Riv. It. Paleont. Strat.	v. 96	n. 2-3	pp. 219-240	Novembre 1990

NEOGENE AND QUATERNARY SEDIMENTATION PATTERNS IN THE NORTHWESTERN HYBLEAN PLATEAU (SE SICILY): THE EFFECTS OF A COLLISIONAL PROCESS ON A FORELAND MARGIN

MARIO GRASSO* & H. MARTYN PEDLEY**

Key-words: Paleogeography, Synsedimentary tectonics, Neogene-Quaternary, Underthrusting, Hyblean Plateau.

Riassunto. La tettonica sinsedimentaria neogenico-quaternaria ha effettuato un energico controllo sulla sedimentazione lungo il margine nord-occidentale del Plateau Ibleo. Tale controllo si riflette in repentini cambi di facies e di spessore nelle formazioni sedimentarie e nella distribuzione dei centri vulcanici supramiocenici e plio-pleistocenici.

Durante il Miocene medio e superiore si delineano, nei settori nord-occidentali del plateau (zona di Mineo-Grammichele), strutture ad horst e graben a direzione NE-SW, ben evidenziate dalle isopache delle Formazioni Ragusa (Miocene inferiore-medio) e Tellaro (Miocene medio-superiore). Nel Tortoniano superiore si hanno le prime manifestazioni basaltiche dovute essenzialmente ad attività fissurali lungo le zone di cerniera tra horst e graben. I sedimenti messiniani sono costituiti da carbonati di acque basse deposti su alti strutturali, mentre le evaporiti sono confinate entro depressioni strutturali (graben) allungate parallelamente alle direttrici regionali precedentemente individuatesi.

Altri bacini evaporitici si sviluppano verso SW (zona di Licodia Eubea) all'interno di pieghe di trascinamento (sinclinali) connesse con movimenti traspressivi lungo le faglie bordiere del margine occidentale del plateau. Il Messiniano superiore è caratterizzato dallo sviluppo di fenomeni carsici nelle evaporiti e dalla deposizione di sedimenti fluvio-lacustri. Deformazioni sinsedimentarie mediopliioceniche e infrapleistoceniche originano discordanze angolari a carattere locale.

L'evoluzione tettonico-sedimentaria neogenico-quaternaria e la paleogeografia di questo settore del Plateau Ibleo sono il prodotto di un complesso quadro deformativo, dato dal contemporaneo sviluppo di strutture trascorrenti destre che delimitano il margine occidentale del plateau e di strutture tensionali lungo il margine settentrionale. Nel loro insieme queste strutture sono da collegare al collasso dei margini del plateau, connesso con la generale migrazione neogenico-quaternaria del sistema catena-avanfossa-avampaese verso sud.

Abstract. Miocene carbonates and marls in the northwestern margin of the Hyblean Plateau (SE Sicily) exhibit considerable thickness variations consistent with synsedimentary tectonism. In the Early-Middle Miocene carbonates (Ragusa Formation) a series of parallel swells close to the platform edge encouraged the development of a coarse-grained bioclastic facies. The overlying Middle-Late Miocene marls (Tellaro Forma-

---

* Istituto di Scienze della Terra, Università di Catania, Corso Italia 55, 95129 Catania (Italy).

** Geology Department (Leicester), School of Geography & Earth Resources, University of Hull. Cottingham Road, Hull HU6 7RX (U.K.).

tion) thin over these seafloor highs and associated mafic Tortonian volcanics are particularly developed along the hinge zones between swells and local sea-floor depressions. The basic extrusives appear to have followed incipient NE-SW fault lines propagated from deeper basement fractures.

During the succeeding Messinian these faults were activated to produce horst structures (Vallone Lamia horst, Monte Caratabia horst and Cameme horst). These separate local NE-SW oriented narrow grabens in which thick Messinian evaporites were deposited, probably connected with the main Central Sicilian Basin.

Further subaerial deposits and volcanics levelled the Hyblean horst and graben topography prior to the major Early Pliocene marine high-stand. The ensuing transgression covered the study area with a thick pelagic Early Pliocene chalk. Local regressions, the product of Middle Pliocene and Early Pleistocene major tectonic activity along the margins of the plateau, are associated with local unconformities. Final emergence along the margins of the plateau occurred at the close of Early Pleistocene times when the emplacement of the Gela Nappe, from the NE, partly filled the foredeep basin. The withdrawal of the sea from the foredeep occurred shortly afterwards.

The excellent exposure of the Neogene and Quaternary sequences, and the interplay between sedimentation and tectogenesis, provides an opportunity to establish precise time constraints on the tectonic progression, and detailed analysis of the mechanism. The model presented involves the onset of shear progression during the Late Miocene but with further development during the Pliocene to Early Pleistocene. This progression was accomplished by dextral wrenching along the Margi Fault and the Scicli-Ragusa-Irminio Fault system, at the western margin of the Plateau. These major tectonic lines are linked by a horst and graben extension zone near Mineo and by transpressive structures to the south in the Licodia area where a convergent setting is recorded in the fault pattern.

The driving mechanism for shear progression is probably connected with relatively low rates of underthrusting of the buoyant Hyblean Plateau in comparison with higher rates for Pelagian Block areas further west. This is reflected in the present distribution of the Gela Nappe which buries the Pelagian Block beneath up to 4 km of allochthon west of Hyblean Plateau. However, the nappe thins dramatically in association with a northwards flexed sinus, in order to accomodate the rigid and deformation resistant Hyblean Plateau.

Introduction.

The area under consideration (see Fig. 1A, 1B) was chosen as a case study area in order to investigate the interplay between sedimentation and tectonics in critical structural zone where antagonistic processes were reaching a climax. The area offers good natural exposure, with some borehole control, of a mixed carbonate and volcanic succession affected by synsedimentary tectogenesis.

The northwestern margin of the Hyblean Plateau was chosen in preference to others because it best illustrates the effects of two opposed tectonic regimes:

a) Convergent plate motion characteristic of the Pelagian Block at its leading margins, led to the formation of the Maghrebian thrust belt, from Early Miocene to Pliocene times. This convergence is marked by an approximately NE-SW oriented collision front (Lentini, 1983; Carbone, Cosentino et al., 1984; Carbone, Grasso et al., 1984; Lentini et al., 1987; Bianchi et al., 1989).

b) Divergent plate motion along a NW-SE oriented zone (Pantelleria Rift System of Illies, 1980) located within the Pelagian Block in the submerged areas to the south of Sicily. Thus, the rigid Pelagian Block to the south responded entirely by means of brittle deformations.

The divergent motion of the Pantelleria Rift System was associated with taphrogenesis by Late Miocene times onwards after a brief start (NE-SW systems) in the Early

Miocene (Illies, 1981; Reuther & Eisbacher, 1985; Pedley, 1989). This effected a constraining NE directed pushing and played a major role on the deformation of the rigid carbonates along the western margin of the Hyblean - Malta Plateau (Grasso et al., 1986; Grasso & Reuther, 1988).

The application of environmental modelling to the syntectonic sediment succession permits the applications of tight time constraints on the ongoing tectonic events and allows detailed recognition of the faulting kinematics.

The conclusions gained can be directly applied to a regional interpretation of the tectonic evolution of SE Sicily.

General Stratigraphy and Sedimentology of the NW Region of the Hyblean Plateau.

Throughout this section details and interrelationships discussed are illustrated in Fig. 1A, 1B and 2.

Ragusa Formation.

The oldest carbonates exposed in the marginal areas of the Hyblean Plateau consist of about 80 m of pale yellow to brown marine bioclastic Irminio Member (the upper member of the Ragusa Fm. of Rigo & Barbieri, 1959). The lowest exposed beds consist of wackestones with small benthonic foraminifers and abundant indeterminate bioclasts. Although massively bedded, these strata do contain thin (less than 2 m thick) packestone and grainstone beds.

The uppermost 30 m of the exposed member is principally composed of packstones and grainstones in 1 to 3 m thick massive beds separated rarely by wackestone beds. Scattered glauconite and phosphorite grains occur throughout. Scour surfaces and small channels are developed at the base of some beds, the latter generally with NW-SE axial orientations.

Macrobiota are rare although coralline algal fragment (*Rhodophyta*) appear in thin-section principally towards the top of the member; the increase in *Rhodophyta* debris coincides with a similar increase in *Amphistegina* and echinoid debris. Planktonic microfaunas occur throughout the exposed part of the Ragusa Formation and date the deposit as Early-Middle Miocene (Langhian) in age (Rigo & Barbieri, 1959; Cita, 1959; Di Grande et al., 1977; Di Grande & Grasso, 1979; this study).

Tellaro Formation.

In many areas the basal contact is sharp or rapidly transitional with the Ragusa Formation. The Tellaro Formation (Rigo & Barbieri, 1959) consists of a uniform pale to medium grey coloured marl sequence without observable sedimentary structures other than parallel bedding. Generally, the thickness is variable from 50 m to over a hundred metres (Grasso et al., 1980; Pedley, 1981). Frequently this formation contains a variable thickness of basic extrusive volcanics at its top (Fig. 2). These may be either submarine

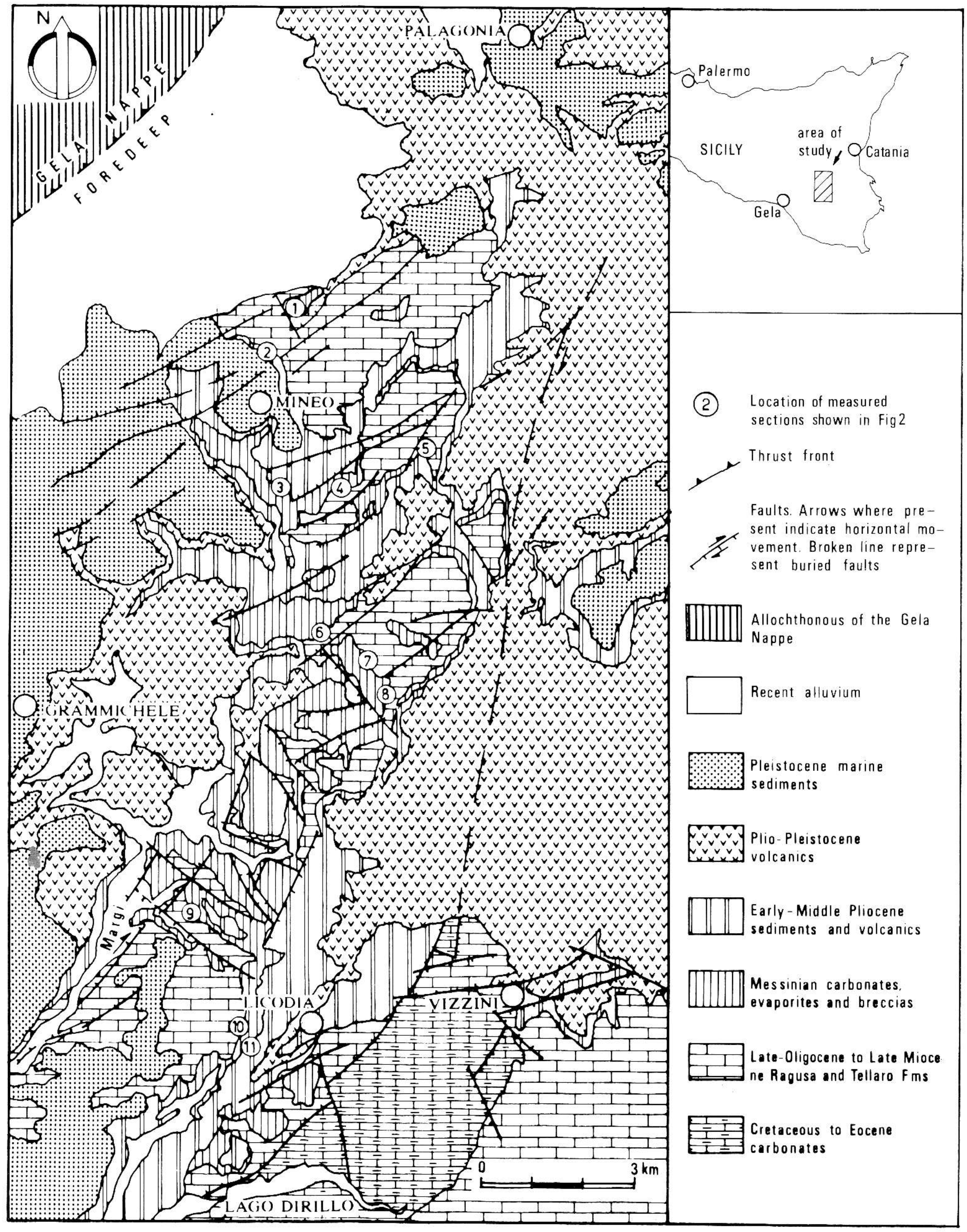

Fig. 1A - Detailed geological map illustrating the region between Palagonia, Mineo, Grammichele, Licodia Eubea and Vizzini at the northwestern margin of the Hyblean Plateau. Numbers within circles represent sampling sites of the bar columns shown on Fig. 2. Inset map (upper right) location of the study area.

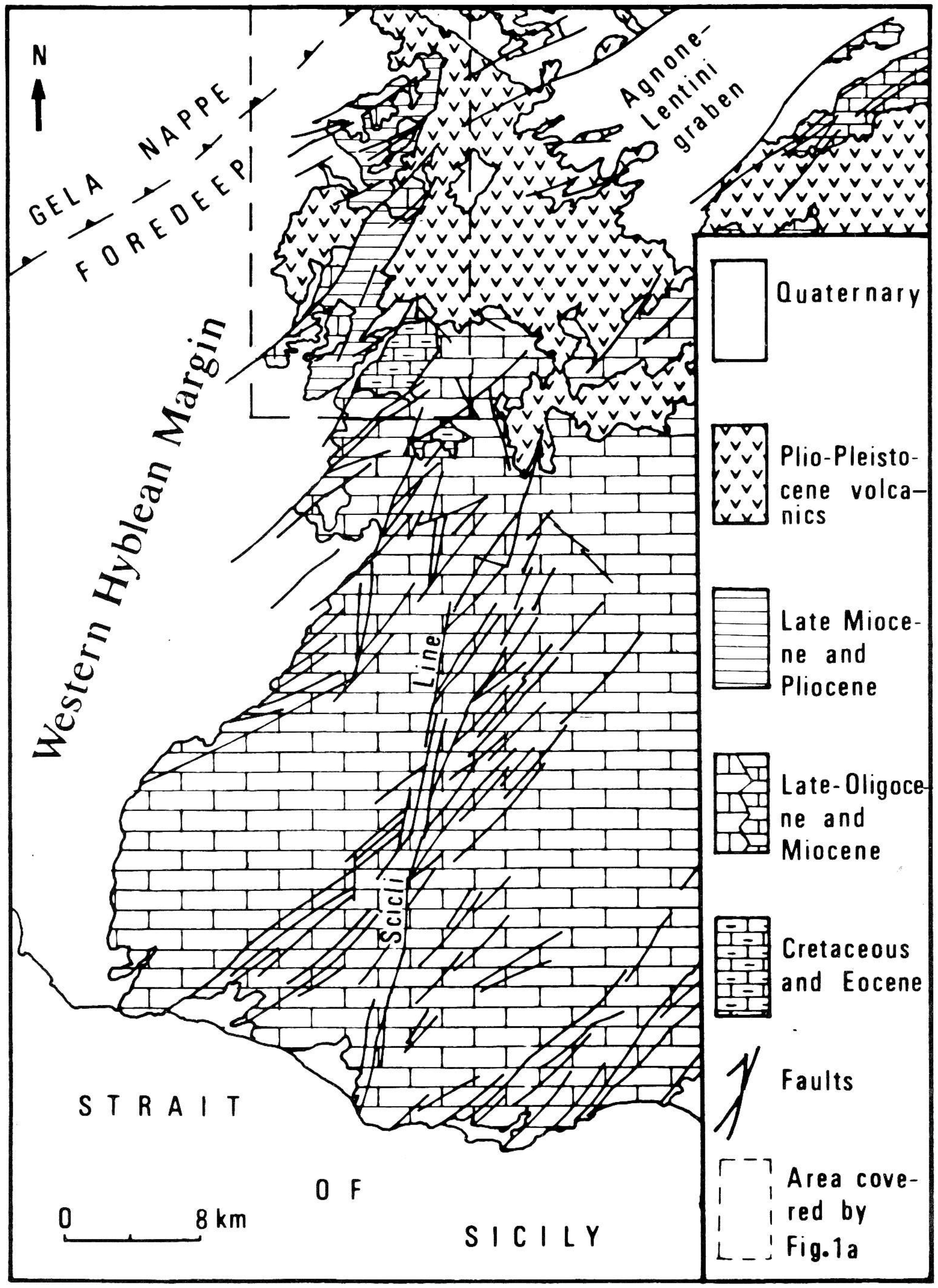

Fig. 1B - Structural map of the western Hyblean Plateau showing the study area (broken box). Note the Scicli-Ragusa-Irminio fault complex (Scicli Line) which extends northwards into the study area with its northern splaying, being in part buried beneath the Plio-Pleistocene volcanics.

lavas or volcaniclastics and are often strongly developed in the vicinity of NE-SW fault-lines.

Macrofaunas within the marls are rare, however, in the Vallone Lamia area, close to the northern margins of the Hyblean Plateau, abundant solitary corals, bivalves, gastropods, cephalopods and irregular echinoids occur. This faunal assemblage is quite similar to that described by Di Geronimo et al. (1981) for both the Maltese Blue Clays Formation and the Tellaro marls cropping out along the sea-shore areas of the southern side of the plateau facing the Strait of Sicily. These faunas are now preserved in iron oxide as a result of goethite replacement of primary shell material. The abundant planktonic microfauna indicates a Middle to Late Miocene (Serravallian to Tortonian) age for these strata (Cita, 1959; Di Grande & Romeo, 1980; this study).

Monte Carrubba Formation.

The so-called "Calcare di Base" (as referred to in previous literature) in the Mineo-Licodia Eubea areas, consists of a thin development (2-8 m) of pale yellow lime mudstones, wackestones and occasional packstones and grainstones containing a marine fauna of molluscs, echinoids, foraminifers and bryozoans.

Coralline algal debris may also be present. Peloidal and ooidal beds are locally present and indicate that, in part, the beds are of shallow water facies, although in other places they were deposited in locations deep enough to permit the influx of planktonic foraminifers. Widely distributed at the base of the beds is a metre or more of thinly laminated lime mudstone generally containing teleost fish fragments such as *Syngnathus* sp. and scattered scales. This level occasionally shows traces of vegetation (marine grass) and attached foraminifers.

Above the fish beds the sequence may be massively bedded, however, sheets of coarse grained resediments occur commonly above the erosional base and may themselves be intercalated with finer laminae showing normal grading and even groove casts such as in the lower section at Vallone Mangalavite (Fig. 2). Generally these mixed deposits are associated with soft sediment deformation, especially slumping. A Late Tortonian to Early Messinian age is ascribed to the formation (Grasso et al., 1980, 1982).

Evaporites.

Directly overlying the Monte Carrubba Formation with sharp contact occurs a thick, though localized sequence of gypsum deposits. Generally it consists of regular bedded units (5-20 cm thick) of swallow tail twin selenite crystals which have grown normal to the bedding. Locally, the total thickness is in excess of 60 m. Rare intercalated lime mudstone laminae occur, however, in a few localities (e.g. S. Nicola) and up to 8 m of gypsrudite and gypsarenite are developed at the base of the evaporite column.

No sedimentary tectonic effects have been recognized in these deposits despite them being localized into narrow corridors in the Fiume Caldo, San Nicola and Mangalavite areas. Away from these corridors evaporite deposits are virtually unknown, though the presence of occasional scattered clasts in the overlying Upper Messinian conglomerates may indicate the former presence of a thin cover over the intervening areas.

Late Messinian Conglomerates.

Well rounded oligomictic carbonate pebble and cobble conglomerates (0-15 m thick) overlie the earlier deposits unconformably. The carbonate matrix is generally loose and the resulting massive bedded and friable deposits are poorly exposed. They are associated with lenticular to thin sheet spreads (locally up to 2 m thick) of pale grey to red marls and clays containing a diagnostic freswater fauna (Congerie fauna of Cafici, 1880). This is particularly well developed at Scorciavitelli (Grasso et al., 1983) and Contrada Signorino (Fig. 2).

Collectively the beds may be considered as Late Messinian in age and appear to have developed concurrently with subaerial basic extrusives which are also well developed locally in the area.

Pliocene Sediments and Volcanics.

The earliest post-Miocene strata consist of massive bedded white lime mudstones (chalks) of the Trubi Formation (60 m thick). They contain a diverse planktonic microfauna and are extensively bioturbated by Thalassinoidean and *Chondrites* burrows systems. In the Mineo area Late Miocene conglomerates are reworked into the basal ten metres of the deposit, elsewhere there is little evidence of transportation other than local small-scale slumping. The formation is succeeded conformably by grey pelagic marls of Middle Pliocene age which were preserved locally within grabens. In other areas the full thickness of the Trubi Formation is not seen.

Submarine lavas, pillow breccias and hyaloclastites are extensively developed, in the area, being intercalated within the Pliocene succession.

Quaternary Sediments.

Whereas continuous marl and clay deposition occurred immediately to the north of Mineo (area of Catania-Gela Foredeep) the marginal Hyblean areas show a variable break in the marine record with sedimentation resuming in the Early Pleistocene. The earliest deposits, up to 120 m thick, consist of planar bedded clays and marls containing *Hyalinea baltica* and *Arctica islandica*, together with a diverse mollusc and foraminifer association (Amore et al., 1984). These strata pass transitionally up to palaeoslope. Time-equivalent, Early Pleistocene, grainstones and packstones with a shallow water pectinid dominated molluscs and algal-bryozoan fauna (Di Geronimo et al., 1982) cap the faulted Tertiary hills around Mineo and Grammichele within a thin (<10 m thick) irregular bedded succession. In the vicinity of Grammichele the planar bedded silts, sands and clays become clay dominated and contain a bathyal thanatocoenosis (Di Geronimo, 1979) dominated by deep water coral banks and molluscs.

A considerable amount of resedimentation is developed in channels on the NW slopes of Mineo hill. Here, coarse bioclastic grainstones and mud-clast conglomerates occur in lenses within contemporaneous dark-grey deep-marine clays and marls. These are related to the argillaceous succession widespread farther west in the Grammichele area.

Structural Setting.

The present tectonic setting of the western and northwestern Hyblean margin is characterized by approximately N-S trending and NE-SW trending faults. The principal complex of the region is the Scicli-Ragusa-Irminio system, which transects the western part of the Hyblean Plateau (Fig. 1B). In detail this system (also known as the "Scicli Line") is composed of N-S oriented segments displaying dextral strike-slip motion (Ghisetti & Vezzani, 1981) on recent fault scarps. Collectively, these faults comprise a complex Riedel shear system (Fig. 1B).

The northernmost extension of this system is concealed beneath Plio-Quaternary volcanics, however, water borehole data demonstrate a persistant downthrow to the east along the inferred position of the Scicli-Ragusa-Irminio Fault. Elsewhere, this partly exposed area is characterized by splayed branch faults and these as well as the master faults flanking the graben developments will be discussed later.

A further NNE-SSW trending fault system, is developed north and west of Comiso along the extreme western margin of the Plateau. It extends from Chiaramonte to Licodia Eubea (Autori vari, Carta Geologica della Sicilia Sud-Orientale, 1984) cutting Miocene and Pliocene sediments and volcanics en route. This system is intersected by NE-SW trending faults to produce a "basin and range" topography. Collectively this fault set gives rise to a complex system of feather structures in the associated transtensional zones.

Transpressive structures dominate between Licodia Eubea and Vizzini. These consist of folds which have developed sub-parallel to the main faults. Incipient thrust faults characterize the belt of convergence between the obliquely orientated NNE-SSW and the NE-SW structures.

The northern margin of the Hyblean Plateau near Mineo is truncated by a further development of the NE-SW trending faults which here have produced a northerly downstepped margin to the plateau. A collapsed foreland area now deeply buried beneath Quaternary deep water marls and clays separates the plateau from the outcropping front of the Gela Nappe. This nappe is a thrust-fold wedge which commenced migration southwards in the Late Miocene and arrived at its present location during Early Pleistocene times (Di Geronimo et al., 1979; Lentini, 1983: Argnani, 1989; Bianchi et al., 1989). It represents the most external segment of the Maghrebian thrust belt in southern Sicily.

Tertiary volcanics are ubiquitous along the northern margin of the Hyblean Plateau (see Fig. 1A). Activity commenced in the Late Tortonian and continued un-

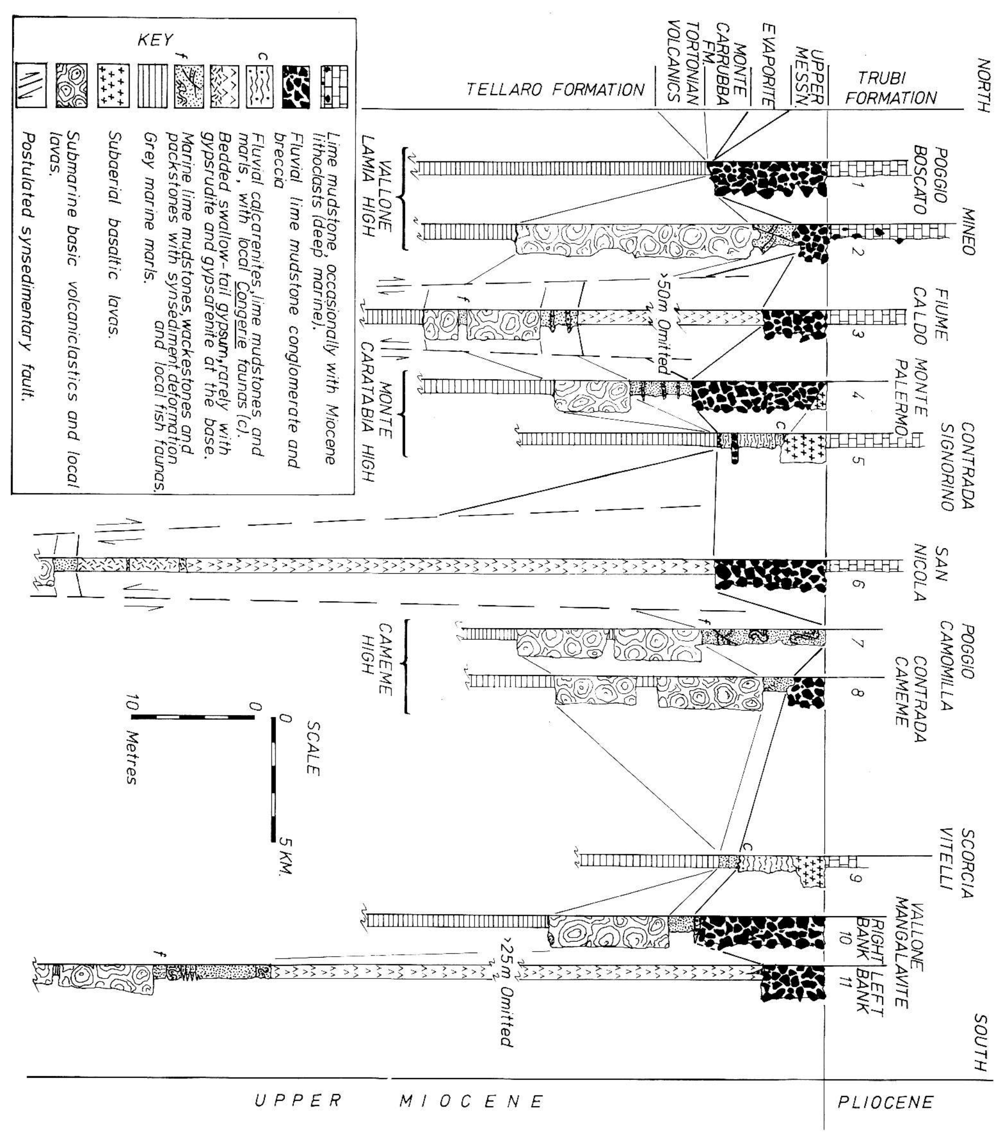

Fig. 2 - Bar columns illustrating the correlation of the Neogene succession in the NW margins of the Hyblean Plateau. Of particular note is the relatively constant thickness of the Monte Carrubba Formation across the region which developed on a seafloor levelled by Tortonian submarine volcanics. The principal horst and graben phase followed shortly afterwards. Note the absence of evaporites on the synsedimentary horst blocks and exceptional thicknesses of "swallow- tail" gypsum confined within the narrow grabens. Note also the intercalation of the Congerie beds within the fluviatile Upper Messinian conglomerates.

abated until Early Pleistocene times. These mafic volcanics are mainly composed of submarine lavas. Extrusive point sources are uncommon, the majority of eruptions being associated with fissures. The sources are generally aligned parallel to the prevailing tectonic trends (NE-SW or NNE-SSW) with larger major extrusive piles at the intersection of these trends. Eruptive centres in this region have remained dormant or have become extinct since Early Pleistocene times.

Structure-Sediment Interrelationships.

The significant local variations in formation thicknesses over the area under consideration are interpreted as being the product of synsedimentary tectogenesis. The earliest manifestations of this appear during Late Burdigalian or Langhian times (upper part of the Ragusa Formation) in the form of low amplitude undulations of the sea floor. These were later to develop into the NE-SW oriented horst and graben structures referred to in the structure section.

In the following account the interplay between local sedimentation and tectonics will be explored as the former provides a very precise record of the timing of these tectonic events.

Ragusa and Tellaro Formations.

Thickness variations of the Ragusa Formation (Fig. 3A) and Tellaro Formation (Fig. 3B) demonstrate the pronounced development of NE-SW structural control. Thicknesses of the Ragusa Formation (400 m in central and western region of the Hyblean Plateau, according to Rigo & Barbieri, 1959; Rigo & Cortesini, 1961) are here much tinner and more variable.

The NE-SW oriented structural control continues into the Middle Miocene with persistent thinning around Mineo but with two further areas 3 km and 5 km south where the Tellaro Formation thins to 50 m (Fig. 3 B). These areas of thinning appear to have been associated with seafloor bulging rather than faulting. The intervening lows received up to 150 m of marl deposition. Some of the "thinning" about the NE-SW bulges is undoubtedly due to local erosion, as interformational contacts here are often sharp (e.g. Ragusa-Tellaro contact at Poggio Boscato in Fig. 4). Allogenic glauconite and phosphorite clasts are also unusually abundant in association with the NE-SW oriented areas of seafloor cambering.

The first manifestation of volcanicity in the region occurred towards the end of Tellaro Formation deposition (Cristofolini, 1967, 1969; Di Grande, 1969). Vents and feeder dykes can be seen to follow the same NE-SW tectonic trends which controlled sedimentation. In particular, the hinge zones between maximum and minimum thickness in Fig. 3A, B are favoured sites for intrusion. This is well illustrated in Fig. 4 which also shows the abrupt thickness change within the Tellaro Formation from the graben zone south of Poggio Boscato to the horst zone to the north.

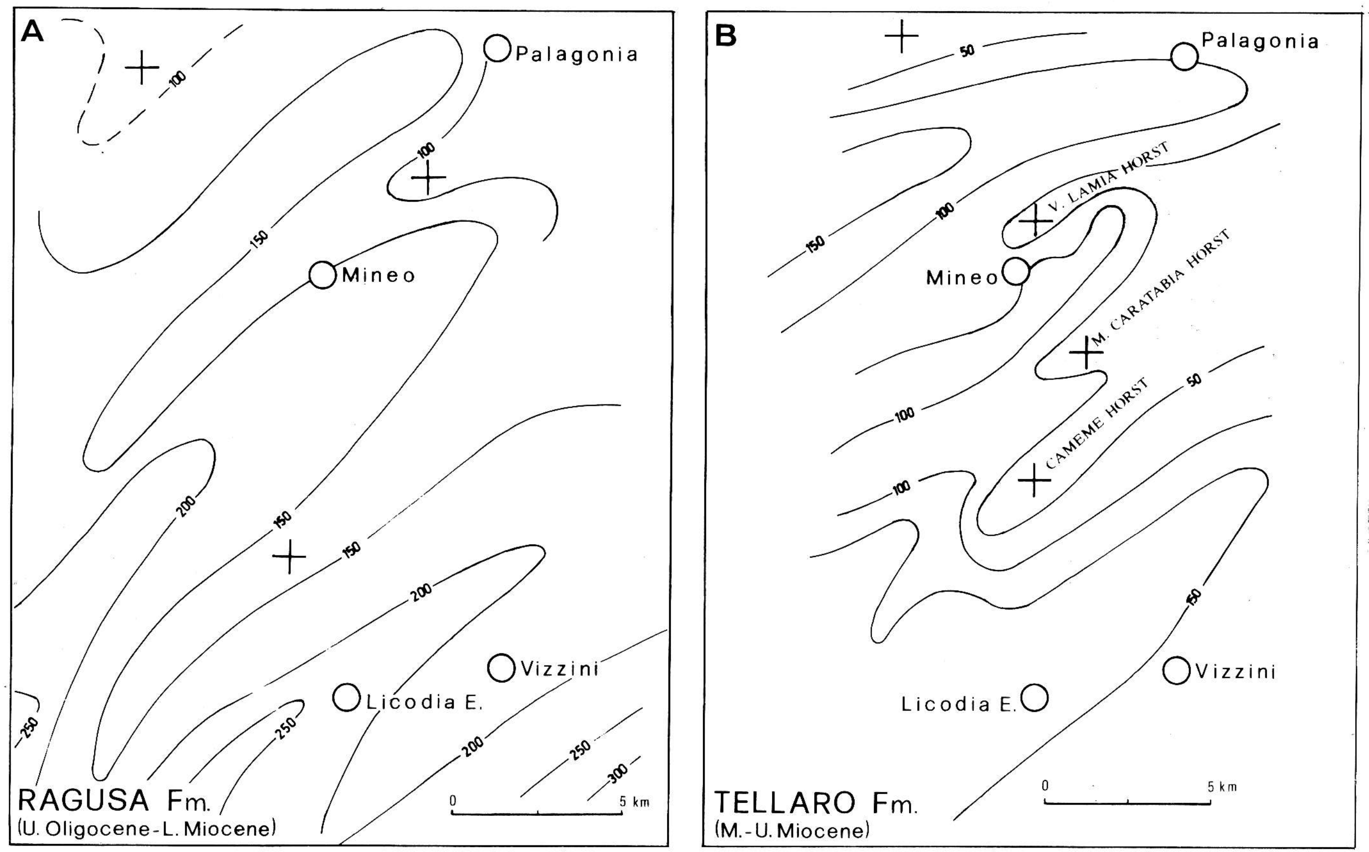

Fig. 3 - A) Isopachyte map of the Ragusa Formation (values in metres). Note the broad NE-SW trend of the contours with marked thinning over what will later develop into horst blocks.
B) Isopachyte map of the Tellaro Formation (values in metres). The greater irregularity of contour flexures compared with 3A emphasizes deeper fault movement yet to penetrate the sea-floor. Already the three incipient horst areas are identifiable, namely, the Vallone Lamia, Monte Caratabia and Cameme structures.

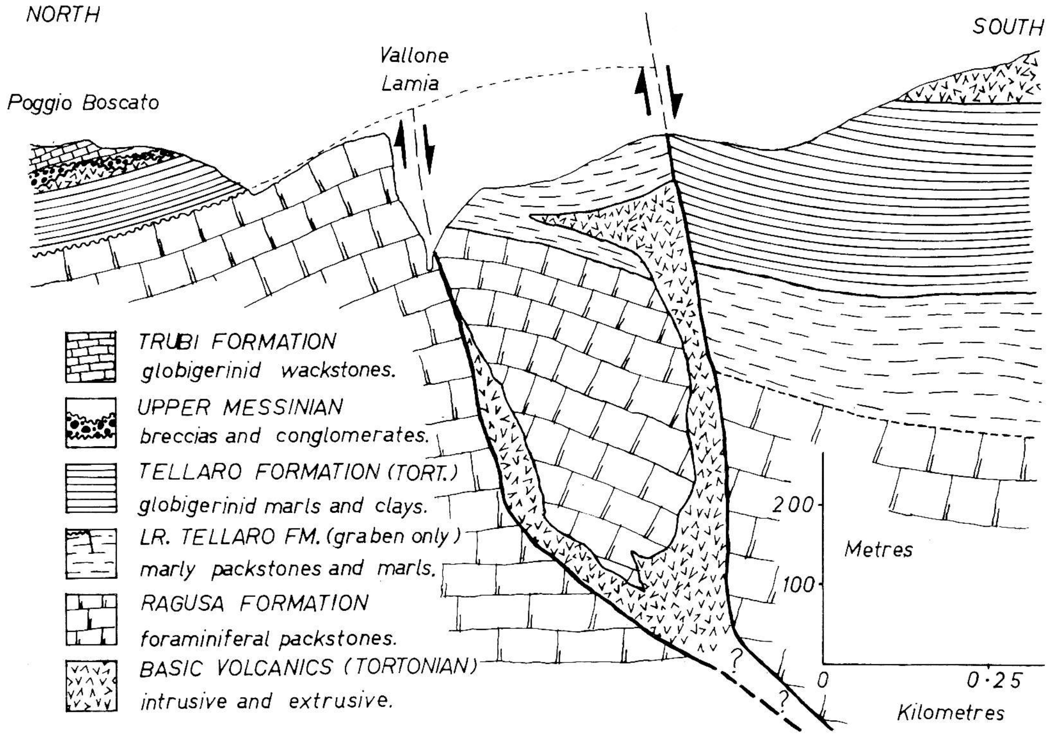

Fig. 4 - Line profile (drawn from photographs and fields sketches) south from Poggio Boscato to illustrate the mode of emplacements of Tortonian dykes along NE-SW trending fractures. These faults developed further during the Early Messinian to produce the SE boundary fault of the Vallone Lamia horst. Tortonian movement along the fault is demonstrated here by the thinner marl sequence of Poggio Boscato when compared with the full succession half km to the south. Here an additional lower interval occurs, consisting principally of allogenic packstones and marls, derived by erosion, from the Poggio Boscato area, lying to the north.

Monte Carrubba Formation.

Bed thicknesses remained fairly constant across the entire study area indicating that seafloor relief had effectively been levelled by the volcanic episodes which terminated the Tellaro Formation. Nevertheless, the abundant gravity-flow phenomena in the Monte Carrubba Formation carbonates testify to renewed tectonic activity with small-scale synsedimentary faulting (displacements less than 1 m) especially along the incipient hinge line around Mineo and Poggio Camomilla (Fig. 2). Field relationships show that larger displacements were developing towards the close of deposition. Intertidal ooidal and oncoidal sedimentation developed on NE-SW oriented horst blocks centred on Mineo and to the south at Monte Palermo, whereas the developing grabens accumulated wackestone lithologies. The thicker development of the formation at Vallone Mangalavite (Fig. 2, left bank section) contains both calciturbidites and debris flow deposits derived from the SE. This was the fastest developing basin of the area.

Evaporites.

The Messinian evaporite phase developed synchronously with major NE-SW horst and graben development. Thick evaporites developed within the local graben corridors whereas non-deposition typified the horst block palaeohighs.

The detailed interrelationship between evaporite corridor and palaeohigh is well demonstrated in the S. Nicola and Poggio Camomilla sections. The two sections are a little over 1 km apart, yet despite a closely comparable Monte Carrubba succession at both sites the former exhibits 60 m of evaporites below the Upper Messinian continental conglomerates whereas the latter contains no evidence of former evaporite development. Instead, synsedimentary faulting has produced a marked cambering of the shoulder of the hill and much of the bedding is distorted by synsedimentary slumping. The S. Nicola evaporite deposits now lie some 125 m lower in elevation than the top of Monte Carrubba Formation at Poggio Camomilla.

The virtual absence of carbonate contaminants within the evaporite succession, argues strongly against evaporite formation in deep depressions but rather suggest constant subsidence of the corridors which effectively kept pace with evaporite precipitation. Furthermore, there is no indication of evaporite beds thinning towards the corridor margins which might be expected if the basin was already formed prior to the onset of precipitation.

In conclusion it is believed that the evaporite beds formed by direct precipitation within the partly enclosed corridors of a desiccating marine basin. The final thickness of evaporites was determined by the amount of subsidence affecting the grabens, though actual topographic relief between corridors and palaeohighs need never have been great.

Fig. 5 depicts the hypothetical sequence of events leading to the development of the corridors. The lower profile depicts Tortonian lava intrusions along incipient fault planes and associated sea-floor extrusive followed by deposition of beds of Monte Carrubba Formation (stipples). The middle profile illustrates the evaporite phase with precipitation (inverted V and dots symbols) keeping pace with fault movement. The upper profile shows the Late Miocene terrestrial episode which effectively levelled the landscape. Late Messinian volcanics (+ symbols) gained access to the surface locally along the old faults, suggesting continuing movement. Local topographic depressions were occupied by small standing bodies of freshwater containing characteristic Congerie faunas.

Plio-Quaternary.

To some extent the reconstruction of the Plio-Quaternary environment is more difficult than earlier formations as there has been extensive erosion of the NW plateau margin, especially at the close of Early Pleistocene times. In particular, valley incision has left both the Pliocene Trubi Formation and the Quaternary coastal deposits as isolated hill capping (Fig. 6). The Early Pliocene Trubi Formation effectively levelled the Late Miocene terrains in the Mineo-Licodia area though there is little evidence for the Early Pliocene transgression extending much further east than Scicli-Ragusa-Irminio Fault. The deep water Trubi chalks are incompletely preserved in the region, though a

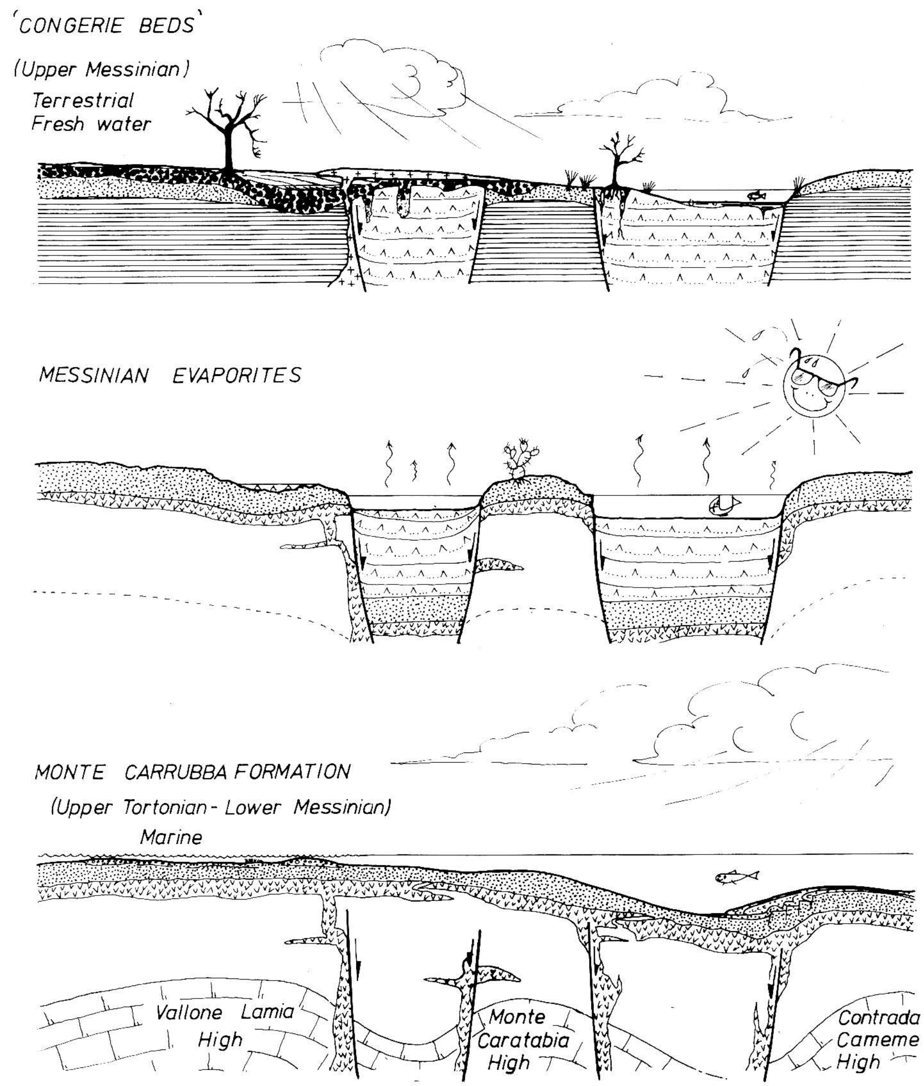

Fig. 5 - Paleoenvironment reconstructions for the Late Miocene deposits. *Monte Carrubba Formation* (Late Tortonian-Early Messinian). Incipient movement on the horst flank faults creating sediment instability and slumping on the "Camene High" flanks and development of shallow water deposits on the crest of the "Vallone Lamia High". The fault planes provided zones of weakness along which the Tortonian dykes were injected (random V symbols). Tortonian marls are unshaded. Other symbols as on Fig. 3.

Messinian Evaporites (Early Messinian). The graben development kept place with evaporite deposition. Extreme aridity prevented major subaerial erosion of the Monte Carrubba Formation (stippled). Symbols as for lower profile.

Congerie Beds (Late Messinian). Temporary cessation of the graben development and onset of humid fluvio-lacustrine conditions associated with the Late Messinian conglomerates and Congerie beds (black block symbol and cross bedding). These lie on an irregular erosion and dissolution surface affecting earlier deposits.

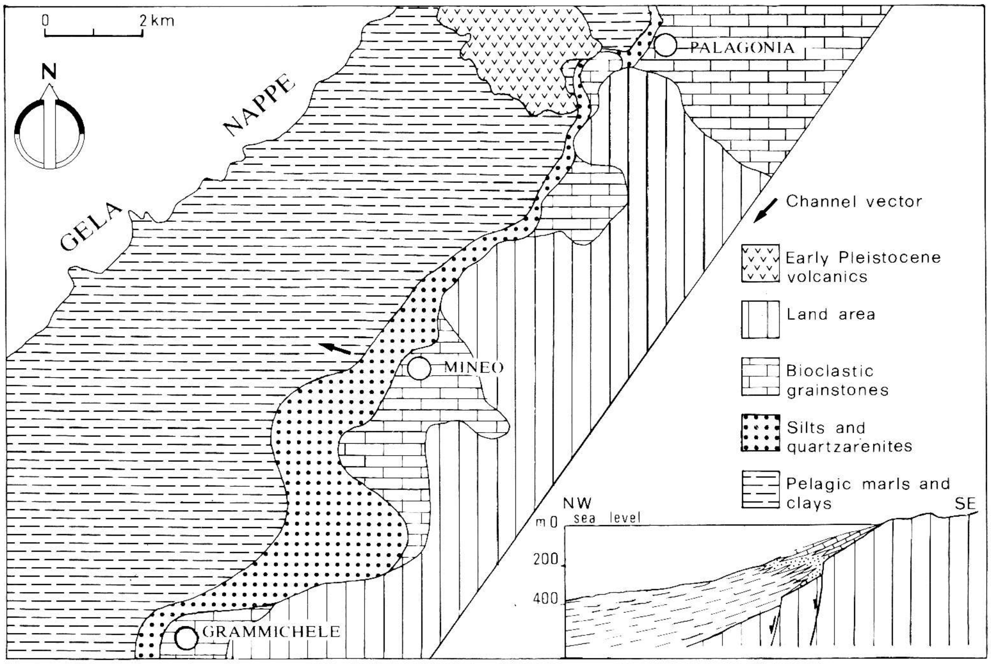

Fig. 6 - Sketch map of the Quaternary lithofacies of the Palagonia-Mineo-Grammichele zone along the NW Hyblean margin. The preserved strata represent a regressive succession which spanned Early Pleistocene times. The deep water marls and clays with *Hyalinea baltica* of the Pleistocene foredeep pass transitionally landwards into arenaceous silts and sands containing *Arctica islandica*. The youngest beds consist of shallow water coarse bioclastic carbonates marking a rapid shallowing of the environment and subsequent emergence (intrapleistocene tectonic phase). This was associated with extensive downslope resedimentation now occupying channel sites.
Inset profile: reconstruction of the Early Pleistocene depositional environment along a NW-SE line, through the town of Mineo and extending northwest into the north plain (foredeep zone). Note the rapid northwesterly increase in inferred Pleistocene water depths.

full sequence together with Middle Pliocene pale-grey marls is preserved in the graben between the Vallone Lamia and Monte Caratabia horst, thus indicating continuing Pliocene development of this structure.

Plio-Pleistocene basic lavas occupy most of the northern Hyblean area (Fig. 1) and conceal in part the Scicli-Ragusa-Irminio dextral wrench system. A series of deep water clays, marls and sands is banked against the landmass along a north-south line passing through Mineo. This contrasts with the usual NE-SW oriented coastline of more eastern areas (Fig. 1, 6).

It would appear, therefore, that the Margi wrench system continued to function as a basinal boundary fault until Early Pleistocene times.

Rapid uplift occurred towards the close of the Early Pleistocene (c. 550 m around Mineo up to over 750 m westwards near Grammichele) and probably uplift continues until recent times.

Tectonic Mechanism.

The geometrical solution to the structural style of the NW Hyblean Plateau margin (Fig. 7) is illustrated as an inset (lower left, A). The inset illustrates a buttress zone which is flanked by two major transfer faults. The most easterly transfer fault is represented by the northern extension of the Scicli-Ragusa-Irminio Fault (see also Fig. 1B), a dextral strike-slip fault (Ghisetti & Vezzani, 1981) which has recorded a complex history of movement commencing in Late Miocene times (Grasso et al., 1986).

The sub-parallel western transfer fault system is represented in the south of Fig. 7 as the Margi Fault. It extends as en échelon fracture system as far north as Mineo town. This fault system is the northern extension of the Acate River Line (see Ghisetti & Vezzani, 1981) which extends south to the Strait of Sicily.

Such an active mechanism (see lower left inset B in Fig. 7) as demonstrated by Crowell (1974), Rodgers (1980), Mann et al. (1983) and several other authors, creates a zone of transtension associated with feather edges or pull-apart grabens. Southwards, due to the crooked course of the fault pattern, a zone of transpression is created which is associated with folding, thrusting and uplift.

The predictive model agrees well with the observed geology. The transtentional zone is associated with the Vallone Lamia, Monte Caratabia and Cameme horst and complimentary grabens. The transpressive zone lies south of the secondary Mangalavite fault and is manifest in the Licodia syncline which also hosts evaporites, and in the Monte Boschitello anticline.

Discussion.

Significantly, the deformation of this northwestern marginal area of the Hyblean Plateau was concurrent with the onset of the main rifting phase in the Strait of Sicily (Illies, 1981; Finetti, 1982; Reuther & Eisbacher, 1985; Boccaletti et al., 1987; Pedley, 1989; Reuther, 1989). Available seismic profiles examined during the present study from offshore southeastern Sicily confirm the southerly continuation of the described major tectonic lines, namely the Scicli-Ragusa-Irminio line and western margin boundary faults, into the rift zone of the Sicily Strait. These faults roughly separate the rigid Malta-Hyblean Shelf from the submerged rifted area to the west.

It is suggested that rift progression in the Pantelleria Rift zone was responsible for the activation of northwestern Hyblean deformation. Accompanying mafic volcanicity was almost continuous from Late Miocene to Early Pleistocene times. Focal centres for this were located at the intersection points between the wrench faults and associated tensional faults (Grasso et al., 1986). Consequently, the greatest volumes of extruded magma occur in the study area, as this was the area of maximum transtension and crustal break-up.

Further to the north, beyond the study area, occurs the Gela Nappe (partly present in the north of Fig. 1A, B and 7). The nappe front makes a major northwards de-

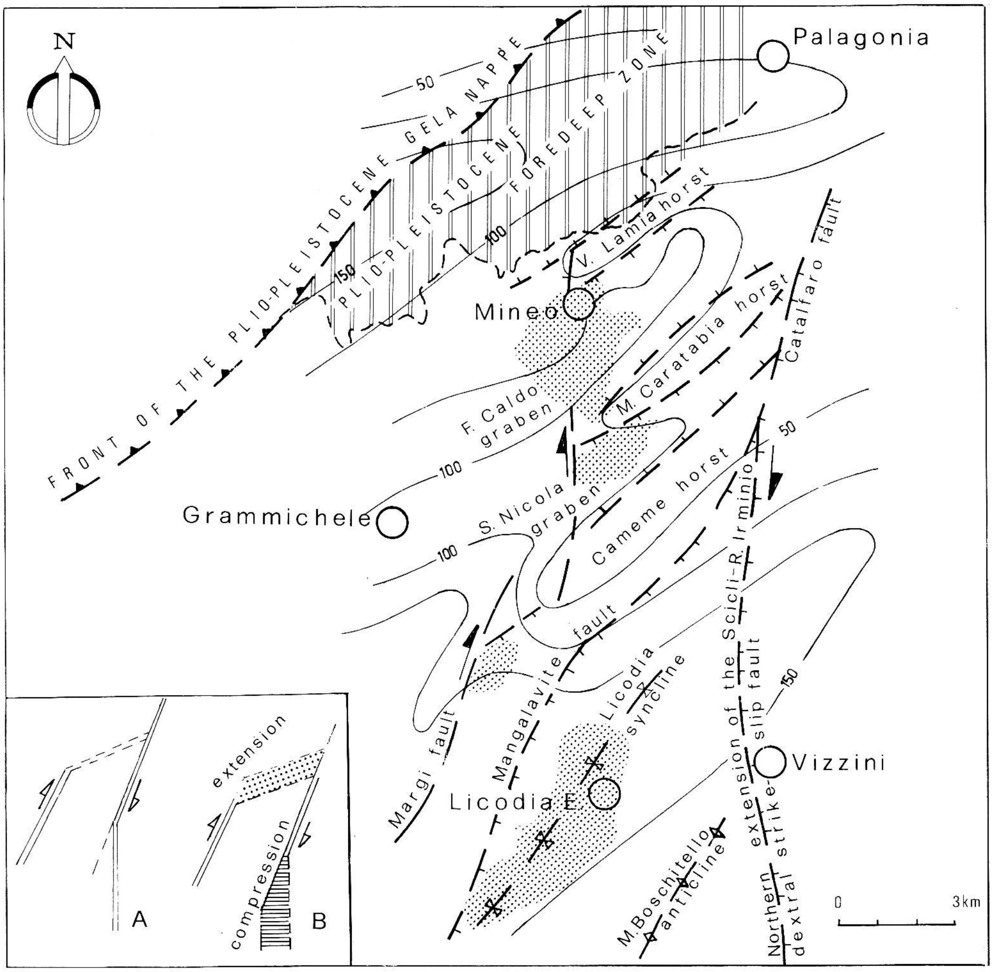

Fig. 7 - Tectonic sketch map of the NW margin of the Hyblean Plateau with the principal horst blocks and faulting named. The isopachyte map of the Tellaro Formation (Fig. 3 B) is superimposed upon this in order to illustrate the close interrelationships between synsedimentary horst movement and sediment thickness variation. Note also the distribution of evaporite deposits (stipple symbol) which are entirely confined to the inter-graben areas.

Between Licodia and Vizzini synsedimentary drag folds developed which permitted a further thick evaporite accumulation along the negative fold axis (Licodia syncline).

Isopach values in the Plio-Pleistocene foredeep zone north of Mineo, indicate further developments of the "Basin and Range" morphology during the Late Miocene. The present day thrust fold wedge (the Gela Nappe) superimposed over the earlier "basin and range" morphology and the modern location of the Plio-Pleistocene foredeep zone, emphasize the southerly migration of the Maghrebian Chain (at least 10 km during the last 5 MA) with its resulting consumption of the marginal areas of the foreland. The inset tectonic solution (lower left) demonstrates how the symultaneous extension and compression has occurred as the result of dextral wrenching along the Margi Fault system and the Scicli-Ragusa-Irminio Fault system. *A* represents a period immediately prior to movement; *B* represents a period after movement had commenced.

flection on encountering the Hyblean Plateau before subsequently turning again in both inland and offshore areas, west of the Hyblean Plateau. The northwards continuation of the plateau at shallow depth in the subsurface beneath the nappe, can be followed for over 10 km beyond its outcropping northern margin (Bianchi et al., 1989). In contrast those areas of the Pelagian Block west of the Hyblean Plateau are deeply underthrusted as demonstrated in the Gela oilfield and related offshore areas (Rocco, 1959; Pacchiarotti, 1986; Antonelli et al., 1988). Clearly, the two areas exhibit significantly different rheological behaviours.

The most buoyant parts of the crust (i.e. the Hyblean Plateau) might be expected to resist downbending and deep burial. They would become separated from areas of more rapid underthrusting along zones of crustal failure acting as transform faults of pivotal aspect. The described dextral wrench system of the western Hyblean margins are believed to represent one such zone (Grasso et al., 1986; Grasso & Reuther, 1988; Grasso et al., 1990). The reasons behind the enhanced buoyancy of the Hyblean Plateau are not clear but may be a manifestation of greater crustal thickness than areas to the west (Ben Avraham & Grasso, 1990).

Finally, the exceptionally high rates of post Early Pleistocene uplift along the northern margin of the Hyblean Plateau must be explained. Actual maximum amount of uplift (up to 800 m near Grammichele) have been calculated from the Pleistocene lithofacies (see Di Geronimo, 1979; Di Geronimo et al., 1982; Amore et al., 1984 for faunal details). Loading of the thin Gela Nappe cover on the modern foredeep zone, north of the studied area (no more than 1000 m thick according to Bianchi et al., 1989) is considered too little by itself to have caused sufficient peripheral bulging to account for this uplift. If, however, there was crustal weakening during the Late Miocene-Pleistocene tectonic extension in the northern margin of the Plateau, by concurrent sub-crustal erosion associated with the ascending of the magma, this might be sufficient to damage the crust and thus enhance the loading effect of the overriding Gela Nappe.

Thus sufficient bulging could have been induced to account for the observed uplift.

Acknowledgements.

The authors are pleased to acknowledge financial support from M.P.I. (grants 60% n. 20120131/87; 40% n. 20120226/87) and C.N.R. Bilateral Project grant n. 8700900-05. In addition HMP is pleased to acknowledge a grant from the European Scientific Exchange programme. Finally, the authors thank Prof. F. Lentini for presenting the paper to the R.C.M.N.S. interim colloquium on "*Neogene paleogeography of the western Mediterranean: Problems related to the palinspastic reconstruction*, held in Gargnano, 27th - 29th October 1988.

REFERENCES

Amore C., Casale V., Costa B., Di Geronimo I., Giuffrida E. & Zanini A. (1984) - Evoluzione sedimentologica e faunistica dei sedimenti pleistocenici di Poggio Spica (Mineo, Catania). *Boll. Soc. Geol. Ital.*, v. 103, n. 4, pp. 755-786, 7 fig., 7 tab., Roma.

Antonelli M., Franciosi R., Pezzi G., Querci A., Ronco G. P. & Vezzani F. (1988) - Paleogeographic evolution and structural setting of the northern side of the Sicily Channel. *Proc. 74th Congr. Soc. Geol. Ital.*, pp. 79-86, Sorrento.

Argnani A. (1989) - The Gela Nappe: evidence of accretionary melange in the Maghrebian foredeep of Sicily. *Mem. Soc. Geol. Ital.*, v. 38 (1987), pp. 419-428, 7 fig., Roma.

Autori vari (1984) - Carta Geologica della Sicilia sud-orientale. Map scale 1:100.000, S.El.Ca., Firenze.

Ben Avraham Z. & Grasso M. (1990) - Collisional zone segmentation in Sicily and surrounding areas in the Central Mediterranean. *Ann. Tectonicae* (in press), Firenze

Bianchi F., Carbone S., Grasso M., Invernizzi G., Lentini F., Longaretti G., Merlini S. & Mostardini F. (1989) - Sicilia orientale: profilo geologico Nebrodi-Iblei. *Mem. Soc. Geol. Ital.*, v. 38 (1987), pp. 429-458, 1 pl., 8 fig., Roma.

Boccaletti M., Cello G. & Tortorici L. (1987) - Transtensional tectonics in the Sicily Channel. *Journ. Struct. Geol.*, v. 2, pp. 869-876, Oxford.

Cafici I. (1880) - La formazione gessosa del Vizzinese e del Licodiano (provincia di Catania). *Boll. R. Com. Geol. Ital.*, v. 11, pp. 37-54, 1 fig., Roma.

Carbone S., Cosentino M., Grasso M., Lentini F., Lombardo G. & Patanè G. (1984) - Elementi per una prima valutazione dei caratteri sismotettonici dell'Avampaese Ibleo (Sicilia sud-orientale). *Mem. Soc. Geol. Ital.*, v. 24 (1982), pp. 507-520, 6 fig., Roma.

Carbone S., Grasso M. & Lentini F. (1984) - Considerazioni sull'evoluzione geodinamica della Sicilia sud-orientale dal Cretaceo al Quaternario. *Mem. Soc. Geol. Ital.*, v. 24 (1982), pp. 367-386, 9 fig., Roma.

Cita M.B. (1959) - Stratigrafia micropaleontologica del Miocene siracusano. *Boll. Soc. Geol. Ital.*, v. 77 (1958), n. 1, pp. 71-165, 54 fig., Roma.

Cristofolini R. (1967) - Le vulcaniti plio-pleistoceniche al margine settentrionale dell'Altopiano Ibleo. *Atti Acc. Gioenia Sc. Nat. Catania*, s. 6, v. 18, pp. 265-270, 2 fig., Catania.

Cristofolini R. (1969) - Le vulcaniti del Miocene superiore e del Pliocene inferiore della zona compresa tra Mineo, Palagonia e Vizzini (Altipiano Ibleo). *Atti Acc. Gioenia Sc. Nat. Catania*, s. 7, v. 1, pp. 211-238, 3 fig., 3 tab., Catania.

Crowell J. C. (1974) - Origin of the Late Cenozoic basins in southern California. In Dott R.H. & Shaver R.H. (Eds.) - Modern and ancient geosynclinal sedimentation. *SEPM Spec. Publ.*, v. 19, pp. 293-303, Tulsa.

Di Geronimo I. (1979) - Il Pleistocene in facies batiale di valle Palione (Grammichele, Catania). *Boll. Malacolog.*, v. 15, n. 5-6, pp. 85-156, Milano.

Di Geronimo I., Ghisetti F., Lentini F. & Vezzani L. (1979) - Lineamenti neotettonici della Sicilia Orientale. *Mem. Soc. Geol. Ital.*, v. 19 (1978), pp. 543-549, 2 fig., Roma.

Di Geronimo I., Grasso M. & Pedley H. M. (1981) - Palaeoenvironment and palaeogeography of Miocene marls from Southeast Sicily and the Maltese Islands. *Palaeogeogr., Palaeoclimat., Palaeoecol.*, v. 34, n. 3-4, pp. 173-189, 4 fig., 1 tab., Amsterdam.

Di Geronimo I., Li Gioi R. & Sciacca V. (1982) - La fauna pleistocenica dell'Abbeveratoio Conzo (Grammichele, Catania). *Geol. Romana*, v. 21, pp. 577-601, 9 fig., 4 tab., Roma.

Di Grande A. (1969) - L'alternanza neogenico-quaternaria di vulcaniti e di sedimenti al margine nord-occidentale dell'Altipiano Ibleo. *Atti Acc. Gioenia Sc. Nat. Catania*, s. 7, v. 1, pp. 91-125, 11 pl., 1 fig., Catania.

Di Grande A. & Grasso M. (1979) - Lineamenti geologici del margine occidentale ibleo nei dintorni di Comiso-Ragusa. *Boll. Soc. Geol. Ital.*, v. 96 (1977), pp. 209-224, 1 pl., 8 fig., Roma.

Di Grande A., Grasso M. & Romeo M. (1977) - Stratigrafia dei terreni affioranti nei dintorni di Ragusa. *Riv. Ital. Paleont. Strat.*, v. 83, n. 1, pp. 137-178, 5 pl., 8 fig., Milano.

Di Grande A. & Romeo M. (1980) - Caratteri lito-biostratigrafici dei depositi messiniani nell'area iblea (Sicilia sud-orientale). *Riv. Ital. Paleont. Strat.*, v. 86, n. 4, pp. 855-916, 18 fig., Milano.

Finetti I. (1982) - Structure, stratigraphy and evolution of Central Mediterranean. *Boll. Geofis. Teor. Appl.*, v. 24, pp. 247-312, Trieste.

Ghisetti F. & Vezzani L. (1981) - The structural features of the Iblean Plateau and of the Mount Judica area (South-Eastern Sicily): a microtectonic contribution to the deformational history of the Calabrian Arc. *Boll. Soc. Geol. Ital.*, v. 99 (1980), n. 1-2, pp. 57-102, 29 fig., Roma.

Grasso M., De Dominicis A. & Mazzoldi G. (1990) - Structures and tectonic setting of the western margin of the Hyblean-Malat Shelf, Central Mediterranean. *Ann. Tectonicae* (in press), Firenze.

Grasso M., Lentini F., Lombardo G. & Scamarda G. (1980) - Distribuzione delle facies cretaceo-mioceniche lungo l'allineamento Augusta-M. Lauro (Sicilia sud-orientale). *Boll. Soc. Geol. Ital.*, v. 98 (1979), pp. 175-188, 1 pl., 9 fig., Roma.

Grasso M., Lentini F., Nairn A.E.M. & Vigliotti L. (1983) - A geological and paleomagnetic study of the Hyblean volcanic rocks, Sicily. *Tectonophys.*, v. 98, pp. 271-295, 8 fig., 2 tab., Amsterdam.

Grasso M., Lentini F. & Pedley H. M. (1982) - Late Tortonian-Lower Messinian (Miocene) palaeogeography of SE Sicily: information from two new formations of the Sortino Group. *Sediment. Geol.*, v. 32, pp. 279-300, 6 fig., Amsterdam.

Grasso M. & Reuther C.D. (1988) - The western margin of the Hyblean Plateau: a neotectonic transform system on the SE Sicilian foreland. *Ann. Tectonicae*, v. 2, n. 2, pp. 107-120, 8 fig., Firenze.

Grasso M., Reuther C. D., Baumann H. & Becker A. (1986) - Shallow crustal stress and neotectonic framework of the Malta Platform and the Southeastern Pantelleria Rift. *Geol. Romana*, v. 25, pp. 191-212, 8 fig., 1 tab., Roma.

Illies J. H. (1980) - Form and formation of graben structures: the Maltese Islands. In Closs H., Gehelen K. V., Illies J. H., Kuntz E., Neumann J. & Seibold E. (Eds.) - Mobile Earth, pp. 161-184, Boppard, Boldt.

Illies J. H. (1981) - Graben formation - The Maltese Islands - a case history. *Tectonophys.*, v. 73, pp. 151-168, 10 fig., Amsterdam.

Lentini F. (1983) - The geology of the Mt. Etna basement. *Mem. Soc. Geol. Ital.*, v. 23 (1982), pp. 7-25, 11 fig., Roma.

Lentini F., Grasso M. & Carbone S. (1987) - Introduzione alla geologia della Sicilia e guida all'escursione. *Conv. Soc. Geol. Ital.* su: Sistemi Avanfossa-Avampaese lungo la Catena Appennico-Maghrebide, Naxos-Pergusa, 22-25 aprile 1987, 66 pp., Catania.

Mann P., Hempton M. R., Bradley D. C. & Burke K. (1983) - Development of pull-apart basins. *Journ. Geol.*, v. 91, pp. 529-554, Chicago.

Pacchiarotti E. (1986) - Attività di ricerca di idrocarburi nei mari italiani. *Mem. Soc. Geol. Ital.*, v. 27 (1984), pp. 287-301, 13 fig., Roma.

Pedley H. M. (1981) - Sedimentology and palaeoenvironment of the southeast Sicilian Tertiary

platform carbonates. *Sediment. Geol.*, v. 28, pp. 273-291, 1 pl., 4 fig., 1 tab., Amsterdam.
Pedley H. M. (1989) - Controls on Cenozoic carbonate deposition in the Maltese Islands: review and reinterpretation. *Mem. Soc. Geol. Ital.*, v. 38 (1987), pp. 81-94, 9 fig., Roma.
Reuther C. D. (1989) - Extensional tectonics within the Central Mediterranean segment of the Afro-European zone of convergence. *Mem. Soc. Geol. Ital.*, v. 38 (1987), pp. 69-80, 6 fig., 1 tab., Roma.
Reuther C. D. & Eisbacher G. H. (1985) - Pantelleria Rift: crustal extension in a convergent intraplate setting. *Geol. Rundsch.*, v. 74, n. 3, pp. 585-597, 6 fig., Stuttgart.
Rigo M. & Barbieri F. (1959) - Stratigrafia pratica applicata in Sicilia. *Boll. Serv. Geol. Ital.*, v. 80 (1958), n. 2-3, pp. 351-441, 14 pl., 10 fig., Roma.
Rigo M. & Cortesini A. (1961) - Contributo alla conoscenza strutturale della Sicilia sud-orientale. *Boll. Serv. Geol. Ital.*, v. 81, n. 2-3, pp. 349-369, 5 pl., Roma.
Rocco T. (1959) - Gela in Sicilia. Un singolare campo petrolifero. *Riv. Min. Sicil.*, v. 10, pp. 167-188, Palermo.
Rodgers D. A. (1980) - Analysis of pull-apart basin development produced by en-échelon strike-slip faults. In Ballance P. F. & Reading H. G. (Eds.) - Sedimentation in oblique-slip mobile zones. *Spec. Publ. Int. Assoc. Sediment.*, v. 4, pp. 27-41, Oxford.