A Geological and Geomorphological Review of the Maltese Islands with Special Reference to the Coastal Zone

Odette Magri
Geography Division, Mediterranean Institute, University of Malta, Msida MSD06, Malta
odette.magri@um.edu.mt

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A GEOLOGICAL AND GEOMORPHOLOGICAL REVIEW OF THE MALTESE ISLANDS WITH SPECIAL REFERENCE TO THE COASTAL ZONE

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ABSTRACT: Relationships between tectonics, geology and landforms are very evident in the Maltese Islands. Two rift systems belonging to different ages and having different trends dominate the structural setting of the Islands. The older rift generation creates a horst and graben structure north of the Great Fault. The second rift generation –the Maghlaq Fault– is associated with the Pantelleria Rift. The fault determines the south-west littoral of Malta and is responsible for the north-east tilt of the Islands. The geology is made up of Tertiary limestones with subsidiary marls and clays. The geological formations are very distinctive lithologically and this is reflected in characteristic topography and vegetation. The main focus of this paper is on the coastal zone where the relationship between geology and geomorphology is particularly evident. The coast although being only about 190 km long features a large variety of landforms. Lower Coralline Limestone forms vertical plunging cliffs reaching more than 200 m in some places. Globigerina Limestone features cliffs which in most cases are fronted by shore platforms. Blue Clay displays itself as slopes which extend from the base of the Upper Coralline Limestone plateau to sea-level. Where Greensand occurs at the coast this does not produce any particular landform as it is often assimilated into the base of the Upper Coralline Limestone plateau. The latter runs parallel to the coast in north-west Malta. Moreover tectonics play a very important role especially in the formation of bays and cliffs. During the Quaternary period there has been tilting of Malta towards the north-east together with a general subsidence of the archipelago which is probably still going on.
KEYWORDS: tectonics, geology, geomorphology, coastal zone, Maltese Islands.

RESUM: A les illes Malteses s'observa de forma evident la relació entre tectònica, geologia i paisatge. Dos sistemes de fractures (rift) de diferent edat i que mostren direccions diferents dominen la disposició estructural de les Illes. El sistema de rift més antic va crear una estructura en horst i graben al nord de la Gran Falla. La segona generació de rift –la falla Maghlaq– s'associa amb el rift de Pantelleria. Aquesta fractura condiciona el litoral del sud-oest de Malta i és la responsable del basculament cap al nord-est de les Illes. La constitució geològica està formada per calcàries del Terciari i, de forma subsidiària, per margues i argiles. Les formacions geològiques són litològicament molt diferents, la qual cosa es reflecteix de forma característica en la topografia i la vegetació. El principal objectiu d'aquest treball se centra en la zona costanera, on es fa particularment evident la relació entre geologia i geomorfologia. Encara que la costa té 190 km i escaig de longitud presenta una gran varietat de paisatges i morfologies. La calcària coral·lina inferior forma penya-segats verticals que poden arribar a superar els 200 m d'altitud. Les calcàries amb globigerines formen penya-segats que en molts de casos desenvolupen en la seva part frontal plataformes litorals. Les calcàries blaves desenvolupen pendents que s'allarguen des de la base de la plataforma de les calcàries coral·lines superiors fins al nivell de la mar. La costa no presenta cap paisatge particular quan afloren les «arenes verdes», que sovint

s'assimilen a la base amb la plataforma de les calcàries coral·lines superiors. Aquestes darreres van paral·leles a la costa al nord-oest de Malta. Malgrat tot, la tectònica hi fa un paper molt important, especialment en la formació de badies i penya-segats. Durant el Quaternari hi ha hagut un basculament de Malta cap al nord-est juntament amb una subsidència general de l'arxipèlag que probablement continua avui dia.
PARAULES CLAU: tectònica, geologia, geomorfologia, zona costanera, illes Malteses.

1. Overview of the Maltese Islands

The Maltese Islands are located in the central Mediterranean region between Italy and North Africa, at a latitude of 35º48'28" to 36º05'00" North and a longitude of 14° 11' 04" to 14° 34' 37" East (Schembri, 1993). The archipelago consists of three main islands – Malta, Gozo and Comino – and several small uninhabited islets which include Cominotto (Maltese: *Kemmunett*), Filfola (Maltese: *Filfla*), St.Paul's Islands (Maltese*: Il-Gzejjer ta' San Pawl* or Selmunett Islands), Fungus Rock (Maltese: *Il-Hagra / Il-Gebla tal-General* or General's Rock) and few other minor rocks (Figure 1).

The Islands have a total land area of 316 km^2 (Malta: 245.7 km^2, Gozo: 67.1 km^2, Comino: 2.8 km^2) and a coastline about 190 km long, with a submerged area (up to 100 m) of 1940 km^2 (Schembri, 1990). The length of the whole archipelago is 45 km; Malta being 27 km long, Gozo 14.5 km long and Comino 2.5 km. The North Comino Channel, separating Gozo from Comino, is 1 km wide whereas the South Comino Channel, separating Comino from Malta is 2 km wide.

The Islands lie approximately 96 km from Sicily to the north, 290 km from North Africa to the south, 1836 km from Gibraltar to the west and 1519 km from Alexandria, Egypt to the east (Figure 1). The archipelago is situated on a shallow shelf, the Malta-Ragusa Rise, part of the submarine ridge which extends from the Ragusa peninsula of Sicily southwards to the North African coasts of Tripoli and Libya. Geophysically the Maltese Islands and the Ragusa peninsula of Sicily are regarded as forming part of the African continental plate. The archipelago is linked to the Ragusa peninsula in the Sicilian Channel by a submarine ridge, which reaches a maximum depth of 200 m below the present sea level and is mostly less than 90 m deep. The sea depth between the Islands and North Africa is much deeper, sometimes reaching more than 1000 m (Morelli *et al.*, 1975 *in* Schembri, 1993). Spratt (1867) claims that the submarine ridge was an epicontinental land bridge during the Pleistocene and facilitated the migration both northwards and southwards of exotic fauna.

The Maltese Islands were settled continuously from the middle Neolithic onwards. Important stone temples were constructed in the period 2600 – 1700 BC (Evans, 1971 *in* Alexander, 1988). Since then the Islands have been occupied by Phoenicians, Greeks, Carthaginians, Romans, Arabs, Normans, Angevins, Aragonese, the Knights of St. John, French and finally the British. Malta became an independent country in 1964. In 2005 when the last population census was carried out the Islands had a population of 404,039 (Census, 2005). The latter shows an increase of 25,907 persons (6.9%) over ten years when the Islands had a population of 378,132 (Census, 1995). This figure results in a population density of 1282 persons per square kilometre, one of the highest in the world and the highest in the European Union.

The aim of this paper is to provide a review on the geology and geomorphology of the Maltese Islands with special reference to the coastal zone. The physical landscape is characterised by distinct lithologies which have developed different landforms. Tectonic activity is also a predominant factor on landform development and its role is especially evident at the coastal zone where despite the restricted coastal length of the Islands, various landforms have been developed.

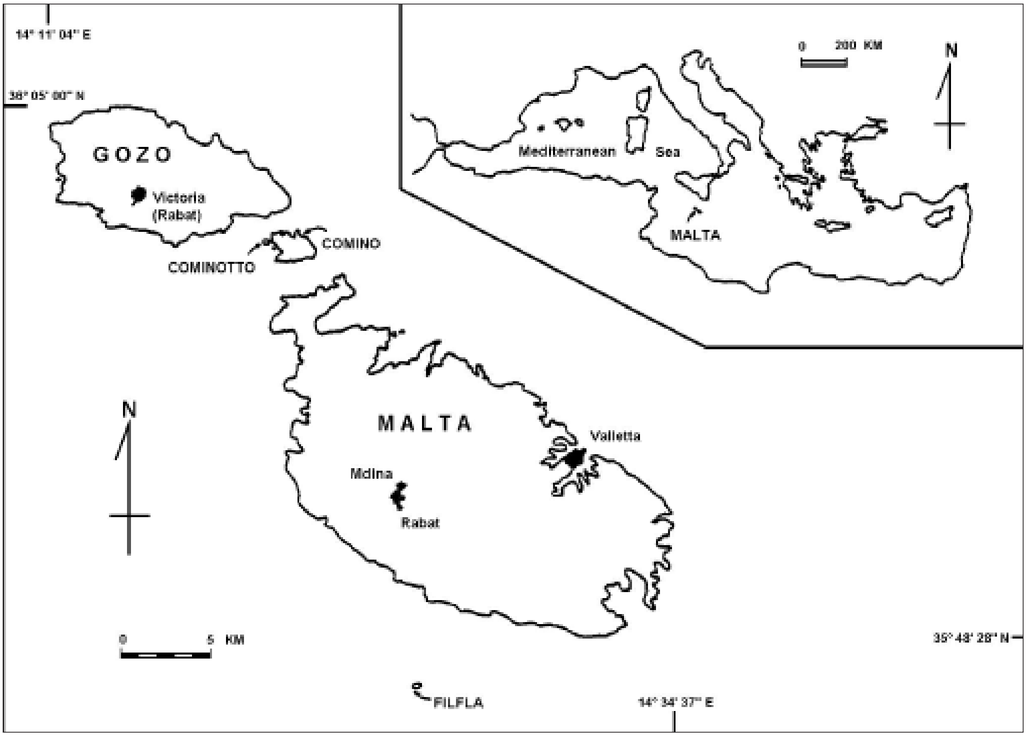

Figure 1. Location of the Maltese Islands.
Source: Alexander, 1988

2. Geology of the Maltese Islands

The Maltese Islands are entirely composed of Tertiary limestones with subsidiary marls and clays. Quaternary deposits, mostly Pleistocene in age, are limited to few localities and include cliff breccias, cave and valley loams, sands and gravels. Deposition occurred in the following simple succession.

1. Upper Coralline Limestone
2. Greensand
3. Blue Clay
4. Globigerina Limestone
5. Lower Coralline Limestone

Table I shows the litho- and chronostratigraphy of the Maltese Islands. The geological succession represents a varied cross-section of Oligo-Miocene lithologies and facies, but consists almost entirely of carbonates. The geological formations of the Islands are very distinct lithologically and this is reflected in characteristic topography and vegetation (House *et al.*, 1961a). The Lower Coralline Limestone is responsible for forming spectacular cliffs, some reaching 140 m in height, which characterize the Islands especially in the west. Inland the Lower Coralline Limestone forms barren grey limestone-pavement topography. The succeeding Globigerina Limestone, which is the most extensive formation on the Islands, forms a broad, rolling landscape. The soil is thin but intensively cultivated and hillslopes on it are densely terraced. The Blue Clay produces slopes that tend to slide over the underlying Globigerina Limestone Formation. It forms the most fertile bedrock on the Islands, especially where springs seep from the overlying Upper Coralline Limestone. The latter, which also includes Greensand, forms massive cliffs and limestone pavements with karstic topography similar to Lower Coralline Limestone. This formation caps tabular hills and mesas reaching a maximum height of 253 m above sea level at Ta' Zuta, near Dingli in south-west Malta (Pedley *et al.*, 1978). Figure 2 represents the spatial distribution of the different geological formations of the Maltese Islands.

Table I. Stratigraphy of the Maltese Islands

Epoch Stage	**Years BP**	**Formation**	**Maximum thickness (m)**
U. Miocene	Tortonian (12-7.5 Ma)	Upper Coralline Limestone	104-175
		Greensand	0-16
M. Miocene	Serravallian (13-12 Ma)	Blue Clay	0-75
M. Miocene	Langhian (15-13 Ma)	Upper Globigerina Limestone	5-20
		Upper Main Conglomerate (C2)	
L. Miocene	Burdigalian (20-15 Ma)	Middle Globigerina Limestone	0-110
		Lower Main Conglomerate (C1)	
L. Miocene	Aquitanian	Lower Globigerina Limestone	5-110
U. Oligocene	Chattian	Lower Coralline Limestone	140

Lithostratigraphy mainly after Murray (1890); chronostratigraphy after Felix (1973)
Sources: Pedley *et al.,* 1978; Alexander, 1988

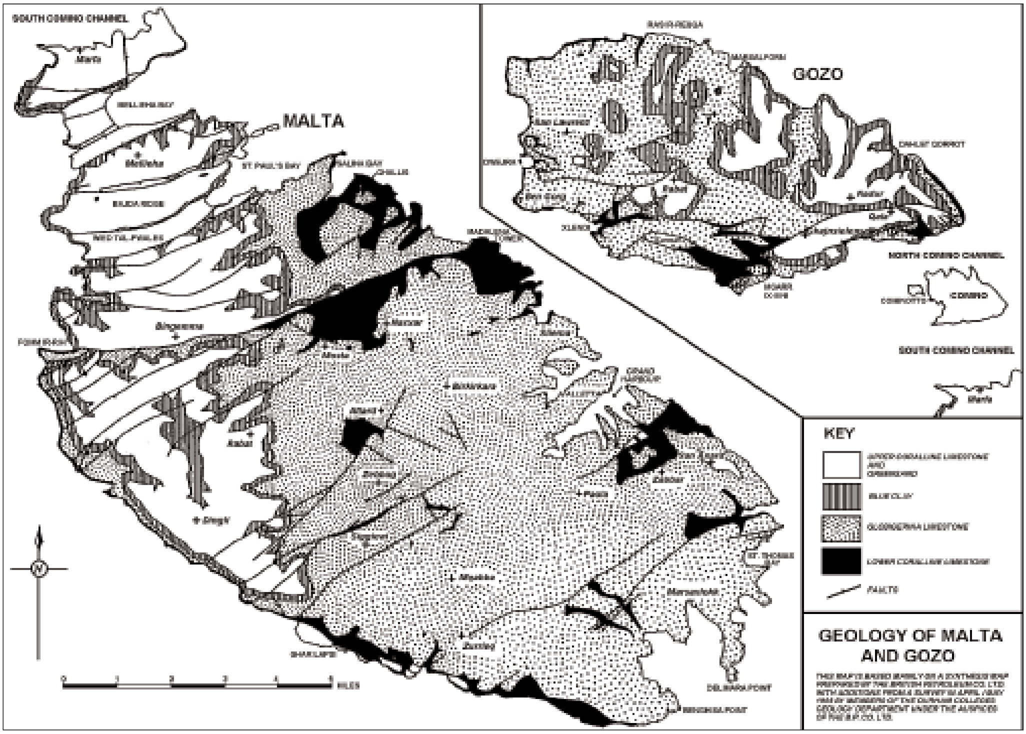

Figure 2. The geology of the Maltese Islands.

Source: House et al., 1961a

The lithostratigraphy of the Maltese Islands has been well known since the time of Spratt (1843) due to its simple structure and the gentle regional dips. The current terminology applied to the individual formations originated from the detailed work of Murray (1890). Although Murray's lithostratigraphy is still generally accurate, work by Pedley (1975) has substantially improved the detailed understanding of both lithostratigraphy and palaeoecology, especially within the two Coralline Limestone formations. Spratt (1867) was the earliest worker to publish on the Quaternary geology. A more detailed study was carried out by Trechmann (1938).

The sequence of rock units of limestones and associated marls represents a succession of sediments deposited within a variety of shallow marine environments (Pedley *et al.*, 1978). In many respects these resemble the mid-Tertiary limestones occurring in the Ragusa region of Sicily and North Africa. The succession gives the impression that the depositional area first subsided and then there was a gradual shallowing (Felix, 1973). The sequence starts with the Lower Coralline Limestone, deposited in a shallow gulf-type area followed by a sea with shoals. The Globigerina Limestone and Blue Clay show a deepening in an open marine environment, to a maximum depth of 150 m to 200 m, as suggested by the foraminiferal fauna. The upper two formations, the Greensand and Upper Coralline Limestone and their foraminiferal associations, indicate a gradual shallowing to an area with shoals but still in an open marine environment.

2.1. The Geological Formations

2.1.1. Lower Coralline Limestone

The Lower Coralline Limestone is the oldest formation visible on the Islands. Outcrops are mainly limited to coastal sections along the western sides of Malta and Gozo (Pedley *et al.*, 1976). Vertical cliffs extend up to 140 m in south-west Gozo and about 100 m in the sections between Fomm ir-Rih and Benghisa Point in western and southern Malta respectively. Inland exposures are mostly associated either with valley-gorge sections, as in southern Malta, or with faulted inliers such as at Naxxar. The upper part of the Lower Coralline Limestone Formation is exploited in quarries (Pedley *et al.*, 1978). The lowest horizons of the formation are exposed in cliff sections around Maghlaq, south-west Malta (Pedley *et al.*, 1976). Pedley (1978) has subdivided the Lower Coralline Limestone Formation into four members: Maghlaq Member (oldest), Attard Member, Xlendi Member and Il-Mara Member (youngest). The name attributed to each member indicates the site where the member is best exposed. Local terminology for this formation is *Zonqor*.

2.1.2. Globigerina Limestone

The Globigerina Limestone Formation is given this name due to the high percentage of planktonic foraminifera present in the rock (Pedley *et al.*, 1976, 1978). The formation covers large areas of central and southern Malta and Gozo. The outcrops are frequently obscured by housing and agricultural development. The most accessible sections in Malta are along the Qammieh coastline, northern Malta. In Gozo the formation is well exposed in the valley gorges around San Lawrenz, western Gozo. The formation shows marked thickness variations ranging from 23 m near Fort Chambrey, southern Gozo, to about 207 m around Marsaxlokk, southern Malta. The usual colour of the formation is pale-yellow. A pale-grey subdivision, bounded both above and below by phosphorite conglomerate horizons, occurs in the middle of the sequence. The Globigerina Limestone provides most of the building stone in Malta and in local terminology is referred to as *Franka* (Pedley *et al.*, 1976). This formation is further subdivided into Lower, Middle and Upper Globigerina Limestone separated by two phosphorite conglomerate horizons.

2.1.3. Blue Clay

The Blue Clay Formation comprises a sequence of alternating pale grey and dark grey banded marls, with lighter bands containing the highest proportion of carbonate (Pedley *et al.*, 1978). The formation never contains more than 30 per cent carbonate material (Murray, 1890). This lithology is found throughout the Islands and possibly also at the base of the cliffs on the island of Filfla, off the western coast of Malta (Pedley *et al.*, 1976). The maximum thickness of the Blue Clay Formation is approximately 75 m recorded at Xaghra, northern Gozo, and on the western coast of Malta north of Fomm ir-Rih Bay (Pedley *et al.*, 1976, 1978). Marked thinning occurs towards the south and east, where the formation has been mostly removed by erosion. Fossils are common but are restricted to microfauna or crushed specimens of macrofauna, except in the upper horizons of the Blue Clay around northern Malta and southern Gozo (Pedley *et al.*, 1976).

2.1.4. Greensand

The Greensand Formation is composed of thickly bedded, coarse, glauconitic, bioclastic limestones (Pedley *et al.*, 1978). In unweathered sections the green and black glauconite grains are visible. Usually due to the release of limonite upon weathering and oxidation of the glauconite, the rock possesses a characteristic orange-brown colour. The transitional change upwards from the Blue Clay is frequently sharp, particularly in the western areas of the Islands. In eastern parts assimilation of the top of the Greensand into the base of the overlying Upper Coralline Limestone, as a result of bioturbation, has produced the effect of a gradual change in sedimentation (Pedley *et al.*, 1976). The maximum development of the Greensand Formation is found at Il-Gelmus in west-central Gozo, where 16 m can be measured (Pedley *et al.*, 1976). Throughout the rest of Malta and Gozo the formation, is usually less than 1 m thick and shows extensive reworking and assimilation into the overlying strata (Pedley *et al.*, 1978). The formation largely consists of material transported and deposited into shallow water marine conditions from areas of erosion outside the present confines of the Islands (Pedley *et al.*, 1976).

2.1.5. Upper Coralline Limestone

The Upper Coralline Limestone is the youngest Tertiary formation of the Maltese Islands and is similar in many aspects to the Lower Coralline Limestone Formation, especially in colour and coralline algal content (Pedley *et al.*, 1976). It is a durable sequence, frequently weathering into steep cliffs and featuring a well-developed karst topography. Outcrops occur on all islands of the Maltese archipelago and the formation is extensively developed especially in western Malta, Comino and east-central Gozo, where it displays a wide range of lateral and vertical facies variations. A maximum thickness of approximately 100 m of strata is present in a lithological sequence, which can be divided into three divisions (Pedley *et al.*, 1978). Pedley (1978) divides the Upper Coralline Limestone Formation into four members, each member consisting of several beds: Ghajn Melel Member, Mtarfa Member, Tal-Pitkal Member and Gebel Imbark Member. The Maltese terminology used for this formation is *Tal-Qawwi*.

2.1.6. Quaternary Deposits

Trechmann (1938) carried out a detailed study of the quaternary deposits of the Maltese Islands and has classified them into valley loams and breccias, coastal conglomerates and breccias, and ossiferous deposits in caves and fissures. The earliest of the deposits are the Pleistocene ossiferous deposits of various cave systems in Malta, which have yielded numerous interesting animal remains (Pedley *et al.*, 1978). Ghar Dalam cave, southern Malta, is the most well-known. The oldest fauna include Pleistocene dwarf hippopotami, pygmy elephants, dormice and swans. A later deposit features horse and deer (House *et al.*, 1961a). The presence of so many land quadrupedal animals is taken as evidence that there was land communication between Sicily and Malta at this period (Pedley *et al.*, 1978). Later deposits which possess a distinct red colour, include alluvial fans, caliche soil profiles and calcreted breccias and conglomerates. All are stained red by iron oxidation.

3. Geomorphology of the Maltese Islands

The geomorphology of the Maltese Islands has been discussed by House *et al.* (1961b), Vossmerbäumer (1972) and Alexander (1988). Coastal geomorphology is dealt with in the studies of Guilcher and

Paskoff (1975), Paskoff and Sanlaville (1978), Ellenberg (1983) and Paskoff (1985). More recent sources are lacking.

The predominant control on landforms in Malta is undoubtedly that of tectonic activity including faulting, up-arching and subsidence (Alexander, 1988). The highest land, around south-west Malta and western Gozo, occurs at the intersection of the rift system shoulders (Illies, 1980). Isopachyte maps published by Pedley *et al.* (1976) indicate that the extinct NE-SW trending rift system left eminences of the Lower and Middle Globigerina Limestone at the south-east and north-west ends of the archipelago. The latter was removed by erosion on south-east Malta. The present relief of the Islands corresponds most closely with the isopachytes of the Lower Coralline Limestone, which reflects all stages of subsidence and up warping that the various land areas have gone through. Both main Islands are tilted towards the north-east. The highest point in Malta is 253 m above sea level located at Ta' Zuta on Dingli Cliffs, south-west Malta, whereas in Gozo the highest point is 191 m found at Dbiegi, western Gozo.

House *et al.* (1961b) classify the physical landscape of the Maltese Islands into five categories.

1. Coralline Limestone plateaus: these form the highest areas and are bounded by well-marked escarpments. These uplands range in size from the massive triangular plateau of western Malta to the small mesas of north-west Gozo. In western Malta, the Coralline Limestone plateaus range in heights from 180 m to 245 m. Eastwards the plateaus change into undulating areas developed on Globigerina Limestone, mostly having a height of 120 m. The western plateaus are flanked by deeply incised valleys which have cut back into the upland. The south-west edge has been least affected by such action and the regular line of cliffs is broken only in one place, where the valley complex of Imtahleb forms a deep embayment.

2. Blue Clay slopes: these occur at coastal areas and in valleys which separate the plateau uplands from the surrounding areas. Blue Clay slopes in Malta occur mostly at the coast at the foot of the Upper Coralline Limestone plateau. Inland, Blue Clay corresponds with the location of dry valleys which have watercourses during the wet season only, although some have perennial springs which flow throughout the year (Schembri, 1993) due to the impermeability of Blue Clay. In Gozo, Blue Clay outcrops in coastal slopes and valley slopes and floors which cut through Coralline plateaus and Globigerina Limestone plains.

3. *Rdum* or undercliff areas: these are found where Blue Clay slopes descend steeply to the sea from beneath the Upper Coralline Limestone cliffs, which mark the edge of the limestone outcrop. Faulting and jointing in the bedding planes of the limestone result in rockfall of the Upper Coralline Limestone Formation onto the Blue Clay. In Malta these landforms are situated mainly on the western coast, although there are some present on the north-east coast. In Gozo *rdum* areas occur on the eastern coast.

4. Flat-floored basins: in most cases these are the result of faulting, such as Pwales Valley, or downwarping, such as Bingemma Basin. Sometimes flat-floored basins occur due to erosion and subsequent alluvial deposition, such as Wied il-Ghasel, limits of Mosta, central Malta. The region north of the Victoria Lines Fault consists of a series of ridges and valleys. From north to south, the major divisions are: Marfa Ridge, Mellieha Valley, Mellieha Ridge, Mizieb Depression, Bajda Ridge, Pwales Valley, Wardija Ridge and Bingemma Basin (Figure 3).

5. Globigerina Limestone hills and plains: these include large areas of gently sloping land which, in Malta, consist of a series of low ridges and shallow valleys and in Gozo have a more varied topography. The central, southern and eastern regions of

Malta mostly consist of areas of gentle relief, although steep slopes occur in a number of places. Flat land is very limited, occurring around the head of Marsa Creek (eastern Malta), Ta' Qali (central Malta) and Luqa airfield (southern Malta).

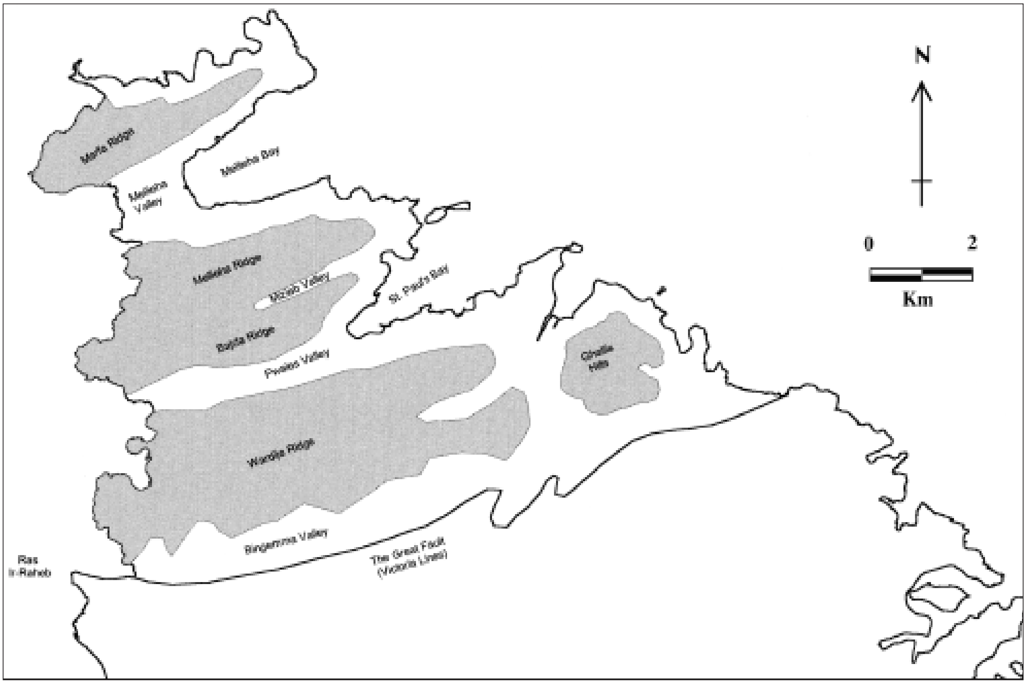

Figure 3. Ridge and valley topography north of the Great Fault.

Source: Ransley and Azzopardi, 1988

4. Coastal geomorphology of the Maltese Islands

Two studies by Paskoff and Sanlaville (1978) and Ellenberg (1983) have made a significant contribution to understanding the coastal geomorphology of the Maltese Islands.

Paskoff and Sanlaville (1978) claim that the general outline of the Maltese littoral zone has been determined by tectonics. Lithology and advanced karstification have to be considered when studying the coast in detail. In spite of the small size, the Maltese Islands display a large variety of coastal features. Bays in northern Malta correspond to downthrown blocks that were partially submerged. High cliffs which characterize the south-west coast are associated with a major fault (Figure 4). Beaches are rare and constitute only 2.4 % of the coastline (Schembri, 1990) (Figure 5). Low limestone coasts display interesting examples of both mechanical and chemical processes such as hydraulic pressure and corrosion (Figure 6). Most of the coasts have a high relief and show different types of cliffs. Some are associated with wave-cut platforms (Figure 7). Others plunge directly into the sea (Figure 4) or are skirted by landslides.

Since its definitive emersion after the Tortonian, the Maltese archipelago has been affected by karstification, now found at an advanced stage of development, which is evident at the south of Malta, Comino and western Gozo. In Malta, for example, one finds important circular depressions such as the doline structure of Il-Maqluba, near Qrendi, south-west Malta, which is 60 m wide and 40 m deep. Long caves, such as Ghar Hasan, south of Hal-Far and especially Ghar Dalam, close to Birzebbuga, explored to about 100 m and famous for its palaeontological richness in bone fossils, are also found (Paskoff and Sanlaville, 1978). The karstification, remarkable in underground structures, is principally cut in Coralline Limestone, which is very sensible to actions of solution because of its purity in calcium carbonate and its dense fractures and thickness (Paskoff and Sanlaville, 1978). In subterranean cavernous areas of karstic origin, revealed by cliff retreat, wave action during storms may provoke roof collapse, which forms roughly semi-circular coves. Blue Grotto (Figure 8), in southern Malta, is an example of such a landform (Paskoff, 1985).

There is evidence of past processes involved in the subsidence of Malta during the Quaternary period accompanied by a tilting movement. The following facts support this idea:

1. General topography and stratigraphic sequence are inclined towards the north-east.
2. Sinking of the bays on the north-east coast.
3. Traces of Neolithic cart ruts passing below sea level in Marsaxlokk Bay, southern Malta.
4. Stalactites hanging at the ceiling of caves which today are found below sea level at the entrance of Grand Harbour in Valletta (Hyde, 1955).
5. The presence of immersed levels about 9-11 m, 17-21 m, 25-30 m and 33-40 m at the foot of high cliffs on the south-west coast (Martineau, 1965 *in* Paskoff and Sanlaville, 1978).

Faults resulting from tectonic activity determine the outline of the Maltese coasts. Some faults are perpendicular to the littoral zone. Horsts at the north of the Island (Wardija, Bajda, Mellieha and Marfa Ridges and the island of Comino) are separated by sunk blocks which the sea has partially (at St.Paul's and Mellieha Bays) (Figure 3) or totally overrun (North Comino and South Comino Channels). Ras ir-Raheb at the end of the projection in Fomm ir-Rih Bay, western Malta coincides with the western extremity of the Great Fault of the Victoria Lines (Figure 3).

The south-west littoral zone of Malta is determined by the Maghlaq Fault (Figure 8), oriented WNW-ESE, and starting from where the Island has been tilted towards the north-east (Paskoff and Sanlaville, 1978). The result is a striking contrast between a south-west coast featuring sheer cliffs of a rectilinear aspect (Figure 4), more than 200 m high near Dingli, and a rocky but shallow north-east coast (Figure 6), gradually descending under the sea. Other evidence of the tilting is the water drainage division which runs near the south-west coast and the location of the highest point of the Island (253 m) at Ta' Zuta, near Dingli, south–west Malta (Figure 8).

The role of tectonics is not as important in Gozo. However numerous faults are located on the southern coast of the Island and very likely determine its outline (Paskoff and Sanlaville, 1978).

4.1. Coastal features

The main coastal features of the Maltese archipelago can be divided into five categories. These include cliffs, *rdum* areas, low rocky coastline, semi-circular coves and sinkholes and drowned valleys. Each category is discussed in more detail in the sections that follow.

4.1.1 Cliffs

Steep cliffs, more than 50 m high and in some places more than 200 m (Figure 4), represent half the length of the Maltese coastline (Guilcher and Paskoff, 1975; Paskoff and Sanlaville, 1978). They characterize southern and south-west Malta, eastern Comino, and most of the coast of Gozo (Ellenberg, 1983). Vertical plunging cliffs are generally cut in the Lower Coralline Limestone and lack shore platforms at their feet, such as at Ghar Hasan, southern Malta. These cliffs are vertical, rectilinear and probably of tectonic origin (Paskoff and Sanlaville, 1978). Marine erosion appears to be biochemical and inefficient. At sea level, an undercut notch is formed. It is quite regular and measures between 0.80 m to 1.50 m in depth and width (average 0.60 m). The immersed lower part features an irregular sloping pavement with a cavity formed by waves.

Figure 4: Plunging cliffs developed in Lower Coralline Limestone characterize the south and south-west coasts from Benghisa to Fomm ir-Rih. These cliffs are associated with the Maghlaq Fault and reach a height of 200 m in some parts.

Figure 5: Sandy beach backed by clay slopes at Ghajn Tuffieha Bay. This Bay which is popular and frequented both by locals and tourists has been designated by the Malta Environment and Planning Authority as an area of ecological importance and is a protected site.

Figure 6: Low rocky shore cut in Lower Coralline Limestone on the north-east coast. Pools and lapiés which produce a very irregular surface are the result of corrosion.

Where cliffs are cut in the Globigerina Limestone they are fronted, in most cases, by shore platforms produced by mechanical action of waves, mainly through hydraulic pressure that dislodge and remove blocks from stratified and jointed rocks (Figure 7). Between Marsaxlokk Bay (southern Malta) and St.Thomas Bay (south-east Malta), the Globigerina Limestone features a perfectly vertical cliff which reaches a height of more than 50 m. At sea level a structural platform, above which there is a notch, is the result of mechanical erosion. The rock here is quite uniform which helps to maintain the steepness of the cliff, and rather soft allowing marine erosion to work efficiently (Paskoff and Sanlaville, 1978).

4.1.2 Rdum *areas*

The *rdum* areas constitute a very original and spectacular element of the Maltese coasts and correspond to a type of marine cliff related to a specific geological structure that is prone to mass movements. The *rdum* areas occur where Blue Clay crops out at sea level and is overlaid with the massive strata of Upper Coralline Limestone (Figure 9). The clay is easily eroded by wave action. In addition, rainwater percolates through fissures of the limestone into the underlying clay. This causes the Blue Clay to become plastic and unstable. Jointing and faulting in the Upper Coralline Limestone causes the latter to dislodge and eventually break up, falling on the clay. The landforms are characterised by a boulder scree at sea level

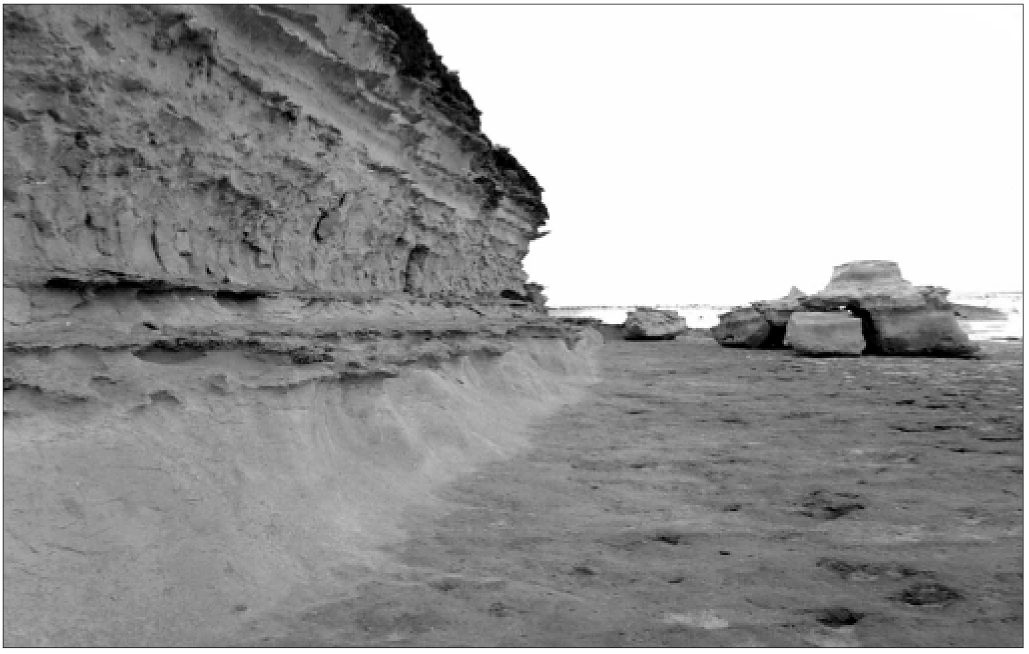

Figure 7: Low cliff and shore platform formed in Globigerina Limestone, characteristic of the southern coast. Globigerina Limestone being a softer material than Coralline Limestone displays a smoother surface. This is mainly the result of the mechanical action of waves, especially hydraulic pressure.

and larger landslides at the foot of the scarp face. As a result cliff retreat is probably slow, since a certain time is necessary for the removal of the boulders. The huge limestone blocks are too large to be displaced by the sea and form a strong protective buttressing to the clayey part of the cliff. This type of cliff probably retreats much less quickly than Globigerina Limestone cliffs (Paskoff and Sanlaville, 1978). *Rdum* areas are especially found north of the Victoria Lines Fault and in eastern Gozo (Figure 8).

4.1.3 Low rocky coastline

In north-east Malta and northern Gozo, cliffs are largely absent. Long tracts of low, rocky coastlines of corrosion (Paskoff, 1985) are found (Figure 6). Pools and lapiés give an extremely irregular topography to shore platforms, particularly when they are cut in Coralline Limestone (Figure 6). Chemical and biological weathering are the prevailing processes in the formation of such coasts. Evidence of abrasion is absent. Structural controls account for the simultaneous development of several platforms at different levels up to more than 10 m above the sea. This is evident in northern Gozo, where the Globigerina Limestone crops out. On exposed coasts large boulders dislodged by storm waves lie scattered on the shore platform, and corrosion microforms are less developed.

4.1.4 Semi-circular coves and sinkholes

Semi-circular coves, such as Qawra, near Dwejra Point and Dwejra Bay in western Gozo (Figure 8), the two creeks on the western coast of Comino, Blue Grotto on the southern coast of Malta, and Paradise Bay on the north-western coast of Malta represent a conspicuous feature of the Maltese coastline. They originate from widely distributed typical karstic landforms inundated by the sea (Paskoff, 1985). Post-Miocene solution of carbonates has reached an advanced stage, producing well-developed sinkholes and extensive subterranean cavern and gallery systems in all formations, especially in the Coralline Limestone.

In Qawra, western Gozo (Figure 8), there is a large (400 m in diameter and 70 m deep) elliptical sinkhole structure of complex origin (Pedley, 1974 *in* Paskoff, 1985), bounded by vertical walls and developed in the Lower Coralline Limestone. Its bottom has been partially inundated because a karstic gallery connects the depression with the open sea and allows small boats to pass. Dwejra Bay (Figure 8), close to Qawra is another former closed depression, measuring approximately 340 m in diameter. It has largely been invaded by the sea and only its eastern half has been preserved. An islet, Fungus Rock, is the last remnant of its western wall, destroyed by marine erosion.

4.1.5 Drowned valleys

Malta and Gozo display inlets that are partially drowned valleys (also known as *calanques*) of subaerial erosion. Typical *calanques* are found: Wied iz-Zurrieq in southern Malta and Il-Bajda in south-west Gozo are narrow, shore inundated valleys with steep sides cut in Lower Coralline Limestone. Wider and more developed inlets, such as Salina Bay in north-east Malta and Marsascala Bay in south-east Malta, correspond to finger-shaped, broad and more open valleys, subaerially eroded in the soft Globigerina Limestone and subsequently submerged (Figure 8). Changes in sea level have also submerged the mouth of some drainage channels on the coast, giving rise to headlands, creeks and bays, especially evident on the north-east coasts, since the seaward tilt of the Island is in that direction. Especially important is the system of drowned valleys which form the creeks of the two main harbours of Malta, Marsamxett Harbour and Grand Harbour, separated by the Valletta headland. Important examples of inundated river valleys in Gozo include Mgarr ix-Xini (southern Gozo) and Xlendi Bay (south-west Gozo).

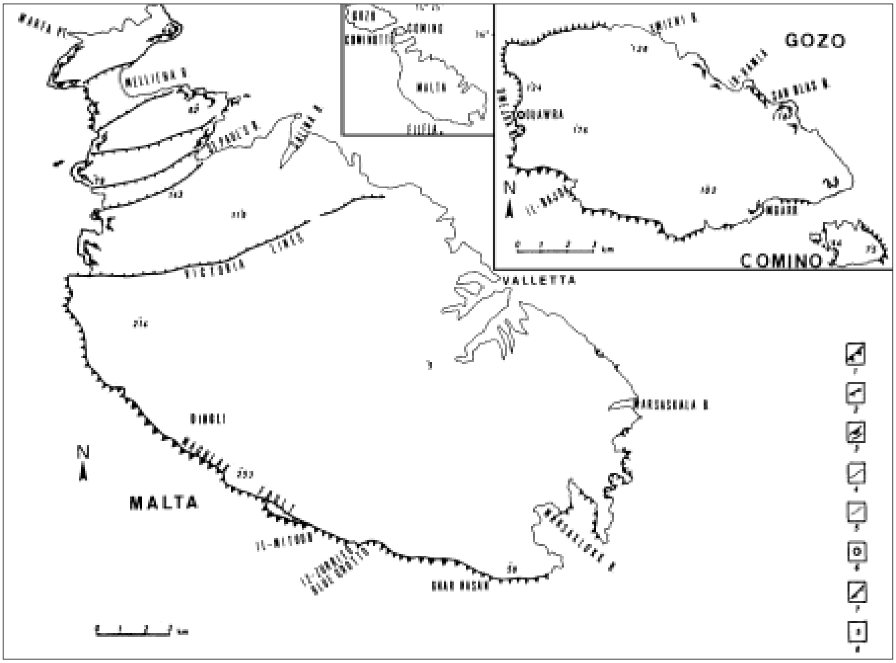

Figure 8. Predominant coastal landforms in the Maltese archipelago.
Source: Paskoff, 1985

Key
1. high cliff (more than 100 m high)
2. cliff (less than 100 m high)
3. *rdum* type cliff
4. low rocky coast
5. sandy beach
6. sinkhole structure
7. major fault
8. height in metres from datum line

Figure 9: Il-Qarraba is a peninsula separating Gnejna Bay from Ghajn Tuffieha Bay on the north-west coast. It features an *rdum* landform and its shape is unique in the Maltese Islands. Il-Qarraba is linked to the mainland by clay slopes and has been assigned the highest level of conservation and protection by the Malta Environment and Planning Authority.

5. Conclusion

This paper has showed that in Malta there are very clear relationships between tectonics, geology and landforms. The morphological response to superimposed phases of strike-slip faulting and rifting, with associated uparching and downwarping can be observed. Stream channel formation and incision, coastal geomorphology, erosion surface formation and scarp morphology have all responded sensitively to the tectonic events of the last 15 Ma (Alexander, 1988).

The structural setting of the Maltese Islands is dominated by two rift systems of different ages and trends (Illies, 1981). The older rift generation, the Great Fault, trends in a NE-SW to ENE-WSW direction. This creates a horst and graben structure in northern Malta, Comino and eastern Gozo. The second rift generation – the Maghlaq Fault – is associated with the Pantelleria Rift and trends in a NW-SE direction. This fault determines the south-west littoral of Malta and is responsible for the north-east tilt of the Islands.

The geological succession represents a varied cross-section of Oligo-Miocene lithologies and facies but consists almost entirely of carbonates. The geological formations of the Islands are very distinctive lithologically, reflected in characteristic topography and vegetation (House *et al.*, 1961a). The NE-SW trending horsts and graben cut through the entire Tertiary rock succession.

The relationship between geology and geomorphology is particularly evident at the coast. The Lower Coralline Limestone forms spectacular vertical plunging cliffs reaching more than 200 m in some places. These are probably of tectonic origin and lack shore platforms. Globigerina Limestone features cliffs which in most cases are fronted by shore platforms produced by the mechanical action of waves. Blue Clay displays itself as slopes which extend from the base of the Upper Coralline Limestone plateau to sea level. Where faulting and jointing in the Upper Coralline Limestone plateau occurs, this results in the breaking of the formation with consequent rockfall taking place. The boulders fall on the Blue Clay underneath forming a characteristic feature of the Maltese littoral – *rdum* areas. These areas are characterised by a boulder scree at sea level and larger landslides at the foot of the scarp face. Greensand does not produce any particular landform where it occurs at the coast as this is often assimilated into the base of the Upper Coralline Limestone plateau which runs parallel to the coast in north-west Malta. Besides there are few outcrops of this formation across the whole archipelago.

The role of tectonics has been recognized by Paskoff and Sanlaville (1978) who claim that the general outline of the Maltese littoral has been determined by tectonic activity. Bays in northern Malta correspond to downthrown blocks that were partially submerged. High cliffs on the south-west coast are related to a major fault. Some cliffs are associated with wave-cut platforms. Others plunge directly into the sea or are skirted by landslides. Landslides and slope instability are especially evident on the western coast north of the Great Fault of the Victoria Lines. Landslides occur both in Upper Coralline Limestone and Blue Clay Formations. The former feature translational and rotational slides whereas the latter displays mudslides (Magri, 2001).

Moreover, as far as Malta is concerned, there has been tilting of its lengthwise axis towards the north-east in addition to the general subsidence of the archipelago during the Quaternary period. No trace of former shorelines higher than the present one has been found in spite of careful investigations (Paskoff and Sanlaville, 1978). Emerged wave-cut terraces or notches as well as marine deposits seem to be entirely lacking. Formerly reported raised beaches (Hyde, 1955) are in fact pediment features. At St.Paul's Bay, cart tracks of Neolithic age enter the sea at one side and emerge on the opposite side of the inlet (Hyde, 1955). The situation suggests evidence of recent crustal subsidence, which is probably still in progress.

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