G. GIUNTA*, F. NIGRO*, P. RENDA*, F. ANDALORO**, A. GIORGIANNI* & V. SPARACINO*

THE STRUCTURAL AND MORPHOTECTONIC FRAMEWORK OF THE NW SICILIAN MAGHREBIDES, IN A SEISMOTECTONIC PERSPECTIVE.

INDEX

ABSTRACT

In the NW Sicilian Maghrebides fold-and-thrust belt, neotectonics is mostly documented by the occurrence of different types of fault systems dissecting the Mio-Pliocene W-E trending belt, both in the submerged northern sector and in the mainland. On land, the fault network consists of three main systems, oriented NW-SE/NNW-SSE, N-S/NE-SW and W-E, showing transcurrent component of motion, with prevalently right-lateral displacement along the NW-SE trend and a left-lateral motion along the NE-SW trend. Faults belonging to the W-E trend are also characterized by dip-slip normal components in the coastal areas of Northern Sicily and by reverse components in the central sectors of the Island.

Neotectonic structures control the genesis of several morphostructures, represented by structural highs (capes and promontories) interposed between depressions (coastal plains). In the coastal areas the general trend of the structural highs is about orthogonal with respect to the Miocene thrust-related morphostructures and progressively swings into the W-E direction in the central sector of the Island (where the main transpressional structures are located). The fault escarpments bounding the neotectonic morphostructures show a very young morphology, which closely defines the shape of the mountain range. The NW Sicilian offshore is also characterized by several morphostructural highs alternated with tectonic depressions, representing the prosecution of those occurring in the emerged sector of the belt. Here, the structural depressions are filled with Plio-Pleistocene clastic deposits and are generally bounded by W-E trending dip-slip fault scarps, by NW-SE right-lateral and by NE-SW left-lateral faults.

Several neotectonic faults in the NW Sicilian Maghrebides are seismically active; associated earthquakes are generally moderate in magnitude and most of them are located along the submerged faults bounding either the morphostructural highs or the shelf slope. On land, the recent tectonic activity is recorded by the presence of faults affecting red-beds, cemented talus and marine and continental deposits of Tyrrhenian age (locally containing mammal fauna); structures affecting the latter deposits have been mapped at different elevation with respect to the sea level, and kinematic indicators on fault surfaces suggest that the area is currently undergoing strike-slip deformation.

Mesostructural data, the remote-sensing analysis, available seismic data from local networks and evidence from the morphological coastal marine outlines, allowed us to work out a preliminary seismotectonic framework for the NW Sicilian Maghrebides. The results of our work emphasize the role played by currently active fault segments, with prevalently strike-slip components, in the development and evolution of this sector of the Maghrebides since Plio-Pleistocene times.

RIASSUNTO

Nel settore nord-occidentale dell'edificio tettonico Maghrebide-siciliano a pieghe e sovrascorrimenti, la neotettonica è documentata prevalentemente dalla presenza di differenti tipologie di sistemi di faglie che dissecano l'edificio mio-pliocenico ad andamento O-E sia nel settore settentrionale sommerso che nell'entroterra; la griglia di faglie è costituita da tre sistemi principali orientati NO-SE/NO-SE, N-S/NE-SO e O-E, tali famiglie mostrano una frequente componente strike-slip del movimento, con spostamento destro, lungo il sistema NO-SE e sinistro, lungo il sistema NE-SO. Le strutture NO-SE che tendono ad assumere un andamento O-E, sono caratterizzate inoltre da una componente dip-slip estensionale nelle aree costiere della Sicilia settentrionale, e inversa nei settori centrali dell'Isola.

Le strutture neotettoniche controllano la genesi di alcune morfostrutture, rappresentate da alti morfologici (capi e promontori) interposti tra depressioni (pianure costiere). Nelle aree costiere l'andamento generale degli alti è all'incirca ortogonale rispetto alle morfostrutture connesse con i sovrascorrimenti miocenici, e progressivamente queste tendono ad orientarsi in direzione O-E soprattutto nel settore centrale dell'Isola dove sono presenti le principali strutture transpressive.

Le scarpate di faglia che bordano le strutture neotettoniche mostrano caratteri morfologici giovanili che definiscono in maniera netta i bordi dei rilievi montuosi. L'off-shore nord occidentale siciliano è caratterizzato da diversi alti morfostrutturali alternati a depressioni tettoniche che rappresentano la prosecuzione di quelli presenti nei settori emersi della catena.

Nelle aree sommerse le depressioni strutturali sono riempite da sedimenti clastici plio-pleistocenici e sono generalmente bordate da scarpate di faglia dip-slip ad andamento O-E, da faglie net-slip destre con direzione NO-SE, e sinistre con direzione NE-SO.

Alcune faglie neotettoniche nel settore nord-occidentale delle Maghrebidi Siciliane sono sismicamente attive; ad esse infatti è associata una sismicità di moderata intensità che si dispone lungo alcune strutture che nel settore emerso bordano le morfostrutture.

Nel settore emerso l'attività tettonica recente è suggerita da faglie che dislocano a tratti terre rosse, detrito cementato, e depositi marini e continentali di età tirreniana; tali strutture coinvolgono i depositi più recenti che sono stati riscontrati e mappati a differenti quote rispetto al livello del mare. La presenza di indicatori cinematici sulle superfici di faglia suggerisce che l'intera area è attualmente soggetta ad un campo di sforzi di tipo strike-slip.

(*) Dipartimento di Geologia e Geodesia dell'Università, C.so Tukory n. 131, 90134, Palermo, Italia.
(**) I.C.R.A.M. (Istituto Centrale per la Ricerca Scientifica e Tecnologica Applicata al Mare), sede di Palermo, via E. Amari n. 124.

L'elaborazione dei dati mesostrutturali, l'analisi aerofotogeologica e il successivo confronto con i dati sismologici e la morfologia sottomarina, hanno consentito l'elaborazione di un modello preliminare di assetto sismotettonico per le Maghrebidi Siciliane. Il risultato del lavoro di ricerca mette in evidenza il ruolo assunto da alcuni segmenti di faglia attivi, con prevalente componente trascorrente del movimento, nello sviluppo e nell'evoluzione dal Plio-Pleistocene di questo settore delle Maghrebidi.

KEY WORDS: Morphotectonic, Sicilian Meghrebides, Seismicity.

PAROLE CHIAVE: Morfotettonica, Meghrebidi Siciliane, Sismicità.

1. INTRODUCTION

Mainland Sicily is a part of the Maghrebian chain, which includes different structural domains (Fig. 1a). The sector of the chain exposed in NW Sicily, is bounded by the Egadi Islands (western boundary), the Palermo Mts (eastern boundary), the Ustica Island-Mt. Anchise alignment (northern boundary) and the Mt. Busambra Ridge (southern boundary, (Fig. 1b). Offshore, this sector of the Sicilian Maghrebides coincides with the Southern Tyrrhenian border. The emerged part represents an uplifting zone between the Tyrrhenian province and the toe region of the belt, where accretionary processes are very recent. Extensional and strike-slip tectonics in the NW Sicilian Maghrebides appear to be related to the recent Tyrrhenian dynamics. The basin opening is counterbalanced, towards the external zones of the belt, by transpression and thrusting.

The main effects of the Plio-Pleistocene Tyrrhenian dynamics are represented by a faults network with different orientations and component of movements. The neotectonic fault strands obliquely cut the Miocene thrust surfaces. These faults also define morphostructural highs, alternated with tectonic depressions, both in the mainland and offshore. The effects of neotectonics are often recorded in marine and continental deposits of Tyrrhenian age. Neotectonics is also supported by the morphotectonic arrangement, which is characterized by different elements. The present-day tectonic activity of the region is also emphasized by the occurrence of earthquakes that are located along the main neotectonic structures.

The present paper reports on the preliminary results of neotectonic studies carried out in NW Sicily and offshore. The aim is to evaluate the seismotectonic framework of the region by integrating marine geology information, mesostructural, aerophotogeological and morphotectonic data with a basic knowledge of the seismicity of the area. Our analysis of seismically active faults, suggests that most of them may be considered as the surface expression of a deep-seated W-E trending shear zone which coincides fairly well with the southern Tyrrhenian border zone. Localized deformation is mostly due to the opening and subsequent spreading migration the Tyrrhenian Basin as a result of the counterclockwise rotation of the African Plate.

2. GEOLOGICAL FRAMEWORK

NW Sicily is composed of a set of W-E trending thrusts and associated fold indicating that this sector of the belt is Africa vergent. The main stages of thrust belt deformation occurred between the Late Miocene and the Early Pliocene. Since the Tortonian, the change in direction of the Africa motion (stage 5 of Dewey *et al.*, 1989) induced stretching in the inner Sicilian Maghrebides units, to form the Tyrrhenian Basin, and the prosecution of thrust tectonics in the more external areas.

The overall tectono-sedimentary evolution of the area is expressed by the foreland migration of the foredeep-deformation front couple and the chain body. The thrust stack progressively incorporated terrigenous foredeep deposits and, in turn, carried piggy-back basins (Nigro & Renda, 1999a, 2000 and references therein). The gently deformed foreland crops out in the south-eastern and westernmost sectors of the island, where the foreland lithosphere bands below the thrust units. The chain front is located off-shore in Southern Sicily, where late Pleistocene deposits rest beneath the toe region of the belt.

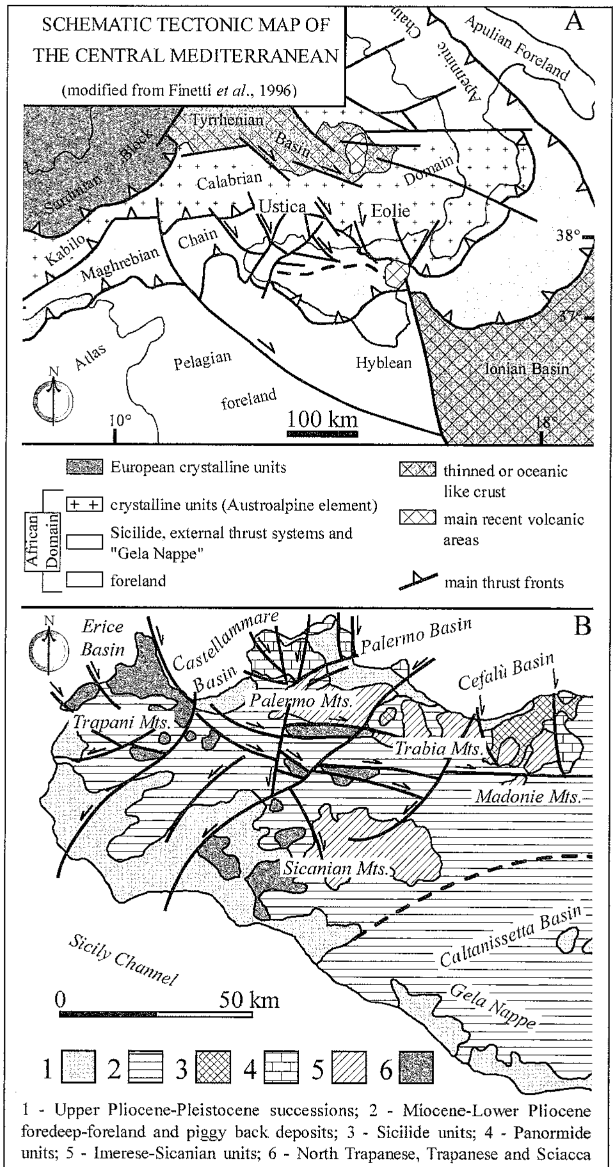


Fig. 1 – **A**. Schematic tectonic map of the Central Mediterranean. **B**. Simplified structural map of Western Sicily.

The Maghrebides (in NW Sicily) are made up of different tectonic units (Fig. 2). These units consist of rock packages derived from the deformation of a pelagic basin (Imerese-Sicano) comprised between two irregular shape carbonate platforms (Panormide and Hyblean-Pelagian). The units are dismembered, partially juxtaposed from the west to east (Fig. 3), and rotated clockwise with values increasing toward the east (OLDOW *et al.*, 1990; GIUNTA, 1991).

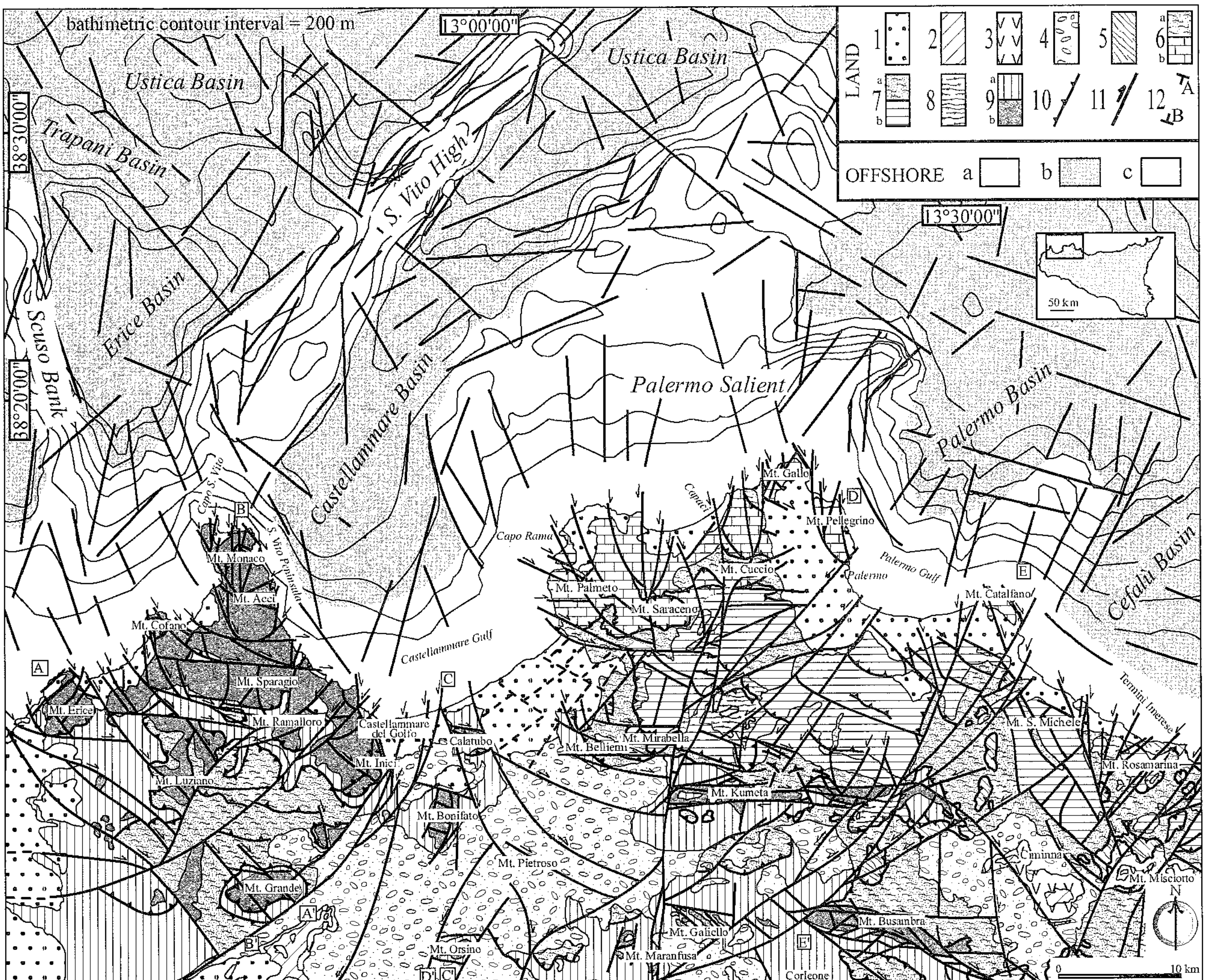
The Panormide successions, outcropping in the Northern Palermo Mts, are made of Triassic to Tertiary platform limestones. The Imerese-Sicanian successions (outcropping in the Southern Palermo Mts) consist of Triassic to Tertiary slope-basinal terrigenous and carbonate limestones. The deformed Hyblean foreland (outcropping in the Trapani Mts) is made of Jurassic to Tertiary platform-to-slope limestones.

The deformation of these successions occurred during the Miocene and the different tectonics units, were progressively emplaced from north to south in a piggy-back sequence. The geometrical position of these units inside the tectonic edifice reflects the ancient palaeogeography (GIUNTA & LIGUORI, 1973; SCANDONE *et al.*, 1974; ABATE *et al.*, 1978; CATALANO & D'ARGENIO, 1982).

Off-shore several Plio-Pleistocene basins (Trapani, Erice, Castellammare and Palermo Basins) alternating with structural highs (Banco Scuso, S. Vito High; CATALANO *et al.*, 1989; AGATE *et al.*, 1993) are located in the shelf slope, forming a roughly belt (TRICART *et al.*, 1990; TORELLI *et al.*,1991; AGATE *et al.*, 1993).

Available stratigraphic information about the Meso-Cainozoic submerged bedrock derive from dredge hauls, while Plio-Pleistocene sequences have been recognized by means of seismostratigraphic analysis.

The structural highs are made of Triassic to Neogene carbonate platform-to-slope and basinal successions (D'ARGENIO, 1998). In particular, in the Palermo Mts offshore, a Triassic to Neogene Panormide-like platform limestone sequence has been recognized. The S. Vito High is made up of a Jurassic to Eocene shallow-water and slope-



1 - Upper Pliocene-Pleistocene clastic deposits; 2 - Lower Pliocene deposits; 3 - Messinian evaporites; 4 - Piggy back successions of Terravecchia Fm. (Upper Miocene); 5 - Sicilide units (Cretaceous-Tertiary); 6a and 7a - Panormide- Imerese foredeep successions of external Numidian Flysch and Sicanian deposits (Oligocene-Lower Miocene); 6b - Panormide successions (Mesozoic-Tertiary); 7b - Imerese-Sicanian successions (Mesozoic-Tertiary); 8 - Mufara-Lercara Fms (Palaeozoic ?-Triassic); 9a - North Trapanese and Trapanese foredeep successions (Miocene); 9b - North Trapanese and Trapanese successions (Mesozioc - Tertiary); 10 - main thrust; 11 - main strike and dip slip faults; 12 - traces of geological cross-sections of Fig. 3. A - Morphostructural highs; B - Plio-Pleistocene subsiding sedimentation areas; C - Plio-Pleistocene uplifting sedimentation areas.

Fig. 2. Schematic structural map of north-western Sicily and its off-shore.

to-basin deposits, while in the Banco Scuso a Jurassic-Cretaceous slope and basinal succession occurs (AGATE & D'ARGENIO, 1998; D'ARGENIO, 1998). The slope-to-basin successions of the S. Vito High and Banco Scuso may represent the western submerged prolongation of the more external Imerese-Sicanian thrust stack (NIGRO & RENDA, 1999c).

The seismic succession of the intra-shelf basin fills is characterized by Early Pliocene deposits evolving to Late Pliocene-Pleistocene slope and shelf facies (AGATE *et al.*, 1993).

The main fold axes involving the Plio-Pleistocene clastic fills, recognized through interpretations of high-resolution seismic reflection profiles, show E-W and NE-SW trends, while the main extensional structures that controlled the basin formation are oriented N-S to NE-SW (AGATE *et al.*, 1993).

The opening of these basins appears to be diachronous towards the east. The oldest are the Trapani and the Erice Basins (Early Pliocene), while the Castellammare Basin originated during the Late Pliocene (AGATE *et al.*, 1993; MAUZ & RENDA, 1995).

On land, structural depressions filled with clastic deposits during the Late Pliocene-Pleistocene, have been interpreted as pull-apart basins controlled by dextral wrench faults located in the Castellammare del Golfo area (MAUZ & RENDA, 1995).

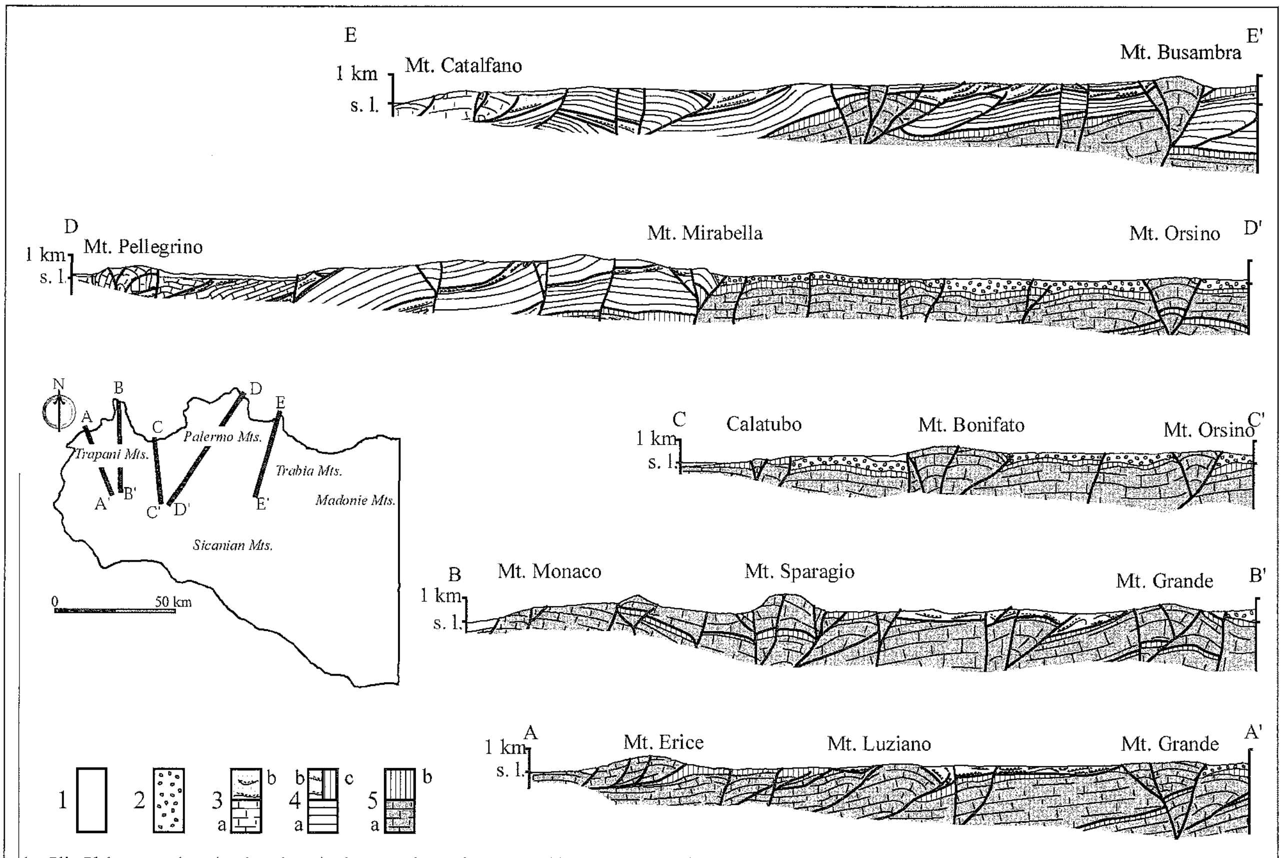
2. MORPHOLOGY AND MORPHOSTRUCTURES

Fig. 4 shows the main morphotectonic elements of NW Sicily deriving from field data and aerophotogeological analysis. For the offshore areas, the main morphological coastal marine outlines are reported on the bases of existing published data (AGATE *et al.*, 1993, 1998a and b; D'ARGENIO & MANCUSO, 1998) and by means of I.C.R.A.M. (Istituto Centrale per la Ricerca Scientifica Applicata al Mare) unpublished data.

On land we had recognized several morphological elements that may be connected to the recent tectonic evolution of the area. They are, principally, straight crests (often associated with scarps) sometimes break off by faults that determine plano-altimetric crest discontinuity and, along the slopes, straight valleys and drainage anomalies (elbow, ditch etc.). In the hinterland between Carini and Palermo, has also been observed the presence of incised meanders, and asymmetric valleys. These elements seem to be strictly connected to the structural trends shown in Fig. 1. and, generally, they record the recent uplift history of different portions of the chain. Uplift may be related to the recent activity of the major net- and strike-slip structures.

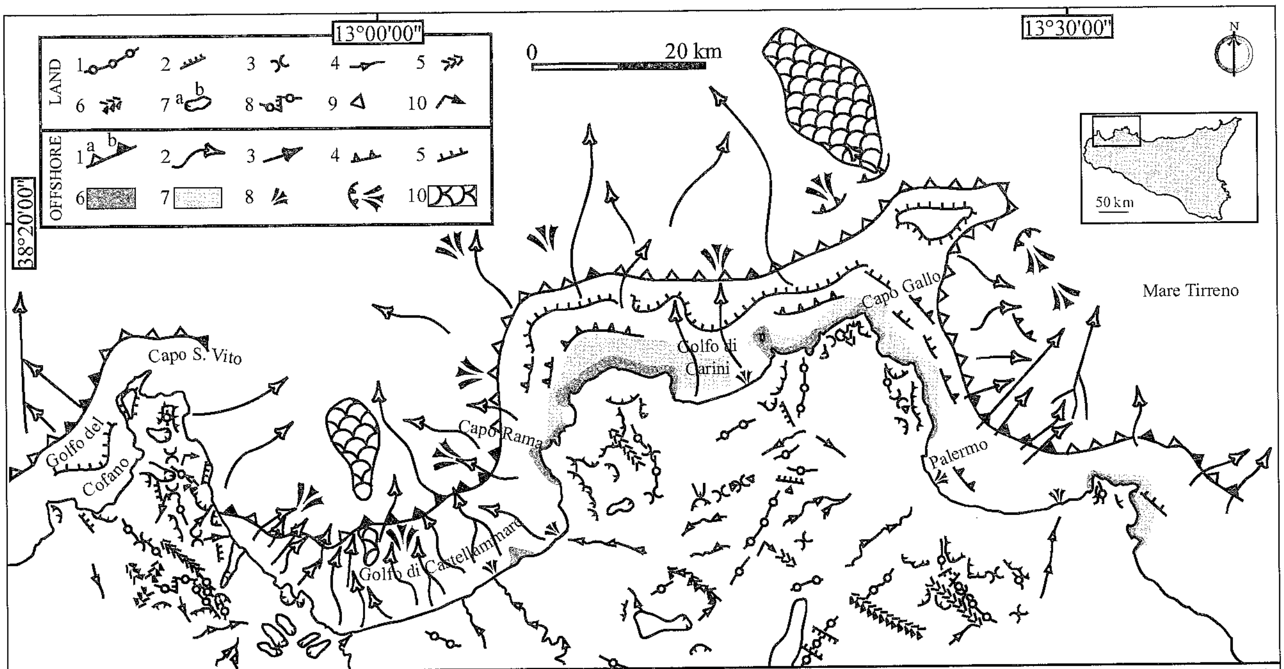
In offshore three sectors may be distinguished: the Castellammare Gulf, the Capo Rama-Capo Gallo continental shelf and the Palermo Gulf.

The continental shelf have different extension of its



1 - Plio-Pleistocene deposits; 2 - Piggy back successions of Terravecchia Fm. (Upper Miocene); 3a Panormide successions -; 3b - Oligo-Miocene Panormide-Imerese foredeep successions; 4a - Imerese-Sicanian successions; 4b - Oligocene-Lower Miocene Imerese-Sicanian foredeep successions; 4c - Middle Miocene Imerese-Sicanian foredeep successions; 5a - North Trapanese and Trapanese successions; 5b - Middle Miocene North Trapanese and Trapanese foredeep successions.

Fig. 3 – Schematic geological cross-sections of Western Sicily.



On land: 1) straight crest; 2) scarp; 3) saddle; 4) ditch; 5) straight valley; 6) valley asimmetry; 7) landslide: a=crown, b=body; 8) plano-altimetric crest discontinuity; 9) block relief or peak; 10) elbow. In offshore: 1) continental shelf edge (a), withdrawing (b); 2) main draining channels; 3) canyons; 4) convex slope discontinuity; 5) paleo-shoreline; 6) coastal active abrasion platform, locally buried by gravel and sand, 7) irregular rock outcrops; 8) fan deposits; 9) scarps and slumps; 10) mass wasting deposits.

Fig. 4 – Main morphotectonic elements recognized in the NW Sicily and morphological features of its offshore.

shape. From the coastal line, the more extended characterizes the Palermo Mts submerged prolongation (from 6 to 15 km; Agate *et al.*, 1998b), followed by the Castellammare and Palermo shelves (2.5 to 7 km).

In the Palermo Mts offshore, the shelf ends abruptly towards east and west, bounded by the submerged prolongation of the Mt. Gallo and Capo Rama morphostructures (Agate *et al.*, 1998b). The shelf is also less extended in the western Palermo and Castellammare gulfs. The shelf slopes are generally incised by canyons, while debris and shingled turbidites have been recognized in its base (Agate *et al.*, 1998b). In the Castellammare Gulf, recent progradational system tracts (delta-like complex) overlie Late Pliocene-Pleistocene shelf-to-basin clastic deposits, overall showing increase in thickness towards the north.

Along the coastal areas of north-western Sicily, N-S to NW-SE trending neotectonic morphostructural highs are recognizable. They are closely related to net-and strike-slip faults, and interposed to coastal plains. The coastal plains represent tectonic depressions filled by Plio-Pleistocene marine deposits (Giunta *et al.*, 2000).

The main morphostructural highs correspond, from west to east, to S. Vito Peninsula, Capo Rama, Capo Gallo and Mt. Pellegrino and Mt. Catalfano. The main structural depressions coincide, from west to east, with the Castellammare, Carini, and Palermo coastal plains. The slopes of the morphostructural highs mostly consist of faults scarps, which displace Mesozoic and locally Recent deposits.

This morphostructural setting progressively changes toward the hinterland, where the N-S and the NW-SE trends are replaced by W-E trend (Kumeta and Busambra Mts).

The above morphostructures continue in the off-shore areas, where they form the structural highs of Banco Scuso, S. Vito High, and the Palermo salient, alternating with the Plio-Pleistocene depressions of Trapani, Erice and Castellammare Basins. The Mt. Bonifato-S. Vito Peninsula range thus continues in the submerged areas, where it merges with the S. Vito High. This morphostructure separates the Erice Basin from the Castellammare Basin. The Mt. Palmeto morphostructural high continues offshore, where separates the Castellammare Basin from the Palermo Basin. Finally, the Mt. Catalfano morphostructure represents the on-land continuation of the submerged rise, dividing the Palermo Basin from the Cefalù Basin. The fault scarps which define the basin flanks show Plio-Pleistocene activity (Agate *et al.*, 1993, 1998a and b).

4. NEOTECTONIC STRUCTURES

In NW Sicily, Plio-Pleistocene strike-slip features are composed of three main fault systems (Figs. 5 and 6):

1) the NW-SE to W-E trending right-lateral system, with associated antithetic N-S structures and variously trending high-angle reverse faults, forming positive flower structure at different scale.

2) the NE-SW/N-S trending left-lateral transcurrent fault system with kilometric course;

3) a NW-SE and W-E trend including dip-slip extensional faults, mostly located in the coastal sectors.

The NW-SE trending faults of the first system are well exposed in the coastal sectors of the Trapani and Western Palermo Mts. In the southern sector, the system swings toward a W-E direction, and the main W-E trending faults bound the Mt. Kumeta and Mt. Busambra mor-

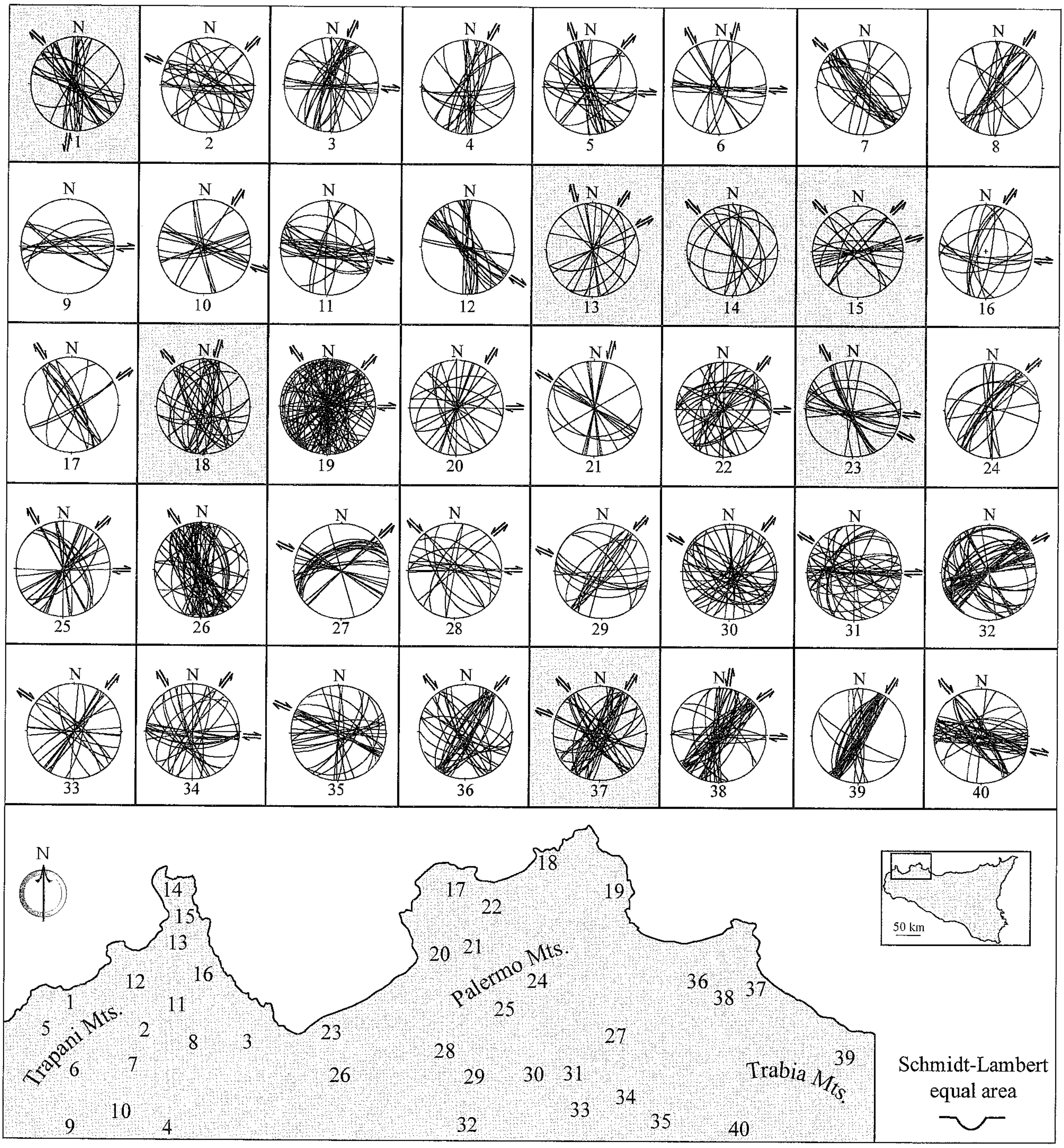


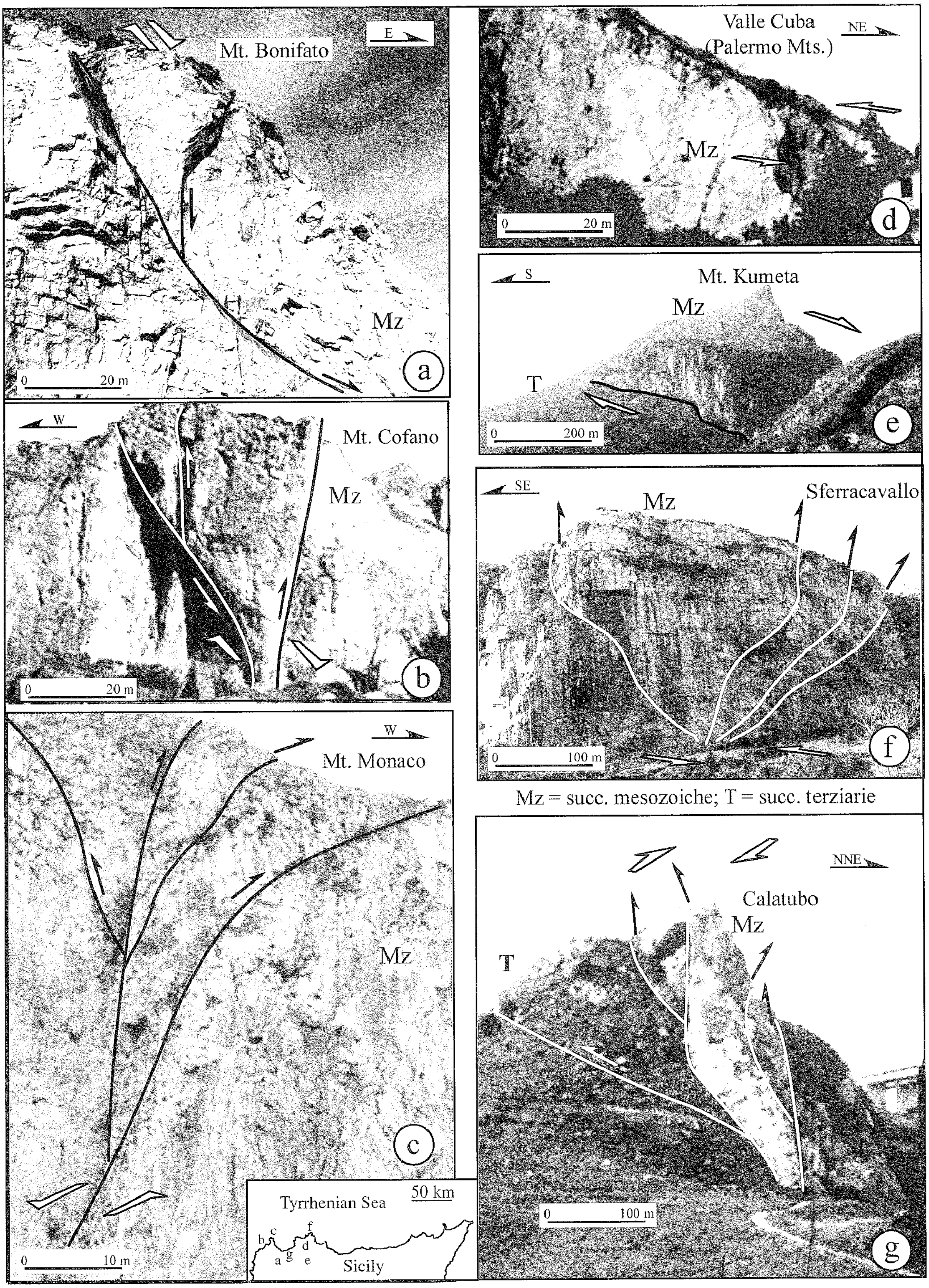
Fig. 5 – Stereographic projections of neotectonic mesostructural trend sampled in 40 sites in Western Sicily. The grey squares represent the sites where the Plio-Pleistocene strata are deformed.

phostructures, which may be interpreted as two positive flower structures. Differently sized NW-SE to W-E trending flower structures also characterize the areas of Calatubo, Mt. Pietroso, Mt. Belliemi, Mt. Mirabella, Mt. Palmeto and Mt. Pellegrino (Fig. 6).

The NE-SW/N-S trending system is represented by several fault strands dissecting the NW-SE system. In this system are included those structures which join, from west to east, Mt. Inici to Montagna Grande, Mt. Gallo to Mt. Mirabella and Mt. Maranfusa, and Mt. Catalfano to Mt. Maranfusa (Fig. 2).

The NE-SW seems to be the last transpressive fault

Fig. 6 – Examples of brittle structures related to Plio-Pleistocene strike-slip deformation. **a)** NNW-SSE trending right-lateral transtensional system, represented by a listric master fault and by an antithetic reverse fault. These faults displace Mesozoic carbonatic successions (Mz) outcropping in the Trapani-Castellammare Mts.; **b)** NNW-SSE trending positive flower structure, represented by a net-slip right-lateral fault strands. These structures displace Mesozoic carbonatic successions (Mz) outcropping in the Trapani-S. Vito Mts.; **c)** N-S trending positive flower structure, represented by a left-lateral faults strand. This structure displaces Mesozoic carbonatic successions (Mz) outcropping in the S. Vito Peninsula; **d)** NE-SW trending left-lateral transcurrent fault displacing Mesozoic carbonatic successions (Mz) outcropping in the Palermo Mts.; **e)** W-E trending right-lateral macroscopic transpressional structure (positive flower), deriving from the convergence of NW-



SE trending right-lateral net- and strike-slip faults strands. The latter affect the southern Palermo Mts. to the northern coastal areas, whereas they mostly show transtensional dislocations. In the example, the high-angle net-slip reverse faults system superposes Mesozoic carbonatic successions (Mz) to Cretaceous and Miocene deposits (T); **f)** example of NNE-SSW trending positive flower structure, involving Mesozoic carbonatic successions (Mz) near Palermo; **g)** NW-SE to WNW-ESE trending positive flower structure, represented by reverse net- and right-lateral strike-slip faults, involving either Mesozoic carbonates (Mz) or Tertiary clays (T) outcropping in the Castellammare Plain.

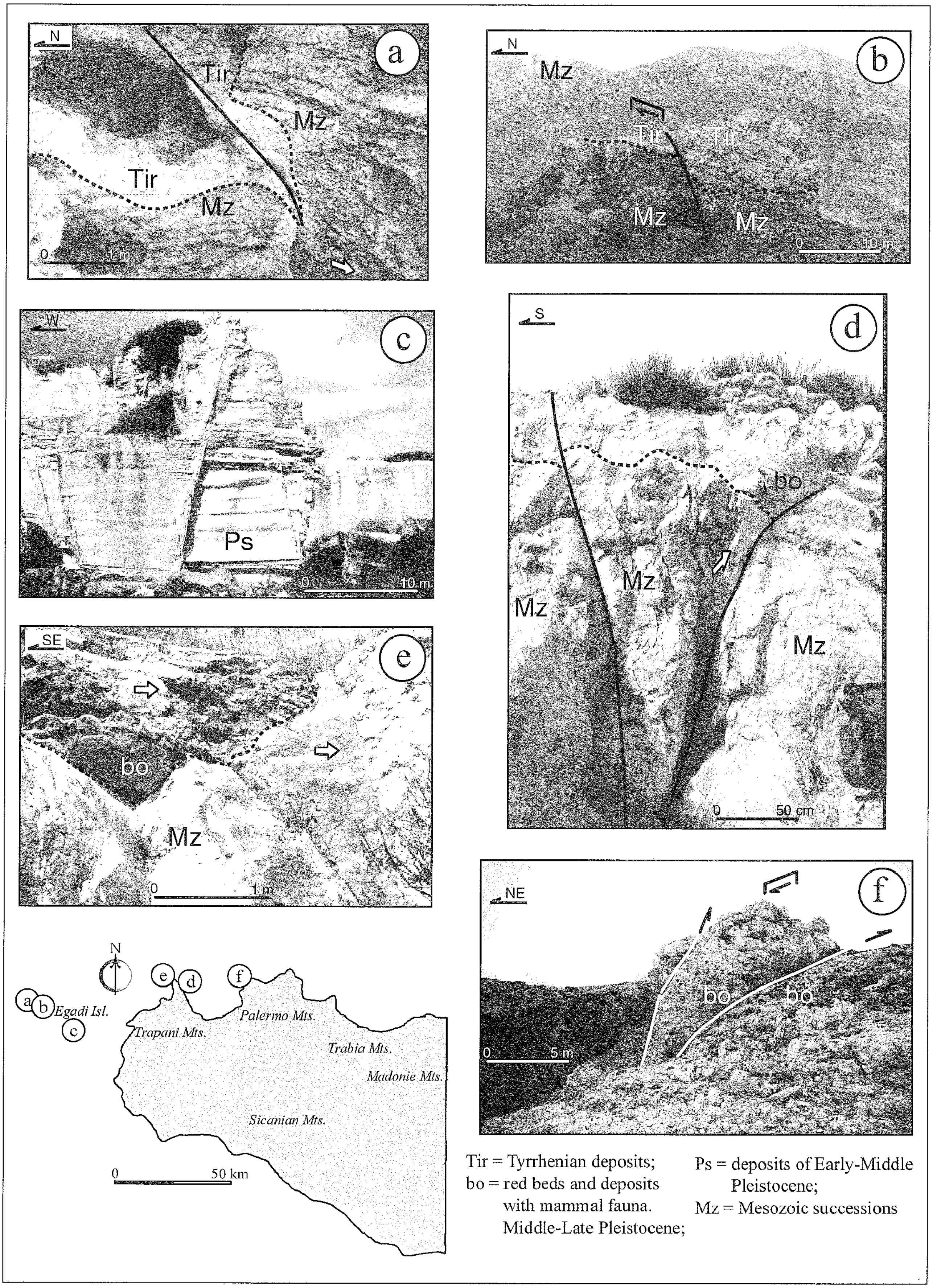


Fig. 7 – Examples of brittle structures related to strike-slip deformation, affecting Plio-Pleistocene deposits. **a-b)** neotectonic faults cutting deposits of Tyrrhenian age in the Marettimo Island; **c)** conjugate set of neotectonic faults involving the early Pleistocene deposits outcropping in the Favignana Island; **d)** meso-scale flower structure involving both Mesozoic carbonates and deposits of Tyrrhenian age in the Capo S. Vito Peninsula; **e)** transcurrent fault involving red-beds in the Capo S. Vito peninsula; **f)** positive flower structure involving continental deposits with remnant of mammal fauna of Tyrrhenian age, near Capo Rama.

system. In places it shift toward the east by the reactivation of the dextral W-E systems.

The extensional fault system widely affects the coastal sectors, where it assumes a W-E to ENE-WSW trend. In the eastern sides of the Mt. Erice and S. Vito Peninsula, the extensional fault system is oriented NW-SE and better shows transtensional component of displacement. In these areas, the NW-SE transtensional system appears to be the origin of the overall tilting of the macrostructures towards the east, as for example described by D'ANGELO *et al.* (1997).

The Tyrrhenian-dipping extensional fault system controls the coastal morphology and locally re-activates previous Miocene-Pliocene thrust surfaces.

The occurrence of slickensides within the Pleistocene deposits (Fig. 7) indicates that the deformation is characterised by strike-slip mechanisms (ABATE *et al.*, 1998). In addition, some continental deposits with remnants of Middle Pleistocene mammal faunas red-beds and cemented talus are affected by left- and right-lateral strike-slip faults near S. Vito lo Capo Village, and Capo Rama (ABATE *et al.*, 1998; GIUNTA *et al.*, 2000; NIGRO & RENDA, 1999b and d).

Several segments of the above-mentioned fault systems also displace tyrrhenian deposits outcropping from Egadi Islands to the Palermo Mts (NIGRO *et al.*, 2000), as also revealed by the different elevation respect to the sea level (Fig. 8). In NW Sicily, along the morphostructural highs, this deposits are crossed more frequently by NW-SE right-lateral strike-slip faults (Mt. Cofano, eastern side of the S. Vito Peninsula, Capo Rama). N-S left-lateral neotectonic strike-slip faults are common in the northern side of the S. Vito Peninsula and in the Palermo Mts.

In the offshore, the main faults controlling the basin formation are oriented NW-SE and NE-SW (FABBRI *et al.*, 1981 and 1982; WEZEL *et al.*, 1981; AMBROSETTI *et al.*, 1983; SELLI, 1985; WEZEL, 1985; FINETTI & DEL BEN, 1986; AGATE *et al.*, 1993). The NW-SE system bounds submerged structural highs in the Trapani and western Palermo Mts offshore. The NE-SW system bounds the S. Vito High and the submerged prolongation of Mt. Gallo and Mt. Catalfano structures. In the basin plains of Erice, Castellammare and Palermo Basins, faults trend appears more dispersal in the W-E direction.

The basin asymmetry observed off-shore, with simple NNW-SSE sharp edges and more complex E-W margins, suggests that the former are controlled by right-lateral overstepping strike-slip faults (ABATE *et al.*, 1998). The margins of the basins are controlled by transtensional faults.

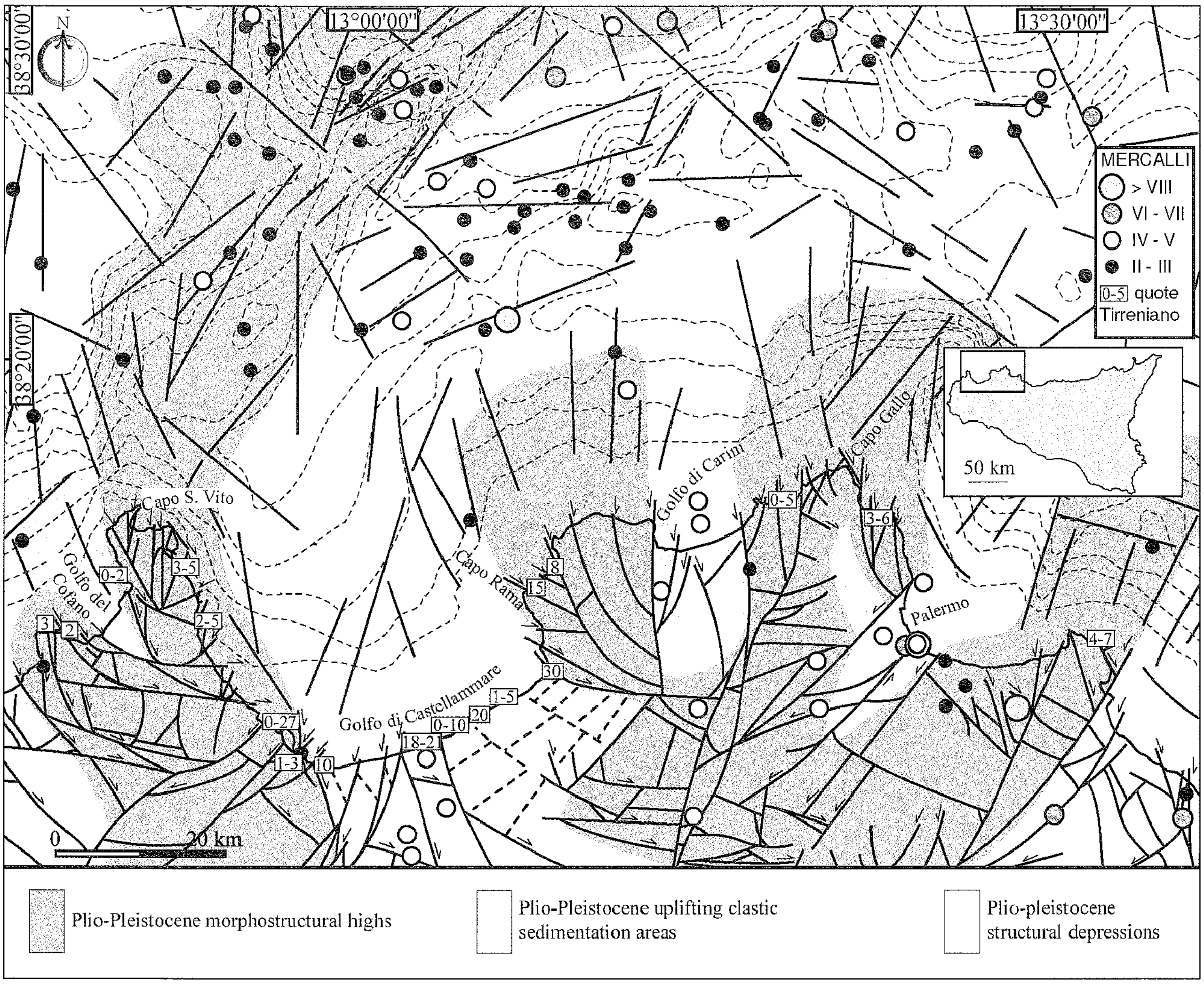


Fig. 8 – Morphostructural setting of NW Sicily and its offshore, and epicenters of earthquakes occurred to last 40 years). See text for explanations.

The connection between the submerged Plio-Pleistocene deposits filling the basinal areas and their coeval counterparts in the coastal plains, appears to occur through fault steps, which overall divide the Plio-Pleistocene uplifted depositional areas (filled by thin sequences) from the subsiding equivalents (where the thickness of the fill deposits is up to 1 km).

5. SEISMICITY

Seismicity in NW Sicily and offshore, data provided by I.N.G. form local networks (C.N.R., 1985), is mostly related to the tectonic activity of the W-E fault trend. This trend is parallel to the Southern Tyrrhenian Margin and coincides seismically with the line joining Ustica to the Aeolian volcanic archipelago. The Ustica-Aeolian line separates the northern Sicilian shelf slope from the Tyrrhenian abyssal plain. This area may be considered as a significative seismogenic volume related to the Southern Tyrrhenian dynamics.

In mainland seismic activity, during the last century, have characterized both western and eastern Sicily. In north-eastern and north-western Sicily earthquakes are distributed along the main tectonic lineaments, as the Aeolian-Patti and the Belice "lines". This lineaments are also well recognizable from aerial and satellite images.

In NW Sicily and offshore the hypocentres span in depth from shallow to several tens of kilometres. Fig. 8 shows the earthquake epicentres occurred in the last 40 years. In the submerged areas they are mostly located along the NE-SW trending S. Vito High and S. Vito Canyon, while on land their alignment coincide with the main neotectonic fault strands, mostly ranging NE-SW as in the Palermo Mts. The epicentres are mostly located inside the main morphostructural highs (Fig. 8). Also in the coastal areas, near several neotectonic fault strands, the deposits of Tyrrhenian age assume different altitude with respect to the sea level (from 0 to up 30 m); (Fig. 8).

Fault plane solutions from the most recent earthquakes are very poor and differ in interpretation. The existing data indicate that the thrust and strike-slip solution of recent events, located both in western Sicily offshore (Banco Scuso, Egadi Islands) and in the outcropping belt, have generally a P-axes oriented NW-SE (MONTONE *et al.*, 1997). In central Sicily the fault plane solutions from the 1968 Belice earthquake sequence show thrusting with considerable strike-slip motion along WNW-ESE oriented planes (KIRATZI, 1994).

The common opinion about the seismotectonic behaviour of NW Sicily is that the strike-slip mechanisms are dominant, and that the strike of the main shear zone is nearly parallel to the regional W-E trend (GHISETTI & VEZZANI, 1982a; GASPARINI *et al.*, 1982-1985).

6. SEISMOTECTONIC CONSTRAINTS

An attempt to arrive at a seismotectonic zoning of the NW Sicilian Maghrebides, has been carried out through the comparison of the above-mentioned neotectonic, morphostructural and seismic elements. The main constraints of our model (fig. 9) are due to the close relationships existing between the on land-submerged Plio-Pleistocene structural highs and/or adjacent depressions, the fault strands which define their shapes, and the earthquake epicentres, distribute along several of these fault strands.

Epicentres populations belonging to earthquakes which occurred during the last half century, may be grouped into three areas, characterising 1) in the submerged S. Vito High-S. Vito Canyon, 2) the Palermo Mts-Mt. Kumeta, and 3) southwards of the Ustica-Mt. Anchise line. The last family shows a W-E trend, whereas the first and the second ones display a NE-SW trends.

In these three seismically active areas morpho- and neotectonic structures are represented by:

1) NE-SW trending fault strands, forming a step which divides the S. Vito High from the S. Vito Canyon (area 1 of Fig. 9a). On land this fault strand mostly shows a left-lateral component of displacement. In the S. Vito Peninsula, the fault strand is prevalently directed NW-SE and the right-lateral components of displacement prevail.

2) N-S and NNE-SSW fault strands ranging from the western Palermo Gulf to the Mt. Kumeta positive flower structure (area 2 of Fig. 9a). The NE-SW system characterizes the Palermo-Monreale sectors (Fig. 9b). The neotectonic evolution of these area has been described by NIGRO (1998) to whom the reader is referred to for further details. The N-S system ranges from Capo Gallo and Capo Rama to Mt. Kumeta. The two fault stands mostly show left-lateral components of displacement and their offshore prolongation controls the recent evolution of the shelf in the Carini Gulf (D'ARGENIO & MANCUSO, 1998), in the western Palermo Gulf, similar to Castellammare Gulf;

3) roughly W-E trending fault strand (area 3 of Fig. 9a). This trend is parallel to the Mt. Anchise-Ustica volcanic alignment, and on land it is mostly represented by transpressive right-lateral faults occurring in the Mt. Kumeta-Mt. Busambra sectors (Fig. 9b).

The faults strands displacing the Tyrrhenian deposits in the NW Sicily coastal areas are represented by associations of N-S and NE-SW trending strike- (mostly left-lateral) and dip-slip normal faults. These fault associations form meso-scale rhegmatic depressions in the westernmost Sicily and Egadi Islands (NIGRO *et al.*, 2000). The NW-SE and W-E trending strike-slip (mostly right-lateral) and dip-slip reverse faults form meso-scale positive flower structures in the S. Vito Peninsula and Palermo Mts. (Figs. 7d,f).

In the Fig. 9b an attempt to depict the seismotectonic zoning is shown. The present-day seismic activity indicates that only some areas are subjected to deformation, and they are located inside the morphostructural highs or in the uplifting areas. The neotectonic faults arrangement and the kinematic indicators suggest that in the region strike-slip mechanisms are dominant and represented by a Riedel-like configuration. Inside the Riedel shear bend different orders of NW-SE synthetic and NE-SW antithetic structures are present. This zone may coincide northwards with the Mt. Anchise-Ustica-Aeolian line, southwards with the Kumeta-Busambra Mts. Within this zone, the synthetic and antithetic faults are marked by morphostructures (highs and depressions), active since the Pliocene (ABATE *et al.*, 1998; GIUNTA *et al.*, 2000; NIGRO & RENDA, 1999d). The synthetic faults strands are organized in an overall horsetail splay

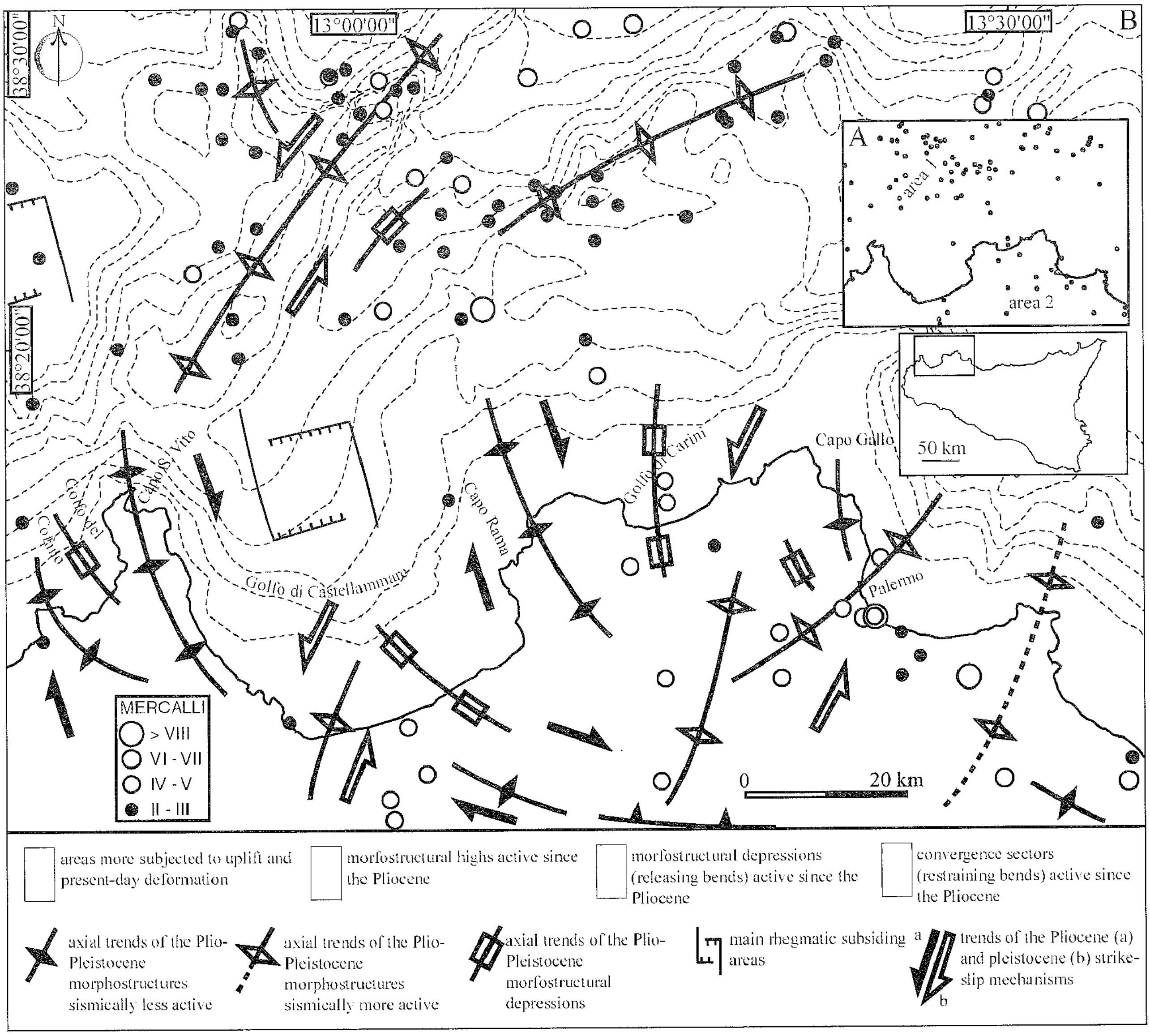


Fig. 9 – **A**. Seismotectonic zoning schematic map of NW Sicily and its offshore. **B**. Sketch of neotectonic macrostructures activity and related morphostructures development during the Plio-Pleistocene. See text for explanations.

geometry (GIUNTA *et al.*, 2000), in which releasing and restraining processes are present. Inside of the NW-SE trending releasing bends, the Plio-Pleistocene subsiding rhegmatic depression are located (submerged intra-shelf basins) and bounded by highs showing an overall eastward tilting and transtensional displacements (D'ANGELO *et al.*, 1997). Towards the mainland, more and more W-E trending restraining bends are present, bounding the coeval uplifted basin fill clastic deposits. The NE-SW antithetic structures mostly show transpressional displacements and generally appear more recent respect to the synthetic ones, confirmed by the geometric relationships between fault sets and by the seismicity.

In this way, the present-day seismic activity well fit with the model of GIUNTA *et al.* (2000), which expresses the active development of the antithetic structures (and related morphostructures) inside of the northern side of the W-E trending shear zone.

7. CONCLUSIONS

The widespread presence of neotectonic faults displacing Tyrrhenian deposits in NW Sicily coastal areas propose the theme of their role in the context of the recent evolution of the Southern Tyrrhenian Margin, controlled during the Plio-Pleistocene by two deep-seated W-E regional trending right-lateral shear zones, as the "Ustica-Eolian Line" (BOCCALETTI & DAINELLI, 1982; BOCCALETTI *et al.*, 1984,1990a and b) and the "Kumeta-Alcantara Line" (GHISETTI & VEZZANI, 1982b-1984).

The angular relationships between the recognized neotectonic transcurrent fault systems and their type of displacement, well fit in right-lateral simple shear regime, active since the Pliocene in the Norther Sicilian Maghrebides.

Fig. 10 shows the neotectonic model proposed by GIUNTA *et al.* (2000) for the Northern Sicilian Maghrebides. For the authors, the Plio-Pleistocene structural pattern of the area was acquired through the continuous activation of multiple overstepping strike-slip faults. The shear zone is

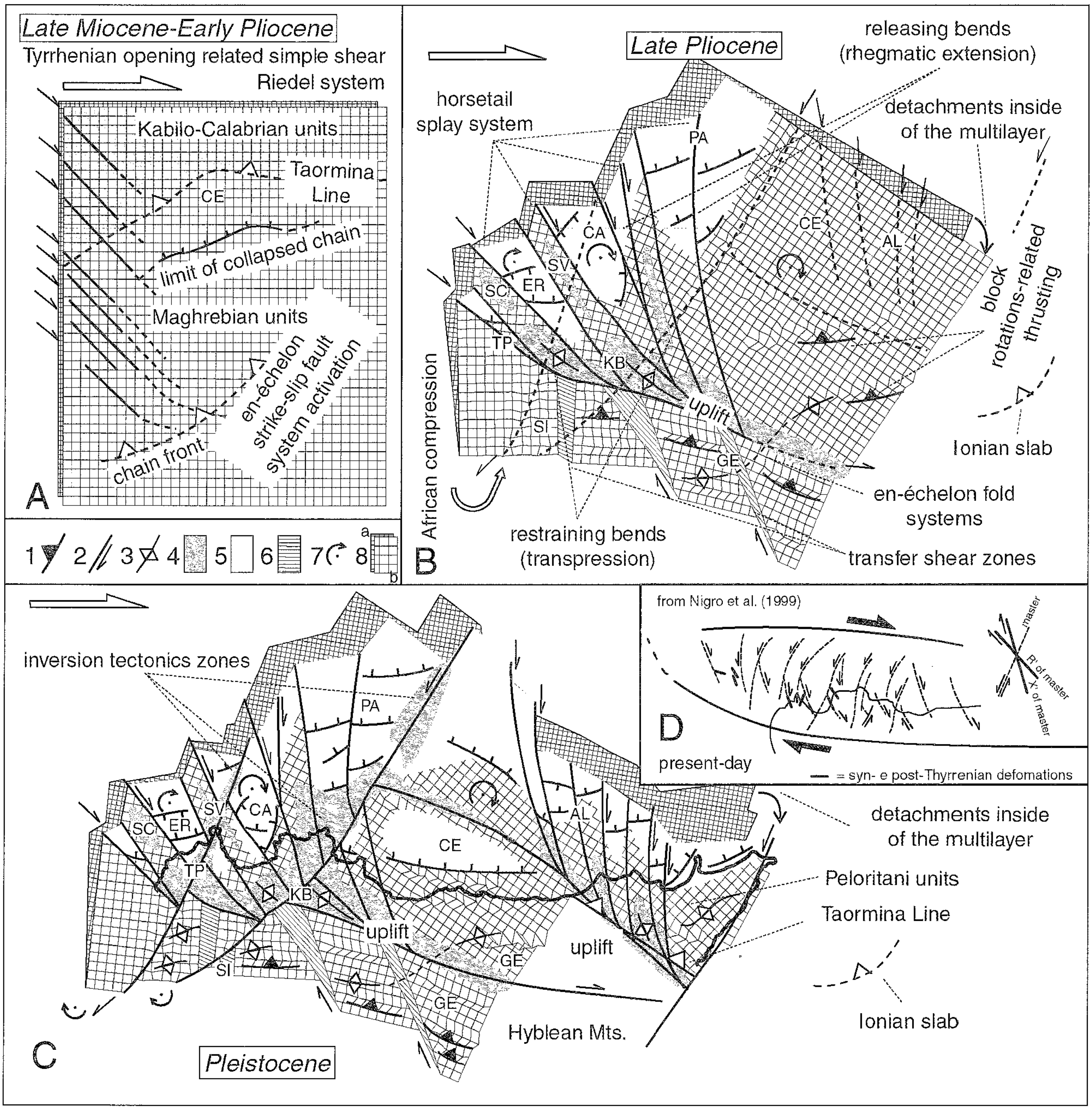


Fig. 10 – Neotectonic evolutionary model of Northern Sicilian Maghrebides, based on the deformation in a simple shear regime of a multilayer, composed by two superposed grids, representing the Maghrebian chain-foredeep couple (from GIUNTA *et al.*, 1999). The finite squared elements of the grid are constant in each scheme, allowing to reconstruct semi-quantitatively the proposed neotectonic kinematic evolution. The simple shear mechanism is supported both by the counterclockwise rotation of the stable Africa and the variable clockwise rotation of the detached chain body. **A**. Sketch of the constructing Sicilian-Maghrebian Chain during late Miocene-early Pliocene, made of Kabilo-Calabrian ("Austroalpine") and more external tectonic units. The simple shear regime allows the activation of a set of multiple left overstepping dextral strike-slip faults (first order synthetic structures), progressively migrating (in B) toward the east and southward in a W-E Principal Displacement (transpressional) Zone. **B**. During middle-late Pliocene, these synthetic structures determine the progressive individuation of alternated structural highs and depressions, located between stepover zones in the inner sectors of the belt, in an overall releasing horsetail splay system, recognizable in the westernmost Northern Sicilian shelf slope, as demonstrated by the more and more subsidence rate in the submerged depressions (light grey) towards the east and uplifting of interposed structural highs (dark grey). The increasing of extensional processes progressively induce stretching in the chain body towards the east, counterbalanced by folding, thrusting and transpressional tectonics in the more external portion of the chain (Central Sicily). Here, uplifting processes are dominant, as demonstrated by the positive flower macrostructures of Mts. Kumeta-Busambra (KB) and their eastern prosecution, in an overall restraining configuration. The strain is also accommodated by macrofolds, NW-SE trending inside the restraining bends, and en-echelon NE-SW trending along the main W-E transpressional zones. The "hinge" zones between releasing and restraining bends are located along the present day coastal sector of Northern Sicily, where portions of Plio-Pleistocene basinal clastic fill crop out. The different clockwise rotation rate of blocks also should characterizes at different levels the belt, encouraged by the pre-existing detachments or thrust, as well as the local "disarticulation" of the shallow portion of the positive flower macrostructures respect to their "roots". **C**. In the Pleistocene, the continuous deformational mechanism in simple shear regime induces the activation of antithetic structures, progressively affecting the western Sicilian Belt. These structures may have determined inversion tectonics in the submerged basins, accentuated clockwise rotations of blocks, and control the formation of new NE-SW trending uplifting zones, both in the submerged sector and in the mainland. Contemporaneously, in the more eastern

portions prosecutes the development of the first order synthetic structures, affecting the Nebrodi-Peloritani areas, where wrench tectonics is characterized by releasing geometries in the submerged areas and restraining geometries in the mainland. At the overall evolution of the deep-seated simple shear Riedel system during Pleistocene should be connected the folding and thrusting of the more external Sicilia-Maghrebian Chain. 1) thrust; 2) strike-slip faults; 3) fold axes; 4) uplifted areas; 5) collapsed areas; 6) transfer shear zones; 7) rotations; 8) Maghrebides deformed belt (a = deeper levels; b = shallow levels); AL) Alicudi Basin; CA) Castellammare Basin; CE) Cefalù Basin; ER) Erice Basin; GE) "Gela Nappe"; KB) Kumeta-Busambra Ridges; PA) Palermo Basin; TP)Castellammare-Mt. Grande Ridge; SC) Scuso Bank; SI) Sicanian thrust stack; SV) S. Vito High. D. Transcurrent faults segments displacing Late Pleistocene deposits (bold lines; from NIGRO *et al.*, 1999). These faults represent both segments of first-order synthetic and antithetic structures of Fig. 10c and minor-order associated structures, as showed in the right side of the figure.

represented at every scale by first and associated minor order synthetic and antithetic Riedel structures, similar to the theoretical wrench-fault models of MOODY & HILL (1956) and SWANSON (1989).

At several releasing junctions between the main strike-slip faults, sedimentary basins of fault-wedge depressions occur. The deformation accommodation rate along the main faults and by the different rotation of blocks, allow the diachronous collapse, from west to east, of different portions of the chain. The uplift and emersion of the Plio-Pleistocene marine deposits may be interpreted as the result of the fault interference geometries, which induces tilting and collapse of blocks, both in the submerged areas and in the coastal hinge zone.

According to GIUNTA *et al.* (2000), starting from the Early Pliocene (Figs. 10a,b), the earliest left-stepping dextral strike-slip faults produced the Banco Scuso and the S. Vito High *p. p.* The adjacent transtensional depressions of Erice and Trapani and Castellammare Basins developed in different releasing oversteps. The onland prolongation of these submerged structures are represented by the strike-slip fault systems bounding the Trapani and the western Palermo Mts. The Late Pliocene strike-slip tectonics is characterized by a more extended overlapping of the main en-échelon right-stepping transcurrent faults, leading to further opening of the Erice and Castellammare Basins and the increasing of the stretching processes in the Palermo Basin.

During the Pleistocene (Fig. 10c), the activation of the more eastern en-échelon strike-slip system (and the further development of the synthetic NW-SE fault system and related antithetic structures) controlled the inversion tectonics in the Erice and Castellammare Basins. The on-land prolongation of the main submerged structures is represented from west to east by the strike-slip fault systems bounding the junction between Mt. Inici-Montagna Grande, Palermo Mts-Mt. Kumeta and Mt. Catalfano-Belice River. The rhegmatic development of the basinal areas appears confined inside first-order releasing bends (Trapani, Erice, Castellammare, Palermo Basins and their on-land prolongation), organized in an overall horsetail splay system. In these fault-wedge stretched basins, the extension occurs along the main W-E (and locally NNE-SSW) dip-slip faults, which form releasing fault junctions in the westernmost submerged basins.

The releasing process may have developed through the progressive rotation towards the east of the chain blocks bounded by the main NW-SE trending strike-slip faults. In this mechanism the accommodation space produces an increase of the clockwise rotation of dragged blocks from west to east (GHISETTI & VEZZANI, 1981; OLDOW *et al.*, 1989; GIUNTA, 1991), allowed both by the antithetic faults, inversions of previous extensional structures, and more and more active thrusting towards the external areas. The high rate of simple shear induced NW-SE to W-E trending restraining bends, counteracting the collapsed areas. In the mainland the best evidence of restraining overstep faulting and the maximum rate uplift of the orogen is represented by the Kumeta and Busambra Mts push-up blocks and their eastern prolongation. The transcurrent fault convergence and their interference seem to be the cause of the partial emersion of the Plio-Pleistocene basinal areas. In this context, the further clockwise rotation towards the east of the different chain sectors was accommodated along the antithetic faults, and through folding and thrusting (Southern Sicani Mts and Gela Nappe). The above processes may have been controlled by basal detachments becoming deeper and deeper as the instability moved towards the external areas of the deforming system (GIUNTA, 1991).

The transcurrent faults displacing the deposits of Tyrrhenian age, both in westernmost Sicily (where they overall shows transtensional displacements) and in the S. Vito Peninsula-Palermo Mts (where they overall shows transpressional displacements), are located inside of the main uplifting or subsiding morphostructures of the northern Sicilian Maghrebides and may respectively represent small-scale rhegmatic depressions inside releasing oversteps and small-scale transpressional structures inside restraining bends, as theoretically described by CHINNERY (1963) and CHINNERY & PETRACK (1967). The trends of these structures, well fit to the model of GIUNTA *et al.* (2000), as the expression of the recent evolution of the W-E deep-seated shear zone affecting the Northern Sicilian Maghrebides (Fig. 10d). The post-Tyrrhenian faults segments (bold lines in Fig. 10d) represent both NE-SW first-order antithetic Riedel structures and second- or minor-order associated antithetic ones. The occurrence of seismicity along the neotectonic faults grid allow the individuation of the characteristic segments of the seismogenetic structures; it seems that the segments of the described Riedel-like strike-slip system are supposed to be still active, as the synthetic and antithetic faults associated to the NE-SW trending first-order left-lateral structures.

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