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## Geomorphology of the seafloor north east of the Maltese Islands, Central Mediterranean

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### ABSTRACT

This paper presents a geomorphological map of the seafloor north east of the Maltese Islands (Central Mediterranean) at a scale of 1:50,000. The map was compiled following the integration, analysis and interpretation of several high-resolution seafloor bathymetry datasets. Several structural features, coastal and marine landforms and anthropogenic features have been mapped. Most of the mapped submerged landforms – including fluvial, gravity-induced and karst landforms – appear to have been formed during the sea-level lowstand of the last glacial cycle. The map provides valuable insights on the submerged landscape of the Maltese Islands and its evolution since the Last Glacial Maximum.

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### KEYWORDS

Geomorphological mapping; submarine geomorphology; continental shelf; palaeolandscape; Malta

## 1. Introduction

Geo-environmental studies focusing on the Maltese seafloor (central Mediterranean Sea) and adjacent coasts have been recently conducted. They mainly deal with i) the evolution of submerged landscapes since the Last Glacial Maximum (LGM; Fogliani et al., 2016; Micallef et al., 2013; Prampolini et al., 2019), ii) geomorphological mapping integrating land and seafloor (Prampolini et al., 2017, 2018a), iii) characterization of marine substrate and habitat mapping (Micallef et al., 2012; Prampolini et al., 2018b), iv) coastal landslide evolution (Soldati et al., 2018; 2019), and v) neotectonics (Micallef et al., 2019). These studies have shown that the seafloor of the Maltese Islands is characterized by a remarkable record of landforms of both terrestrial and marine origin. However, a detailed geomorphological mapping of the Maltese continental shelf was not conducted earlier.

This paper focuses on the submerged landscapes located adjacent to and north east of the Maltese Islands, and includes a geomorphological map at 1:50,000 scale covering an area of 303.5 km<sup>2</sup>, from northern Gozo to south-eastern Malta and from the coastline down to 400 m below sea level (b.s.l.) (Figure 1). This area experienced remarkable sea-level oscillations during the last glacial cycle and the subsequent deglaciation. The sea level started its fall around 125 kyr ago reaching its minimum during the Last Glacial Maximum (LGM), i.e. about 20 kyr ago, when it was

about 130 m lower than today (Benjamin et al., 2017; Furlani et al., 2013; Lambeck et al., 2014; Marnier et al., 2012). Hence, most of the seafloor investigated here was emergent at that time, and shaped by subaerial processes; the post-glacial sea-level rise drowned the shelf preserving the landforms previously produced. At present, the seafloor on the north-eastern side of the Maltese Islands is sub-horizontal (mean slope 2°) and its extension varies from 1.5 km from the present coastline offshore Gozo up to 10 km offshore St. Paul's Bay in Malta.

The research was carried out within the framework of the European Project EMODnet Geology, aimed at collecting and harmonising geological, geomorphological and submerged landscapes data of European seabeds and making them available for the scientific community, stakeholders and citizens through the EMODnet Geology portal (<https://www.emodnet-geology.eu/>). In particular, this research contributed to the 'Sea-floor geology/ Geomorphology' and 'Submerged landscapes' topics.

## 2. Regional setting

The Maltese Islands are located in the Malta-Sicily Channel on the Malta-Ragusa Rise (Figure 1) (Galea, 2019; Schembri, 2019).

The stratigraphic sequence is constituted by a Late Oligocene – Late Miocene marine carbonate succession of four main lithostratigraphic units, lying almost



**Figure 1.** Physical and geographic setting of the study area (3D view) and its location within the Maltese Islands.

horizontally. From the oldest to the youngest, they are the Lower Coralline Limestone, *Globigerina* Limestone, Blue Clay and Upper Coralline Limestone formations (Baldassini & Di Stefano, 2017; Pedley et al., 2002; Scerri, 2019). The *Lower Coralline Limestone Fm.* (LCL) is made up of bioclastic, compact and stratified limestones outcropping mainly along the coast forming 100-140 m high cliffs. The *Globigerina Limestone Fm.* (GL) is constituted by slightly cemented biocalcarenes with two conglomerate phosphatic beds forming hardgrounds and which characterizes the landscape of southern Malta and western Gozo. The *Blue Clay Fm.* (BC) is an alternation of marls and clays that forms gentle slopes in northern Malta and Gozo. It is occasionally capped by sands rich in glauconite and with very high fossiliferous content forming the *Greensand Fm.* This marks the transition to the *Upper Coralline Limestone Fm.* (UCL) characterized by a hard, bioclastic and stratified limestone often shaped onshore into plateaus bounded by steep cliffs and hosting karst features.

A typical sequence of Quaternary deposits (Pleistocene in age) was found in the Ghar Dalam cave hosting vertebrates remains, testifying to the formation of a strip of land connecting Malta with Sicily that allowed so many quadrupedal animals to reach the Maltese Islands during the last ice age (Hunt, 1997; Pedley, 2011; Pedley et al., 2002; Prampolini et al., 2020).

Two fault systems cross the Maltese Islands: the Early Miocene system is WSW-ENE-oriented and formed the horst and graben structures that characterize the northern sector of the archipelago and the surrounding seafloor (Alexander, 1988; Gauci & Scerri, 2019). The main lineaments of this WSW-ENE system (the South Gozo Fault and the Great Fault, among

them) bound the North Gozo Graben, South Gozo Horst, North Malta Graben and South Malta Horst, having hundreds of meters of upthrow (Galea, 2019). The Late Miocene – Early Pliocene system trends NW-SE, parallel to the Pantelleria Rift, controlling the orientation of the eastern coasts, as well as the main submerged escarpment bounding part of the eastern continental shelf (Dart et al., 1993; Illies, 1981; Jongmsma et al., 1985; Reuther & Eisbacher, 1985).

The seafloor surrounding the Maltese Islands is made of a wide planar continental shelf on the eastern side of Malta and Gozo, bounded by a linear escarpment running parallel to the coast. On the western side of the Islands, the shelf is narrow, extending a few hundreds of meters from the coast and characterized by steep scarps about 100 m high.

### 3. Materials and methods

The research carried out was based on the geomorphological analysis and interpretation of the following data:

- 2 m-resolution multibeam bathymetry and acoustic backscatter of the investigated Maltese continental shelf acquired during MEDCOR 2009 and DECORS 2011 cruises;
- 10 m-resolution sonar bathymetry acquired during ERDF156 project by Malta Planning Authority (MPA) in 2012;
- 1 m-resolution DEM derived from bathymetric LiDAR survey carried during ERDF156 project by MPA in 2012.

The Digital Elevation Models (DEMs) above were merged into a single DEM 5 m-resolution and the

spatial data were then stored in a geographic information system (ESRI ArcGIS 10.1) for the representation of identified geomorphological features.

The geomorphological interpretation benefitted from an integrated analysis of geomorphological and substrate maps of the Maltese seabed (Foglini et al., 2016; Micallef et al., 2012, 2013; Prampolini et al., 2017; 2018a; 2018b), and geological and geomorphological maps of the Maltese Islands (Biolchi et al., 2016; Devoto et al., 2012; Oil Exploration Directorate, 1993; Prampolini et al., 2017; 2018a) available in the literature. The inference on some continental shelf landforms and features was also based on the information available on the Malta Planning Authority geportal and Heritage Malta website, and was supported by literature review.

Geomorphological mapping mainly followed the guidelines proposed by the Italian Geological Survey (Campobasso et al., 2019; Mastronuzzi et al., 2017) and with reference to recent submarine geomorphological maps of the Mediterranean (Buosi et al., 2017; Casalbore et al., 2016a; 2016b; Miccadei et al., 2012; Prampolini et al., 2017, 2018a; Rovere et al., 2015; Sulli et al., 2021). The above-mentioned guidelines envisage the representation of landforms and associated deposits using symbols of different colours according to the geomorphological processes that led to their genesis.

#### 4. The geomorphological map

The ‘Geomorphological map of the seafloor north east of the Maltese Islands, Central Mediterranean’ at the scale of 1:50,000 is draped over a 5 m-resolution digital terrain model and its legend is located on the upper right side of the Main Map. The map includes a geographic and geodynamic setting of the Malta-Sicily Channel and a palaeogeographic reconstruction referring to the LGM. An overview of the geology of the Maltese Islands and their surrounding bathymetry is provided, together with a 3D view of the Maltese landscape, both during the LGM and the present. Finally, three land-sea geological cross sections and a stratigraphic column are included. The main geomorphological features characterizing the investigated continental shelf are described below according to their genesis, and information on the relative chronological framework is provided where possible. The most common landforms are those controlled by the geological structure of the islands and those inherited from subaerial processes, comprising ancient fluvial channels, sinkholes and shore deposits. Marine bedforms (e.g. ripples and contourite drift), developed after post-glacial marine transgression, have also been recognized and mapped.

#### 4.1 Structural elements and landforms

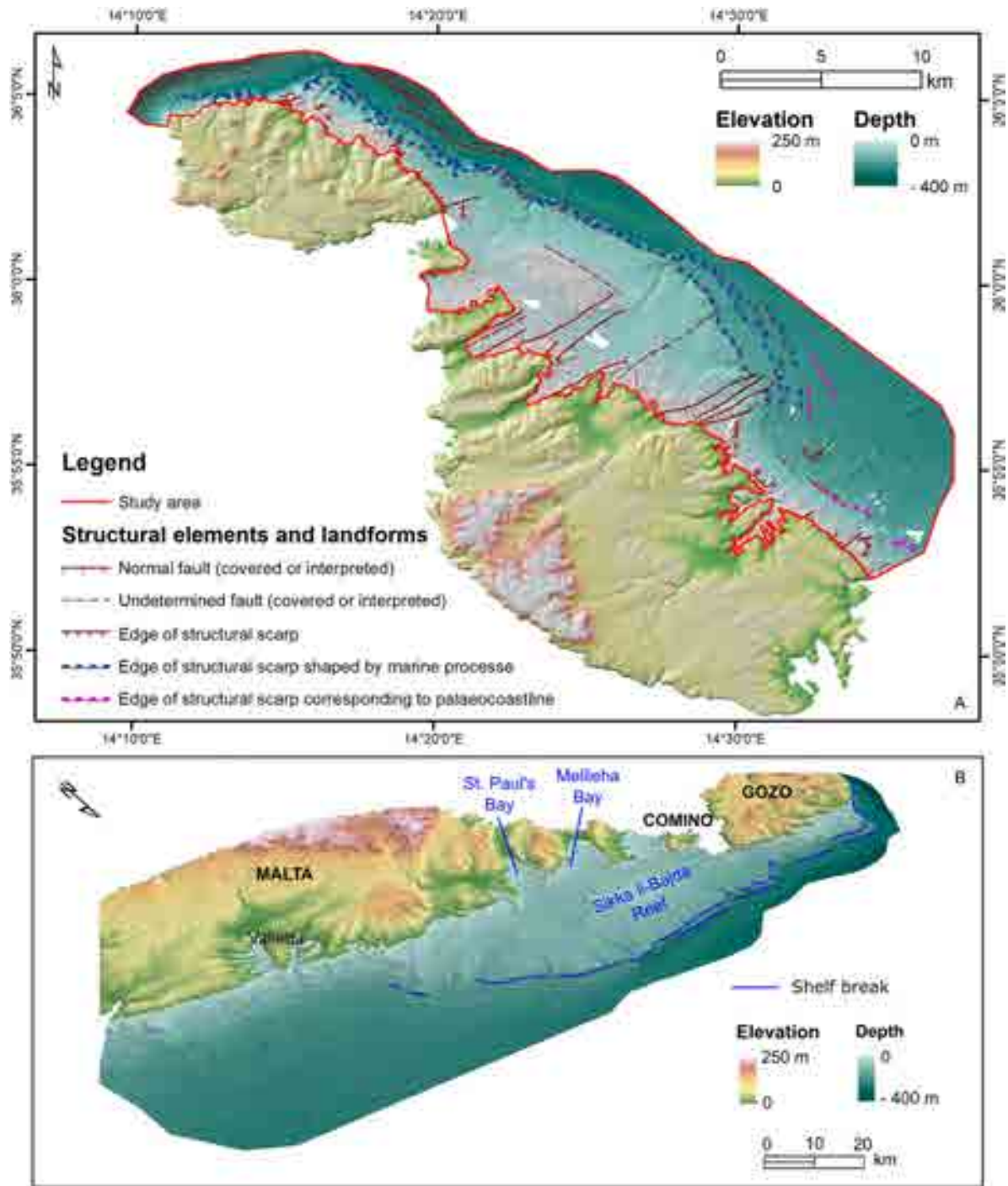
A NW-SE-oriented escarpment, controlled by the fault system parallel to the Pantelleria Rift, bounds the investigated continental shelf (Micallef et al., 2013; 2019). This escarpment is characterized by a break of slope at 50–95 m water depths and a base 130 m deep, while the scarp reaches a maximum slope of 35° (Figure 2). Offshore Salina Bay, the escarpment changes its orientation to NNW-SSE, becoming more fragmented than in the northern segment, and stops offshore Pembroke, probably due to the marine extension/continuation of the Great Fault. This escarpment probably acted as a coastal cliff during the LGM, when the sea level stood 130 m lower relative to the current isobath (Micallef et al., 2013). Other structural scarps, which border the marine terraces and submerged plateaus (e.g. Sikka il-Bajda Reef), are predominantly NW-SE or ENE-WSW oriented, sub-parallel to the Pantelleria Rift fault system. It is likely that they are evidence on the seabed of normal faults (Micallef et al., 2013). They also possibly acted as coastal cliffs during sea-level lowstands of the last glacial cycle.

Numerous elongated and irregularly shaped plateaus occur on the shelf. Their NW-SE or SW-NE orientation is likely controlled by both the fault systems affecting the Maltese Islands. A remarkable example is given by the Sikka il-Bajda Reef, 5.8 km long, 2 km wide and 27 m deep, located offshore Marfa Ridge and Mellieha Bay, which is bounded by faults trending both NW-SE and SW-NE (Prampolini et al., 2017).

#### 4.2 Coastal and marine landforms

The stretch of seafloor offshore St. Paul’s Bay to the Great Fault is characterized by different levels of marine terraces oriented NW-SE or NNW-SSE. The largest range from 5 to 12 km long and are 800–1000 m wide, whilst the smallest are 2 km long and 70–500 m wide (Figure 3). They are characterized by a sub-planar morphology and are apparently carved in Globigerina Limestone. They have been interpreted as palaeo shore platforms analogous to the current shore platforms in Globigerina Limestone located along the eastern coast of Malta (Micallef et al., 2013). It is likely that the terraces formed during the still-stand phases of the sea level which occurred during the last glacial cycle (Micallef et al., 2013; Prampolini et al., 2017 and references therein; Deiana et al., 2021). The terraces would have been drowned during the post-glacial sea level rise.

The active marine landforms include a contourite deposit of fine sediments SE-NW-oriented, located at a depth greater than –130 m b.s.l. and shaped by bottom currents (Béranger et al., 2004). In the eastern



**Figure 2.** A) Overview of the mapped structural elements and landforms; B) 3D view of the investigated continental shelf and of the shelf break represented in the chart as “Edge of structural scarp shaped by marine processes”.

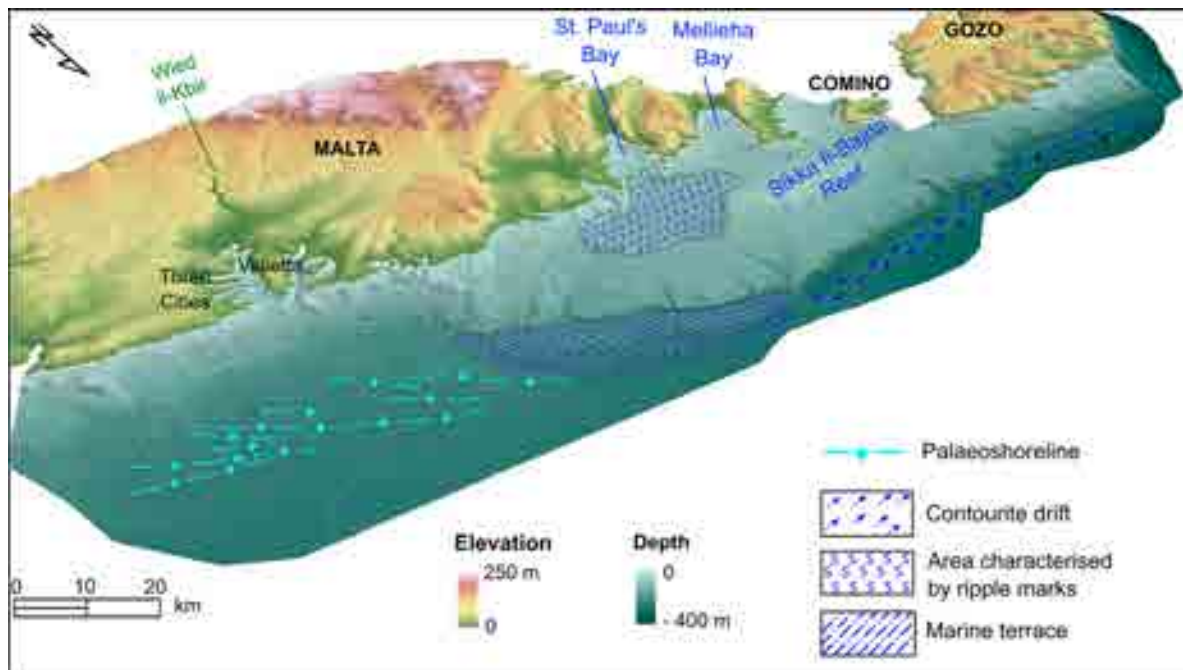
offshore of Comino and NE of Malta, ripple marks shaped by SE-NW oriented background currents occur on the shelf, offshore Melleha and St. Paul's Bay.

Offshore the Valletta Grand Harbour, there are elongated ridges NNW-SSE- or NW-SE-oriented, characterized by a slope  $< 1^\circ$  and ranging between  $-90$  and  $-130$  m of water depth. By comparing their depth with the curves of the sea-level oscillations proposed by Siddall et al. (2003) and Lambeck et al. (2011, 2014), it is likely that these ridges are made of deposits related to shoreline environments developed during

different sea-level stands. It is probable that such deposits – imaged through Sub-Bottom Profiler by Micallef et al. (2013) – originated from Wied il-Kbir draining into the present Valletta and the Three Cities rias.

#### 4.3 Fluvial landforms

The investigated continental shelf is crossed by ENE-WSW oriented channels, which indent the continental escarpment. The main ones are located in front of Marsalforn Bay (Gozo), offshore the



**Figure 3.** Overview of the coastal and marine landforms and topographic profile of selected marine terraces.

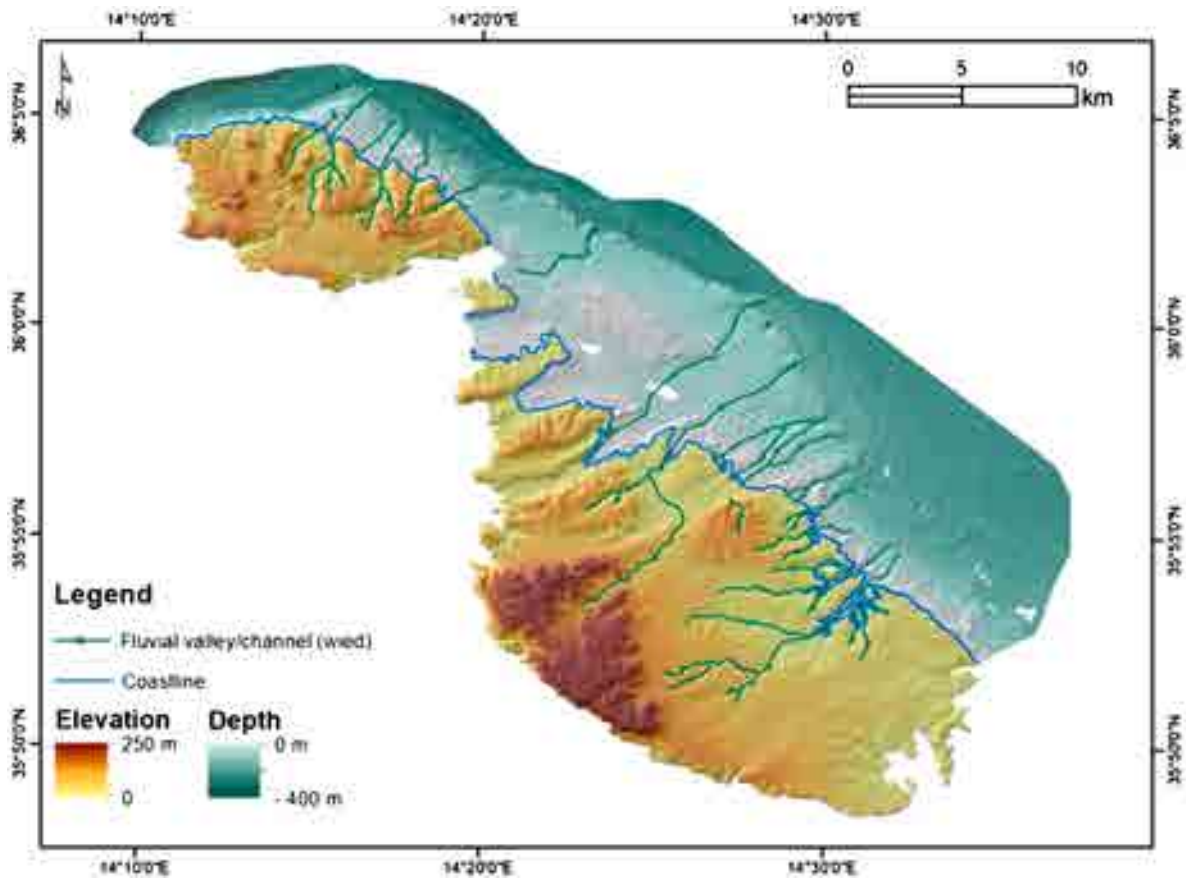
island of Comino and in the area between St. Paul's Bay and St. Julian's Bay (Malta). The channel lengths range from 100 m to almost 4 km and the depth increases with distance from the coast. These channels are characterized by a U-shaped cross section, a linear to sinuous pattern and are laterally delimited by sub-vertical walls (Fogliani et al., 2016; Micallef et al., 2013; Prampolini et al., 2017). The longest channel is located offshore Comino, 3.9 km long, 300 m width and 30 m deep. A number of channels are clearly connected with terrestrial valleys (Figure 4). Thus, they have been interpreted as relict fluvial valleys whose distribution is related to the drainage system of the Maltese Islands (Prampolini et al., 2017). Their direction is tectonically controlled by the NE-tilting affecting the archipelago. The evidence of erosional processes on the present seafloor is likely to be connected to fluvial activity initiating ca. 125 kyr ago when the sea level started falling, reaching its lowest stand during the LGM. Indeed, during the last glacial cycle, wetter climatic conditions allowed the watercourses to cut gorges and deposit sediments. According to Van Heijst and Postma (2001), fluvial incision during sea-level lowstands started developing from the shelf break and then spread upstream. Fluvial erosion seems to have been controlled by sea-level variations. The development of channels was favoured during relatively long periods of sea-level lowering and by wetter climatic conditions. In such situations, channels ran across the whole investigated seafloor becoming connected with their terrestrial counterpart (Figure 4; Peyron et al., 2009). During relatively short sea-level

lowstands, incisions, from 170 m to 1 km long, developed only in proximity to the shelf break.

Gullies caused by fluvial erosion up to 500 m-long are located offshore Ramla Bay (Gozo). They were carved into Globigerina Limestone surfaces and are now partially filled by fine marine sediments (Prampolini et al., 2018a; 2018b). Flat areas located offshore St. Paul's Bay, characterized by fine sediments and ripple marks, possibly acted as alluvial plains during sea-level lowstands connecting the current terrestrial fluvial valleys to the edge of the shelf (Micallef et al., 2013; Prampolini et al., 2017; 2018b).

#### 4.4 Gravity-induced landforms

Isolated gravity-induced block deposits were recognized and mapped. They can be referred to various types of landslides (lateral spread, block slide, rock fall) that occur in the eastern inner continental shelf (Micallef et al., 2013). In particular, the south-eastern portion of the submerged plateau Sicca il-Bajda is characterized by a dense network of fractures (probably related to tectonic discontinuities; Micallef et al., 2019) that isolate blocks of large dimensions. The latter have been interpreted as the result of lateral spreading processes affecting the plateau – made up of Upper Coralline Limestone overlying the Blue Clay Fm. – that caused block sliding. These geomorphological features are clearly reminiscent of similar features occurring along the coasts of northern Malta and Gozo (Devoto et al., 2012; Panzera et al., 2012; Prampolini et al., 2018a; Soldati et al., 2019).



**Figure 4.** Palaeofluvial valleys and their possible connection with their terrestrial counterparts.

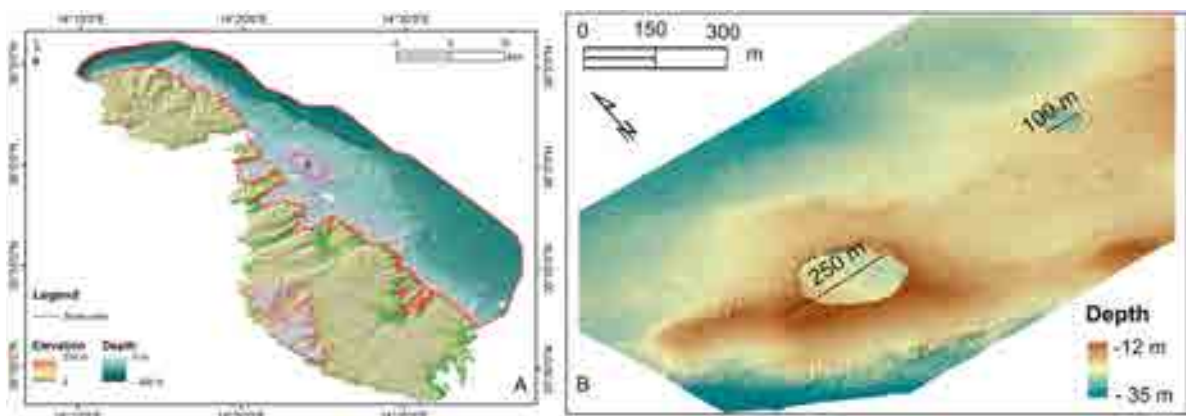
Further blocks can be found at the base of the continental slope, at a depth of  $-130$  m. They have been interpreted as the result of rock falls associated with coastal erosion.

Gravity-induced deposits occur also in near shore areas and represent the submerged portion of onshore landslides. The latter largely characterize the north-eastern coast of Gozo, as well as other Maltese coastal areas, where Upper Coralline Limestones overlie Blue Clay terrains favouring the development of lateral spreads and block slides (Devoto et al., 2020; Mantovani et al., 2016; Prampolini et al., 2018a). With reference to the

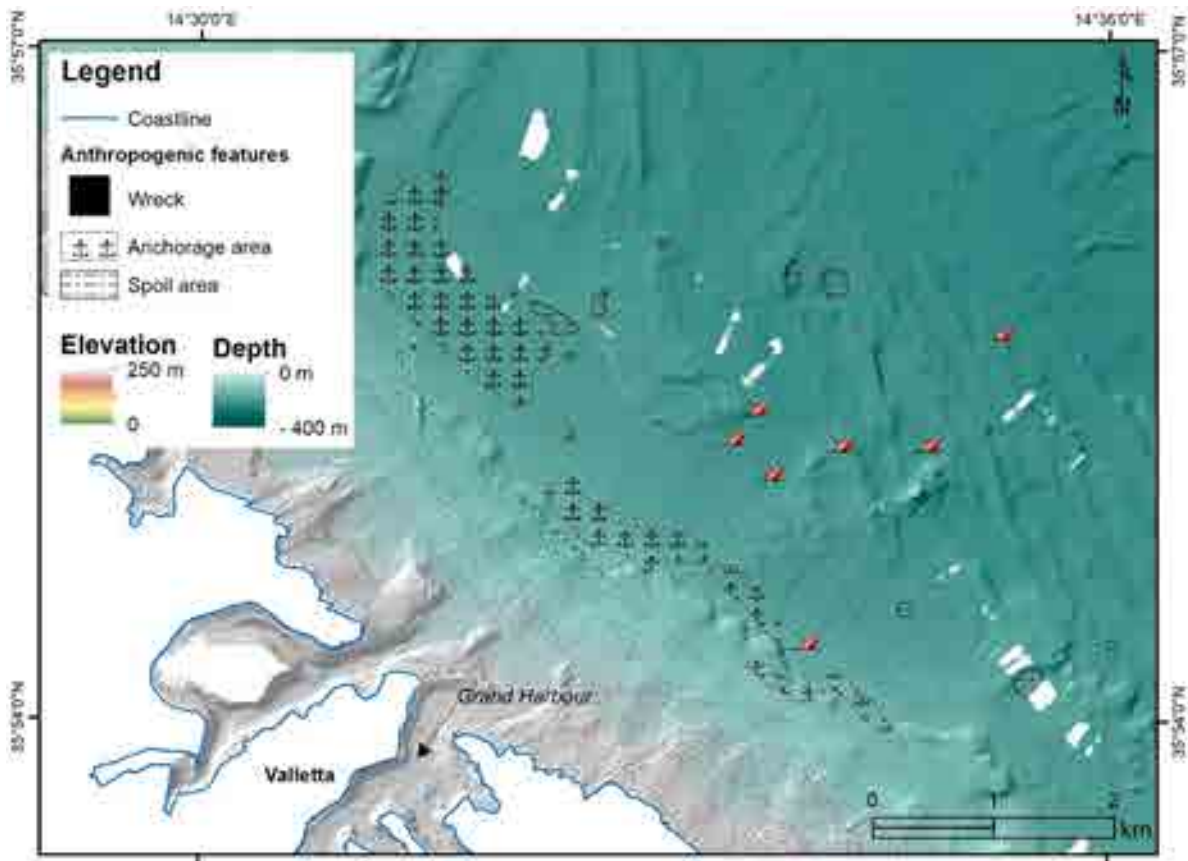
chronological framework provided for landslide evolution at the north-west coast of Malta (Soldati et al., 2018), it is likely that these landslides developed in a subaerial environment and were submerged during the post-glacial sea-level rise (Prampolini et al., 2018a).

#### 4.5 Karst landforms

Most of the structural plateaus occurring on the shelf are characterized by an altered surface that was shaped by karst processes following emergence. They are probably composed either of Upper or



**Figure 5.** 3D view of the two largest bedrock-collapse sinkholes located on the Sikka il-Bajda Reef.



**Figure 6.** Anthropogenic features mapped offshore the Grand Harbour of Valletta.

Lower Coralline Limestone that are characterized by a very high calcium carbonate content. These limestones are likely to have been affected by karst processes in subaerial conditions which favoured the development of karst pavements. The surface roughness of Sikka il-Bajda plateau provides evidence of such karst processes. The karst pavement is characterized by fissures, clints and grykes (Micallef et al., 2013) and is covered by a meadow of *Posidonia oceanica* on matte (<http://geoserver.pa.org.mt/publicgeoserver>). Sikka il-Bajda Reef is also characterized by the presence of four depressions with a shape ranging from circular to elliptical, and diameters ranging from 60 to 250 m. They have almost vertical walls up to 11 meters high, and a flat bottom, smooth or covered with rock blocks (Figure 5). These depressions have been interpreted as bedrock-collapse sinkholes (*sensu* Gutiérrez et al., 2014; Prampolini et al., 2017), by analogy with those described onshore Malta and Gozo (Galve et al., 2015; Soldati et al., 2013).

#### 4.6 Anthropogenic features

In some places, anthropogenic features characterize the investigated seafloor. Their highest concentration is offshore the Valletta Grand Harbour where several anthropogenic activities have left their mark on the seafloor: an anchorage area characterized by several

trawl and anchor marks as well as circular mounds of dumped inert construction spoil have been recognized and mapped (Figure 6; Micallef et al., 2013). This sector of the seafloor is also characterized by the presence of wrecks sunk during the Second World War (including HMS Olympus, HMS Russell, HMS Trusty Star, ORP Kujawiak), and now used as scuba-diving sites (Heritage Malta – Underwater Cultural Heritage).

On the seabed of Ramla Bay (Gozo), at a depth of about 10 m, the remains of historic defence walls – built by the Knights of the Order of St. John around the 1870s to protect the bay from enemy attacks from the sea – have been mapped.

## 5. Conclusions

The geomorphological research carried out has enabled the first comprehensive and systematic geomorphological mapping of the north-eastern Maltese seafloor. The study made it possible to provide insights on the Maltese submarine landscape and its evolution since the Last Glacial Maximum.

The geomorphological map shows evidence of erosional and depositional landforms typical of subaerial environments. This witnesses the clear imprint on the present submerged landscape left by geomorphological processes acting during the last glacial cycle when the sea level was significantly lower than today. The area



corresponding to the investigated submerged landscapes was emergent during the last glacial cycle, the terrestrial landscape reaching its maximum extension during the LGM when the sea level was about 130 m lower than today. The landscape was then drowned as a result of the post-glacial marine transgression which preserved the landforms generated in submarine conditions. The excellent preservation of relict terrestrial landforms on the seafloor can be ascribed to the carbonate lithology that characterizes the Maltese Islands and surrounding offshore areas, and to the scarce contribution of terrigenous sediments from inland. Thus, once submerged, the landscape was only partially modified by submarine processes.

The marine processes currently occurring in the study area are mainly attributable to SE-NW oriented bottom currents, which led to the formation of ripples and drift current deposits.

This study provides the groundwork for further research activity in the Maltese Islands, which may include the coupling of marine datasets with terrestrial ones. Although the generation of seamless DEMs and DTMs is often a challenge in coastal regions, mainly due to technical issues, a variety of promising techniques – capable of providing a homogeneous representation of the Earth's surface from onshore to the seafloor – are now available (Prampolini et al., 2020). A number of applications in geo-environmental research, most of which related to geohazard assessment, have been recently undertaken with remarkable perspectives in terms of a holistic and sustainable approach to coastal management (Soldati et al., 2021), which would be crucial for the Mediterranean.

## Software

The map and the layout were produced using ESRI ArcGIS and Adobe Illustrator.

Once the map was embedded into the A0 size map frame, the legend of the geomorphological features and the following settings were inserted: a geographic and geodynamic setting, geology and bathymetry of the Maltese Islands, a palaeo-geography sketch of the Sicily Channel during the LGM, and a 3D view of Maltese Islands and seafloor at present and during the LGM. In addition, a stratigraphic column and three geological sections, as well as authors' names and details were inserted.

The symbology followed the guidelines proposed by the Italian Geological Survey (Campobasso et al., 2019; Mastronuzzi et al., 2017) and with reference to recent submarine geomorphological maps of the Mediterranean (Buosi et al., 2017; Casalbore et al., 2016a; 2016b; Miccadei et al., 2012; Prampolini et al., 2017, 2018a; Rovere et al., 2015; Sulli et al., 2021). The above-mentioned guidelines envisage the

representation of landforms and associated deposits using symbols of different colours according to the geomorphological processes that led to their genesis.

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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## Data availability statement (DAS)

The base map of the marine areas is a 5-m resolution Digital Terrain Model (DTM) resulting from the merge of bathymetric data acquired during different oceanographic campaigns:

- MEDCOR2009 carried out on board the R/V Urania of the CNR using the Kongsberg Simrad multibeam EM3002D and processed using CARIS HIPS & SIPS;
- DECORS2011 carried out on board the R/V Urania of the CNR using the Kongsberg Simrad multibeam EM710 and processed using CARIS HIPS & SIPS;
- MAPSCAPE2012 carried out on board the ISIS catamaran of the AquaBioTech Group using the SEA Company interferometric system SWATHplus-L (see also Fogliani et al., 2016; and Prampolini et al., 2017, for technical specification on devices and surveys) and processed using CARIS HIPS & SIPS;
- ERDF156 carried out by Malta Environment & Planning Authority (MEPA) on board the ISIS catamaran of the AquaBioTech Group using the SEA Company interferometric system SWATHplus-L;

Bathymetry from MEDCOR2009, DECOR2011 and MAPSCAPE2012 is available for public consultation and downloadable at the resolution  $1/16 * 1/16$  arc minutes from the EMODnet Bathymetry Portal (<https://www.emodnet-bathymetry.eu/>).

The DTM of the Maltese Islands is 10 m-resolution and is provided by the Malta Planning Authority.

Data on marine geomorphological interpretation are available for public consultation and downloadable at the scale 1:25,000 from the EMODnet Geology Portal (<https://www.emodnet-geology.eu/>).

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# GEOMORPHOLOGICAL MAP OF THE NORTH-EASTERN CONTINENTAL SHELF OF THE MALTESE ARCHIPELAGO (MEDITERRANEAN SEA)

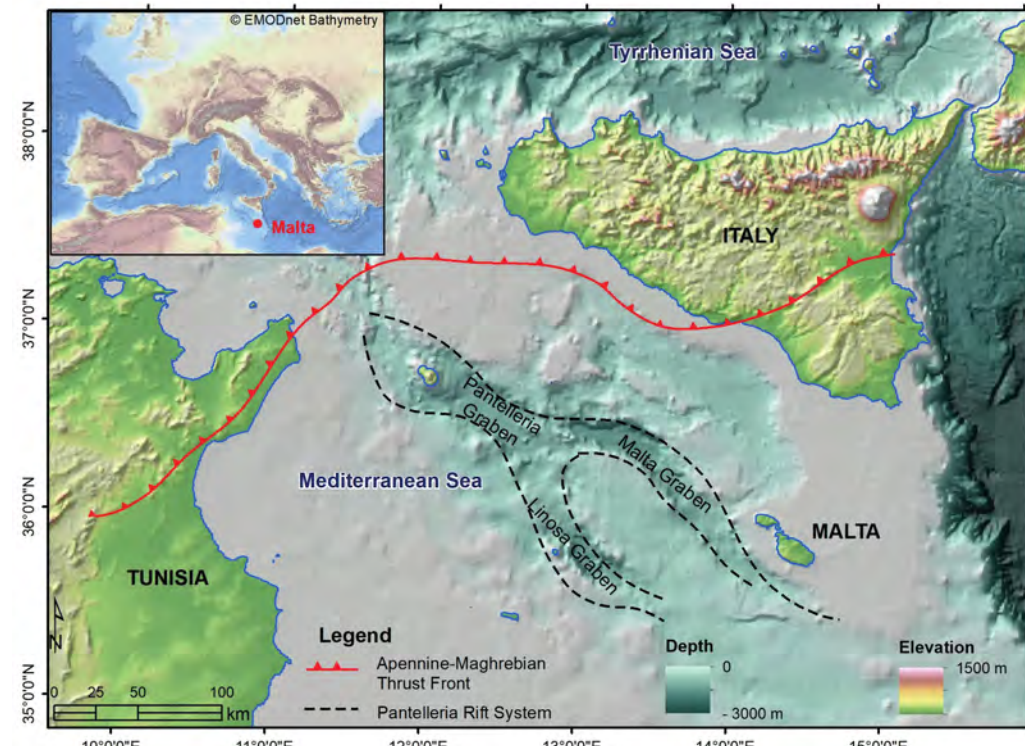
Mariacristina PRAMPOLINI (1), Paola CORATZA (2\*), Sofia ROSSI (2), Carlotta PARENTI (2), Charles GALEA (3), Albert CARUANA (3), Mauro SOLDATI (2)

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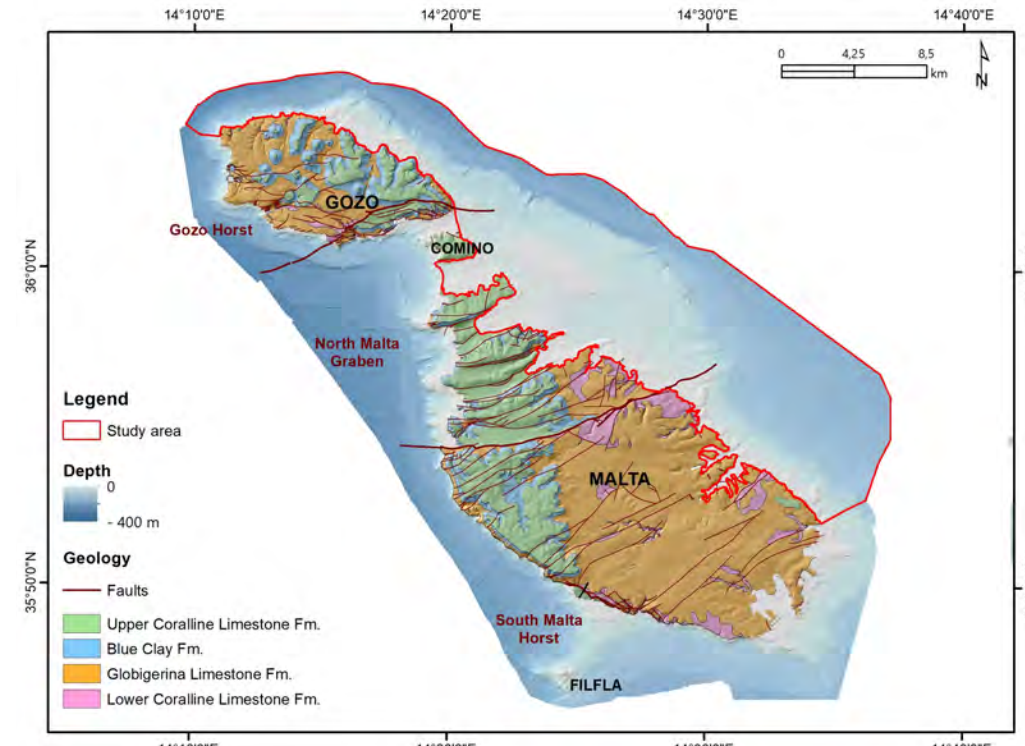
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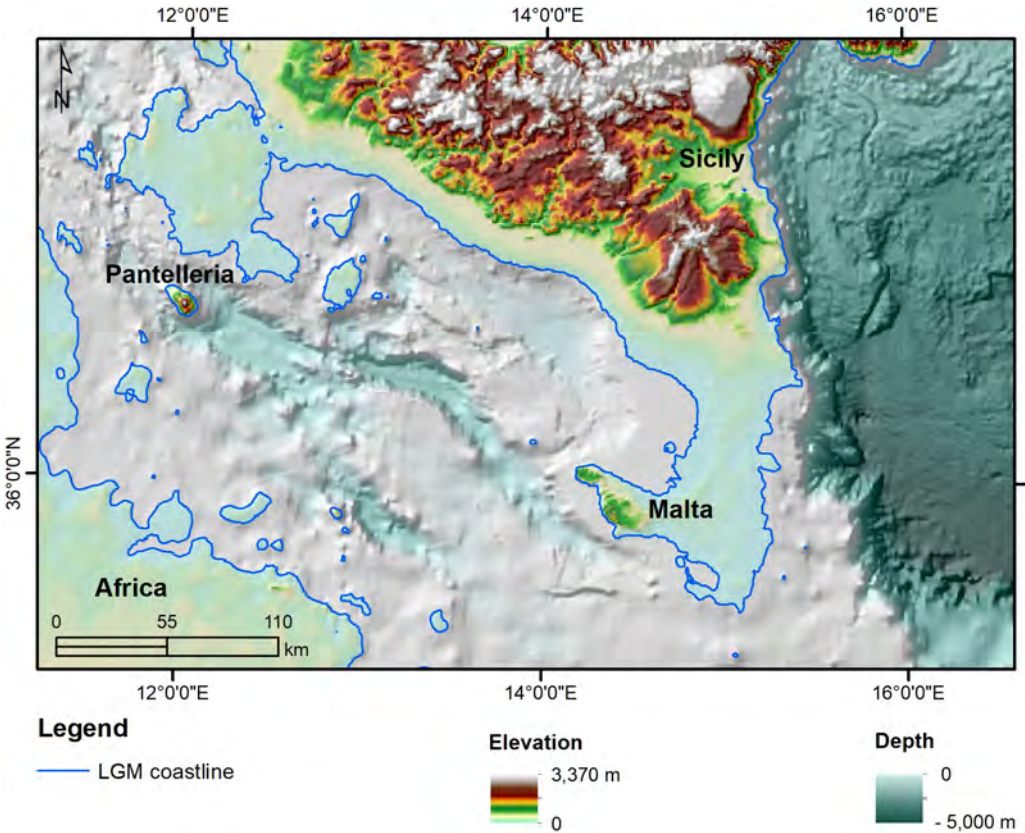
## GEOGRAPHIC AND GEODYNAMIC SETTING



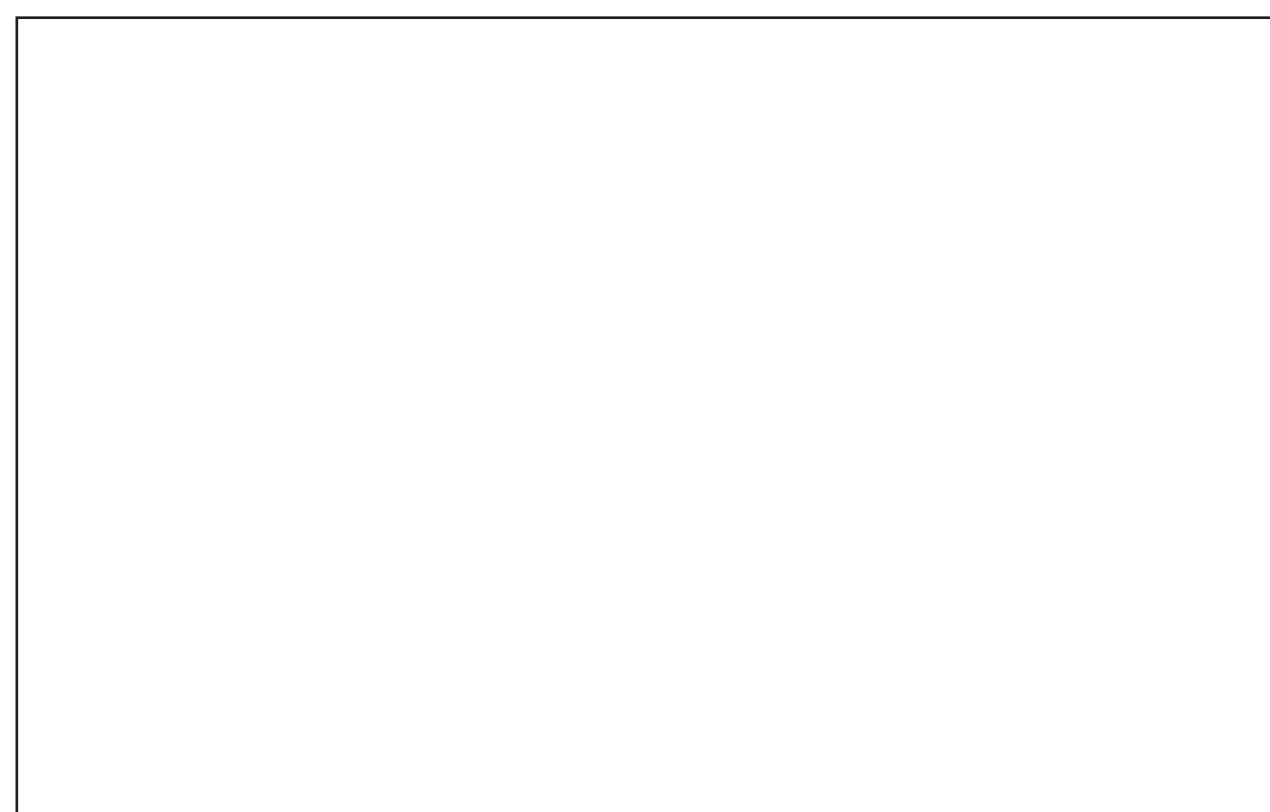
## GEOLOGY AND BATHYMETRY OF THE MALTESE ISLANDS



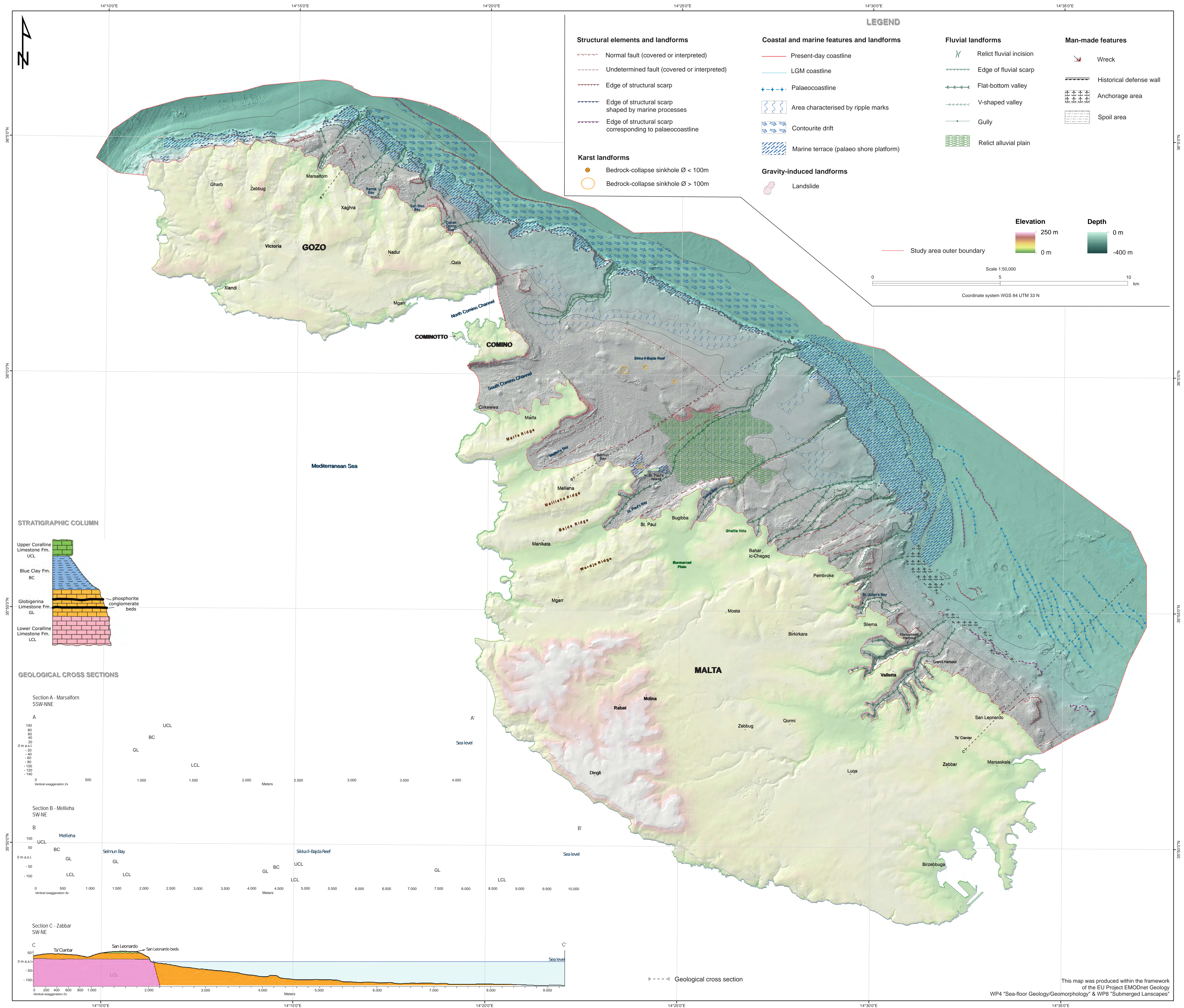
## PALAEOGEOGRAPHY OF THE SICILY CHANNEL DURING THE LGM



## PRESENT DAY 3D VIEW

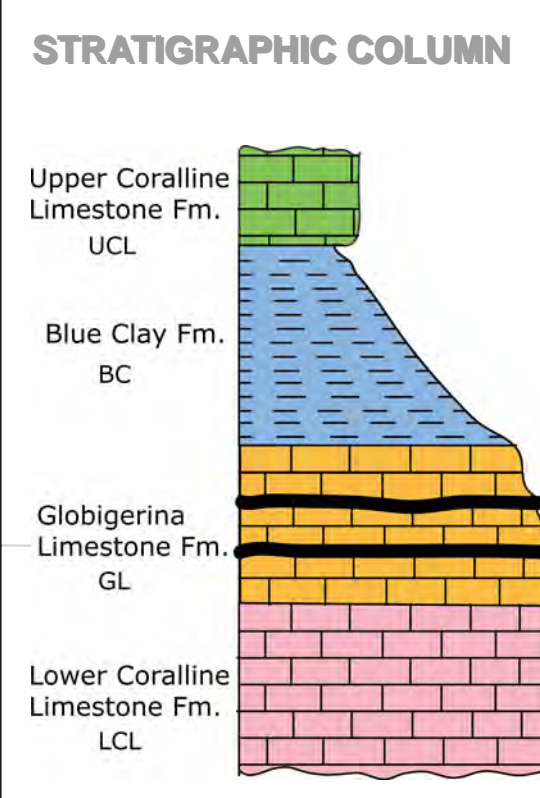


## LGM 3D VIEW



### LEGEND

<b>Structural elements and landforms</b> Normal fault (covered or interpreted) Undetermined fault (covered or interpreted) Edge of structural scarp Edge of structural scarp shaped by marine processes Edge of structural scarp corresponding to palaeocoastline  <b>Karst landforms</b> Bedrock-collapse sinkhole $\varnothing < 100\text{m}$ Bedrock-collapse sinkhole $\varnothing > 100\text{m}$	<b>Coastal and marine features and landforms</b> Present-day coastline LGM coastline Palaeocoastline Area characterised by ripple marks Contourite drift Marine terrace (palaeo shore platform)  <b>Gravity-induced landforms</b> Landslide	<b>Fluvial landforms</b> Relict fluvial incision Edge of fluvial scarp Flat-bottom valley V-shaped valley Gully Relict alluvial plain	<b>Man-made features</b> Wreck Historical defense wall Anchorage area Spoil area
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### GEOLOGICAL CROSS SECTIONS

