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Controls on Plio-Quaternary foreland sedimentation in the Region of the Maltese Islands

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ABSTRACT

Plio-Quaternary sediments on the southern foreland of the orogen produced by African-Eurasian plate convergence vary in thickness from >1km in foreland basin and rift graben depocentres to metre-thick deposits over platform environment where depositional hiatuses merge along widespread subaerial surfaces around the Maltese Islands. The syntectonic sedimentation is the result of three episodes: (i) The development of the Pantelleria Rift south of the Maltese Islands by passive rifting, which became the main depocentre for Lower Pliocene sedimentation until rift shoulder upwarping re-directed subaerial drainage to the NE and towards (ii) the evolving Pliocene Gela foredeep in the NW. (iii) Tectonic uplift and erosion diminished over the Malta region during the Quaternary, gradually increasing the preservation of sediments.

Pleistocene sedimentation was controlled by palaeoclimatic fluctuations and accompanying glacio-eustatic sea level changes, ending in seasonal arid climatic conditions. The flooding of the Maltese shelf during the Holocene deposited transgressive sand and gravel directly over Tertiary carbonates. Post-transgressive carbonate sedimentation is controlled by the distal location of the shelf within non-tropical and oligotrophic nutrient conditions that allow moderate to low carbonate production along most of the shelf area down to >50m water depth. The geographical variations in the content of metastable carbonates within biogenic sand are related to shelf long profile and coastal lithology.

KEY WORDS: *Malta Platform, Synsedimentary tectonics, Holocene transgression, Pantelleria Rift.*

RIASSUNTO

Controlli sulla sedimentazione plio-quaternaria dell'avampaese nella Regione delle Isole Maltesi.

I sedimenti plio-quaternari dell'avampaese meridionale dell'orogene legato alla convergenza fra Africa e Eurasia presentano spessori che variano fra >1km nel bacino di avanfossa e nelle fosse di rift, e pochi metri sulla piattaforma delle Isole Maltesi, dove hiatus deposizionali passano a estese condizioni di emersione. La sedimentazione sintettonica è il risultato di tre episodi: (i) lo sviluppo del Rift di Pantelleria a sud delle Isole Maltesi che risulta il principale depocentro per i sedimenti del Messiniano e Pliocene inferiore, finché il sollevamento delle spalle del graben non ha ridiretto il drenaggio subaereo verso NE, ovvero verso (ii) il bacino Pliocenico di avanfossa di Gela posto a NO del graben di Pantelleria; (iii) nella regione maltese il sollevamento tettonico e l'erosione sono diminuite durante il Quaternario, portando ad un graduale incremento nella preservazione dei sedimenti.

La sedimentazione pleistocenica era controllata da fluttuazioni paleoclimatiche e dalle relative variazioni glacio-eustatiche del livello del mare, ed è terminata con condizioni climatiche aride e stagionali. L'inondazione della piattaforma maltese durante l'Olocene ha portato alla deposizione di sabbie e ghiaie trasgressive direttamente sopra ai carbonati terziari. La sedimentazione carbonatica post-trasgressione è controllata dalla ubicazione distale della piattaforma in un ambito di condizioni di nutrienti oligotropiche e non-tropicali che hanno consentito una moderata-bassa produzione di carbonato lungo la maggior parte dell'area di piattaforma fino a profondità dell'acqua >50m. Le variazione geografiche nel contenuto di carbonato metastabile delle sabbie biogeniche sono legate alle litologie delle aree costiere e al lungo profilo della piattaforma.

TERMINI CHIAVE: *Piattaforma maltese, sedimentazione sintettonica, Trasgressione Olocenica, Rift di Pantelleria.*

INTRODUCTION

The Central Mediterranean is an elevated >400km-wide region flanked on each side by the distinct Western and Eastern Mediterranean Basins. Sedimentation has been controlled since the Neogene by variations in the influx of Atlantic water that caused crustal unloading during desiccation events and tectonism related to the convergence of the African and Eurasian continental plates. The Maltese Islands and shelf area provide a record of eustatic and regional tectonic signals within this central region, although published works on the Maltese Tertiary succession (e.g. FELIX, 1973; PEDLEY, 1987a) have overlooked the Pliocene Epoch, primarily because these sediments are not preserved in the Maltese Islands. Following the end of the Messinian desiccation event, the re-flooded surface began to show contrasting sedimentation styles linked to the different tectonic settings evolving within the African foreland region. The Malta Area (delimited by the Malta maritime boundary shown in fig. 1a) undergoes rifting in the SW followed by uplift, and in the NW begins to show subsidence associated with the development of a foreland basin. As tectonic uplift and concomitant erosion diminished in the south Malta Area, increasing quantities of Quaternary sediment is preserved on the Maltese Islands, culminating in Holocene deposits over the flooded shelf area, about which very little has been published.

This paper attempts a comprehensive analysis by combining tectonic, glacio-eustatic and environmental controls to explain Plio-Quaternary sedimentation. Offshore depositional and bathymetric data is based on published seismic lines shown in fig. 1a, boreholes, and maps by the BRITISH ADMIRALITY (1969) and IOC-UNESCO (1981). Beach sediments are used as proxies for Recent shallow shelf sedimentation using carbonate mineralogy data by TURI *et alii* (1990). Sediment samples were gathered from 13 beaches in the Maltese Islands and assessed by point counting technique for grain size and shape using the classification by PETTIJOHN *et alii* (1987).

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GEOTECTONIC SETTING

The Maltese Islands form an emergent part of the Pelagian Block on the North African continental margin (BUROLLET *et alii,* 1978). This elevated region is bound on the east by the Malta Escarpment and on its north by the Maghrebian thrust-fold belt, developed by plate convergence and collision after the Mid-Miocene (JONGSMA *et alii,* 1985). By the Early Quaternary, the Eurasian and African plates were interlocked in Northern Sicily (PEDLEY & GRASSO, 1991). The African foreland comprises the Malta Platform on the east, a narrow foredeep in SE Sicily and the Gela Basin, which began to form since the Pliocene to the NW of the Malta Area by frontal nappe loading (ARGNANI, 1987; CATALANO *et alii,* 1993a; LICKORISH *et alii,* 1999). African foreland underthrusting was more rapid north of the Gela Basin than in the east. This stress difference developed the N-S trending Scicli transform fault (PEDLEY & GRASSO, 1991).

The Malta Platform lies mostly to the east of this strike-slip fault (fig. 1a), forming a distinctly elevated area (<–200m deep) showing positive Bouguer gravity anomalies (AGIP, 1978). The platform culminates in an asymmetric submerged N-S Ridge (<–100m deep) in the east that connects its two emergent margins: The Hyblean Plateau in SE Sicily which has evaded underthrusting, and the Maltese Islands in the south (fig. 1a). Regional NE-SW faulting has affected both emergent areas since the Miocene, forming the Ispica grabens within the Hyblean Plateau and the North Malta Graben (fig. 1b), which is interpreted by ILLIES (1981) to have initially developed by syndepositional rift uparching, resulting in local thinning of the Globigerina Limestone Formation. However, recent work by GATT (2005) shows that graben formation was preceded by faulting at the Oligocene-Miocene boundary in Malta which produced thickening of sediments in the Valletta Basin, away from the North Malta Graben.

East of Malta, a narrow neck joins the N-S Ridge to the 1 to 6km-wide shelf that surrounds the Maltese Islands. The Maltese shelf area is <–100m deep and shows a steep break in slope on its northern and southern margins, associated with the development of the Pantelleria Rift. Rifting from the Upper Tortonian to Pliocene (ILLIES, 1981; REUTHER, 1984) generated NW-SE trending synthetic faults in the S and antithetic faulting in the N of the Maltese Islands, creating the Malta Horst (fig. 1b). The horst consists of 5 Tertiary Formations shown in fig. 2a. The base of the sequence comprises shallow carbonate platform sediments (Lower Coralline Limestone Formation) overlain by pelagic carbonates (Globigerina Limestone Formation) which are sub-divided by 3 main phosphorite conglomerate beds, partly outcropping at sea level (GATT, 2005). These pure carbonates are succeeded by the Blue Clay Formation, consisting of 60-85% phyllosilicates (JOHN *et alii*, 2003).

The sequence terminates with the Upper Coralline Limestone Formation, interpreted by PEDLEY (1987a) as an eastward-facing carbonate ramp. The base of this Formation shows deeper platform sediments succeeded by wackestone facies rich in planktonic foraminifera in the east and shallowing-upward algal biostrome facies and patch reefs in the west. The Formation terminates with erosional surfaces in the west and unconformable development of peritidal facies, namely the San Leonardo bed [604 707] in the east (PEDLEY, 1978). Synsedimentary tectonism in the Late Miocene (PEDLEY, 1987a) produced the Great Fault and other parallel NE-SW trending faults (fig. 1b) that grow westward along the North Malta Graben and S Gozo. From the Quaternary onwards, the S Gozo fault (fig. 1b) was re-activated by E-W intra-plate motion, becoming a strike-slip fault with associated feather structures (ILLIES, 1981; REUTHER, 1984).

PLATFORM SEDIMENTATION

Plio-Quaternary sedimentation in the Malta Area has been controlled by glacio-eustatic sea level changes and the development of the Pantelleria Rift, resulting in prolonged depositional hiatuses on the Maltese shelf. The distal location from Sicily (95km) and the deep grabens (>1000m) along the rift zone south of the Malta Platform have mostly isolated the Maltese shelf since the Late Neogene from inputs of siliciclastic sediments from continental areas.

PLIO-PLEISTOCENE SEDIMENTS

The Early Pliocene transgression brought an inflow of Atlantic water over Messinian evaporite deposits, although euxinic conditions persisted in the basins east of the N-S Ridge. Pliocene sediments are absent on the Malta Horst and platform sediments thin to below seismic resolution (MAX *et alii,* 1993). South of the Malta Horst, >1000m-thick Plio-Quaternary deposits consisting of marls and carbonate mudstones infill the Malta Graben (DART *et alii,* 1993) within the Pantelleria Rift Zone. Associated with the rifting episode are the NW-SE fault displacements of >100m within the Magħlaq Fault Zone, which appear in Malta during the Late Tortonian-Lower Messinian (REUTHER, 1984). Syntectonic sediments exposed in the Għar Lapsi area [493 647] consist of a Messinian coral reef capped by >20m of calciturbidites sourced from Malta, that flowed in the direction of the evolving Malta Graben. The sequence is terminated by rhizoid fabrics showing a Late Messinian emergence (PEDLEY, 1987b).

By the Late Pliocene, subaerial drainage was redirected over the Malta Horst to the N in Gozo and NE in Malta. This resulted in the development of several submarine canyons reported by VOSSMERBÄUMER (1972) that connect to the mouths of the larger valley systems in the Maltese Islands and extend beyond the NE margin of the Malta Horst. Further north, the development of the African foreland basin by nappe emplacement resulted in <1km-thick Pliocene syn-tectonic deposits (PATACCA & SCANDONE, 2004) including pelagic chalks of the Trubi Formation that extend up to the marginal areas and over parts of the Hyblean Plateau. Well data from the Gela Basin south of Sicily shows 7 Plio-Quaternary depositional sequences controlled by third and fourth order eustatic changes. The earliest sediments consist of pelagic chalks succeeded by hemipelagites with turbidites, terminating in offshore marine sediments (CATALANO *et alii,* 1993b). Seismic data shows thinning of the Pliocene basin sediments towards the SE margin of the Gela Basin, especially immediately east of the Scicli transform fault.

A seismic line crossing the platform to basin margin environment in the NW Malta Area (fig. 1a) shows Plio-

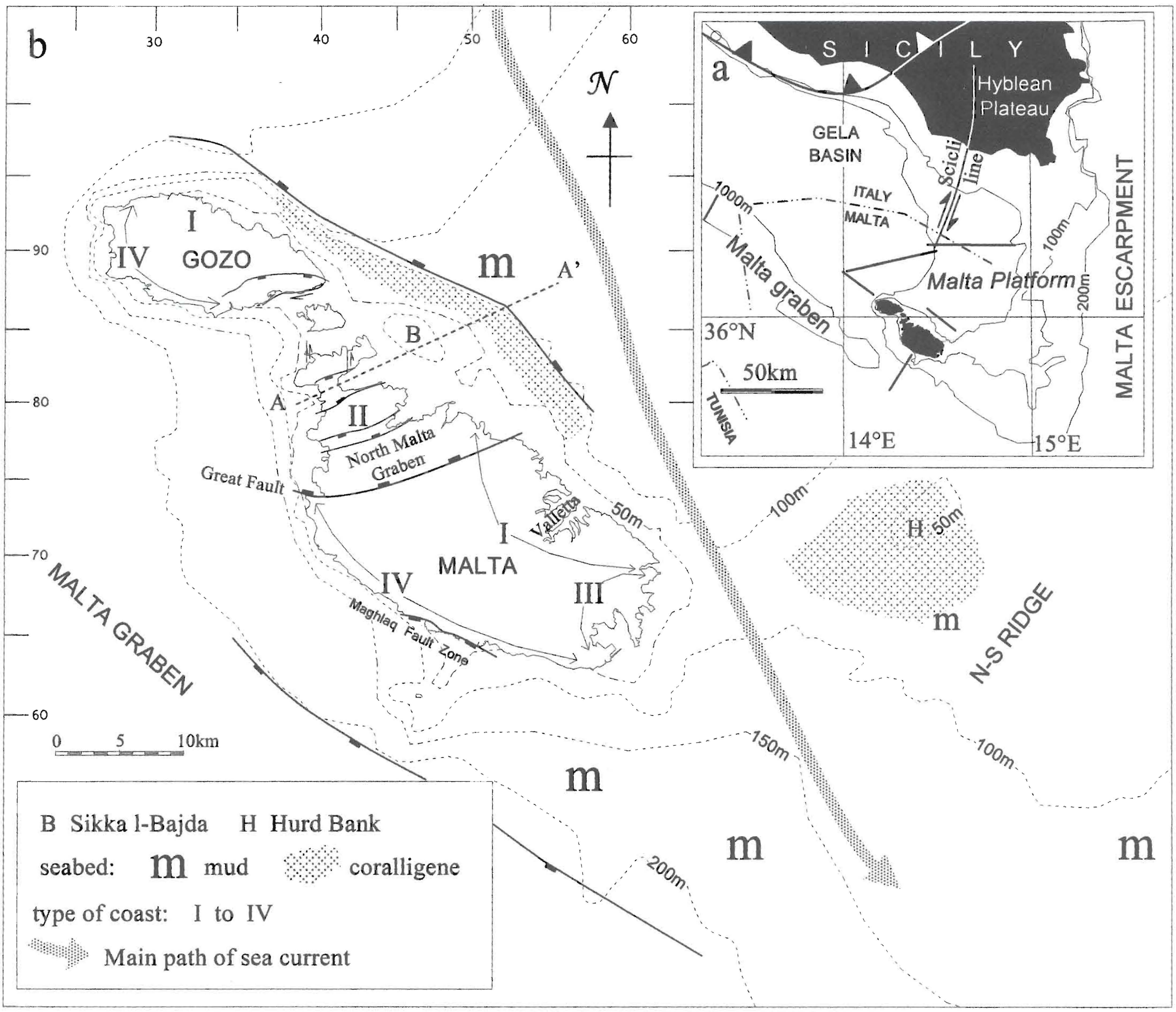

Fig. 1 - (*a*) Simplified bathymetry of African foreland and location of front of nappes in Sicily and N-S Scicli transform fault. Solid lines refer to seismic lines. Dash-dotted line is the international maritime boundary; (*b*) Classification of types of coastal areas and seabed sediments (modified from British Admiralty map, 1969). Tectonics partly after Reuther (1984). Cross section A-A' is shown in fig. 4.
– (a) *Batimetria semplificata dell'avampaese africano con l'ubicazione del fronte dei sovrascorrimenti in Sicilia e della faglia trasforme di Scicli a direzione N-S. Le linee continue indicano i profili sismici, quelle in tratto e punto rappresentano i confini marittimi internazionali;* (b) *Classificazione dei tipi di zone costiere e dei sedimenti del fondale (modificata da British Admiralty map, 1969). La tettonica è in parte modificata da Reuther (1984). La sezione A-A' è mostrata in fig. 4.*

Pleistocene clinoforms that prograde towards the Gela Basin over syn-rift Lower Pliocene sediments and Messinian evaporites (Gardiner *et alii,* 1993). South of the Maltese Islands, syn-rift Lower Pliocene sediments in the Malta Graben are overlain by post-rift Upper Pliocene/Quaternary sediments (fig. 2b), showing onlapping parallel reflectors. In E Malta, SE trending palaeorivers delivered sediments to the eastern divide of the Malta Platform.

During the Quaternary, topographical highs on the Malta Platform remained starved of sediment (Max *et alii,* 1993). Immediately north of the Malta Horst, seismic data shows a thin layer of Quaternary sediments deposited unconformably over a featureless Tertiary surface on the gently westward dipping Malta Platform. Very low angle westward-prograding downlaps extend to 5km west of the N-S Ridge.

Palaeotemperature fluctuations during the Pleistocene were more marked relative to the Pliocene (Emelyanov & Shimkus, 1986). In Tunisia (Jedoui *et alii,* 2002) and in the Maltese Islands, interglacial periods were more humid, producing pale-coloured soil and tufa deposits in Malta described by Pedley (1980), while glacial periods are considered more arid by Hunt (1997) and resulted in loess deposits in W Gozo (fig. 3c). Glacio-eustatic regressions intermittently exposed parts of the N-S Ridge, thereby allowing the migration of species from Sicily to Malta. Isolation during sea level highstands and

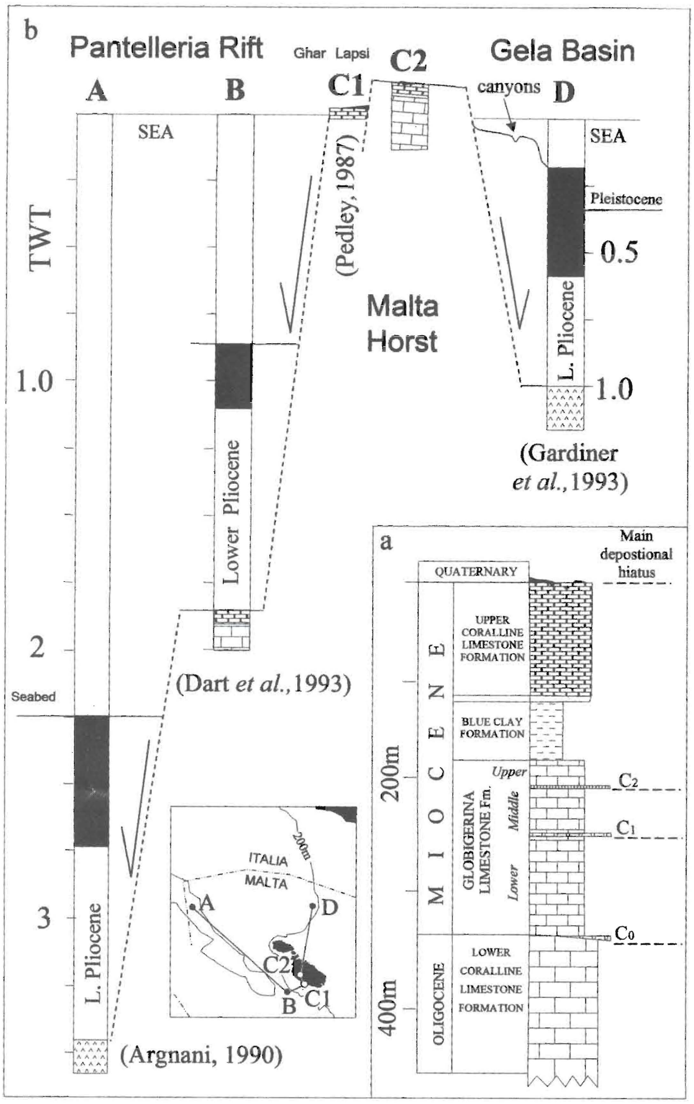

Fig. 2 - (*a*) Stratigraphic section through Tertiary sediments in Malta, showing maximum thickness of each Formation; (*b*) Stratigraphic relationships based on outcrops and seismic lines (sections A, B & D) with interpretation by various authors (hatched sections show Tertiary sediments: limestone, phosphates (CO-2), clays and evaporites; Upper Pliocene-Quaternary sediments shaded black).
– (a) *Sezione stratigrafica attraverso i sedimenti terziari di Malta che mostra il massimo spessore di ciascuna formazione;* (b) *Relazioni stratigrafiche basate su affioramenti e profili sismici (sezioni A, B e C) con le interpretazioni dei vari Autori (le decorazioni indicano i sedimenti terziari: calcari, fosfati (CO-2), argille ed evaporiti; in nero sono rappresentati i sedimenti del Pliocene superiore-Quaternario).*

changing environmental conditions resulted in the development of endemic mammals in Malta that generally evolved towards dwarfism (e.g. *Elephas falconeri, Hippopotamus melitensis*). During the Middle Pleistocene, marine transgression limited migration to a sweepstake route, changing to the Pendel route by the Late Pleistocene, when species endemism in Malta declined (MARRA, 2005). Pleistocene sediments over the Maltese Islands have been mostly eroded and only remain preserved in topographical lows as remanié fossil beds within karstic depressions and caves e.g. Għar Dalam [575 663], fissures and valley alluvium (ADAMS, 1870; ZAMMIT-MAEMPEL, 1981).

HOLOCENE SEDIMENTS

Preservation of sediments increases by the end of Pleistocene to Holocene. Calcrete and rhizoliths are preserved up to the modern swash zone along the NE coast. Terra rossa soil is also widespread over the surface of the Maltese Islands, forming small fanglomerates at the end of valleys in S Malta. At Ras Ħanżir [485 650], several cycles of reddish stony soil succeeded by thin fine-grained soil preserve evidence of episodes of valley erosion with mudflows followed by stable episodes with pedogenesis, suggesting that deglacial sea level rise was not monotonic but marked by intervals of rapid rise (FAIRBANKS, 1989). In N Malta (fig. 3c), terra rossa soil is overlain by lithified back beach sand deposits, raised <4m above the present sea level at ta' L-Imgħarrqa [422 818] (BOSENCE *et alii*, 1981) and Ċirkewwa [395 829].

Holocene sediments become thicker across the marine environment. Carbonate sands are widespread on the submerged Malta Platform, comprising 50-92% of sediments down to depths of 200m (EMELYANOV & SHIMKUS, 1986) and >90% of total shelf and beach sands around the Maltese Islands. These sands are predominantly relict sediments, as is the case of most continental shelves (EMERY, 1968), but also include variable quantities (0 to ~50%) of Recent biogenic sand. Sediments are here described in terms of sequence stratigraphic tracts *sensu* HAQ *et alii* (1987), produced in response to Holocene (last 10kyr) sea level changes:

Lowstand tract: The pre-Holocene global sea level drawdown of –100m exposed most of the Malta Horst (fig. 4), producing a karst terrain with extensive calcrete. Downcutting by palaeorivers was limited in extent because valley long profiles were already adjusted to lower sea levels during the Pliocene. Coarse stony sediments forming narrow steep-angled slopes are interpreted as lowstand wedges developed along the margins of the Malta Horst during the arid glacial period.

Transgressive tract: The rapid Holocene marine transgression caused the retreat of palaeorivers up the valley thalweg and shoreface erosional retreat, forming a ravinement surface along the shelf, cut into the calcrete surface and Tertiary limestone. The eroded sediments were transferred to the shelf floor in an accommodation-dominated regime with fines winnowed and bypassing the shelf, leaving coarser-grained lag sediments. Holocene sediments from offshore boreholes (HARRISON & CO., 1989) located between Malta and Gozo (fig. 3d) at 6-7m water depth, show *circa* 5m-thick fine to medium sand over a basal lag deposit of coarse sand, including re-worked calcrete and Upper Coralline Limestone gravel and pebbles. Sediments overlying the Blue Clay Formation may show several metres of re-worked clay with limestone gravel, capped with a gravelly lag deposit and a ~5m sandy fining-upward sequence which includes boulders and cobbles eroded from the overlying Upper Coralline (fig. 3d). These transgressive sediments formed barrier beaches in N Malta (fig. 4), where sea level rise drowned the back beach area.

Highstand tract: The drowned sediment-starved zone behind the barrier beaches in N Malta e.g. Għadira [414 810] and the drowned valley mouths became sediment traps, forming marshland and microtidal estuaries at Burmarrad [475 775] and Marsa [545 705]. Winnowing of fines along the marine shelf area produced low angle fans

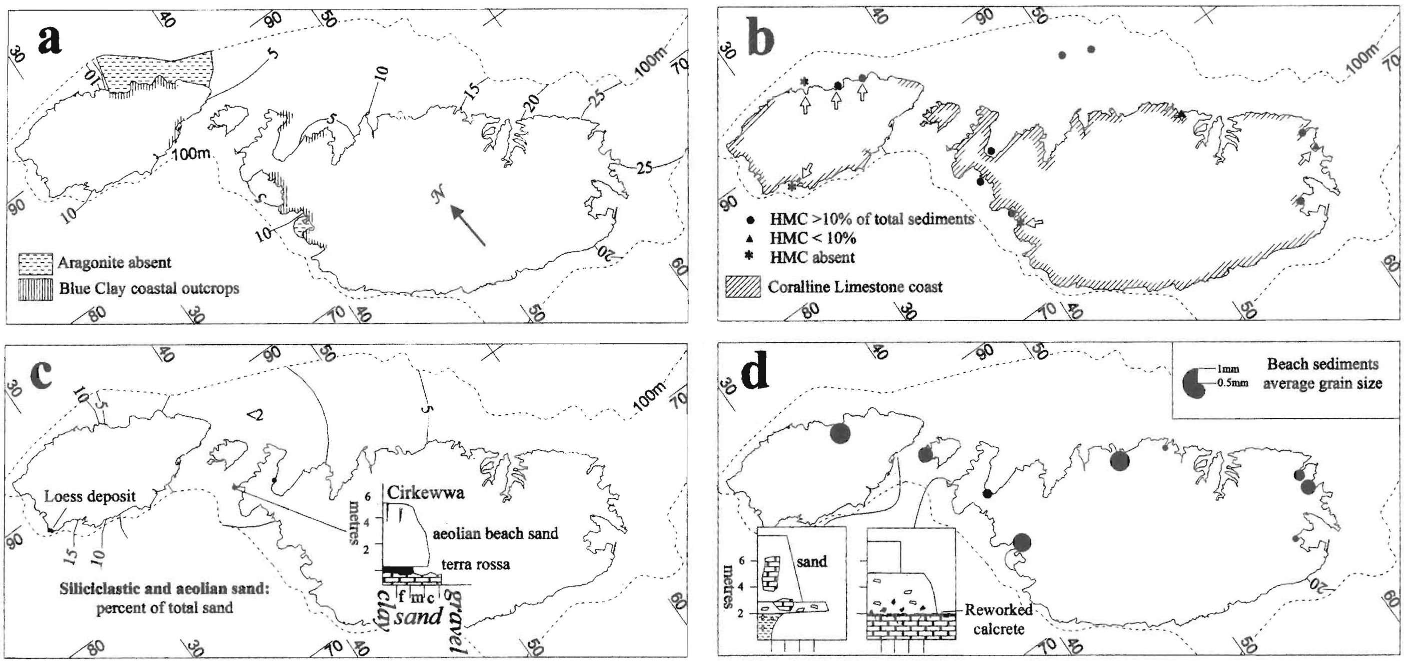

Fig. 3 - (*a*) Percent of aragonite sand along the coast (modified from TURI *et alii*, 1990); (*b*) Abundance of High Magnesium Calcite (HMC) sand. White arrows indicate Globigerina Limestone coast; (*c*) Percent of non-carbonate sand (partly based on TURI *et alii*, 1990); (*d*) Holocene offshore shelf sediments and beach sand granulometry.
– (a) *Percentuale di sabbia aragonitica lungo la costa (modificata da TURI* et alii, *1990);* (b) *Abbondanza di sabbia a calcite alta in magnesio (HMC). Le frecce bianche indicano la costa a Calcare a Globigerina;* (c) *Percentuale di sabbia non-carbonatica (basata in parte su TURI* et alii, *1990);* (d) *Granulometria delle sabbia di spiaggia e dei sedimenti di piattaforma dell'Olocene.*

extending over large area beyond the Malta Horst. These differ from steep highstand wedges along low latitude carbonate platforms where shelf carbonate productivity is high (GLASER & DROXLER, 1989). Shelf biogenic sand in the offshore boreholes increases further up the Holocene transgressive/highstand sequence, suggesting that carbonate production around the Maltese Islands recuperated as the sea level stabilised approximately 6kyr ago, although surface biogenic sand constitute an average of <30% of total sediments.

SHELF GEOMORPHOLOGY AND SEDIMENTS

Modern shelf and coastal geomorphology is the result of lithological differences and tectonism, which together with environmental factors exert an important control on carbonate productivity. Four types of coast and shelf are identified in the Maltese Islands (fig. 1b), partly after PASKOFF & SANLAVILLE (1978):

Type I: Drowned valleys along Lower Coralline Limestone and Globigerina Limestone coast that form narrow inlets <0.5km long on the NE coast of Malta, Comino and in N Gozo, although the concordant ria coast around Valletta [560 730] is >3km long. The shelf profile is a ramp with a distinct shelf break at circa –90m depth, along the NW-SE trending fault lines of the Malta Horst.

Type II: Predominantly Upper Coralline Limestone coast with a configuration controlled by Miocene tectonism that produced the North Malta Graben. Drowned NE-SW trending grabens form relatively large bays and a wide shelf covered with sand and boulders of failed Coralline Limestone slabs. Mainland-attached beaches facing the Pantelleria Rift are bounded by Coralline Limestone cliffs and clay slopes. Along the NE coast, barrier beaches (fig. 4) span across drowned valley mouths at Mellieħa Bay [420 810] and St. Paul Bay [445 784].

The NE-facing shelf area passes to an offshore slope ending in a >1km-wide terrace at 70-90m water depth. The terrace coincides with the top of the Globigerina limestone, exposed by erosional retreat of the overlying softer Blue Clay Formation during glacio-eustatic lowstands. The terrace is bounded by an escarpment formed along the Malta Horst fault line (fig. 4).

Type III: In east Malta, >100m thick chalky outcrops of Middle Globigerina Limestone have been eroded by marine action to form rapidly receding cliffs. Coves are separated by headlands of the harder Upper Globigerina Limestone. Narrow mainland-attached beaches lead to a ramp-like shelf profile, connected to the N-S Ridge.

Type IV: Lower Coralline Limestone cliff coastline formed mainly by retreat parallel to NW-SE faulting. Cliff recession has produced a narrow (<1km) shelf adjacent to intra-shelf grabens developed along the margin of the Pantelleria Rift.

BIOGENIC SEDIMENTS

Maltese shelf water temperature is >15°C down to 100m depth (BÉRANGER *et alii*, 2004) and shows a seasonal thermocline variation (*circa* 15 to 25°C) within the top ~20m (DRAGO, 1991). The photic zone (<50m deep) extends to large parts of the shelf area. These conditions are typical of the temperate to sub-tropical environmental interface across the southern Mediterranean. The constituents of the modern biogenic sediment fraction sug-

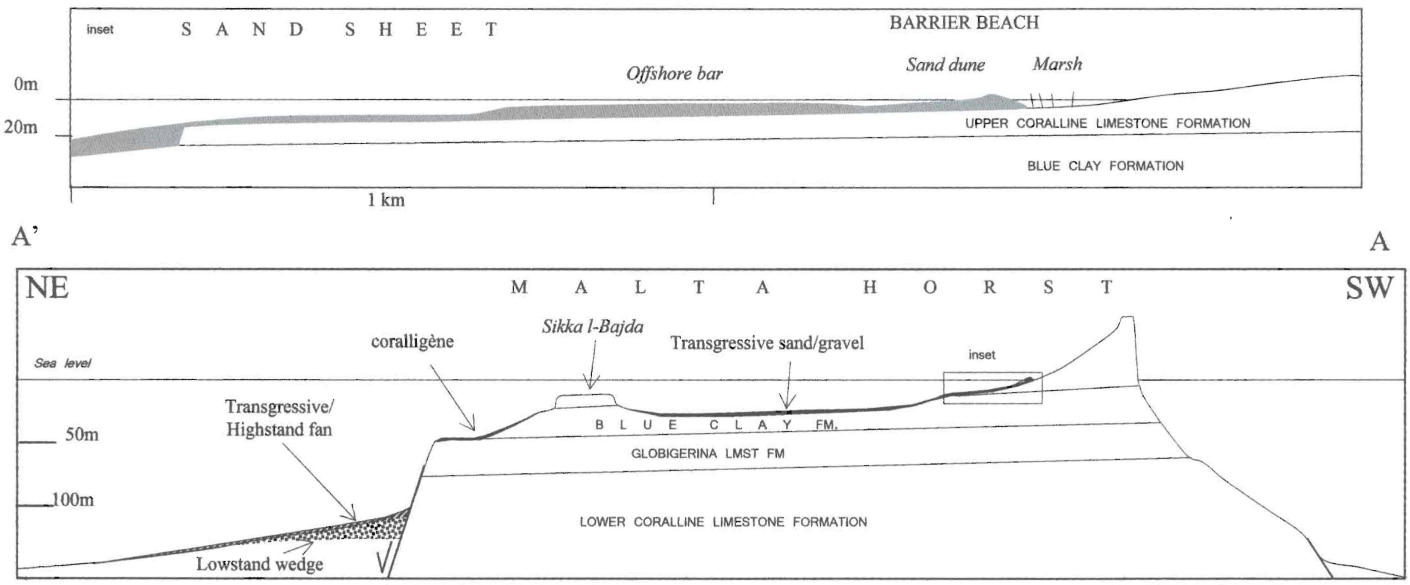

Fig. 4 - Cross sections through Mellieħa graben (line of section in fig. 1b) showing sequence stratigraphic tracts (vertical exaggeration). Inset shows transgressive beach barrier with drowned sediment-starved back beach that has become a marsh.
– Sezione geologica attraverso il graben di Mellieħa (traccia in fig. 1b) che mostra i tratti della stratigrafia sequenziale (si noti l'esagerazione verticale). L'inserto mostra una barriera di spiaggia trasgressiva con la retrospiaggia inondata e sottosedimentata che è diventata una palude.

gest a Heterozoan Association (as proposed by JAMES, 1997) especially in the deeper shelf, with minor elements of Photozoan Association. The chief aragonite-secreting organisms producing sand on the shallower part of the Malta Platform (<100m) are molluscs, pteropods and to a lesser extent, corals (EMELYANOV & SHIMKUS, 1986). High magnesium calcite (HMC) sand is produced by red

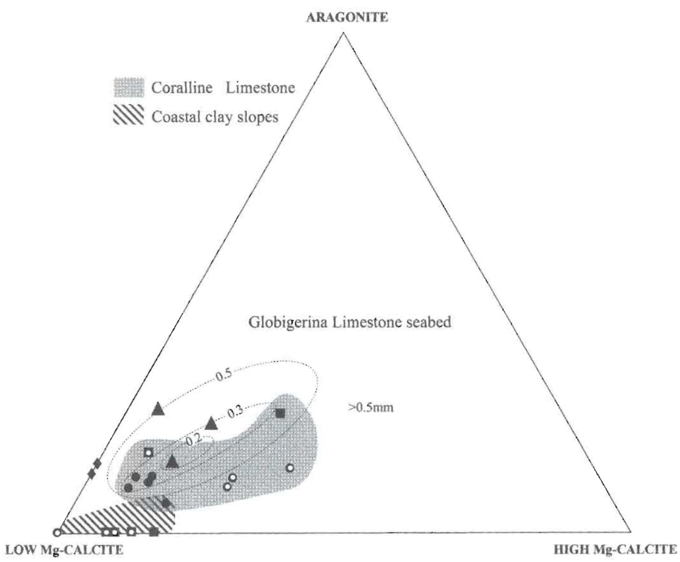

Fig. 5 - Ternary diagram of beach sand mineralogy (based on TURI *et alii*, 1990) with superimposed seabed and coastal lithology: (■) Type I coast; (●) Type II; (▲) Type III; (♦) Type IV coast. Internal white circle indicate localities where roundness index >4 (*sensu* PETTIJOHN *et alii*, 1987). Isopleths show average grain size in mm.
– Diagramma ternario della mineralogia delle sabbie di spiaggia (basata su TURI et alii, *1990) con sovraimposta la litologia della costa e del fondale: (■) costa di tipo I; (●) costa di tipo II; (▲) costa di tipo III; (♦) costa di tipo IV. I* cerchi *bianchi all'interno dei simboli indicano le località dove l'indice di arrotondamento è >4 (*sensu *PETTIJOHN* et alii, *1987). Le isoplete mostrano la granulometria media in mm.*

calcareous algae, foraminifera and echinoids, although coralline algae tend to be over-represented in modern beach sediments (BATHURST, 1975).

Many carbonate-secreting organisms inhabit sea grass meadows of *Posidonia oceanica* growing on the shelf area within the photic zone. These stabilise sand by building mattes, although occasional storm blow-outs of the sea grass cover releases this sand. In most bays, mobile sand sheets occupy the drowned thalweg area within the central part of the bays, flanked by *Posidonia* mattes in shallower water which supply biogenic sediments derived from carbonate-secreting organisms. The abundance of the two metastable carbonate sands shows a distinct relationship to the seabed and coastal lithology and the shelf long profile:

a. Lithology of coastal area:

Exposed shores in types I and II coastal zones consist of hardgrounds formed by Cenozoic diagenesis and lithification of Tertiary limestone Formations. Biogenic production of metastable carbonates shows significant geographical differences which are related to coastal lithology and the textural differences between limestone Formations (fig. 5). The coast and nearshore zone along the coarse-grained Upper and Lower Coralline Limestone Formations shows relatively higher levels of production and accumulation of HMC sand compared to Globigerina limestone coasts (fig. 3b). The latter is a fine-grained wackestone to packstone, physically less heterogeneous and softer rock, producing a smooth seabed surface. Beached Globigerina Limestone boulders ripped by storms from nearshore Sliema [553 750] show centimetre wide dense borings down to 0.2m from the surface. In contrast, beached Coralline Limestone boulders in many coastal localities display more surface encrustation by organisms and only surface bioerosion. SCHEMBRI *et alii* (2005) report greater species diversity and abundance, especially of sessile organisms (including red calcareous algae and other organisms with a HMC skeleton) on Coralline Limestone seabed, which they attribute to complex seabed microtopography creating more microhabitats for these organisms.

Aragonite sand along Globigerina Limestone coasts is relatively more important than HMC sand, except where steep slopes of the Blue Clay Formation directly overlie these coasts in N Gozo and parts of W Malta. Along these coasts, aragonite sand in beaches is anomalously low (fig. 3a).

b. Shelf long profile:

(i) Ramp-like shelf: Shelf areas adjacent to type III and most of type I coasts do not show significant breaks in slope. This allows additional biogenic sediments inputs from deeper water to reach the coast. Bottom currents over the N-S Ridge bring an influx of biogenic sand shorewards to E Malta. These molluscan sands are dispersed along type III coasts where aragonite constitutes >20% of total carbonate beach sand (Turi *et alii,* 1990), decreasing westward (fig. 3a). Offshore, sediments are dispersed by surface sea current (0-100m) circulation dominated by the eastward moving Atlantic current that meanders from the NW around the cyclonic vortex on the Malta platform (Béranger *et alii,* 2004). Fine sediments along the N-S Ridge are winnowed and transported to the leeward side where they by-pass the shelf and accumulate as mud (fig. 1b). On the windward side of the shallower (<50m) parts of the N-S Ridge and in offshore E Malta, where environments are less muddy, a number of biogenic growths including coral and calcareous algae (which range from attached to free-living types with increasing depth) have developed over areas of antecedent high topography.

(ii) Terraced shelf: Shelf area adjacent to type II coast shows significant breaks in slope that inhibit the transport of sediments from deeper shelf areas. Borg *et alii* (1998) report algal and molluscan gravel dominated by free-living calcareous algae growing on the deeper (40-75m) part of the shelf. This coincides with a >1km-wide Globigerina Limestone terrace on the NE margin of the Malta Horst shown in fig. 4. These «coralligène de plateau» algal frameworks are described by Laubier (1966) in other deep-water environments of the Mediterranean. The algal framework is mostly HMC, however, unlike the temperate shallow shelf algal sediments known as maerl, the coralligène may also show extraskeletal cement of aragonite and HMC (Bosence, 1985), indicating either significant flushing by sea currents (the presence of rhodoliths points to some agitation by sea currents) or very slow growth rates.

Non-Carbonate sedimentation

Non-carbonate sand consisting of quartz and heavy minerals is highest in type IV coast (fig. 3c). Offshore, non-carbonate sediments increase to 51%, nearly half consisting of quartz (Emelyanov & Shimkus, 1986). Aeolian sedimentation from North Africa was important over west Gozo. Hunt (1997) describes loess deposits of the last glacial lowstand along the western margin of Gozo. The narrow shelf (<1km) is also affected by high hydrodynamic energy levels and flow acceleration along the shelf that winnows lighter carbonate sediments. In west Gozo, deposition along the cliff coast is mostly in the form of coarse sand to pebble-sized grains.

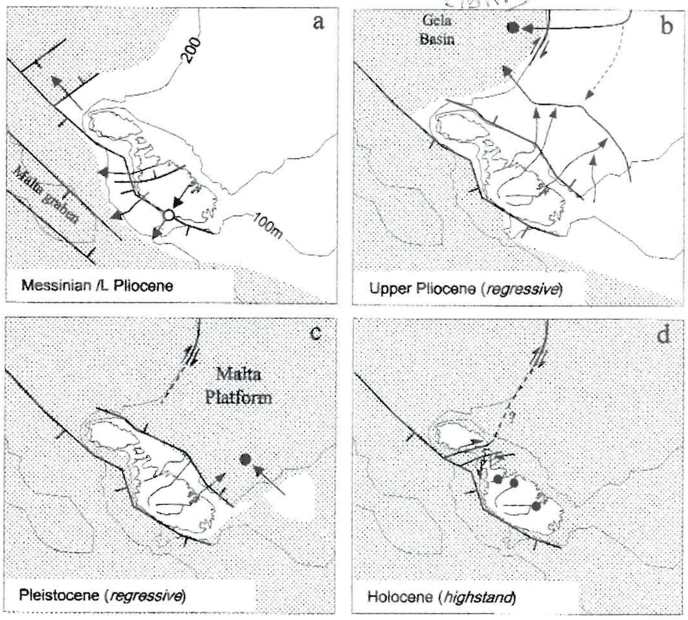

Fig. 6 - Palaeogeographical reconstruction of Plio-Quaternary environments. Shading shows flooded area. (*a*) Lower Pliocene transgression: Drainage directed towards Pantelleria Rift (o: Messinian gravity flows, Pedley, 1987b); (*b*) Uplift and tilting of Malta Horst. Drainage re-directed NE and NW. Dot denotes location of clinoforms along seismic line; (*c*) Lowstand fan beyond shelf; (*d*) Minor and local tectonic uplift along strike-slip faults. Valleys flooded. Dots denote microtidal estuaries and marshland.
– *Ricostruzioni paleogeografiche degli ambienti plio-quaternari. In grigio sono indicate le aree inondate.* (a) *Abbassamento del mare Messiniano/trasgressione del Pliocene inferiore. Drenaggio diretto verso il Rift di Pantelleria (o: flusso gravitativo messiniano, da Pedley, 1987);* (b) *Sollevamento e inclinazione dell'horst di Malta. Drenaggio ridiretto a NE e NO. Il circolo nero indica l'ubicazione dei clinoformi lungo il profilo sismico;* (c) *Conoide di livello del mare basso oltre il ciglio della piattaforma;* (d) *Sollevamenti tettonici minori e locali lungo faglie trascorrenti. Valli inondate. I circoli neri indicano estuari microtidali e paludi costiere.*

DISCUSSION

The African foreland shows a persistent N-S tectonic imprint that controlled the orientation of carbonate facies in Malta before and during the Miocene (Pedley, 1987a; Pedley, 1990; Gatt, 2005) and produced structures that trend parallel to the Miocene Malta Escarpment, which in the Mesozoic formed the passive continental margin-oceanic crust transition. Similar trending structures include the N-S Ridge of the Malta Platform, the Scicli fault and similar transform faults further west (Argnani, 1990). Tavarnelli *et alii* (2004) consider some of these structures as inherited from reactivated Mesozoic faults and shear zones. During the Tertiary, the N-S faults linked intra-plate rifting south and west of the Maltese Islands to plate convergence and foredeep development in S Sicily.

The Malta Area shows contrasting Plio-Quaternary depositional environments produced by three successive and related tectonic episodes: (i) The Late Tortonian development of the Pantelleria Rift over the south Malta Area; (ii) The development of the Gela foredeep Basin in the NW Malta Area and offshore south Sicily and the associated Late Pliocene sedimentation, followed by; (iii) Relative tectonic quiescence over the Maltese Islands during the Quaternary that preserved mostly Late Pleistocene to Holocene sediments. These developments had a profound affect on marine sedimentation and subaerial drainage patterns:

Pantelleria Rift syn-tectonic sedimentation phase:

The relative motion of the converging African and Eurasian plates was NW-SE prior to the Late Miocene (JONGSMA *et alii,* 1984). The NW-SE trending axis of maximum horizontal shortening initiated the development of the Pantelleria Rift into composite pull-apart grabens with the same trend (REUTHER, 1990). Lithospheric extension produced significant offshore thickening of the Early to Mid-Miocene Maltese Tertiary succession within the rift zone (DART *et alii,* 1993). By the Late Miocene, the Lower Coralline Limestone Formation developed as an eastward-facing carbonate ramp, possibly as a result of initial weak uplift in the west where shallow marine bioconstructions accumulated over western Malta and Gozo. Further lithospheric extension produced rifting and faulting along the SW of the Maltese Islands within the evolving Magħlaq Rift Zone. Sediments in the intra-shelf graben exposed at Għar Lapsi partly fill accommodation space created by the rift zone.

During the Messinian desiccation event, drainage in the Malta Area remained mainly directed westwards along the grabens within the North Malta Graben and towards the SW over the evolving Magħlaq Fault Zone. Syn-rift sediments accumulating in the rift zone during the Lower Pliocene (sections A and B in fig. 2b) preceded the tilting of the Malta Horst away from the rift zone. The main phase of rifting in the Upper Pliocene thinned the crust to 20km over the rift zone (BOCCALETTI *et alii,* 1984; ARGNANI, 1990), causing the upwelling of mantle and upwarping of the rift shoulder which tilted the Malta Horst towards the NE (ILLIES, 1981). As in the case of modern African rift zones (FROSTICK & REID, 1989), the tilting of the Malta Horst shifted sedimentation away from the rift zone, switching sedimentation from a W and SW direction (towards the depocentre in the Malta Graben) to a NE direction.

Gela Basin sedimentation phase:

During the Late Pliocene lowstand, Mediterranean rivers extended to the basin margins (EMELYANOV & SHIMKUS, 1986). A main drainage trunk also developed north of the Malta Horst, trending parallel to the rift zone and terminating at the NW margin of the Malta Platform. Its drainage basin extended over the Malta Platform and received sediments from the south via the presently submerged canyons originating in the valley systems of the Maltese Islands, and was fed from the north by the tectonically emerging southernmost coast of Sicily (GARDINER *et alii,* 1993).

The main drainage trunk deposited prograding clinoforms of Late Pliocene to Quaternary sediments at the platform margin that infill accommodation space created by the southern extension of the Gela Basin, west of the Scicli transform fault. The thickness of these Upper Pliocene/Quaternary sediments is greater along the NW platform margin compared to the intra-shelf grabens along the Pantelleria Rift (fig. 2, compare section B to D), further adding to the suggestion of a shift in direction of sedimentation. Fig. 6 shows the evolution of drainage patterns in response to tectonic and glacio-eustatic signals.

Tectonic quiescence sedimentation phase:

Interlocking of plates in Sicily during the Quaternary was accompanied by substantial tectonic uplift of the Hyblean margins (PEDLEY & GRASSO, 1991) and rapid graben subsidence within the Pantelleria Rift (WINNOCK, 1979). However, the Maltese Islands experienced an increasingly quiescent tectonic phase, where fault growth within the Magħlaq Fault Zone diminished and rift shoulder upwarping in Malta was <3° (VOSSMERBÄUMER, 1972). Sedimentation in the Malta Area was controlled by large glacio-eustatic variations of the Pleistocene and the emergent southern Sicilian coast. Climatic conditions became drier and warmer, producing the Late Pleistocene/Early Holocene terra rossa soil, widely preserved as regional tectonic uplift diminished. The Quaternary to Recent shift to E-W intra-plate motion produced the neotectonically remodelled right-lateral strike-slip fault in S Gozo, parallel to the Miocene NE-SW trending North Malta Graben. This fault re-activation has been tentatively linked by GATT (2005) to the southern extension of the Scicli fault (fig. 6). The N-S strike-slip movement is also considered to have produced associated faulting in NW Gozo (KIM *et alii,* 2003), while in north Malta, subordinate N-S sinistral strike-slip fault in Ċirkewwa produced minor uplift that raised carbonate beaches (fig. 3c) by the late Holocene. GRASSO *et alii* (1986) describe similar neotectonic strike-slip remodelling of the Ispica faults in SE Sicily linked to the Scicli fault.

Shelf sedimentation during the Holocene comprises two phases: Firstly, the Versillian marine transgression (10kyr B.P.) re-worked the Tertiary surface and produced a coarse basal lag deposit draped with sand dominated by relict carbonates eroded from the shelf. Secondly, the ensuing stillstand sea level and relative tectonic quiescence initiated a phase of carbonate production on the Maltese shelf, although productivity in this non-tropical environment remains moderate. Sedimentation along the present Maltese coastal and shelf areas shows these characteristics:

Sedimentological controls

The present beach and inner shelf sediments in the Central Mediterranean are the outcome of the Holocene marine transgression that brought a shoreward migration of sand (PASKOFF, 1991). However, TURI *et alii* (1990) suggest that the bulk of beach sand in the Maltese Islands is related to deposits from subaerial drainage basin processes. This is unlikely under the Holocene semi-arid climatic conditions.

Average sand size generally decreases with the increase in aragonite content in sand (fig. 5). These finer sands are also less rounded, indicating that the main mechanism for biogenic sand production is bioersion, rather than abrasion by wave energy. Bay configuration has an overall influence on grain size. Where bay length-to-width ratio exceeds 4, sand accumulating on beaches is relatively finer (fig. 3d) and better sorted. Channelling of hydrodynamic energy and wave reflection along these narrow bays disintegrates the coarser sediment and traps finer sand.

Equilibrium profile has not been attained along the shelf and adjustments to the present hydrodynamic conditions are continuous within the storm wave base and over offshore submerged antecedent topography such as Sikka l-Bajda (figs. 1 and 3). Where the shelf has a ramp-like profile without topographical highs (type I and III coasts), long profile is closer to equilibrium conditions and hydrodynamic erosion of Tertiary limestone along the shelf is less significant, although partly compensated by bioerosion from borers in Globigerina limestone seabed. This has resulted in the accumulation of relatively smaller quantities of low magnesium calcite sand in the beach environment and dilution by biogenic sand transported from deeper marine environments, including the N-S Ridge.

Environmental controls

Carbonate production under the mid-latitude conditions found in the Maltese Islands could not keep up with sea level rise during the last marine transgression estimated by Donovan & Jones (1979) to be 10m/1000yr^{-1}, and consequently drowned. Highstand conditions further isolated the Maltese shelf from continental siliciclastics, while the semi-arid climate reduced terrigenous sedimentation from local sources which resulted in low levels of nitrate, phosphate and turbidity within most bays (Agius & Jaccarini, 1989). This allowed moderate carbonate production over the shelf that peaks in water depths from 0m to *circa* –15m over rocky hardgrounds, sand immobilised by *posidonia* mattes and offshore topographical highs. In deeper water shelf environment (>40m), carbonate production is low, although significant quantities of coarse sediments including coralligène de plateau have accumulated over long periods of time.

In specific localities increased nutrient conditions reduced carbonate production in the following areas: (*a*) the Valletta ria coast, which shows higher nutrient levels during the rainy season (Agius & Jaccarini, 1989) and significant accumulations of terrigenous mud; (*b*) Coastal outcrops of the Blue Clay Formation along parts of type I and II coast, where seasonal mudflows of clay increases water turbidity and hinders carbonate productivity, resulting in the absence of aragonite sand or all biogenic sand along the shallow shelf; (*c*) Erosion of coastal outcrops of Tertiary phosphorite conglomerates which are associated with localised eutrophic conditions.

CONCLUSIONS

Plio-Quaternary sedimentation over the Malta Area was controlled by an early phase of tectonism linked to the development of the Pantelleria Rift and later the Gela Basin, followed by a phase of glacio-eustatic and environmental controls during the Quaternary. The dynamics and timing of these controls lead to the following conclusions:

(1) Crustal extension controlled sedimentation over the Malta Area from the mid-Neogene to the Pliocene, although Argnani (1990) considers rifting to be mostly of Pliocene age. The early rift phase started from the mid-Miocene, when the evolving Pantelleria Rift became the depocentre for the developing Globigerina Limestone and Blue Clay Formations (Dart *et alii,* 1993). Rifting throughout the Late Miocene triggered faulting in the Malta Area and created accommodation space for SW prograding clinoforms of the Upper Coralline Limestone Formation, succeeded by substantial Lower Pliocene sedimentation within the rift zone.

(2) The temporal relationship between extension and uplift in the Pantelleria Rift and possibly the North Malta Graben, suggests passive rifting by lithospheric stretching *sensu* McKenzie (1978) as the main mechanism for rift development within the Malta Area. The thinning of the lithosphere south of Malta by tensional stresses associated with the Pantelleria Rift was followed by passive upwelling of hot aesthenosphere that resulted in rift flank uplift during the Upper Pliocene. This triggered a shift in the drainage patterns and sedimentation diametrically away from the rift area, which partly starved the rift zone of sediments.

(3) The post-rift phase slowed down rift shoulder uplift. Extensive subaerial erosion along the uplifted rift flank during sea level lowstands supplied sediments to a drainage system developed over the Malta Platform which deposited prograding clinoforms along the platform margin, towards the evolving Gela foreland basin. The end of rift shoulder uplift following the interlocking of the African and Eurasian plates during the Quaternary, increased the preservation of subaerial sediments in the Maltese Islands. Sedimentation was now controlled by glacio-eustatic sea level changes, culminating in the Versillian marine transgression which deposited re-worked Holocene sediments directly on Tertiary carbonates along the Maltese shelf. The ensuing relative stillstand brought an increase in carbonate production which reached moderate levels depending on shelf long profile geometry and the environmental effects of coastal lithology.

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