LINKING COASTAL AND SEAFLOOR MORPHOLOGICAL FEATURES ALONG THE EASTERN SIDE OF THE MALTESE ARCHIPELAGO

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Abstract – The integration of detailed geomorphological information from the present subaerial exposures of the Maltese archipelago, with morphobathymetric data obtained from the adjacent continental margin may serve in understanding processes active in shaping the archipelago since the Last Glacial Maximum. In perspective, this appears also to be of fundamental importance to better define the kinematics of active gravitational processes occurring along the coastlines. Preliminary results reveal the existence of submerged morphologies comparable to subaerial analogous. A case in point is circular depressions at shallow depth interpreted as inundated former karst features like sinkholes on-land. This is probably the case also of fractured plateaus surrounded by detached blocks identified offshore, which are comparable to terrestrial landforms formed by lateral spreading. Other relevant features identified on the continental margin and easily correlatable with morphologies on land include meandering river valleys.

1. Introduction

Standard geomorphological descriptions of maritime areas rather typically deal either with subaerial landscapes or with subaqueous topographies only seldom combining the two in a single picture. An on-going project by the present authors aims precisely at merging detailed morphological analyses on-land with accurate submarine mapping of drowned landscape. The area chosen for this exercise is the Maltese archipelago which, due to its geological setting and climatic conditions, presents various advantages for such integrated studies. Experience gained by multiyear studies of geomorphic processes active in shaping the emerged landscape is combined with the first detailed morphobathymetric information recently obtained from the Maltese continental margin (fig. 1). The final scope of this project is a better definition of the processes governing the shaping of the Maltese coastal landscape since the Last Glacial Maximum (LGM) up to present, exploiting the fact that the now-drowned subaerial landscape has been only slightly affected by post-glacial modification. Basically, due to its geological setting (with a relative scarcity of terrigenous deposits) and semi-arid climatic conditions, Malta largely presents in its submerged shelf area an almost intact inherited subaerial geomorphology.

([19]).

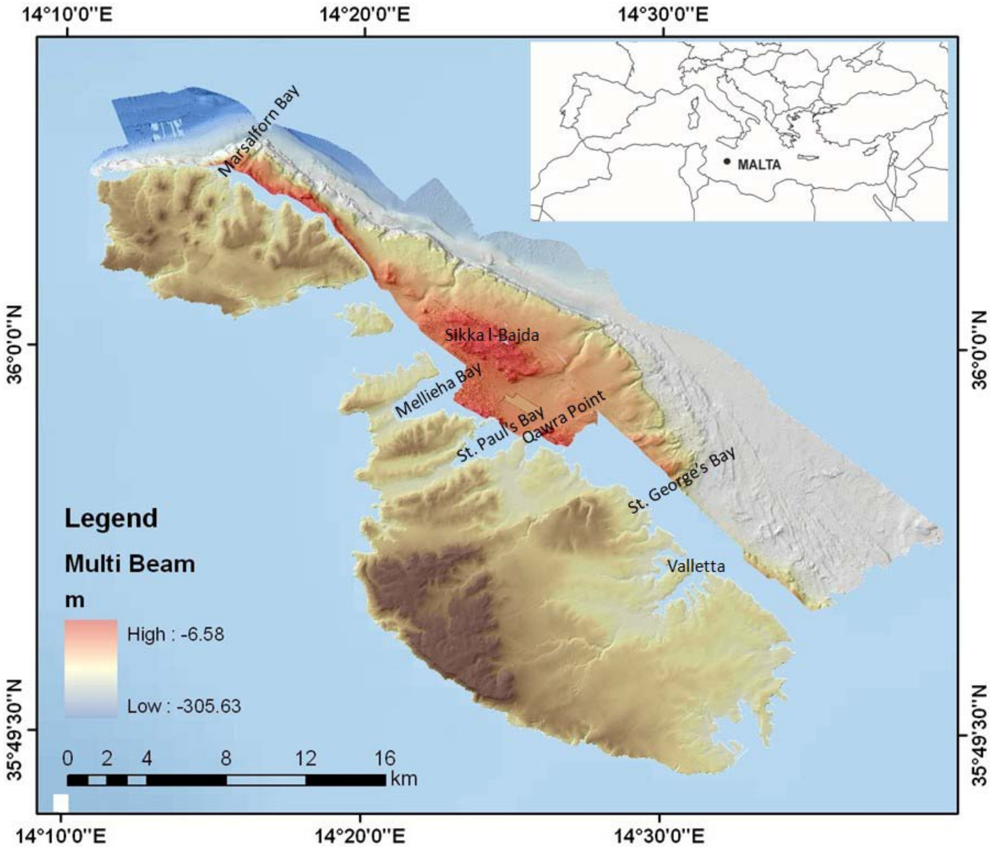

Figure 1 – Location of the Maltese archipelago and overview of the multibeam data acquired from the submerged continental shelf (modified after [19]).

1.2 Structural and geological setting

The Maltese archipelago is located in the Sicily Channel on the Pelagian Platform, about 200 km south of the convergent segment of the Europe-Africa plate boundary that runs through Sicily (fig. 1). The structural setting of the Maltese Islands is characterised by two normal fault systems with different orientations. The first system is oriented ENE-WSW, forming a horst-and-graben structure along the archipelago, and whose principal lineament is the Victoria Lines Fault. This fault has a maximum displacement of 195 m and divides the island in two different portions (North Malta Graben and Malta Horst). The second system is oriented NW-SE, parallel to the Pantelleria Rift trend, and its most important fault is the Maghlaq Fault, which outcrops in the southern coast of Malta ([3],

[5], [6], [7], [9], [14], [15], [24] and [25]). The geology of the archipelago is characterised by the presence of four main sedimentary formations, ranging from Late Oligocene to Late Miocene, which lie almost horizontally across the islands (fig. 2). From the bottom, the stratigraphic succession consists of (i) Lower Coralline Limestone Formation (Chattian); (ii) Globigerina Limestone Formation (Aquitanian - Lower Langhian); (iii) Blue Clay Formation (Upper Langhian – Lower Tortonian); (iv) Greensand Formation; (v) Upper Coralline Limestone Formation (Upper Tortonian – Lower Messinian).

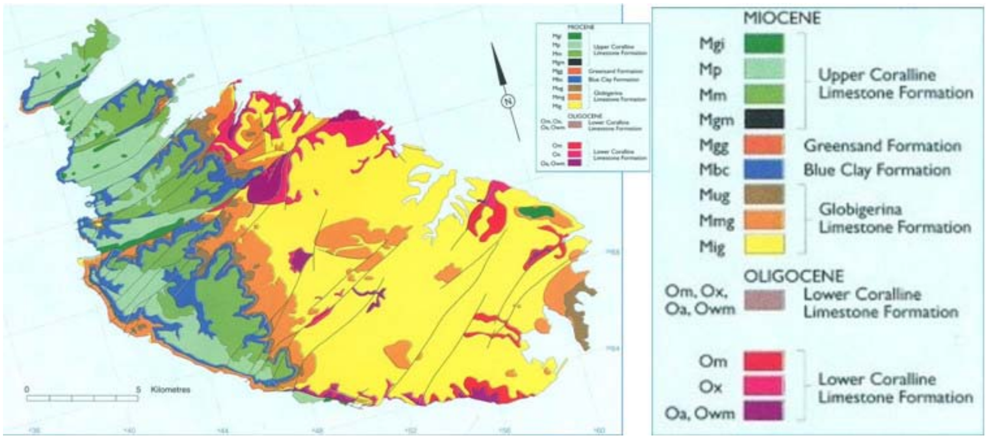

Figure 2 – Simplified geological map of Malta (modified after [21]).

2. Materials and methods

The onshore research has foreseen detailed geomorphological mapping in the northern sector of the Island of Malta and in Gozo allied with engineering geological and geophysical investigations ([4], [10] and [19]). Within the survey of all geomorphological processes and landforms, the attention was focused on the recognition, identification, mapping of different types of landslides. Among the latter, worthy of note are extensive lateral spreading and block sliding phenomena which have been monitored to define their state of activity and rate of movement. A network of GPS benchmarks were distributed on the edge of a limestone plateau affected by rock spreading and block sliding. GPS monitoring results have been combined with the outputs of extensometric measurements. In order to identify the main discontinuities within rock masses, Resistivity Tomography profiles and GPR investigations have also been carried out.

Attention was also focused on the recognition and genetic interpretation of sinkholes, which make up a relevant landmark especially in the Island of Gozo ([8], [23] and [28]). Attention was specifically focused on the sinkholes depicted in the geological map of the Maltese Islands, some of which displaying features of notable size which can be defined as caprock collapse sinkholes according to [12].

The offshore data partly discussed here were obtained by three oceanographic missions that surveyed the north-eastern Maltese margin in the period 2009-2011. Cruise

MEDCOR and DECORS were carried out in December 2009 and August 2011 respectively onboard R/V *Urania*. Both surveys mapped a substantial part of the north-eastern Maltese continental margin from off north Gozo to the southern tip of Malta. Cruise RICS 2010 on-board R/V *Hercules* investigated in detail a portion of the shallow eastern margin between southern Gozo and north Malta. High-resolution multibeam data were acquired from these missions using Konsberg Simrad systems (EM710 and EM3002D), coupled with a differential Global Positioning System (DGPS) and a motion sensor unit (MRU). Chirp-sonar records and various bottom samples from *Urania* cruises integrated the overall dataset from the study-area.

Multibeam data were then processed to generate a first map of the submerged morphology resulting in the Digital Terrain Model (DTM) of the seafloor offshore east Malta ([19], fig. 1). Multibeam data were processed using the software CARIS HIPS and SIPS 7.0 by importing raw data, loading tide (through predictive model) and merging the data. A base surface (DTM) of the seafloor was then generated with a resolution of 1 m, using the swath angle algorithm developed in CARIS. Spikes have been removed to clean the DTM from errors and noise.

The DTM has been exported from CARIS as .xyz file and converted into a raster grid in order to visualise the data in GIS software (ArcGIS 9.3). A hillshade map was derived from the DTM using the spatial analysis extension and the morphological features were mapped. Backscatter data were extracted from multibeam data using Caris HIPS and SIPS to understand the spatial distribution of seafloor texture and composition.

3. Discussion

3.1 Emerged features

The Maltese landscape has been described by numerous authors ([1], [2], [8], [10], [13], [14], [18], [20] and [22]). It is predominantly controlled by tectonic processes such as faulting, up-arching and subsidence. In fact, the ancient ENE-WSW fault system is responsible for a basin-and-range-like morphology and controls the drainage pattern, while the fault system oriented NW-SE, particularly the Maghlaq fault, controls the south coast of Malta and its cliffs. In general fractures and faults are weakness zones, so they are preferentially eroded areas. Another important modelling agent is water, which is responsible of fluvial, karst and coastal processes and related morphological features.

Mass movements occur mainly along the coasts and, in particular, where Upper Coralline Limestone and Blue Clay formations outcrop juxtaposed, especially along the NW coast of Malta. Of particular interest is the common occurrence of lateral spreading and block sliding phenomena, which are clearly favoured by the different mechanical properties of the two main rock types outcropping in the area, such as those belonging to the brittle Upper Coralline Limestone Formation and the Blue Clay Formation, the latter being a softer and unconsolidated material. The Upper Coralline Limestone plateaus are 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. These two geological formations show also different hydrogeological characteristics which favour mass movement processes and landslide activity ([18]).

Sinkholes make up another relevant landmark, especially in Gozo. Some of these karst features reach a few hundreds of metres in diameter and depth, and display different geomorphic expressions depending on the resistance to erosion of the lithotypes outcropping inside and outside the structures. The majority of these sinkholes still show their original infill deposited during the subsidence or afterwards. Some of them gave rise to relief inversion due to selective erosion processes ([8] and [28]).

3.2 Offshore morphology

The north-eastern Maltese seafloor is very gently sloping forming a platform that is confined offshore by an escarpment at a depth of 120-130 m. The deeper part is a smooth, featureless surface almost entirely covered by fine to medium sand ([19]). The majority of this part is covered by maerl deposits associated with sand and gravel, and *Posidonia oceanica* forming *matte*. Maerl, prominently formed by living and calcareous red algae, is a widespread type of coarse sediment in the Maltese inner continental shelf ([26]).

The most prominent feature N-NE offshore the islands of Gozo, Comino and Malta is a long escarpment at a depth of 120-130 oriented parallel to the Maltese coastline ([19]). It displays a total length of ca. 18 km and a height of 50 m with a slope steeper than 60°. It has been hypothesised that this feature represents a former coastline at the time of the Last Glacial Maximum (LGM; [19]) when sea level was ca. 125 m below present, as reconstructed by [11], [16], [17] and [27].

In addition, other elongated features can be observed. These include ridges with an arcuate shape have been recognised offshore in front of St. Julian’s Bay and rectilinear ridges have been found in front of the Grand Harbour of Valletta. It is possible to observe a distinct terrace, with a smooth surface and limited basinwards by a step, which is visible on the deeper side of the escarpment.

Several channels incise the platform and the escarpment ([19]). The three major channels are situated in front of Marsalforn Bay of Gozo, in front of Comino Island and in front of St. Paul’s Bay of Malta; while the others are situated along the stretch of coast from St. Paul’s Bay to St. George’s Bay. Channels have a slightly meandering shape and are aligned with bays and valleys on the islands (fig. 3D).

A slightly depressed area deprived of *Posidonia oceanica* meadows is present upslope of the channels in front of Comino Island and St. Paul’s Bay. We tentatively interpret the channels as the submerged continuation of river valleys identified on-land, therefore, as marks of lowstand riverine activity ([19]). On the same line of reasoning, the depressed areas are likely to be interpretable as alluvial plains coeval to these ancient river valleys.

On the shallower part of the platform, the most evident feature is Sikka l-Bajda reef ([19]). Similar reefs of smaller size are located to the NE of Gozo. The reefs are colonized by *Posidonia oceanica*, resulting in the formation of the so-called *matte* ([19]), regularly dissected by intramatte channels.

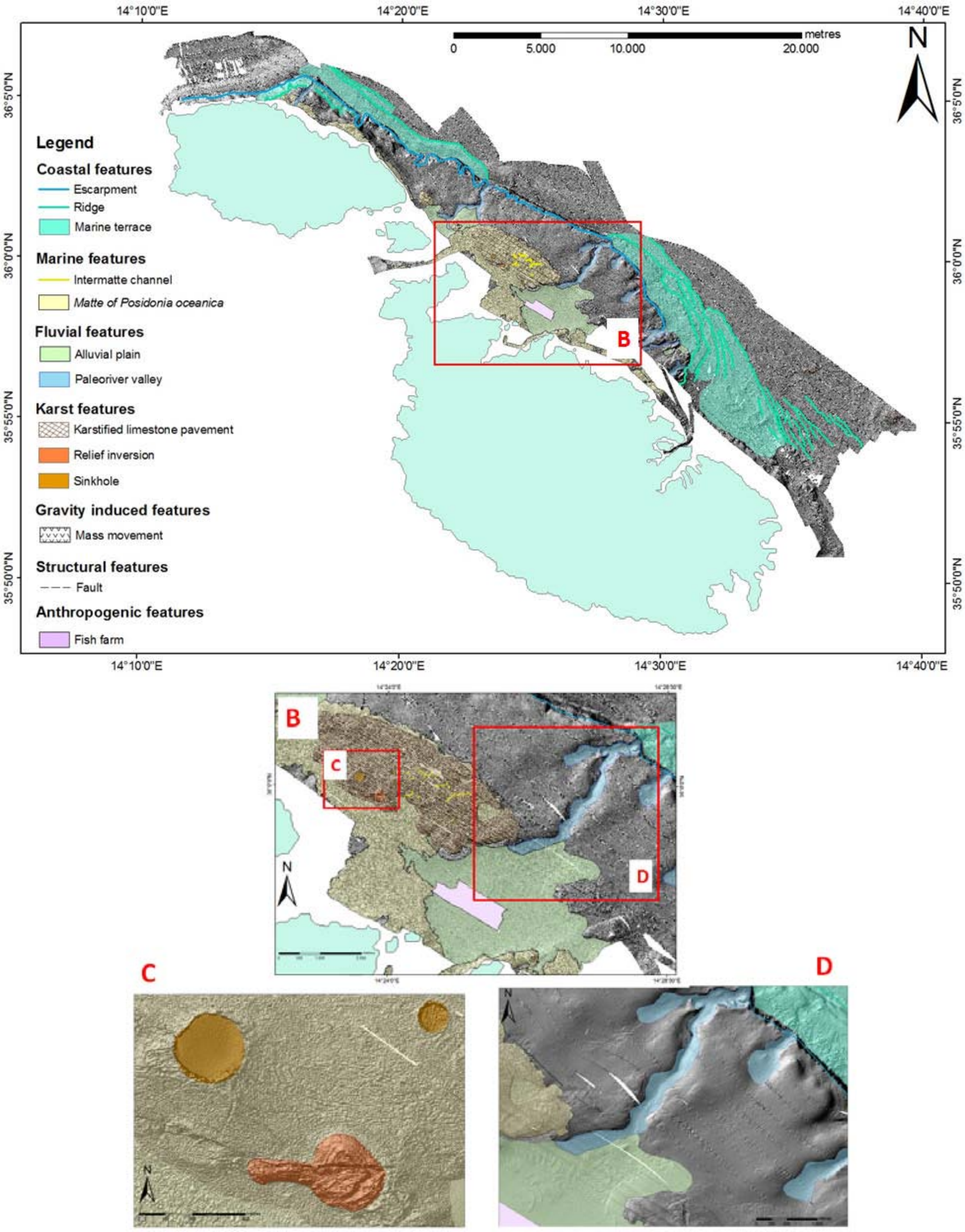

Figure 3 – Submerged geomorphological features on the Maltese eastern shelf; A) complete map of the submerged geomorphology; B) shelf offshore Mellieha Bay and St. Paul's Bay; C) image showing two sinkholes (in orange) and a possible case a relief inversion (in reddish colour), both located on a karstified limestone plateau where there is also *Posidonia oceanica* on *matte*; D) detail showing some paleoriver valleys (in blue), the alluvial plain (in light green) and part of a marine terrace offshore the escarpment (in dark green);(all figures modified after [19]).

Submerged morphologies well comparable to subaerial features observed on-land are scattered on the Maltese shelf. A case in point are circular depressions at shallow depth interpreted as inundated former karst features alike sinkholes resulting from dissolution of carbonate rocks ([8] and [19]). For instance, the area of Sikka l-Bajda is an Upper Coralline Limestone plateau whose boundaries are in all likeness structurally fault-controlled. This feature represents a limestone pavement karstified at a time of lower-than-present sea level ([19]). In the same area, the plateau is also characterised by the presence of four depressions and another one situated in front of Qawra Point. They have a variable shape from circular to ellipsoidal, and their diameters vary from 60 to 270 m. These depressions have very steep, almost vertical, walls, and a nearly flat bottom that can be smooth or covered by rocky blocks. The boundaries of some of these depressions are characterised by radial fractures (fig. 3C). It is possible that these depressions were originally hypogene caves that enlarged until the roof collapsed, forming circular-elliptical depressions. Similar depressions found on Gozo have been interpreted as "caprock collapse sinkholes" (see [8], [25] and [28]), according to the classification proposed by [12].

Figure 4 – Emerged and submerged geomorphological features. A) detail of the map of the NW coast of Malta by [10], showing the presence of lateral spreading, block slides and earth flows; B) detail of the map produced by this research showing submerged mass movements (in grey); C) karstified limestone pavement made up of Upper Coralline Limestone Fm. affected by lateral spreading; D) sinkhole of Dwejra Bay, Gozo (to be compared with those of fig. 3C); E) case of relief inversion related to a sinkhole (to be compared with fig. 3C).

Another solution feature situated near the depressions described above is a positive relief that in plan view has a similar shape (fig. 3C). According to [8] and [28], it could possibly represents a case of relief inversion, characterising an area that was depressed due to karst processes and then infilled and subjected to differential erosion.

It is possible to observe that the positive relief, the escarpment and other limestone plateaus are surrounded by rock blocks: these features seem to be affected by mass movements such as lateral spreading and block sliding. These phenomena occur because of fracturing of the plateau, expansion of these fractures and then sliding of the blocks detached above the ductile Blue Clay Formation. These landslides are very similar to those affecting the NW and NE coasts of Malta [10].

4. Final remarks

As shown, DTM data help imaging with accuracy the subaqueous morphology of the northeastern Maltese continental margin ([19]). The resulting maps evidenced many bottom features to such a degree of resolution that permits educated interpretations of former subaerial environments very little modified by their post-LGM drowning. Examples here treated include former karst-solution depressions, meandering river valleys and potential lateral spreading sliding processes, all well-documented onshore in the Maltese archipelago.

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6. References

[1] Alexander D. - *A review of the physical geography of Malta and its significance for tectonic geomorphology*, Quaternary Science Review (1988) 7, 41-53.

[2] Anderson E. W. - *The wied: a representative Mediterranean landform*, GeoJournal (1977) 41.2, 111-114.

[3] Argnani A. - *The strait of Sicily rift zone: foreland deformation related to the evolution of a back-arc basin*, Journal of Geodynamics (1990) 12, 311-331.

[4] Barbieri, M., Biolchi, S., Devoto, S., Forte, E. Furlani, S., Gualtieri, A., Mantovani, M., Mocnik, A., Padovani, V., Pasuto, A., Piacentini, D., Prampolini, M., Remitti, F., Schembri, J., Soldati, M., Tonelli, C. and Vescogni, A. - *Multidisciplinary geological excursion in the open-air laboratory of the Island of Malta*, 11-18 November 2010 Field-Trip Guide (2010).

[5] Boccaletti M., Cello G. and Tortorici L. - *Transtensional tectonics in Sicily Channel*, Journal of Structural Geology (1987) 9(7), 869-876.
[6] Cello G. - *Structure and deformation processes in the Strait of Sicily "rift zone"*, Tectonophysics (1987) 141, 237-247.
[7] Civile D., Lodolo E., Accettella D., Geletti R., Ben-Avraham Z. and Deponte M. - *The Pantelleria graben (Sicily Channel, Central Mediterranean): An example of intraplate passive rift*, Tectonophysics (2010) 490 (3-4), 173-183.
[8] Coratza P., Galve J. P., Soldati M. and Tonelli C. - *Recognition and assessment of sinkholes as geosites: lessons from the Island of Gozo (Malta),* Quaestiones Geographicae (2012) 31(1), 27-37.
[9] Dart C. J., Bosence W. J. and McClay K. R. - *Statigraphy and structure of the Maltese graben system,* Journal of Geological Society of London (1993) 150, 1153-1166.
[10] Devoto S., Biolchi S., Bruschi V.M., Furlani S., Mantovani M., Piacentini D., Pasuto A. and Soldati M. - *Geomorphological map of the NW Coast of the Island of Malta (Mediterranean Sea,*. Journal of Maps (2012), 8(1), 33-40.
[11] Furlani, S., Antonioli, F., Biolchi, S., Gambin, T., Gauci, R., Lo Presti, V., Anzidei, M., Devoto, S., Palombo M. and Sulli, A. - *Holocene sea level change in Malta,* Quaternary International (in press).
[12] Gutiérrez F., Guerrero J. and Lucha P. - *A genetic classification of sinkholes illustrated from evaporite paleokarst exposures in Spain*, Environmental Geology (2008b) 53, 993–1006.
[13] Hughes K. J. - *Persistent features from palaeo-landscape: the ancient tracks of the Maltese Islands*, Geographical Journal (1999) 165(1), 62-78.
[14] Illies J. H. - *Graben formation-The Maltese Islands-A casa history,* Tectonophysics (1981) 73, 151-168.
[15] Jongsma D., Van Hinte E. J. and Woodside J. M. - *Geologic structure and neotectonics of the North African Continental Margin south of Sicily,* Marine and Petroleum Geology (1985) 2, 156-179.
[16] Lambeck, K., Antonioli, F., Anzidei, M., Ferranti, L., Leoni, G. and Silenzi, S. - *Sea level change along the Italian coasts during Holocene and prediction for the future,* Quaternary International (2011) 232, 250-257.
[17] Lambeck K. and Purcell A. - *Sea-level change in the Mediterranean Sea since the LGM: model predictions for tectonically stable areas,* Quaternary Science Reviews (2005) 24, 1969-1988.
[18] Magri O., Mantovani M., Pasuto A. and Soldati M. - *Geomorphological investigation and monitoring of lateral spreading along the north-west coast of Malta*. Geografia Fisica e Dinamica Quaternaria (2008) 31(2), 171-180.
[19] Micallef A., Foglini F., Le Bas T., Angeletti L., Pasuto A. and Taviani M. – *The submerged coastal paleolandscape of the Maltese Islands: Morphology evolution and relation to Quaternary environmental change*, Marine Geology (in press).
[20] Paskoff, R. and Sanlaville, P. - *Observations geomorphologiques sur les cotes de l'archipel Maltais*, Zeitschrift für Geomorphologie (1978) 22, 310-328.
[21] Pedley H. M., Clarke M. H. and Galea P. - *Limestone Isles in a crystal: The Geology of the Maltese Islands*, (2002) Publisher Enterprises Group.

[22] Pedley H. M. and Waugh B. - *Easter Field Meeting to the Maltese Islands*, Proceedings of the Geologists' Association (1976) 87(3), 343-358.

[23] Pedley H. M. - *Miocene Sea-Floor Subsidence and Later Subaerial solution Subsidence Structures in the Maltese Islands*, Proceedings of the Geologists' Association (1974) 85(4), 533-547.

[24] Putz-Perrier M. W. and Sanderson D. J. - *Distribution of faults and extensional strain in fractured carbonates of the North Malta Graben*, AAPG Bulletin (April 2010) 9(4), 435–456

[25] Reuther, C. D. and Eisbacher, G. H. - *Pantelleria Rift crustal extension in a convergent intraplate setting*, International Journal of Earth Sciences (1985) 74 (3), 585-597.

[26] Sciberras, M., Rizzo, M., Mifsud, J.R., Camilleri, K., Borg, J.A., Lanfranco, E. and Schembri, P.J. - *Habitat structure and biological characteristics of a maerl bed off the northeastern coast of the Maltese Islands (central Mediterranean)*, Marine Biodiversity (2009) 39, 251-264.

[27] Siddall, M., Rohling, E.J., Almogi-Labin, A., Hemleben, C., Meischner, D., Schmelzer, I. and Smeed, D.A. - *Sea-level fluctuations during the last glacial cycle*, Nature 2003) 423, 853-858.

[28] Tonelli C., Galve J. P., Soldati M. and Gutiérrez F. - *Erosional morphostructures related to Miocene paleosinkholes in the Island of Gozo, Malta*, XII Reunión Nacional de Geomorfologia, Santander, Spain (2012).