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AN INTEGRATED APPROACH FOR LANDSLIDE HAZARD ASSESSMENT ON THE NW COAST OF MALTA

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Introduction

This contribution presents the outputs of multidisciplinary research carried out along the north-western coast of Malta aiming at landslide hazard assessment. The investigated area extends on a surface of 15 km2 and it is situated between Paradise Bay and Il-Pelegrin promontory. Elevation ranges from the sea level to about 120 m of altitude. The stability conditions of this stretch of coast are deeply controlled by a linkage of different factors, such as tectonics and lithology, which control the landslide onset. Landslides certainly make up a predominant geomorphological feature in this area and they have been investigated in detail by means of mapping, monitoring and modelling since 2005 by a composite team of Italian researchers supported by Maltese institutions.

Geological setting

The Maltese archipelago is composed of Tertiary limestones, clays and marls capped by very thin superficial deposits, such as red soils or colluvial sediments. In the north-western part of Island of Malta, two geological units are dominant and influence the types of landslides: Upper Coralline Limestone and Blue Clay Formation.

Figure 1. Geographical setting of the investigated area and examples of block slides: A) north-western area of Marfa Ridge; B) stretch of coast between Rdum id-Delli and Ras Il-Wahx; C) Il-Qarraba peninsula.

Inland the Upper Coralline Limestone produces a barren grey pavement, bordered by vertical cliffs of varying heights, which range from a few metres to over 30 m. The underlying Blue Clay forms gentler and sometimes terraced slopes that in some cases reach directly the sea. The different mechanical behaviour of clays and limestone favours the development of impressive lateral spreading and block sliding phenomena, which occur in particular along the north-western sector of Marfa Ridge, at Ras Il-Wahx and at Ghajn Tuffieha Bay (Fig. 1).
Block slides are particularly widespread on the large terraces which slope gently towards the sea. Other types of landslides are earth flows, earth slides, affecting clayey slopes, as well as rock falls and topples, which are favoured primarily by persistent fissures and cracks of tectonic origin enlarged by lateral spreading (Devoto et al., 2013a).

Landslide investigation

In order to recognize, inventory and map coastal slope movements, a geomorphological survey was conducted at a scale of 1:5000. This phase of research also included a check of the existing bibliography and maps. Geomorphic information deriving from land surveying was integrated and controlled by multitemporal aerial photo interpretation. Field surveys permitted to observe directly landforms, processes and deposits whereas orthophotos helped to understand their evolution and to map particular morphological features of landslides identified on the ground, such as cracks related to limestone fragile behaviour. Parallel to structural escarpments, vertical fissures and cracks situated on karst plateau can exceed 200 m length.

In order to evaluate the state and style of activity of lateral spreading and block sliding phenomena, different monitoring techniques were applied. In particular, two GPS networks have been operating since 2005 which enabled to define the investigated mass movements as active. The latter can be classified as extremely slow, according Cruden and Varnes classification (1996). All surveying data were digitized at a scale of 1:5000, compiled and stored in an AutoCAD Map® software and mapped using the symbology of the legend proposed by the Italian Working Group for Geomorphological Mapping of the Italian Geological Service (1994). The final product is a detailed geomorphological map at a scale of 1:7500 including the coastal area between Paradise Bay and the Great Fault (Devoto et al., 2012). This map may represent a useful and comprehensive tool for identifying geomorphological risk along the coast.

Integrated landslide monitoring

Integrated monitoring techniques have been adopted to investigate lateral spreads and block slides in order to define the kinematics and the triggering mechanisms. These phenomena may evolve into faster movements, which can determine catastrophic failures (i.e. block slides), or they can favour a series of collateral landslides (i.e. sudden block slides, flows, falls and topples) occurring at the edges of the areas affected by spreading (Pasuto and Soldati, 2013). In this context, the coupling of traditional and innovative monitoring techniques makes up a reliable solution for the detection and survey of active deformations due to rock spreading, with promising perspectives in terms of hazard assessment and mitigation (Magri et al., 2008; Devoto et al., 2013b; Mantovani et al., 2013).

An example of site analysed through different methods is the Il-Qarraba peninsula (Fig. 1C). This peninsula is composed by a limestone plateau surrounded by an extensive block slides deposit with a subcircular shape and connected to the land through an isthmus made up of Blue Clay that is eroded by the marine action. At this site a GNSS network has been working since 2006 and tape extensometer measurements have been carried out since the end of 2009. Moreover, to support and confirm the monitoring results, interferometric analyses (satellite SAR) and geophysical investigations (GPR and Electrical Resistivity Tomographies - ERT) were carried out (Devoto et al., 2013b; Mantovani et al., 2014).GNSS monitoring is taking place with reference to eight benchmarks located both on the plateau and on rock masses and blocks detached due to rock spreading and block sliding. Considering the extremely slow rate of deformation, the static relative positioning technique was employed in order to achieve more accurate results. Surveys have been carried out twice a year at the end of the wet and dry seasons, in order to investigate the relationship between recorded displacements and rainfall. Since the very beginning, it was clear that rock spreading was active over a large area, and the series of readings carried out showed continuous evidence of activity (Magri et al., 2008; Devoto, 2012; Devoto et al., 2015). The interferometric analyses took into account ERS radar images, to evaluate the deformation eventually occurred before the realization of the GNSS control network, and images acquired from ENVISAT and Terra SAR-X satellites, in order to define the present state of deformation and to integrate and validate the results achieved with the monitoring system. This kind of analysis allowed also to evaluate any change in rate of deformation, state and style of activity. In the site of Il-Qarraba, the interferometry highlighted displacements ranging between -3,5 mm to +0,5 mm in 9 years with the same style of activity (Piacentini et al., in press).

ERT profiles acquired with a multielectrodes (48) system allowed to evaluate the thickness of limestones and to highlight some tectonic structures. GPR data were acquired using 300 and 500 MHz shielded antennas. The investigation was concentrated on blocks showing significant vertical and planar displacement in order to obtain a precise imaging of the rock mass and to reconstruct the 3D discontinuity network (Mantovani et al., 2013). The integration of results obtained with this multi-technical integrated approach have been of fundamental importance for describing quantitatively the evolution of lateral spreading and block sliding affecting Il-Qarraba and the other monitored sites.

Landslide susceptibility analysis

The results from Permanent Scatterer Interferometry were used as input data in the Weight of Evidence (WofE) model to produce a landslide susceptibility map, validated through field survey and GNSS measurements (Piacentini et al., in press)

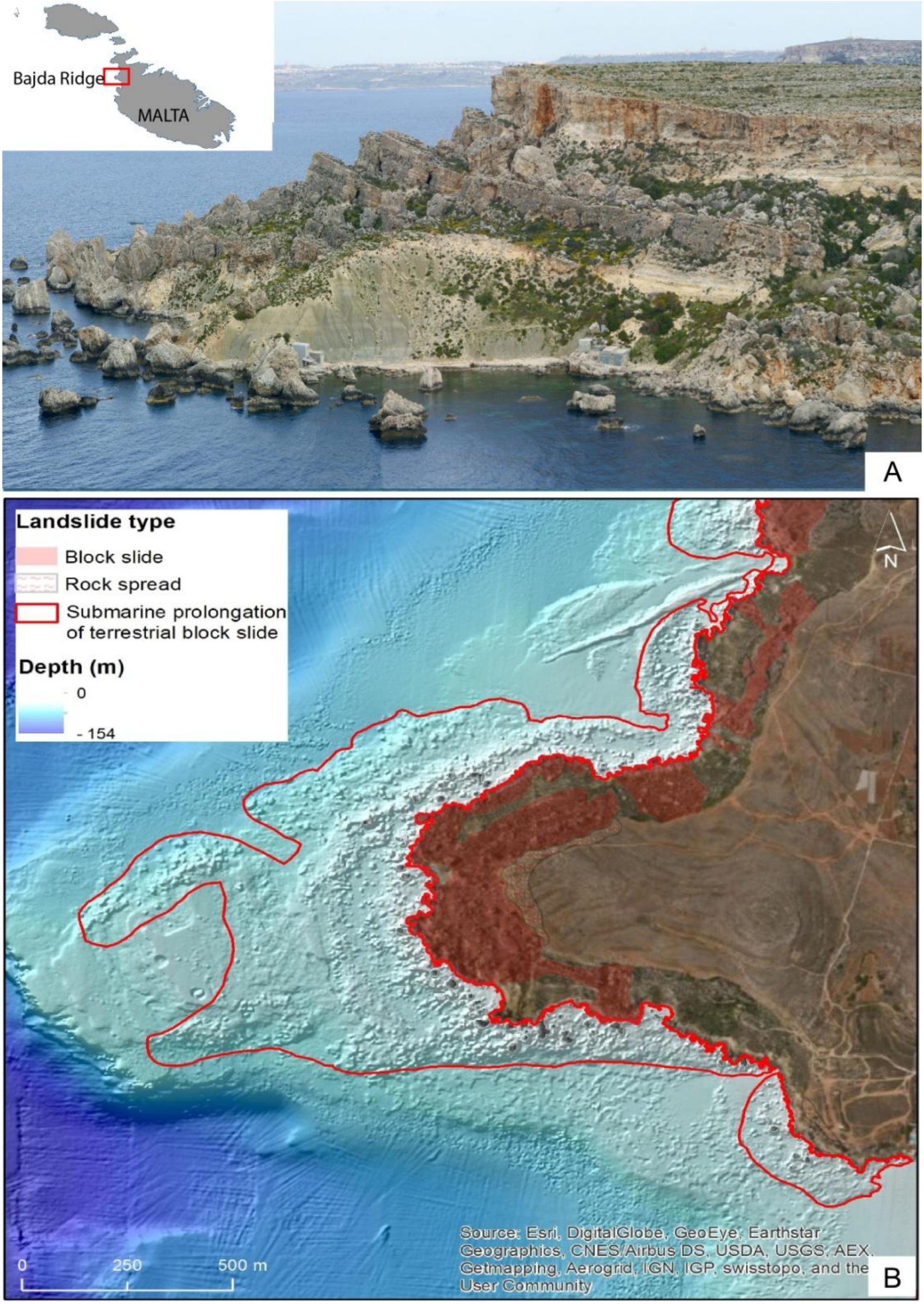

Figure 2. Ras Il-Wahx block slide at Bajda Ridge (A); landslide deposits largely extending under the sea level are evident (B).

and resulting in a reliable method to produce susceptibility maps at medium and regional scale. Geomorphological data were compared with the model output with a satisfying fitting between the inventoried block slides and the spatial distribution of high landslide susceptibility classes. In particular, the active block slides affecting the northern part of Marfa Ridge, at Il-Prajjet, in the coastal sector between the southern part of Ghadira Bay and Ras Il-Wahx promontory (Figure 9) and at Il-Qarraba peninsula have been correctly identified by the model. Finally, the model outputs were quantitatively compared with the surface displacements derived from GNSS campaigns reported in Mantovani et al. (2013) with a positive feedback. The landslide susceptibility map of the north-western coast of Malta can be considered as an easy-to-use tool for the implementation of further hazard analyses and land management activities.

Coupling terrestrial and marine datasets

A deep understanding of the processes acting on the coastal areas (such as landslides) is crucial for coastal hazard assessment, especially landslide hazard assessment and mapping. To this aim, integrated investigations of emerged and submerged areas resulting in geomorphological mapping represent an innovative way to provide the necessary knowledge for preventing hazards and reducing risks, understanding the evolution of the processes in a framework of climatic changes.

A Multibeam survey has recently been carried out offshore the north-western coast of Malta to acquire high resolution bathymetry (2 m) and backscatter data. A LiDAR-derived DEM was used to cover the gap between the bathymetric survey and the land (courtesy of the AcquaBioTech Group).The seafloor sediments were analysed through the analysis of the reflectivity (backscatter) data exploiting the TexAn software (University of Bath, UK) to produce a sediment distribution map. The submerged geology was inferred drawing geological section exploiting the Geological Map of Malta published by the Oil and Exploration Directorate (1993). Morphological features of the seafloor were recognized and mapped thanks to bathymetry analysis and geomorphological interpretation. A series of these features were emerged during the Last Glacial Maximum, when the sea level was about 130 m lower than at present (Lambeck et al., 2011; Micallef et al., 2013). An integrated geomorphological map of emerged and submerged coastal areas of north-western Malta was produced, which is also crucial to understand the geomorphological evolution of the archipelago since the Last Glacial Maximum (LGM). It should be emphasized that the most relevant features offshore the north-western coast of Malta are landslide deposits which are the continuation of terrestrial ones below the sea level down to a depth of about 50 m (Fig. 2). In most cases the largest part of the block slide deposits is under the sea level.

Conclusions and perspectives

The multidisciplinary and integrated research carried out (and still ongoing) along the north-west coast of Malta has allowed (i) the reconstruction of the geomorphological evolution of the area, (ii) the characterization of slope instability phenomena there occurring, and (iii) the definition of the areas which are more susceptible to landslide processes.

The outputs of the research have provided the basis for defining future scenarios of evolution, which are essential for landslide hazard assessment in an area which is visited by many tourists and locals throughout the whole year.
At present no time constraints are available for past landslide activity in the study area. Landslide dating would be however needed to provide a more precise temporal frame to the overall geomorphological evolution of the north-western coast of Malta. To this aim, a recent geomorphological campaign enabled to collect samples from scarps and blocks that are presently under dating using cosmogenic nuclides (36Cl) at the University of Exeter, UK. Achieving information on the temporal occurrence of landslides will be beneficial in outlining future evolution scenarios which are crucial for land planning and civil protection.

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