

These geometries are part of more extended detachment faults, which thinned the multilayer through listric faults and extensional duplexes at several scales of observation, linking and inverting the most important flat horizons, located along the bottom of the Oligo-Miocene Numidian Flysch and the top of the Permian(?)–Late Triassic Mufara-Lercara fms. Between Trabia Mts-Madonie Mts the Mufara-Lercara Fms are more than 2–3 km thick (Caflisch & Schmidt di Friedberg, 1967) and form an older compressional duplex stack in the Roccapalumba 1 and Lercara 1 wells.

"Chaos"-like structures (Wernicke & Burchfiel, 1982) characterise several outcrops. Near Roccapalumba village (Fig. 11), discontinuous thin Mesozoic carbonatic remnants

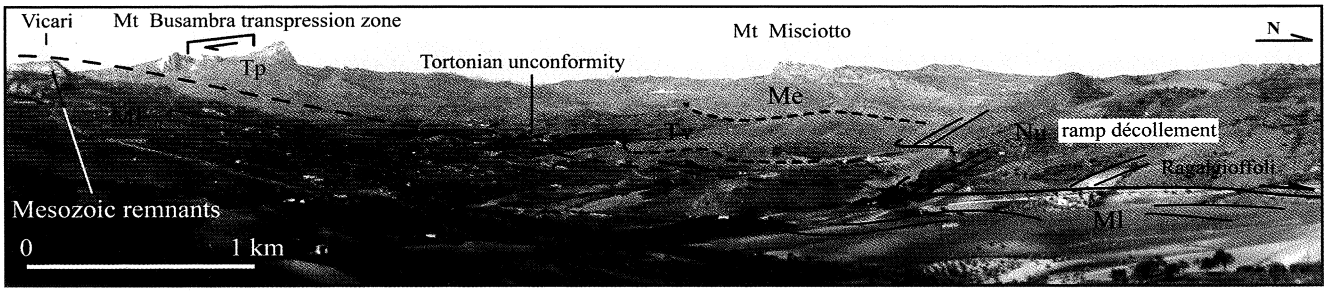

Fig. 10. Ragalgioffoli décollement ramp. In the area the tectonic superposition in a younger-on-older geometry of the Numidian Flysch over the Mufara-Lercara fms is well visible. Low-angle extensional fault system induces tectonic omission, also represented by Mesozoic remnants outcropping near Vicari Village. Over these structures, late Tortonian and Messinian deposits unconformably outcrop. They are in places affected by younger low-angle extensional faults. In the background the W–E trending Mt Busambra positive flower structure is located, that have arched the southern low-angle fault system limit. *Me* – Messinian evaporites; *Tv* – Terravecchia Fm. (Tortonian–early Messinian); *Nu* – Numidian Flysch (Late Oligocene–Early Miocene); *Ml* – Mufara-Lercara fms (Permian–Triassic); *Tp* – Trapanese unit (Mesozoic–Tertiary)

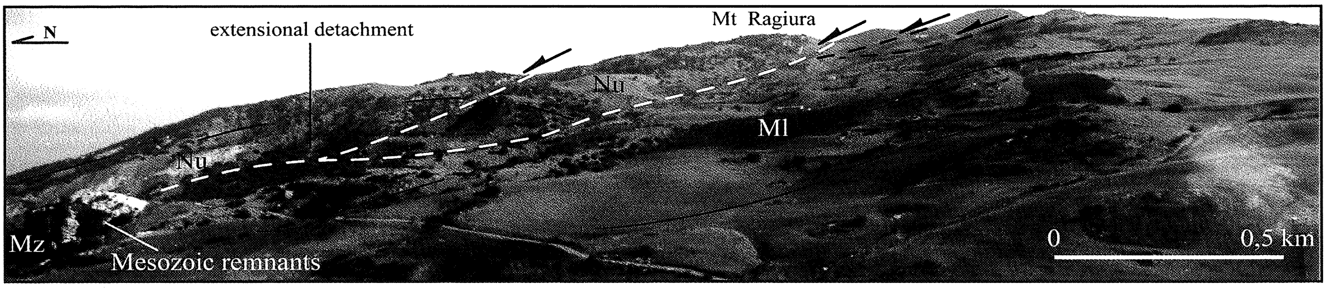

Fig. 11. Extensional detachment system outcropping near Roccapalumba village. The tectonic setting is represented by superposition of Numidian Flysch over Mufara-Lercara fms, in an younger-on-older geometry. Along the flat, remnants of Mesozoic carbonates are present. *Nu* – Numidian Flysch (Late Oligocene–Early Miocene); *Ml* – Mufara-Lercara fms (Permian–Triassic); *Mz* – Mesozoic remnants

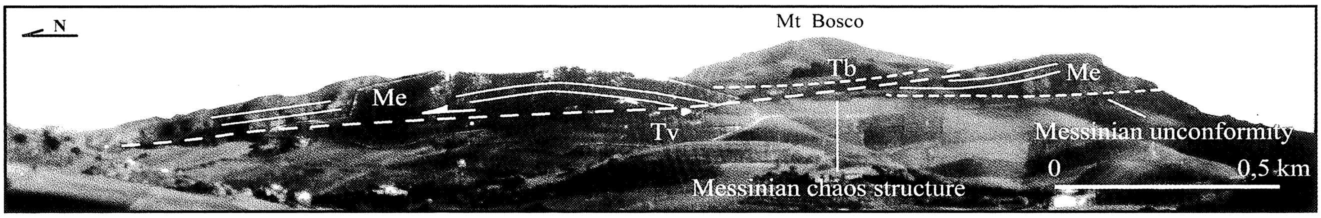

Fig. 12. Chaos structure affected Messinian evaporites near Mt Bosco (Trabia Mts). In places, extensional geometries entirely annul the Messinian deposits inside the multilayer and are probably buried by early Pliocene marls (so-called Trubi). *Tv* – Terravecchia Fm. (Tortonian–Early Messinian); *Me* – Messinian evaporites; *Tb* – early Pliocene marls (Trubi)

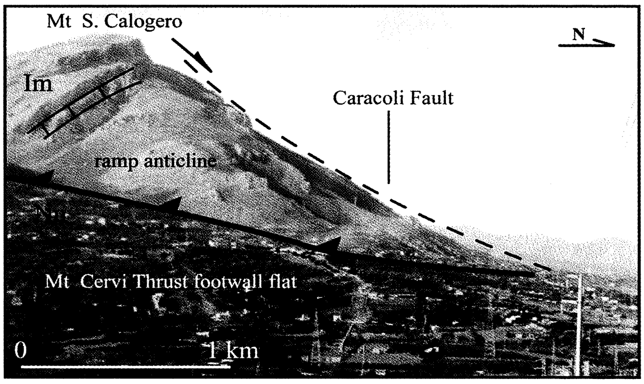

Fig. 13. Caracoli Fault, displacing the back of Mt Calogero ramp anticline. *Im* – Imerese succession, *Nu* – Numidian Flysch (Late Oligocene–Early Miocene)

are geometrically interposed between Numidian Flysch and Mufara-Lercara fms. Chaos structures are also recognised inside the Mesozoic Imerese carbonates and in the Messinian evaporites (Fig. 12).

The southern limit of the extensional system is shown in cross-sections B-B' and C-C' of Fig. 3, where the younger-on-older geometry of the Numidian Flysch over the Mufara Fm. is stratigraphically covered by the Terravecchia Fm. deposits of late Tortonian age.

The discontinuity in outcrop of the main detachment fault is related to the presence of the eastern prosecution of the Mt Kumeta and Mt Busambra transpressional structures, which has exposed the geometrically underlying external substrate.

In the coastal areas, the low-angle extensional fault system is in places cross-cut by a higher angle normal faults, as in the Termini Imerese areas and in the Palermo Plain, where respectively the detachments inverting the Mt S. Calogero, S. Cristina and Mt Dipilo thrust are displaced by the Caracoli (Fig. 13), Gibilrossa and Gratteri Faults.

In north-eastern Sicily and its off-shore areas extensional faults of late Miocene–Pliocene age are also recognisable. On land, they are widespread in the coastal areas and again show listric geometries. In the example in Fig. 14 an extensional faults fan displaced the Sicilidi and Numidian thrust system (cross-section A-B) in the Nebrodi Mts, which has a wedge slope gently dipping towards the Tyrrhenian Basin. In the coastal and submerged areas this fan links along a basal detachment inside the geometrically innermost Peloritani units and also cuts deposits of late Miocene–Pleistocene age (cross section C-D). From interpretations of MS 3 seismic line of Finetti & Del Ben (1986) it is possible to reconstruct at least two main tectonic extensional stages of late Miocene–early Pliocene and Pleistocene age.

The extensional regime characterising the sedimentation during this geological time is recognisable at different scales, from kilometric (Agate *et al.*, 1993; Nigro & Sulli, 1995) to hectometric, where growth faults are present inside the evaporitic deposits of Messinian age and clastic deposits of Plio-Pleistocene age.

Late Tortonian molassic tectono-sedimentary evolution: the example of the Scillato Basin

The Terravecchia Fm. deposits unconformably overlie the Panormidi and Imeresi tectonic units, as well as the extensional detachment geometries in some places. These deposits also mostly derive from the erosion of the innermost tectonic units of the Sicilian-Maghrebian Chain (Peloritani units), the last today located in the north-eastern sector of the Sicily mainland and its submerged areas.

In the areas crossed by the geological section F-F' the Terravecchia Fm. is well exposed (Scillato Basin), gently folded in a brachysyncline structure. It unconformably covers the Sicilide and Numidian successions and is formed by a group of northward diachronous facies associations, which become younger towards the north. The sedimentary succession records environments from an alluvial fan to lacustrine and marine (Abate *et al.*, 1998b; Fig. 15A) and is organised in three cycles. The age of these deposits is between middle Tortonian and early Messinian; particularly, the lowermost portion of the succession outcrops in the southern areas and is represented by an older and eroded 1st cycle, formed by marine sandy marls. Over it, the 2nd cycle unconformably starts with thick-bedded and disorganised conglomerates (Mt Riparato), representing subaerial alluvial fan deposits with upward decrease of energy. This facies association mostly contains either quartz-arenites of the Numidian Flysch or about 10% of metamorphic clasts, deriving from the more internal areas (Peloritani Mts). Northward the conglomerates interfingers with yellow thin and cross-bedded well-sorted sand-dominated deposits, locally containing channelled conglomerates and affected by synsedimentary northward dipping extensional faults. Abate *et*

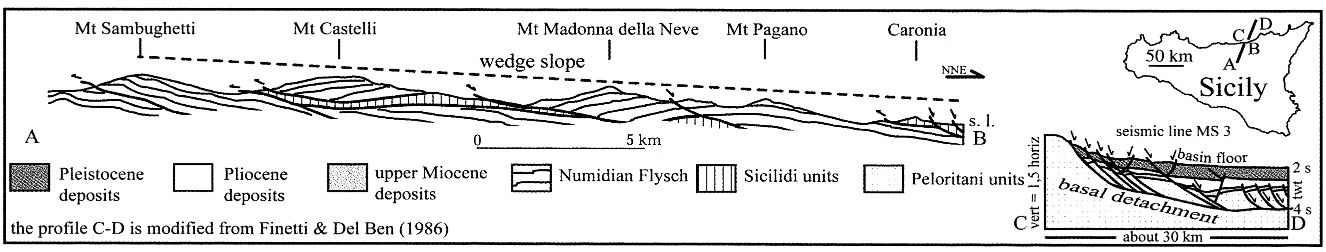

Fig. 14. Schematic geological cross sections of the Nebrodi Mts and its off-shore areas, showing the prosecution towards the east of the extensional systems. In the submerged areas the extensional system shows listric ramps linking along a basal detachment. In these areas the fan is active since the late Miocene–early Pliocene and displaced Pleistocene deposits towards the mainland progressively. Horizontal scale is equal to vertical

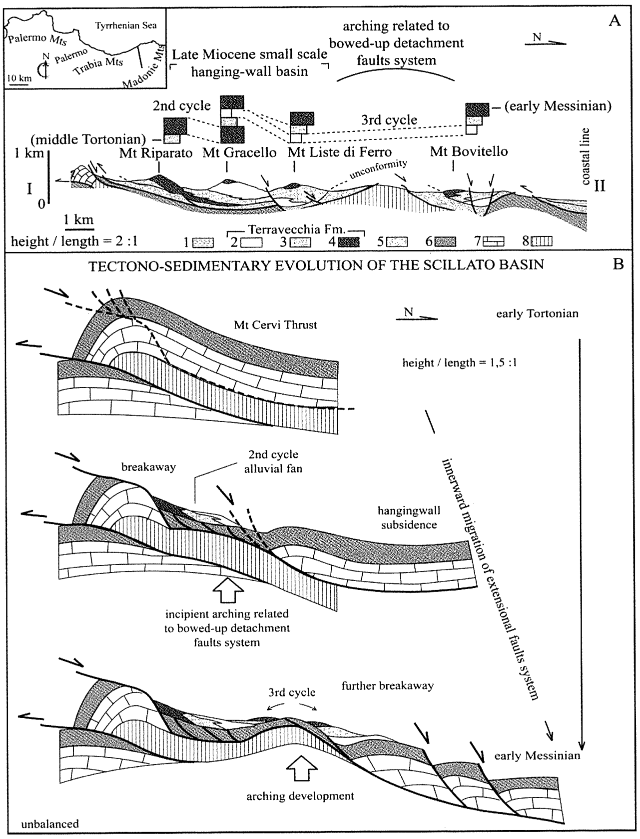

Fig. 15. **A.** Geological section across the Madonie Mts, showing the Terravecchia Fm. (Tortonian–early Messinian) facies associations. *1* – Plio-Pleistocene deposits. Terravecchia Fm.: *2* – shale complex; *3* – sandy complex; *4* – conglomeratic complex. *5* – Sicilide units (Cretaceous–Tertiary); *6* – Numidian Flysch (Late Oligocene–Early Miocene); *7* – Imerese successions; *8* – Mufara-Lercara fms (Permian–Triassic). **B.** Tectono-sedimentary evolution model of the area during Late Tortonian. See text for further explanations

al. (1998b) interpreted these deposits as braided river passing to lacustrine-delta system. These facies associations change toward the north and to the high of the succession in favour of thick massive structureless mudstones, well exposed near Mt Gracello, and are laterally replaced, toward the coastal areas, by grey calcareous mudstones and siltstones with marine faunas. The mudstone complex may be related to lacustrine deposits evolving to marine shelf environments and represents the top of the 2nd cycle, showing a proximal-to-distal trend.

Over it, at Mt Gracello, the topmost of the succession is represented by another conglomeratic deposit outcrops, composed mainly of Numidian Flysch and Imerese-derived clasts and containing thin beds of Messinian evaporites in the topmost portion. Northwards it covers another sand complex (Mt Liste di Ferro) that may be interpreted as a fluvial sequence, covering the mudstones of the 2nd cycle at Mt Bovitello.

According to Abate *et al.* (1998b), the overall Scillato 2nd sedimentary cycles display a palaeoenvironmental evolution from continental alluvial fan to shallow marine, while the 3rd cycle represents a change of palaeobathymetry, from distal to proximal environments. These cycles may be connected with changes of rate of subsidence and/or amount of materials supplied.

The Terravecchia Fm. facies distribution implies that the sedimentation was generally controlled by syn-sedimentary extensional tectonic movements and a northward migration of basement subsidence. In the Madonie Mts these "orogenic" clastic deposits are made of clasts of more external rocks, show dispersal pathways (Jones & Grasso, 1995) and are organised from south to north in a coarsening-to-fining-to-coarsening upward trend.

Fig. 15B shows the hypothetical tectono-sedimentary evolution of the Scillato Basin sedimentation, controlled by a "mobile" hangingwall block during the Tortonian extensional stage. The facies distribution and the age of rocks, younger northward, may be explained as the interplay between the footwall uplift and the Mt Cervi thrust-inverted detachment fault hangingwall subsidence, as generally predicted in the model of Lister & Davis (1989) for sedimentation related to denudation processes. Uplift of the footwall has its maximum rate in the Mt Rasolocollo area, where the master detachment fault become progressively more bowed-up, in consequence of further detachment fault activation toward the innermost zones of the constructing orogen. The subsidence of the hangingwall may be represented by two breakaway stages: the first produces the accommodation space for the proximal-to-distal facies association and the increasing arching of footwall during extension, which in the area controls the sedimentary processes related to the Terravecchia Fm. uppermost cycle. The development of footwall doming induces a further breakaway stage and subsidence towards the north during late Tortonian–early Messinian. Extensional tectonism affecting the belt during Messinian time is also recorded in the evaporitic deposits outcropping in the area.

Neotectonic lineaments

Along the coastal areas of Northern Sicily, N–S to NW–SE trending neotectonic morphostructures are recognised (Abate *et al.*, 1998a; Giunta *et al.*, 1998), providing morphologic evidence of a complicated grid of net- and strike-slip faults (Abate *et al.*, 1998a; Giunta *et al.*, 1998; Nigro, 1998; Fig. 16). Mesostructural analysis reveals that this system is composed of fault strands trending NW–SE, W–E e NE–SW; the NW–SE and W–E fault strands often show dextral displacements, while the NE–SW trending system shows a left slip (Fig. 16). The NW–SE trending fault strands have an extensional net-slip component along the coastal sectors of the mainland (Fig. 17), cut deposits of Plio-Pleistocene age in some places and connect along a W–E trending system, especially in the Kumeta and Busambra transpressional structures (Ghisetti & Vezzani, 1984) and their eastern prosecution.

The overall course of transcurrent faults on land is correlatable with the off-shore structures (Abate *et al.*, 1998a; Giunta *et al.*, 1998), particularly, along the submerged Northern Sicilian Chain they bound a group of structural highs interposed between depressions. The submerged structural highs (Banco Scuso, S. Vito High, Palermo Rise) represent the prosecution of the mainland coastal morphos-

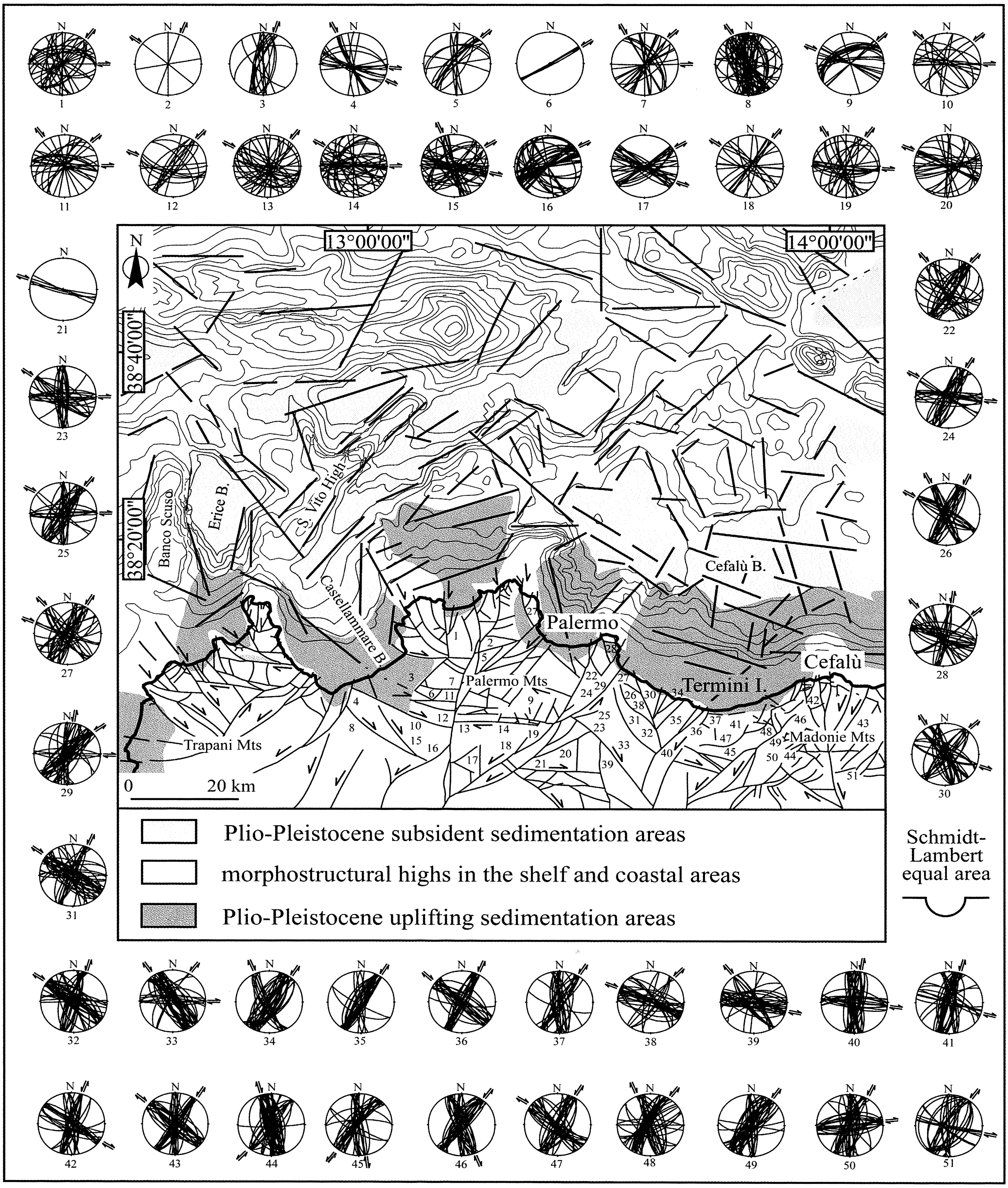

Fig. 16. Schematic neotectonic structural map of North-Western Sicily, showing the main strike-slip faults and the related morphostructures

tructures. The tectonic depressions, filled by Plio-Pleistocene clastic deposits, are interpreted by Mauz & Renda (1995), Abate *et al.* (1998a) and Giunta *et al.* (1998) as rhegmatic basin inside releasing bands, affected by inversion tectonics during early Pleistocene (Tricart *et al.*, 1990).

The neotectonic transcurrent fault system is still active, as documented by faulting in recent deposits and fault-plane solution of earthquakes (e.g., Riuscetti & Schick, 1975; Michetti *et al.*, 1992).

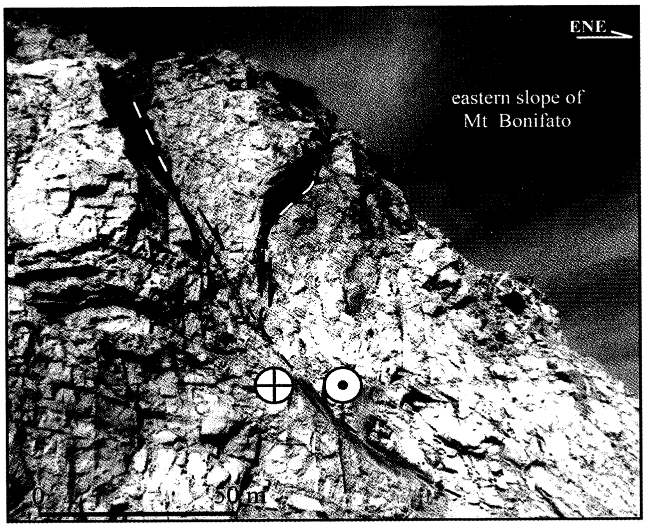

Fig. 17. Transtensional neotectonic fault affecting the eastern Mt Bonifato slope, formed of Trapanese-like Mesozoic carbonates. The northward prosecution of the connected fault strand displaced in the coastal areas deposits of late Pleistocene age

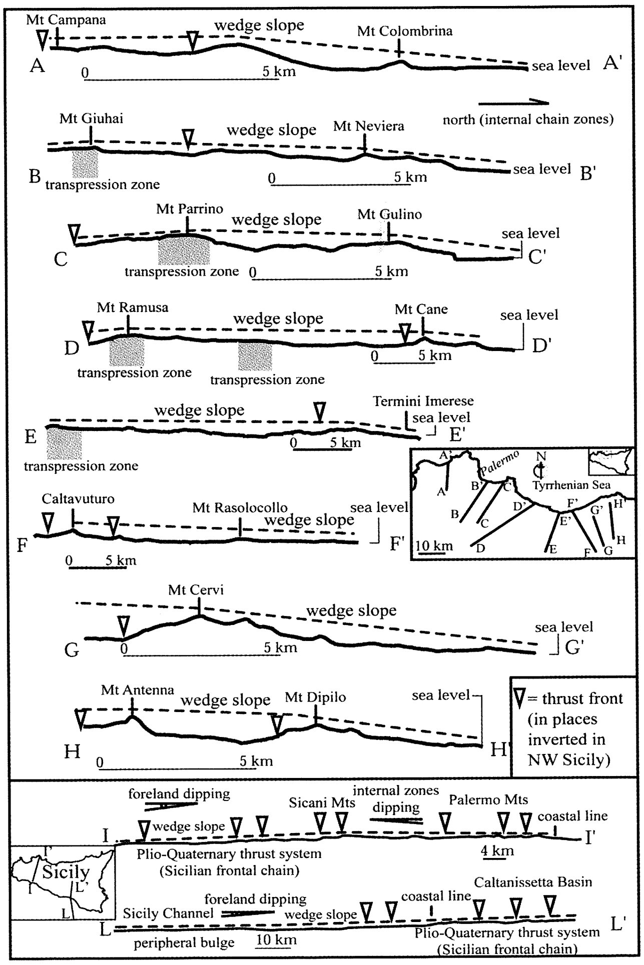

Fig. 18. Several topographic sections showing the present-day wedge slope of Sicily. See text for further explanations. Horizontal scale is equal to vertical

DISCUSSION AND GEODYNAMIC IMPLICATIONS

Mainland Sicily and its off-shore areas represent a belt composed by a foreland, located in the Sicily Channel, and the chain bulk characterising the island to the Tyrrhenian (Fig. 20A). The orogen is affected by an extensional regime with effects from Northern Sicily.

During the Miocene, the constructing Sicilian-Maghrebian chain is characterised by a chain body-foredeep couple migrating towards the foreland, progressively incorporating syn-orogenic deposits (Numidian Flysch and Serravallian deposits), which in turn carried piggy-back basins. Thrust tectonics is characterised by superposition of tectonic units over a gentle chain-dipping foreland, underplating below the basal detachment horizon as a passive footwall (Nigro, 1998).

The extensional structures recognised inside the Northern Sicilian-Maghrebian tectonic edifice overall dip towards the inner sectors of the orogen, mostly decoupling the inner tectonic units. They are unconformably overlaid by the Terravecchia Fm. of late Tortonian age and displaced by Plio-Pleistocene high-angle net- to strike-slip fault systems. This system, constituted by detachment faults that in places reactivated previous thrust surfaces, involves shallow portions of the outcropping chain building, from the Northern Sicanian Mts. It has a NE direction of displacement, towards the Cefalù Basin, in which subsidence starts beginning from Messinian, achieving it maximum rate during the Pliocene (Wezel *et al.*, 1981). Offshore, the low-angle extensional system is bounded by a more northward-dipping orogen-parallel fault system, linking to a shallow crustal necking level (Pepe *et al.*, 1998). Other examples of listric extensional systems linking along a several km deep décollement horizons are also recognised in the Sardinia Channel and in the Western Tyrrhenian areas (Finetti & Del Ben, 1986; Torelli *et al.*, 1992).

The start of this important tectonic phase, producing several tens of kilometres of extension, is ascribed to early Tortonian and is related to the collapse processes of the more internal constructing chain, as a consequence of exceeded values of critical taper.

In the orogens deriving from continental collision, regional elevation (topographic slope) is expressed in cross-section by the line envelopment of the main ramp anticline crests. These wedge-shaped geometries are based on Coulomb's theory, as discussed by Davis *et al.* (1983) and Dahlen *et al.* (1984), based on non-cohesive or cohesive thrust belts. Several numerical models (e.g., Willet, 1992) indicate that the wedge slope surfaces, more or less corresponding to the line envelopment of ramp anticline crests, dip toward the foredeep and that the rheologic properties of wedge control the rate of angular parameters of critical taper (defined by the β basal décollement and α wedge slope angle sum; Platt, 1986), and in consequence the stability of the system. The Coulomb wedge is also characterised by properties ρ (density of wedge materials), S_0 (cohesion), μ (internal friction coefficient), λ (Hubbert-Rubey, 1959 fluid pressure ratio) and χ (strength ratio). λ_b and μ_b (Byerlee's law, 1978) also represent λ and μ along the basal décollement (Davis *et al.*, 1983; Dahlen *et al.*, 1984). Other factors that affect critical

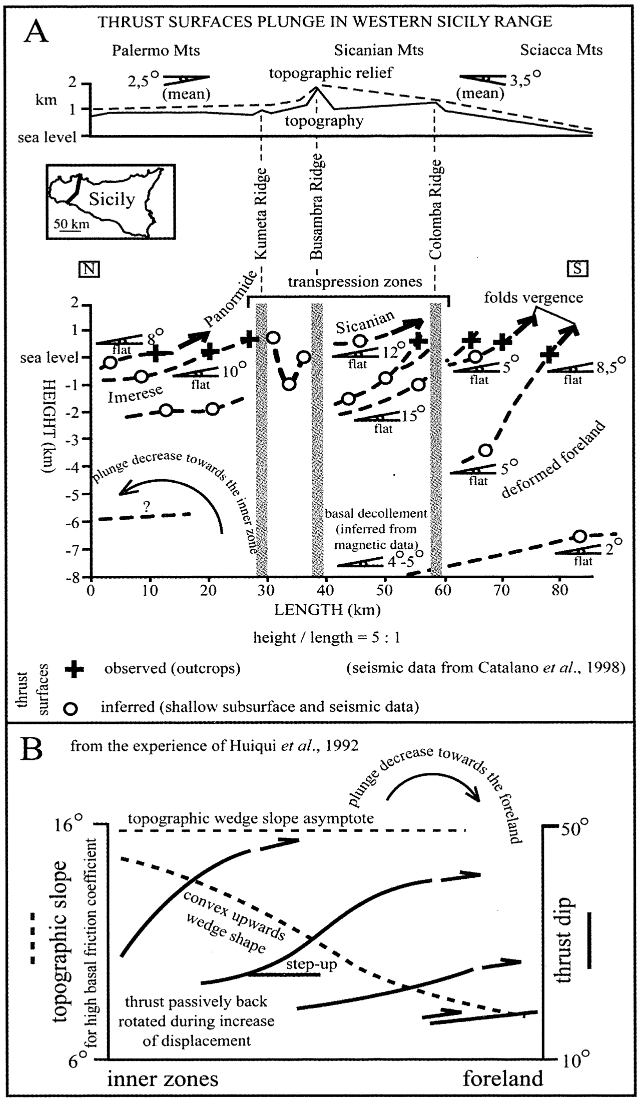

Fig. 19. A. Chart showing the step-up thrust setting in the Western Sicily Chain. **B.** Theoretical step-up and topographic slope setting in a fold-and-thrust belt. See text for further explanations

taper are erosion and synchronous sedimentation of the top of the wedge and underplating material at the base of the wedge (Dahlen & Suppe, 1988; Roure *et al.*, 1990). An increase of basal friction induces both an increase of thrust fault spacing (and of thrust length) and of the wedge taper (Huiqi *et al.*, 1992), in an overall uplift-like process. If the wedge taper becomes too large (supercritical) with regard to its basal strength (basal weakening), it may deform in extension to reduce the wedge taper, with the exception of the toe region, which may contemporaneously remain in compression if accretion continues (Howell, 1984; Willet, 1992). As discussed by Dahlen *et al.* (1984), for non-cohesive submarine accretionary complexes and fold-and-thrust belts, the low internal friction coefficient (μ) is the effect of an increase of the Hubbert-Rubey basal fluid pressure ratio (λ_b). Increasing λ_b lowers the critical stability realm enough for the wedge to be on the verge of extensional failure. For the author, if λ_b continues to increase even further, the wedge will thin and subside in the back by gravity spreading.

In Eastern Sicily, Adam (1996) applies the wedge critical taper model to explain the frontal accretion of the wet orogen in the late Miocene–Pleistocene (mostly composed of plastic nappes), with in places contemporaneous opposite extensional tectonic stresses in the inner portion of the wedge, caused during middle Tortonian by the joining of supercritical taper values ($\alpha + \beta$ about 6° versus about 3.5–4° of estimated critical taper values). For the Tortonian interval, he assumes ρ to be equal to 2500kg/m^3, μ equal to 0.85, λ equal to 0.6 (wet), λ_b ranging from 0.6 to 0.8 and μ_b ranging from 0.3 to 0.45 (weak base).

The present-day large spacing of the inner Western Sicily tectonic units appears to be the result of extensional processes through the recognised detachment system. The semi-quantitative balancement of cross-sections indicates that the Miocene tectonic units may be less length, but still characterised by large spacing and high step-up thrust values towards the inner zones.

From the morphostructural point of view, the inner tectonic units of the Maghrebian Chain outcropping in the Northern Sicily mainland generally have a lower altitude than the more southern reliefs, where the geometrically deeper Sicanian tectonic units, the foredeep successions of the Numidian Flysch and the Terravecchia Fm. outcrop. In this area the regional elevation corresponds to the Miocene thrust fronts, characterised by ramp anticline geometries, which in turn are displaced in the back by extensional fault systems with Tyrrhenian immersion. The topographic profiles transversal to the chain trend (A-A' to H-H' of Fig. 18) show a wedge slope (α angle) dipping towards the more internal zones of the Sicilian Chain, between the Sicanian Mts and the Northern Sicily coastal areas and the off-shore, where several strongly subsiding submarine tectonic depressions (Trapani, Castellammare, Palermo, Cefalù Basins; Wezel *et al.*, 1981) are located. These basins have a depth up to 2000 m below sea level and are filled by 500–1000 m thick of clastic Plio-Pleistocene deposits. They represent the clastic sedimentation area of the Southern Tyrrhenian Border, superimposed onto the Apenninic-Maghrebian orogen, thinning since the Tortonian (Selli, 1985; Wezel, 1985). The wedge slope plunges toward the external sectors, about of 3°, from the Sicani Mts to the Sicily Channel Maghrebian Foreland (profiles I-I' and L-L' of Fig. 18).

Summarising the field data set and the seismic interpretation of Catalano *et al.* (1998), the internal geometry of the Sicilian deformational wedge is constituted by foreland-vergent thrust surfaces, showing a less and less northward plunging from the external to the internal zones and a basal décollement plunging from about 2° to 4° (β angle) toward the hinterland (Fig. 19A), where it is located at shallow depth beneath the Palermo Mts. This arrangement is in contrast with the theoretical models which predict the development of thrust wedges (Huiqi *et al.*, 1992), where the overall foreland-vergent thrust δ step-up angles (Dahlen *et al.*, 1984) increase towards the inner zones (Fig. 19B). This would be a consequence of the passive back rotation connected to the progressive nucleation of thrust in the footwall and therefore to the progressive development of the Coulomb wedge. Furthermore, the observed large superposition of the inner main foreland vergent tectonic units in the

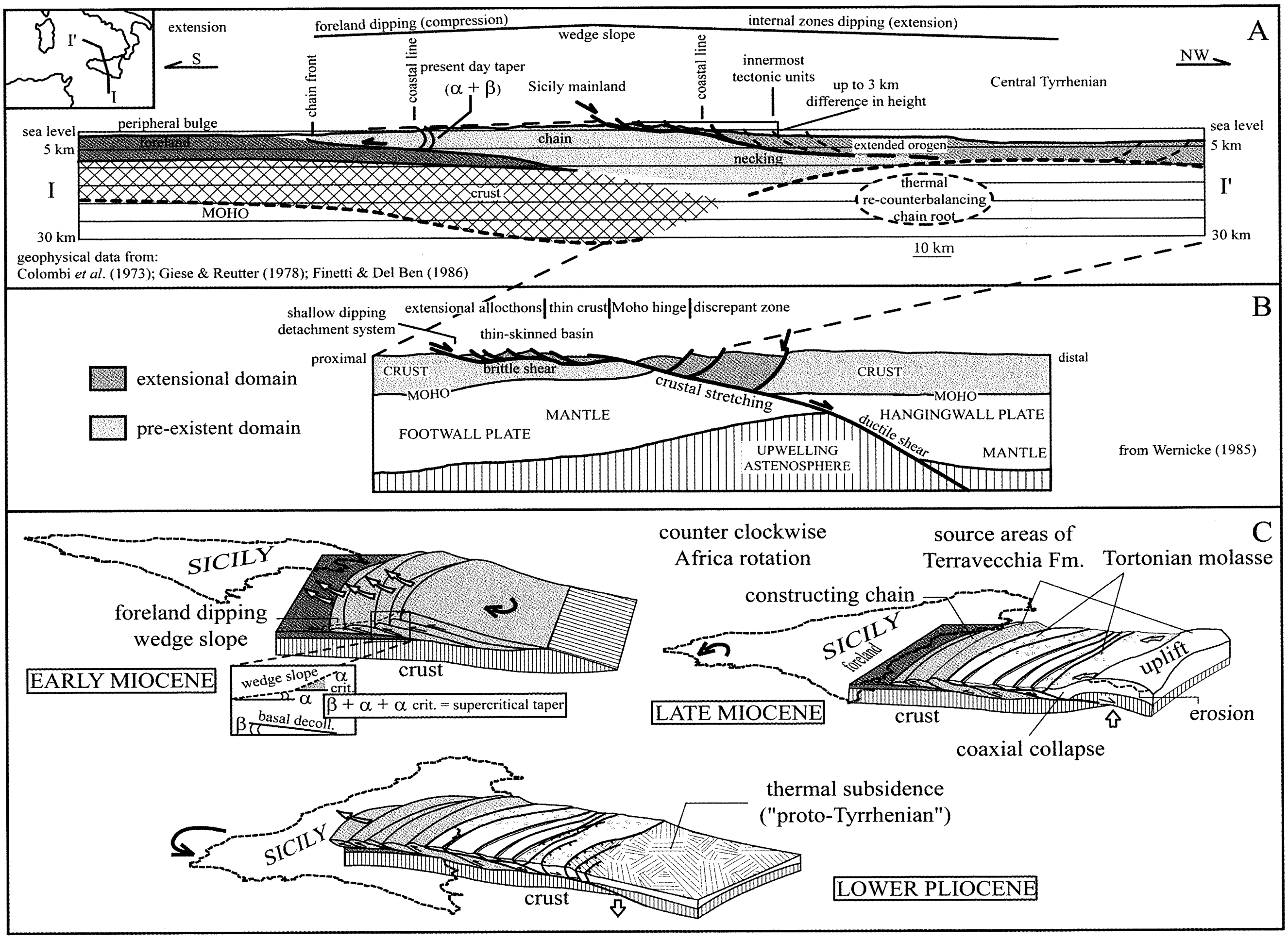

Fig. 20. A. Schematic crustal section across the Sicilian-Maghrebian foreland-chain couple, showing the present-day Moho depth, the compressional and extensional domains of the orogen and their related wedge slopes. **B.** Model of crustal stretching under a simple shear regime of Wernicke (1985). **C.** Model of extensional collapse of the Sicilian-Maghrebian Chain during late Miocene, as a consequence of the exceeded values of critical taper. The mechanisms of extension are supposed similar to the Wernicke's model. See text for further explanation

Western Sicily Belt (and the large spacing of thrust faults) and the lack of back-thrust in the ramp region, suggest a high basal friction of the wedge and in origin a highest plunge angle of thrust towards the inner zones (as theoretically predicted by Huiqi *et al.*, 1992), allowing the possible excess of critical taper values, as estimated in Eastern Sicily by Adam (1996), and a high $(\alpha + \beta)/\lambda_b$ ratio. The high basal friction of the Sicilian wedge may also be supported by the large spacing of the inner tectonic units and its "non-asymptotic" step-up geometry with respect to the basal décollement beneath the Palermo Mts, as shown by the seismic interpretation of Catalano *et al.* (1998).

The present-day setting of the thrust angular variation, more reduced toward the inner zones, may thus be interpreted as the result of the collapse of the tectonic edifice, following wedge thickening by folding and imbrication. Thrust tectonics may have steepened the wedge top and in consequence the palaeo-topographic elevation; the excessive values of critical taper may have characterised the Sicilian-Maghrebian wedge during late Miocene and the consequent collapse of its inner sector through the activation of an extensional fault system with Tyrrhenian vergence, expressed by the overall backslide of the inner Sicilian tectonic units. This collapse coincides in age with the instantaneous and accentuated rotation vector of the Africa motion (phase 5 onset of Dewey *et al.*, 1989).

The recognised detachment fault systems, may overall represent the low-angle extensional shear zones displacing the shallow portion of the emergent inner Sicilian-Maghrebian Chain since Tortonian. The extensional system also represents a "thin-skinned" movement limit, probably linking along the sole thrust in the inner zones of the submerged belt, where it shows an overall bowed-up geometry, and that prosecutes toward the Central Tyrrhenian with effect from the northern coastal sectors. Here it progressively changes in deepening into the chain root to connects in a more extended heterogeneous lithospheric stretching system under a simple shear regime (Fig. 20A).

On land, the shallow-dipping detachment fault system is characterised by brittle shear, while in the off-shore areas the shallow necking level recognised by Pepe *et al.* (1998) may represent a change in characteristics of shear zone from brittle to ductile.

The model for crustal stretching proposed by Wernicke

(1981, 1985; Fig. 20B) predicts the development of thin-skinned basin induced by a low-angle shear zone gently dipping inside the crust. The extension is accommodated by thinning and affects the lower crust and mantle, as well as the initial tectonic uplift and erosion of the "discrepant zone", where beneath the astenosphere is affected by cooling processes. The discrepant zone is subsequently characterised by thermal subsidence, restoring the crust to its initial level. According to the model of Wernicke, the detachment faults systems recognised in the emergent northwestern Sicilian Belt may have produced the overall arching during the collapse of the thrust pile, while the late Tortonian Terravecchia Fm. molasse may represents the syntectonic thin-skinned basin fill (Fig. 20C), unconformably covering the incipient extensional allocthons. These deposits may result of the erosion of the collapsing inner zone of the constructing orogen, related either to the "proximal" Wernicke zone or to the uplifting zone. The heterogeneous crustal stretching may have progressively affected more and more deeper crustal levels toward the root zones of the chain. In the lower crust and mantle the ductile stretching, accommodating the same amount of extension of the chain above its sole thrust, taking the start at cooling processes (thermal event), as the effects of the progressively further mantle upwelling. In this way, the stretching of the inner chain portions may have induced a thermal re-counterbalancing of its root, while the upwelling of the mantle may have primed roll-back mechanisms of the subducted African lithospheric slab, as a consequence of instability of the downgoing asthenospheric flow.

The uplift of the crust-mantle boundary (Giese & Reutter, 1978; Schutte, 1978) may be related by a combination of bowing upward of the chain body (footwall plate of Wernicke) and the result of ductile attenuation of the lower part of the lithosphere beneath the Southern Tyrrhenian Border. The Sardinia shelf may thus be interpreted as an upper plate "large faulted blocks chain", located in the distal side "core complex" of Wernicke (1981, 1985). The latter coincides with the Tyrrhenian Basin.

The Plio-Pleistocene basins located along the Northern Sicilian shelf slope represent the Southern Tyrrhenian margin and connect the emergent orogen to the abyssal plain, were the Moho is less than 9 km in depth (Finetti & Del Ben, 1986; Fig. 20A). The connection is realised through a faults escarpment dipping northward and linking along the shallow necking level of Pepe *et al.* (1998), while towards the Sardinia Shelf faults escarpment south-eastern and eastern dipping has been recognised (Wezel *et al.*, 1981; Selli, 1985; Wezel, 1985; Finetti & Del Ben, 1986), linking along a deeper necking level (about 25 km depth; Spadini *et al.*, 1995).

This Moho course in the Tyrrhenian and peri-Tyrrhenian areas fits well with the simple shear stretching model of Wernicke, in which the opening of the upper plate is asymmetric. Also, the recognised extensional detachment system affecting the inner Sicilian Chain since Tortonian changes in deepening with effect from the northern coastal sectors, where it shows an overall bowed-up geometry The bowing-up of the Northern mainland orogen may be supported by the shallow depth of the underplated foreland. It indicates a low β angle of wedge beneath the inner thrust pile, also characterised by the low steep-up thrust angle of Panormide and Imerese units already described. In the present model, the basal décollement downbending during late Miocene, as a sinking of the lithospheric slab (Patacca & Scandone, 1989; Giunta, 1991), may be partly isostatically "re-equilibrated" below the Sicilian emergent Belt (thin-skinned zones of Wernicke) through the overall back-wedge bowing-up during extension, as suggested by seismic data of Catalano *et al.* (1998). The "isostatic re-equilibrium" may be related to the roll-back processes of the lithospheric slab, in the hypothesis of a viscous-elastic behaviour of the African continental plate.

The Plio-Pleistocene Tyrrhenian opening could be interpreted as the consequence of the further thermal subsidence of these areas and therefore the effect of the evolution of an extending orogen. In its Sicilian-Maghrebides more external zones, the α and/or β exchange and erosion during bowing-up isostatic adjustment cause the wedge to become subcritical and, according to Adam (1996), encourages renewed deformation in the toe (Gela Nappe). The Plio-Pleistocene thrusting related to the return of subcritical taper values is also expressed by out-of-sequence and breaching mechanisms in the Sicilian Belt, as well as in the Southern Apennines (Patacca & Scandone, 1999).

During this time, a further increasing of the counterclockwise Africa motion (Dewey *et al.*, 1989) induces along the Southern border of the Tyrrhenian (more and more rotated along a W–E direction) a progressive activation of the W–E trending simple shear-related Riedel system, producing the grid of neotectonic strike-slip structures in the northern Sicily mainland and in the surrounding submerged thinned orogen. The strike-slip system, organised in different orders of restraining and releasing bends, controls the evolution of the submerged Plio-Pleistocene basins, bounded by a horsetail splay transtensional system (Abate *et al.*, 1998; Giunta *et al.*, 1998; Nigro, 1998). The Plio-Pleistocene transpressional regime, counteracting the Tyrrhenian spreading, characterises the central Sicily areas, in which the main effects are represented by the positive flower structures of the Kumeta and Busambra ridges, cutting and arching upward the previous detachment systems. The evolution of rhegmatic tectonics during late Pliocene–Pleistocene is also represented by high angle dip-slip faults systems in the Northern Sicily coastal areas that displace the older extensional faults and are related to the overall further W–E trending uplift of the orogen.

Acknowledgements

We wish to acknowledge the Prof. Paolo Scandone and the anonymous referee for comments and criticisms, very helpful for the improvement of the paper. Work supported by M.U.R.S.T. ex 60% (P. Renda) and ex 40% and 60% (G. Giunta) financial grants.

REFERENCES

Abate, B., Catalano, R. & Renda, P., 1978. Schema geologico dei Monti di Palermo. *Bollettino Società Geologica Italiana*, 97:

807–819.

Abate, B., Incandela, A., Nigro, F. & Renda, P., 1998a. Plio-Pleistocene strike-slip tectonics in the Trapani Mts. (NW Sicily). *Bollettino Società Geologica Italiana*, 117: 555–567.

Abate, B., Incandela, A., Renda, P. & Ślączka, A., 1998b. Depositional processes in a late Miocene, post tectonic basin (Terravecchia Fm., Scillato, Sicily). *Annales Societatis Geologorum Poloniae*, 69: 27–48.

Adam, J., 1996. Kinematik und Dynamic des neogenen Falten- und Deckengurtels in Sizilien. Quantifizierung neotektonisher Deformationsprozesse in der zentralmediterranen Afro-Europaischen Konvergennzone. *PhD. Thesis*, Herausgegeben von geowissenschaftlichen Instituten, Berlin, 171 pp.

Agate, M., Catalano, R., Infuso, S., Lucido, M., Mirabile, L. & Sulli, A., 1993. Structural evolution of the Northern Sicily Continental Margin during Plio-Pleistocene. In: Max, M. D. & Colantoni, P. (eds), *Geological development of the Sicilian-Tunisian Platform*, Proceedings of the International Scientific Meeting held at the University of Urbino, *UNESCO Reports in Marine Science*, 58, pp. 25–30.

Anderson, R. E., 1971. Thin skinned distension in Tertiary rocks of southeastern Nevada. *Geological Society of America Bulletin*, 82: 43–58.

Avigad, D., Garfunkel, Z., Jolivet, L. & Azanon, J. M., 1997. Back arc extension and denudation of Mediterranean eclogites. *Tectonics*, 16: 924–941.

Beneo, E., 1961. Carta geologica della Sicilia al 500.000, Studi e indagini per ricerche di idrocarburi. *Assessorato Industria e Commercio Regione Siciliana*, Palermo, 66 pp.

Bianchi, F., Carbone, S., Grasso, M., Invernizzi, G., Lentini, F., Longaretti, G., Merlini, S. & Mostardini, F., 1987. Sicilia orientale: profilo geologico Nebrodi-Iblei. *Memorie Società Geologica Italiana*, 38: 429–458.

Boccaletti, M., & Sani, F., 1998. Cover thrust reactivation to internal basement involvement during Neogene–Quaternary evolution of the Northern Apennines. *Tectonics*, 17: 112–130.

Brewer, J. A., & Smythe, D. K., 1984. MOIST and the continuity of crustal reflector geometry along the Caledonian-Appalachian orogen. *Journal Geological Society of London*, 141: 105–120.

Broquet, P., 1968. Étude géologique de la région des Madonies (Sicile). *PhD Thesis*, Fac. Sc. Lille, 797 pp.

Byerlee, J., 1978. Friction of rocks. *Pure Applied Geophysics*, 116: 615–626.

Caflisch, L., & Schmidt di Friedberg, P., 1967. Un contributo delle ricerche petrolifere alla conoscenza del Paleozoico in Sicilia. *Bollettino Società Geologica Italiana,* 86: 537–551.

Carmignani, L., & Kligfield, R., 1990. Crustal extension in the Northern Apennines: The transition from compression to extension in the Alpi Apuane core complex. *Tectonics*, 9: 1275–1303.

Carmignani, L., Decandia, F. A., Fantozzi, P. L., Lazzarotto, A., Liotta, D. & Meccheri, M., 1994. Tertiary extensional tectonics in Tuscany (Northern Apennines). *Tectonophysics*, 238: 295–315.

Catalano, R., D'Argenio, B., Montanari, L., Renda, P., Abate, B., Monteleone, S., Macaluso, T., Pipitone, G., Di Stefano, E., Lo Cicero, G., Di Stefano, P. & Agnesi, V., 1978. Contributo alla conoscenza della struttura della Sicilia Occidentale: Il profilo Palermo-Sciacca. *Bollettino Società Geologica Italiana*, 19: 485–493.

Catalano, R., Franchino, A., Merlini, S., Sulli, A., Agate, M. & Basilone, L., 1998. Materiali per la Comprensione dell'Assetto Profondo della Sicilia Centro-Occidentale. In: Catalano, R. & Lo Cicero, G. (eds), *La Sicilia Occidentale*. Field Trip Guide of the 79° Congresso Nazionale Società Geologica Italiana, Mondello (Pa), pp. 175–185.

Cheadle, M. J., McGeary, S., Warner, M. R. & Matthews, D. H., 1987. Extensional structures on the western UK continental shelf: a review of evidence from deep seismic profiling. In: Coward, M. P., Dewey, J. F. & Hancock, P. L. (eds), *Continental extension Tectonics*, *Geological Society of London*, *Special Publication*, 28, pp. 95–107.

Colombi, B., Giese, P., Luongo, G., Morelli, C., Riuscetti, M., Scarascia, S., Schutte, K. G., Strowald, J. & Visentini, G., 1973. Preliminary report on the seismic refraction profile Gargano-Pantelleria. *Bollettino Geofisica Teorica ed Applicata*, 15: 225–259.

Constain, K. & Coruh, C., 1989. Tectonic setting of Triassic half grabens in the Appalachians: seismic data, acquisition, processing and results. In: Tankard, A. J. & Balkwill, H. R. (eds), *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*, *Memoir America Association Petroleum Geologists*, 46, pp. 155–174.

Constenius, K. N., 1996. Late Paleogene extensional collapse of the Cordilleran foreland fold and thrust belt. *Geological Society of American Bulletin*, 108: 20–39.

Crespo-Blanc, A., 1995. Interference pattern of extensional fault system: a case study of the Miocene rifting of the Alboran basement (North of Sierra Nevada, Betic Chain). *Journal of Structural Geology*, 17: 1559–1569.

Cusimano, G., & Liguori, V., 1988. Idrodinamica e potenzialità delle risorse idriche sotterranee del sistema idrogeologico dei Monti di Trabia-Termini Imerese (Sicilia). *Acque Sotterranee*, 5: 49–63.

Dahlen, F. A. & Suppe, J., 1988. Mechanics, growth and erosion of mountain belts. In: Clarck, S. P. Jr., Burchfiel, B. C. & Suppe, J. (eds), *Processes in Continental Lithospheric Deformation*, *Geological Society of America*, *Special Paper*, 218, pp. 161–178.

Dahlen, F. A., Suppe, J. & Davis, D., 1984. Machanics of fold-and-thrust belts and accretionary wedges: cohesive Coulomb theory. *Journal of Geophysical Research*, 89: 10087–10101.

Dahlstrom, C. D. A., 1970. Structural geology in the western margin of the Canadian Rocky Mountains. *Bulletin of Canadian Petroleum Geologists*, 18: 332–406.

Davis, D., Suppe, J. & Dahlen, F. A., 1983. Mechanics of Fold-and-Thrust Belts and Accretionary Wedges. *Journal of Geophysical Research*, 88: 1153–1172.

Davis, G. A., 1988. Rapid upward transport of mid-crustal mylonitic gneisses in the footwall of a Miocene detachment fault, Whipple Mountains, southeastern California. *Geologische Rundschau*, 77: 191–209.

Davis, G. A., & Lister, G. S., 1988. Detachment faulting in continental extension: Perspectives from the southwestern U.S. Cordillera. In: Clark, S. P., Burchfiel, B. C. & Suppe, J. (eds), *Processes in continental lithospheric deformation*, *Geological Society of American Bulletin*, *Special Paper*, 218, pp. 133–159.

Davis, G. A., Anderson, J. L., Frost, E. G. & Shackleford, T. J., 1980. Regional Miocene detachment faulting and early Tertiary mylonitization, Whipple-Buckskin-Rawhide Mountains, south-eastern California and western Arizona. *Memoir Geological Society of America*, 153: 79–130.

Davis, G. H., 1983. Shear-zone model for the origin of metamorphic core complex. *Geology*, 2: 342–347.

Davis, G. H., & Coney, P. J., 1979. Geologic development of the Cordilleran metamorphic core complexes. *Geology*, 7: 120–124.

Dewey, J. F., Helman, M. L., Turco, E., Hutton, D. H. W. & Knott,

S. D., 1989. Kinematics of the Western Mediterranean. In: Coward, M. P., Dietrich, D. & Park, R. G. (eds), *Alpine Tectonics*, *Geological Society of London*, *Special Issue*, 45, pp. 265–283.

Ellis, P. G., & McClay, K. R., 1988. Listric extensional fault system-result of analogue model experiments. *Basin Research*, 1: 55–70.

Ferranti, L., Oldow, J. S. & Sacchi, M., 1996. Pre-Quaternary orogen-parallel extension in the Southern Apennine belt, Italy. *Tectonophysics*, 260: 325–347.

Finetti, I. & Del Ben, A., 1986. Geophysical study of the Tyrrhenian opening. *Bollettino Geofisica Teorica e Applicata*, 28: 75–155.

Finetti, I., Lentini, F., Carbone, S., Catalano, S. & Del Ben, A., 1996. Il sistema Appennino meridionale-Arco Calabro-Sicilia nel Mediterraneo Centrale: studio geologico-geofisico. *Bollettino Società Geologica Italiana*, 115: 529–559.

Froitzheim, N. & Eberli, G. P., 1990. Extensional detachment faulting in the evolution of a Tethis passive continental margin, Eastern Alps, Switzerland. *Geological Society of America Bulletin*, 102: 1297–1308.

Ghisetti, F. & Vezzani, L., 1984. Thin-skinned deformation in Western Sicily. *Bollettino Società Geologica Italiana*, 103: 129–157.

Gibbs, A. D., 1984a. Structural evolution of extensional basin margins. *Journal Geological Society of London*, 141: 609–620.

Gibbs, A. D., 1984b. Clyde field growth fault secondary detachment above basement faults in North Sea. *Bulletin American Association of Petroleum Geologists*, 68: 1029–1039.

Gibbs, A. D., 1989. Structural styles in basin formation. In: Tankard, A. J. & Balkwill, H. R. (eds), *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*, *Memoir American Association of Petroleum Geologists*, 46: 81–94.

Giese, P. & Reutter, K. J., 1978. Crustal and structural features of the margins of the Adria microplate. In: Closs, H., Roeder, D. & Schmidt, K. (eds), *Alps, Apennines, Hellenides*, Schweizerbart, Stuttgart, pp. 565–588.

Giunta, G., 1985. Problematiche ed ipotesi sul Bacino Numidico nelle Maghrebidi Siciliane. *Bollettino Società Geologica Italiana*, 104: 239–256.

Giunta, G., 1991. Elementi per un modello cinematico delle maghrebidi siciliane. *Memorie Società Geologica Italiana,* 47: 297–311.

Giunta, G. & Liguori, V., 1973. Evoluzione paleotettonica della Sicilia Nord-Occidentale. *Bollettino Società Geologica Italiana*, 92: 903–924.

Giunta, G., Nigro, F., Renda, P. & Giorgianni, A., 1998. Un modello neotettonico del margine tirrenico delle Maghrebidi Siciliane (exten. abs). In: Catalano, R. & Lo Cicero, G. (eds), *acts book*, 79° Congresso Nazionale Societa Geologica Italiana, Palermo (Italy) 21-23 September 1998, pp. 498–501.

Hossack, J. R., 1984. The geometry of listric growth faults in the Devonian basins of Sunnfjord, W. Norway. *Journal Geological Society of London*, 141: 629–637.

Howard, K. A. & John, B. E., 1987. Crustal extension along a rooted system of imbricate low-angle faults: Colorado River extensional corridor, California and Arizona. In: Coward, M. P., Dewey, J. F. & Hancock, P. L. (eds), *Continental extension Tectonics*, *Geological Society of London*, *Spec. Publ.*, 28, pp. 299–311.

Howell, D. G., 1984. *Principles of Terrane Analysis. New applications for global tectonics*. Chapman & Hall, pp. 245.

Hubbert, M. K., & W. M. Rubey, 1959. Role of fluid pressure in mechanics of thrust faulting: I. Mechanics of fluid filled porous solids and its application to overthrust faulting. *Geological Society of America Bulletin*, 70: 115–166.

Huiqi, L., K. R. McClay, & D. Powell, 1992. Physical models of thrust wedges. In: McClay M. R. (Ed.), *Thrust Tectonics*, Chapman & Hall, pp. 71–81.

Jarrige, J. J., 1992. Variation in extensional fault geometry related to heterogeneities within basement and sedimentary sequences. *Tectonophysics*, 215: 161–166.

Jones, R. E. & Grasso, M., 1995. Palaeotectonics and sediment dispersal pathways in North-Central Sicily during the Late Tortonian. In: Cello, G., Deiana, G. & Pierantoni, P. P. (eds), *Geodinamica e tettonica attiva del sistema Tirrenno-Appennino*, *Studi Geologici Camerti*, *Special Issue*, 2, pp. 279–291.

Lavecchia, G., Federico, C., Stoppa, F. & Karner, G. D., 1995. La distensione tosco-tirrenica come possibile motore della compressione appenninica. In: Cello, G., Deiana, G. & Pierantoni, P. P. (eds), *Geodinamica e tettonica attiva del sistema Tirrenno-Appennino*, *Studi Geologici Camerti*, *Special Issue*, 2, pp. 489–497.

Lister, G. S. & Davis, G. A., 1989. The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, U.S.A. *Journal of Structural Geology*, 11: 65–94.

Lucchitta, I., 1990. Role of heat and detachment in continental extension as viewed from the eastern Basin and Range Province in Arizona. *Tectonophysics*, 174: 77–114.

Malinverno, A. & Ryan, W. B. F., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as the result of arc migration driven by sinking of the lithosphere. *Tectonics*, 5: 227–245.

Martinez-Martinez, J. M. & Azanon, J. M., 1997. Mode of extensional tectonics in the southeastern Betics (SE Spain): Implications for the tectonic evolution of the peri-Alboran orogenic system. *Tectonics*, 16: 205–225.

Mascle, G., 1979. Etude geologique des Monts Sicani. *Rivista Italiana Paleontologia e Stratigrafia*, 16: 1–431.

Mauz, B. & Renda, P., 1995. Tectonic features at the NW-coast of Sicily (Gulf of Castellammare). Implications for the Plio-Pleistocene structural evolution of the southern Tyrrhenian continental margin. In: Cello, G., Deiana, G. & Pierantoni, P. P. (eds), *Geodinamica e tettonica attiva del sistema Tirrenno-Appennino*, *Studi Geologici Camerti*, *Special Issue*, 2, pp. 343–349.

McClay, K. R. & Ellis, P. G., 1987. Analogue models of extensional fault geometries. In: Coward, M. P., Dewey, J. F. & Hancock, P. L. (eds), *Continental extension Tectonics*, *Geological Society of London*, *Spec. Publ.*, 28, pp. 109– 125.

Meletti, C., Patacca, E. & Scandone, P., 1995. Il sistema compressione-distensione in Appennino. In: Bonardi, G., De Vivo, B., Gasparini, P. & Vallario, A. (eds), *Cinquanta anni di attivitŕ didattica e scientifica del Prof. Felice Ippolito*, Liguori Editore, Bologna, 2, pp. 361–370.

Michetti, A. M., Brunamonte, F. & Serva, L., 1992. Paleoseismological Evidence in the Epicentral Area of the January 1968 Earthquakes, Belice, Southwestern Sicily. *Association of Engineering Geologists*, *Special Publication*, 6, pp. 127–139.

Miller, J. M. G. & John, B. E., 1988. Detached strata in a Tertiary low-angle normal fault terrane, southeastern California: a sedimentary record of unroofing, breaching and continued slip. *Geology*, 16: 645–648.

Nigro, F., 1998. Neotectonic events and kinematic of rhegmetic-like basins in Sicily and adjacent areas. Implications for a structural model of the Tyrrhenian opening. *Annales Societatis Geologorum Poloniae*, 68: 1–21.

Nigro, F. & Sulli, A., 1995. Plio-Pleistocene tectonics in the Western Peloritani area and its offshore. *Tectonophysics*, 252:

295–305.

Oldow, J. S., D'Argenio, B., Ferranti, L., Pappone, G., Marsella, E. & Sacchi, M., 1993. Large-scale longitudinal extension in the Southern Apennines contractional belt, Italy. *Geology*, 21: 1123–1126.

Patacca, E. & Scandone, P., 1989. Post Tortonian mountain building in the Apennines. The role of the passive sinking of a relict lithospheric slab. In: Boriani, A., Bonafede, M., Piccardo, G. B. & Vai, G. B. (eds), *The Lithosphere in Italy. Advances in Earth Science Research*, Italian National Committee for the International Lithosphere Program, *Accademia Nazionale dei Lincei*, 80, pp. 157–176.

Patacca, E. & Scandone, P., 1999. Late thrust propagation and sedimentary response in the thrust belt-foredeep system of the Southern Apennines (Pliocene–Pleistocene). In: Vai, G. B. & Martini, I. P. (eds), *Anatomy of a Mountain: The Apennines and adjacent Mediterranean basins*, Chapman & Hall.

Patacca, E., Sartori, R. & Scandone, P., 1992. Tyrrhenian Basin and Apenninic Arcs: kinematic relations since late Tortonian times. *Memorie Società Geologica Italiana*, 45: 425–451.

Pepe, F., Bertotti, G., Cella, F., Catalano, R. & Marsella, E., 1998. Rifting and Passive Continental Margin Formation in the Southern Tyrrhenian Sea: a High-Resolution Seismic Profile Across the Northern Sicily margin. In: Catalano, R. & Lo Cicero, G. (eds), *acts book*, 79° Congresso Nazionale Società Geologica Italiana, Palermo (Italy) 21-23 September 1998, pp. 663–666.

Platt, J. P., 1986. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. *Geological Society of America Bulletin*, 97: 1037–1053.

Platt, J. P. & Compagnoni, R., 1990. Alpine ductile deformation and metamorphism in a Calabrian basement nappe (Aspromonte, Southern Italy). *Eclogae geologica Helvetica*, 8: 47–58.

Riuscetti, M. & Schick, R., 1975. Earthquakes and tectonics in Southern Italy. *Bollettino Geofisica Teorica e Applicata*, 17: 59–78.

Roure, F., Howell, D. G., Guellec, S. & Casero, P., 1990. Shallow structures induced by deep-seated thrusting. In: Letouzey, J. *et al* (eds), *Petroleum and Tectonics in Mobile Belts*, Edition Technip, Paris, 43, pp. 15–30.

Ruggieri, G., 1966. Primi risultati di ricerche sulla tettonica della Sicilia occidentale. *Geologica Romana*, 5: 453–456.

Scandone, P., Giunta, G. & Liguori, V., 1974. The connection between Apulia and Sahara continental margins in the Southern Apennines and in Sicily. *Memorie Società Geologica Italiana*, 13: 317–323.

Schutte, K. G., 1978. Crustal structure of Southern Italy. In: Closs, H., Roeder, D. & Schmidt, K. (eds), *Alps, Apennines, Hellenides*, Springer-Verlag, Stuttgart, pp. 315–321.

Selli, R., 1985. Tectonic evolution of the Tyrrhenian Sea. In: Stanley, D. J. & Wezel, F. C. (eds), *Geological Evolution of the Mediterranean Basin*, Springer-Verlag, Stuttgart, pp. 131–151.

Spadini, G., Bertotti, G. & Cloetingh, S., 1995. Thermomechanical modelling of the Tyrrhenian Sea: lithospheric necking and kinematic of rifting. *Tectonics*, 14: 629–644.

Torelli, L., Tricart, P., Zitellini, N., Argnani, A., Bouhlel, I., Brancolini, G., De Cillia, C., De Santis, L. & Peis, D., 1992. Une section sismique profonde de la Chaine Maghrébides-Apennins, du bassin tyrrhenien à la plateforme pélagienne (Méditerranée centrale). *Compte Rendue Academie Science Paris*, 315: 617–622.

Tricart, P., Zitellini, N., Torelli, L., De Angelis, A., Bouhlel, H., Creuzot, G., Morlotti, E., Ouali, J. & Peis, D., 1990. La tectonique d'inversion récente dans le Canal de Sardaigne: résultat de la Campagne MATS 87. *Compte Rendue Academie Science Paris*, 310: 1083–1088.

Wernicke, B., 1981. Low-angle normal faults in the Basin and Range Province – nappe tectonics in an extending orogen. *Nature*, 291: 645–648.

Wernicke, B., 1985. Uniform sense simple shear of the continental lithosphere. *Canadia Journal of Earth Science*, 22: 108–125.

Wernicke, B. & Burchfiel, B. C., 1982. Modes of extensional tectonics. *Journal of Structural Geology*, 4: 105–115.

Wezel, F. C., 1985. Structural Features and Basin Tectonics of the Tyrrhenian Sea. In: Stanley, D. J. & Wezel, F. C. (eds), *Geological Evolution of the Mediterranean Basin*, Springer-Verlag, Stuttgart, pp. 153–194.

Wezel, F. C., Savelli, D., Bellagamba, M., Tramontana, M. & Bartole, R., 1981. Plio-Quaternary depositional Style of sedimentary basins along insular Tyrrhenian margins. In: Wezel, F. C. (Ed.), *Sedimentary basins of Mediterranean margins*, *C.N.R. Italian Project of Oceanography*, Tecnoprint, pp. 239–269.

Willet, S. D., 1992. Dynamic and Kinematic growth and Change of a Coulomb wedge. In: McClay, M. R. (Ed.), *Thrust Tectonics*, Chapman & Hall, pp. 19–31.

Yin, A. & Dunn, J. F., 1992. Structural and stratigraphic development of the Whipple-Chemehuevi detachment fault system, suotheastern California: Implications for the geometrical evolution of domal and basinal low-angle normal faults. *Geological Society of America Bulletin*, 104: 659–674.