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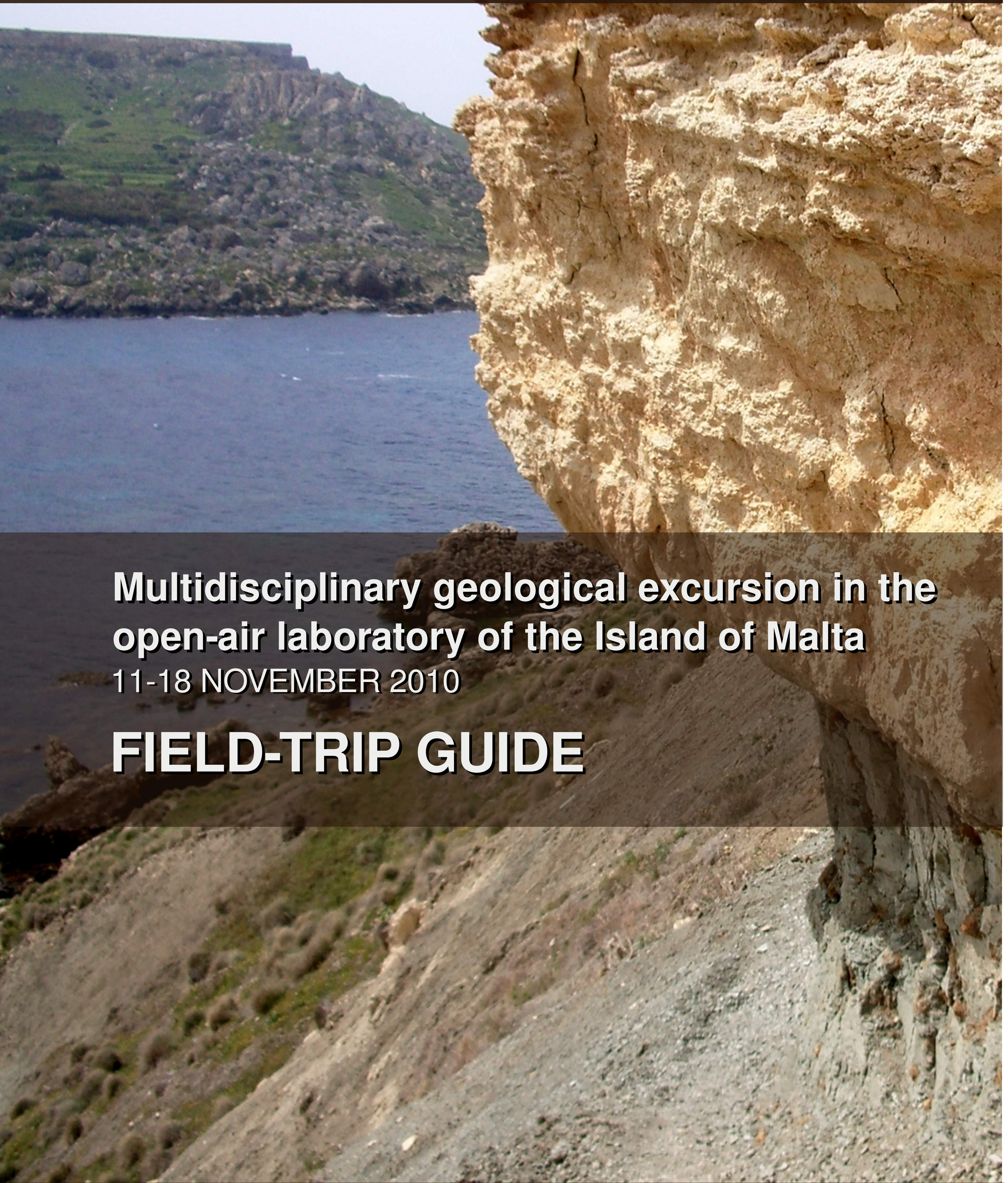

Multidisciplinary geological excursion in the open-air laboratory of the Island of Malta

11-18 NOVEMBER 2010

FIELD-TRIP GUIDE

Dipartimento di Scienze della Terra - Università degli Studi di Modena e Reggio Emilia

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Il Qarraba, north-west coast of Malta

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Mauro Soldati, Massimo Barbieri, Sara Biolchi, Fabrizio Buldrini, Stefano Devoto, Emanuele Forte, Stefano Furlani, Alessandro Gualtieri, Stefano Lugli, Matteo Mantovani, Arianna Mocnik, Veronica Padovani, Alessandro Pasuto, Daniela Piacentini, Mariacristina Prampolini, Francesca Remitti, John. A. Schembri, Chiara Tonelli, Alessandro Vescogni

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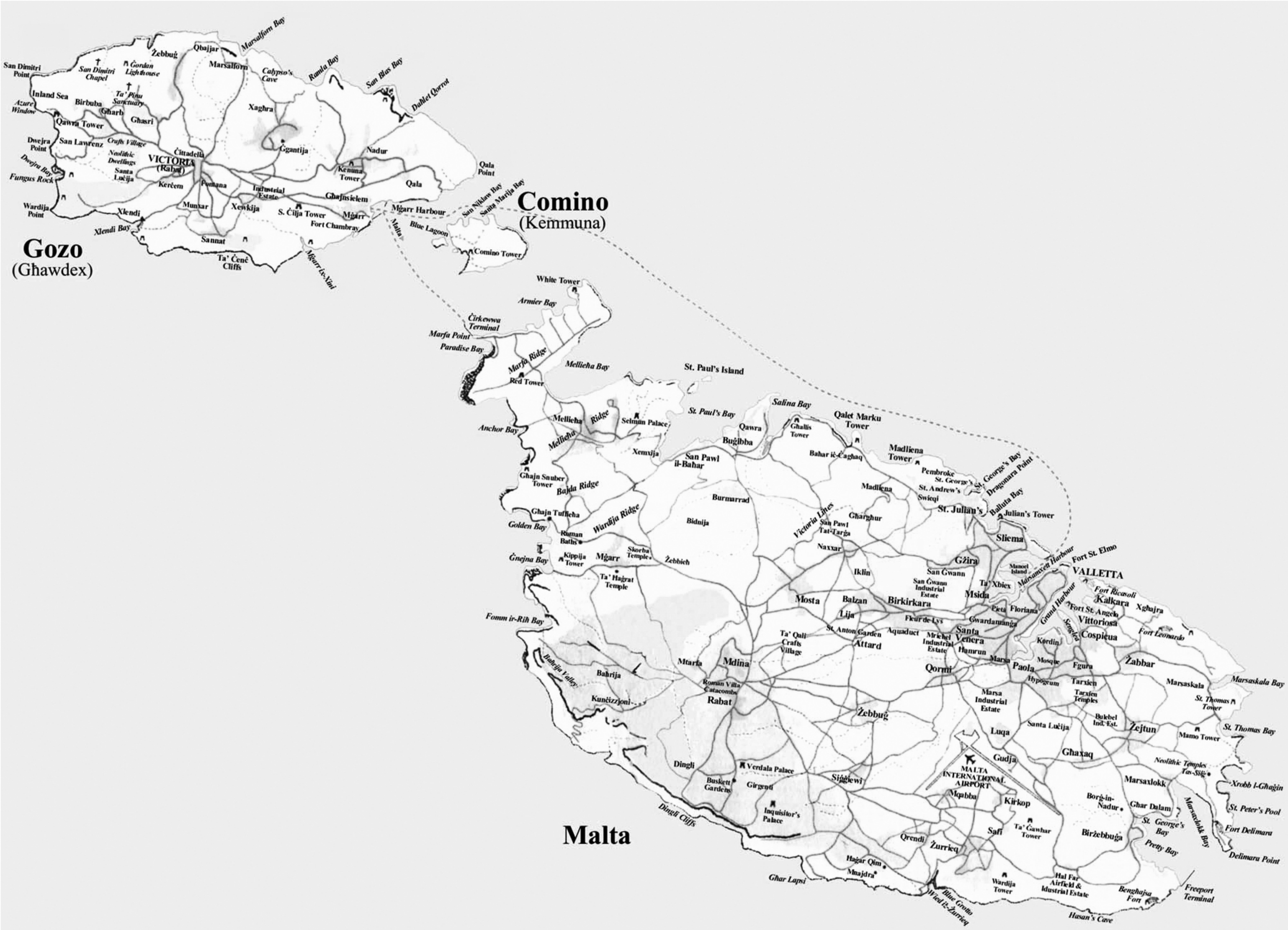
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(Għawdex)
Comino
(Kemmuna)
Malta
VICTORIA
(Rabat)
VALLETTA
Mdina
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Sliema
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Birżebbuġa
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Attard
Naxxar
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Buġibba
St. Paul's Island
St. Paul's Bay
Mellieħa Bay
Marfa Ridge
Xagħra
Nadur
Qala
Marsalforn
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Xlendi
Sannat
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Xewkija
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San Lawrenz
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MALTA
INTERNATIONAL
AIRPORT
Dingli Cliffs
Għar Lapsi
Blue Grotto

1. THE MALTESE ISLANDS: A SHORT DESCRIPTION

Introduction

The Maltese Islands are a group of central Mediterranean Islands located about 96 km from Sicily and 290 km from North Africa (Fig. 1a). They are 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 Tunisia and Libya. The total area is of 315.6 km² with the largest being Malta (245.7 km²) having the administrative capital, Valletta. The other islands Gozo (67.1 km²) and Comino (2.8 km²) together with a small number of uninhabited islets and rocks complete the archipelago (Fig. 1b). Table 1 shows additional details. The total population is estimated at 412,000 (2010) of which, about 30,000, live in Gozo.

The history of the islands has been characterized by a succession of occupiers who left their imprint on the culture of the population and affected changes to the landscape and also built a range of architectural expressions. These were either the peoples who were powerful in Europe or the Mediterranean and who occupied various lands and islands or nations for whom Malta had an important strategic value. Table 2 gives a chronological sequence of the history of the Islands.

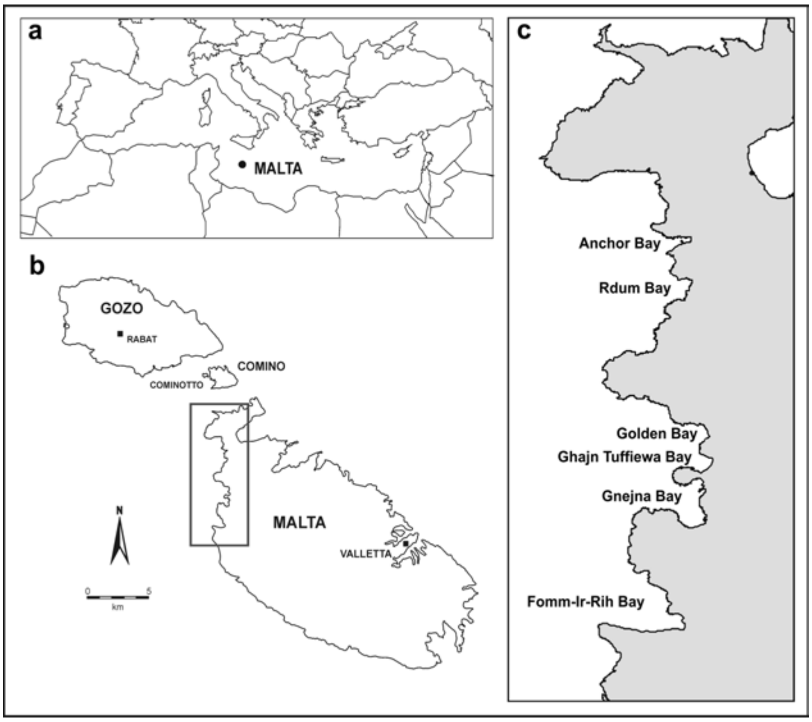

Fig. 1: a) Location of the Maltese Islands; b) The Maltese Archipelago; c) North-western coast of Malta Island (from Magri et al., 2008).

Demographic and spatial change

The increase of the population of Malta since the middle of the 16th century has been attributed to the strategic importance of the islands in the central Mediterranean. From a population of around 15,000 in 1530 the population increased to 100,000 by the end of the 18th century when the Knights of St John left the islands. During the British period (1800-1964) the population continued to increase reaching about 300,000, even though emigration was rampant for a few decades after 1945.

The growth of settlements in Malta has been largely characterized by the encroachment of buildings, industrial areas and roads on the rural environment. The isolated settlement serving mainly a rural community has slowly been transformed into an urban environment offering services normally associated with towns. In addition, agricultural areas have been built over and rural communities becoming a remnant of the past. This settlement pattern of Malta developed out of a number of factors. These range from the clustering of small villages and hamlets to form large settlements to the abandonment of small clusters of farmhouses with their population moving to larger localities. Population changes, proximal to market facilities and personal and communal security against military and plundering attacks are some of the main reasons for these movements.

The transfer of the administrative capital of Malta from the inland locality of Mdina to the coastal ones of Vittoriosa and then Valletta by the Knights of St. John in the 1560s influenced to a large extent the geography of settlement of Malta. This was accompanied by changes to the socio-economic fabric of the islands that was made possible by improvements to the defensive and physical protection from invaders. The provision of better services found in larger settlements and the possibilities of having a wider range of jobs with the improvement in employment opportunities caused both shifts to the population geography and the well-being of the people in general. Thus, by the end of the eighteenth century, settlements in Malta included a cluster around Grand Harbour, centred around Valletta and the Cottonera area extending to the harbour hinterland, and a number of rural inland settlements.

The demographic situation in Malta as a whole has been one of a constant increase of the population. However, the coastal localities have experienced a variety of different demographic situations. The localities adjacent to the Grand Harbour have experienced a decline, especially the walled towns of Valletta, Floriana, Cospicua, Senglea and Vittoriosa whilst the coastal localities to the north and south of the island saw their populations increase. The former trend was due to the decline in the services offered by the marine-related industries (e.g. the decline of the dockyard as a ship-repairing facility for the British fleet) in the Grand Harbour.

	Area km²	Length (km) trending NW to SE	Width (km) trending SW to NE	Approximate Shoreline length (km)
Malta: Main island with administrative Capital, Valletta	**246**	**27.3**	**14.5**	**136.8**
Gozo: situated 8 km to NW of Malta	**67**	**14.5**	**7.2**	**45**
Comino: two km to NW Malta 1 km to SE of Gozo	**6**	**2.75**	**2.25**	**7.5**
Cominotto: near Comino	**9.9 ha**	**450 m**	**225 m**	
St. Paul's Islands (Selmunette)	**0.02 ha**	**100 m**	**200 m**	
Manoel Island: within Marsamxett Harbour; land bridge	**included within area of Malta**	**1.25 km**	**0.45 km**	**2.8**
Filfla: three km off S. Malta coast	**2.0 ha**	**400 m**	**250 m**	
Fungus Rock: Gozo	**0.7 ha**			
Gebla tal-Halfa: Gozo	**0.4 ha**			

Tab. 1: Selected dimensions for the Maltese Islands.

Taking the Grand Harbour littoral alone, the situation is dramatic. Whereas in 1842 almost half of the Maltese population lived within the fortified precincts of the five walled towns mentioned above, by 1985 this had reduced to only 8 per cent and to 6.4 per cent in 1995. Contributory factors were the spread of industrialization beyond the Harbour area, good accessible roads leading to the harbour hinterlands, additional work places in the manufacturing industries, more efficient public transportation, increased car ownership, and the availability of land elsewhere on the island. In the immediate post-war situation unemployment was high and job prospects were low and substandard housing in the densely populated inner city areas was evident. Emigration was the considered to be the main demographic and economic safety valve, thus further decreasing the Grand Harbour population. The population increase in the coastal localities has been mainly due to the job opportunities in the tourism sector especially for St. Paul's Bay and Mellieha, land made available for urban development and the new industries in the southern part of Malta, such as Marsaxlokk, Birzebbugia and Marsascala.

It is apparent from the above that the high population density and the development of the Maltese Islands was partly due to the strategic location of the Islands, with the system of harbours and practically all-weather creeks, attracted strong maritime powers, with an interest in the central Mediterranean, who for the last four centuries gave an importance far greater than its size. This situation provided employment opportunities, a system of a military defensive network which reflects the underlying geology and geomorphology, and a foreign investment culture that is still on-going today.

The growth of the urban conurbation and the development of tourism and coastal industry, that at times mask the historical and military architectural heritage, and the land-use conflict situation over the whole territory including the coast is a reflection of these scenarios. The dependence on British military spending, the textile and leather industries and high state-dependent employment has by now changed into investment opportunities in education, language schools and developing the multi-lingualism, ICT and communications, the maritime economy, tourism, financial institutions, and real estate. In keeping pace with these developments the coastal rural environment has been afforded some form of legal designation and this includes the north-west coast.

Period/Occupiers	Years
Neolithic	5000 - 2000 BC
Megalithic	3750 - 1800 BC
Phoenician	800 - 480 BC
Carthaginian	480 - 218 BC
Roman	218 - 395 AD
Byzantine	395 - 870 AD
Arabic	870 - 1090 AD
Norman	1090 - 1194 AD
Sicilian and other Europeans (Swabians, Angevins, Aragonese, Castillians Monastic orders influential)	1184 - 1530 AD
Knights of St. John	1530 - 1798 AD
French	1798 - 1800 AD
British	1800 - 1964 AD
Independence	1964
European Union Member	2004

Tab. 2: Brief chronological sequence of the history of the Maltese Islands.

The population geography of coastal settlements

The local coastal urban environment has undergone many changes over the last century due to the rapid development occurring in the last decades. Most of the coastal areas in Malta, especially those located on the east coast, have experienced radical transformations to their land-use fabric over the last century. Initially many of these areas were inhabited by local fishermen, living in one-storey houses that doubled as boat shelters in the winter. These were generally built along the littoral parallel to the shoreline. Later two- and three-storey coastal town houses and additional facilities such as wider roads, churches and promenades were added to the urban littoral. Further development changed these areas into zones accommodating hotels and other amenities such as bars, restaurants and other forms of entertainment together with seven-storey blocks of flats. The area stretching from St. George's Bay through St Julian's to the Sliema-Msida-Pieta sea front is a clear example of this on-going process. In addition the localities to the south and south-east of Malta and Marsalforn and Xlendi on Gozo are going through the same process though not at such a fast rate.

Year	Maltese Islands	Increase or decrease Per cent
1891	164,870	-
1901	184,427	11.9
1911	218,304	18.4
1921	204,565	-7.3
1931	234,843	14.8
1948	305,435	30.1
1957	319,645	4.7
1967	305,119	-4.6
1985	365,901	19.9
1995	378,142	3.3
2005	404,962	7.1

Tab. 3: Population growth and change between 1891 and 2005.

Coastal land use

Land use along the coastal margin is partly the result of the physical processes outlined above. In areas where the low sloping rock prevails and access to the coast is high, development has taken place. The opposite is true for areas with high cliffs and boulder scree slopes. In addition, development has been attracted to areas where bays, creeks and inlets are located. Table 3 gives an outline of the main coastal land uses. The area of coast represented covers approximately 19 km² with the distance inland running approximately parallel to the shoreline. The results show clearly the difference between Malta and Gozo/Comino where a greater economic activity in Malta is reflected in the type of coastal land use.

The rural nature of the Gozitan littoral is expressed in the 87 per cent of coastal land being either undeveloped, consisting of bare rock, scree slopes and shore platforms or arable land where agricultural activity predominates.

The contemporary land use scenario is partly the result of the importance of the islands as a strategic location in the Mediterranean. Archaeological remains, military fortifications, maritime industrial areas and urban sprawl along the harbours marked coastal land use development up to the middle of the last century. Touristic development in northern areas, second home ownership and the industrialization of the south of Malta are the contemporary additions to the coastal cultural fabric. This situation brought about elements of land use conflict along the coast especially in areas with a high degree of accessibility.

Up to 1989 the only land use data available for the Maltese Islands was that dealing with the extent of urban areas. These data indicated an urban sprawl growing from 5.5 per cent of the surface area of Malta in 1955 to 16.5 per cent in 1985 (Malta Structure Plan, Inception Report, 1988). However, in 1990 it was estimated that the island of Malta alone had 28 per cent of its surface used for urban, industrial, touristic and airport facilities. Table 4 shows the most recent data collected.

Locality	1901	1931	1948	1957	1967	1985	1995	2005
Valletta	22,768	22,779	18,666	18,202	15,279	9,340	7,262	6,300
Floriana	5,687	6,241	5,074	5,811	4,944	3,327	2,701	2,240
Cospicua	12,148	11,536	12,163	4,822	9,123	7,731	6,085	5,657
Senglea	8,093	7,683	2,756	5,065	4,749	4,158	3,258	3,047
Vittoriosa	6,093	6,573	3,816	4,242	4,017	3,572	3,069	2,071
Mdina	304	982	1,384	823	988	421	377	278

Tab. 4: Population change in walled towns for census years.

2. CLIMATIC SETTING

The climate of Malta is typically Mediterranean, with hot, dry and long summers, warm and short winters. Obviously weather and climate are strongly influenced by the sea and by the relatively flat morphology of the Island of Malta that do not favour precipitation.

Malta has a very sunny climate with an average of twelve hours of sunshine a day in summer while in midwinter the light hours do not exceed the hours.

The the monthly temperature averages ranges from 12° C (January) to 27° C (August).

Months	Mean rainfall (mm)	Mean temperature (C°)
January	87	12.4
February	60	12.4
March	42	13.6
April	22	15.7
May	10	19.2
June	3	23.2
July	0	26.0
August	8	26.5
September	42	24.3
October	87	21.1
November	89	17.4
December	104	14.0

Tab. 5: Monthly weather data collected in the last century in Malta.

The average annual precipitation is 530 mm for the period 1951-1990 (source: Malta Meteorological Office) and hardly exceed 600 mm, with an average of about seventy rainy days during the year.

Four-fifths of rain falls during the period from October to February, on the contrary, July and August are characterized by an almost complete drought. Storms with hail are not so uncommon.

Table 5 summerises monthly weather data collected in the last century in Malta.

Rainfall and temperature data for the Maltese Islands has been aviable since 1922 from Malta Meterological Office, located in Luqa Airport.

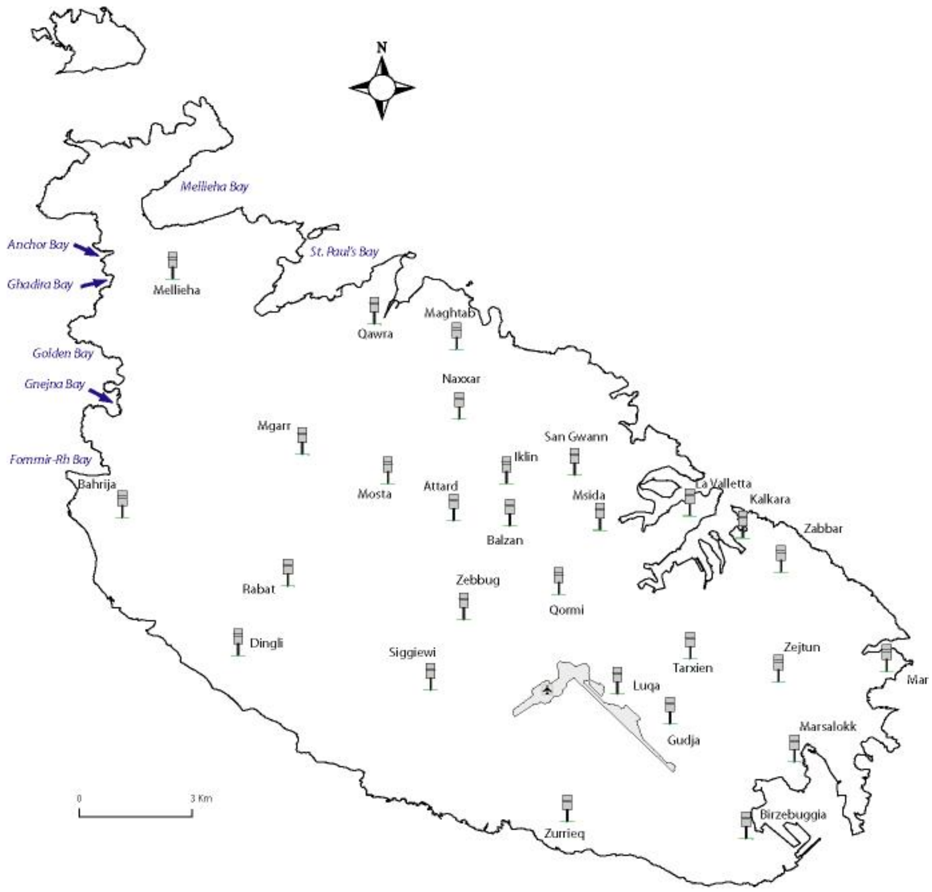

Fig. 2: Malta Weather network.

Currently the most complete network is property of Malta Weather company. It includes 28 automatic weather stations in Malta Island and 7 in Gozo (Fig. 2). The first one was installed in 2002 near Balzan.

Winds are frequent and strong; the most common are:

- the Mistral
- the Grecale
- the Sirocco.

The most common wind is the cold Mistral, called also from Maltese population “Majjistral”; it comes from the north-west; the dry Grecale blows from the north-east, the last one is the Sirocco that comes from south and is common only on September.

The phenomenon known as “blood rain” depends mainly on Sirocco wind. “Blood rain” is water mixed with red coloured sand from Sahara Desert in northern Africa. When the wind is blowing strongly from a southerly direction, sand is carried over to the Maltese Islands and beyond (e.g. Italy).

Thunderstoms, heavy rain showers and strong wind cause frequently severe damages.

In the last years the highest 24-hour rainfall total was at Valletta (Central Malta) with 87 mm on January 2009, when a violent storm hit whole Maltese archipelago. The rainest day in the last seven decades occurred on 25 october 2010, when 102 mm of rain fell at Luqa. This is the second heaviest rainfall ever recorded after that of 26 october 1939 (132 mm).

There was flooding in the usual low-lying areas of Malta with some cars being carried away by the flood waters. Wind speed often exceeds 100 km/h, a maximum gust of 142.5 km/h from the SSE was registered at Mellieha at 4 March 2009. This spring storm caused some damages, including damage to historical Xarolla windmill in Zurrieq (Central Malta), built in 1724, and the protective shelter installed over Mnajdra Temples.

3. THE FLORA OF THE MALTESE ISLANDS

The flora of the Maltese Islands, given the position of the archipelago, is influenced by all parts of the Mediterranean Sea and includes also elements typical of northern Africa; as one can easily understand, it is similar to Sicilian flora and particularly to the one of Hyblaean Mountains, to which Malta was sometimes connected till 12.000 years ago (Lanfranco, 2010). In every case, the flora of the archipelago is not a simple appendix of the Sicilian one (Weber and Kendzior, 2006). The climate is classically Mediterranean, with minimum temperatures rarely below 5° C and maximum ones rarely under 35°. Annual rainfall is about 500 mm, so the vegetation depends much on the sea-level water table, originated by marine seepage into the rocks. The islands are considerably exposed to strong winds, especially to north-eastern ones, thus plants show adaptations typical of the arid, salty and windy environments (Lanfranco, 2010): exactly for this reason, about 50% of the Maltese flora is composed by annual species, the annual life being an excellent xerophilous adaptation (Sommier, 1916).

The colonisation of the archipelago is dated to 5.000 years B.C., and they were populations that already knew advanced agricultural techniques: so the Maltese Islands have been under an anthropic pressure much higher than the one we can find in other Mediterranean islands of comparable extension. As a consequence, the vegetation has been subjected to great alterations (Lanfranco, 2010), now irrevocably, so that one hundred years ago Sommier (1916) observed that "*...not easy is the access to the localities where could resist the primigenial flora. Great is the extension of cultivated lands, fenced by walls and traversed by dusty paths, in which are found almost only anthropophilous plants very common in the Mediterranean region. The uncultivated lands most interesting for the botanist are principally at the periphery of Malta and Gozo, far away from the towns and mostly inaccessible from the side of the sea, so that for to reach them it needs to rent a coach for all the day, loosing a lot of time in the going and return.* […] *Everywhere the industrious Maltese farmer could till the soil, has disappeared the ancient flora. None terrain with ancient associations remained, except in the inaccessible places on the steep sides of the valleys and on the cliffs of the coast, or in the bare rocky plateaus where cultivation could not be profitable*".

The original tree and shrub vegetation, hopelessly compromised since a lot of time, includes only the survived 25-30 exemplars of *Quercus ilex* L., someone of them more than one thousand years old (Weber and Kendzior, 2006), growing in a few localities in the island of Malta, that are the last remains of the ancient forests that covered large parts of the archipelago until a few centuries ago. The woodlands of *Pinus halepensis* Mill. have been destructed, too, but the numerous replantings have allowed the creation of some areas (especially Buskett and Mizieb) with characters of forest (Lanfranco, 2010), that seem to maintain themselves and self-regenerate as a semi-natural woodland communities. On the contrary, we cannot say the same thing about the woodlands of Acacia of the eastern parts of Marfa Ridge (Weber and Kendzior, 2006). Human impact is surely responsible of the almost total extinction of several species typical of the Mediterranean basin, such as *Arbutus unedo* L., *Juniperus phoenicea* L., *Lavatera arborea* L., *Chamaerops humilis* L., *Cistus*, *Myrtus* (Sommier, 1916). The corresponding vegetal communities of *A. unedo* and *J. phoenicea* still exist; this last is naturalized in Wardija near a small *Q. ilex* wood, while the first one is sporadically cultivated and used in projects of environment restoration. We can still see some little populations of *Myrtus*, but without doubts it is a rare species (Lanfranco, pers. comm.). Another plant characteristic of the Mediterranean region, *Erica arborea* L., probably never existed in Malta, likely because the soil is not suitable for the species (Lanfranco, pers. comm.).

The maquis vegetation is still diffused, especially on the slopes and in the bed of the widien. In every case, they are secondary formations, dominated by non-indigenous species such as *Ceratonia siliqua* L., *Pistacia lentiscus* L., *Laurus nobilis* L., *Olea europaea* L. Given the great reduction in grazing, there is now a notable increase in maquis vegetation, that sometimes shows uncommon species like *Rhamnus alaternus* L., *Pistacia terebinthus* L. and overall *Tetraclinis articulata* (Vahl) Mast., a tree typical of Maghreb, in Europe known only in Murcia, Malta and Liguria. Many centuries ago it was widespread in the Maltese Islands, but now it is restricted to a few localities on rocky slopes (Lanfranco, 2010). The species has a characteristic ecology: it looses the terminal little branches during the arid season, that fall to the ground and form a thick layer maintaining humidity; the little branches are degraded rapidly thanks to the proliferation of the fungal symbiotic communities, and the result is a sort of recycling of the resources, advantageous both for the plant and for the fungi, that can develop communities much wider than the tree roots (Buhagiar, pers. comm.).

The garigue is the most typical vegetal formation. Characteristic of the karstic regions of the archipelago, it is rapidly disappearing for the urbanization, opening of new roads and dumps and other kinds of habitat disturbance. It shows important shrub species, such as *Thymus capitatus* (L.) Hoffm. *et* Link, *Erica multiflora* L., *Anthyllis hermanniae* L., the endemic *Euphorbia melitensis* Parl., *E. dendroides* L., *Teucrium fruticans* L. In some cases, one can find also *Cistus incanus* L. and *C. monspeliensis* L., while the herbaceous species are numerous and many of them grow both in rocky steppes and open maquis (Lanfranco, 2010).

The steppe vegetation is widespread all over the islands and shows a great variety of species. The dominant herbaceous are *Stipa capensis* Thunb., *Hyparrhenia hirta* (L.) Stapf and *Brachypodium retusum* (Pers.) Beauv.; the thistle steppes are characterised by *Carlina involucrata* Poir., a North African species that in Europe occurs only in Malta and in the Pelagian Islands. The most common geophyte in these formations is *Asphodelus microcarpus* Viv., abundant on frequently burnt grounds (Lanfranco, 2010). A particular kind of steppe grows on clay slopes, usually dominated by

Lygeum spartum L., stabilizing the clays by means of its rhizomes (Lanfranco, pers. comm.).
The cliffs are an important feature of the topografy of these islands, especially present in the southern and western zones of Malta and in many parts of the perimeter of Gozo and Comino. The vegetation of these areas is similar to a particular type of maquis or garigue, but the flora is very interesting because here survive many endemic species or plants of North African affinity (Lanfranco, 2010). In these formations, the most typical species are the endemic *Palaeocyanus crassifolius* (Bertol.) Dostal, *Darniella melitensis* (Botsch.) Brullo, *Capparis orientalis* Duhamel, various species of wild carrots (*Daucus* spp.) not yet investigated and *Cremnophyton lanfrancoi* Brullo *et* Pavone, a plant that probably has problems of pollination and germination, because seed production is very scarce and the same seeds are little viable (Buhagiar, pers. comm.).
In Malta there are also humid areas, salty swamps and sand coasts, although these environments are not so common. Great part of the vegetation of these communities in the Mediterranean is similar to the one of analogue communities of continental Europe. All the salty swamps have been degraded by human presence, while someone has been restored or is being restored as a natural reserve (e.g. Ghadira). The local vegetation is dominated by various Chenopodiaceae and rushes (Lanfranco, 2010). In certain valleys, the temporary presence of watercourses or the little permanent springs (very rare in Malta – Weber and Kendzior, 2006 –) allow the growth of a vegetation characterised mostly by reeds (especially *Arundo donax* L., now weed – Lanfranco, pers. comm. –), by sedges, various herbaceous plants and rushes. *Typha domingensis* Pers., rare in past times, is now expanding in several ponds and watercourses. In a few cases, these places show an arboreal deciduous vegetation, with species like *Populus alba* L., *Ulmus canescens* Melville, infrequent in Malta, and *Salix alba* L. and *S. pedicellata* Desf., endangered with extinction despite the efforts of non-governmental organizations for propagating them (Lanfranco, 2010). On the contrary, given the canalisations of watercourses, the drainages, the destruction of the salinas, a lot of herbaceous hydro-igrophilous species have become extinct since many decades: for example, *Iris pseudacorus* L., *Schoenoplectus lacustris* (L.) Palla, *Cyperus papyrus* L. (Sommier, 1916; Lanfranco, pers. comm.). One can find *Lemna minor* L., instead, probably due to recent accidental reintroductions (Lanfranco, pers. comm.).
A particular kind of humid area is associated with karstlands, typically in garigue zones on coralline limestones (Weber and Kendzior, 2006), where some depressions can fill up with water during the rains and maintain it in general until mid-spring (Weber and Kendzior, 2006; Lanfranco, 2010). These temporary pools host an extremely interesting flora and fauna: we cite only *Damasonium bourgaei* Coss., with a very restricted Mediterranean distribution, *Isoëtes histrix* Bory, extremely rare (Weber and Kendzior, 2006) and *Elatine gussonei* (Sommier) Brullo, Lanfranco, Pavone *et* Ronsisvalle, endemic of Malta and of the Pelagian Islands (Lanfranco, 2010).
Sand dunes have been compromised a lot in the last fifty years (Lanfranco, 2010), because of tourists frequentation of the beaches (Weber and Kendzior, 2006), and now show a very empoverished vegetation, except at the Ramla in Gozo. The dominant species are *Elytrigia juncea* (L.) Nevski, *Sporobolus arenarius* (Gouan) Duval-Jouve, *Cakile maritima* Scop. and *Pancratium maritimum* L.; *Ammophila litoralis* (P. Beauv.) Rothm., on the contrary, seems to have become extinct (Lanfranco, 2010).
Due to the very strong human presence, the communities of disturbed soils have become absolutely the most frequent of the archipelago, so that the most familiar plants are those typical of these zones. Many of them are aliens or adventives, naturalized over the years: the most common Maltese wild species (now weed – Buhagiar, pers. comm. –) is *Oxalis pes-caprae* L., native of southern Africa and introduced in Malta at the beginning of XIX century, as a plant cultivated in the botanical garden. Thence it spread more and more all over the Mediterranean Sea and along the Atlantic coasts of Europe: now one can find it also in southern England (Lanfranco, 2010). *Chrysanthemum coronarium* L., probably an oriental species, was likely introduced several hundreds of years ago. *Aster squamatus* (Sprengel) Hieron., now common everywhere in the country, was only introduced in 1930s; *Nicotiana glauca* R.C. Graham, instead, was introduced as an ornamental plant and nowadays is widely naturalized especially on rubble, like *Ricinus communis* L., rapidly spread and now invasive in the valleys (Lanfranco, 2010).
The Maltese Islands show a lesser presence of endemic species than many other comparable Mediterranean territories. It may seem strange, for these lands are the most isolated and thus would be expected to have a higher degree of endemism. This situation is likely due to the intense human influence on the environment: it is not improbable that some endemic, particularly vulnerable species have been lost (Lanfranco, 2010). Nevertheless, isolation has left its marks, because two endemic species of the archipelago are classified as a monotypic genera (*Palaeocyanus crassifolius* and *Cremnophyton lanfrancoi*), so they are very isolated *taxa*. Some endemic species are in reality palaeoendemic, relicts of the preglacial Mediterranean flora, witnesses of important evolutionary processes and the biogeography of this part of the Mediterranean basin (Weber and Kendzior, 2006). Apart from the real endemic species, there are also some others with a very restricted Mediterranean distribution: they are often exclusive of Malta and Sicily (siculo-maltese) or Malta and the Pelagian Islands (pelago-maltese), such as *Daucus lopadusanus* Tineo, *Desmazeria pignattii* Brullo *et* Pavone, *Senecio pygmaeus* D.C., *Iris sicula* Todaro (Lanfranco, 2010).
In addiction, there are other plants described only at level of forma or local race, that could be ulterior endemic species not yet known: for example some rupestral species of wild carrots (*Daucus*) and at least two other types of *Limonium* (Lanfranco, 2010).
The so-called Maltese Fungus (*Cynomorium coccineum* L., of the Cynomoriaceae family), firstly described at Fungus

Rock and then discovered in various islands and coastal localities of the Mediterranean Sea, is an angiosperm parasiting the roots of many alophilous shrubs, like *Inula crithmoides* L. (Lanfranco, 2010).
One can say that Maltese flora is quite poor: in 316 km², we can count a thousand of species, while the island of Elba, having a surface of 223 km², shows 1080 species (Sommier, 1916). This fact is due to the great uniformity of ecological conditions (monotone configuration of the terrain, generally flat, absence of hills, little variety in soil composition, water scarcity). The uncultivated rocky uplands, denuded of the maquis by human, until a few decades ago were made even more stark by the goats that were sent to pasture (activity now become extremely rare, visible only in a few areas near Had-Dingli – Seguna, pers. comm. –). "*But we can have an idea of how could be the Maltese vegetation, also without a change of climate, if human and goats action ceased, observing how much it is lush at the bottom of some valley and on the abrupt faces of inaccessible crags*" (Sommier, 1916).

4. GEOLOGICAL ASPECTS

During the Late Oligocene to Miocene the Maltese Islands and southern Sicily were part of a large platform located on the more distal segment of the African continental margin (Fig. 3). From the Late Miocene to recent time this structure was constituted by a shallow carbonate platform (maximum depth about 200 m) placed between Europe and Africa.

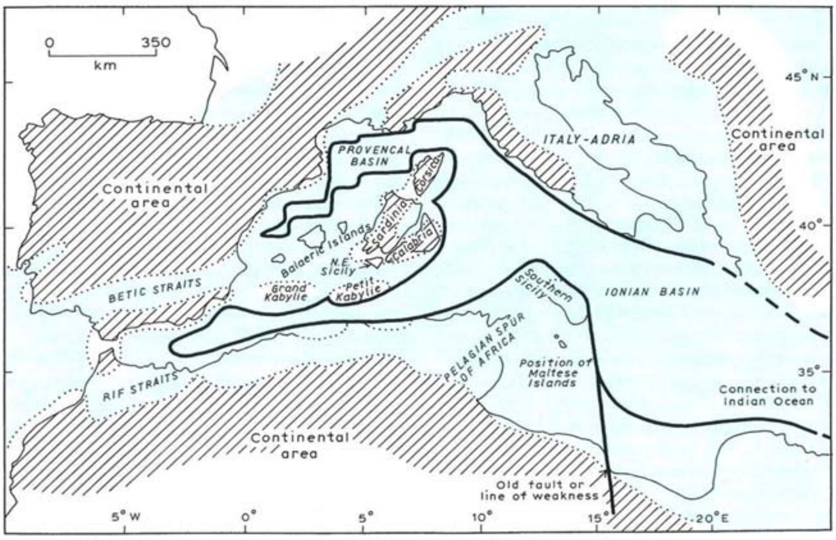

Fig. 3: Structural setting of the Mediterranean area during the Oligocene (from Pedley et al., 2002).

All formations cropping out on the Maltese Islands are of sedimentary origin and have been deposed on this relatively shallow-water setting. This sedimentary succession comprises four major lithostratigraphic units (Fig. 4) that, although slightly disturbed by fault displacement, lie almost horizontally across the islands. Their age span from the Late Oligocene to the Late Miocene, when the Archipelago finally emerged. A detailed description of the lithostratigraphy of the sediments of the Maltese Islands has been given by Pedley (1978) and is summarised below.

Lower Coralline Formation
> 50 m; Upper Oligocene (Chattian – 28.4/23 Ma).
This basal unit is represented by a hard, pale grey limestone that form sheer cliffs from ten to over one hundred meter high. Lower Coralline Limestone is made mainly by reef-building organisms and reef-related sediments. Reef bodies are characterized by calcareous coralline algae, arranged in superimposed laminar crusts and forming ball-shaped masses called "rhodoliths". Scattered mounds made by coral colonies are also present. A large number of other organisms, such as bivalves, gastropods, foraminifera, bryozoans, echinoids and serpulids can also be found: they are commonly preserved as small fragments, representing the main components of the coarse, bioclastic sands associated to the reef structures. Fine-grained lime sediments are also present, related to the deposition within more sheltered and/or deeper environments. The top of the Lower Coralline Limestone is usually underlined by the presence of the so-called "*Scutella* Bed", a layer (few centimeters to a meter thick) with a great concentration of large, flat sea-urchins. This level can be used as a marker to define the passage to the overlying *Globigerina* Limestone Formation.

***Globigerina* Limestone Formation**
25/200 m; Lower Miocene (Aquitanian/lower Langhian – 23/14 Ma).
The *Globigerina* Limestone appears as a lightly cemented, yellowish, fine-grained limestone that forms irregular slopes, where the presence of slightly harder strata produces small terrace-like steps. This formation takes its name from the planktonic foraminifera *Globigerina*, which is the most abundant fossil contained in this limestone. Macroscopic fossil remains are represented by large bivalves and echinoderms. However, the most prominent visible fossil are the traces of burrowing animals, that sometimes form a complex system of tunnels whose appearance can be enhanced by the action of the weathering. This formation is usually divided into three parts by the presence of two prominent hard beds. These

“hardgrounds” are up to 30 cm thick and are represented by heavily-cemented pebbles, cobbles and fossil remains (molluscs, solitary corals, echinoderms, fish teeth, etc.). The typical reddish-brown color of these beds is related to the presence of the phosphatic mineral Francolite, contained in the cements that replace some fossils and the matrix among the clasts. With a gradual transition, the *Globigerina* Limestone passes to the overlying Blue Clay Formation.

Blue Clay Formation

20/70 m; Middle Miocene (upper Langhian/lower Tortonian – 14/10 Ma).

This is a very soft unit forming low slopes, usually covered by soil or scattered rubble. In its origin, this formation is very similar to the underlying one. This is suggested by the high content of very fine-grained sediment, dominated by skeletal material from planktonic organisms. However, the additional presence of abundant clay minerals (almost 50%) gives to these sediments completely different properties and appearance, allowing them to weather easily and form low to round slopes. This clay fraction, mainly represented by kaolinite, can only have come from a land source.

This source has been identified with the area north of Sicily, at that time subject of an intense uplift related to the convergence of African and European plates. In addition, some part of the clay minerals could have been produced as volcanic ash, perhaps from eruptions associated with the formation of the Pantelleria Rift.

The uppermost part of the Blue Clay Formation shows an increase in brown phosphatic sand grains and green grains of the mineral Glauconite. Often separate by an erosional surface, these deposits pass up into a sand made almost entirely of green grains, together with abundant fossil fragments (mainly foraminifera, echinoderms, etc.). This level, rarely thicker than one meter, is known as the <u>Greensand Formation</u> and underline the passage to the overlying Upper Coralline Limestone Formation.

Upper Coralline Limestone Formation

10/160 m; Upper Miocene (upper Tortonian/ lower Messinian – 10/6 Ma).

The topmost unit is, again, a hard, pale gray limestone that appears very similar to the lowermost formation, also forming steep cliffs of varying height. Like the Lower Coralline Limestone, this formation is mostly made up of reefal limestone and related sediments. Bioconstructed levels are mainly built by calcareous coralline algae (again forming rhodoliths, often associated to laminar structures) together with less common coral colonies forming small, scattered reefs. Bioclastic sediments, constituted of fossil fragments and/or oolitic accumulations, surround these structures, sometimes developing cross-bedded sand bodies. Different kinds of finer sediments (fine sands and muds), often containing benthic and planktonic foraminifera, are typical of less exposed environments, such as protected lagoons or deeper waters.

The Upper Coralline Limestone Formation represents the last marine sediments on the Malta Islands. Subsequently, during the late Messinian, the Mediterranean basin suffered a progressive emptying and a partial desiccation, with the deposition of thick deposits of evaporite sediments (salt and gypsum). A small area of the Ghar Lapsi coastline (SW Malta) is the only place in the Maltese succession where this kind of sediments can be observed.

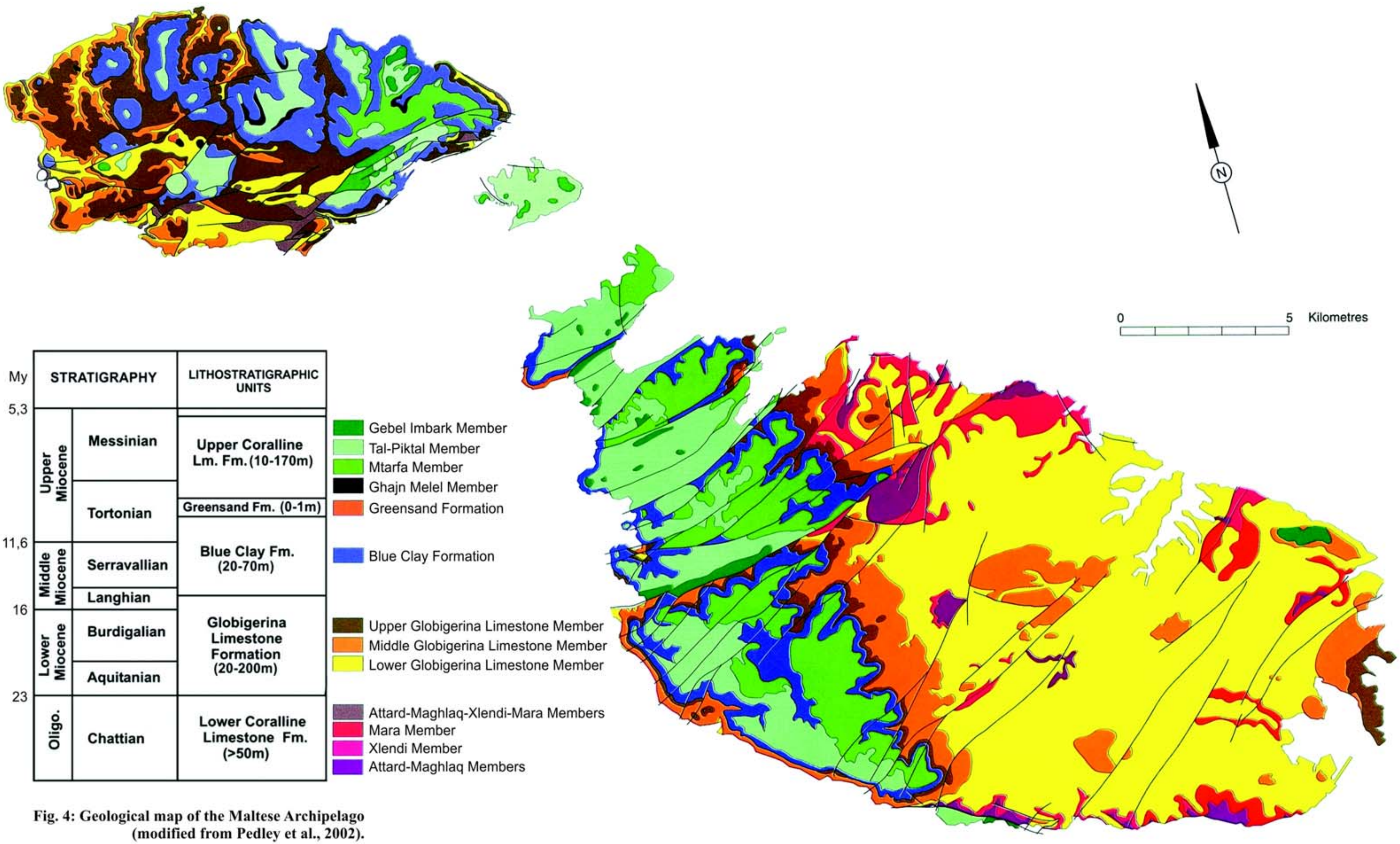

Fig. 4: Geological map of the Maltese Archipelago (modified from Pedley et al., 2002).

5. STRUCTURAL SETTING

The Maltese Islands lie in the Sicily Channel on a relatively stable plateau of the African foreland, the Pelagian Platform, about 200 km south of the convergent segment of the Europe-Africa plate boundary that runs through Sicily (Fig. 5) (Reuther and Eisbacher, 1985; Argnani et al., 1990; Dart et al., 1993; Galea, 2007). The Pelagian Platform forms a shallow shelf separating the deep Ionian Basin from the Western Mediterranean.

The Sicily Channel has been affected during Neogene–Quaternary (Dart et al., 1993; Civile et al., 2010) by a process of continental rifting which produced several geological features: (a) the Pantelleria, Malta and Linosa tectonic depressions, controlled by NW-directed sub-vertical normal faults clearly observable in seismic lines (Finetti, 1984); (b) two volcanic islands (Pantelleria and Linosa) and a series of submarine magmatic manifestations; (c) a thinning of the crust beneath the troughs up to about 17 km along the Pantelleria graben axis; (d) positive Bouguer anomalies ranging between +40 and +80 mGals.

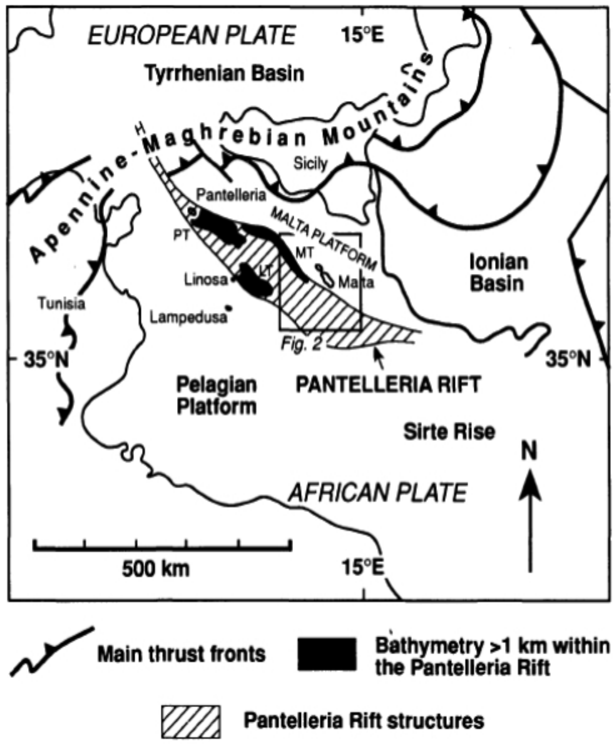

Fig. 5: Location of the Maltese graben system within the central Mediterranean. PT, Pantelleria Trough; LT, Linosa Trough; MT, Malta Trough (from Dart et al., 1993).

The tectonic style of the Sicily Channel is remarkably symmetrical and has been attributed to the McKenzie-style pure shear extension with an upper brittle layer overlying a ductile lower layer, producing a symmetrical lithospheric cross section.

The Sicily Channel Rift Zone has been interpreted in different ways. Some authors consider the tectonic depressions as large and discrete pull-apart basins involving deep crustal levels, developed along a major dextral wrench zone (Jongsma et al., 1985; Reuther and Eisbacher, 1985; Ben-Avraham et al., 1987; Finetti, 1984). Others interpret the rifting as due to mantle convections developed during the roll-back of the African lithosphere slab beneath the Tyrrhenian basin (e.g. Argnani, 1990). Lateral crustal density variations are invoked for explaining the remarkable segmentation along the central Mediterranean collision zone, which may lead to the formation of transform faults, as in the case of the Sicily Channel Rift Zone (Reuther et al., 1993). A mechanism of intraplate rift, related to NE directed displacement of Sicily away from the African continent, has been also proposed (Illies, 1981).

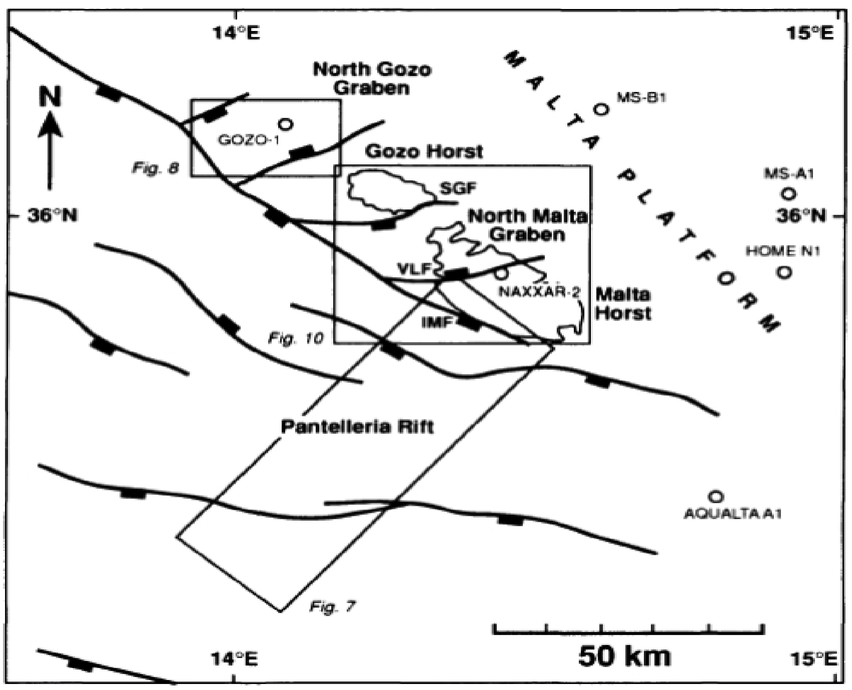

Fig. 6: Principal structures of the Maltese graben system. SGF, South Gozo fault; VLF, Victoria Lines fault; IMF, I1 Maghlaq fault (from Dart et al., 1993).

The Maltese graben system forms a small part of the arcuate, 600 km long, rift system (Fig. 6). It dominates the Malta archipelago and its surrounding offshore area. The graben transect Mesozoic to Tertiary shallow marine and pelagic limestones of the central Mediterranean Pelagian Platform (Fig. 7), and have exerted a profound control on deposition from the Lower Miocene to the present day and it has also been responsible for the major tectonic and geomorphological development of the Maltese Islands (Illies, 1981).

The Maltese graben system is characterized by two intersecting fault trends (Fig. 6). To the SW of Malta lies the 100 km wide NW-SE-trending Pantelleria Rift (Reuther and Eisbacher, 1985). The Malta

Platform forms the Rift's northeastern shoulder and is dissected by the two important ENE-WSW trending graben: the North Gozo and North Malta Graben, and the intervening Malta and Gozo Horsts (Fig. 6, 7). They intersect the Pantelleria rift at an acute angle of 66° and 32° respectively (Fig.6). The North Gozo Graben is by far the deepest of the two with a throw of 1600 m on its northwestern bounding fault. The Victoria Lines fault has the greatest displacement (195 m) within the North Malta Graben (Costain, 1957-1958). Within these three main graben the extensional faults are generally sub-parallel to the boundary faults and no transfer faults have been mapped. The faults within the graben systems are generally planar with average dips of 64° to 73° (range 43° to 90°) .

Graben architectures include “full-graben” bounded by faults of opposite polarities and half-graben bounded by faults of like polarities. Symmetrical full graben dominate. Both the Pantelleria Rift and the North Malta Graben are symmetric with central keystone fault blocks and marginal terraces. Fault block dips are generally shallow and rarely exceed 10°. Significant stratal rotations occur locally, in the vicinity of major faults. Hanging wall deformation is usually characterized by synclines and, less commonly, by roll-over anticlines. The synclines are often associated with minor contractional faults.

Onshore exposures show that major fault offsets are distributed across narrow zones of synthetic faults which are generally less than 35 m wide.

The most active period of extension on both fault trends was during the Plio-Quaternary (Jongsma et al., 1985), although minor extension associated with an early syn-rift period occurred throughout the Miocene (Illies 1980). The major faults all influence the entire Oligo-Miocene succession and there is evidence that movement has been continuous since Miocene times (Magri et al., 2008).

Some Authors (Illies, 1980; Reuther and Eisbacher, 1985 and references therein) have divided the kinematic evolution of the Maltese graben system into three distinct phases:

The ENE-WSW faults of the North Malta Graben formed during phase one, and the NW-SE faults associated with the Pantelleria Rift during phase two. The third phase involved the reactivation of the ENE-WSW trend by dextral strike slip motions. Illies (1980) suggested that on the Maltese islands NE-SW-trending faults ubiquitously cross cut NW-SE-trending faults.

Dart et al. (1993), instead, suggest that the kinematic evolution of the Maltese graben system can most simply be explained by a single phase of N-S orientated extension, which resulted in the formation of two distinct fault trends. They based their conclusions on (a) the synchroneity of pre-rift, early syn-rift and late syn-rift tectono-stratigraphic divisions across the North Malta Graben, North Gozo Graben and Pantelleria Rift; (b) the extension direction for the Maltese region determined using fault slip data (fault plane orientation, striae lineation orientation and sense of slip) from exposed fault planes and stratigraphic offsets; (c) the lacking of evidence for significant strike-slip deformation. The coeval development of two distinct rift trends has been explained either in terms of triaxial strain or reactivation of a pre-existing tectonic fabric.

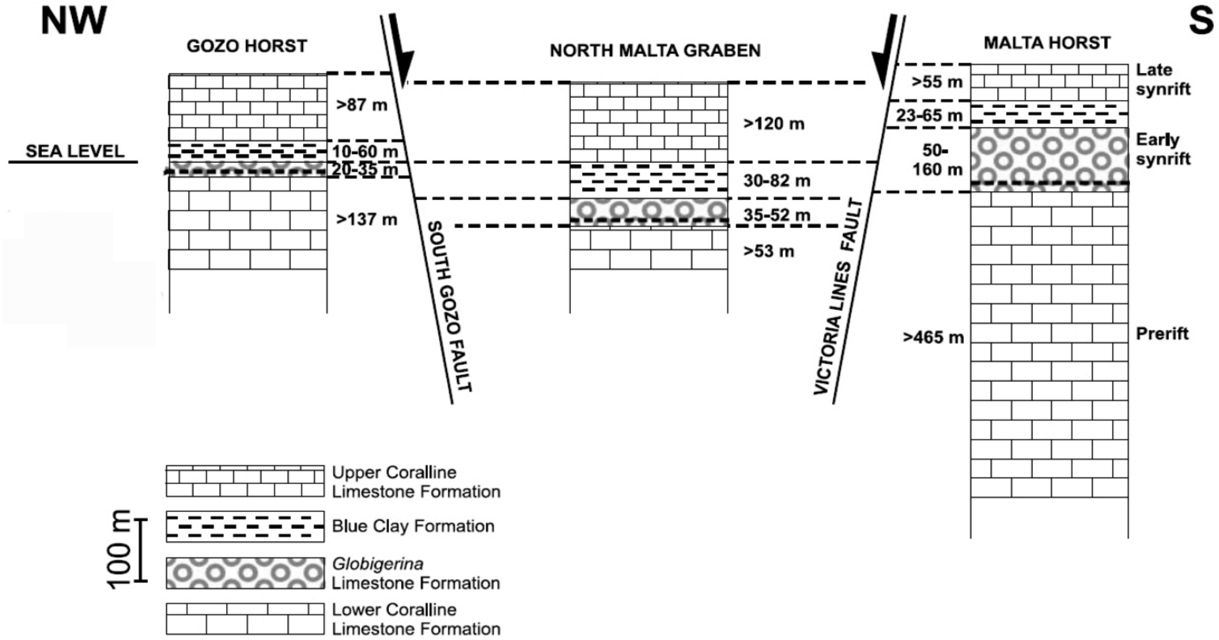

Fig. 7: Stratigraphic correlation between the structural elements of the North Malta Graben system. The Gozo and Malta horsts are separated by the North Malta Graben, which is bound by the south Gozo fault and the Victoria Lines fault to the north and south, respectively (modified from Putz-Perrier and Sanderstone, 2010).

Tectonic structures of the north-west coast of Malta

In the study area the tectonic structures related to the North Malta Graben can be observed (Fig.8). The simple stratigraphic column, the sub-horizontal or horizontal beddings, the high erosion rates of the lithological units and the predominance of extensional faults make the tectonic displacements apparent, especially along the coast.

1. From N to S the first structure is a horst-graben system which caused the subsidence of Mellieha Valley relatively to the Marfa Ridge and Mellieha Ridge. The nothernmost observable fault lowered the limestones belonging to the Upper Coralline Formation with a vertical throw of more than 100 m.
2. In the middle of Mellieha Valley occurs the famous “Popeye Village”, at “Il-Prajjet”, a normal fault brings into contact different units of the Upper Coralline Limestones.
3. The graben of Mellieha Valley is bordered in its southern part by a normal fault, which brings into contact the limestones of the Upper Coralline Formation with the Blue Clays.
4. South of the uplifted block that constitutes the Mellieha Ridge, the Mizieb Depression occurs. It is caused by another normal fault. There are no evidences of this fault from the carbonate plateau but there is a clear difference in the altitude of the base of the Upper Coralline limestone outcropping, although the sub-horizontal bedding.
5. South of the Mizieb Depressione, the Bajda Ridge occurs. Its southern border is a fault that downlifts both the Blue Clays and the Upper Coralline formations. A spectacular sight of it can be observed from Ras il Wahx.
6. Pwales Valley, where San Paul Bay occurs, is bordered by two antithetic faults. Here the limestones belonging to the Upper Coralline Formation are lowered up to the sea level. The southernmost fault is clearly visible from Ghain Tuffieha Bay, where the Blue Clays are uplifted and crop out again at the sea level.
7. The next horst is the Wardija Ridge. The normal faults are visible at Gnejna Bay, where the *Globigerina* Limestones prevail. Their horizontal beddings help to recognize the vertical displacements.
8. The coastal sector between Ras Il Pellegrin and Fomm Ir Ridh is characterized by spectacular *Globigerina* Limestone plunging cliffs with shore platforms at their base. In correspondence to faults and fractures, marine caves have developed.
9. Moving towards South, the last depression is Bingemma Valley. Along the shoreline, the Blue Clays crop out. At Fomm Ir Ridh Bay, the famous Victoria Line occurs. It is a normal fault, has a vertical throw of more than 200 m and uplifts the Lower Coralline Limestone Formation up to the sea level.
10. South from the Victoria Line, other small normal faults displace the Lower Coralline and the *Globigerina* Limestone formations.

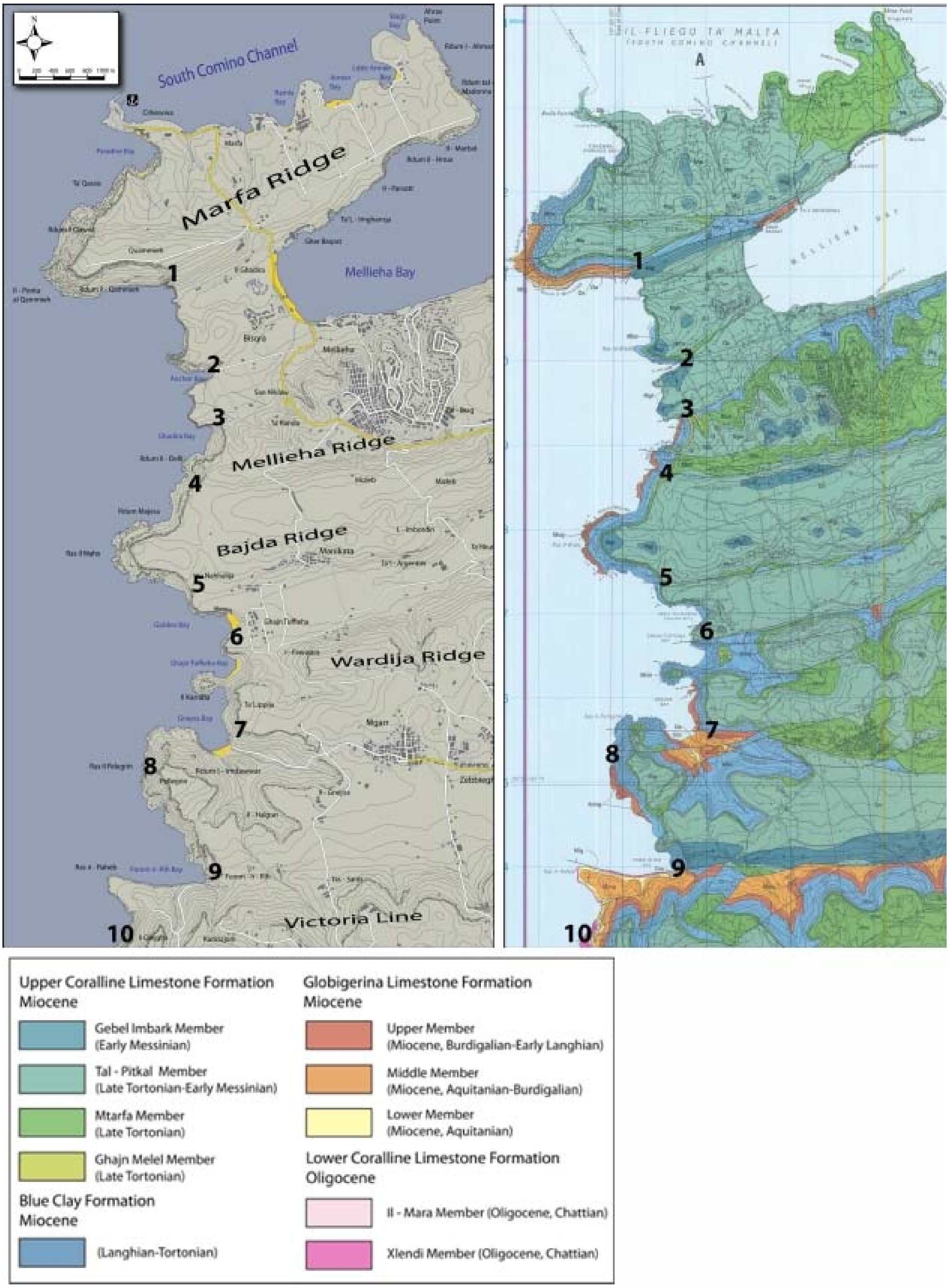

Fig. 8: The NW sector of Malta and location of some tectonic structures (the geological map is taken from Various Authors, 1993).

6. INTEGRATED STRATIGRAPHY AND ASTROCHRONOLOGY OF THE BLUE CLAY FORMATION

Compiled from the papers of Abels et al. (2005) and Hilgen et al. (2005)

Introduction

The sequences of strata composing the sedimentary record of the Earth commonly show strikingly rhythmic patterns in which rock types alternate or succeed each other at regular intervals. These patterns record rhythmic oscillations in the sedimentary process that may be related to climatic oscillations induced by the orbital variations of the Earth, which influence the spatial and temporal distribution of solar energy.

The episodic nature of the Earth's glacial and interglacial periods within the present Ice Age have been caused primarily by cyclical changes in the Earth's circumnavigation of the Sun in the last few millions of years. Variations in the Earth's eccentricity (periodicity of 100.000 years) axial tilt (41.000 years), and precession (21.000 years) comprise the three dominant cycles, known as the Milankovitch Cycles.

Astronomical tuning is based on the correlation or tuning of cyclic sedimentary successions to astronomical target curves (precession, obliquity, eccentricity, insolation) computed with the help of astronomical solutions for the Solar System. The orbital tuning provided direct astronomical ages for magnetic reversal and biozonal boundaries by integrated high-resolution stratigraphy. Astronomical tuning now underlies the age calibration of the new Neogene time scale and its extension into the Mesozoic.

The combination of orbital tuning and integrated high-resolution stratigraphic records is an extremely powerful tool and has helped to solve numerous problems in Earth Sciences (Hilgen et al., 2005).

The Miocene global cooling

One of these problems is the understanding of the middle Miocene global cooling at around 14 Ma that represents a very important step in the evolution of Cenozoic climate following the Miocene climate optimum between 16 and 14.5 Ma (Abels et al., 2005). The climate change did go along with changes in ocean circulation and floral and faunal distribution, with an increase in the southern temperature gradient, and with the permanent installation of a larger East Antarctic Ice Sheet. The cause of the middle Miocene cooling has been ascribed to increased weathering of silicate rocks due to uplift in the Himalayan-Tibetan region and to increased burial of organic carbon, both leading to the withdrawal of CO2 from the atmosphere and hence a reduction of the greenhouse capacity. However, available reconstructions based on different proxies do not show convincing evidence for lower atmospheric CO2 values after or during middle Miocene cooling. Further, changes in ocean circulation patterns, for example, due to tectonic closure of basins, may have increased moisture transport or reduced heat transport to the Antarctic region. Additionally, orbital parameters and especially long period variations in obliquity amplitude may have played an important role in Cenozoic climate change by punctuating longer-term trends or by positive feedback mechanisms that pushed climate into a new state. To determine the possible role of long-period orbital forcing on the middle Miocene cooling it was necessary to develop high-resolution astronomical age models for climate proxy records across the critical time interval. Increased ice volume and lowered ocean temperatures during the middle Miocene are particularly evident from open ocean benthic oxygen isotope records.

The Blue Clays in Malta

One of the few places where the middle Miocene climate transitions can be studied in continuous marine successions on land is on Malta and Gozo. The Ras il Pellegrin section (RIP), exposed along the FommIr-Rih Bay on the west coast of Malta covers the middle Globigerina Limestone up to the Upper Coralline Limestone Formation and shows excellent and distinct sedimentary cycles that can be used for integrated stratigraphy (magneto, isotope, bio) and orbital tuning (Sprovieri et al., 2002; Abels et al., 2005).

The Blue Clay at Ras il Pellegrin shows a very distinct and characteristic pattern of homogeneous grey and white colored marls. The presence of two sapropels and several levels with chondrite trace fossils in the grey marl beds point to occasional anoxic or dysoxic bottom water conditions.

In the lower and middle part of the Blue Clay six whitish colored marly intervals can be distinguished, numbered I to VI in Figure 1 corresponding to the large-scale cyclicity. The small-scale cyclicity is less easy to distinguish in the field. Abels et al. (2005) defined a small-scale cycle to consist of a greyish marl bed at the base followed by a whitish marl at the top. The Blue Clay part of the studied section contains 44 small-scale cycles labeled I.1 to VI.16 as subdivision of the larger scale intervals.

Discrimination of small-scale cycles is particularly difficult in some intervals and thus the calcium (mostly related to carbonate minerals) and potassium (clay minerals) content was measured to obtain a quantitative expression of the lithology (carbonate vs clays) and hence the cyclicity (Figure 2). The largescale cycles, observed in the field, are prominently visible in the Ca/K record.

The orbital tuning and the comparison with other Mediterranean sections indicate that the distinct white part of intervals III, IV, and V correspond to eccentricity minima and that the small-scale cycles are precession controlled, because the number of small-scale cycles based on the combination of lithology and the Ca/K record agrees well with the number of precessional cycles in the astronomical curves between the biostratigraphically controlled age calibration points.

The tuning of the RIP confirms that the formation boundary between the Globigerina Limestone and the Blue Clay Formation and the oxygen and carbon isotope shift at this boundary most probably correspond to the second and major step (Mi3b; CM6) in middle Miocene global cooling. This major isotope enrichment event is now astronomically dated at 13.82 ± 0.03 Ma and coincides with a period of minimum amplitudes in obliquity related to the 1.2-Myr cycle and minimum values of eccentricity as part of both the 400- and 100-kyr cycle.

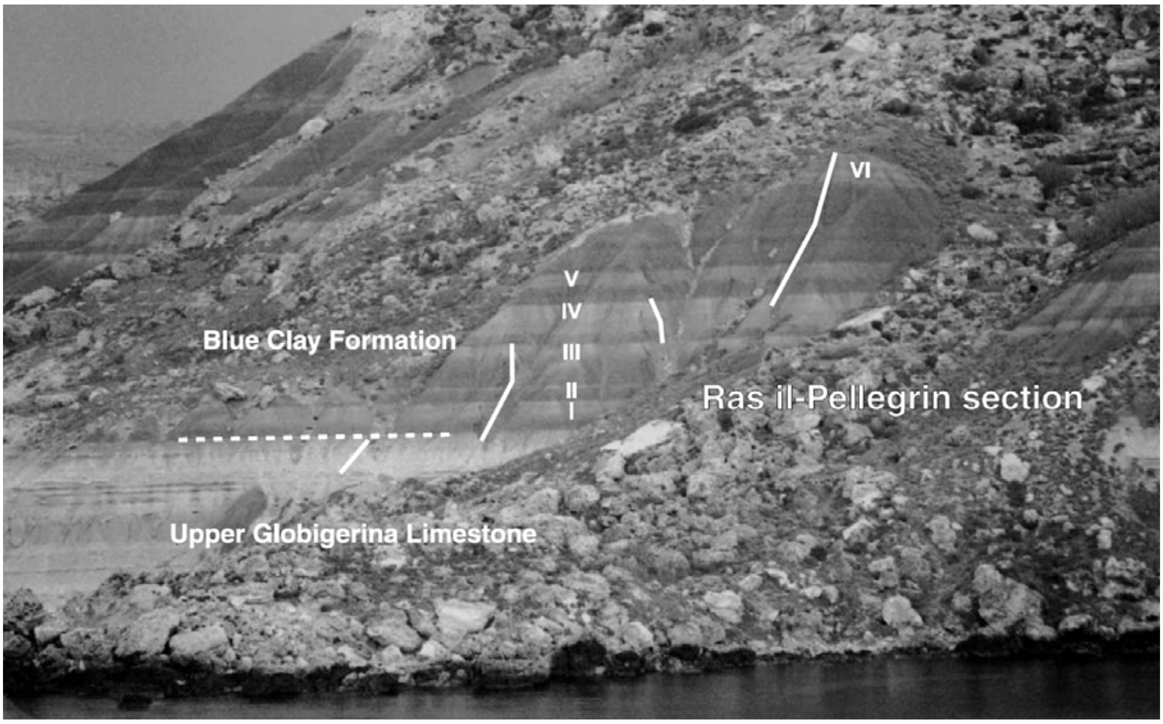

Fig. 9: The spectacular cyclicity visible in the Blue Clay at Ras il Pellegrin section (Abels et al., 2005).

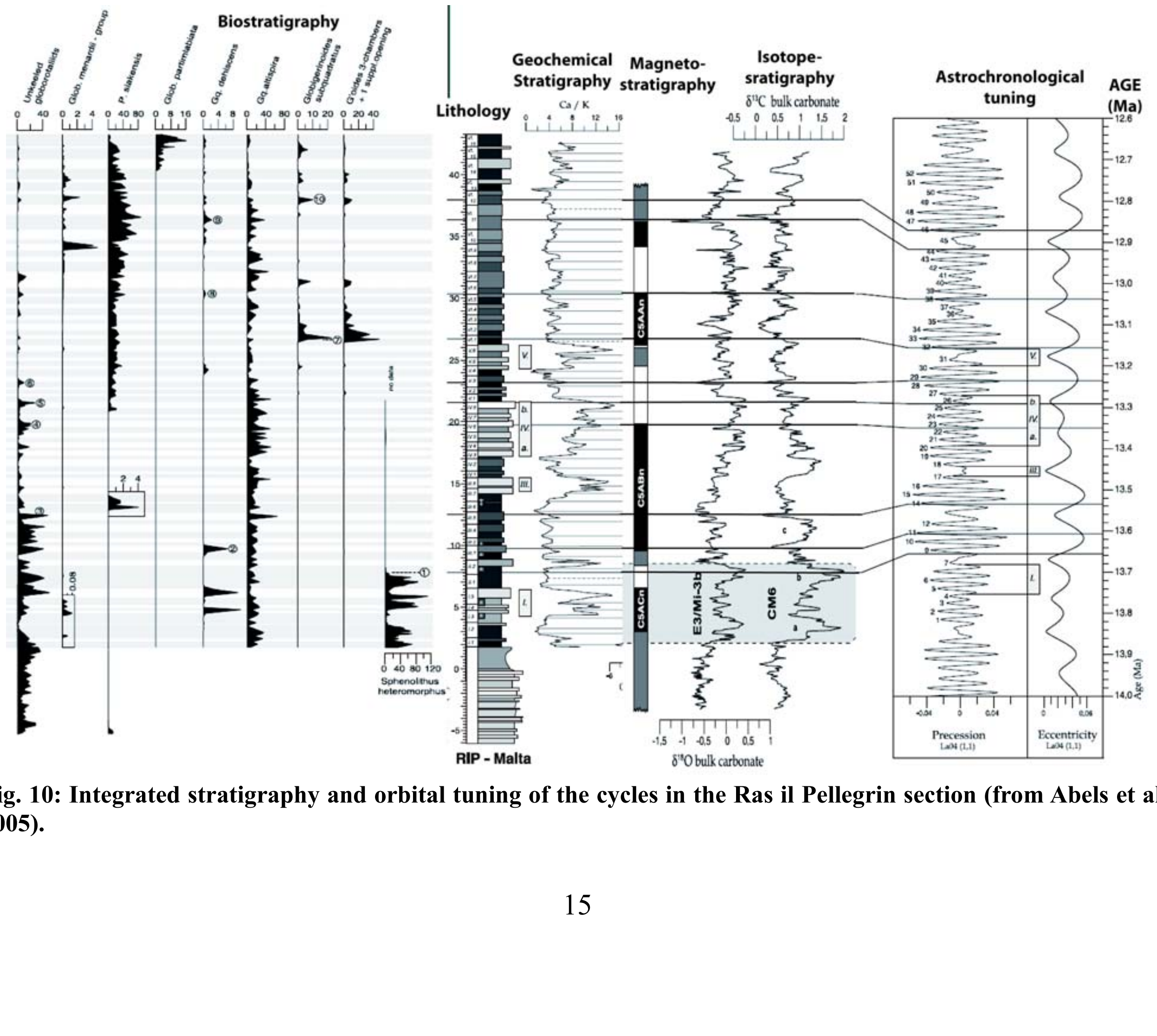

Fig. 10: Integrated stratigraphy and orbital tuning of the cycles in the Ras il Pellegrin section (from Abels et al., 2005).

7. PALEONTOLOGICAL ASPECTS

Most of the geological formations cropping out on the Maltese Islands are made of carbonate rocks. A carbonate rock is a sediment containing at least 50% of carbonate minerals; the two major types are limestone (the most widespread in Malta - composed of calcite or aragonite) and dolostone (composed of dolomite) (Bosellini et al., 1989).
While siliciclastic sediments are formed by the disintegration of parent rocks and are transported to the depositional environment, carbonates are mainly biological in origin. Shells, other skeletal remains and various carbonate particles can create thick deposits (sands, muds) that usually accumulate not far from their original place of formation. Carbonates can also be produced by the *in situ* growth of different kinds of animals and plants. For example, in modern tropical seas, the intergrowth of corals, sponges, molluscs, coralline algae, etc. can originate very large structures (bioconstructions) generally indicated as "coral reefs". Finally, some limestones (e.g. travertines) can be produced by direct chemical precipitation of carbonate minerals (Flugel, 2004).
This deep relation between biotic activity and carbonate production has strong implications on the features of the geological settings in which carbonates are involved. The original geometries of sedimentary deposits and the main physical/chemical properties of the rocks are influenced by the types and abundance of carbonate-producing organisms. In this way, the presence of different biotic associations, due to their control on sediment texture, porosity, mechanical resistance, etc., can also influence the response of rocks to weathering and erosion, thus affecting the morphology of present-day landscapes. The scheme in Fig. 11 summarizes the complex relations among biosphere, carbonate production and landscape evolution.

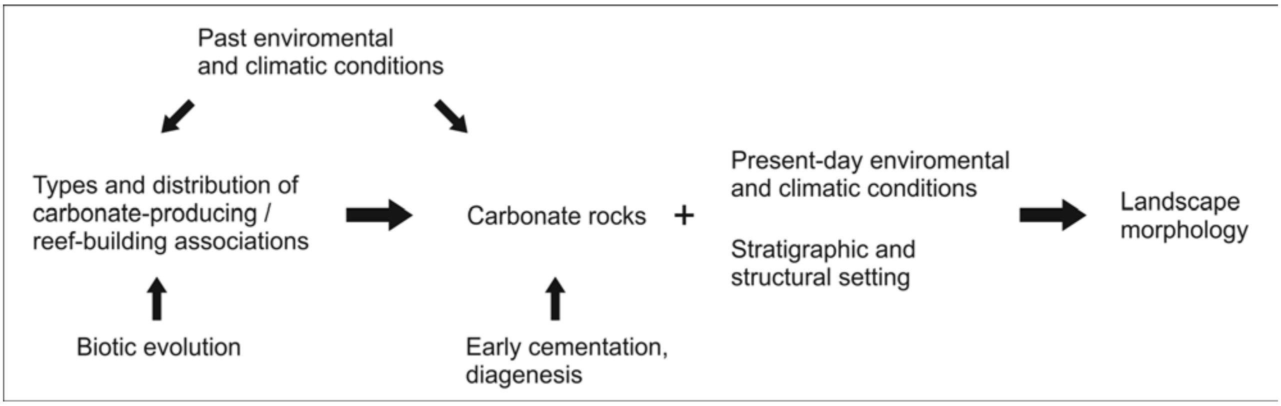

Fig. 11: Relations among biosphere, carbonate production and landscape evolution.

The profound connection between carbonate production and biosphere also opens the way to other important fields of study, mainly related to Palaeoecology and Palaeoclimatology. Presence, abundance and distribution of carbonate-producing organisms are particularly sensitive to the main environmental parameters, such as temperature, light, depth, salinity, nutrients, oxygen and CO_2 amount. This is particularly true for reef-building organisms (corals, coralline algae, bryozoans, etc.): small modifications of environmental factors can often produce remarkable changes within these associations. For this reason, through the analysis of fossil carbonate-producing organisms, it is possible to obtain important information on the past evolution of marine environments and climatic conditions.
Among the rich palaeontological heritage of the Maltese Islands, some fossil groups are particularly important, due to their abundance or their remarkable significance in palaeoecological interpretations:

Coralline Algae
Coralline algae belong to the group of "calcareous algae", plants that are able to deposit calcium carbonate within their cells, producing hard crusts which can very easily fossilize. They appeared in the Early Cretaceous and in modern seas they still represent one of the most important carbonate-producing taxon. Present-day coralline algae occur from the equator to the subpolar areas and extend within the photic zone from intertidal environments to as deep as 270 m (Braga et al., 2010).
Subfamilies, genera and species of coralline algae change from warm to cool water, as well as with depth and other environmental gradients (Fig. 12)

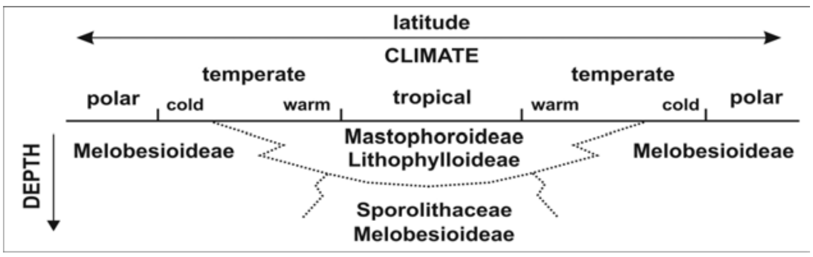

Fig. 12: Distribution of coralline algae subfamilies in relation to climate and depth (from Aguirre et al., 2000).

(Aguirre et al., 2000).
The growth-forms of these plants also vary along palaeoenvironmental gradients, mainly as a function of changes in hydrodynamic conditions. These variations in assemblage composition and morphology can be very useful to interpret certain palaeoecological parameters, such as hydrodynamic conditions, depth and temperature (Braga et al., 2010).

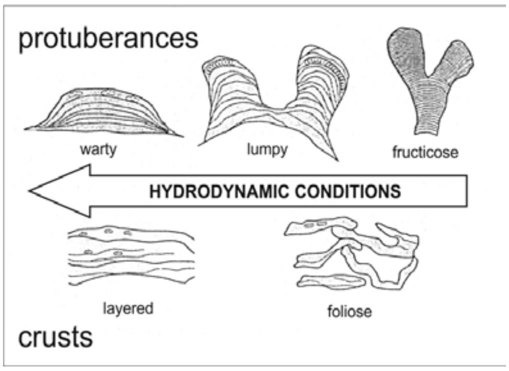

Fig. 13: Relations between coralline algae growth forms and hydrodynamic conditions (modified from Nebelsick and Bassi, 2000).

Coralline algae can encrust hard substrates (rocks, coral skeletons, shells) or even colonize loose sediments or soft plants (seagrasses). During their growth they develop laminar crusts of few millimeters up to several centimeter in thickness, often with the presence of protuberances on the top. The morphology of these crusts and protuberances are mainly a function of hydrodynamic conditions (Fig. 13) (Nebelsick and Bassi, 2000).
Coralline algae can also grow unattached on the sea floor. After encrusting small particles (skeletal fragments or other small clasts), they are kept in movement by the action of waves and currents. In this way they form "ball-shaped" nodules (called "rhodolithes") that can reach more than 10 cm in diameter (Fig. 14). Rhodoliths size, form and inner structure depend mainly on the frequency of their overturning, thus on the hydrodynamic energy of the environment (Fig. 15) (Bosence, 1991).

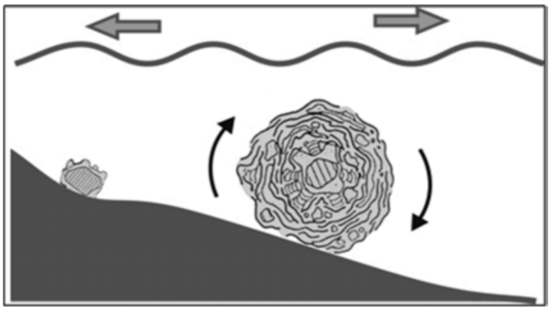
Fig. 14: Formation of coralline algae rhodolithes.

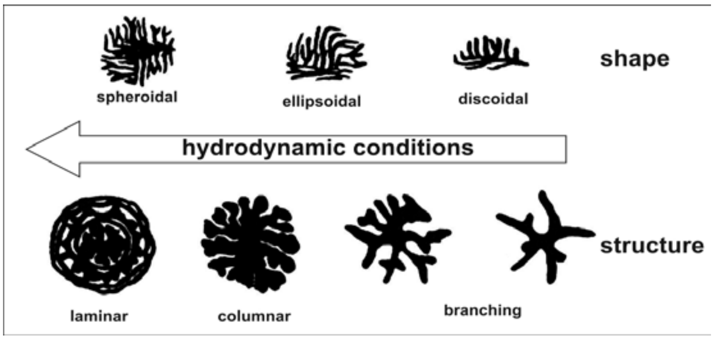

Fig. 15: Relations among rhodolithes shape and structure and hydrodynamic conditions (modified from Bosence, 1991).

Coralline algae represent one of the most abundant fossils in Malta. Their presence is mainly concentrated in the lowermost and uppermost geological formations (Lower Coralline Limestone and Upper Coralline Limestone Formations).

Planktonic foraminifera
The Lower Miocene *Globigerina* Limestone Formation takes its name from a widespread genus of planktonic foraminifera that appeared at the beginning of the Paleocene. *Globigerina* has a very small calcareous shell formed by a spiral aggregate of spheroidal chambers of increasing size (Fig. 16). Present-day *Globigerina* lives in great numbers in open waters, near the surface of the sea. After the death, the shells accumulate on the bottom of the sea, forming deep layers (600 down to 4000 m of depth) of fine-grained calcareous sediment.

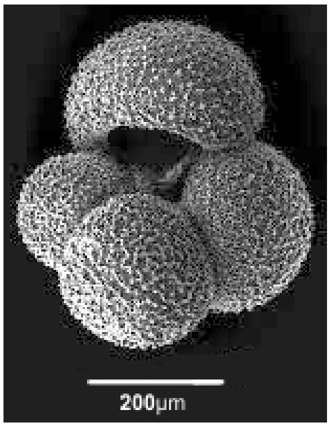

Fig. 16: A *Globigerina* specimen showing the aggregation of spheroidal chambers.

Echinoderms
Fossil echinoderms are quite frequent in most of the Maltese carbonate rocks. They are represented by a large number of genera, mainly belonging to the family Clypeasteridae. Concentrations of *Scutella* sea-urchin (sand-dollar) characterize the uppermost part of the Lower Coralline Formation, just below the contact with the *Globigerina* Limestone. Small "heart-shaped" echinoids of the genus *Schizaster* can be found in great amounts within the *Globigerina* Limestone, while larger, "cone-shaped" *Clypeaster* are more typical of the Greensand Formation.
In modern seas all these taxa live on the top or just beneath the surface of sand or mud deposits. But while *Clypeaster* prefers shallow-water, tropical environments, *Scutella* and *Schizaster* can live at considerable depth in temperate to tropical zones.

8. GEOMORPHOLOGICAL ASPECTS

The combination of the geological nature of the Maltese Islands, composed mainly of sedimentary deposits of marine origin, and the prevailing tectonic activity, give a varied structure to the island (Table 6) and especially the coastline. Lower Coralline Limestone (LCL) formations present steep cliffs in areas where the land was tectonically uplifted and a low lying coastline in zones of land subsidence. In general, the coastal margin formed is rather linear with few inlets. *Globigerina* Limestone (GL) formation has a highly erodible lithological structure that produced large-scale coastal indentations and a shore platform that skirts the areas with high cliffs; a low sloping coastline being an additional feature in some localities. Malta's harbour network is partly the end product of these processes. Clay, being unconsolidated material, exhibits unique properties. It produces spectacular concave cliffs and slopes where it outcrops alone and boulder fields where Upper Coralline Limestone (UCL) plateaux are to be found above it. The latter becomes unstable as a result of the wetting of the clay. Large blocks being dislodged from the cliff face fall on to the slopes below creating boulder scree zones. The scenery here is spectacular with the coastline having an irregular shape from the large boulder spread at sea level. The major fault zone that produced the Great Fault in Malta and isolated Comino was also responsible for the formation of a number of bays to the north. This process produced a succession of ridges and valleys; the latter formed due to the lowering of sections of the plateau as a result of faulting. The sea drowned part of the valleys and formed bays and inlets. A substantial part of the coast has been covered with concrete platforms to accommodate industrial zones, recreational areas, pedestrian promenades and roads. Differences in the physical properties of the coast of the two main islands are apparent with the higher accessibility for Malta represented by low sloping rock face and concrete platforms.

	Upper Coralline Limestone	Greensand /Blue Clay	Globigerina Limestone	Lower Coralline Limestone
Max. Thickness (metres)	160	70	25-200	140
Surface Area Outcropping (%) (Malta) (Estimate) [1]	22.6	12.3	44.5	20.6
Percentage of Coastal Length (Estimate) [1]	16.4	9.4	35.1	36.0
Main Geomorphological Features	low sloping rock/rdum	beach/ rdum/talus	low sloping rock/shore platform	plunging cliff, shore platform

Tab. 6: Main geological Formations of the Maltese Islands: selected data. Main source: Zammit-Maempel (1977). [1] Measured on 1:25000 scale maps at 25 m intercept intervals. The remaining 3.1 per cent is covered by beaches and other coastal deposits.

Geomorphology of the north-west coast of Malta

The relief and landforms of the north-west coast of Malta are predominantly controlled by geological structure and particularly by faults oriented ESE-WSW (Alexander, 1988).

Upper Coralline Limestone features a plateau about 75 metres to 100 metres above sea level, whereas Blue Clay produces steep slopes which in most cases extend from the base of the Upper Coralline Limestone scarp face to sea level. The Upper Coralline Limestone plateau is heavily jointed and faulted, resulting from past tectonic activity. Chemical weathering, especially solution processes, have produced a karst terrain which aids in further widening the joints and faults and allows deeper infiltration of rainwater and wind erosion.

Structural landforms include platforms and scarps remodelled by coastal erosion and/or gravitational processes occurring mainly within the Upper Coralline Limestone Formation. Very often the edges of the structural platforms are characterised by faults and fractures, widened by chemical weathering and rock spreading. Fissures present in this rock formation play an important role in instability of the limestone cap rock, favouring processes of detachment and the subsequent displacement of the rock boulders (Fig.17).

In general, the north-west coastal region is characterised by gravitational processes which have induced the occurrence of diverse types of landslides. In particular, exemplary cases of deep-seated gravitational slope deformations (especially lateral spreading) due to the different mechanical behaviour and diverse hydrogeological conditions of the outcropping lithology, are representative of the main types of landslides occurring on the island (Magri et al., 2008). Lateral spreading phenomena occur within the Upper Coralline Limestone formation which overlies the Blue Clay formation, the latter being a softer and unconsolidated material. The occurrence of these two geological formations characterises the entire north-west coast of Malta. Coastal landslides, in fact, feature prominently where these two formations outcrop in juxtaposition all along the north-west coast. Rock falls, block slides and earth flows are sometimes closely associated to these phenomena (Fig. 18).

Fig. 17: Overlapping of the Upper Coralline Limestone on the Blue Clay Formation at Il Quarraba (Courtesy of Ten. Col. M. Marchetti).

Fig.18: Lateral spreading at Anchor Bay.

Rock falls caused from the breaking, dislodgement and falling from the limestone plateau, are very common. Large blocks extend to sea level and protect the coast from further erosion, or else they rest close to the scarp face from which they have been detached.
The Blue Clay slopes experience earth slides and earth flows which are triggered as a result of rainfall during the autumn and winter months, when the material becomes saturated with water and increases in volume. Such a movement occurs especially where the clay slopes are bare of any vegetation cover or where boulders, rock fragments or debris are absent.
High and steep cliffs remodelled by the mechanical action of waves (Paskoff, 1985) and two sandy beaches represent the main coastal landforms of the research area. Marine erosion plays an important role in shaping the landscape, producing inlets and bays with small pocket beaches at the head of the bays.
Regarding fluvial landforms, both depositional and erosional landforms can be observed. V-shaped small dry valleys in the Upper Coralline Limestone are of particular importance. These dry valleys, currently converted to agricultural land or terraced fields, are relicts of former pluvial conditions and extensive groundwater sapping. Other landforms resulting from the action of running water are large valley beds and alluvial/colluvial cones consisting of Quaternary sediments transported and deposited through the action of water as well as gravitational processes. Examples of badland topography occur in the steep Blue Clay slopes, which being bare of vegetation cover, are exposed to the action of water which forms deep channels or gullies at the sides of the slopes.
Due to the presence of the Coralline Limestone terrain, a rock formation that is very sensible to solution due to its content of calcium carbonate and its high fissure density (Paskoff and Sanlaville, 1978), karstification is well develop in the area. The most widespread karstic feature is the surface topography of plateaus characterised by highly irregular and rugged shapes, resulting from solution processes.
The area has been significantly influenced through time by human activity due to the exploitation for agricultural and tourism purposes. In particular, both at the coastal and inland slopes have been remodelled into terraced fields retained by rubble walls (dry stone walls) and utilised as agricultural land (Cyffka and Bock, 2008). Archaeological features in the north-west region include rock-cart ruts, small scale erosional landforms incised into the bedrock of uncertain origin and age (Mottershead et al., 2008), numerous corbel huts (giren) and notable remains of British military architecture.

9. MINERALOGY

The minerals found on the Maltese Islands can be subdivided into four main macro-groups with respect to the occurrence in different geological formations: Limestone formations, Hard Grounds, Blue Clay formation and Greensand Formation. A mineral may occur in different Formations (e.g. calcite obviously occurs in the Limestone Formations but also in the Blue Clay Formation).
The Limestone formations essentially contain carbonate minerals (aragonite, calcite, Mg-calcite. Iron oxides (hematite) or hydroxides (mainly goethite) may also be present.
The Hard Grounds of brown color intercalated within the Globigerina Formation are composed of a phosphate mineral named francolite. Apatite and iron-bearing minerals such as hematite and goethite may also be present.
The clay sediments composing the Blue Clay Formation may contain the clay minerals kaolinite, illite, chlorite, smectite, and Interlaminated Illite-Smectite (I/S) phase. The non-clay minerals are quartz, sanidine, gypsum, calcite, dolomite. Accessory minerals are augite $(Ca,Mg,Fe^{2+},Fe^{3+},Ti,Al)_2\,(Si,Al)_2O_6$, rutile TiO_2, topaz $Al_2SiO_4(F,OH)_2$, and tourmaline $(Ca,K,Na)(Al,Fe,Li,Mg,Mn)_3\,(Al,Cr,Fe,V)_6(BO_3)_3(Si,Al,B)_6O_{18}(OH,F)_4$.
The Greensand formation may contain the minerals which occur in the Blue Clay Formation but is mainly characterized by the presence of glauconite and phosphatic (apatite) grains.
Below is a systematic concise general description of the minerals found on the Maltese Islands in alphabetical order.
Apatite is actually a group of phosphate minerals, usually referring to hydroxyapatite, fluorapatite, and chlorapatite, named for high concentrations of OH^-, F^-, Cl^- or ions, respectively, in the crystal lattice. The general formula of the three most common end-members is written as $Ca_{10}(PO_4)_6(OH,F,Cl)_2$, and the formulae of the individual phases are written as $Ca_{10}(PO_4)_6(OH)_2$, $Ca_{10}(PO_4)_6(F)_2$, $Ca_{10}(PO_4)_6(Cl)_2$. It is of sedimentary origin and associated with condensed pelagic sediments. Francolite is a microbially precipitated carbonate fluorapatite of low crystallinity. It is the major component of phosphorites, a phosphate-rich rock of sedimentary origin that contains 18-40 wt% P_2O_5. The CO_3^- group in francolite is considered to be a part of the fluorapatite structure, substituting for PO_4^- groups in the naturally occurring mineral.
Calcite, the most common sedimentary mineral of the Earth's crust, and aragonite are the polymorphic forms of calcium carbonate $CaCO_3$. Calcite is rhombohedral whereas aragonite is orthorhombic. They are mostly of biochemical origin and form the rocks called limestones. Many mineralizing organisms selectively form either calcite or aragonite. Many limestones have gained their structure and textures during diagenesis. Aragonite was deposited and subsequently transformed into the calcite of some limestones; Mg-calcites that constitute some organic skeletal parts and cements of marine sediments were the precursors of the calcite of many other limestones. During diagenesis, most of the Mg-calcites were transformed into stable assemblages of rather pure calcite, often along with scattered grains of dolomite.

Calcite is thermodynamically more stable than aragonite at ambient T and P. The presence of Mg^{2+} in solution as well as a variety of small organic molecules, favors the formation of aragonite. At Maltese Islands, the major part of the limestone formations is composed of calcite, aragonite can be attributed to recent mollusk shells, and Mg calcite is attributable to recent foraminifers and to red algae and echinoids remains.

Chlorite is a family of hydrous sheet silicates (TOT+O, 14 Å) incorporating medium-size octahedral cations, primarily Mg, Al, and Fe. There is a continuous solid solution series between the Mg (end-member clinochlore of chemical formula $(Mg_5Al)Si_3AlO_{10}(OH)_8$) and Fe (end-member chamosite of chemical formula $(Fe^{2+}{}_5Al)Si_3AlO_{10}(OH)_8$) species. In sedimentary rocks, chlorite is a common but usually minor component. Occasionally, chlorite makes up the bulk of the clay mineral fraction of sedimentary rocks. Some chlorite is of detrital origin in sediments but some chlorite forms during diagenesis. In most cases, soil chlorite is probably inherited from parent material. Generally, abundance of chlorite (and illite) in the sediments may indicate a dry environment in the source are, with physical alteration dominant.

Dolomite is a common sedimentary rock-forming mineral that can be found in massive beds several hundred feet thick (e.g dolomites). They are found all over the world and are quite common in sedimentary rock sequences. Dolomite is rhombohedral and differs from calcite in the addition of magnesium ions to make the formula, $CaMg(CO_3)_2$. Mg ions are not the same size as Ca and the two ions seem incompatible in the same layer. In calcite, the structure is composed of alternating layers of carbonate ions, CO_3, and Ca ions. In dolomite, Mg atoms occupy one layer by themselves followed by a CO_3 layer which is followed by an exclusively calcite layer and so forth. Post-compactional late-stage dolomite may occur as (i) finely disseminated rhombic microspar in argillaceous lime mudstone, (ii) sparry cement within voids in argillaceous carbonates, and (ii) sparry cement within carbonates adjacent to marine shales. The distribution and abundance of these dolomites correspond with that of clay deposited in the marine environment and cannot easily be explained by alternative models of dolomite formation. Conversion of smectite to illite during burial is a common diagenetic process which is capable of releasing large amounts of Fe, Mg, Ca, Na, and Si. Smectite-illite conversion may be invoked as the source of ions that formed late-stage dolomites.

Gypsum is the most common sulphate mineral. Found as both massive material, including the alabaster variety, clear crystals, the selenite variety, and, parallel fibrous, the satin spar variety. When totally hydrated, its chemical formula is $Ca(SO)_4{\times}2H_2O$. The presence of gypsum is usually ascribed to an arid phase during which opal, gypsum and alunite would have formed. In the Maltese clay, it is likely that secondary gypsum has formed in sediments by capillary rise from water tables (*per ascensum*), or by movement downwards following incomplete wetting (*per descensum*). The source of sulphur may be related to that of the clay fraction transported as volcanic ash, perhaps from eruptions associated with the first movements that formed the Pantelleria Rift.

Glauconite is a sheet mineral which belongs to the Mica Group (Muscovite subgroup, TOT, 10 Å) of empirical formula $(K,Na)Fe^{3+}{}_{1.3}Mg_{0.4}Fe^{2+}{}_{0.2}(Al,Si)_4O_{10}(OH)_2$. It is a green mineral formed in shallow marine environments that are mildly reducing when little or no sedimentation is taking place, hence found in shallow marine sedimentary rocks-limestones, siltstones, shales and sandstones. "Greenstones" are named that because if their typically high glauconite content.

Goethite (iron hydroxide, α-FeOOH, orthorhombic) and hematite (iron oxide, α-Fe_2O_3, rhombohedral) are commonly found together in limonite-rich sediments. Goethite transforms into hematite at T > 250 °C. These minerals are commonly formed as weathering product, primary hydrothermal mineral, bog and marine environments.

Illite is a dioctahedral (TOT, 10 Å) K-deficient mica with an interlayer cation content of 0.6–0.85 atoms per formula unit. 1M and $2M_1$ are the illite polytypes more abundant in nature. An approximate formula for this clay mineral can be written as $K_{0.88}Al_2(Si_{3.12}Al_{0.88})O_{10}(OH)_2$. It was observed that the formation of aluminous illite from sediments deposited in marine environments is negligible. Illite is described in diagenetic series and its formation has been described in three different environments: (i) the recrystallization of clay minerals in shales and clay-rich sandstones (ii) the direct precipitation from solutions on kaolinite or quartz grain surfaces; (iii) clay transformation in bentonite beds. The first occurrence is assigned classically the smectite-to-illite conversion and has been abundantly studied.

A continuous series exist between illite and smectite. The intermediate metastable terms are termed I/S (illite/smectite or interlaminated or mixed-layered I/S, or I-S). In I/S, the unit cell scale layers of illite and smectite are shuffled like a deck of cards. I/S is common in shales. The percent of illite typically increases with depth and temperature in most of the world's sedimentary basins and with geologic age.

Kaolinite is the most common clay mineral found on Earth. It is a TO (one tetrahedral and one octahedral sheet with ratio 1:1 and unit cell size along the c axis of 7 Å) sheet mineral with chemical formula $Al_2(OH)_4Si_2O_5$. It is usually formed in hydrothermal environment or by weathering. As major component of Maltese clays, kaolinite must have come from a land source. It is possible that during Miocene, a progressive uplift of the mountain ranges in the north of Sicily occurred, induced as the African and European plates converged, leading to intensive erosion of the uplifted areas. Although quite distant from the uplift, the finest detritus (mainly clay minerals) was carried as fine suspension in seawater into the area where the Maltese Islands now lie. It is likely that part of the clay fraction may have originated as volcanic ash, perhaps from eruptions associated with the first movements that formed the Pantelleria Rift System.

Quartz (α-quartz, trigonal of empirical formula SiO_2) is the most common mineral found on the surface of the Earth. A significant component of sedimentary rocks (but not only!), found in an impressive range of varieties and colors. The presence of quartz in the clay formation of Maltese Islands may goes along with that of clay minerals of terrestrial

environment but in general, levels relatively rich in quartz are interpreted as corresponding to relatively dry periods.
Sanidine is the high temperature monoclinic polymorphic form of K-feldspar ($KAlSi_3O_8$). It is stable above 900 °C. Sanidine (and anorthoclase) are a common components in extrusive igneous rocks such as rhyolites, where the rock cooled quickly. On the other hand, orthoclase is the main K-feldspar in granites and syenites that cooled somewhat more slowly, and microcline is the K-feldspar associated with granites, pegmatites, and syenites that cooled slowly. It is possible that the occurrence of sanidine in the Maltese clay formation is related to that of the clay fraction transported as volcanic ash, perhaps from eruptions associated with the first movements that formed the Pantelleria Rift.
Smectite is a general term indicating a family of important hydrous aluminum sheet silicates with a layered structure and very small (nanometric) particle size. Smectites represent 2:1 type (TOT + H_2O + compensating cation with a variable unit cell size along the c axis of 14 to 21 Å, 10 Å if collapsed to an illite-like structure) sheet silicates with expandable structure carrying a certain amount of excess negative layer charge. The most important species of the smectite family is montmorillonite (Ca-smectite). The structural formula of dioctahedral aluminous smectites in the series montmorillonite-beidellite is $(Al_{2-y}Mg_y)(Si_{4-x}Al_x)O_{10}(OH)_2E_{x+y}\cdot nH_2O$ when $y > x$, smectite is called montmorillonite. Smectites are usually the products of weathering. They occur in such sedimentary rocks as mudstones and shales, in marine sediments, and in soils. smectite is either a degradation product in temperate climates or a neoformation mineral in sub-arid climates. The presence of smectite in sediments suggests an environment with contrasted seasons.

10. PLANNING AND MANAGING THE MALTESE ENVIRONMENT

The physical planning and management of the Maltese Islands has a long history dating back at least a millennium when according to legend the locals could not build houses higher than their occupiers. The Knights of St. John also applied detailed and strict rules pertaining to the urban development of Valletta ensuring amongst other things that each house has provisions for a well to ensure the availability of water. During the British period, and especially after the war, a number of measures aimed at introducing more control over the rebuilding of parts of the island after the war. The overall emphasis here was concentrated on urban areas with proposals for the establishment of a Town Planning Act, preparations for an Outline Plan for the Maltese Islands, suggestions for the setting up of a Lands Department, a national Physical Plan and a Tourism Master Plan (Italconsult, 1964). After independence the emphasis on continuing the series of proposals and plans but implementation started to materialize with, for example, a Building Development Areas Act (1983) emphasis on Tourism and the establishment of the Planning Services Division in 1987, turning into the Planning Authority in1992, and later merging with the Environment Division into the Malta Environment and Planning Authority.
The policies to be followed are established in the Structure Plan, and they serve as a guide towards controlling development in Malta. Their main aim is to balance development with environmental requirements. In addition to the policies, two types of more detailed development plans are put forward: Local Plans and Subject Plans. A Local Plan is essentially site-specific and deals with areas that require attention due to problems in managing the environment of the area brought about as a result of a rapid rate of development. A Subject Plan deals with policies as stipulated in the Structure Plan with a more detailed approach. Public consultation is a key feature in the formulation of the Local and Subject Plans.
With the particular interests of this field class the rural environment of the north-west coast of Malta together with stretches of the southern littoral and parts of the northern coast and selected areas in Gozo, have been designated as Special Areas of Conservation (SACs) in line with the EC Habitats directive and Special Protection Areas (SPAs) in line with the EC Birds Directive. A number of areas have been designated as part of the EU Natura 2000 Network. This is a network of protected sites across the EU. These sites merit special conservation measures as they support habitats and species of community interest. Marine sites between Rdum Majjesa and Ras ir-Raheb areas and at Dwejra in Gozo covered 11 km^2 of territorial waters. By 2008 Malta had 73 Areas of Ecological Importance and/or Sites of Scientific Importance scheduled under the Development Areas Act of 1992 that amount to 20.5% of the land area.

Issues of landslide hazard and risk
The north-west region, being characterized by coastal landslides and frequented by different users especially for leisure purposes, shows hazard and risk situation (Magri, 2009). Thus although not so obvious, especially for the local population, who might not be aware of the presence of landslides, a landslide problem and associated hazard in fact do exist for the multiple users of this region. Although not frequent, accidents have been reported in the media (for example 4th October 2004, 17th August 2005), where people have been injured due to rock fall and difficult accessibility while walking along the north-west coast. Warning signs, indicating the areas most prone to landslides and mass movement processes and making people aware of the evident hazard, have been installed in some areas only recently.
Issues of hazard and risk are also evident with regards to the location of Popeye's Village and a historical coastal tower. Popeye's Village situated at Anchor Bay is a popular tourist attraction in the Maltese Islands, constructed as the setting for the production and filming of a movie in the early 1980s. The coastal tower at Ghajn Tuffieha Bay was built for

defence purposes in 1637 by Grand Master Lascaris. This tower constitutes one of the three towers built for coastal defence purposes along this coastal stretch. At present only two towers remain, the third one fell during the times of the Knights of St. John in Malta (1530-1798) due to rock fall. In fact by 1730 ruins of the tower have already been recorded (Spiteri, pers. comm.).

Landslide monitoring at north-west coast

Landslides, and especially lateral spreading, produce the main landforms observable in the north-west coast of the Maltese islands. In order to understand the state of activity of these phenomena and to determine their displacement a GPS network consisting of 19 benchmarks was installed in September 2005 at two field sites (Ghajn Tuffieha Bay and Il Prajjet).

Ghajn Tuffieha Bay is one field site being investigated along the north-west coast of Malta. The outcropping rocks belong to the Upper Coralline Limestone and to the Blue Clay. The northern part of the Bay is composed of an Upper Coralline Limestone plateau. The latter features a cliff face, 27.5 metres high which plunges into the sea where Blue Clay is absent. Where the latter formation is present, Blue Clay slopes descend from the base of the plateau to sea-level. A coastal defence tower built in the 17th century, dominates the northern part of the Bay. The tower is situated at the edge of the cliff which is retreating due to the presence of coastal landslides, and is thus at risk of being damaged. To the southern part, the Bay is delimited by a promontory, known as Il-Qarraba, composed of an Upper Coralline Limestone cap, ranging in height between 7.5 metres and 23 metres. Below there are Blue Clay slopes which descend to sea-level and are characterised by the presence of large blocks detached from the above plateau. The Bay itself consists of a sandy beach, stretching over a distance of 273 metres and backed by Blue Clay slopes reaching an altitude of about 60 metres above sea-level. An Upper Coralline Limestone cap is found above the clay slopes, covering an area of 0.03 km^2. At this site the monitoring of the landslides is taking place both on the southern promontory where 11 benchmarks have been installed and on the northern cliff where 2 benchmarks have been set up. A reference point has been fixed further inland on the northern plateau and is being used for both monitoring sites in this Bay. Four benchmarks – one near the tower and three on Il-Qarraba have been lost between September 2005 and April 2006.

Il-Prajjet consists of a narrow inlet, with a minimum width of 72 metres and maximum width of 238 metres. Geologically it is composed of Upper Coralline Limestone. Blue Clay is present on the northern side of the inlet below the Upper Coralline Limestone. The site features an Upper Coralline Limestone plateau, ranging in height between 10 metres and 12 metres. The southern side presents a sheer cliff face, 22.5 metres high above sea-level, composed of Upper Coralline Limestone, whereas the northern side features excellent examples of lateral spreading phenomena. The landslides on this part of the inlet are posing a hazard to Popeye's Village, which is one of the most popular tourist attractions of the Maltese Islands. At this site monitoring of the lateral spreading is taking place through the installation of 8 benchmarks on detached blocks and a reference point located at a more stable site further inland. The fixed reference point has been lost twice between September 2005 and October 2006 and eventually was replaced at a more secure location.

The GPS technique has been chosen because it has already been tested as a powerful tool in ground deformation analysis with high accuracy and reliability. Since the deformations occurring in lateral spreading phenomena are usually extremely slow, particular attention was especially given to the planning of the survey procedures. The static relative positioning technique was employed in order to achieve more accurate results within an acquisition time at each point of 20 minutes and a 2 second sampling rate. In order to guarantee the uniformity of the surveys, avoiding positioning errors, a forced centring device for the antenna was performed for each benchmark. Surveys are carried out approximately every six months in March and November corresponding to the end of the wet season and dry season respectively. These months have been chosen on purpose so as to determine whether rainfall plays an important role in the instability and displacements of the landslides. Ten surveys have been carried out so far. During each survey, the baselines between each benchmark and its reference point are measured. Displacements caused by the landslides can be determined with a theoretical precision of up to about 3 mm to 10 mm + 1 ppm when differences in the baselines are compared between one survey and the other. The displacements recorded by the benchmarks are summarized in Figs. 19, 20 and Tables 7, 8.

Several benchmarks recorded significant displacements. Results collected over a 54 months (September 2005 - March 2010) indicate that the coastal landslides are active, with planar displacements ranging from 0.79 cm to 4.71 cm.

Fig. 19: Positions of the benchmarks and displacements recorded at Il-Prajjet (Anchor Bay).

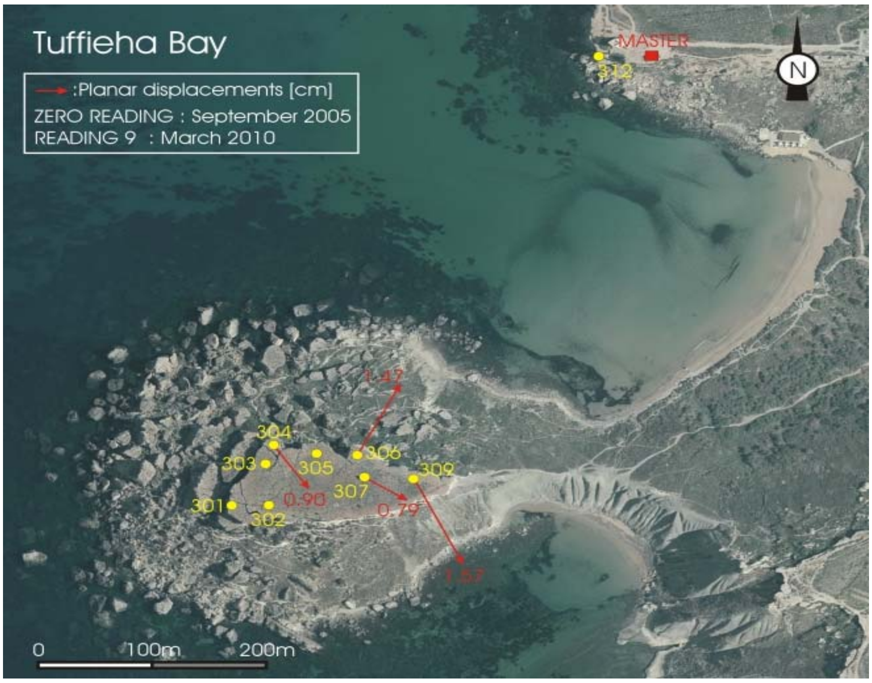

Fig. 20: Positions of the benchmarks and displacements recorded at Tuffieha Bay.

Il-Prajjet Displacements October 2006 – March 2010					
POINT ID	NORTH [m]	EAST [m]	HEIGHT [m]	3D [cm]	2D [cm]
101	-0.0218	0.0023	-0.0115	2.48	2.19
102	-0.0149	-0.0266	-0.0526	6.08	3.05
103	-0.0050	-0.0261	-0.0811	8.53	2.66
104	-0.0471	0.0015	-0.0387	6.10	4.71
105	-0.0423	0.0030	-0.0374	5.65	4.24
106	-0.0265	-0.0106	-0.0059	2.91	2.85
107	-0.0359	-0.0084	-0.0148	3.97	3.69
108	-0.0192	-0.0100	-0.0129	2.52	2.16

Tab. 7: Displacement recorded at Il-Prajjet (Anchor Bay) during October 2006 - March 2010.

Tuffieha Bay Displacements September 2005 – March 2010					
POINT ID	NORTH [m]	EAST [m]	HEIGHT [m]	3D [cm]	2D [cm]
301	-0.0001	-0.0017	-0.0103	1.04	0.17
302	0.0003	0.0009	-0.0067	0.68	0.09
303	-0.0052	0.0057	0.0037	0.86	0.77
304	-0.0071	0.0056	-0.0075	1.17	0.90
305	0.0011	-0.0028	-0.0006	0.31	0.30
306	0.0133	0.0062	0.0011	1.47	1.47
307	-0.0041	0.0068	-0.0022	0.82	0.79
309	-0.0135	0.0081	-0.0037	1.62	1.57
312	0.0033	0.0048	-0.0182	1.91	0.58

Tab. 8: Displacement recorded at Tuffieha Bay during September 2005 - March 2010.

11. GEOLOGICAL AND GEOMORPHOLOGICAL SETTING OF THE COSPICUA AREA

The geological sequence of rocks of the Maltese Islands has a direct control upon the surface topography. In fact, the four geological formations outcropping in Malta are dissected by a SW-NE system of faults that is dominant factor in influencing the relief of the islands: it controls the direction and shape of depressions such as the one forming the Grand Harbour on Malta.
About the Grand Harbour, the most widespread lithology is the lowest member of the Globigerina Limestone Formation which comprises sediments deposited in deep water. In the legend of the geological map of Malta, it is described as follows.

- *Globigerina* Limestone, *Lower Globigerina Limestone Member*: pale cream to yellow planktonic foraminiferal packstones rapidly becoming wackestones above the base. Glauconite is common in western outcrops south of Fomm ir-Rih. Pectinid bivalves and *Shizaster* echinoids are frequent. The top of the member is marked by a ubiquitous hardground. This is phosphatised in western areas and carries a conglomerate. Common fossils include fish teeth, mollusks, solitary corals and echinoids. Thickness 0-80 m. (Miocene, Aquitanian).

According to the geological map of Malta, the Marija Immakulata Church (Fig. 21) of Cospicua should be built on the uppest member of the Lower Coralline Limestone (Il Mara Member), but after surveys it has been verified that the church is built on the Globigerina Limestone Fm. and the fault that makes the Il Mara Member outcrop in the area of Cospicua passes SE of the church.
The major factors controlling the relief and the landscape are:

- the lithological characteristics;
- the fact that the stratigraphic sequence is tilted, resulting higher in the SW and lower in the NE part;
- the structural characteristics: especially the SW-NE system of faults that crosses the island which determines areas of lesser resistance to the erosion that are represented by the valleys around that area (for example, fluvial erosion in the past);
- the presence of the sea.

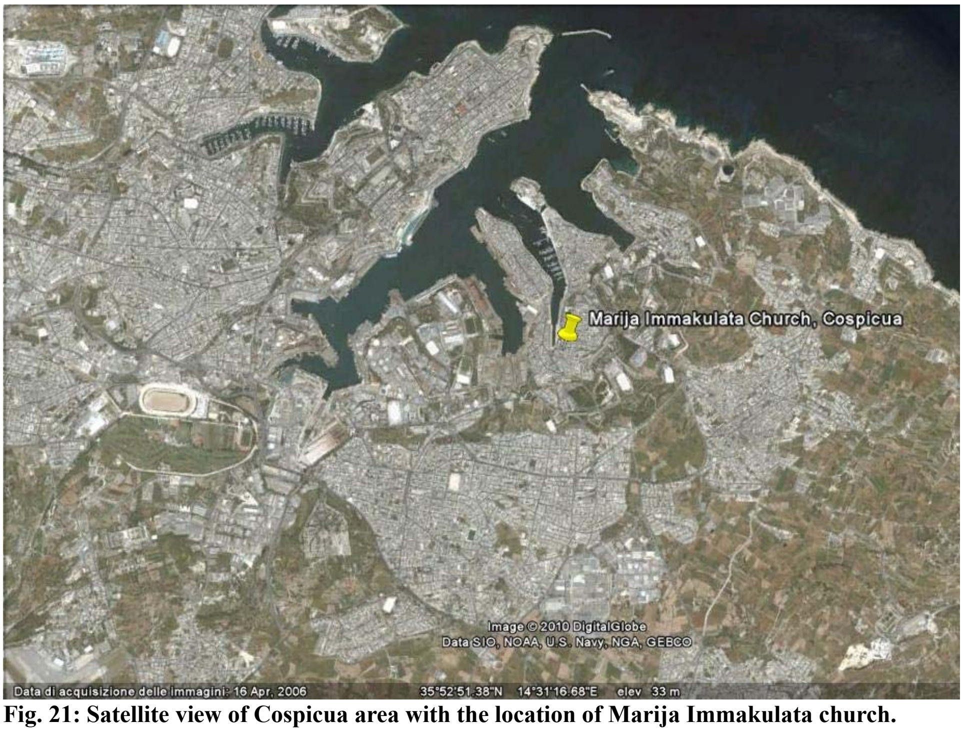

Fig. 21: Satellite view of Cospicua area with the location of Marija Immakulata church.

12. THE ISLAND OF GOZO: GEOLOGY AND CULTURAL HERITAGE

The Island of Gozo (Fig. 22) provides striking examples of the relationship between geology and cultural heritage.
Victoria: It is known to all as Rabat, which mean *suburb,* has been in existence well before the Citadel became the refuge for locals. It grew over centuries to become the officially called town of *Victoria* 1887, in honour of Queen Victoria during her jubilee year. Besides being the administrative centre of the Island, one also finds the law courts hospital and schools here. The beautiful Basilica of St. George was rebuilt in 1693 following an earthquake. Market stalls are set up daily in the main square of Victoria.
Citadel – The Gran Castello: The old capital of Gozo was the center of activity since Neolithic times has impressive battlements which offer a superb view around the Island with vistas over the fields dissected by rubble walls. The imposing Cathedral dedicated to Santa Marija is believed to have been built on the site of a Roman temple dedicated to Juno, watches over the quaint remains of the old houses and winding narrow streets that had once housed locals that scurried into the Citadel for safety whenever corsairs were sighted off the coast of Gozo. One of these, the so-called Norman House, has been transformed into a Folklore Museum which offers a fine display of the way of life from classical to recent times.
The Citadel also houses an Armory and the Old Prison, which was in use from the mid-16th century until the beginning of the 20th century. The walls of the cells and corridors in the old prison are covered with incredible graffiti. It is considered as the largest collection of historical graffiti in one single place on the Maltese islands. The representations are often of ships, and date from different periods. There are also handprints, crosses, names, dates, games, and anthropomorphic figures etched into the limestone walls. They provide an interesting insight into the lives of those incarcerated there.

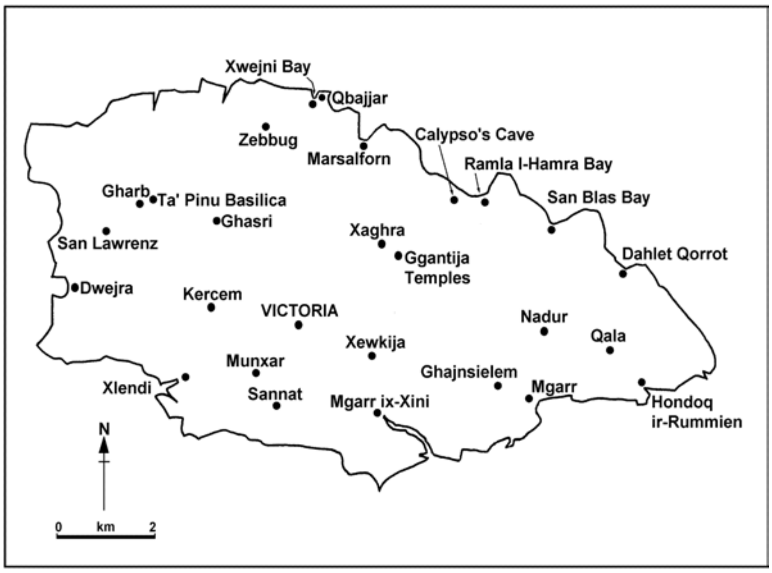

Fig. 22: Map showing main locations in Gozo.

The ĠgantijaTemples
The Ġgantija temples stand in the island of Gozo at the end of the Xagħra plateau, facing towards the southeast. They are one of the most important archaeological sites in the world and date from around 3600 to 3200 BC. Due to the gigantic dimensions of the megaliths, in past centuries some locals believed that the temples were the work of giants. The temples were first excavated in 1827 but remained uncared for and open for depredations until the 1930s, when the ruins became property of the Government.
The Ggantija megalithic complex consists of two temples surrounded by a massive common boundary wall, which was built using the alternating header and stretcher technique, with some of the megaliths exceeding five meters in length and weighing over fifty tons. Each temple contains five apses connected by a central corridor leading to the innermost trefoil section. A roof, which has not survived, would have covered the structures.
The complex stayed in use until the mid-third millennium BC, when the Maltese Temple Culture disappeared abruptly. The excellent state of preservation of its materials - hard chalky coralline and the softer globigerina limestone - makes it an excellent testament of megalithic prehistoric art.
A few artifacts have been found at the site, which are now displayed in the national museum. They include a small clay figure of a full-figured sleeping goddess that was found in an egg-shaped chamber. Some architectural decoration can still be seen in its original position in the temple, including three stone blocks with spiral carvings and several stones with decorative pitting.
The Ġgantija temples were listed as a UNESCO World Heritage Site in 1980 (Fig. 23).

Fig. 23: ĠgantijaTemples: Altar arrangments in south temple.

13. THE CAPITAL CITY OF MDINA: SLOPE INSTABILITY AFFECTING AN HISTORICAL SETTLEMENT

(extract from Bonnici et al., 2008)

Mdina, Malta's medieval capital (Fig.24), can trace its origins back more than 4000 years. It is located on the northeast margin of the Rabat-Dingli Limestone Plateau at about 180 m above sea level.

From the mid-9th century to the mid-13th century, during Arab domination, for defence reasons the higher limestone plateau was encircled with a fortified belt, creating the actual citadel of Medina. The city, one of Europe's finest examples of an ancient walled city, lies on a geologically sensitive area.

The rocks exposed on the slopes of the plateau comprise: Upper *Globigerina* Limestone Member at the base; Blue Clay Formation; Greensand Formation; Upper Coralline Limestone Formation, at the top.

Upper *Globigerina* Limestone is an approximately 18 m thick unit composed of two yellow medium grained moderately weak foraminiferal limestone beds with a 5 m Bluish Grey marl interbed. The rock unit is overlain by the Blue Clay Formation - Blue plastic caolinitic clay with up to 25% carbonate content. This unit is about 30 m thick beneath Mdina and forms the slopes of the Rabat - Dingli Plateau. The Greensand Formation overlies the Blue Clay and is about 2 m thick and consists of medium grained friable orange glauconitic sand. The Upper Coralline Limestone on which the city is founded is a cap about 3-6 m thick and is composed of moderately weak to moderately strong limestone exposed in vertical cliff sections on the margin of the plateau, overlying the Greensand.

Over the years the fortifications and adjoining structures in Mdina have suffered severe structural damages due to undermining of the underlying friable sand and plastic clay causing the overlying limestone to shear accompanied by settlement and toppling of columnar limestone blocks.

Many historic buildings and bastion walls, lying on the outer perimeter of the town, have serious structural problems. One such building is the Vilhena Palace, situated on the north-eastern tip of Mdina. This monumental building erected by Grand Master Manoel de Vilhena as part of his programme to rekindle Mdina in the early 18th century is considered to be among the most beautiful, elegant and refined examples of baroque palatial architecture to be found in the Maltese islands. Vilhena Palace is located near the main entrance into the old city, just behind the main monumental gate (Fig. 24).

The foundation problems of the area have long been recorded, and in the past various attempts to resolve this delicate situation were undertaken. The most recent study campaign was carried out by an interdisciplinary team of experts. Surveys included photogrammetric, meteorological, topographical and structural monitoring, corroborated by a number of laboratory tests to determine the material properties of the superstructure and underlying strata.

The interventions in progress future have the aim of arresting the rotation and movement of the bastions walls by limiting the plasticization of the clay due to excessive bearing pressures confine the clay under the structures tie together the fractured upper coralline limestone reduce the erosion of substrata composed of orange sand, yellow and blue clay ground improvement by geotechnical processes to increase the allowable bearing pressures and to reduce settlement.

Fig. 24: Aerial view of Mdina showing the location of Vilhena Palace.

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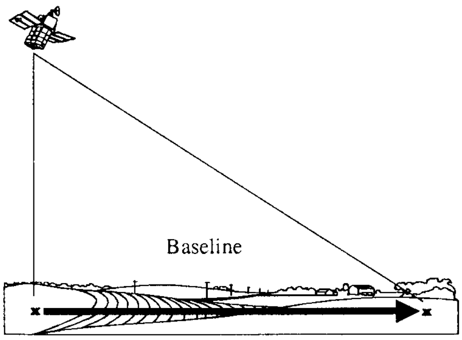
METHODS AND TECHNIQUES

A. GPS (Global Positioning System)

GPS is a radionavigation, timing and positioning system. By tracking the electromagnetic waves that the GPS satellites are sending continuously to the Earth, the system can obtain the antenna position on a common reference system. The accuracy of the positioning will depend on the quantity of information that a receiver is able to decode and on the strategy used to calculate the position (Hofmann-Wellenhof et al., 2001).The advantages of this technique are the flexibility, accuracy and relative ease of operation (Mantovani et al., 1996). Due to a reduction in cost and the development of new operating modes and software, the GPS is being increasingly used in a large variety of applications. The latter include establishment of control points for photogrammetry or remote sensing applications, positioning of drillings, coastline evolution and DEM generation (Malet et al., 2002). In the field of surveying, GPS applications were progressively conceived and developed in the early 1980s. In environmental research, GPS has been used to follow the movements of spoil heaps or quarry faces; to survey active volcanoes or major tectonic faults; to monitor the flow and behaviour of glaciers or snow thickness. The technique also applies, with sufficient accuracy, to the monitoring of man-made structures, such as dams, bridges and viaducts (Malet et al., 2002). In landslide monitoring, where the degree of accuracy required is millimetric, GPS has been used only for repeated measurements as a complement to conventional geodetic methods. Continuous monitoring of landslides with GPS is not usually performed operationally, mainly because of the cost of such a system compared to conventional deformation monitoring techniques (Malet et al., 2002). Since at present, the highest accuracies are achieved in relative positioning mode, usually this technique is employed to measure deformations. Relative positioning consist in determining the position of a GPS antenna by measuring its distance from a reference point of known coordinates where another antenna is collecting data simultaneously.



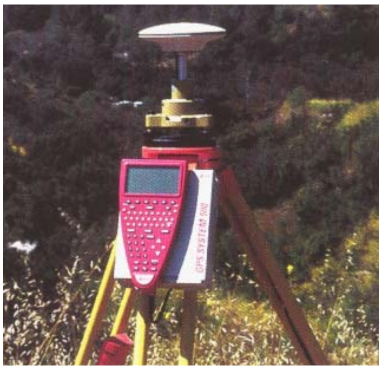


Fig. 1: The Global Positioning System (from Hofmann-Wellenhof et al., 2001).

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B. GEOPHYSICAL METHODS

Introduction

Geophysical methods register "*geo-physical anomalies*" related to contrasts of *physical proprieties* of the subsurface. An example of gravimetric and magnetic anomalies, related to buried objects, is provided in Figure 1.

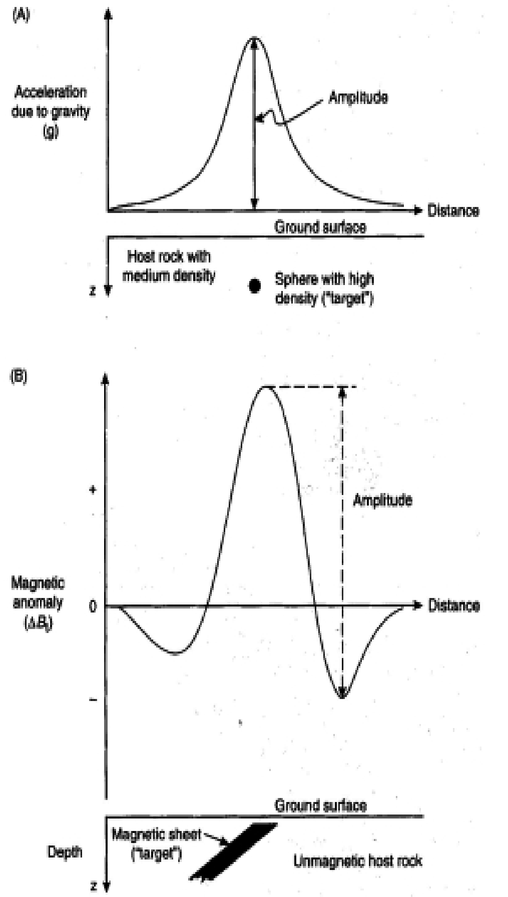

Fig. 1: A) Gravimetric anomaly due to the presence of a sphere with high density in the ground;
B) Magnetic anomaly due to the presence of a magnetic sheet below the ground surface.

In order to be detected, the *target* should be characterized by:

- Adequate contrast of physical properties respect to the surrounding materials
- Dimensions consistent with the attainable resolution
- Distance not exceeding the instrument range of penetration

Ground penetrating radar (or Georadar)

RADAR is an acronym coined in the 1934 for RAdio Detection And Ranging. The first experimental survey of Radar applied to ground sounding was performed in Austria in 1929 to sound the depth of a glacier (Stern, 1929, 1930). The technology was largely forgotten until the late 1950's when U.S. Air Force radars were seeing through ice as planes tried to land in Greenland, but misread the altitude and crashed into the ice. This started investigations into the ability of radar to see into the subsurface not only for ice sounding but also for mapping subsoil properties and the water table (Cook, 1964; Barringer, 1965; Lundien, 1966). Ground Penetrating Radar is sometimes called georadar, ground probing radar, subsurface radar or simply GPR.

GPR uses electromagnetic wave (EM) reflections to image, locate and quantitatively identify changes in electrical (and magnetic) properties of the ground. This methodology has the highest resolution in subsurface imaging if compared with any other geophysical method, approaching centimeters under the right conditions. The detectability of a subsurface feature depends upon contrast in electrical and magnetic properties, and the geometric relationship with the antennas. Quantitative interpretation can also be derived from ground penetrating radar data extracting and modeling information such as depth, orientation, size and shape of buried objects, density and water content of soils.

Basic principles

Figure-2 provides a simplified scheme or a GPR equipment. A radar system includes one or more transmitting and receiving antennas coupled to the ground, a sampling unit, a storage unit and a display for real time data quality control. A GPR system can be equipped with different antenna pairs having a central frequency within the range from about 10 MHz to 2 GHz.

GPR registers traveltimes and amplitudes of Direct, refracted, diffracted and REFLECTED EM waves due to variations of the electrical properties. The latter waves are used to image the subsurface.

There is a basic relation between the frequency (f), the velocity (v) and the wavelength (λ) of a EM signal: $v = f\lambda$

Using this equation we can estimate the wavelength of a signal, which has an inverse proportionality with the attainable RESOLUTION (i.e. the minimum distance between two objects that can be detected as separated by a specific GPR signal).

In other words: increasing the wavelength (and decreasing the frequency for a fix velocity), the resolution will decrease and therefore the subsurface detail level will also be smaller.

On the other hand an higher frequency has a larger attenuation an the attainable penetration depth will also be smaller.

Since the subsurface EM velocity cannot be change by the operator the choice of the proper GPR frequency for a survey should be a trade-off between the desired resolution and the maximum depth of interest.

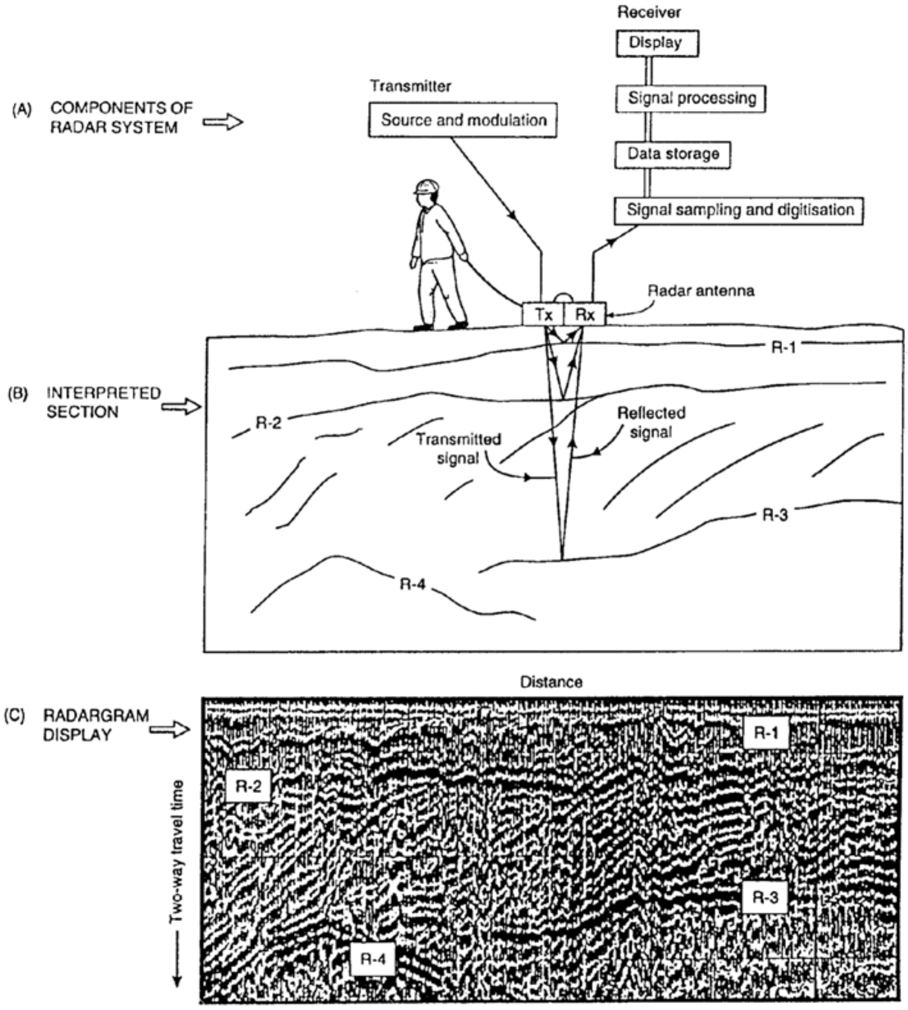

Fig. 2: Simplified GPR scheme (from Davis and Annan, 1989).

MATERIAL	ε_r	σ (mS/M)	v (m/ns)	α (dB/m)
Air	1	0	0.30	0
Distilled Water	80	0.01	0.033	$2x10^{-3}$
Fresh Water	80	0.5	0.033	0.1
Sea Water	80	$3x10^{3}$	.01	10^{3}
Dry Sand	3-5	0.01	0.15	0.01
Saturated Sand	20-30	0.1-1.0	0.06	0.03-0.3
Limestone	4-8	0.5-2	0.12	0.4-1
Shales	5-15	1-100	0.09	1-100
Silts	5-30	1-100	0.07	1-100
Clays	5-40	2-1000	0.06	1-300
Granite	4-6	0.01-1	0.13	0.01-1
Dry Salt	5-6	0.01-1	0.13	0.01-1
Ice	3-4	0.01	0.16	0.01

Tab. 1: Typical values of dielectric constant (εr), conductivity (σ), EM velocity and attenuation (α) for some geological materials.

TYPE OF MATERIAL	Antennas frequency (MHz) 120	500	900
SILTY SOIL (v=7.5cm/ns)			
Max expected penetration depth (m)	4	2.5	1
R_v (m)	0.16	0.04	0.02
LIMESTONE (v=11cm/ns)			
Max expected penetration depth (m)	25	15	8
R_v (cm)	0.23	0.06	0.03

Tab. 2: Examples of typical resolutions and penetration depths attainable using different antennas for a silty-soil and for a limestone.

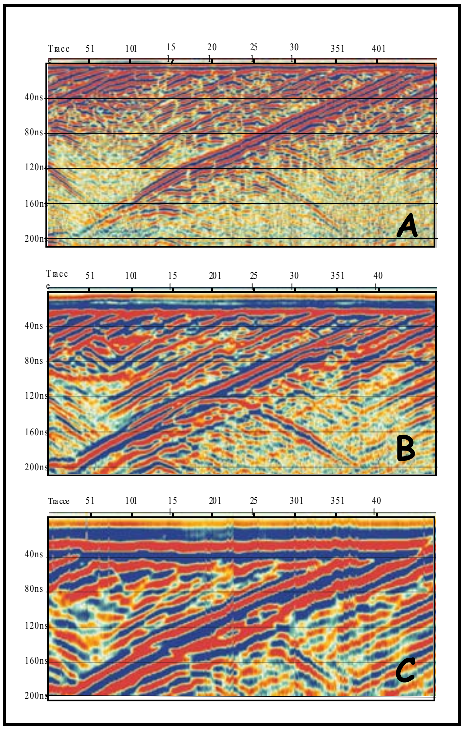

Fig. 3: Example of GPR profiles acquired along the same path using 200MHz (A), 100MHz (B) and 50MHz (C) antennas. The resolution becomes lower from A) to B), while the penetration depth increases.

Usually GPR data cannot be interpreted in real time, but several processing and analysis steps must be applied. A basic processing flow includes the following operations:

<u>Editing and Pre-processing</u>

11. DC removal
12. De-wow
13. Drift removal
14. Background removal

<u>Processing</u>

15. Amplitude decay analysis and corrections
16. Filtering
17. Velocity analysis
18. Depth conversion
19. Migration

C. ELECTRICAL METHODS

Introduction and history

Electrical methods were first used for geological applications in the 1940s (Atkinson, 1952). These methods are divided into the non-contacting electromagnetic (sometimes called EM, or induction) methods, and the soil contacting (sometimes called galvanic or resistivity) methods.

One of the most popular techniques is the resistivity method (including Vertical Electric Sounding, Electric Resistivity Tomography,…).

Resistivity methods are active: an electric current is driven thought the ground and the resulting potential differences are measured at the surface. Usually a very low frequency or direct (DC) is applied to measure the resistivity.

Fundamental theory

Ohm's law deals with the relationship between voltage (potential difference) and electric current in a conductor (ohmic material). This relationship states that the potential difference across a conductor is proportional to the circulating current. The constant of proportionality is called the "resistance", R.

So Ohm's Law states that:

$V = R\,I$

where V is the potential difference between two points and I is the current flowing between that points. It-s interesting to note that spontaneous electric potentials (i.e. not related to artificially currents) usually originates in the subsurface and can be used to keep information of the properties of the materials. This techniques is therefore “passive” and it’s called “Self Potential”.

The resistance (R) depends by the electric properties of the considered materials but also by its shape and geometry. Therefore it’s better to use the RESISTIVITY (ρ): a quantity depending only by the physical properties of a material.

$$\rho = \frac{\Delta V}{I} K$$

Where K is the geometric coefficient of the conductor; for a linear conductor K it’s simply equal to the S/l (S=the area of the conductor and l the length).

In the resisitivity methods an electric current is driven thought the ground by “current electrodes” and the resulting potential differences are measured at the surface by “potential electrodes”.

Material	Nominal resistivity (Ω m)
Sulphides:	
Chalcopyrite	1.2×10^{-5}–3×10^{-1}
Pyrite	2.9×10^{-5}–1.5
Pyrrhotite	7.5×10^{-6}–5×10^{-2}
Galena	3×10^{-5}–3×10^{2}
Sphalerite	1.5×10^{7}
Oxides:	
Hematite	3.5×10^{-3}–10^{7}
Limonite	10^{3}–10^{7}
Magnetite	5×10^{-5}–5.7×10^{3}
Ilmenite	10^{-3}–5×10
Quartz	3×10^{2}–10^{6}
Rock salt	3×10–10^{13}
Anthracite	10^{-3}–2×10^{5}
Lignite	9–2×10^{2}
Granite	3×10^{2}– $\times 10^{6}$
Granite (weathered)	3×10–5×10^{2}
Syenite	10^{2}–10^{6}
Diorite	10^{4}–10^{5}
Gabbro	10^{3}–10^{6}
Basalt	10–1.3×10^{7}
Schists (calcareous and mica)	20–10^{4}
Schist (graphite)	10–10^{2}
Slates	6×10^{2}–4×10^{7}
Marble	10^{2}–2.5×10^{8}
Consolidated shales	20–2×10^{3}
Conglomerates	2×10^{3}–10^{4}
Sandstones	1–7.4×10^{8}
Limestones	5×10–10^{7}
Dolomite	3.5×10^{2}–5×10^{3}
Marls	3–7×10
Clays	1–10^{2}
Alluvium and sand	10–8×10^{2}
Moraine	10–5×10^{3}
Sherwood sandstone	100–400
Soil (40% clay)	8
Soil (20% clay)	33
Top soil	250–1700
London clay	4–20
Lias clay	10–15
Boulder clay	15–35
Clay (very dry)	50–150
Mercia mudstone	20–60
Coal measures clay	50
Middle coal measures	>100
Chalk	50–150
Coke	0.2–8
Gravel (dry)	1400
Gravel (saturated)	100
Quaternary/Recent sands	50–100
Ash	4
Colliery spoil	10–20
Pulverised fuel ash	50–100
Laterite	800–1500
Lateritic soil	120–750
Dry sandy soil	80–1050
Sand clay/clayey sand	30–215
Sand and gravel	30–225
Unsaturated landfill	30–100
Saturated landfill	15–30
Acid peat waters	100
Acid mine waters	20
Rainfall runoff	20–100
Landfill runoff	<10–50
Glacier ice (temperate)	2×10^{6}–1.2×10^{8}
Glacier ice (polar)	5×10^{4}–3×10^{5} *
Permafrost	10^{3}–$>10^{4}$

Surface waters (sediments)	10 – 100	
Soil waters		100
Natural waters (ign. rocks)	0.5 – 150	9
Natural waters (sediments)	1 – 100	3
Sea water		0.2
Saline waters, 3%		0.15
Saline waters, 20%		0.05

Tab. 1: Mean resistivity values for some geological materials.

In real cases, there are subsurface inhomogeneities of the resistivity and therefore the values obtained on the field are just apparent resistivities (δ_a).
There are two distinct procedures to perform resistivity surveys: vertical electric sounding (VES) and electric profiling (or ERT). The VES is based on the principle that the current penetrates continuously deeper increasing the separation between the current electrodes; in this way it is possible to obtain information about the resistivity variations with depth.
The electric profiling is based on the principle of moving the electrodes along a defined survey line: the result will be a "resistivity pseudosection" for the 2-D case (Fig. 1) or a "resistivity pseudovolume" for 3-D surveys.
Fig. 2 provides a sketch of the equipment and geometrical electrodes positioning for a Wenner pseudosection acquisition.

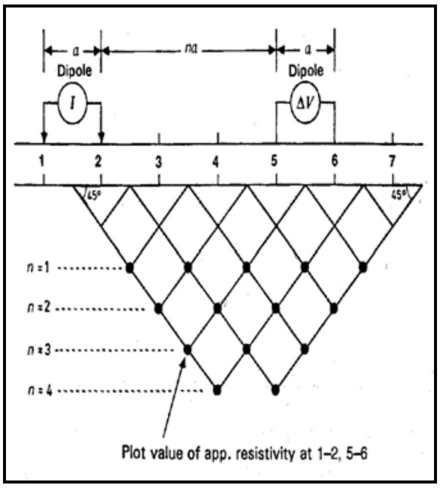

Fig. 1: Scheme of resistivity pseudosection (Dipole-Dipole electrodes configuration).

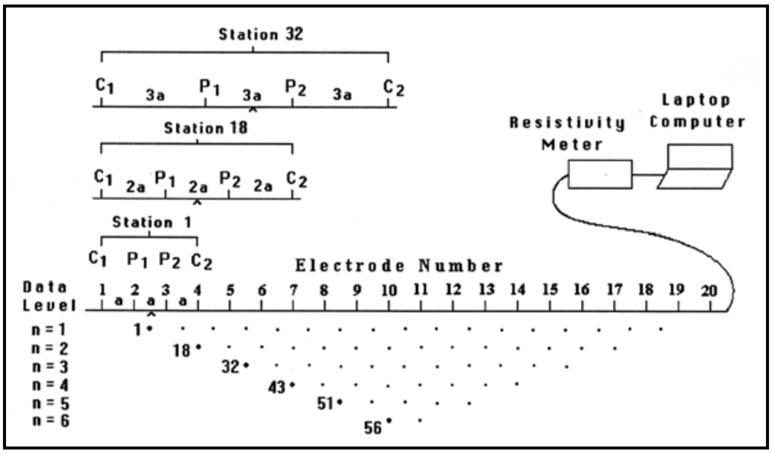

Fig. 2: Sequence of electrodes combinations to acquire a resistivity pseudosection (Wenner array).

The field resistivity values are not a true representation of the real distribution of resistivities in the subsurface. An inversion procedure should be performed in order to estimate the real resistivity distribution. This procedure consists of interactively computing (modelling) an apparent resistivity model until the calculated resistivity section matches the values measured on the field.
Several real media exhibit polarization phenomena at various scale (electrons, atoms, molecules, grain polarization,…). Analysing the overvoltage effect related to these phenomena it is possible to extract additional information about the electric material characteristics. High polarization effects occur for clay. Using the "Induces Polarization" methods (IP), combined with traditional resistivity measures it is therefore possible to estimate the clay content.
Fig. 3 shows a schematic diagram for I and V within a polarisable medium; V_p represents the electric potential related to polarization phenomena.

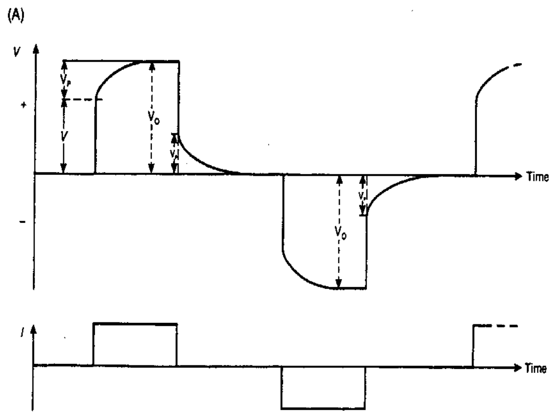

Fig. 3: Scheme of V and I variations with time in a polarizable medium.

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D. MEM and TMEM to study rock surface lowering

The study of rock lowering rates is considered to be very useful in order to explain the total amount of rock denudation. It is carried out mainly using the micro erosion meter (MEM), following High and Hanna's (1970), or the traversing micro erosion meter (TMEM), following Trudgill et al. (1981). Now, an improvement of these instruments is in progress.

The instruments

Both the MEM and TMEM are equipped with three specially-shaped supports which adhere to three iron or titanium nails, two semi-spherical and one flat shaped firmly fixed into the limestone rock. The re-location on the fixed bolts derives from this particular configuration, called Kelvin Clamp Principle. The TMEM, more useful and precise, is equipped with a millesimal-resolution electronic dial gauge, so that readings can be directly downloaded on a laptop computer. The particular configuration allows to obtain a large data set, up to 238 measurements at a site. A calibration steel base is used to check periodically the instrument. The electronic dial gauge has a resolution of 0.001 mm, while the error, determined by the manufacturer, is ±0.003 mm. Probe erosion was estimated by Cucchi et al. (2009) and Furlani et al. (2009). The instrument is set in equilibrium with air temperature in order to reduce the temperature-related error. Readings below 0.010 mm must be considered with caution (Stephenson et al., 2004).

Fig. 1: The TMEM on the samples of the experimental station in Muggia, Trieste (I).

Applications

Different applications are possible with the MEM and TMEM. In fact, they have been used in different environments and geomorphological conditions all over the world. In Italy, first studies started in Trieste, on the Classical Karst area (Forti, 1980) then, the method has been used all over Karst zones in Europe Many studies concern the coastal environment.

Recently, the TMEM has been used to study the evolution of particular coastal morphologies, as the notch. In this case, a rock removable slab (RRS) permits to estimate the lowering rates on vertical limestones. It consists in a smooth limestone surface, which has been obtained by mechanical cutting. Further details on the method is reported by Furlani et al. (2010). The slab is 1.80 m long and it has been vertically set in the intertidal zone. In our case, the stations have been set at +0.75 m, +0.5 m, +0.25 m, 0.0 m, -0.25 m, -0.5 m adn -0.75 m.

Gomez-Pujol et al. (2007) and Furlani and Cucchi (2007) studied also the diurnal variation on rock surfaces both in the coastal environment and on some samples located on a experimental site (stations in the figure). Researches demonstrate that the rock surface is affected by diurnal variations, probably due to variations in temperature and humidity or to the presence of lichens.

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E. GEOMECHANICAL SURVEY

Introduction

The following part summarises geomechanical methods, giving some guidelines for field work and some practical rules for the preliminary studies in Malta.

Geomechanical surveys will be conducted along Maltese limestone cliffs. The objective is to identify the amount of discontinuity sets and their orienatation (Dip directions and dips). Properties of discontinuity sets will be defined through a survey form and Q system will be applied in Il-Qarraba and Il-Prajjet sites.

Q System

The Q-system was developed in Norway in 1974 by Barton. It is a quantitative classification system and it help geologists and engineers to define qualities of rock masses.

The Q-system uses six different parameters to assess the rock mass quality. The parameters are:

- Rock Quality Designation RQD
- Joint set number Jn
- Roughness of the most unfavorable joint or discontinuity Jr
- Degree of alteration of filling along the weakest joint Ja
- Water inflow Jw
- Stress Reduction Factor SRF

Each of the six parameters is assigned a value corresponding to the characteristics of the rock mass and properties of discontinuities (joints, layer planes, faults, etc).

These values are derived from field surveys.

Q Parameters

RQD

It is a index that measures the degree of jointing or fracture in a rock mass, worked out as a percentage of the drill core in lengths of 10 cm or more.

In order to work out the RQD value, Palmstrom formula permits to correlate Jv with RQD.

$$RQD = 115 - 3.3*(Jv)$$

Jn

The parameter Jn describes the number of discontinuity sets.

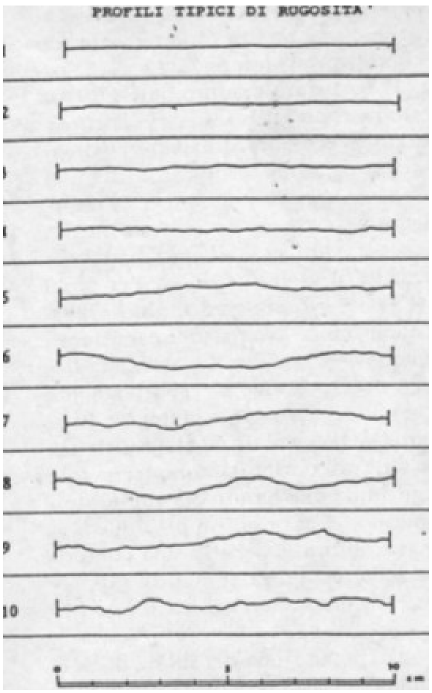
	Jn
Massive rock mass	0.5-1
1 Discontinuity sets	2
1 D. Sets + casual joints	3
2 Discontinuity sets	4
2 D. Sets + casual joints	6
3 Discontinuity sets	9
3 D. Sets + casual joints	12
4 or more	15
Deeply jointed r.masses	20

Jr

The Jr parameter describes the roughness of discontinuity.

In order to evaluate the roughness, Barton's diagram will be used.

	Jr
Short discontinuties	4
Very rough joints	3
Rough joints	2
Slighty rough joints	1.5
Polished joints	1.5
Slightly undulating joints	1
Planar joints	1
Planar and filled joints	0.5



From Bruschi (2004).

Ja

The Ja parameter describes the infilling materials, the aperture of joints and weathering, according to BS 1981.

		J_a
A	**Pareti discontinuità a contatto**	
1 -	Discontinuità serrate, impermeabili ev. riempite da materiale non plasticizzabile	0,75
2 -	Discontinuità con bordi non alterati	1,0
3 -	Discontinuità con bordi leggeremente alterati. Materiale di riempimento sabbioso, non plastico (senza argilla)	2,0
4 -	Discontinuità con materiale di riempimento sabbioso o siltoso, con poca frazione argillosa (non plasticizzabile)	3,0
5 -	Discontinuità con riempimento parziale di materiale a comportamento plastico, con potenza < 1-2 mm (miche, talco, gesso, grafite, argilla etc.)	4,0
B -	**Pareti discontinuità a contatto con scorrimento di taglio < 10 cm**	
6 -	Discontinuità con materiale di riempimento sabbioso (roccia disgregata senza argilla)	4,0
7 -	Discontinuità con riempimento continuo di argille non plastiche, fortemente sovraconsolidate, di pot. < 5mm	6,0
8 -	Discontinuità con riempimento continuo di argille plastiche, mediamente o poco sovraconsolidate, di potenza < 5mm	8,0
9 -	Discontinuità con riempimento continuo di argilla rigonfiante di potenza < 5mm	8,0 ÷ 12,0
C -	**Pareti discontinuità non a contatto**	
10 -	Fasce di roccia frantumata con presenza di argilla (Le tre classi dipendono dal tipo di argilla come in 7, 8, 9)	6,8 o 8 ÷ 12
11 -	Fasce di roccia ridotta a un silt o a una sabbia argillosa (con poca argilla non plastica)	5,0
12 -	Sottili ma continue fasce argillose (le tre classi dipendono dal tipo di argilla come in 7, 8 e 9)	10,13 o 1:

Jw

The Jw parameter takes into account the presence of water in the rock masses and its velocity.

	Definizione	J_w	Pressione acqua [MPa]
1 -	Acqua assente o scarsa (localm. venute < 5 l/min)	1,0	0,1
2 -	Venute d'acqua limitate o a media pressione, con occasionale dilavamento dei materiali di riempimento delle discontinuità	0,66	0,1 - 0,25
3 -	Venute d'acqua forti o ad alta pressione in roccia coerente con discontinuità aperte	0,5	0,25 - 1
4 -	Venute d'acqua forti o ad alta pressione, con notevole dilavamento del materiale di riempimento delle discontinuità	0,33	0,25 - 1
5 -	Venute d'acqua eccezionalmente forti o ad altissima pressione dopo le volate, ma decrescenti nel tempo	0,2 - 0,1	> 1
6 -	Venute d'acqua eccezionalmente forti o ad altissima pressione, senza apprezzabile diminuzione nel tempo	0,1 - 0,005	> 1

SRF

The parameter SRFdescribes the stresses in undeground. The system was developed for tunnelling and later adapted for open air engineering works.

FATTORE DI RIDUZIONE PER PRESSIONE LITOSTASTICA	SRF
Molte fratture riempite di argilla o di rocca alterata chimicamente	10
Singole fratture con argilla o roccia alterata chimicamente (prof. di scavo <50 metri)	5
Singole fratture con argilla o roccia alterata chimicamente (prof. di scavo >50 metri)	2,5
Multiple zone di taglio in rocce competenti (qualsiasi profondità)	7,5
Singole zone di taglio in rocce competenti (prof. di scavo <50 metri)	5
Singole zone di taglio in rocce competenti (prof. di scavo >50 metri)	2,5
Rocce molto fratturate, giunti molto aperti (qualsiasi profondità)	5
Bassa pressione (vicino alla superficie	2,5
Condizioni di carico medie	1
Alta pressione, roccia a struttura compatta	2
Moderati scoppi di roccia (roccia massiva)	5-10
Intensi scoppi di roccia (roccia massiva)	10-20
Roccia moderatamente deformata	5-10
Roccia intensamente deformata	10-20
Roccia con moderata pressione di rigonfiamento	5-10
Roccia con intensa pressione di rigonfiamento	10-15

Q formula and quality classes

The "Q value", which ranges between 0.01 and 1000, is obtained by the following formula:

$$Q = \frac{RQD}{J_n} \frac{J_r}{J_a} \frac{J_w}{SRF}$$

The Q values permit to assess rock qualities of rock masses.

The classes are eight and each class describe a degree of quality which ranges from extremely poor to extremely good.

Quality descrip.	Values
Extremly poor	0.01-0.1
Very poor.	0.1-1
Poor	1-4
Fair	4-10
Good	10-40
Very good	40-100
Very very good	100-400
Extremly good	400-1000

Cohesion and friction angle formula

Cohesion and friction angle can be work out from the Bieniawski formulas:

Cohesion (Kpa) = 5(BRMR)*
Friction angle = 5 + (BRMR)/2

Where BRMR rating is obtained by the following formula:

BRMR= 9 ln (Q) + 44

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F. TAPE EXTENSOMETER

The TE is used to detect and monitor changes in the distance between two reference points. The tape is stretched hooking its free end to one point and the instrument body to the other and then tensioned. By comparing the current reading to the initial reading, the change in distance between the two reference points can be calculated (Fig.1, 2).

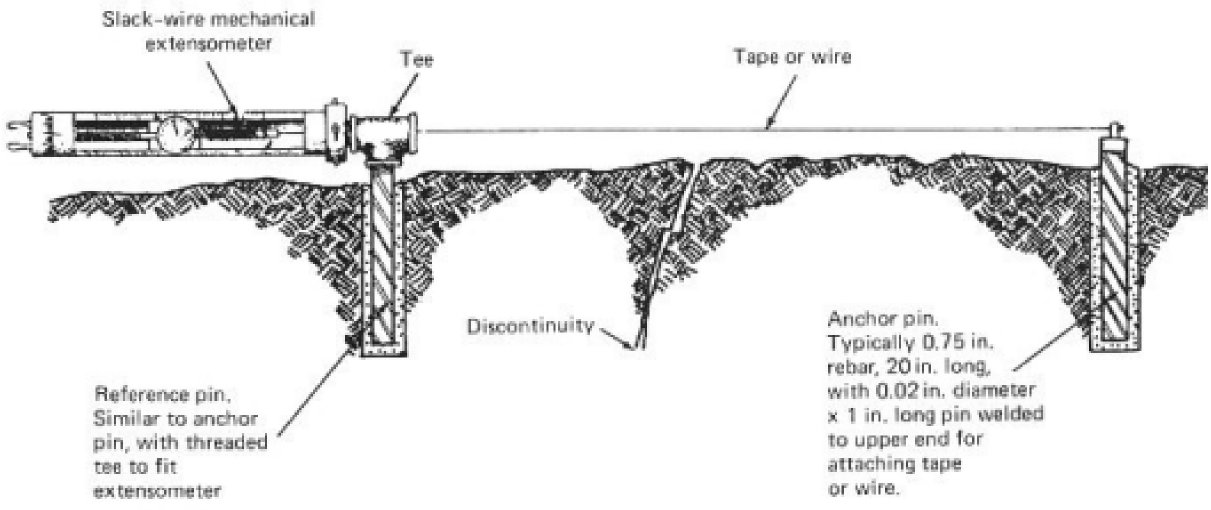
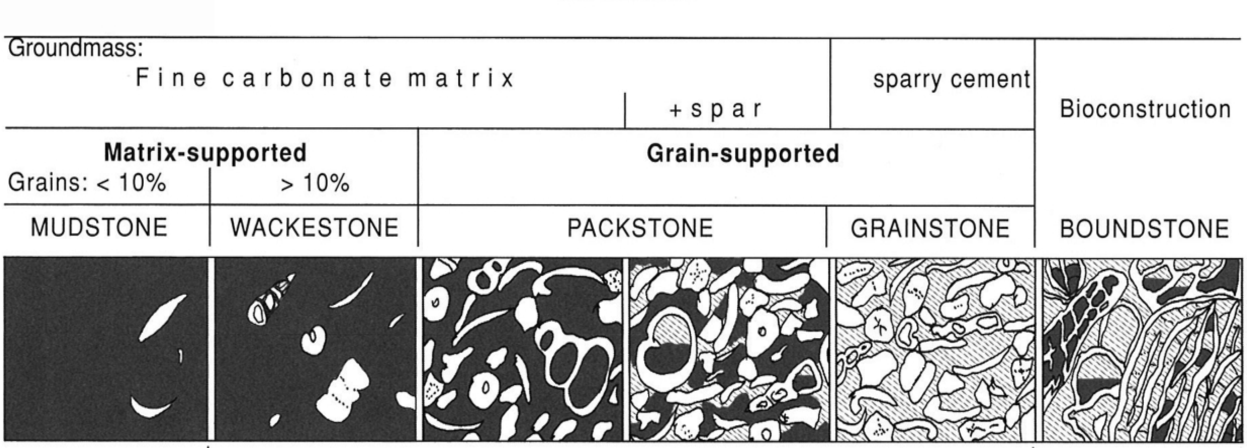


Fig. 1: The TE technique uses a steel wire and pins were the instrument is anchored.

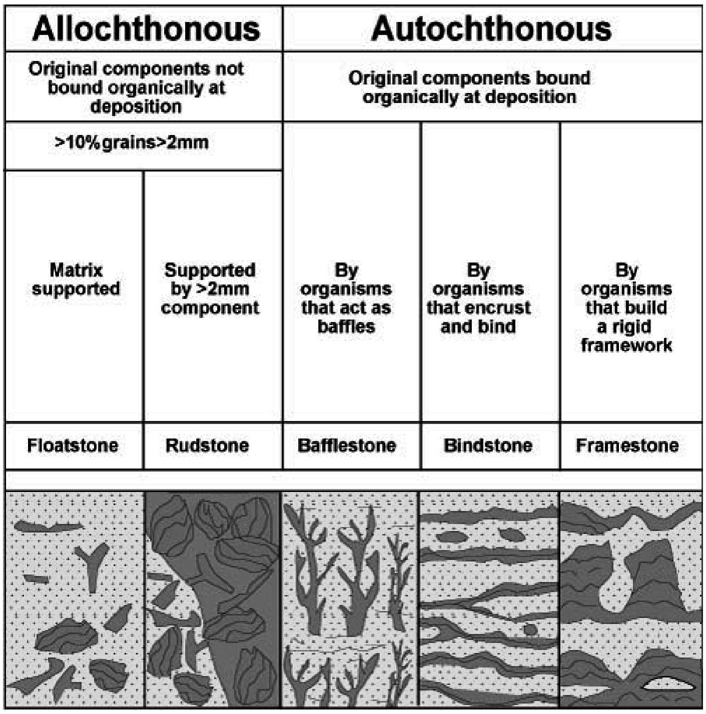
Fig. 2: The photo shows the instrument anchored at the reference pin.

This technique, widely used in tunnelling, was chosen to integrate the displacements measured by GNSS surveys.
A tape extensometer network consisting of 3 reference pins (E1, E2, E3) and 5 anchor pins (1, 2, 3, 4, 5) was installed at Il-Prajjet on December 2009.

E. CLASSIFICATION OF CARBONATE ROCKS



Textural classification of carbonate rocks after Dunham (1962).



Classification of carbonate limestones after Embry & Klovan (1971) and James (1984).

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