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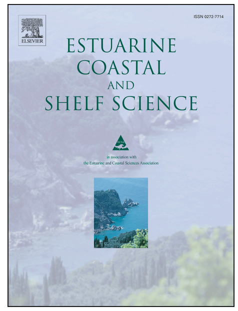

Habitat mapping of the Maltese continental shelf using acoustic textures and bathymetric analyses

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PII: S0272-7714(17)30600-5

DOI: 10.1016/j.ecss.2017.06.002

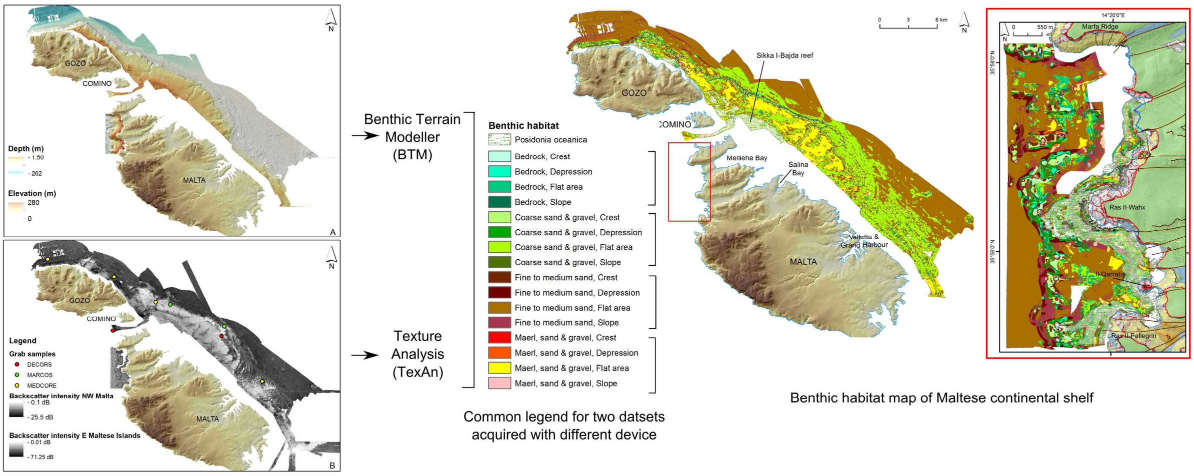
Reference: YECSS 5491

To appear in: *Estuarine, Coastal and Shelf Science*

Received Date: 10 May 2016

Revised Date: 19 April 2017

Accepted Date: 2 June 2017



GOZO
COMINO
MALTA
Depth (m)
- 1.50
- 262
Elevation (m)
280
0
A
Legend
Grab samples
DECORS
MARCOS
MEDCORE
Backscatter intensity NW Malta
- 0.1 dB
- 25.5 dB
Backscatter intensity E Maltese Islands
- 0.01 dB
- 71.25 dB
B
Benthic Terrain Modeller (BTM)
Texture Analysis (TexAn)
Benthic habitat
Posidonia oceanica
Bedrock, Crest
Bedrock, Depression
Bedrock, Flat area
Bedrock, Slope
Coarse sand & gravel, Crest
Coarse sand & gravel, Depression
Coarse sand & gravel, Flat area
Coarse sand & gravel, Slope
Fine to medium sand, Crest
Fine to medium sand, Depression
Fine to medium sand, Flat area
Fine to medium sand, Slope
Maerl, sand & gravel, Crest
Maerl, sand & gravel, Depression
Maerl, sand & gravel, Flat area
Maerl, sand & gravel, Slope
Common legend for two datsets acquired with different device
Sikka l-Bajda reef
Mellieha Bay
Salina Bay
Valletta & Grand Harbour
0
3
6 km
N
Marfa Ridge
Ras il-Wahx
Qarraba
Ras il-Pellegrin
Benthic habitat map of Maltese continental shelf

Habitat mapping of the Maltese continental shelf using acoustic textures and bathymetric analyses

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ABSTRACT

The uneven mapping of the Maltese continental shelf precludes a full assessment of its marine habitats, important for their monitoring and conservation in line with the EU Marine Strategy Framework Directive and local initiatives. From 2009 to 2012, high-resolution multibeam echosounder (MBES) surveys offshore the NW and E coasts of the Maltese archipelago were carried out, covering a total area of 1,408.3 km^2 with a maximum resolution of 1 m, at depths from 1.5 to 263 m. The types of benthic habitats occurring on the continental shelf often showed subtle acoustic variations. This article aims at 1) integrating analyses of the bathymetry and acoustic textures with ground-truthing (grab samples) in key areas; 2) validating this combined approach by rewriting an existing benthic habitat map of the eastern continental shelf of Malta; 3) exploiting this ground-truthed classification to calibrate an unsupervised classification of a dataset acquired with a

different sonar. The main results obtained from these analyses are i) a sediment map of the continental shelf of NW Malta and east of the Maltese archipelago – classifying in detail bedrock, rocky blocks, coarse sand and gravel, fine to medium sand and maërl, sand and gravel – that supports the geomorphological interpretation of the seabed features; ii) an automatic classification of the seafloor morphology, highlighting a very gentle sloping seabed crossed by the shelf break and by palaeo-river valleys; iii) the first full benthic habitat map of the continental shelf offshore E and NW coast of Malta obtained with a semi-automatic classification. In this work, we highlight and explain the main differences in seafloor sediment coverage, its morphology and the relative occurrences of benthic habitats between the NW and E sides of the Maltese archipelago.

KEYWORDS: Seafloor classification; Marine sediments; Acoustic textures; Benthic habitat; Malta

1. INTRODUCTION

Shallow waters host the most complex mosaic of benthic habitats, making them the most productive marine environments (Eyre and Maher, 2011; Gray, 1997). Increasingly, anthropogenic activities are concentrating along the coasts, in shallow waters in particular. They include fishing (comprising trawl fishing), aquaculture, harbour and shipping activities, mineral exploration and exploitation, and offshore construction (e.g. for marine renewable energy, like wind farms). These activities all have potentially important impacts on the marine environments and habitats, which need to be monitored and controlled. The knowledge of marine ecosystems spatial distribution and their quality is fundamental to protect them from anthropogenic actions (Jackson et al., 2001). Thus, habitat maps are a necessary tool for marine environmental assessment and management, protection of valuable habitats, hazards assessment and monitoring human activities.

There are many approaches to benthic habitat mapping, depending on the type of acoustic data and its spatial resolution, the types and varieties of habitats under investigation, the size of the datasets and the quality of any ancillary information available (from ground samples to video transects of sub-bottom profiles). For a rapid view of the current state of the field, the reader is directed toward the more recent articles of Brown and Blondel (2009), Brown et al. (2011), Ierodiaconou et al. (2011), Lucieer and Lamarche (2011), Micallef et al. (2012), Diesing et al. (2014), McGonigle and Collier (2014) and Montereale Gavazzi et al. (2016) and references therein. It is possible to apply a single method or to combine several (e.g. hybrid approaches, multi-method ensembles) as suggested by Diesing et al. (2014) or Montereale Gavazzi et al. (2016). This second approach has been repeatedly shown as the most effective way to improve any kind of classification since the final seabed classification is supported by more than one analysis (Erdey-Heydorn, 2008; Wright and Heyman, 2008; Marsh and Brown, 2009; Lamarche et al., 2011; Micallef et al., 2012).

These different procedures can use automatic or manual classification of the data. Automatic classification uses either signal-analysis or image-analysis methods: the latter can be applied to data acquired with different instruments, and both methods are repeatable, quantitative and objective – as suggested by Diesing et al. (2014) – allowing to process large amounts of data faster. Signal-based analyses are associated to individual measurements, at the level of the backscatter value, whereas image-based ones better described the larger-scale organisations of seafloor substrate and benthic habitats. Again, there is a plethora of approaches developed specifically for sonar measurements. These include Principal-Components Analyses of multiple attributes within proprietary software packages, e.g. QTC-Sideview (Preston et al., 2000; McGonigle et al., 2009; Preston, 2009); artificial neural network techniques (Marsh & Brown, 2009); Bayesian decision rules (Simons & Snellen, 2009); decision trees (Dartnell and Gardner, 2004; Rooper and Zimmermann, 2007; Rattray et al., 2009; Ierodiaconou et al., 2011; Che Hasan et al., 2012a); support vector machines (Che Hasan et al., 2012b); Random Forest (Che Hasan et al., 2012b; Lucieer et al., 2013); Maximum Likelihood Classifier (Buhl-Mortensen et al., 2009; Ierodiaconou et al.,2011; Che Hasan et al.,2012b); Texture Analysis (Blondel, 1996; Blondel et al., 1998; Gao et al., 1998; Huvenne et al., 2002; Cochrane and Lafferty, 2002; Gómez Sichi et al., 2005; Huvenne et al., 2007; Blondel and Gómez Sichi, 2009).

The Mediterranean Sea represents an ideal natural laboratory for benthic habitat mapping and monitoring due to: i) its complex geological setting and seafloor geomorphology; ii) high diversity of its important ecosystems; iii) high density of human activities impacting on seafloors and habitats. The Maltese seafloors in particular host habitats of high ecological value, going from white, red and black corals (Deidun et al. 2010) to seagrass meadows and maërl beds (Borg et al., 1998, 2005, 2009; Galdies and Borg, 2006; Sciberras et al., 2009). They are often located in touristic areas, close to harbour zones and fisheries, and part of these habitats are recognized as marine Natura 2000 sites.

The present study focuses on the Maltese archipelago and its marine habitats, presented in Section 2. The Materials and Methods are explained in Section 3, showing the different types of acoustic measurements and supporting data (grab samples in representative locations) that we collected, along with recent information on marine habitats from the Malta Environment and Planning Authority (MEPA; Borg et al., 1998, 2005, 2009; Scieberras et al., 2009). The first objective is to outline a quantitative, repeatable, automatic or semi-automatic procedure to map the distribution of benthic habitats around Malta. The large amounts of high-resolution acoustic data (bathymetry and backscatter), in two different locations (E and NW continental shelves of the Maltese archipelago) and with different echosounders, justify the need for image-based approaches, namely the automatic analysis of seafloor morphology (Section 3.2) and semi-automatic classification of backscatter with Textural Analysis (Section 3.3). The second objective of this study is to extend an existing and ground-truthed classification (Micallef et al., 2013) to an adjacent dataset where no seafloor samples are available. These results are presented for each region individually (Section 4). Thus, we present a single benthic habitat classification for two adjacent datasets acquired with different devices. The differences in habitat distributions between the E and NW sides of the Maltese archipelago are analysed in Section 5, compared to each other and to previous works in neighbouring areas, showing the synergy between approaches and contributing to the knowledge of the marine habitats around Malta at depths ranging from 1.5 (immediate near-shore) to 263 m (continental break).

2. STUDY AREA

The Maltese archipelago is located in the Sicily Channel on the Malta Plateau and comprises the islands of Malta, Gozo and Comino. An Oligocene-Miocene succession made up of mainly carbonatic formations (Pedley et al., 2002) characterises the geological setting of the archipelago (Fig. 1): (a) Lower Coralline Limestone Formation; (b) Globigerina Limestone Formation; (c) Blue Clay Formation; (d) Upper Coralline Limestone Formation. The whole succession slopes 4° towards NE because of the uplift and tilting due to the location of the archipelago on a shoulder of the Malta Graben (part of the Pantelleria Rift system; Pedley et al., 2002). The islands are also affected by two fault systems: the WSW-ENE-oriented system is the oldest one and its major lineament is the Great Fault; the NW-SE-oriented system is the most recent one, parallel to the Pantelleria Rift, and its major fault is the Maghlaq Fault (Dart et al., 1993; Putz-Perrier and Sanderson, 2010). This tectonic setting and the superimposition of lithologies with different mechanical behaviour and resistance to erosion are the main agents controlling the land- and seascape.

The geomorphology of the Island of Malta has been largely investigated by Alexander (1988), Magri (2006), Devoto et al. (2012), Mantovani et al. (2013), Biolchi et al. (2016). The Maltese landscape is tectonically and lithologically controlled and modelled by marine action processes, karst, fluvial and gravity-induced processes. The ENE-WSW fault system is responsible for the *horst-and-graben* structure both at small and large scale (Dart et al., 1993), especially in the area north of the Great Fault. The NW-SE fault system controls the trend of the northern and southern coasts of the islands. Generally, on the E side of the archipelago, low-lying coasts occur (i.e. sloping coasts and shore platforms), while plunging cliffs and boulder screes characterise the western and southern coasts of the islands. Screes are widespread, especially along the NW coast of Malta, and are due to the development of mass movements, mainly block slides. The latter involve the Upper Coralline Limestone plateaus and the underlying Blue Clay terrains: limestone blocks detached from the carbonate plateaus and slide downhill over the clayey slopes. Rock fall and superficial earth flow/slides are common processes too. Also karst processes are widespread, creating karst pavements, speleothems, caves, dolines and sinkholes (Pedley et al., 2002; Galve et al., 2015). Due to the 4°-tilting toward NE, the hydrography developed with a SW-NE orientation, with river valleys and temporary water streams (named *wied* in Maltese).

Preliminary results about the morphological features and evolution of the continental shelf of the Maltese archipelago were presented by Micallef et al. (2013) and Foglini et al. (2016). The differences in landscape between the E and NW areas of Malta observable on land are reflected on the seafloor. On the E side of the islands, there is a wide and almost flat continental shelf, bordered by an escarpment parallel to the present-day coast and crossed by the submerged prolongations of the river valleys. Karst features and marine terraces are also present. On the NW side of Malta, the continental shelf is very narrow and fragmented and the escarpment is constituted by subvertical cliffs and marine terraces; the main landforms of the shelf are given by the submarine extension of the coastal landslides resulting in large accumulations of rocky blocks.

The marine habitats of the Maltese seafloor are characterised by the presence of white corals deeper than 400 m, red and black corals at intermediate depths (Deidun et al. 2010), seagrass meadows in the infralittoral zone and maërl in the circalittoral zone (Borg et al., 1998, 2005, 2009; Galdies and Borg, 2006; Sciberras et al., 2009). The prevailing occurrence of red coral on the seafloor offshore the NW coasts of the Maltese Islands, as recorded by Deidun et al. (2010), might be attributed to the seabed morphology and composition (mainly rocky with pockets of coralligenous biocoenosis), the sea currents chiefly from the NW and the restriction of the continental shelf causing an abrupt increase in sea depth, forming submarine cliffs and vertical walls.

The dominant benthic habitats in shallow waters, and mainly offshore the E coasts of the archipelago, are sandy bottoms with seagrass meadows (*Posidonia oceanica* and *Cymodocea nodosa*); at 40 m and even deeper, bare sands occur with seagrass meadows; the circalittoral zone is characterised by a strip of *maërl* and then fine sediments at 80 m and deeper (Borg et al., 1998). In particular, Borg et al. (2009) described the types of bed on which *P. oceani*ca could be settled. From shallow to deep water, they vary from small patches of *P. oceanica* on rocky substratum, to reticulate beds settled on soft sediment interspersed with bare sand, continuous and/or reticulate beds on matte and finally both reticulate or patches of *P. oceanica*. The abundance of seagrass meadows on the Maltese seafloors can be attributed to water clarity with no eutrophication, due to the absence of permanent hydrography, and can also be influenced by the submarine geomorphology and the hydrodynamic conditions of the area (Drago, 1999).

Deeper than 44 m, *P. oceanica* and *Cymodocea nodosa* habitats are replaced by the occurrence of *maërl*, a type of benthic habitat characterised by a high diversity of associated macrobenthos (Borg et al., 1998; Sciberras et al., 2009). It is formed by accumulations of calcareous rhodophytes forming a rhodolith-like shape and, in the NW Mediterranean, it can occur down to 65 m deep (Pérès, 1985). On the seafloor offshore the E Maltese coasts, a small patch of relict *maërl* was first found in 1994 at a depth of 42 m offshore the Island of Comino, as confirmed by Borg et al. (1998). Sciberras et al. (2009) characterised the species occurrence in Maltese *maërl*. It has been found at depths of ca. 40 – 100 m, in particular the rocky shoal of Sikka Il-Bajda (off Mellieha Bay) is covered by beds extending north-eastward offshore Gozo.

3. MATERIALS AND METHODS

3.1 Data

The datasets analysed were collected offshore the E coasts of the Maltese archipelago and offshore the NW coast of the Island of Malta, north of the Great Fault (Fig. 1).

The E dataset (offshore from north Gozo to south-east Malta – 1,390 km^2) was acquired with a Kongsberg multibeam echosounder (MBES) EM710 (70-100 kHz) installed on board the R/V Urania of the CNR (Italy). In this area, grab samples of the seafloor were also collected (Fig. 2). Bathymetric and backscatter data offshore the NW coast of Malta (from Marfa Ridge to Ras Il-Pellegrin promontory – 18.53 km^2) were acquired with the wide swath sonar system SWATHplus-L (117 kHz) installed on board the Isis II catamaran of the AquaBioTech Group. High-resolution bathymetry (2-m resolution seafloor DEM; Fig. 1) and backscatter data (1-m resolution for the NW dataset and 2-m resolution for the E dataset) of the Maltese continental shelf were processed using CARIS HIPS and SIPS, in order to analyse the seafloor geomorphology and the backscatter image.

Data on the distribution of *Posidonia oceanica* on the Maltese seafloors are available from MEPA and have been published by Borg et al. (1998, 2005, 2009) and Sciberras et al. (2009). This biological information will be overlaid on the final maps resulting from the combination between the geomorphological and backscatter texture analyses.

3.2 Morphological classification

In the present work, a morphometric analysis of the Maltese seafloor was carried out in order to produce an automatic seafloor morphological classification into crests, depressions, slopes and flat areas. The morphometric analysis was performed using the Benthic Terrain Modeller (BTM) toolbox implemented for ArcGIS 10.x (Wright et al., 2005; Lundbland et al., 2006). This toolbox is made of several functions that allow to calculate environmental variables, such as Bathymetric Position Index (BPI) and standardised BPI that will be defined below. Among these tools, we used the Zone Classification Builder which is a codified flow chart that automatically classifies seafloor morphology combining the properties of slope, Bathymetric Position Index (BPI; the same as Topographic Position Index described by Wright and Heyman, 2008 and Jenness et al., 2011) and standardised BPI (calculated in order to overcome scale-dependency of BPI data, as suggested by Verfallie et al., 2007). In Zone Classification Builder, we were asked to manually set a slope threshold to distinguish between gentle and steep slopes: we selected the value of 5° in order to highlight also subtle variations of the slope. Then, the variables derived from the bathymetric DEM and the selected parameter were combined to identify distinct seafloor morphometric regions..

The resulting seafloor morphological classification is presented in Fig. 2, where we extracted four classes: crests, depressions, flat areas and slope.

3.3 Backscatter Texture Analysis

The decision to apply TexAn Texture Analysis to the Maltese datasets instead of any other methodology was motivated by the following factors:

i. it is an image-based segmentation method and a feature-based approach: it identifies acoustic patterns and specific features at the local or regional level. An image-based segmentation can be applied to different datasets giving comparable results, as in this work. Moreover, the analysis of acoustic patterns typical of specific features is the best way to describe the seafloor substrate, since the analysis of the backscatter signal would have been a partial characterisation of the seafloor due to the occurrence of features with the same signal or more signals for the same features according to the variation of grazing angle.

ii. it identifies textures not distinguishable by human eye, making the classification more objective (Blondel, 1996);

iii. it is based on Grey Level Co-occurrence Matrices (GLCMs) that have been proved to be the most adaptable tools for textural analyses of sonar imagery (Blondel, 1996; Gao et al., 1998; Micallef et al., 2012);

iv. it is not influenced by depth, data acquisition choices and variation in pulses lengths during the acquisition: along with the adequate processing performed with CARIS software, any variations at very large scales would be ignored by the localised texture analyses (Blondel et al., 2015). The individual acoustic responses from seabed patches are combined into MBES pixels, 1-m^2 in this case. They are modulated by the spatial scale at which the seabed changes, which can be smaller or larger than 1 m, and by the amount of acoustic penetration into the seabed (estimated at centimetres for the frequencies used here). Their variations are best expressed as textures, and the TexAn software (Blondel, 1996) has been used successfully to identify and quantify subtle acoustic patterns in sidescan sonar imagery (e.g. Huvenne et al., 2002) and in MBES imagery (e.g. Blondel and Gómez Sichi, 2009), in particular for similar terrains in the coastal regions of Malta (Micallef et al., 2012), and to relate them to specific habitats, validated with ground-truthing;

v. two benthic habitat maps are already available for the dataset located offshore the E coasts of the Maltese archipelago. The first one was performed by Micallef et al. (2012) for a portion of the seafloor located in coastal waters (6-57 m deep), between Marfa Ridge and Salina Bay (see Fig. 1B in Micallef et al., 2012), that is not comprised in the dataset analysed here. A more recent classification of the entire E dataset was produced by Micallef et al. (2013). We decided to apply the same approach that they used in the previous works: a combination of morphometric classification with textural analysis of the backscatter image to produce a ground-truthed benthic habitat map. This decision was motivated by the fact that we wanted to reproduce the same classification for the E dataset in order to extend it to the NW dataset that cannot rely on seabed samples and was acquired with an interferometric system, different from the MBE used for the E dataset.

Textures are quantified by the co-occurrence of identical grey levels at specific distances from each other, within computation windows of a size commensurate to the morphological processes of interest. The full details are given in Blondel (1996), Blondel and Gómez Sichi (2009) and Micallef et al., (2012) *inter alia*, and they will not be repeated here. MBES backscatter imagery expressed pixels as calibrated dB values: they are initially resampled to 8-bit grey levels, yielding resolutions of ca. 0.3 dB and 0.1 dB per grey level, for the E and NW datasets respectively. Quantified over a specific number of grey levels (noted *NG*, decreasing from 256 down to 8 by factors of 2), this high radiometric resolution should allow distinguishing the more subtle variations in textural patterns. These are quantified using the indices of entropy and homogeneity, calculated over windows of different sizes (noted *WDSZ*, varying from 60 down to 10 pixels square by steps of 5 pixels) and for inter-pixel displacements (noted *SZ*) from slightly less than the window size down to 5 pixels, again by steps of 5 pixels.

In order to classify the backscatter image for the different type of substrate, it is necessary to select Training Zones, areas representative of the main acoustic facies within each dataset. They are used to train the model in the identification and separation of the acoustic patterns representative of each type of seafloor substrate. Training Zones need to be small enough to incorporate only one type of facies, if possible, but they also need to be large enough that they yield enough textural signatures (entropy/homogeneity pairs) to be statistically significant. For the E dataset, Training Zones of 80 × 80 pixels (i.e. 160 × 160 m on the ground) were used to define 10 Training Zones, further identified with grab samples (Fig. 3A; Table A1). The selection of Training Zones centred on the location of grab samples allow an automatic ground-truthing of the classification for the E dataset. For the NW dataset, they were chosen as 82 × 82 pixels (i.e. 82 × 82 m on the ground), and 12 different Training Zones were selected (Fig. 3B; Table A2).

After the selection of the Training Zones, GLCMs were calculated for these selected areas, averaged over all orientations possible, using different values of the number of grey levels NG, the extent of the area over which their textures are distinct enough (WDSZ) and the intrinsic scale at which these changes occur (SZ). At this stage, it is necessary to identify the optimal combination of NG, WDSZ and SZ that better separate the Training Zones within the diagram. The indices reported on the horizontal and vertical axes are entropy and homogeneity: the best textural indices to be applied for seafloor backscatter image classification, as evaluated by Blondel (1996) and later confirmed by Gao et al. (1998) or Cochrane and Lafferty (2002). Entropy is higher for rougher textures, lower for smoother or more organized textures. Conversely, homogeneity quantifies the amount of local similarities (it is also called inverse-difference moment by some authors; see Blondel, 1996). The inverse scale used in TexAn means it is lower for more organised textures, and higher as textures include more heterogeneous objects, e.g. blocks within a smooth background.

For the E dataset, the optimal separation between Training Zones was found for NG = 64 grey levels, WDZ = 50 pixels and SZ = 5 pixels. This means that, based on their textures, the different regions were best distinguished if looking at differences of more than 1 dB, over scales of 10 m but within ranges less than100 m. The progression in entropy and homogeneity is associated with increasing grain sizes. The parts covered by fine to medium sand and the more homogeneous areas have lower entropies and homogeneities (Fig. 4). Both textural signatures increase for coarse sand (slightly rougher but less homogenised), coarse sand, gravel and blocks of calcarenite (rougher textures at this scale, with local organisation but no organisation visible at scales close to 60 m).

For the NW dataset, TexAn found an optimal separation between Training Zones (Fig. 4) for NG = 64 grey levels, WDSZ = 60 pixels and SZ = 5 pixels. This means that, based on their textures, the different regions are best distinguished if looking at differences of more than 0.4 dB (the full radiometric range of 25.5 dB, Fig. 3, resampled onto 64 grey levels), over scales of 5 m but within ranges of less than 60 m. These values are comparable with those of the E dataset.

The textural parameters identified as optimal for the E dataset are then used to process the entire E backscatter mosaic, producing one image of entropy and one image of homogeneity, co-located and at the same resolution as the backscatter image (Fig. A1 for E dataset and Fig. A2 for NW dataset). These images are clustered using K-means, as presented in Blondel and Gómez Sichi (2009), in order to get an objective combination of entropy and homogeneity within the dataset. This simple partitioning scheme (Duda and Hart, 1973) results in mutually exclusive clusters of entropy/homogeneity signatures, recursively adapted until convergence. The initial number of classes is generally chosen as slightly higher than the number of acoustic *facies* expected, allowing provision for “mixed” classes, “unexpected classes” etc. (Blondel and Gómez Sichi, 2009). Through K-means, we combined the entropy and homogeneity maps to produce a map of 20 classes for the E dataset of Malta. Then, user-led contextual editing allows re-assigning clusters to physically meaningful processes such as habitats and morphologies, guided by any ground truth or other available measurements. The final sediment classification highlights the occurrence of 4 types of seabed sediments: bedrock; coarse sand and gravel; maërl, sand and gravel; fine to medium sand (see Fig. 5). The same procedure was conducted on the NW dataset, allowing to produce a map of seafloor sediments including the same classes of the E dataset and adding the class rocky blocks (Fig. 6). Thus the two datasets have a common legend for the seafloor sediments distribution.

4. RESULTS

4.1 E Malta dataset

The seafloor offshore the E coasts of the Maltese archipelago is flat or almost flat from the coastal waters (1.5 – 2-m deep) to the basin area. The main seafloor feature is the shelf break dividing the continental shelf from the basin area and well highlighted in the BTM morphological classification, where it is represented as a crest (Fig. 2). The main feature of the basin area is an elongated mound drift due to contouritic currents (Micallef et al., 2013), located just downslope the escarpment and extending from NE Gozo to Comino. It has a very gentle slope, thus only the external boundary of this deposit is classified as crest and slope, while the rest of this feature is classified as flat areas. The shelf break and the breaks of slope of the marine terraces are classified as crests, while the cliffs of the escarpments are classified as slopes. The occurrence of the channels crossing the continental shelf in direction SW-NE and interpreted as palaeo-river valleys by Micallef et al. (2013) and Foglini et al. (2016) area highlighted by the BTM classification, especially in their final part, the mouth cutting the continental escarpment. According to their inclinations, the lateral walls of the channels are classified as crests or slopes. In shallow waters, offshore Mellieha Bay, in the Comino Channel and in front of Comino, there are slightly elevated plateau-like areas showing an irregular, rough surface. The largest of these areas is Sikka l-Bajda, a bedrock reef identified as a potential offshore wind farm location (as reported in the Global Offshore Wind Farm Database; Micallef et al., 2013). In the southern part, from Sliema to south of Valletta, features parallel to each other, and interpreted by Micallef et al. (2013) and Foglini et al. (2016) as palaeo-shoreline deposits formed during the post-glacial sea level rise are classified as crests.

Through K-means, we obtained the seafloor sediment map shown in Fig. 5, where the geological map of the Maltese archipelago is reported, so that we can relate the Texan sediment map of the seafloor to the geology on land. The seafloor located downslope the escarpment is principally characterised by an almost flat and smooth seafloor with low backscatter intensity, except for the southern area where some parts of high intensity are scattered across the seafloor. The habitat map classified this deeper area as flat seafloor, mainly covered by fine to medium sand and with some scattered bedrock outcrops in its southern sector, highlighted both in the morphological and sediment maps.

On the continental shelf, both the morphology and the sediment coverage vary considerably: generally, the seafloor is almost flat and characterised by some bedrock outcrops in positive relief and by channels crossing the shelf with an orientation NW-SE. The seabed is mainly constituted by coarse sand and gravel, often the substrate is characterised by wide maërl beds. The presence of finer sediment is primarily located within the channels, whose bottom is characterised by ripples. Fine to medium sand is alternated with coarse sand and gravel in a shallow area offshore Comino Island, in correspondence of a meandered channel, where the seafloor is almost flat, smooth and slightly lowered with respect to the surrounding bedrock outcrops. It is interpreted as a palaeo-alluvial plain filled by mobile sediment and characterised by lobes and ripples.

The seafloor located in front of Valletta and the Grand Harbour shows a very singular acoustic pattern highlighted through the entropy and homogeneity maps: in a flat area, that is supposed to be covered by fine sediment since it is situated at the mouth of an important hydrographic network, a number of high intensity “dots” are scattered over a low backscatter matrix. It was classified as a great variety of sediments covering the seafloor: medium to fine sand alternated with small bedrock outcrops and coarse sand and gravel with the presence of blocks of calcarenite (Fig. 5B). This is due to the human activities that highly disturbed the seafloor integrity, resulting in an area exploited for dumping, excavating and trawling activities (Micallef et al., 2013; Foglini et al., 2016).

We combined the BTM morphological classification with the Texan sediment map through the tool Combine of ArcGIS (Spatial Analyst toolset): we produced the final map showing 16 types of seafloor substrate, on which we overlaid the biological data on *Posidonia oceanica* by MEPA (Fig. 7). The richest area in *Posidonia oceanica* and *maërl* is the continental shelf. There, the *P. oceanica* occurs up to a depth of about 50 m and is settled on bedrock or coarse sand and gravel substrate. The largest *P. oceanica* bed is located on the Sikka Il-Bajda reef, offshore Mellieha Bay and the Island of Comino. The *maërl* distribution confirmed by the only one sample reporting the occurrence of *maërl* bed at a depth of 102 m, offshore Salina Bay (sample DECORS47 from one of our surveys) agrees with the records by Borg et al. (1998) and Sciberras et al. (2009).

4.2 NW Malta dataset

The continental shelf offshore the NW coast of Malta is flat or gentle sloping and bounded offshore by the shelf break, classified as crest in the BTM classification (Fig. 2). From coastal waters to ca. 50 m deep, the shelf is characterised by an irregular surface with crests, slopes and depressions of limited extension alternated with almost flat and smooth areas. These features are located especially in correspondence of the headlands of Bajda Ridge, Il-Qarraba and Ras Il-Pellegrin and also on the seafloor close to the coast just north of Bajda Ridge and were interpreted as the submerged portion of the landslides affecting the NW coast of Malta (Foglini et al., 2016). The continental slope is characterised by different levels of marine terraces delimited by breaks of slope are classified as crests; while the cliffs constituting the escarpments are recoreded as slopes with depressed areas at their base. The area located mainly downslope the continental escarpment is almost flat and characterised by the presence of scattered features in positive relief of different size and shape. The most relevant feature is like a plateau 1000 x 210 m offshore Ghadira Bay, at depths of 70-130 m and ENE-WSW-oriented. Its shape is highlighted by the classification of its boundaries as crests, its cliffs as slopes and its top as flat area. The other features are scattered, with almost rounded shapes and ~50 m in diameter.

TexAn classification brought to the production of 5 classes seafloor sediment map shown in Fig. 6. The terrestrial geomorphology shown in Fig. 6 comes from an updated and simplified version of the geomorphological map by Devoto et al. (2012) and is inserted here to relate the seafloor sediment map to the terrestrial geology and geomorphology.

The area can be considered as divided into two main parts: a very shallow area (maximum depth 50 m) and the deeper area (maximum depth 154 m). The latter is mainly characterised by a flat and smooth seafloor where the backscatter is lower than in the shallower area and the TexAn analysis identified a very homogeneous texture for the entire area. This portion of the seafloor is covered by fine to medium sand with scattered small bedrock outcrops. The shallower area is highly diversified both in geomorphology and in sediment coverage.

In correspondence of the promontories there are large accumulations of rocky blocks alternated with the outcrops of bedrock and filled by a matrix of coarse sand and gravel. Since the NW coast of Malta is largely affected by block slides (called *rdum* in Maltese; Devoto et al., 2012, 2013) creating wide deposits of large limestone blocks sliding on the clayey terrains towards the sea, the submarine accumulations of rocky blocks constitute the prolongation of the terrestrial mass movements (Foglini et al., 2016) and TexAn succeeded in isolating the acoustic pattern typical of these accumulations from the surrounding bedrock outcrops (see Fig. 4B).

In correspondence of inlets in shallow waters (such as Ghadira Bay and Gnejna Bay), there are some *maërl* beds and alternation of sand and gravel, sediments coming from the sandy pocket beaches present on land. For example, the submarine area of Gnejna Bay (in the southern part of the dataset) is a flat and smooth seafloor showing a high variation in sediment type, from rocky blocks to coarse sand and gravel with or without *maërl*.

The last step of the analysis is the combination of the maps resulting from BTM and Texan classification through the Combine tool of ArcGIS: we obtained a 20-class substrate map, over which we overlaid the information on *Posidonia oceanica* occurrence, extracted from the MEPA map server (Fig. 8). The area covered by *Posidonia oceanica* is the most extended habitat of this area. The *Posidonia oceanica* is mainly settled on hard substrate (bedrock, rocky blocks) or on matte (Borg et al., 2009) and occurring on the continental shelf up to the continental escarpment.

5. DISCUSSION

This study presents a multi-method approach to map the marine habitats of the continental shelf off the NW coast of Malta and the E coasts of the Maltese Islands, using predominantly MBES bathymetry and backscatter with ground-truthing in selected locations in the E part only.

Generally, we can say that TexAn succeeded in isolating the most representative patterns of sedimentary coverage (Collier and Brown, 2005), as proved in past applications (e.g. Blondel and Gómez Sichi, 2009). This is confirmed for the E dataset where the grab samples available were used to define the Training Zones and validate the classification. A benthic habitat map of the E continental shelf of Malta was already provided by Micallef et al. (2012, 2013). Micallef et al. (2012) focused on a small area in shallow water along the E coast of the Island of Malta, adjacent but not overlapping with the zone analysed in the present work. Micallef et al. (2013) extended the same methodology used in the 2012 paper to the whole E dataset. We reproduced the classification applying their same methodology, but identifying different training zones. On the whole, the results that we obtained are comparable to those produced by Micallef et al. (2012, 2013), with some dissimilarities that could be ascribable to the different processing techniques applied and to the different selection of the Training Zones, the latter playing a key role in our case.

The area offshore Valletta and the Grand Harbour is affected by anthropogenic activities that had and still have a large impact on the seafloor. The location and the size of the Training Zones that we selected did not allow the isolation of the pattern typical of spoil ground, apparently at larger spatial scales than the one achievable by the Training Zones. For this reason, the seabed was classified on the basis of the sediment distribution. The inability of isolating this pattern could be considered both as a negative point – since we do not have a “spoil” class in the final map – and as an advantage – since combining our information and the one from Micallef et al. (2013), we know that this portion of seafloor is made of coarse sand and gravel and fine-to-medium sand with blocks of calcarenite, and that this mixture of sediments is due to spoil.

Also, the inability in isolating the *Posidonia oceanica* pattern in the present work is mainly caused by the absence of a Training Zone located in the *P. oceanica* meadow. Furthermore, even though the ground samples MEDCOR 51 and 42 (Table A1) recorded the occurrence of *P. oceanica* leaves and rhizomes, Texan was not able to identify its pattern. Micallef et al. (2012) also highlighted this difficulty. In the case of vegetation overlaying a hard substrate, it might be explained by the fact that the acoustic response is predominantly that of the seabed, and only modulated by the vegetation depending on its density, its areal cover within each pixel or groups of pixels, and its intrinsic acoustic reflectivity at the frequencies used (which can vary with photosynthesis or gas content) (e.g. Blondel and Pouliquen, 2004; Kruss et al., 2012). This means that TexAn focused on the key attributes of the substrate but does not appear as good at detecting subtle acoustic modifications if they do not occur over large enough areas.

The rationale for the classification of the E dataset was to extend this classification, validated with comparison with ground-truthing dataset, to the NW Malta dataset which was totally lacking ground-truthing. This approach is possible mainly because the TexAn analysis is an image-based segmentation, thus allowing to overcome the fact that the datasets were acquired with different sonar instruments.

The differences between the classifications of the E and the NW areas of Malta are shown also in Tables 1 and 2, describing backscatter and bathymetry distributions for each sediment class. The bedrock class in the E dataset is located mainly in correspondence of the continental escarpment, while, on the NW side, bedrock outcrops are widespread at all depths. The class made of coarse sand and gravel is characterised by medium to low values of backscatter and, in the E area, it is quite uniformly distributed down to a depth of 160 m; while on the NW area, it occurs at all depths, with a peak for shallow waters (< 38 m). The sediment class of fine to medium sand has the narrower distribution of backscatter intensity for the E dataset, where it is characterised by low values of backscatter; while in the NW dataset, it is characterised by higher values of backscatter. In both the areas, it is predominant in deeper water. The *maërl* beds are located only on the continental shelf on both the sides of the islands. In the E dataset, they are widespread and present high backscatter intensity, while in the NW area, they have a limited distribution and show medium backscatter intensity. The rocky blocks are present only in the NW dataset, down to a depth of about 40 m and show mainly medium values of backscatter.

The E and the NW areas show some differences in sediment distribution that are due to the distinct tectonic and geological settings resulting in a tilt of the archipelago of 4° towards NE that originated a wider continental shelf offshore the E coasts of the islands (continuing the low lying coasts of the

E side of Malta) and a narrower continental shelf offshore the NW coast of Malta. The first one is mainly covered by coarse sand and gravel with extensive *maërl* beds; the bedrock outcrops predominantly in correspondence of the continental escarpment and in some scattered reliefs across the dataset, while the deeper area is made of fine and medium sand shaped by bottom currents and contourites. The presence of loose material on the shelf is due both to the temporary streams on land which have their submerged prolongations that acted as channels of sediment transport and to marine sediments deposited during the post-glacial transgression. The NW continental shelf is characterised by coarser and harder sediments: the most significant features are made up by the submarine prolongations of the coastal landslides made up of rocky blocks accumulations, where also bedrock and coarse sand and gravel alternate. The deeper area is flat, smooth and mainly covered by fine and medium sand with some scattered harder outcrops. The most important habitat of the NW area are the *P. oceanica* meadows, while in the E area both *P. oceanica* meadows and *maërl* beds occur. This could be due to the difference in sediments and, especially, to the currents: the NW shores of Malta are characterised by high hydrodynamics (Drago, 1999; http://ioi.research.um.edu.mt/capemalta/stations@malta/INDEX/), which does not favour the formation of *maërl* biocoenosis.

Finally, the advantages of combining data and methods are also discussed by Ierodiaconou et al. (2007), Marsh and Brown (2009) and Che Hasan et al. (2014), who integrated bathymetry and backscatter using different methods. For example, Che Hasan et al. (2014) integrated also analysis of backscatter angular response with that of backscatter image, considering that the contribution of bathymetry represents the most important predictor of marine benthic habitats. They all proved that data integration is more efficient in predicting the benthic habitats than classifications based solely on backscatter or on bathymetry.

In the end, the methodology that we propose in this paper could overcome the difficulty of integrating datasets acquired within different cruises, with different instruments and different samples coverage.

6. CONCLUSIONS

The novelty of the present work is that, through a combined approach, we were able to draw a full benthic habitat map of the continental shelf offshore E and NW coast of Malta drawn from a validated dataset (the E one) and then extended to an adjacent dataset – the NW one, acquired with a different device – where no seabed samples were collected.

The combined approach applied here is based on the quantitative automatic classification of seafloor morphology with semi-supervised analyses of seafloor backscatter imagery, guided at key points by the biological information already available, either from ground samples or from the MEPA database:

i. The morphological classification was obtained using the ArcGIS-based tool BTM, different from the technique used by Micallef et al. (2012, 2013), but allowing to extract the same types of quantitative attributes. This kind of analysis can be conducted also through open source software (e.g. GRASS), through additional toolboxes or extensions (e.g. SEXTANTE for QGIS) or through self-built scripting (Lecours et al., 2016 online and references therein).The seafloor features were distinguished in terms of crests, depressions, slopes and flat areas.
ii. The backscatter mosaics were classified through the TexAn Texture Analysis from which we obtained the sediment distribution map of the seafloor offshore NW Malta and offshore E the Maltese archipelago, distinguishing bedrock, rocky blocks, coarse sand and gravel, fine to medium sand and the occurrence of maërl beds.
iii. The morphological and the sediment classifications have been combined to obtain a seafloor substrate map. Since, the seagrass pattern was not isolated by TexAn (as it was not clearly visible on the acoustic data), the resulting map has been integrated with existing biological data (from literature and environmental servers) to produce the benthic habitat map of the continental shelf offshore E and NW coast of Malta.

We can confirm the reliability of TexAn in classifying the backscatter image, since the sediment distribution map of the seafloor is comparable to those previously produced by Micallef et al. (2012,

2013) despite the differences in backscatter processing and the identification of the Training Zones. This kind of automated methods for habitat mapping, reliable also with limited ground-truthing, revealed to be a good and less time-consuming solution to produce seascape maps both at local or regional scale. They offer a valid support to marine resources management, marine spatial planning, habitats monitoring and conservation, usable by Governments and decision makers.

ACKNOWLEDGEMENTS

This research 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, 2012-2015 (led by Prof. M. Soldati, Università di Modena e Reggio Emilia). It is also supported by European projects HERMIONE (grant agreement No. 226354), COCONET (grant agreement No. 287844) and SCARP (grant agreement No. PCIG13-GA-2013-618149) within the European Community's 7th Framework Programme (FP7 2007–2013); project PANACEA, (Italy–Malta 2007–2013 Operational Programme I) and project RITMARE (The Italian Research for the Sea) coordinated by the Italian National Research Council and funded by the Italian Ministry of Education, University and Research within the National Research Program (2011–2013). We kindly acknowledge the RPM Nautical Foundation, the captain and crew of R/V Urania of the CNR and of R/V Isis of the 'AquaBioTech Group', and Highland Geo Solutions for their assistance with data collection. Part of this research was carried out at the University of Bath (UK) during an exchange in 2014. A subset of the earlier results was presented at conferences EUROGEO 2014 in Malta, GEOHAB 2015 in Salvador (Brazil) and AIGeo 2015 in Cagliari (Italy).

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Physical Oceanography Online – http://ioi.research.um.edu.mt/capemalta/stations@malta/INDEX/

FIGURE CAPTIONS

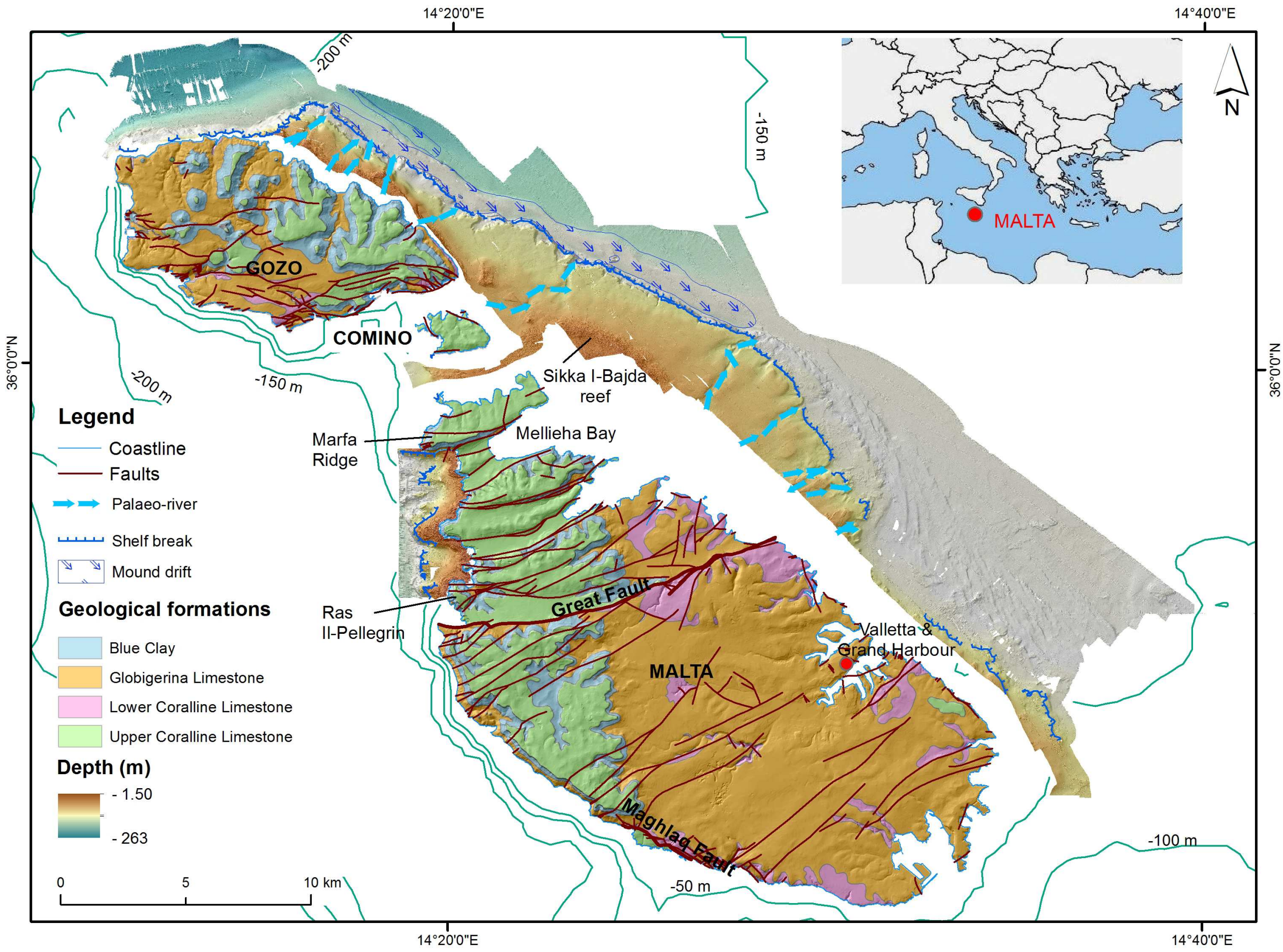


Figure 1. Geology and acquired bathymetry of the Maltese archipelago. Geographical and geological setting of the Maltese archipelago (see text for references about geology) and new high-resolution (2 m) bathymetry of the study area, acquired with SWATHplus-L (NW coast of Malta) and Kongsberg EM710 (E coasts of the Maltese Islands). The main faults are highlighted in brown, showing the WSW-ENE system and the NW-SE orientations parallel to the Pantelleria Rift, further offshore west of Malta.

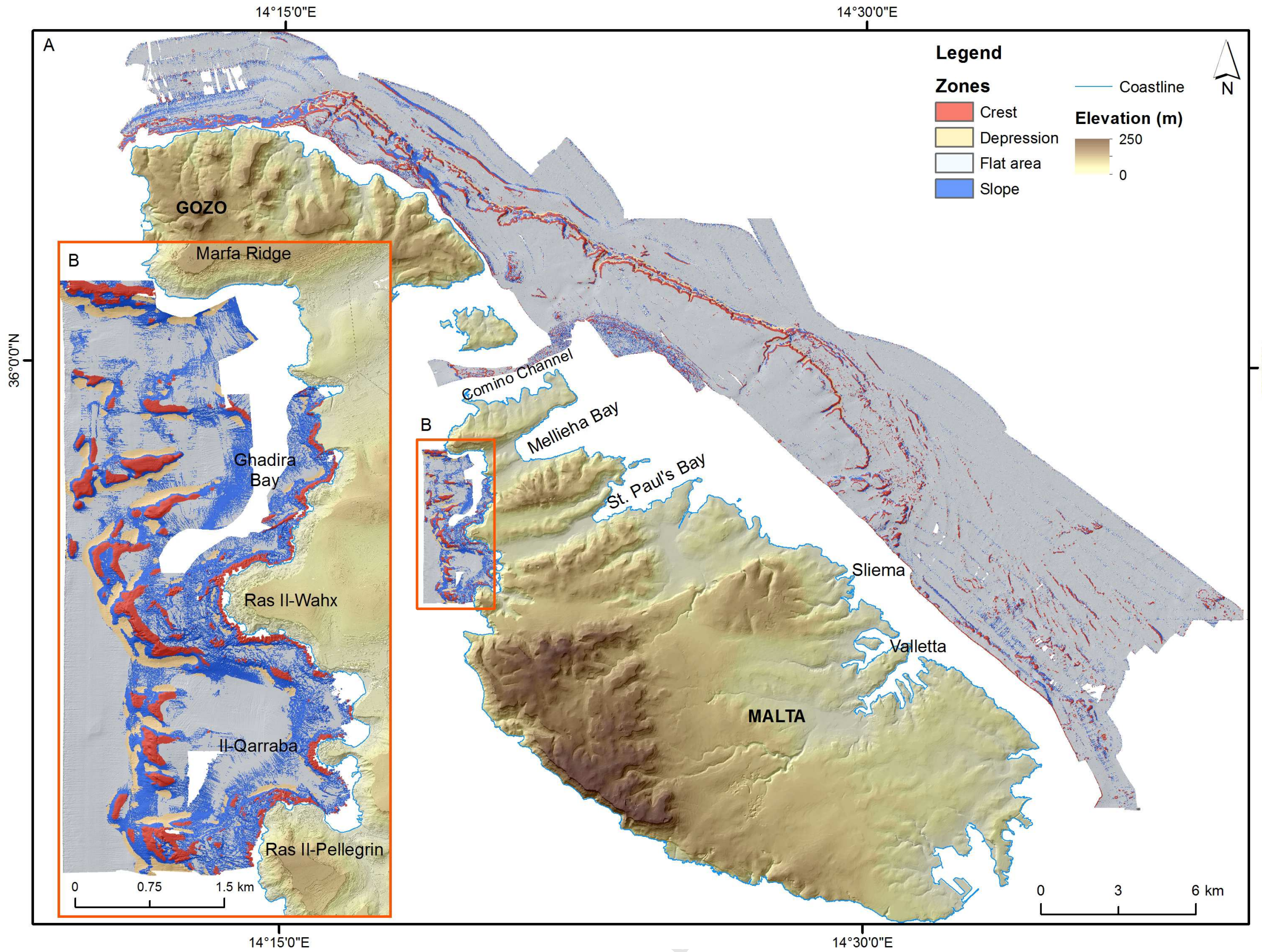


Figure 2. Seafloor morphological classification, related to land topography of the Maltese Islands. Maps obtained with the Benthic Terrain Modeler (BTM) toolbox of ArcGIS 10.x (Wright and Heyneman, 2005). A) Global overview of all areas; B) Details of the NW Malta dataset, showing a clearly more complex morphology.

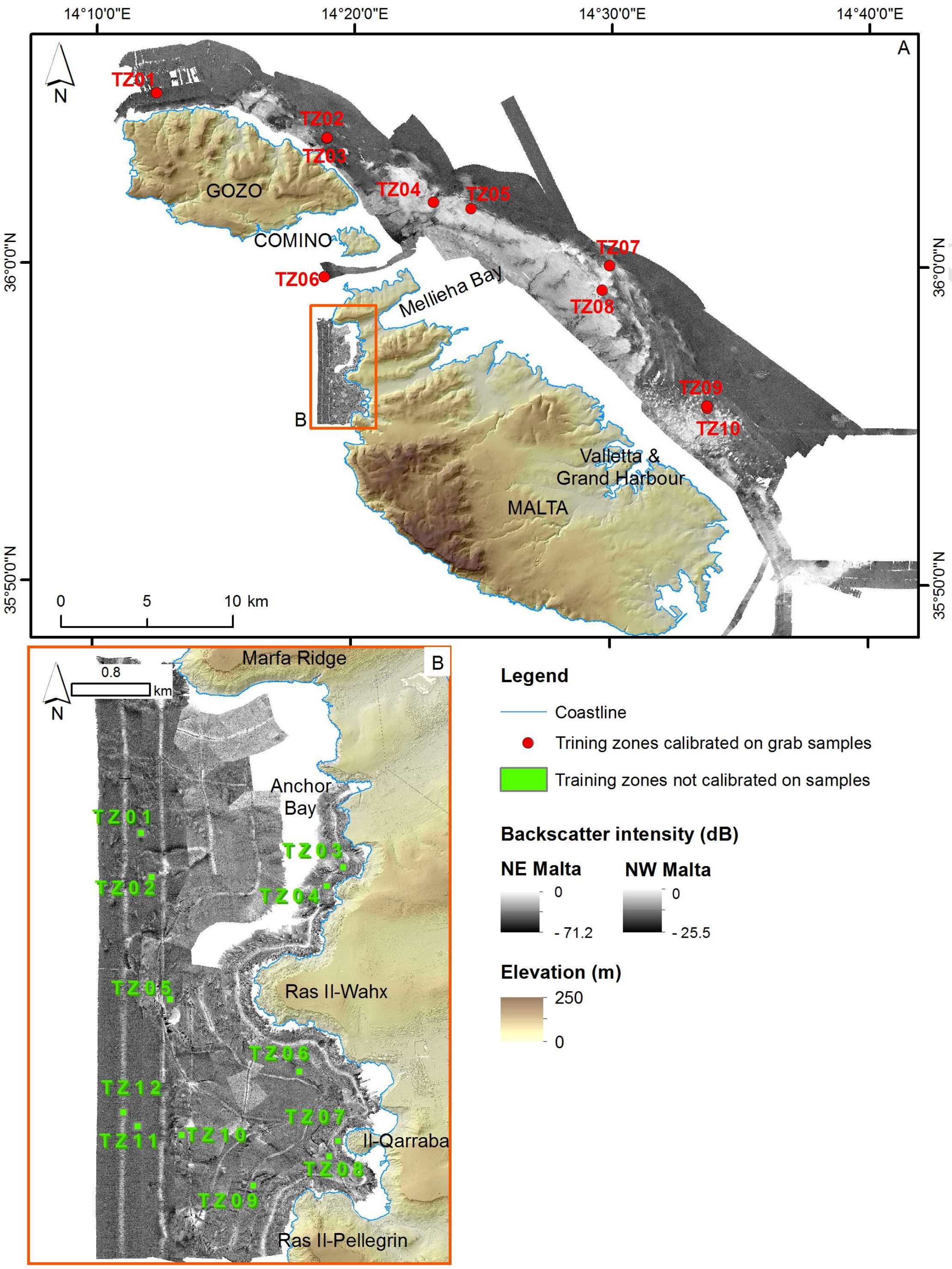


Figure 3. A) Backscatter of the area located offshore the eastern coasts of the Maltese archipelago and B) of the area offshore the NW coast of the Island of Malta. Note the grey level scales are slightly different, to better emphasize local features. Training Zones for the E dataset are defined around grab samples at coinciding locations (red circles). Training Zones for the NW

dataset are not based on grab samples and are represented as green squares. Onshore elevation data from 0 to 250 m.

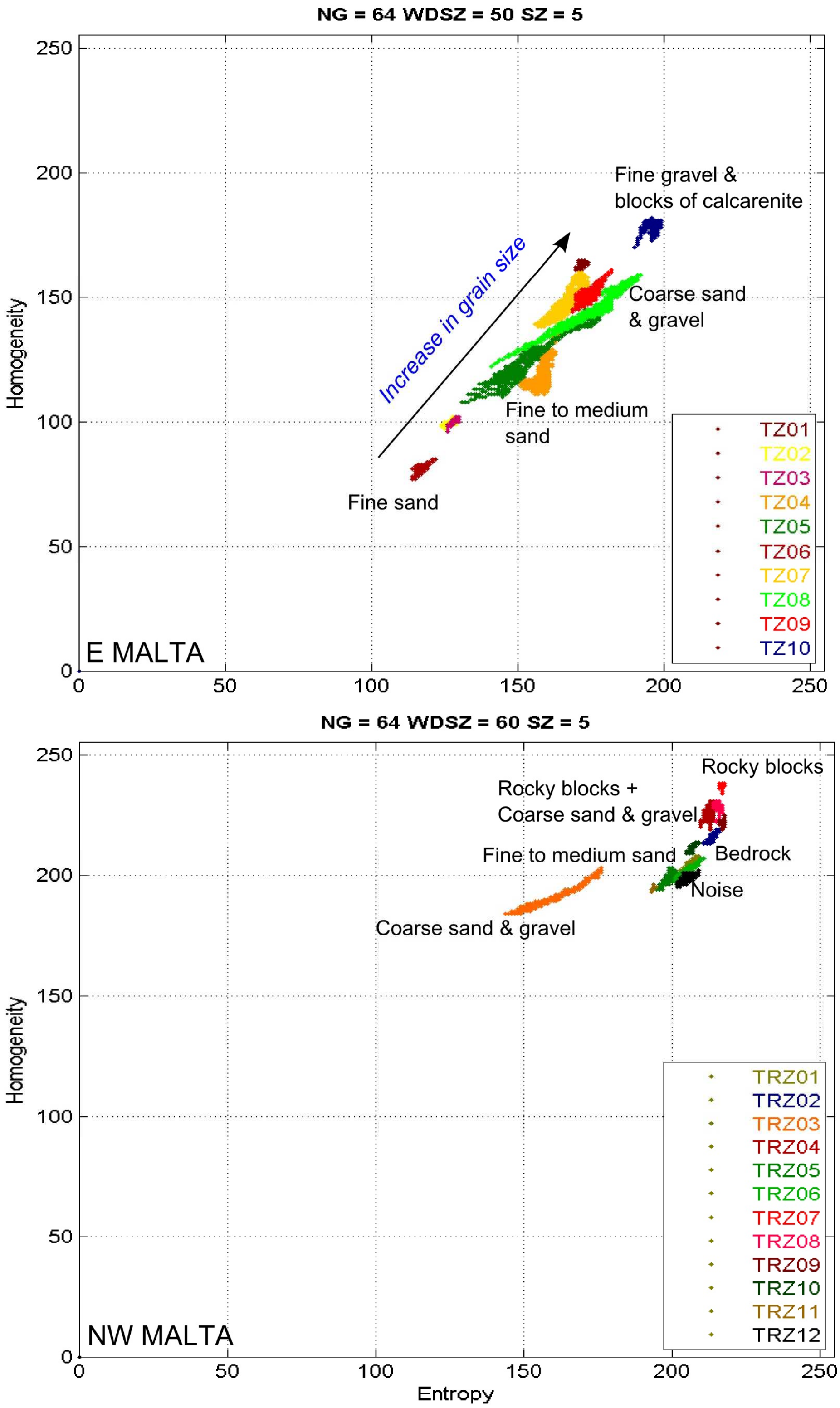


Figure 4. Entropy/homogeneity distributions of Training Zones of both datasets. Textures have been tested on a large number of Training Zones (10 for the E Malta dataset, 12 for the NW Malta

dataset), defined as representative of the different acoustic facies (Tables A1 and A2 respectively) and associated to grab samples for the E dataset. Entropy and homogeneity were computed on backscatter images resampled onto 64 grey levels (NG), with moving windows of similar sizes (WDSZ = 50 and 60 pixels respectively) and looking at co-occurrences 5 pixels away (SZ). Top (NE Malta): the clear separation of training zones shows a progression in entropy and homogeneity associated to increasing grain sizes, with more sedimented areas at the bottom-left part of the plot and the more rocky areas at the top right. Bottom (NW Malta): the same progression is seen, with smaller variations in homogeneity but similar variations in entropy. This is explained by differences in the local geology (see text for details).

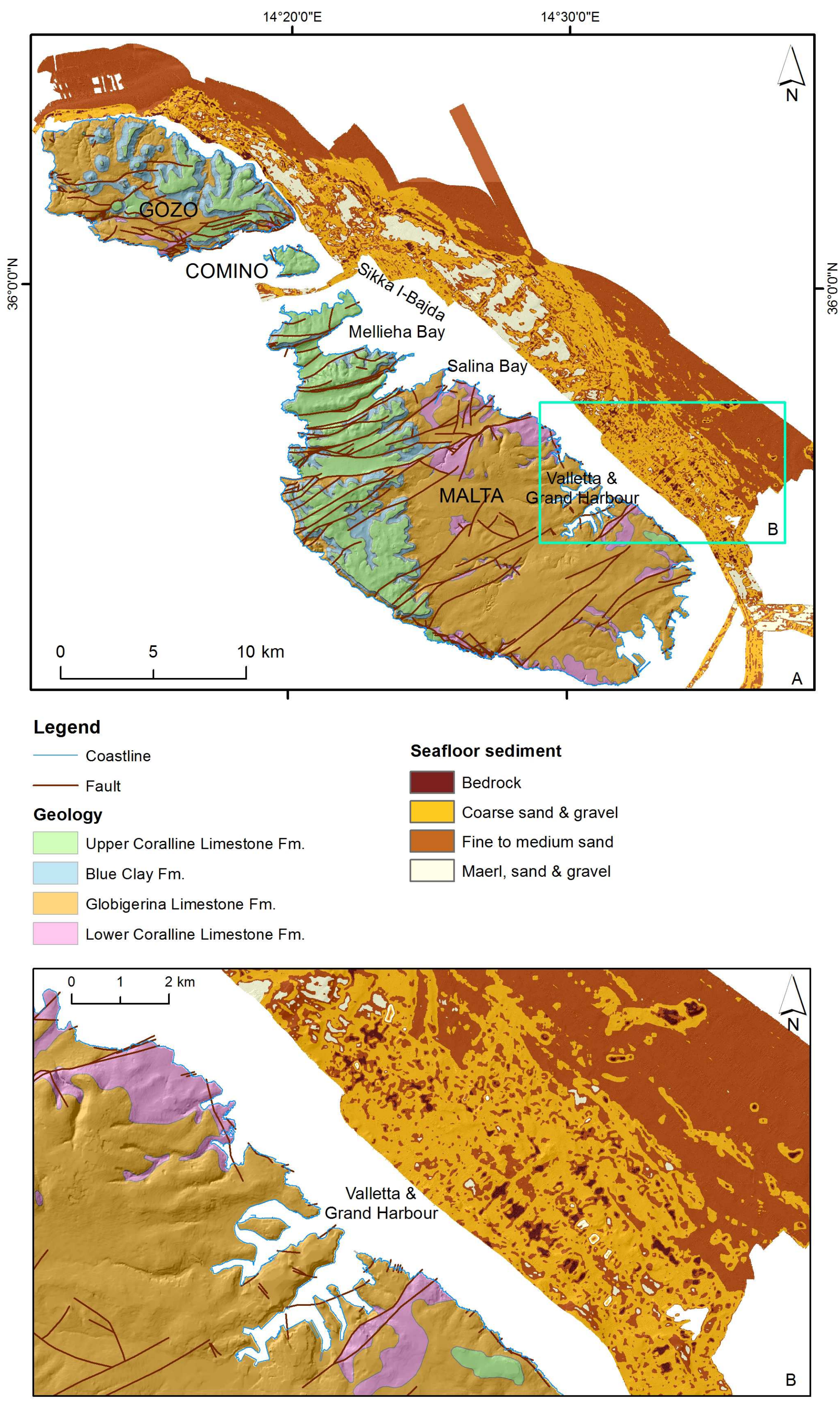
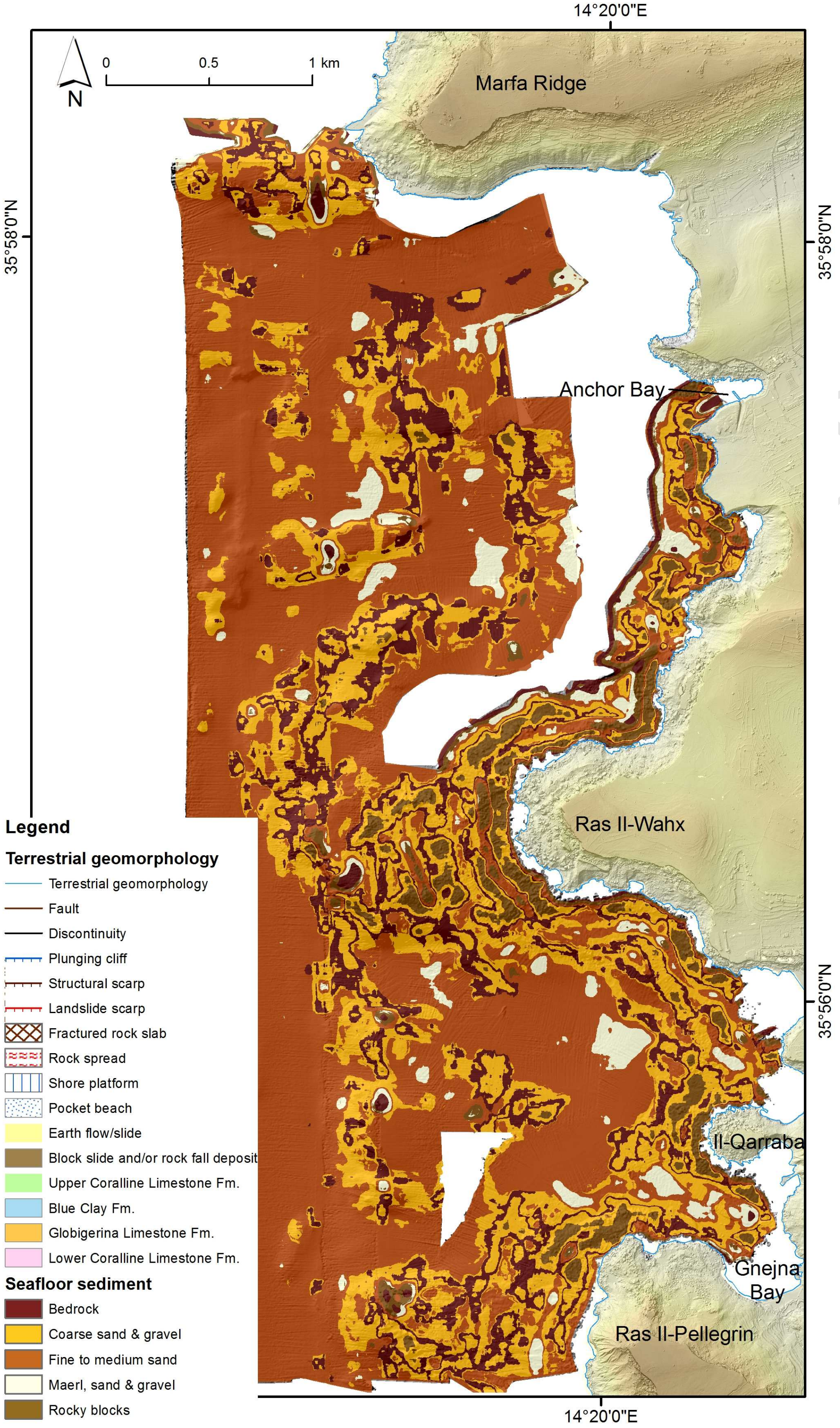
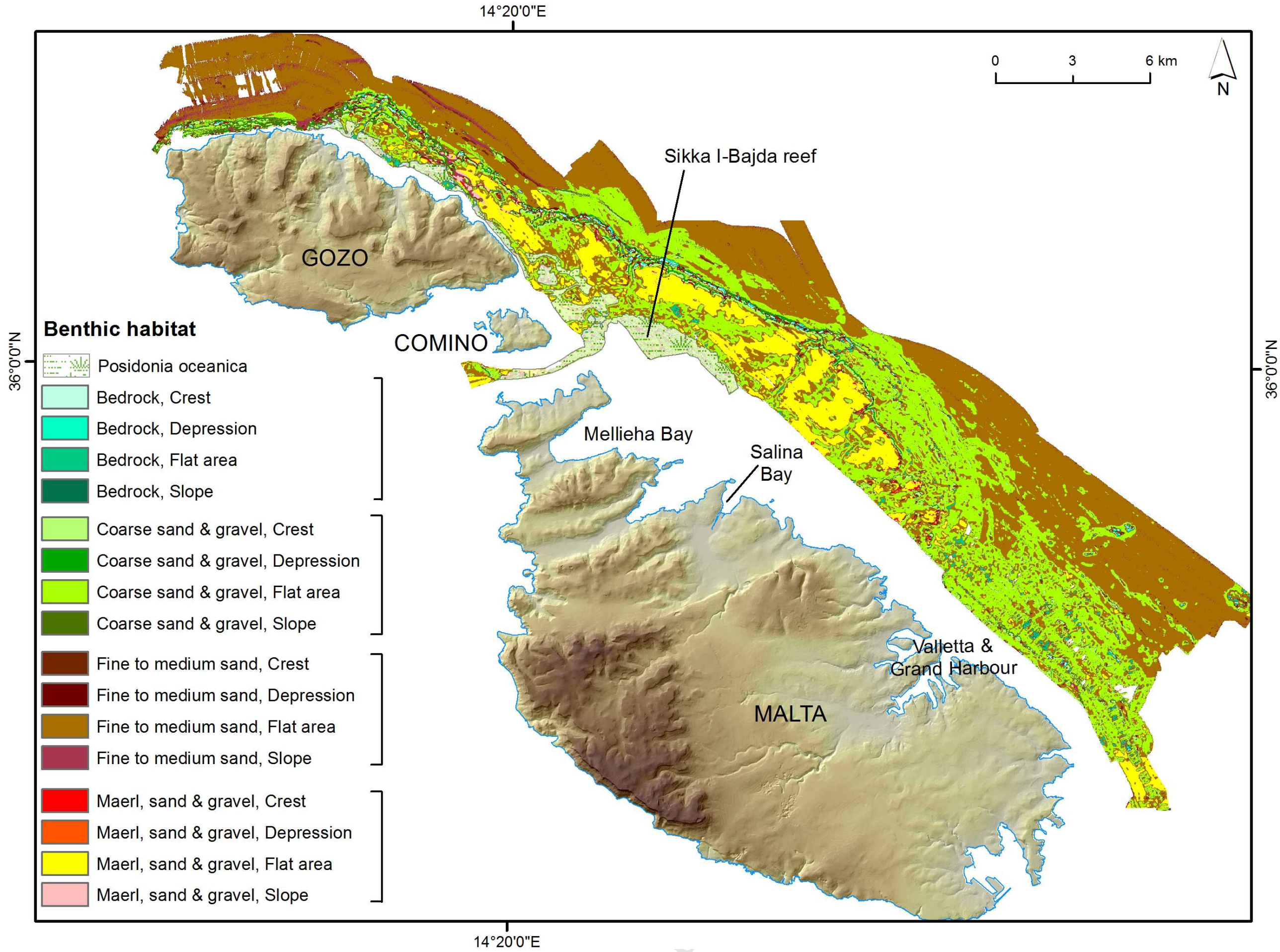


Figure 5. A) Seafloor sediment maps derived from TexAn classification – E Malta dataset. B) Detail of theseafloor offshore Valletta and the Grand Harbour affected by anthropogenic activities.

787

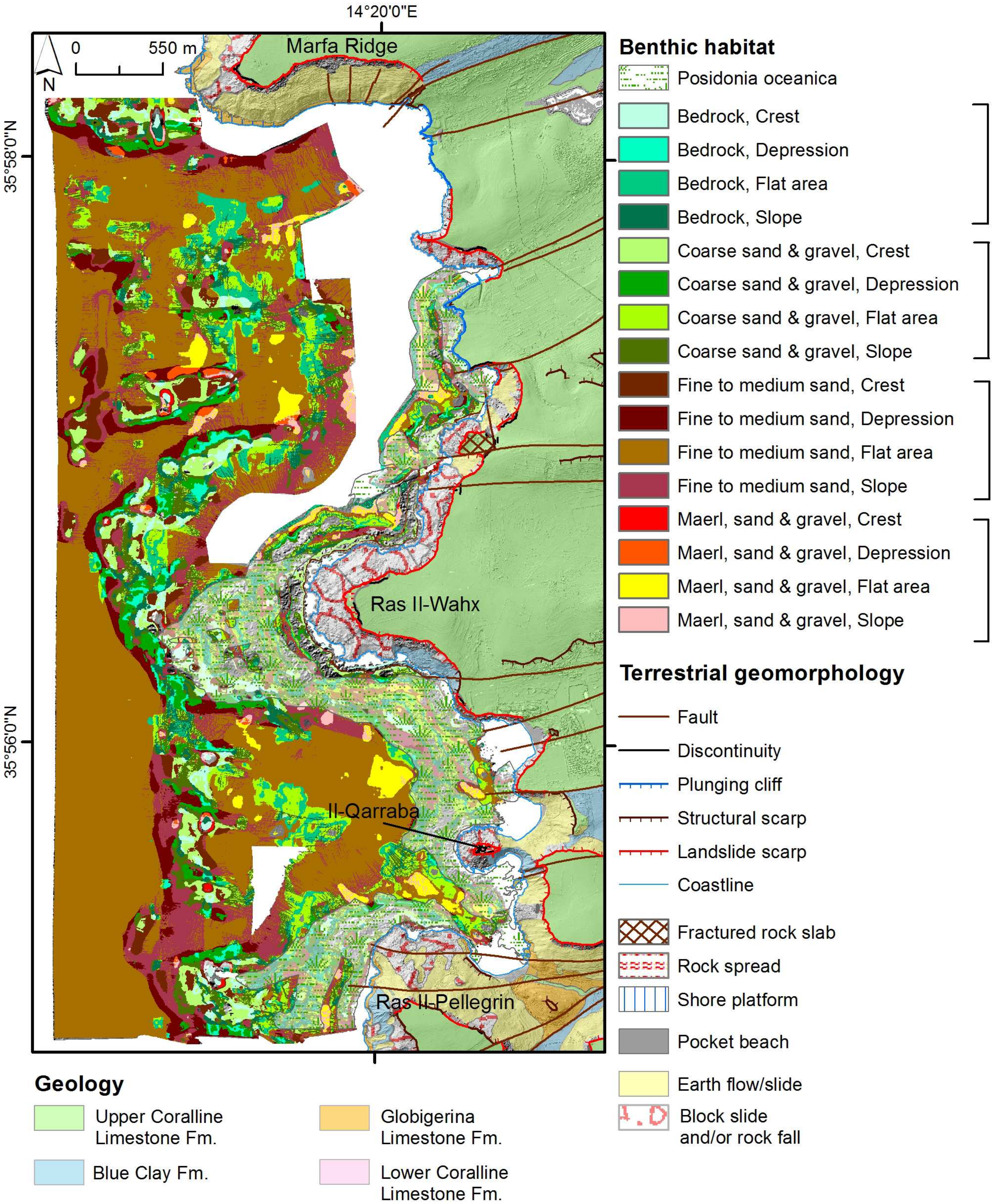


788 **Figure 6.** Benthic habitat map for the E Malta dataset derived from the combination of BTM (Figure
789 2) and Texan (Figure 5) classifications, combined with available MEPA information on *Posidonia*
790 *oceanica* and *maërl* distribution.

791 

792 **Figure 7.** Seafloor sediment maps derived from TexAn classification – NW Malta dataset. The
793 continuation of terrestrial geomorphology (modified from Devoto et al. 2012) on the seafloor is
794 highlighted.

795



796

797 **Figure 8**. Benthic habitat map for the NW Malta dataset derived from the combination of BTM
798 (Figure 2) and Texan (Figure 5) classifications, combined with available MEPA information on
799 *Posidonia oceanica* distribution.

800

TABLE CAPTIONS

Table 1. Comparison of backscatter intensity values and bathymetric distribution of each sediment class for the E dataset.

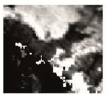
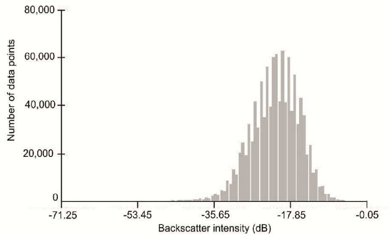
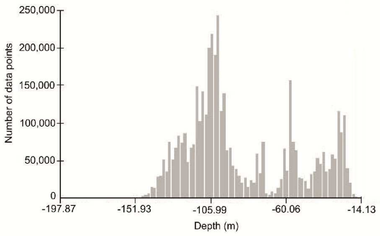
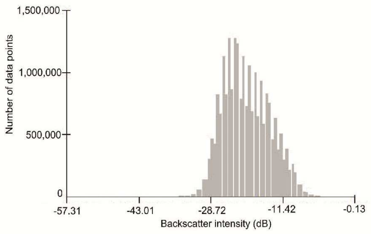
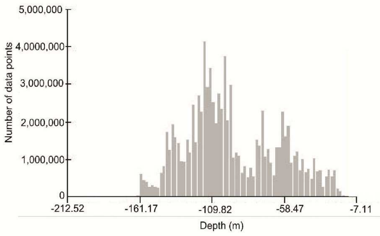
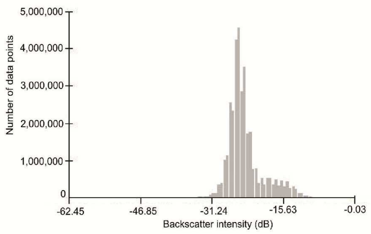
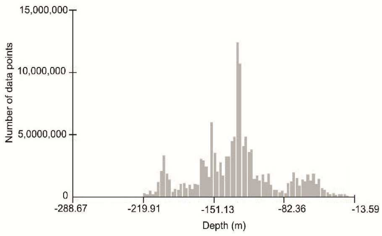
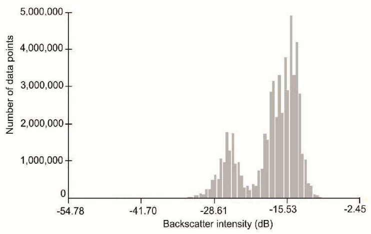
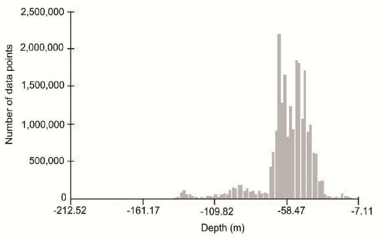
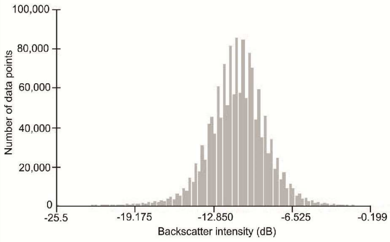
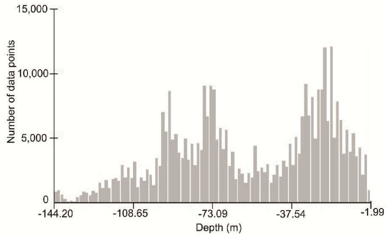
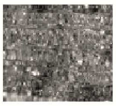
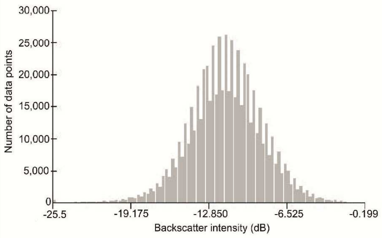
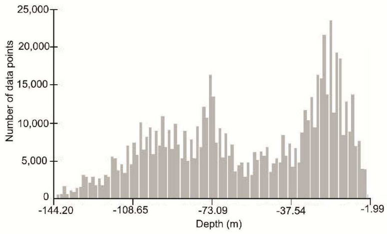
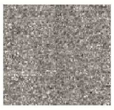
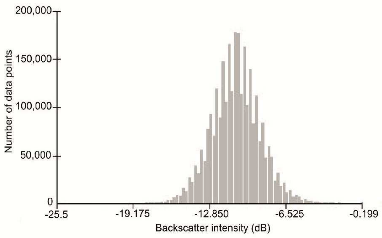
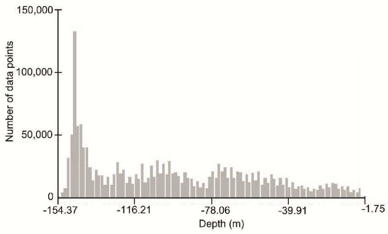
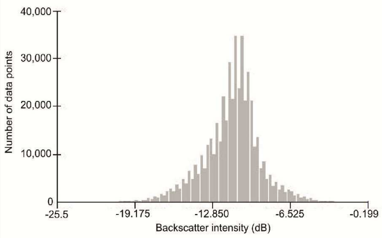
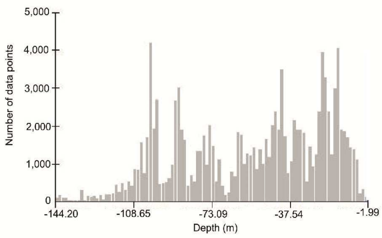
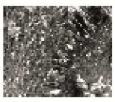
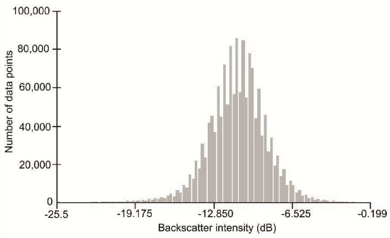
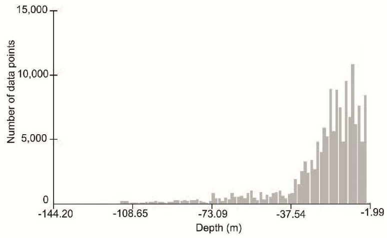
Sediment class	Backscatter image	Backscatter histogram	Bathymetry histogram	Notes
Bedrock	 			Characterised by high values of backscatter intensity and including different type of patterns, this class is located mainly in two bands of depth: from shallow waters to 690 m deep (where some positive reliefs occur) and from 80 to130 m deep (corresponding to the shelf break).
Coarse sand & gravel				Characterised by slightly lower backscatter than bedrock class, it is more uniformly distributed down to a depth of about 160 m.
Fine to medium sand				Characterised by a frequency peak around -25 dB, it is distributed mainly in deeper areas with a peak at ca. 130 m deep.
Maërl, sand & gravel				Occurring mainly on the continental shelf, down to ca. 70 m deep, it is characterised by two modes of backscatter intensity.

Table 2. Comparison of backscatter intensity values and bathymetric distribution of each sediment class for the NW dataset.

Sediment class	Backscatter image	Backscatter histogram	Bathymetry histogram	Notes
Bedrock				The bedrock class is present mainly near-shore and between 70 and 90 m deep (the latter representing the shelf break). The characteristic backscatter intensity shows the same distribution as the intensity of the entire dataset.
Coarse sand & gravel				Two main areas of the seafloor are made up of coarse sand and gravel: one in shallow water (maximum depth of about 38 m) and the other between ca. 70 and 105 m deep. The backscatter intensity is more centred on the medium values of the dataset.
Fine to medium sand				It is present in the whole dataset, especially in deep waters (> 118 m). The majority of intensity values between ca. -8 and -10 dB characterises this sediment class.
Maërl, sand & gravel				It is generally widespread at all depths with the exception of deep waters (> 110 m). The predominant backscatter intensity within this class is medium (from ca. -13 to -8 dB).
Rocky blocks				Class located mainly in shallow water (maximum depth of ca. 37 m). The backscatter intensity distribution is Gaussian: predominantly medium values of intensity but with low number of records.

SUPPLEMENTARY MATERIAL CAPTIONS

Table A1. Training Zones of the E mosaic, 80 x 80 pixels (i.e. 160 x 160 m on the ground), with associated description of the sample centred in the Training zone, the type of sediment (from grain-size analyses) and seabed composition (from the entropy/homogeneity diagram).

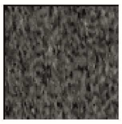
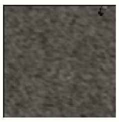
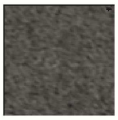
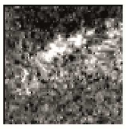
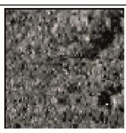
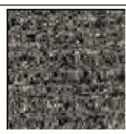
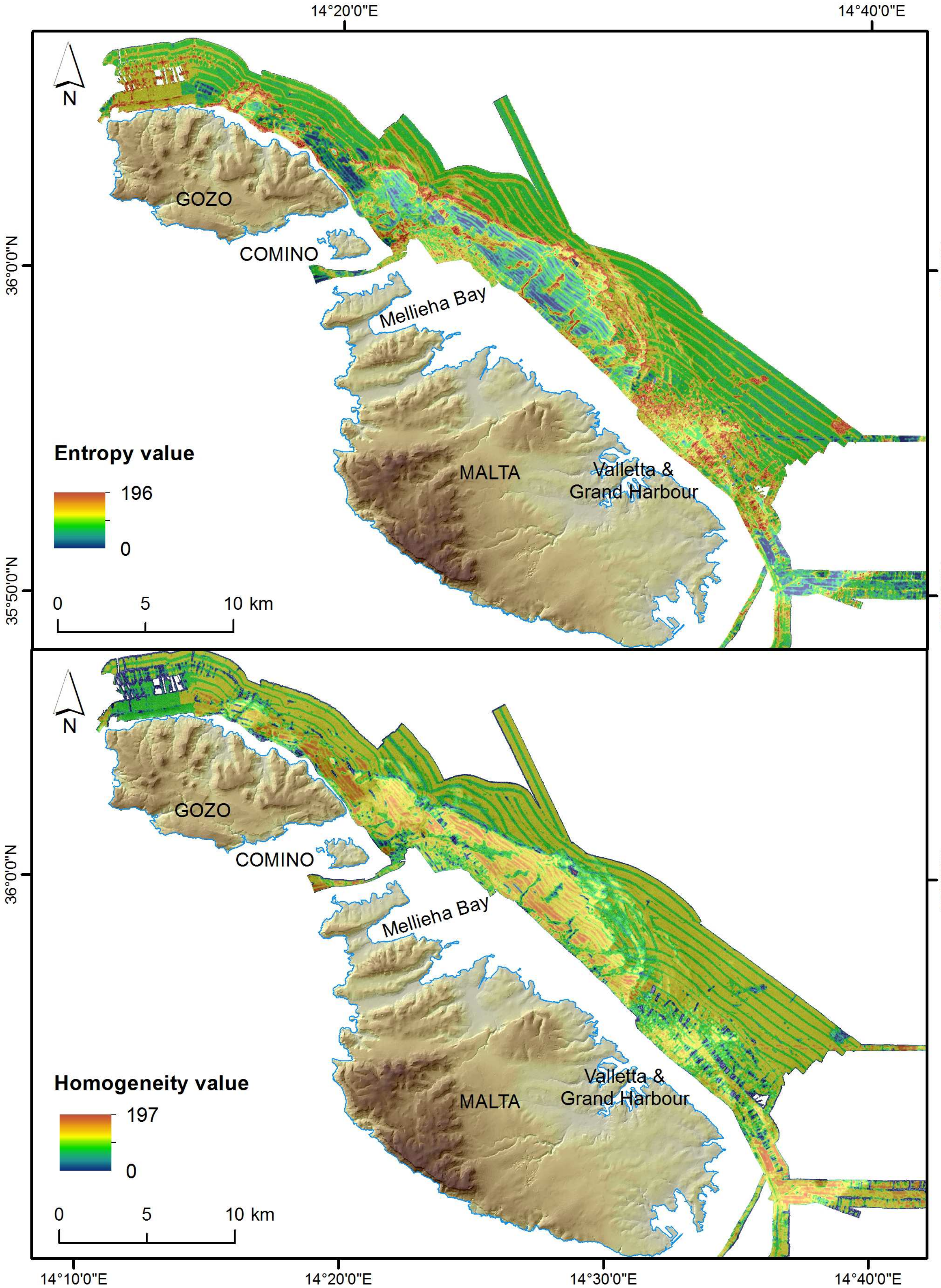
NAME	MOSAIC	SAMPLES	SEDIMENT TYPE	TEXAN CLASSIFICATION	NAME	MOSAIC	SAMPLES	SEDIMENT TYPE	TEXAN CLASSIFICATION
trz01		MEDCORE 40 TOP	Very well sorted fine sand	Fine to medium sand	trz06		DECORS 45 TOP	Muddy fine sand	Fine to medium sand
trz02		MEDCORE 51 TOP	Fine sand; Posidonia leaves and rhizomes	Maërl sand & gravel	trz07		MARCOS 77 TOP	Muddy fine sand & gravel	Coarse sand & gravel
trz03		MEDCORE 42 TOP	Coarse sand; Posidonia leaves and rhizomes	Maërl sand & gravel	trz08		DECORS 47	Medium sand; Maërl	Coarse sand & gravel
trz04		MEDCORE 57 TOP	Gravelly fine sand	Fine to medium sand	trz09		MEDCORE 60 TOP	Muddy fine sand	Fine to medium sand
trz05		MARCOS 76	Muddy coarse sand	Coarse sand & gravel	trz10		MEDCORE 59	Fine gravel; Blocks of calcarenite (ø 5-20cm)	Coarse sand & gravel

Table A2. Training Zones of the NW mosaic, 82 x 82 pixels (i.e. 82 x 82 m on the ground), with associated description of backscatter and morphology, and the seabed composition (from the entropy/homogeneity diagram).

NAME	MOSAIC	DESCRIPTION	TEXAN CLASSIFICATION	NAME	MOSAIC	DESCRIPTION	TEXAN CLASSIFICATION
TZ01		Area downslope the escarpment with a block (ø 69x54 m; height 11 m) buried under medium-fine sediment.	Fine to medium sand; Coarse sand & gravel	TZ07		Really close to the coast, sloping area characterised by numerous, not spatially organised, blocks (ø 13x16 m; 12x17 m; 12x14 m; height 1-2-5 m)	Rocky blocks; Bedrock; Coarse sand & gravel
TZ02		Area downslope the escarpment. Presence of a break of slope oriented ENE-WSW (height 21 m; mean slope 30°)	Coarse sand & gravel; Bedrock	TZ08		Flat and smooth area, close to the coast, located immediately downslope the accumulation of blocks accumulation (mosaic TZ07, above). Presence of acoustic imaging artefacts (a few straight lines).	Rocky blocks; Coarse sand & gravel
TZ03		Area close to the coast, flat, generally smooth and with variation of sedimentary coverage	Rocky blocks; Fine to medium sand; Coarse sand & gravel	TZ09		Generally flat area, presence of some blocks (ø 10x8 m, 12x14 m, 8x8 m; height 40cm, 1 m, 3 m)	Rocky blocks; Coarse sand & gravel
TZ04		Area close to a promontory, presence of blocks (27x17 m; 14x17 m; 10x18 m; height 3-5 m).	Bedrock; Rocky blocks; Coarse sand & gravel	TZ10		Area characterised by irregular, N-S oriented continental escarpment (40-50° sloping and 20 m high)	Bedrock; coarse sand & gravel
TZ05		Shelf area, flat and quite smooth, interpreted as palaeo-shore platform. Presence of artefacts.	Fine to medium sand	TZ11		Flat and smooth area with some imaging artefacts (faint horizontal lines).	Fine to medium sand



838

839 **Figure A1.** Entropy and homogeneity maps for the E Malta dataset. The square shows a detail of

840 the bottom of the palaeo-river channels and of the variations of entropy and homogeneity values

inside the channels. Entropy and homogeneity distributions obtained from the TexAn processing of the whole E dataset show similar characteristics. The navigation lines are very visible and characterised by high entropy and low homogeneity values, but they are easily removed later, during the K-means classification. Generally, the basin area presents an almost homogeneous seafloor, with medium entropy and homogeneity. The continental escarpment, characterised by high backscatter intensity, is highlighted by high values of entropy and low values of homogeneity, representing an important passage from two different environments (the basin and the continental shelf). We can observe the same for the area characterised by the ridges of the palaeo-shoreline deposits. The continental shelf shows high variations of entropy and homogeneity values: the platform is generally homogeneous in substrate type, but it is characterised by some highly heterogeneous features. The bottoms of the palaeo-river valleys show high entropy and low homogeneity, and their uppermost parts are more marked than their mouths. This mixed area is due to the variations in sediment type characterising the bottom of the channels and similar to a pattern typical of ripples. Also the shallow area offshore Comino and Mellieha Bay shows high values of entropy and low homogeneity. Another interesting zone is the seafloor in shallow water offshore Valletta: its shows a dotted distribution of high and medium values of entropy and homogeneity, explained further in this section.

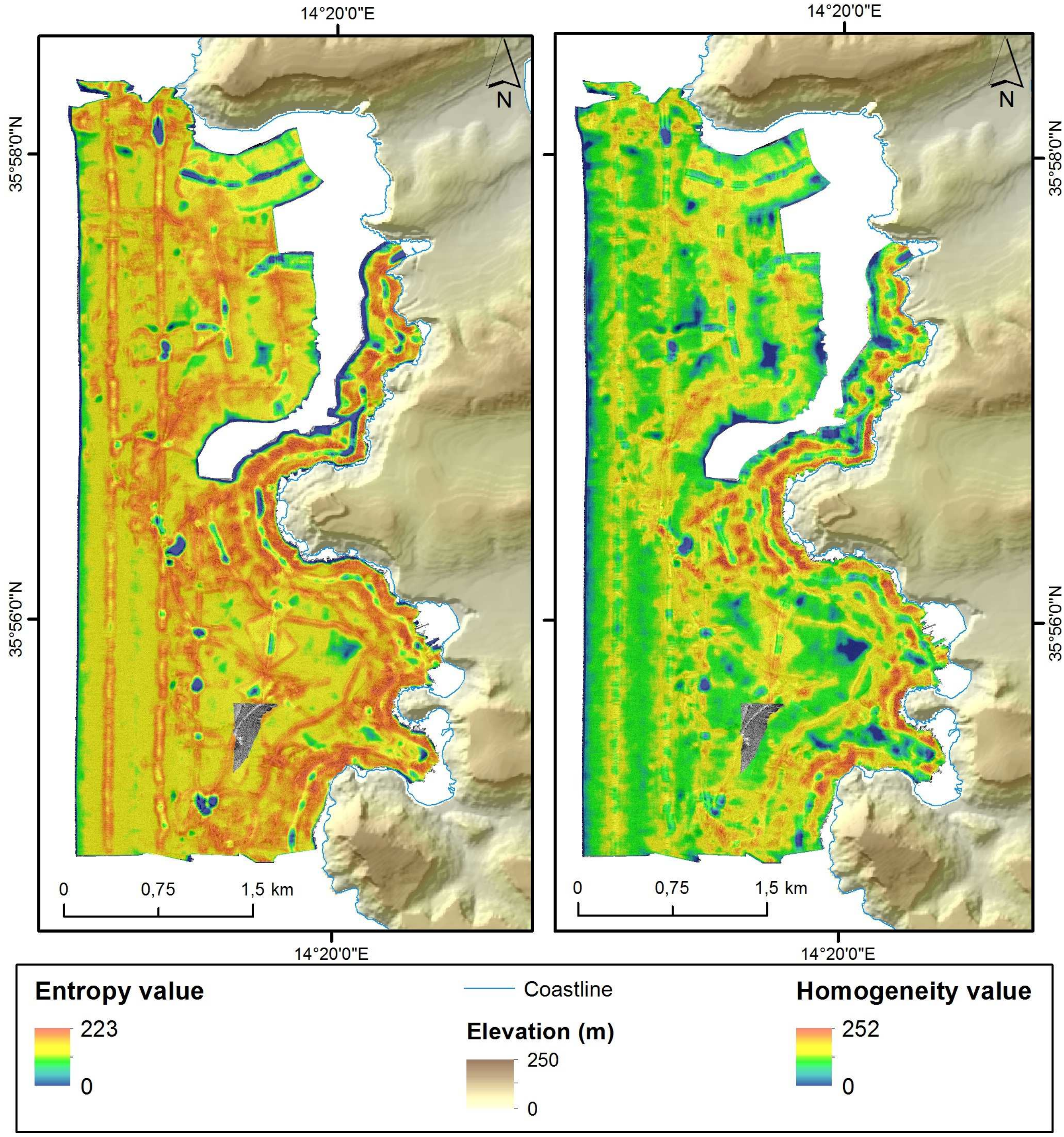


Figure A2. Entropy and homogeneity maps for the NW Malta dataset, showing details of the area. Entropy measures textural roughness, and homogeneity is lower as textures are more organised. Both parameters are visibly sensitive to artefacts introduced at the junction between swaths; this was accounted for in the selection of Training Zones (Table A2) and the classification of entropy/homogeneity signatures. The maps show a continental shelf characterised by high variations in entropy and homogeneity values. On the contrary, the area located downslope the continental escarpment is characterised by medium values of both indices, without variations in intensity, reflecting an almost homogeneous backscatter image, apart from the noisy track lines, highlighted by high entropy and high homogeneity values. The boundaries of the plateau offshore Ghadira Bay are highlighted by values of entropy and homogeneity both higher than the surroundings. Generally, the edges between individual swaths are marked with high entropies and high homogeneities, identified and removed during the next stage.

Highlights

1. Multi-method approach was applied for benthic habitat mapping of Maltese seafloor
2. We combined morphometric and TexAn analyses of sonar image
3. The classifications were compared with those already available in literature
4. We produced comparable classifications of datasets acquired with different devices