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SCIENCE

Geomorphological map of the NW Coast of the Island of Malta (Mediterranean Sea)

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This paper presents the results of geomorphological investigations carried along the north-western coast of the Island of Malta. Field surveys, accompanied by aerial photo-interpretation, have led to the production of a geomorphological map at 1:7500 scale which outlines the main processes and related landforms. The latter are the result of the complex interplay of structural, gravitational, coastal and karst processes. Particular attention was devoted to the recognition, identification and mapping of landslides which affect large coastal sectors of the study area, locally giving rise to hazardous conditions.

Keywords: geomorphology; coast; landslides; Malta

1. Introduction

Geomorphological survey and mapping have been carried out along the north-western coast of the Island of Malta as part of a research project aiming at the assessment of geomorphological hazards in the area. A detailed geomorphological map has been produced as a base document, in order to identify the main processes and landforms. The final product includes 1:7500 geomorphological map, a geological section and a Digital Terrain Model (DTM).

The morphological features in the study area are strictly controlled by structural factors and modelled by gravitational, coastal and karst processes. In particular, the area is largely characterised by the occurrence of landslides which are favoured by structural conditions and triggered by rainfall and marine erosion.

Previous studies conducted in Malta mainly deal with coastal features (Magri, 2006; Paskoff & Sanlaville, 1978; Said & Schembri, 2010), geological and geomorphological issues (Alexander, 1988; Coratza, Bruschi, Piacentini, Saliba, & Soldati, 2011; Dart, Bosence, & Mcclay, 1993; Illies, 1981; Pedley, Clarke, & Galea, 2002; Pedley, House, & Waugh, 1978) or slope instability processes (Dykes, 2002; Magri, Mantovani, Pasuto, & Soldati, 2007; Magri, Mantovani, Pasuto, & Soldati, 2008; Magri, 2009). However, there is a lack of a comprehensive and detailed mapping, which is limited to a 1:31,680 geological map (Various Authors, 1963) and to a 1:25,000 geological map covering the entire archipelago (Oil Exploration Directorate, 1993).

2. Study area

The study area is located in the north-western sector of the Island of Malta, which lies in the central Mediterranean sea, 100 km south from Italy and 290 km east from Tunisia. It covers about 13 km^2, from Marfa Ridge, to the north, to the promontory of Ras ir-Raheb, to the south (Figure 1).

From a geodynamical viewpoint, the Maltese Islands lie in the Sicily Channel, which has been affected, during the Neogene-Quaternary age (Dart et al., 1993; Finetti, 1984), by continental rifting. It produced extensive

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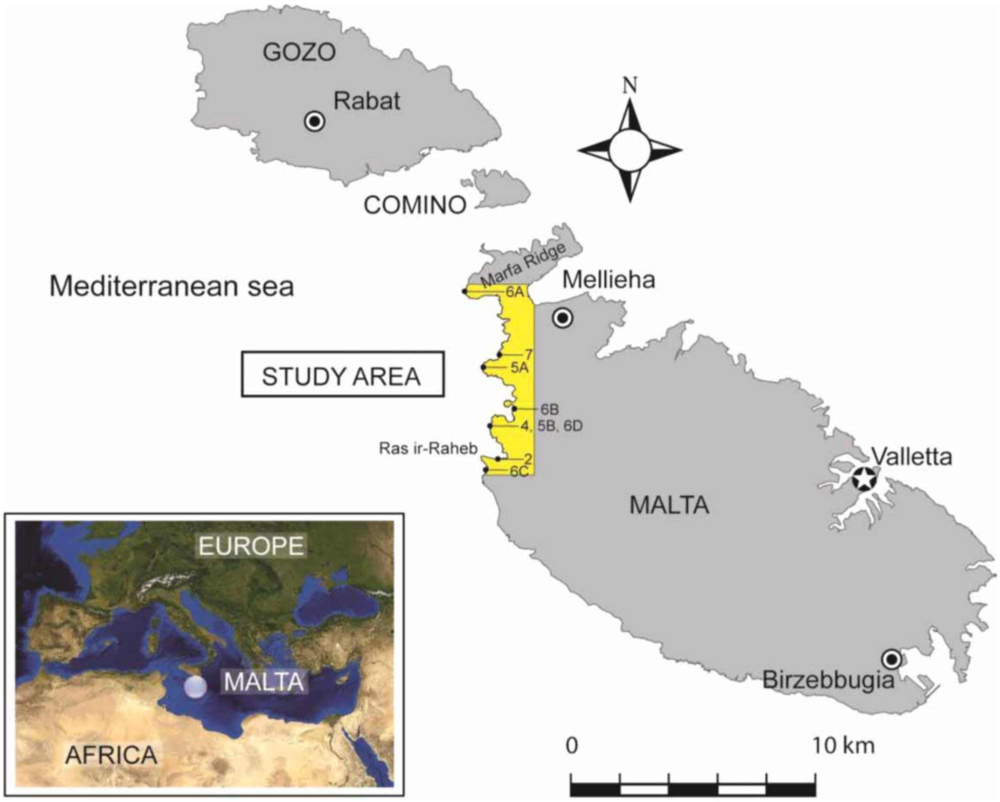

Figure 1. Location of the study area. Numbers indicated within the study area refers to the photographs reported in the paper.

Figure 2. View of the Victoria Lines fault.

structures, such as the Pantelleria, Malta and Linosa tectonic depressions, controlled by NW–SE normal faults. The Maltese tectonic setting is characterised by two intersecting fault trends: the NW–SE trending Pantelleria Rift (Reuther & Eisbacher, 1985), whose major structure is represented by the Maghlaq Fault, and the WSW–ENE horst and graben system, terminating at the Victoria Lines fault (Figure 2).

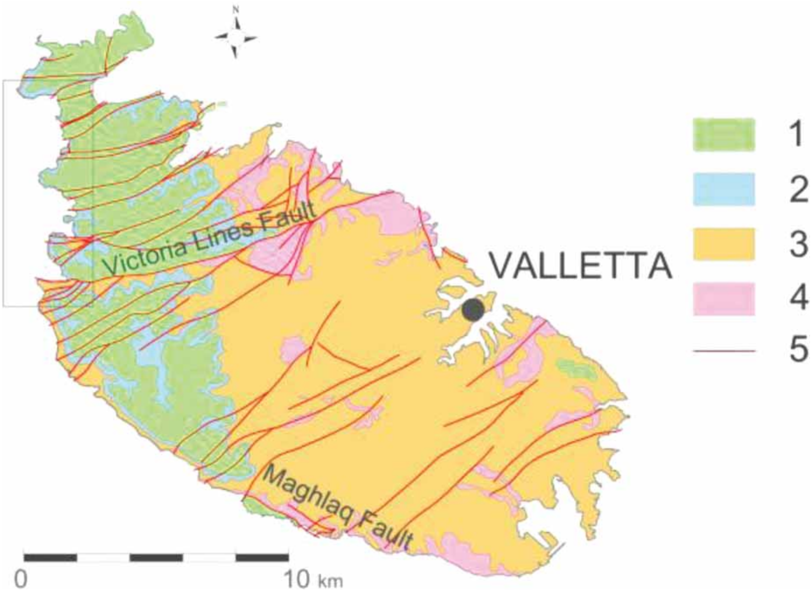

Figure 3. Geological sketch of Malta modified after Pedley et al. (2002) and Oil Exploration Directorate (1993). Legend: Upper Coralline Limestone Formation (1), Blue Clay Fm. (2), Globigerina Limestone Fm. (3), Lower Coralline Limestone Fm. (4), main faults (5).

The Maltese archipelago is composed of sedimentary rocks such as limestones, marls and clays deposited between Upper Oligocene and Miocene (Pedley et al., 1978, 2002).

The most ancient unit is the Lower Coralline Limestone Formation (Upper Oligocene, up to 140 m thick), which is characterised by massive and resistant grey limestones. The soft and yellowish Globigerina Limestone Formation (Lower–Middle Miocene, 20–200 m thick) is composed of fine-grained limestones. The stratigraphic sequence continues with the Blue Clay Formation, formed mainly by marls and clays (Middle Miocene, up to 70 m thick). The sequence ends with the Upper Coralline Limestone Formation (Upper Miocene, 10–160 m thick), which outcrops widely in northern Malta. At the base of the Upper Coralline Limestone, a fossiliferous and poorly cemented unit, the Greensand Formation, outcrops locally. It hardly exceeds 1 m and is composed of glauconitic and bioclastic limestones (Pedley et al., 1978).

North of the Victoria Lines fault, Blue Clay and Upper Coralline Limestone are dominant, whereas Globigerina Limestone prevails in the central and southern part of the Island (Figure 3).The geomorphology of the study area is deeply influenced by the structural setting and lithology. The highest point is situated on Il-Pelegrin promontory (127 m a.s.l.), close to the Victoria Lines fault which truncates the horst-graben setting.

The outcropping terrains are characterised by different physical and geomechanical properties, which control the onset and development of geomorphological processes (Figure 4).

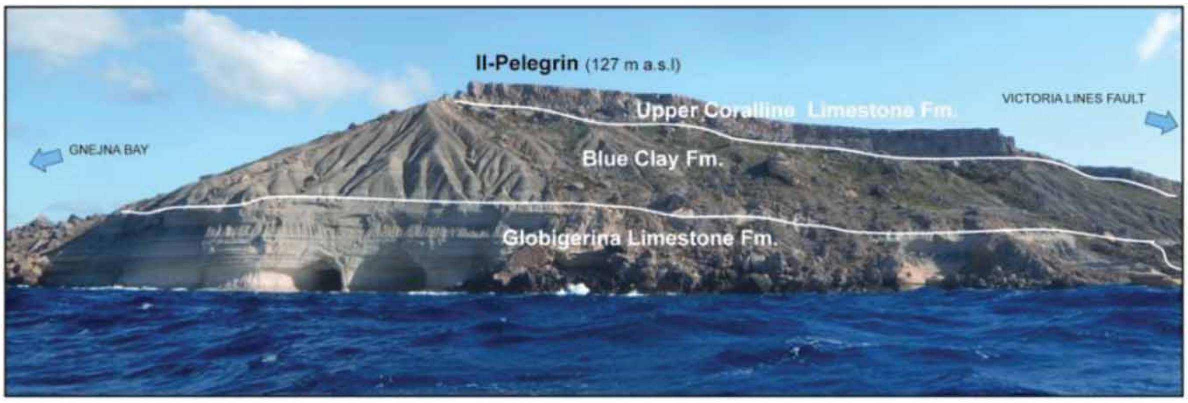

Figure 4. The southern part of Il-Pelegrin promontory where landscape is controlled by different rates of erosion, related to intrinsic geomechanical qualities of rock materials.

Large karst plateaus, bounded toward the sea by vertical cliffs of varying heights, correspond with the outcrops of the Upper Coralline Limestone Formation, while gentle or terraced slopes, locally reaching the sea, are determined by the presence of the Blue Clay Formation.

The Maltese archipelago is characterised by a typically Mediterranean climate, with warm and dry summers and mild winters. In the last decade, the annual rainfall averaged about 550 mm, ranging from a minimum of 455 mm, recorded in 2004, to a maximum of 837 mm in 2003. Average monthly temperatures range from 13°C in January to 27°C in August.

3. Material and methods

A field campaign at a scale 1:5000, accompanied with aerial-photo interpretation, has been carried out along the north-western coast of the Island of Malta, while the final mapping has been performed at 1:7500 scale. Aerial photos from 1957 and 2004 have been analysed, in order to reconstruct the recent geomorphological evolution. The lithological and structural features have been derived from the most recent geological map (Oil Exploration Directorate, 1993), validated and implemented by means of field observations. In order to obtain a high resolution DTM, contours and height points, derived from 1:2500 MEPA topographic maps, have been interpolated in ESRI ArcGIS.

Geomorphological mapping has been performed following the guidelines proposed by the Italian Geological Survey (Gruppo di Lavoro per la Cartografia Geomorfologica, 1994) and with reference to recent Italian geomorphological maps (e.g., Panizza et al., 2011). The guidelines foresee the representation of the genesis of landforms and the type of processes through different colours and the outline of their state of activity by means of colour intensity (more intense for active processes).

Six main sets of landforms and deposits have been identified and mapped: (i) structural landforms, (ii) gravity induced slope landforms, (iii) fluvial and slope landforms due to running water, (iv) coastal landforms, (v) karst landforms, (vi) man-made landforms.

Topographic elements have been drawn in grey and have been represented as point elements (spot heights) and line elements (isohypses and roads). Conversely, we decided to exclude from the 1:7500 map buildings and human-made terraces, in order to avoid intense overlapping between geomorphological and topographic elements.

4. The geomorphological map

4.1 *Structural landforms*

The landscape is primarily dominated by the aforementioned series of ENE–WSW horst and graben systems, which displace the coastline with raised and lowered blocks. Horsts form a series of ridges which correspond to promontories capped by limestone plateaus, whereas graben constitute parallel valleys, which end up as bays and coves, where sometimes small sandy beaches occur, such as Anchor Bay, Golden Bay, Ghajn Tuffieha Bay and Gnejna Bay (Said & Schembri, 2010).

A system of parallel normal faults, clearly visible along the coast because of the sub-horizontal bedding and the scarce vegetation, displace the whole stratigraphic sequence, with different throws. The major faults occur at the northern and southern borders of the study area, at Marfa Ridge and at Ras Il-Pelegrin, where the Lower Coralline Limestone Formation outcrops at sea level. The northernmost fault brings it into contact with the Upper Coralline Limestone, with a throw of more than 100 m. The southernmost one, the Victoria Line, shows a spectacular tectonic contact between Lower Coralline Limestone and Blue Clay, with a throw of about 100 m. The remaining coastal sector is characterised by uplifted and downlifted blocks, where the Globigerina Limestone, the Blue Clay and the Upper Coralline Limestone outcrop.

4.2 *Gravity-induced slope landforms*

The north-western coast of Malta is largely affected by different types of landslides, such as rock spreads, block slides, rock falls and earth flows (Devoto et al., Forthcoming; Magri, 2009). The presence of limestone cliffs overlying clayey terrains favours the occurrence of impressive lateral spreading phenomena (cf. Pasuto & Soldati, 1996) (Figure 5), due to the diverse geomechanical and hydrogeological properties of two rock materials (Magri et al., 2008; Mangion, 1991). Monitoring activities have shown that these rock-spreading phenomena are active, though characterised by very slow deformation rates (Devoto et al., Forthcoming; Magri et al., 2007, 2008).

The clayey slopes are covered by large blocks detached from the edges of the limestone plateaus. The block accumulations, named Rdum by locals, dominate large sectors of the coastal areas and locally reach the sea.

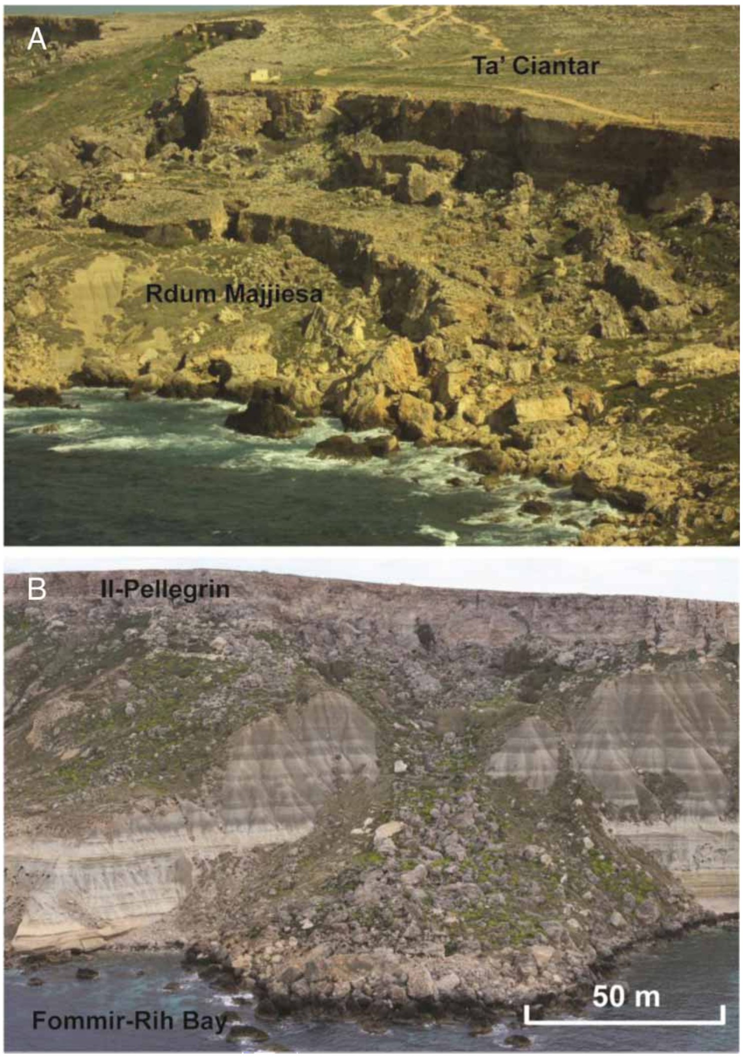

Figure 5. Rock-spreading and block-sliding phenomena affect large sectors of the coast (A). A large complex-landslide deposit reaches directly the sea following a pre-existing incision/depression developed on clayey terrains (B) (Courtesy of Ten. Col. M. Marchetti).

The evidence of rock spreading is widespread all along the edges of karst plateaus (i.e. Anchor Bay, Badja Ridge, etc.) and causes the development of a dense network of persistent cracks.

These vertical discontinuities near the rock slope induce the isolation of large blocks, which can detach, fall, roll or slide, sometimes back-tilting from the plateaus. The lateral extension of rock masses often evolves into block sliding phenomena at the foot of Upper Coralline Limestone scarps. Accumulations composed of limestone plates, pillars or blocks of variable volumes are scattered on clayey slope gently degrading toward the sea, acting as a natural barrier for marine erosion. Earth flows largely occur along clayey slopes (Dykes, 2002).

4.3 *Fluvial and slope landforms due to running waters*

Even if running water is scarce because of the present morphoclimatic conditions, ancient fluvial remodelling is identified by a series of erosion features.

At present, heterometric deposits, composed principally of sands and silts, are carried by temporary streams from plateaus. The dense joint system and the karstification of limestone prevents the development of a permanent superficial drainage pattern on the limestone floor. A significant amount of seepage water percolated by overlaying limestone rock masses and rainfall is conveyed along channels incised into impermeable clayey slopes, which have been mapped as gullies.

4.4 *Coastal landforms*

The coastline pattern is dominated by the succession of headlands and bays which are developed respectively in correspondence with horst and graben (Said & Schembri, 2010). Bays are usually characterised by the presence of mixed grain-size coarse deposits, ranging from pebble to metric-sized blocks and small sandy beaches. Headlands are dominated by cliffs, sometimes associated with shore platforms, extending from a few to more than 100 metres (Figure 6).

Vertical plunging cliffs, with no presence of shore platform at the cliff-foot, are cut both in Lower and in Upper Coralline Limestone formations and are tectonic in origin (Magri, 2006; Paskoff & Sanlaville, 1978). They mainly occur between Gebel Imbarak and Ghadira Bay and along the southern sector of the study area, where the Victoria Lines fault escarpment constitutes an exemplary case.

Excluding the Blue Clay Formation, sea caves occur on all the limestone cliffs.

No traces of former shorelines higher than the present one or wave-cut terraces, notches or coastal deposits have been observed within the site. For these reasons this stretch of Maltese coast can be considered stable or slightly subsiding (Biolchi et al., 2011; Paskoff & Sanlaville, 1978).

4.5 *Karst landforms*

Karst features are common in Malta (Saliba, 2008). Limestone plateaus are widely characterised by small-scale surface features (from centimetres to metres in size), whereas caves and sinkholes are rare. However, at Ghadira Bay, a wide circular sinkhole has been observed. Its development has been favoured by the presence

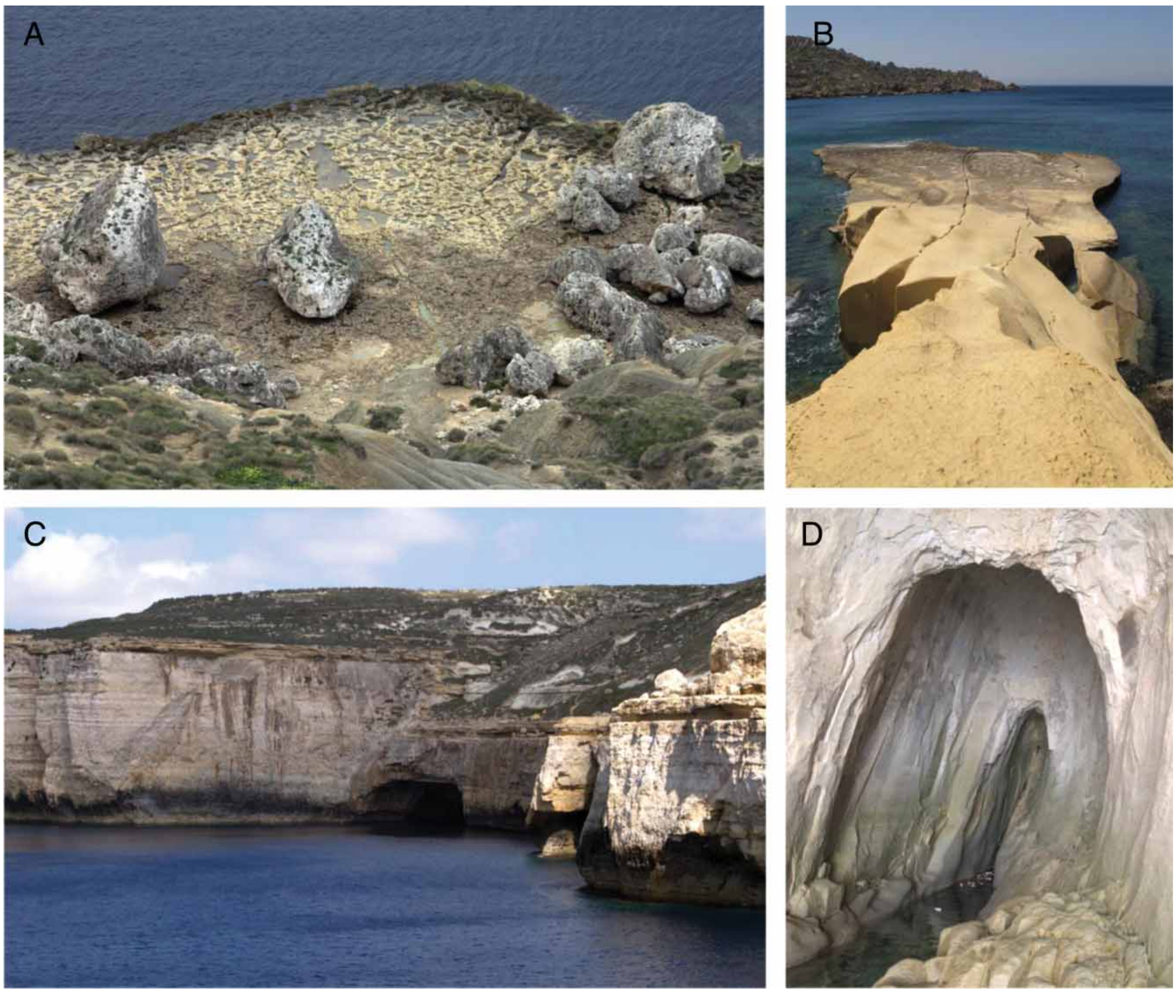

Figure 6. Shore platforms cut in Globigerina Limestone Fm. at Ras il Qammieh (A) and at Gnejna Bay (B); marine caves cut in Lower Coralline Limestone Fm. (C) and in Globigerina Limestone Fm. (D).

Figure 7. Sinkhole located at Ghadira Bay.

of a fault (approximately N–S oriented) and by the lithological setting (limestones over clays gently inclined toward the bay) (Figure 7).

4.6 *Man-made landforms*

The north-western sector of Malta has been slightly affected by human impact, compared to the rest of the island. Beside some touristic structures, two small inactive quarries and several dumping sites have been observed, while terrace fields make up the most significant evidence of human intervention in the study area. They occupy large areas, such as along the gentle slopes that flank Bingemma Valley or along the coastal zones. Their spatial distribution has been outlined with the support of aerial photographs and depicted in a 1:25,000 map, which accompanies the geomorphological map.

5. Conclusions

The results of geomorphological surveys carried out along the north-western coast of the Island of Malta have been illustrated with special reference to the 1:7500 geomorphological map, which have been produced. The latter, in A0 format, is accompanied by a 1:25,000 map of terrace fields, a DTM and a N–S-oriented geological section.

Particular emphasis have been devoted to the identification and mapping of landslides, which may imply hazard situations for locals and tourists. The geomorphological map produced, due to its detail, makes up a reliable base document, which could be useful for the identification of areas exposed to geo-hazards and for the recognition of features of geological interest, such as geomorphosites (Coratza et al., 2011). For this reason, the map can be used by the Maltese authorities for future land planning and management of this pristine portion of coastline.

Software

The geological section and the dataset of the map, including the symbols of the geomorphological legend, have been digitised and managed using AutoCAD 2010 software. The DTM was produced using ESRI ArcGIS 9.2.

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