Geogr. Fis. Dinam. Quat.
36 (2013), 189-198, 9 figg.

DOI 10.4461/GFDQ.2013.36.16

MAURO SOLDATI (*), CHIARA TONELLI (*) & JORGE PEDRO GALVE (*)

GEOMORPHOLOGICAL EVOLUTION OF PALAEOSINKHOLE FEATURES IN THE MALTESE ARCHIPELAGO (MEDITERRANEAN SEA)

ABSTRACT: SOLDATI M., TONELLI C. & GALVE J.P., *Geomorphological evolution of palaeosinkhole features in the Maltese archipelago (Mediterranean Sea)*. (IT ISSN 0391-9838, 2013).

Palaeosinkhole features characterise the Maltese islands, some of them reaching relevant dimensions, especially in the Island of Gozo. They show varied morphostructures: sub-circular bays, large depressions and rounded buttes or mesas (due to relief inversion) are the resulting geomorphic expressions. A detailed geological and geomorphological study of the palaeosinkholes located in the NW sector of the Island of Gozo has been carried out with the aim of investigating the evolution of the associated landforms. A field survey and a mapping campaign at a 1:5000-scale, coupled with aerial-photo interpretation, has been carried out and a spatial database has been implemented within a GIS software. Existing evolutionary models have been critically analysed and new models proposed. Thanks to the detailed exploration of the collapse palaeosinkholes, it has been deducted that at a certain stage, selective erosion has become the main factor influencing their geomorphological evolution. Positive reliefs (rounded buttes or mesas) were formed where more resistant terrains were located inside the sinkholes; conversely, depressions and sub-circular bays developed where the sinkholes infill was surrounded by more resistant rocks. Collapse structures do not seem to be active at present and their activity probably ceased during the Miocene, suggesting that karst subsidence processes are not the only responsible for the final shaping of the above-mentioned sub-circular depressions and bays. The Gozitan rounded bays related to the palaeosinkholes have been compared with similar sub-circular coastal landforms located along the southern coast of the Island of Malta. The investigation showed that the latter are not caused or influenced by karst processes, but linked to the attitude of strata and to their different resistance to erosion. The bays analysed in Gozo and Malta are morphologically similar but genetically different, representing a relevant example of equifinality. The Gozitan sinkhole-related landforms have also been compared with those of the Island of Malta, generally much smaller in size, which allowed their different geomorphological evolution to be pointed out.

KEY WORDS: Palaeosinkholes, Karst, Selective erosion, Malta, Mediterranean Sea.

INTRODUCTION

The Maltese archipelago is characterised by the presence of outstanding palaeosinkholes that may reach a few hundreds of metres in diameter and stratigraphic throw, being comparable in size to the largest sinkholes of the World. They display different landforms depending on the lithologies that crop out inside and outside the subsidence structures. Sub-circular bays, large depressions and rounded buttes are the resulting geomorphic expressions. Despite their large size and impressive associated landforms, these collapse palaeosinkholes have never been referred to in the specialised karst literature and have received scarce attention from the geomorphological perspective. Previous authors provided very detailed sedimentological studies of the units filling the palaeosinkholes and proposed a genetic model (Trechman, 1938; Pedley, 1974; Illies, 1980; Pedley & *alii*, 2002), but they did not analyse in detail the evolution of the current landforms controlled by these structures. Other papers have dealt with these morphostructures from the geomorphological point of view. Paskoff & Sanlaville (1978), based on a study on the coasts of the Maltese archipelago, described the rounded bays related to palaeosinkholes. Alexander (1988) focused on the tectonic aspects of the Maltese palaeosinkholes and suggested to investigate the relations between surface hydrology and vertical tectonics to better understand their mechanism of formation. Coratza & *alii* (2012) have recently analysed the Maltese sinkholes aiming at their recognition and assessment as geosites.

Within this frame, during recent surveys carried out in the Maltese archipelago, a detailed geological and geomorphological study of the palaeosinkholes has been carried out, with the aim of investigating the evolution of the associated landforms. A preliminary analysis of the palaeosinkholes depicted in the geological map of the Maltese islands (Oil Exploration Directorate, 1993) has been carried out and then the western sector of the Island of Gozo has been

---

(*) *Dipartimento di Scienze Chimiche e Geologiche, Università degli Studi di Modena e Reggio Emilia, Largo S. Eufemia, 19, 41121 Modena, Italy*. E-mail: mauro.soldati@unimore.it

This paper is part of the Project «Coupling terrestrial and marine datasets for coastal hazard assessment and risk reduction in changing environments» funded by the EUR-OPA Major Hazards Agreement of the Council of Europe. The Authors are grateful to Francisco Gutiérrez and to an anonymous reviewer for their precious suggestions.

selected for a detailed geological and geomorphological study. The Gozitan palaeosinkholes have also been compared with other sinkhole features and similar landforms in the Maltese archipelago.

A field survey and a mapping campaign at a 1:5000-scale has been developed, an aerial-photo interpretation has been performed and a spatial database has been generated using a GIS software (ArcGIS 8.3®). Existing evolutionary models have been critically analysed and updated, and new models of the Gozitan morphostructures and other similar coastal landforms have been developed.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING

The Maltese archipelago is located in the Mediterranean Sea, about 90 km south of Sicily and 290 km north-east of Tunisia (fig. 1). The Archipelago is composed of three main islands: the larger one is Malta, followed by Gozo located to the North, and Comino, the smallest, located in between, with a total area of 316 km^2 (Magri, 2006). From a geodynamical viewpoint, it is located in the Sicily Channel, which has been affected by continental rifting during Neogene-Quaternary period (Finetti, 1984; Dart & *alii*, 1993; Civile & *alii*, 2010). The tectonic setting is characterised by two intersecting fault patterns: the NW-SE-trending Pantelleria Rift and the ENE-WSW graben system (Illies, 1981). These faults displace the Late Oligocene (Chattian) to Late Miocene (Messinian) succession of marine sedimentary rocks, mainly limestone and marls, which compose the Maltese archipelago (Oil Exploration Directorate, 1993; Pedley & *alii*, 2002). The rock sequence is divided into five main lithostratigraphic units that lie almost horizontally across the islands (fig. 2). From the bottom to the top the units are as follows: (i) «Lower Coralline Limestone Formation», a hard pale grey limestone with abundant fossil corals and marine calcareous algae forming sheer cliffs up to 140 m; (ii) «Globigerina Limestone Formation», a softer yellowish fine-grained limestone unit forming irregular slopes with terrace-like steps, 20 to over 200 m-thick; (iii) «Blue Clay Formation», a unit composed of silty sands, marls or clays, 20 to 70 m-thick; (iv) «Greensand Formation», a greenish glauconite-rich sand, rarely more than one m-thick; (v) «Upper Coralline Limestone Formation», a hard, pale grey limestone unit, very similar to the Lower Coralline Limestone.

The Island of Gozo constitutes a horst within the Maltese graben system. Several ENE-WSW faults in its south-eastern coast (Illies, 1981) and other main faults located in the western part of Gozo, generally associated with the collapse palaeosinkholes, have controlled the development of most of the river valleys. The Gozitan landscape is characterised by the presence of many gorges, named *wied* by locals, formed when the rivers downcutted the Lower Coralline Limestone bedrock because of the uplift of the land or the fall of the sea level (Pedley & *alii*, 2002). Past sea-level changes have indeed significantly modified the

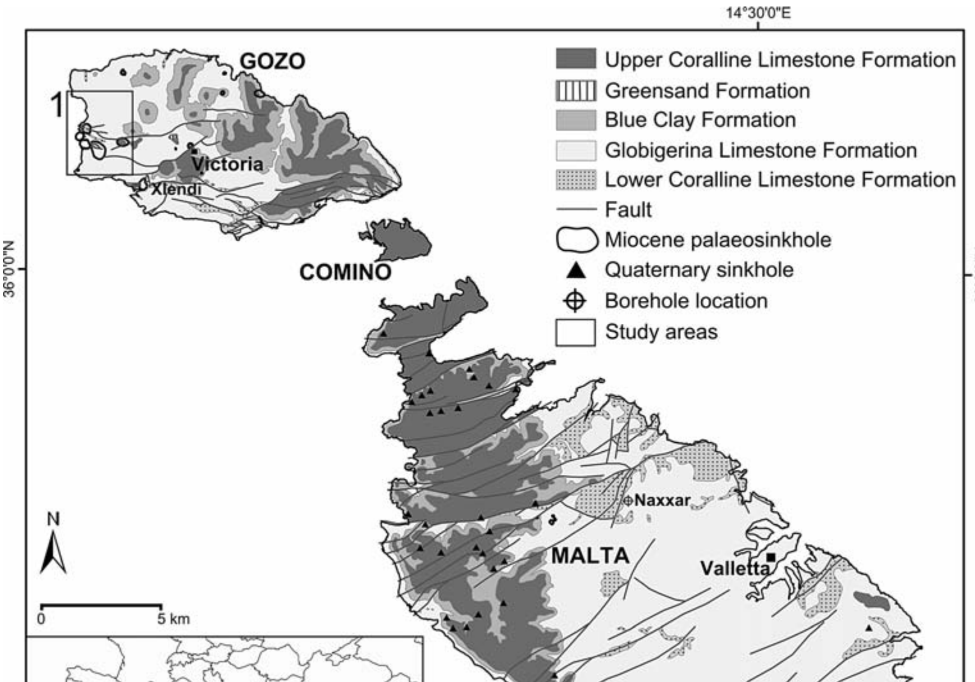

FIG. 1 - Geological sketch map of the Maltese archipelago and location of study areas. 1: NW coast of Gozo; 2: SE coast of Malta.

palaeogeography of Gozo. The Mediterranean coastlines have changed through time, the last large exposure being during the Last Glacial Maximum, when the coastline around Malta was some 130 m below the present sea level (Caruso & *alii*, 2011; Lambeck & *alii*, 2011; Furlani & *alii*, 2013; Micallef & *alii*, 2013).

Apart from the structural features, the different erodibility of the five rock units is the main factor controlling the Gozitan landscape of plateaus, mesas, buttes and gorges (fig. 2). The coralline limestone formations usually form sheer cliffs when located along the sea (*e.g.*, the western coast) and karst pavements inland. The Blue Clay Formation rarely shows at the surface, being usually covered by soil, vegetation and fields; where erosion is more active it forms badlands slopes capped by thin layers of Upper Coralline Limestone. The Globigerina Limestone Formation has several conglomerate beds (hardgrounds), which form different levels of structural scarps alternating with smooth slopes formed by the weaker beds (*e.g.*, the coast located south of Xlendi).

In addition to the structural landforms, gravity-induced slope landforms and processes are spread in the eastern coast of the Island. Recent works have dealt with the Maltese mass movements (Dykes, 2002; Farrugia, 2008; Magri & *alii*, 2008; Magri, 2009; Coratza & *alii*, 2011; Soldati & *alii*, 2011; Devoto & *alii*, 2012; Mantovani & *alii*, 2012). The different mechanical behaviour of the Blue Clay and the Upper Coralline Limestone formations favours the development of a series of landslides, in particular rock spreads, falls and topples, which widely affect the landscape of the Island. As a result, large calcareous blocks are observable on coastal clayey slopes. They are also displaced by earth flows and earth slides affecting these materials (Devoto & *alii*, 2012).

Quaternary deposits are not widespread in Gozo and are restricted to raised-beach deposits, aeolian silts and sediments deposited in river valleys, caves and lakes (Hunt, 1997; Pedley & *alii*, 2002).

Especially significant are karst landforms, in particular the palaeosinkholes of the western coast of Gozo investigated in the present study. Recently a few investigations have been carried out on the Maltese karst features (Marmarà, 2004; Saliba, 2008; Calleja, 2010; Tonelli & Galve, 2011; Coratza & *alii*, 2012; Tonelli & *alii*, 2012). Pedley & *alii* (2002) have recognised two cavern systems, one developed in Miocene times and the other in recent times. The former one, on the one hand, is associated to the Lower Coralline Limestone and gave rise to a series of sea floor collapses that have continued to subside during the Pliocene and the Pleistocene forming the previously mentioned palaeosinkhole (Pedley & *alii*, 2002). On the other hand, the younger cave system developed at the contact between the Upper Coralline Limestone and the Blue Clay and at least three levels of sea caves and associated sinkholes have been described. Submarine sinkholes have recently been recognised offshore the eastern coast of Malta (Angeletti & *alii*, 2012; Micallef & *alii*, 2013), thus other levels of sea caves should be considered. Other karst features, such as dry and blind valleys and the associated fluvial scarps, are common in the Island of Gozo; karst pavements, solution pans, solution holes, sea caves and arches are spread mainly along the coast where the coralline limestone formations outcrop. The Globigerina Limestone shows a very limited karstification; erosive landforms, such as potholes, dominate on the karst ones.

Apart from karst features, the main inland landforms are structural and man-made scarps that form a terrace-like landscape. The Gozitan landscape is highly influenced by human-induced modifications. As a result, the landscape is mainly dominated by terraced fields (Cyffka & Bock, 2008) and locally by urbanised areas. Other notable man-made features are the numerous quarries carved in the Globigerina Limestone.

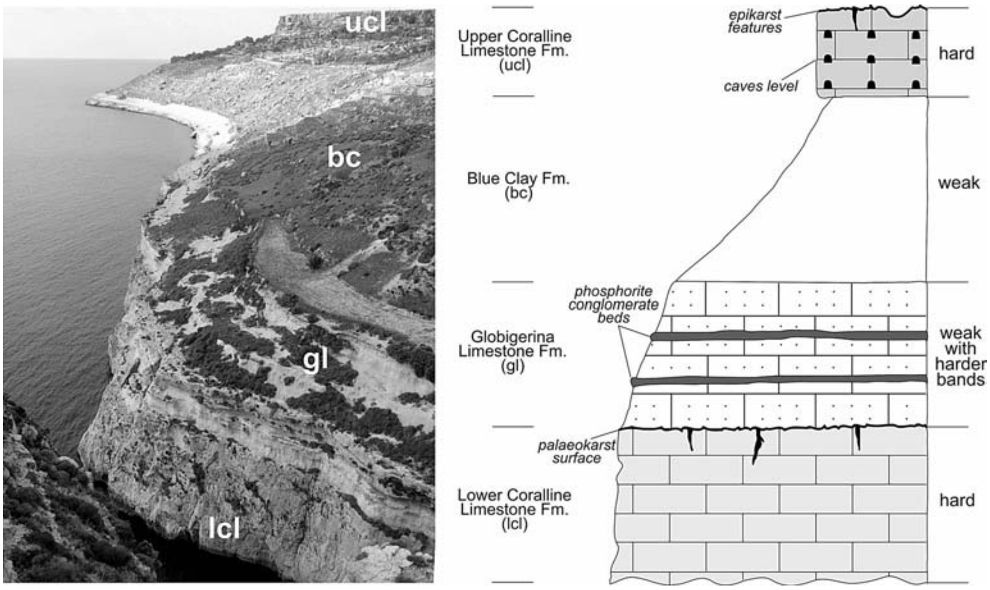

FIG. 2 - Section of the rock units that compose the Maltese archipelago. The profile along the NW coast of the Island of Malta shows the effects of the different resistance to erosion of the rock units: harder rocks correspond to steeper slopes.

THE PALAEOSINKHOLES OF GOZO AND ASSOCIATED MORPHOSTRUCTURES

The palaeosinkholes of the Island of Gozo were ascribed by Pedley (1974) to the oldest phase of karstification developed in the Miocene. Sea-floor depressions would have been formed in the Miocene due to submarine cave roof collapse or, according to Illies (1980), to dissolution of evaporites and consequent subsidence of the overlying sediments. Then the depressions would have been infilled by marine sediments until the Maltese archipelago had emerged at the end of the Miocene. Recent investigations by Tonelli & *alii* (2012) showed that the dissolution-induced subsidence is recorded by collapse structures up to 600 m in diameter, circular to elliptical in plan view and with an average area of 56,000 m^2. These palaeosinkholes are limited by annular dip-slip faults; several stretches of internal annular faults have also been recognised. The subsidence structures can be classified as caprock collapse palaeosinkholes, according to the classification proposed by Gutiérrez & *alii* (2008), because the upward propagation of cavity rock roofs migrates through non-karstic lithologies. The foundered cylindrical blocks generally show limited internal deformation, typically restricted to

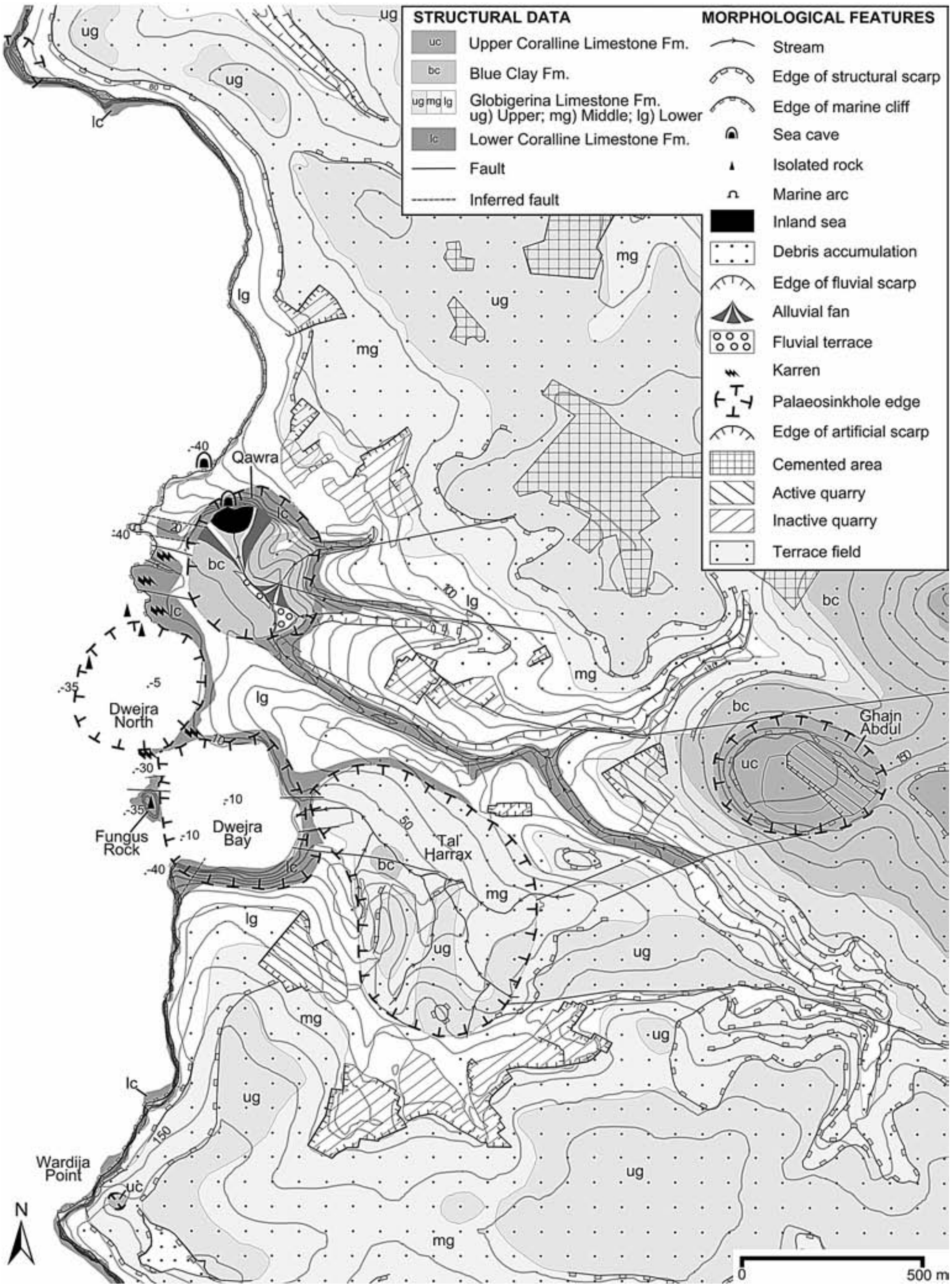

FIG. 3 - Geomorphological map of the NW Gozo study area (see fig. 1).

basin structures with inward dips. Cumulative subsidence in the largest palaeosinkholes reaches more than 120 m.

The detailed geomorphological surveys carried out in the present study (fig. 3) outlined how the Gozitan palaeosinkholes have controlled the evolution of the shoreline stretch in the western coast of the Island; high cliffs formed by massive limestone are here interrupted by rounded bays set within pre-existent sub-circular collapse structures of large dimensions, such as Dwejra Bay and Dwejra North (fig. 4). These bays seem to have been formed by selective erosion driven initially by fluvial processes and finally by the sea; the sea would have entered the outer barrier of country rock (Lower Coralline Limestone Formation) enlarging fractures or karst conduits or caves and would have removed the weaker material of the infill (Globigerina Limestone and Blue Clay). The available information about sea level change in SW Calabria-NE Sicily (Lambeck & *alii*, 2011) indicates that the sub-circular depressions may have been flooded by the sea between 7000 and 5000 years ago. Dwejra Bay still shows part of the outer barrier, which makes up a small island, called Fungus Rock (fig. 3, 4A), while in the bay of Dwejra North, which is located north of Dwejra Bay, the outer barrier has been completely removed and only a partially submerged isolated block has been preserved (fig. 4B). The palaeosinkhole of Qawra (fig. 5A), a large depression located inward, may be ascribed to a previous stage of such a rounded bay formation; a narrow cave developed in its western calcareous cliff allowed the sea to enter the depression, an «inland sea» was formed and the infill sediments were partially removed by erosion.

The sub-circular depressions formed within the Miocene palaeosinkholes, such as Qawra and Tal Harrax (fig. 5A, 5C), show evidence supporting the hypothesis that these subsidence structures are not active at present. In Qawra, the Quaternary alluvial deposits located at the contact (sinkhole annular fault) between the country rock

FIG. 4 - Rounded bays related to palaeosinkholes located along the NW coast of Gozo. A: Dwejra Bay. B: Dwejra North bay.

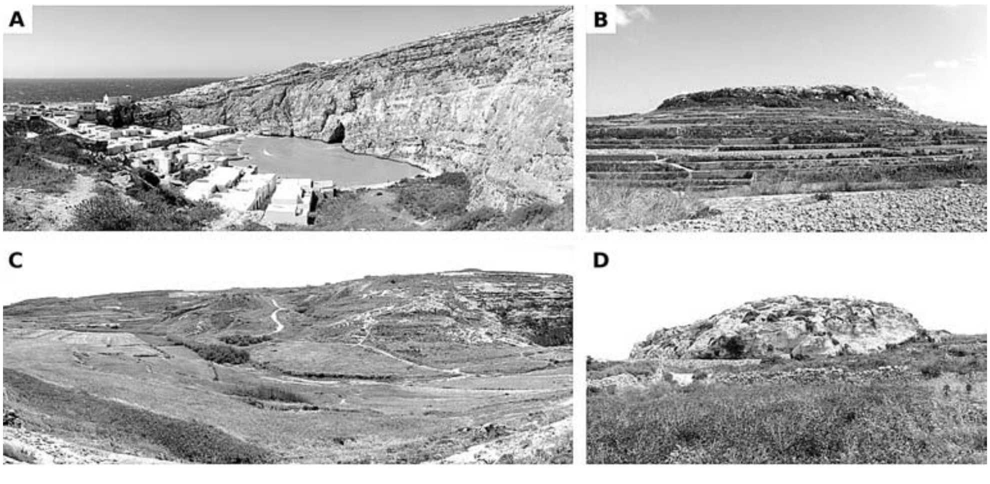

FIG. 5 - Morphostructures related to palaeosinkholes located in the NW of Gozo. A: Qawra depression. B: Ghajn Abdul mesa. C: Tal Harrax depression. D: Wardija Point butte.

(Lower Coralline Limestone) and the Blue Clay infill are undeformed. In Tal Harrax structure seems that the subsidence ceased in the Miocene. The outcrops of the western outer limit of the structure suggest that Burdigalian sediments (Middle Globigerina Fm.) truncate the external annular fault. Moreover there is no evidence of activity in the internal collapse structure that have lowered a block of Blue Clay within the Globigerina Limestone infill. Both Qawra and Tal Harrax have formed by differential erosion of marls (Blue Clay Formation) and more erodible limestone (Globigerina Limestone) collapsed into more resistant limestone formations (Lower Coralline Limestone).

The present study also focuses on some palaeosinkholes located inland that, due to their geomorphological evolution, have generated reliefs, such as the Ghajn Abdul mesa and the Wardija Point butte (fig. 5B, 5D). The rock mass downthrown within the collapse structure was capped by a layer of Upper Coralline Limestone Formation and the surrounding rock was composed respectively of Blue Clay and Globigerina Limestone, both weaker than the coralline limestone. As a result, relief inversion due to differential erosion occurred, giving rise to a butte located in an area once forming a submarine karstic depression. In the case of Ghajn Abdul the stratigraphic throw has been estimated in 40 m, and the morphostructure now forms a 60 m-high hill. At Wardija Point, the contact between the downthrown block and the surrounding rock is evident while in Ghajn Abdul the annular dip-slip fault is only inferred because it is not visible in the altered marls of the Blue Clay Formation.

The palaeosinkholes of Gozo have controlled the development of sub-circular depressions or rounded buttes and mesas, depending on the relative resistance to erosion of the outcropping rock types inside and outside the subsidence structures. Where the rocks capping the downthrown block are more resistant than the country rock, a prominent sub-circular relief is created. Conversely, large round depressions bounded by steep scarps have formed where the downthrown rocks are more erodible than the surrounding terrains.

OTHER SINKHOLE FEATURES IN THE MALTESE ARCHIPELAGO AND SIMILAR LANDFORMS

The geomorphological features associated with the palaeosinkholes of Gozo have been compared with those of sinkholes located in the Island of Malta as well as with other similar landforms.

The sinkholes of the Island of Malta are sub-circular depressions formed by collapse of underlying karst caves or by sinking of the terrain due to solution processes. They are bounded by well-defined vertical walls or covered by soil, respectively. Recent studies on the spatial and morphometric characteristics of the Maltese karst features (Tonelli & *alii*, 2012) pointed out that the Gozitan sinkholes reach larger size and volume with respect to those located in the Island of Malta, and have greater vertical displacement. The latter have a more random distribution and are mainly spread in the NW part of Malta, where the Upper Coralline Limestone outcrops. The sinkholes identified in the Island of Malta are supposed to be mainly related to a more recent, post-Miocene, karst system (Pedley, 1974). Moreover the Maltese sinkholes may be merely described as related to solution or collapse without any significant later evolution related to erosive processes. The outputs of the present study, together with new onshore and offshore surveys that are ongoing, will hopefully enable us to understand why palaeosinkholes are located only in the Island of Gozo.

Rounded landforms located along the south-eastern coast of Malta, which were not ascribed to sinkholes by previous authors though they show very similar shapes, were also investigated to define their origin. These features correspond to two rounded bays located near Marsaxlokk (Hofra Il-Kbira Bay and Il-Hofra z-Zghir Bay; fig. 6, 7B). In this stretch of coast, different members of the Globigerina Limestone Formation outcrop and the coastline is composed of promontories alternating with coves, the former ending with shore platforms showing karren features and the latter with few slope deposits at the foot of the

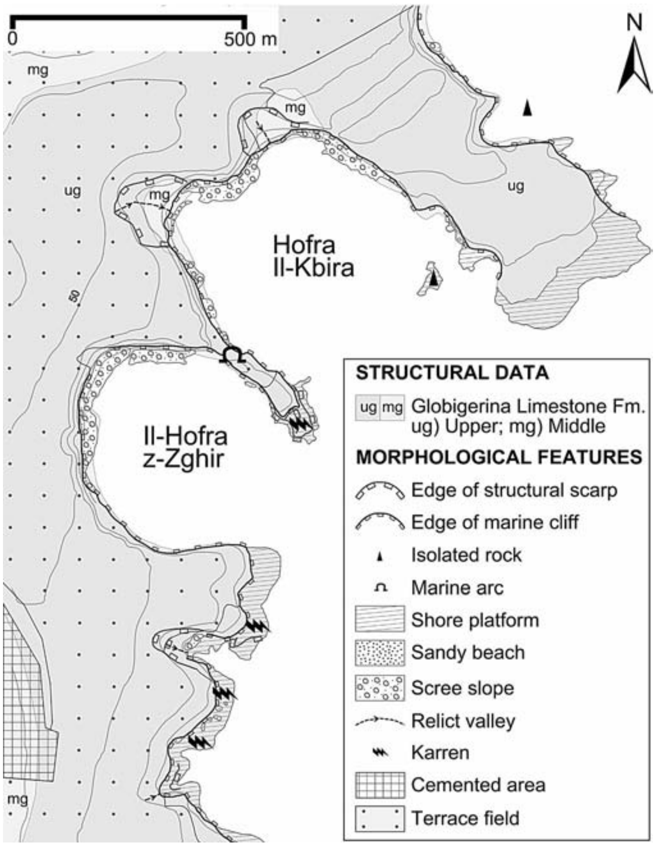

FIG. 6 - Geomorphological map of the study area along the SE coast of Malta (see fig. 1).

cliff. Truncated valleys flow into most of the coves. Man-made scarps dominate the inland terrace-like landscape. Detailed geomorphological surveys allowed the interpretation of these rounded bays as linked to selective erosion due to the presence of lithological units of different mechanical properties. This confirmed that there is no relationship with possible pre-existent large subsidence structures. Strata dipping seawards cause a setting where the more resistant lithology, the Upper Globigerina Limestone member, reaches the sea bounding the weaker one landward, the Middle Globigerina Limestone member (fig. 7A). Thus, rounded bays were created due to the removal of the weaker formation where the outer barrier was locally eroded by the sea. In particular, sea erosion is likely to have taken place preferentially where stream valleys reached the sea. At present, truncated valleys can be observed in the inner part of these rounded bays indicating that they may have been formed in locations corresponding to ancient drainage lines. The first evolutionary phase proposed here implies that retrogressive erosion started to affect the hard rock barrier at the stream mouth (fig. 8A, 8B). As soon as the sea reached the weak formation, refractive wave energy started widening the cove (fig. 8C, 8D). The bays of Hofra Il-Kbira and Il-Hofra z-Zghir show the final stage of evolution (fig. 8E), but other bays located southward display previous phases of development (fig. 7C).

Rounded bays due to selective erosion of rocks with different resistance are spread worldwide and relevant examples are located in the South coast of England (*e.g.*, Lulworth Cove; Bird, 2008) and northern Spain (*e.g.*, Portio Bay; Bruschi, 2007).

DISCUSSION

A detailed geomorphological survey was carried out on the collapse palaeosinkholes located in the NW sector of the Island of Gozo (Malta). Based on field observation and aerial photo interpretation, it was possible to define a model (fig. 9) for the genesis and evolution of the morphostructures related to palaeosinkholes and interpret their influence on littoral dynamics. The model updates that of Pedley (1974). The first stage, in agreement with Pedley & *alii* (2002), would correspond to Miocene submarine collapses due to karst dissolution of the Lower Coralline Limestone Formation or salt dissolution of (possible) underlying evaporites (fig. 9A). Taking into consideration similar sinkholes features in other parts of the World (Whaltam & *alii*, 2005; Ford & Williams, 2007), the latter hypothesis would be more likely. Radial and annular fault pattern within the country rock and infill, synsedimentary deformation structures and low or inexistent breccification of the infill are characteristics not described in collapse sinkholes with more than 400 m in diameter formed on carbonate karst. However, the available stratigraphic data of a borehole drilled onshore the Island of Malta at Naxxar (Pedley & *alii*, 2002) show only a thick sequence of dolomites beneath the Maltese Lower Coralline Limestone and no significant evaporite beds; thus more data on sub-surface geology, currently not accessible, would be needed to validate the second hypothesis. The submarine collapse would have generated a sea-floor depression then filled by marine sediments (Globigerina Limestone Formation; Pedley, 1974; Pedley & Bennet, 1985). Once the Miocene rocks emerged, selective erosion

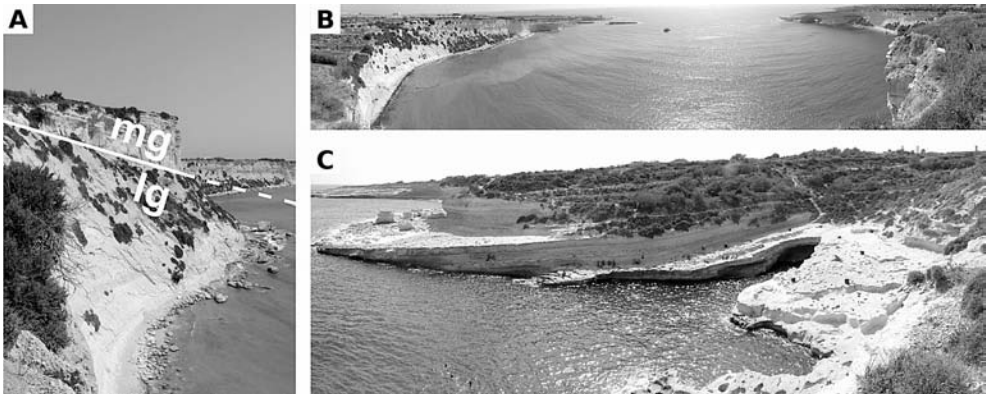

FIG. 7 - Morphological features along the SE coast of Malta. A: Cliff profile showing the contact between the Middle Globigerina Limestone Member (mg) and the Lower Globigerina Limestone Member (lg). B: Hofra Il-Kbira rounded bay. C: Bay located south of Il-Hofra z-Zghir.

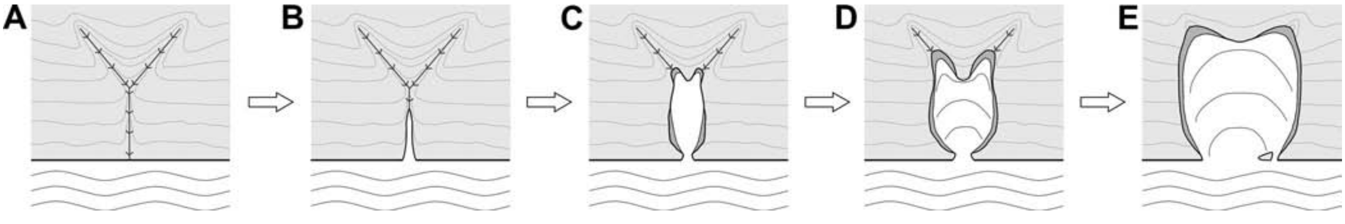

FIG. 8 - Evolutionary phases of the rounded bays located along the SE coastline of the Island of Malta (see text for explanation).

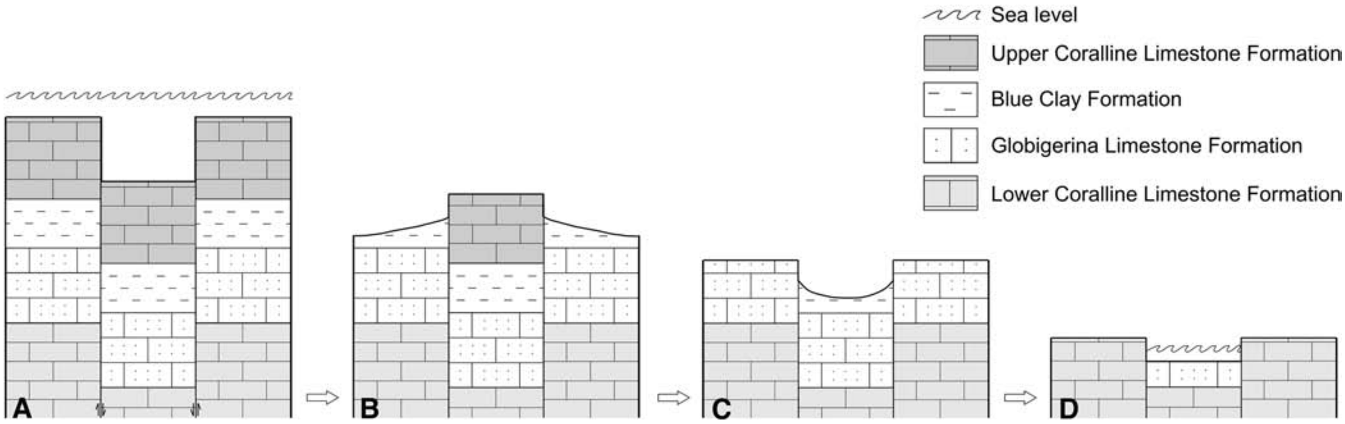

FIG. 9 - Evolutionary model of the Gozitan collapse morphostructures (see text for explanation).

became the main factor influencing the geomorphological evolution of the areas affected by the collapse sinkholes, giving rise to reliefs where more resistant terrains (*i.e.*, the collapsed block of Upper Coralline Limestone) occurred inside the sinkholes (*e.g.*, at Wardija Point; fig. 5D, fig. 9B). Where the erosion continued, reaching the underlying Blue Clay of the downthrown block, selective erosion took place again determining a depression surrounded by the more resistant Globigerina Limestone (*e.g.*, Tal Harrax depression; fig. 5C, 9C). Where the depression was located near the coastline, the evolution may have further continued: in these conditions, the sea would have been able to reach the Blue Clay through karst conduits or fractures and start eroding them (*e.g.*, Qawra depression; fig. 5A). In some cases, the erosion would have continued until the outer barrier (toward the sea) was removed and a rounded bay formed (*e.g.*, Dwejra North bay; fig. 4B, 9D).

Therefore rounded bays described by Paskoff & Sanlaville (1978) as mere submersion of karst depressions, have been here recognised as ultimately related to selective erosion rather than subsidence. Thus the Gozitan rounded bays cannot be assimilated to the sub-circular sinkhole-related embayments which are a common feature along karstified coastlines, *e.g.* in Croatia, where pre-existent karst depressions were drowned by the sea without any significant erosive process. To our knowledge, morphostructures deriving from evolutionary processes, such as those which affected the NW coast of Gozo, have not been described anywhere else in the World. On the other hand, positive reliefs formed from the evolution of sinkhole features similar to those of Gozo (Ghajn Abdul and Wardija Point) have been documented in the Delaware Basin (West Texas and New Mexico, USA). In this basin, cemented breccia pipes related to interstratal evaporite dissolution have been shaped by selective erosion giving rise to prominent reliefs (Stafford & *alii*, 2008).

Regarding the interpretation of other rounded coastal features located north of Dwejra North, Paskoff & Sanlaville (1978) suggest that they are karst depressions coalescent to the Qawra sinkhole at an advanced stage of submersion. Through the analysis of the available bathymetric data, a shallow sea floor appears inside Dwejra Bay and Dwejra North whereas an abrupt deepening is shown outside the bays. This submerged platform may be the remnant of a harder layer of the block lowered during the collapse event. In the rounded features located to the north, the sea floor is very deep right at the foot of the cliff and no evidence of the downthrown block is shown. Thus their interpretation as palaeosinkholes is quite difficult and more detailed bathymetric data would be required to verify the hypothesis.

Submarine sinkholes have been recognised offshore the eastern coast of Malta by Angeletti & *alii* (2012) and Micallef & *alii* (2013). Based on the morphometric parameters, these are similar to those observed in the Island of Malta and possibly related to the same recent karst phase. However, a more extensive bathymetric survey would be needed to check whether larger sinkholes are present offshore the Island of Malta.

CONCLUSIONS

The detailed geomorphological survey carried out in the Maltese archipelago showed relevant examples of morphostructures related to palaeosinkholes showing different phases of evolution. Attention was focused on some features in the NW sector of the Island of Gozo aiming at defining their genesis and evolution. The evolution of the Gozitan sub-circular embayments proposed by previous authors (Paskoff & Sanlaville, 1978; Bird, 2008) was reconsidered. A model was outlined, which attributes a main role to differential erosion after a phase of sinkhole collapse.

The research also showed that there are no similar morphostructures in the Island of Malta; the Maltese karst depressions and other offshore karst-related landforms (Angeletti & *alii*, 2012; Micallef & *alii*, 2013) are smaller than the Gozitan ones and are due to mere collapse or solution sinkholes without any significant erosive evolution.

Two rounded bays comparable in shape and size to those related to the Gozitan palaeosinkholes have been investigated in the SE coast of Malta and their evolution has been analysed. These rounded bays appear to be mostly linked to the geological structure, namely to the attitude of strata and to their different resistance to erosion; no relationship with sinkhole collapse was found. It should therefore be emphasised that the rounded bays analysed in the Maltese archipelago (in Gozo and south-eastern Malta) represent a significant case of equifinality. The bays are, in fact, morphologically similar, but genetically different.

Deep drill data would be needed to better define the origin of the palaeosinkholes, hypothesised as related to karst cave roof collapse or evaporite dissolution and consequent subsidence of the overlying rocks (Pedley, 1974; Illies, 1980; Pedley & *alii*, 2002). However, the outputs of ongoing marine surveys may provide useful information to improve the proposed model and to correlate the morphometric characteristics of the sinkholes with their period and cause of formation.

Finally, it should be noted that the Maltese archipelago offers the possibility to investigate different stages of the same evolutionary process allowing the development of models verifiable in the field.

REFERENCES

ALEXANDER D. (1988) - *A review of the physical geography of Malta and its significance for tectonic geomorphology*. Quaternary Science Reviews, 7, 41-53.

ANGELETTI L., FOGLINI F., GALVE J.P., MICALLEF A., PASUTO A., PRAMPOLINI M., SOLDATI M., TAVIANI M. & TONELLI C. (2012) - *Linking coastal and seafloor morphological features along the eastern side of the Maltese archipelago*. In: Benincasa F. (Ed.), Atti del Quarto Simposio Internazionale «Il Monitoraggio Costiero Mediterraneo: problematiche e tecniche di misura» - Livorno, 12-13-14 giugno 2012. CNR-Istituto di Biometeorologia, Firenze, 237-246.

BIRD E. (2008) - *Coastal Geomorphology - An Introduction*. John Wiley and Sons, Ltd, Chichester, 411 pp.

BRUSCHI V.M. (2007) - *Desarrollo de una metodología para la caracterización, evaluación y gestión de los recursos de la geodiversidad*. PhD thesis, Universidad de Cantabria, Santander, Spain.

CALLEJA I. (2010) - *Solution subsidence structures (dolines) in Malta: their physical development and human use*. MSc Dissertation, University of Malta, Malta.

CARUSO A., COSENTINO C., PIERRE C. & SULLI A. (2011) - *Sea-level changes during the last 41,000 years in the outer shelf of the southern Tyrrhenian Sea: Evidence from benthic foraminifera and seismostratigraphic analysis*. Quaternary International, 232, 122-131.

CIVILE D., LODOLO E., ACCETTELLA D., GELETTI R., BEN-AVRAHAM Z., DEPONTE M., FACCHIN L., RAMELLA R. & ROMEO R. (2010) - *The Pantelleria graben (Sicily Channel, Central Mediterranean): An example of intraplate «passive» rift*. Tectonophysics, 490 (3-4), 173-183.

CORATZA P., BRUSCHI V.M., PIACENTINI D., SALIBA D. & SOLDATI M. (2011) - *Recognition and Assessment of Geomorphosites in Malta at the Il-Majjistral Nature and History Park*. Geoheritage, 3 (3), 175-185.

CORATZA P., GALVE J.P., SOLDATI M. & TONELLI C. (2012) - *Recognition and assessment of sinkholes as geosites: lessons from the Island of Gozo (Malta)*. Quaestiones Geographicae, 31 (1), 5-35.

CYFFKA B. & BOCK M. (2008) - *Degradation of Field Terraces in the Maltese Islands - Reasons, Processes and Effects*. Geografia Fisica e Dinamica Quaternaria, 31 (2), 119-128.

DART C.J., BOSENCE D.W.J. & MCCLAY K.R. (1993) - *Stratigraphy and structure of the Maltese graben system*. Journal of the Geological Society, 150, 1153-1166.

DEVOTO S., BIOLCHI S., BRUSCHI V.M., FURLANI S., MANTOVANI M., PIACENTINI D., PASUTO A. & SOLDATI M. (2012) - *Geomorphological map of the NW Coast of the Island of Malta (Mediterranean Sea)*. Journal of Maps, 8 (1), 33-40.

DYKES A.P. (2002) - *Mass movements and conservation management in Malta*. Journal of Environmental Management, 66, 77-89.

FARRUGIA M.T. (2008) - *Coastal Erosion along Northern Malta*. Geografia Fisica e Dinamica Quaternaria, 31 (2), 149-160.

FINETTI I.R. (1984) - *Geophysical study of the Sicily Channel Rift Zone*. Bollettino di Geofisica Teorica e Applicata, 26 (101-102), 3-28.

FORD D. & WILLIAMS P. (2007) - *Karst Hydrogeology and Geomorphology*. John Wiley and Sons, Ltd., Chichester, 562 pp.

FURLANI S., ANTONIOLI F., BIOLCHI S., GAMBIN T., GAUCI R., LO PRESTI V., ANZIDEI M., DEVOTO S., PALOMBO M. & SULLI A. (2013) - *Holocene sea level change in Malta*. Quaternary International, 288, 146-157.

GUTIÉRREZ F., GUERRERO J. & LUCHA P. (2008) - *A genetic classification of sinkholes illustrated from evaporite paleokarst exposures in Spain*. Environmental Geology, 53 (5), 993-1006.

HUNT C.O. (1997) - *Quaternary deposits in the Maltese Islands: a microcosm of environmental change in Mediterranean lands*. GeoJournal, 41 (2), 101-109.

ILLIES J.H. (1980) - *Form and function of graben structures: the Maltese Islands*. In: Cloos H., Ghelen K., Illies J.H., Kuntz E., Neumann J. & Seibold E. (Eds.), «Mobile Earth». Boldt, Boppard, 161-184.

ILLIES J.H. (1981) - *Graben formation - the Maltese Islands - a case history*. Tectonophysics, 73 (1-3), 151-168.

LAMBECK K., ANTONIOLI F., ANZIDEI M., FERRANTI L., LEONI G. & SILENZI S. (2011) - *Sea level change along the Italian coasts during Holocene and prediction for the future*. Quaternary International, 232, 250-257.

MAGRI O. (2006) - *A geological and geomorphological review of the Maltese Islands with special reference to the coastal zone*. Territoris, 6, 7-26.

MAGRI O. (2009) - *Investigation of landslides along the North-West coast of Malta and related hazard issues*. PhD thesis, University of Modena and Reggio Emilia, Modena, Italy.

MAGRI O., MANTOVANI M., PASUTO A. & SOLDATI M. (2008) - *Geomorphological investigation and monitoring of lateral spreading phenomena along the north-west coast of Malta*. Geografia Fisica e Dinamica Quaternaria, 31 (2), 171-180.

MANTOVANI M., DEVOTO S., FORTE E., MOCNIK A., PASUTO A., PIACENTINI D. & SOLDATI M. (2012) - *A multidisciplinary approach for rock spreading and rock sliding investigation in the north-western coast of Malta*. Landslides, in press (DOI: 10.1007/s10346-012-0347-3).

MARMARÀ G. (2004) - *Development of coastal karst terrains in Malta*. MSc Dissertation, University of Malta, Malta.

MICALLEF A., FOGLINI F., LE BAS T., ANGELETTI L., PASUTO A. & TAVIANI M. (2013) - *The submerged coastal paleolandscape of the Maltese Islands: Morphology, evolution and relation to Quaternary environmental change*. Marine Geology, 335, 129-147.

OIL EXPLORATION DIRECTORATE (1993) - *Geological map of the Maltese Islands*. Office of the Prime Minister, Valletta, Malta.

PASKOFF R. & SANLAVILLE P. (1978) - *Observations géomorphologiques sur les côtes de l'archipel maltais*. Zeitschrift für Geomorphologie N.F., 22, 310-328.

PEDLEY H.M. (1974) - *Miocene sea-floor subsidence and later subaerial solution subsidence structures in the Maltese Islands*. Proceedings of the Geologists' Association, 85 (4), 533-547.

PEDLEY H.M. & BENNETT S.M. (1985) - *Phosphorites, hardgrounds and syndepositional solution subsidence: a palaeoenvironmental model from the Miocene of the Maltese Islands*. Sedimentary Geology, 45 (1-2), 1-34.

PEDLEY H.M., HUGHES CLARKE M. & GALEA P. (2002) - *Limestone isles in a crystal sea: the geology of the Maltese Islands*. Publishers Enterprises Group, Malta, 109 pp.

SALIBA D. (2008) - *Cave formations and processes in Malta*. BSc Dissertation, University of Malta, Malta.

SOLDATI M., MAQUAIRE O., ZEZERE J.L., PIACENTINI D. & LISSAK C. (2011) - *Coastline at Risk: Methods for Multi-Hazard Assessment.* Journal of Coastal Research, Special Issue No. 61, 335-339.

STAFFORD K.W., NANCE R., ROSALES-LAGRADE L. & BOSTON P.J. (2008) - *Epigene and hypogene gypsum karst manifestations of the Castile Formation: Eddy County, New Mexico and Culberson County, Texas, USA*. International Journal of Speleology, 37 (2), 83-98.

TONELLI C. & GALVE J.P. (2011) - *Studio multidisciplinare delle strutture di collasso nell'Arcipelago Maltese*. In: Fredi P. & Guglielmin M. (Eds.), Atti della IV Giornata Nazionale dei Giovani Geomorfologi - Como, 28-30 Settembre 2011. AIGeo, Universitas Studiorum Insubriae, 29-30.

TONELLI C., GALVE J.P., CALLEJA I. & SOLDATI M. (2012) - *Spatial analysis of sinkholes as a tool to understand the karst sytem evolution. A case study from the Maltese archipelago*. In: Scappini S. & Zapparoli S. (Eds.), «Proceedings of the 7th European Congress on Regional Geoscientific Cartography and Information Systems - Bologna, Italy, 12th-15th June 2012». Regione Emilia-Romagna, 1, 243-244.

TRECHMANN C.T. (1938) - *Quaternary conditions in Malta*. Geological Magazine, 75 (1), 1-27.

WALTHAM T., BELL F.G. & CULSHAW M.G. (2005) - *Sinkholes and Subsidence: karst and cavernous rocks in engineering and construction*. Springer Verlag, Chichester, 382 pp.

(Ms. received 1 October 2012; accepted 1 March 2013)