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Transtensional tectonics in the Sicily Channel

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Abstract—Structural, geophysical and volcanological data available for the Sicily Channel demonstrate that the whole area is characterized by the occurrence of transtensional structures activated in a dextral shear zone trending roughly WNW–ESE. These data allowed us to put forward a kinematic model of the area which accounts for both the existence of discrete tectonic depressions and for the localized volcanic activity of this sector of the Pelagian Sea. The proposed model is somewhat different from other rifting mechanisms available for the Sicily Channel in that it may explain the occurrence of extensional features and the associated volcanism in a zone of continental collision through the development of large-scale pull-apart basins involving deep crustal levels.

INTRODUCTION

AMONG THE PROCESSES of continental collision presently occurring in the central Mediterranean and involving the African and European plates, a better understanding of the extensional structures in the domains between the undeformed African margin and the Sicilian–Maghrebid chain, is of importance for deciphering the geodynamic evolution of this sector of the Alpine System. These extensional structures mostly occur in the Sicily Channel, which is part of the Pelagian Block (Burollet *et al.* 1978, Winnock 1981); a tectonic unit characterized by continental crust overlain by Mesozoic–Cenozoic carbonates and extending from the Hyblean platform to the coasts of Tripolitania and Tunisia.

The major morphological features which characterize the Sicily Channel area are a series of deep, NW–SE-trending, tectonic depressions (Pantelleria, Linosa and Malta troughs) bordered by major faults with variable throws (Fig.1). Estimated displacements affecting mostly a Miocene sedimentary cover, range from 500 m in the Pantelleria Trough, to approximately 1000 m in the Linosa and Malta troughs (Winnock 1981). These troughs are filled with turbiditic Plio-Pleistocene deposits (Maldonado & Stanley 1977) reaching thicknesses of about 1000 m in the Pantelleria Trough, 2000 m in the Linosa Trough and 1500 m in the Malta Trough (Colantoni 1975, Winnock 1981), whereas in the remaining portions of the Pelagian Block, the Plio-Pleistocene sediments consist of neritic platform deposits which do not exceed 500 m in thickness (Winnock 1981).

Another major fault system in the area trends NE–SW. Structures in this system interrupt the continuity of the troughs and locally show sinistral transcurrent displacements in Pleistocene time (Winnock 1981). In the northwestern part of the area, where volcanic rocks crop out on the Island of Pantelleria, N–S-trending structures are also present (Fig. 1).

In the basin areas of the Sicily Channel, crustal thickness is reduced to less than 20 km. Heat flow is relatively high, reaching values up to 100 Mw/m^2 in the northwestern zones (Zolotarev & Sochelnikov 1980, Boccaletti *et al.* 1984), whereas gravimetric data (Morelli *et al.* 1975a,b) show Bouguer anomaly values ranging from +40 to +80 mGal.

The structural and geophysical features of this section of the Mediterranean have been explained in terms of classical rifting processes accompanied by second-order shear phenomena related to the displacement of Sicily

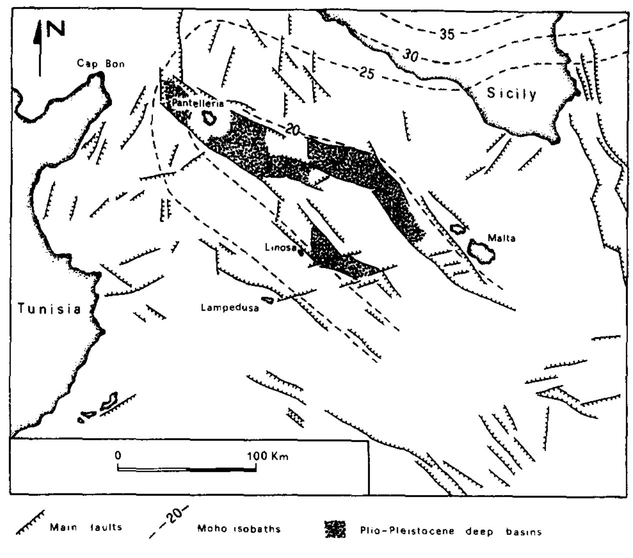

Fig. 1. Structural sketch map of the Pelagian Block.

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away from the African continent (Illies 1981, Winnock 1981, Beccaluva *et al.* 1983, Finetti 1984). According to Illies, the structures of the Sicily Channel can be related to a two-phase intraplate rifting; an intra-Miocene phase, which brought about the formation of NE–SW-trending structures; and a supra-Miocene–Quaternary phase which is responsible for the activation of NW–SE-trending structures. Alternatively, according to Winnock (1981), deformation of this area occurred essentially in Plio-Pleistocene times and rifting, with associated volcanic activity, is of Quaternary age. Finetti (1984) describes a more complex deformation history which includes extension perpendicular to the axis of a rift extending from Pantelleria to the Hyblean–Maltese scarp, and dextral strike–slip motion along E–W-trending faults bounding the northern and southern ends of the rift zone.

Another model for the northwestern portion of the Strait of Sicily, has been proposed by Cello *et al.* (1985) who carried out a detailed structural analysis of Pantelleria. According to these authors the Pantelleria Trough developed in a dextral shear zone where crustal thinning and the associated magmatic activity can be linked to the opening of complex pull-apart basins.

The mechanisms proposed so far for the formation and evolution of the area, are all based either on information derived from limited areas (Illies 1981, Cello *et al.* 1984) or on marine geological data (Winnock 1981, Finetti 1984). Given the importance of this area to our understanding of the geodynamic processes of this segment of the Mediterranean, a detailed structural study of all the emerged portions, including both the rift zone (Pantelleria) and its rims (Maltese Islands, Cape Bon), has been carried out. This paper reports the results of this study together with a kinematic model of the whole area of the Sicily Channel.

STRUCTURAL DATA

Both regional-scale and minor structures have been analyzed in order to derive a kinematic picture and to assess the deformational processes acting in the Sicily Channel.

Maltese Islands

The Maltese Islands are located at the eastern end of the northern border of the Malta graben. The outcropping rocks consist mainly of a carbonate sequence (Late Oligocene–Messinian) enclosed by two reefal formations (Felix 1973, Russo & Bossio 1976, Pedley *et al.* 1978, Mazzei 1980), partly overlain by Quaternary continental deposits.

The main regional-scale structures consist of a series of faults with a marked normal component which can be grouped into two sets: one with an ENE–WSW trend and the other with a NW–SE trend. The major structures belonging to the first system are well developed between the southern portion of Gozo Island and the northernmost areas of Malta (Fig. 2). This area is a tectonic depression within which minor faults, subparallel to the two principal trends, give rise to a series of minor horsts and grabens. The depression is limited to the northwest by the Ras Il Qala-Ta Cenc lineament on Gozo. The southeastern margin is the Victoria Fault (Hyde 1955, Felix 1973, Paskoff & Sanlaville 1978, Pedley *et al.* 1978, Illies 1981) which can be traced across Malta from Fomm ir Rih to Madliena Tower (Fig. 2). Across this fault the Oligo-Miocene sequence has been displaced; the maximum estimated throw being about 200 m. The main fault trends N60°E and dips 65–70°NW. At a few localities the fault plane bears well developed striae pitching 70–80°E and W.

In the northwestern sector, along the Ras il Qala-Ta Cenc lineament, a series of fault surfaces trending N50–60°E were observed. These faults dip 60–70°SE and are marked by 65–75°W pitching striae, indicating that movements were dominantly normal. Minor associated structures also show subvertical striations (Cello *et al.* 1984).

The NW–SE-trending set of faults (the Maghlaq system of Illies 1981) is widely developed along the southwestern coasts of Gozo and Malta where it affects the Oligo-Miocene sediments, as well as ripple notch and shore deposits of Quaternary age (Illies 1981). The major faults trend N120–140°E and are morphologically expressed by spectacular coastal cliffs. They show a normal component of motion and fault surfaces dip mainly to the SW; well-developed striations pitch 65–75°W.

In contrast to regional-scale structures, mesostructures can be grouped in four orientation sets (Fig. 3). Shear sense indicators such as crystal-fibre slickensides, slickolites, accretion steps, lunate tectoglyphs, etc., reveal that the set trending N40–60°E (I) contains both normal and dextral strike–slip faults. Thirty-three per cent of striae examined on faults in this set show pitches ranging from 60 to 90°; 38% from 30 to 60° and 29% from 0 to 30°. Some fault planes showing two generations of striae indicate that the normal movements always postdate the transcurrent ones. The second set (II), trending N70–90°E, is mainly characterized by normal faults, sinistral strike–slip faults being subordinate. Relationships between the two types of movement were not observed. A third set (III), trending N130–140°E, is characterized by normal faults, some of which also show a dextral strike–slip component of motion (the pitch of the striae ranging from 10 to 30°). A fourth set (IV), trending N10–20°E, is the least well developed and is exclusively characterized by sinistral strike–slip faults (striae pitch $<10°$).

Thus, the overall structural pattern of the Maltese Islands appears to be characterized by both strike–slip and normal faults; the latter structures being accompanied by extensional fractures more or less continuously distributed in a sector ranging from N30°W to N69°E with two maxima at N160–170°E and N40–50°E (Fig. 4). The strike–slip faults are distributed in three sets; a dextral set trends N50°E (25%) and two sinistral

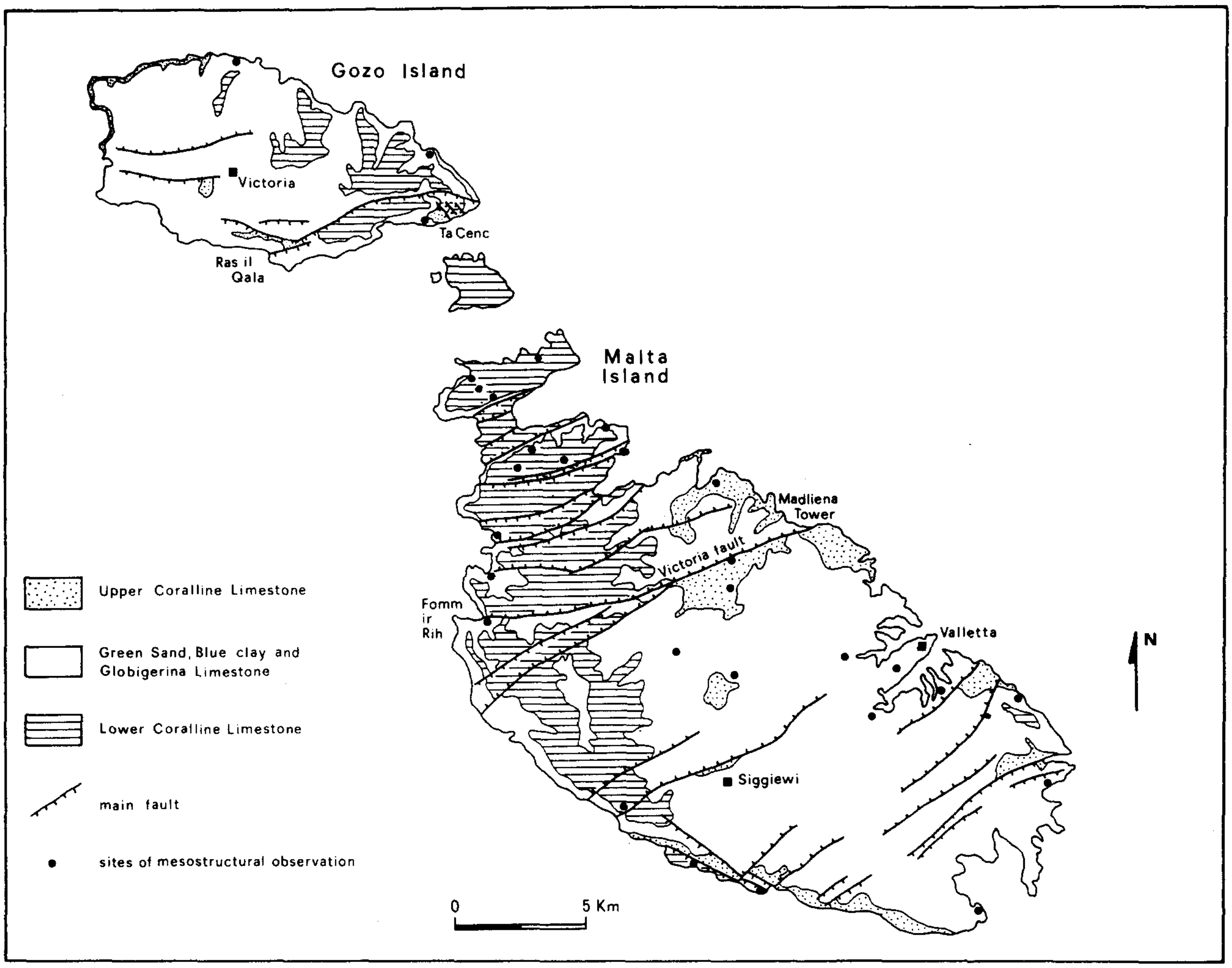

Fig. 2. Structural sketch map of the Maltese Islands.

sets trending N20°E (28%) and E–W (48%), respectively (Fig. 5).

The NW-fractures affect the entire Oligo-Miocene sequence outcropping in the Maltese Islands. Their complex distribution is characterized by extensional and transcurrent structures of the same age suggesting that deformation in the area has been accomplished by a progressive strike–slip mechanism which also allowed the normal faults to be activated as induced structures (Cello *et al.* 1984, Lorenz & Mascle 1984).

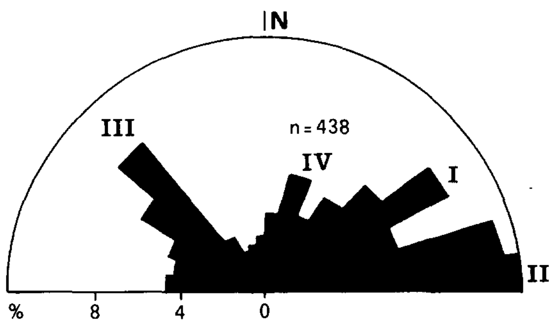

Fig. 3. Rose diagram showing strike azimuths of the observed mesostructures in the Maltese Islands.

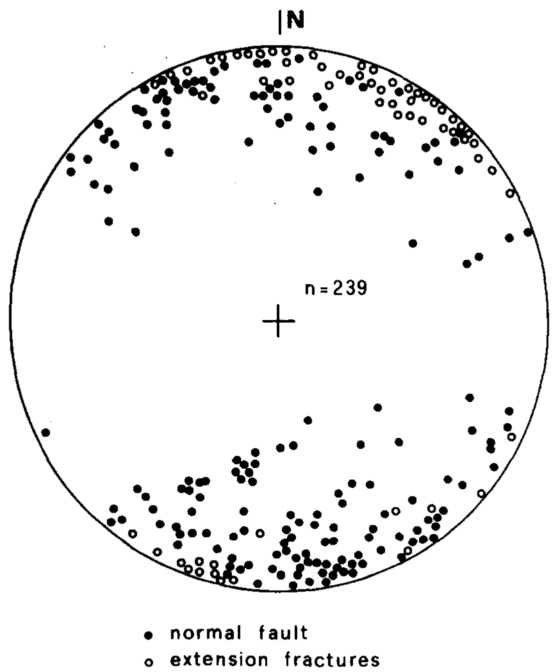

Fig. 4. Equal-area stereogram of normal faults and extension fractures observed in the Maltese Islands.

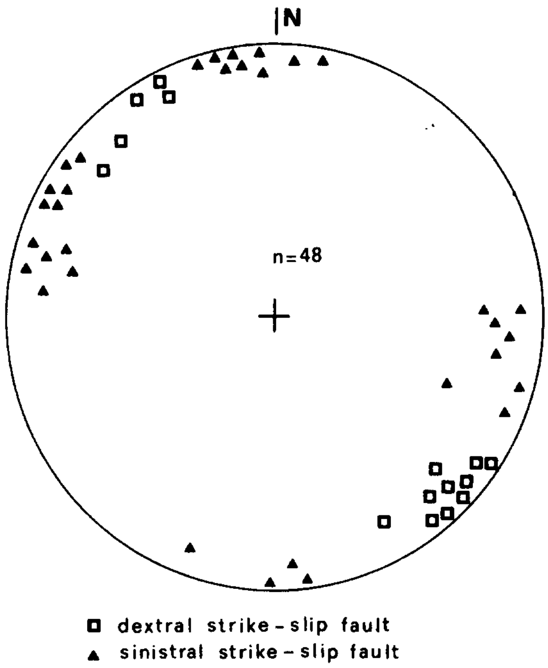

Fig. 5. Equal-area stereogram of strike–slip fault in the Maltese Islands.

Pantelleria Island

The island of Pantelleria is located in the westernmost section of the Sicily Channel and is made up of volcanic rocks, ranging in age from 274,000 BP to the present-day (Mahood & Hildreth 1983). The volcanic rocks include transitional basalts, trachites and peralkaline rhyolites (Pantellerites), belonging to a single evolutionary series (Civetta *et al.* 1984). Trachitic–pantelleritic rocks are the most widely distributed, cropping out all over the island, whereas the basalts are found only in the northwestern areas. The major volcano–tectonic structures are two calderas located in the southeast of the island (Fig. 6); the Serra Ghirlanda Caldera and the Zichidì Caldera (Cello *et al.* 1985). Major regional structures belong to two sets oriented NW–SE and N–S (Fig. 6). Structures belonging to the NW-set are clearly visible mainly along the Cuddia Attalora–Mt Gelkhamar Lineament, which is formed by numerous discontinuities marked by rectilinear cliffs along which a series of pantelleritic domes are aligned. These structures show both normal (downthrow to SW), and dextral strike–slip motion.

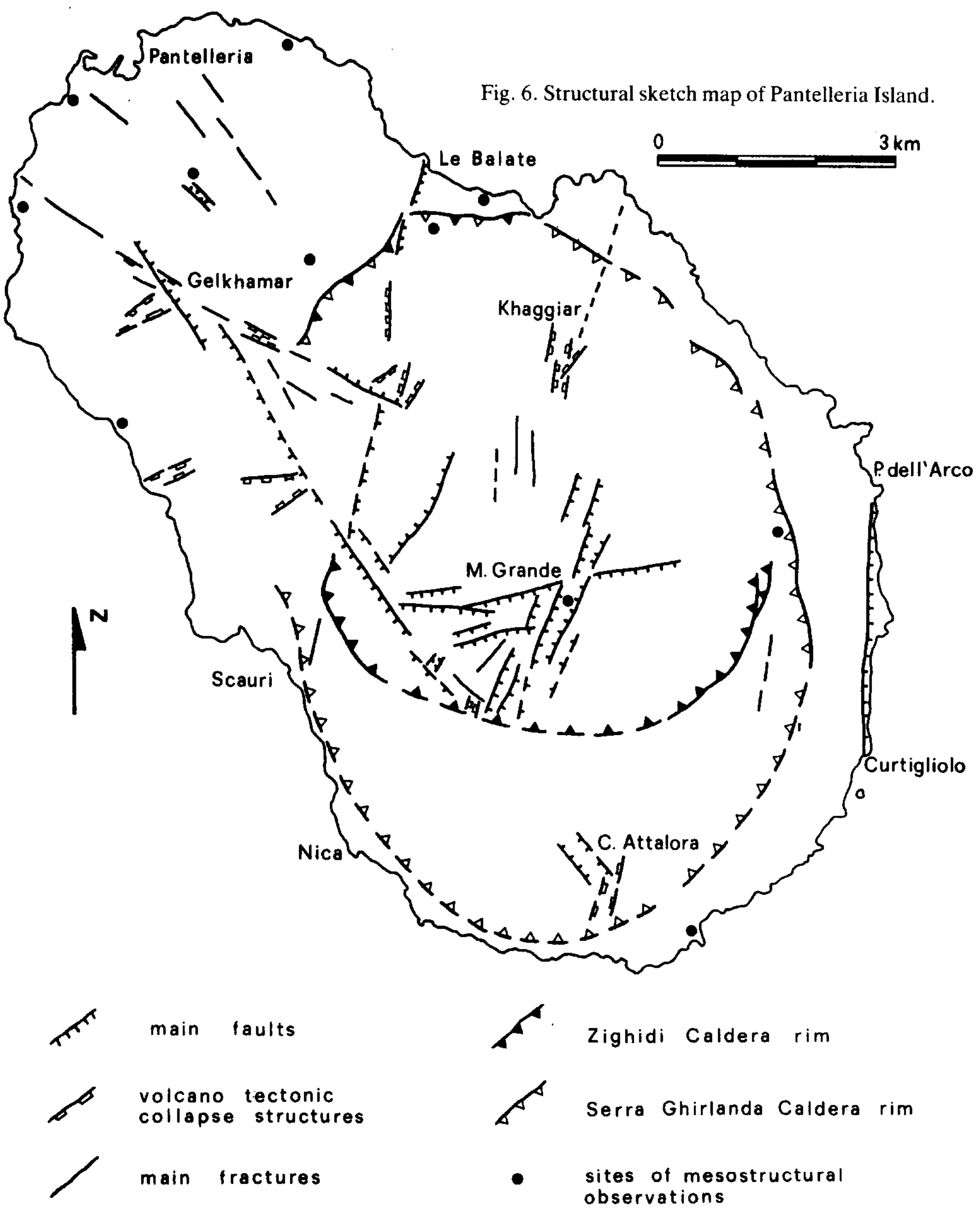

Fig. 6. Structural sketch map of Pantelleria Island.

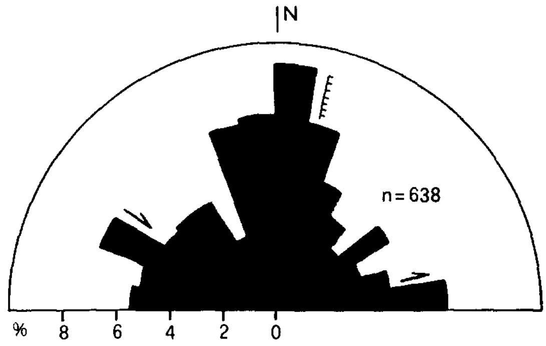

Fig. 7. Rose diagram showing the distribution of the observed mesostructures in the Pantelleria Islands.

The N–S-trending structures are found mainly along the P. dell'Acro-P. Curtigliolo, Kaggiar-Nica and Le Balate–Scauri lineaments. They include normal faults, with displacements exceeding 100 m in places and dips of 75–80°E. Cataclastic bands, 0.5–10 m thick, often fumarolized (Montagna Grande, Scauri, Faraglione), are well developed along the major fault zones. A series of collapse structures are also present along an E–W-trending belt on the southern edge of the Montagna Grande.

The distribution of minor structures is characterized by four modes (Fig. 7). The most common and best represented is the N–S trend which mainly comprises extensional fractures and normal faults showing decimetric and metric displacements and containing striae pitching 65–80°. The N120–140°E-trending set is represented by joints and dextral strike–slip faults with striae pitching <35°. E–W-trending structures are mainly shear fractures and subordinate dextral strike–slip faults with striae pitching 8–36°. NE–SW-trending fractures are interpreted as shear joints.

These data indicate that there is E–W extension across N–S-trending structures, and dextral slip on NW–SE and E–W structures (Fig. 8).

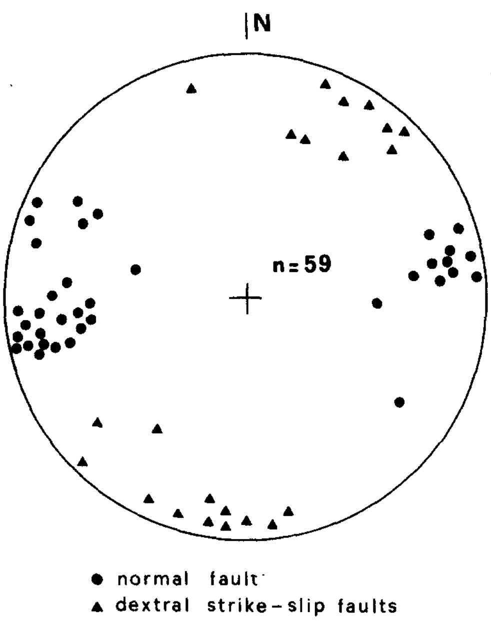

Fig. 8. Equal-area stereogram of normal faults and dextral strike–slip faults in Pantelleria Island.

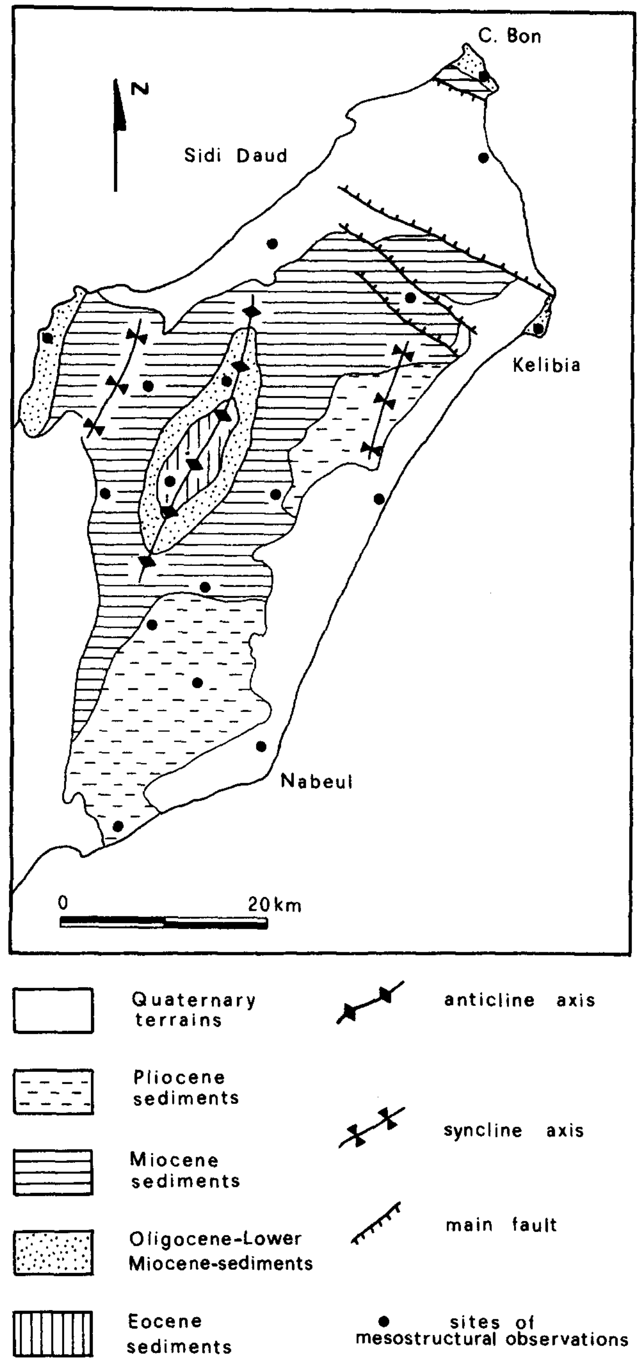

Fig. 9. Structural sketch map of the Cap Bon area.

Cap Bon

Cap Bon is located on the NE tip of Tunisia at the northwestern end of the Pantelleria Trough and consists of a carbonate–clastic sequence, ranging in age from Eocene to Quaternary. The large-scale structures (Fig. 9) are folds with NE–SW-trending axes. To the west they are bounded by a N–S-trending fault system, which forms a depression filled by continental Quaternary deposits, and to the north by a series of NW–SE-trending faults. These structures, which according to Finetti (1984) are characterized by dextral movements, are also responsible for the opening of minor tectonic basins filled with Quaternary continental deposits.

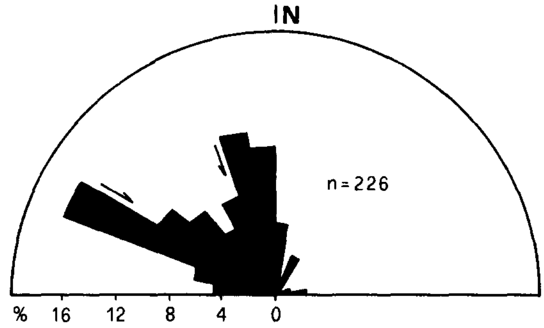

Fig. 10. Rose diagram showing azimuths of faults affecting the pre-Quaternary sediments in the Cap Bon area.

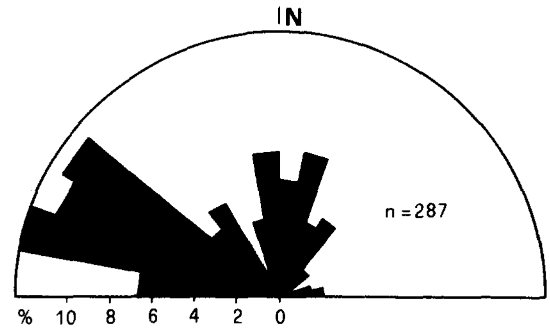

Fig. 11. Rose diagram showing the azimuthal strike distribution of joints cutting Quaternary deposits.

Minor faults mapped in this area can be grouped in two sets trending NW–SE and N–S (Fig. 10). Dextral strike–slip faults are typical of the first set, which cut pre-Quaternary sediments only, and generally dip 70–80° NE. A few of these faults display a normal component of motion, but striations pitching about 50° indicate oblique slip. The N–S set is characterized by both sinistral strike–slip (pitch of striae <30°) and normal displacement, the latter on planes dipping approximately 70°E and containing striae pitching at 80°. The strike of joints in Quaternary continental deposits (Fig. 11) is substantially the same as that of the faults in the older sediments and hence we interpret them in the same way. A few joints trending N140–150°E (about 5% of the whole population) are considered as extensional fractures. The interpretation of the majority of joints as shear fractures is based essentially on their parallelism with the fault systems.

GEOMETRY OF THE STRESS FIELD

The stress field in the region was determined from those fractures on which a displacement direction was determined. There are several methods available for this type of analysis (Arthaud 1969, Angelier 1979, Carey 1979, Etchecopar *et al.* 1981, Armijo *et al.* 1982); in this study the simplified Angelier method (1979) was applied in order to define the three principal stresses.

The solutions obtained for the Maltese Islands (Fig. 12) show a rather complex stress pattern (Cello *et al.* 1984), with the minimum principal stress (σ_3) being subhorizontal and oriented N60°E or, less commonly, NNW–SSE. The maximum principal stress (σ_1) shows a more complex distribution (Fig. 12), within a sub-vertical plane trending ~140°E.

The stress field in Pantelleria is characterized by σ_3 acting on a subhorizontal plane along a NE–SW (N50–60°E) direction, while σ_1 is oriented along a NW–SE (N140°E) direction with important variations in inclination from about 10° to almost vertical. The stress fields for the Pantelleria and Cap Bon areas are similar, with smaller angular dispersions; σ_1 generally lies N150°E and σ_3 N60°E.

These results show that the area is characterized by a general transcurrent tectonic regime with the maximum horizontal stress ($\sigma_{H_{max}}$) oriented NNW–SSE. This stress field is certainly acting at present, as indicated by the recent volcanic activity on Pantelleria and by *in situ* stress measurements in the Maltese islands (Reuther & Eisbacher 1985). Furthermore, the geometry of the present-day stress field is consistent with that acting in the western zones of Tunisia, as shown by the *in situ* stress measurements of Schafer (1980) and by the neotectonic analyses of Kamoun *et al.* (1980).

DISCUSSION AND CONCLUSIONS

The results of the structural analysis carried out on the emerged portions of the Sicily Channel, show a substantial consistency between different areas and between minor and regional-scale structures, the latter being better defined than the former. The main structural features in the Sicily Channel are:

(a) NW–SE-trending faults; those trending N110–120°E are characterized by dextral movements, whereas those trending N140°E (which are well developed in the Malta Trough) are mainly normal faults;

(b) E–W-trending dextral strike–slip faults;

(c) N–S-trending extensional structures, which were reactivated as sinistral strike–slip faults in the border areas (Maltese Islands, Cap Bon);

(d) ENE–WSW-trending normal faults, which are present only in the Maltese Islands.

Structures with a NW–SE-trend bound the three main troughs of Pantelleria, Malta and Linosa, which are dissected by transverse faults trending N–S and ENE–WSW. The distribution, sedimentological character and the thickness of the Plio-Pleistocene deposits in the area (Colantoni 1975, Maldonado & Stanley 1977, Winnock 1981) show that deformation and deposition were contemporaneous, with active faulting since the early Pliocene (Winnock 1981).

These considerations represent the constraints on which we base a new evolutionary model for the Sicily Channel. The Sicily Channel is reinterpreted as a dextral shear zone that developed in a transtensional regime

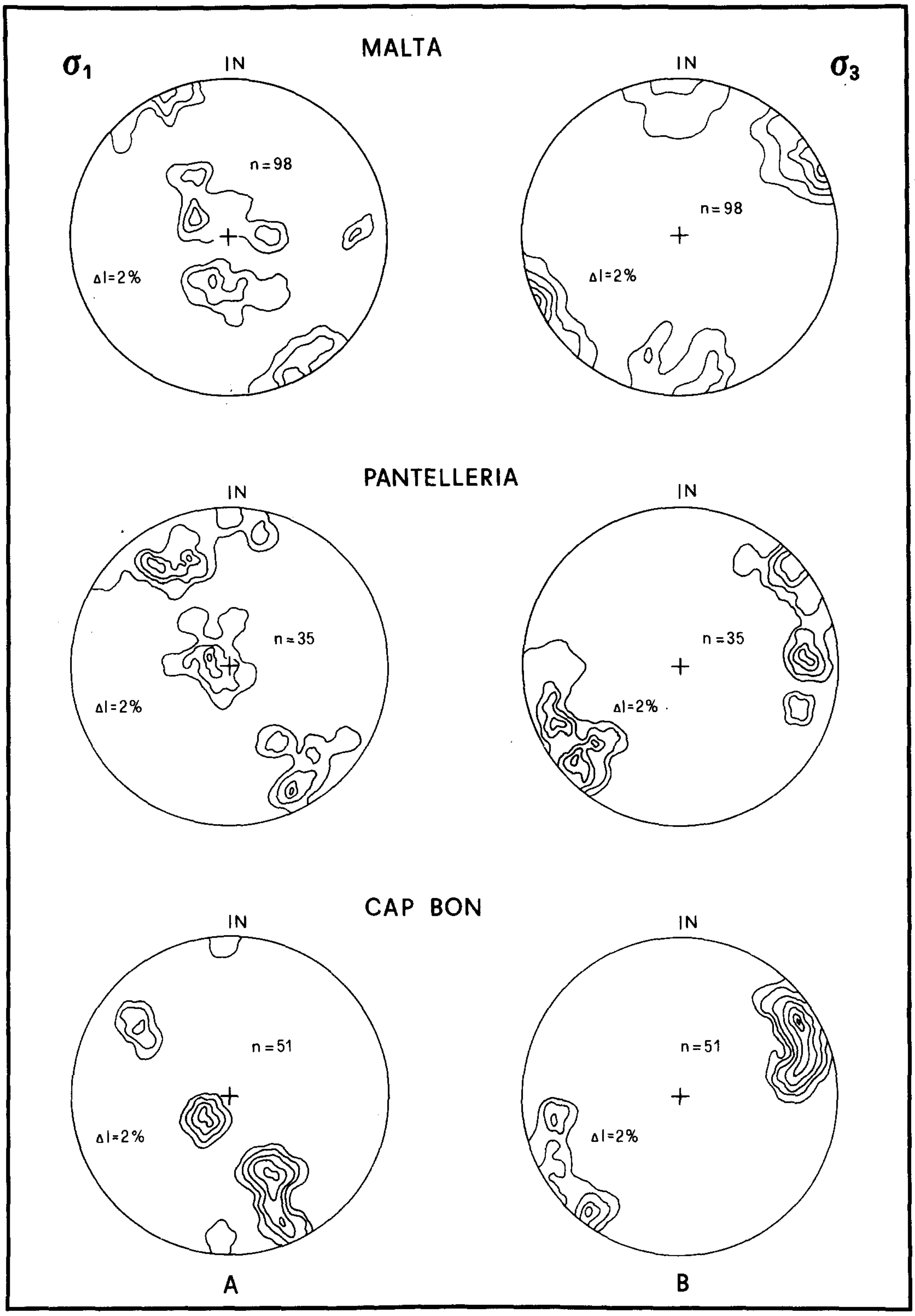

Fig. 12. Contour diagrams of the σ_1 and σ_3 axes as derived from the statistical analysis of striated fault planes collected in the Maltese Islands, Pantelleria Island and Cap Bon areas.

bounded by NW–SE-trending structures (Fig. 13). The presence of the following phenomena support this interpretation:

(a) fault kinematics and stress field data indicate a NE–SW extension;

(b) pull-apart basins are underlain by thinned crust, reflecting an oblique extension;

(c) the nature and distribution of volcanics also reflect abnormally thin continental crust.

In particular, the Malta Trough is interpreted as a pull-apart basin developed between two dextral strike–slip faults trending N110–120°E (Fig. 13). The Pantelleria Trough may derive from the enlargement of original extensional fractures, developed subparallel to the direction of maximum compression and subsequently involved in a pull-apart process due to their favourable orientation within the dextral transtensional regime. In the western areas of the Sicily Channel there is no

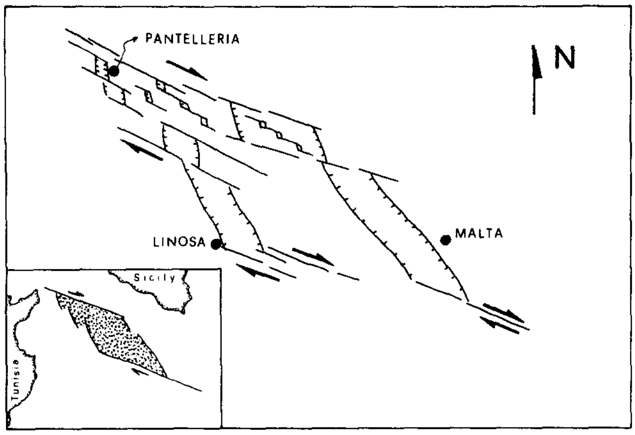

Fig. 13. Structural model for the Sicily Channel; the inset shows a geodynamic model in which the stippled area is underlain by thinned crust (Moho < 20 km depth).

evidence of any important horizontal displacements along the main faults bounding the troughs; it is presumed therefore that this type of pull-apart is derived from the coalescence of several minor pull-apart basins (Aydin & Nur 1983, Cello *et al.* 1985).

The proposed model allows the following observations to be explained:

(a) the presence of discrete tectonic troughs separated by N–S- and NE–SW-trending structures which originated as sinistral faults;

(b) localized volcanism essentially along a N–S-trend which is typical of only the northwestern segment; and

(c) the association of extensional and transcurrent structures related to a single deformational event.

On the basis of the structural data acquired it can be assumed that the Sicily Channel represents a dextral shear zone where the formation of pull-apart basins appears to be a dominant mode of deformation. According to this interpretation it is difficult to consider Sicily as a microplate separated from the North-African margin as suggested by Finetti (1984). It seems more likely that the Sicily Channel might represent a site of intraplate deformation involving the development and opening of a large-scale pull-apart structure.

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