Seafloor Geomorphology (GeoHab Workshop)

Key resources and future challenges

GeoHab Conference – Saint Petersburg – 13 May, 2019

<u>Geomorphology:</u> "Geomorphology is the study (-logy) of the forms (-morpho) of the Earth (geo-). Geomorphologists describe and classify the Earth's surface to investigate the complex interaction between form and process, and to unravel the evolution of landforms and landscapes through space and time." (Micallef et al., 2018).

The intended purpose of this document is to serve as a resource to the seafloor mapping community, as a brief report on the innovative geomorphology mapping and analysis tools demonstrated at the 2019 GeoHab pre-conference workshop, here presented as <u>case-studies</u>. We also summarise workshop discussion points on the demands and applications for seafloor geomorphological analysis, and consider future challenges for the discipline.

Dove, D., Bjarnadottir, L., Guinan, J., Le Bas, T., Nanson, R., Roche, M., Lecours, V., Stephens, D., Walbridge, S., Khadjinova, R., Di Stefano, M., Dolan, M., Debese, N., Jacq, J.J., Harris, P., Lamarche, G., Ryabchuk, D., 2019. Seafloor Geomorphology (GeoHab Workshop); Key Resources and Future Challenges, GeoHab-2019 Conference, St. Petersburg.

Seafloor Geomorphology (GeoHab Workshop); Key resources and future challenges

A one-day workshop on Seafloor Geomorphology was held on 13 May, 2019 as part of the GeoHab Conference in St. Petersburg, Russia (*http://geohab.org/*). Below we describe the context and motivation for holding the workshop, then present seven methodology case-studies (under heading 'Demonstrators'), and finally summarise the key themes and future challenges that emerged from workshop discussions.

Detection, Delineation, and Classification; seeking improved mapping approaches

Mapping and analyzing the geomorphology of the seafloor is not a brand-new discipline, e.g. the 2nd edition of the atlas on the 'Seafloor Geomorphology as Benthic Habitat: GeoHab Atlas of Seafloor Geomorphic Features and Benthic Habitats' will soon be published (Harris et al., 2011; 2019), and Micallef et al. (2018) recently compiled an up-to-date book on a diverse range of geomorphic environments. Seafloor geomorphology is however an evolving science which appears to be a particularly well-suited to the times, and is helping to address a range of contemporary marine science challenges (e.g. benthic ecosystems, submarine hazards, offshore renewables development). Part of the value and demand for this science is in the prospect of fundamental discovery. The ever-increasing availability of high-quality bathymetry data often reveals seafloor features and environments for the first time, and geomorphology provides a useful first-order physical assessment of the seafloor through discriminating and characterising the diverse record of environmental processes preserved at the seafloor.

Geomorphological analysis, in particular when informed by detailed ground-truthing samples, can be employed to inform on active seafloor dynamics, as well as infer shallow sub-surface properties (e.g. Harris et al., 2014; Dove et al., 2016). With the advent of international seafloor mapping initiatives like Seabed 2030 (Woelfl et al., 2019 - https://seabed2030.gebco.net/), we anticipate continued demand for better means to characterise the seafloor environment, progressing our knowledge beyond the fundamental measurement of its depth. Within this context we believed it was worthwhile to assemble a group of expert and interested scientists to explore what concepts, approaches, and geospatial tools can help us to best implement geomorphic mapping and analysis. In short, we believed that a workshop focusing on the mechanics of geomorphological mapping and analysis would be timely and welcome. This workshop summary highlights the breadth of the developing technologies that are being applied by the community.

Seafloor Geomorphology is a 'broad church'

The field of Geomorphology has been developing rapidly over the last century and has matured into comprehensive terrestrial, fluvial, aeolian, coastal, and marine sub-disciplines (Bauer and Goudie, 2004). Of these, marine geomorphology is the youngest discipline, which itself includes several established sub-disciplines (Micallef et al., 2018). It is worth noting here, and this was apparent at the workshop, that 'Geomorphology' still has varied (though complimentary) connotations within marine sciences. For example, some scientists come from the perspective that geomorphology involves the analysis of landforms/bedforms observed at the seafloor to interpret formative environmental processes/dynamics. Others, driven by important applications in spatial ecology, apply the discipline via the quantitative classification of the seafloor based on morphological and geometric thresholds (e.g. morphometry). This diversity of application approaches is a positive attribute of the discipline, and these components are of course not mutually exclusive.

Seafloor geomorphology also can benefit from longer-established terrestrial practices. This is particularly relevant in nearshore environments, and farther out on continental shelves where many seafloor features were formed by terrestrial processes during sea level lowstands. As such, marine geomorphology mapping can incorporate and/or adapt existing terrestrial classification systems, which also supports the development of seamless onshore to offshore maps. In contrast to the terrestrial environment though, direct ground-truthing and sub-seismic scale stratigraphy have typically been difficult to obtain and have been of limited extent. In one sense this explains the flourishing of seafloor geomorphological mapping based primarily on 'shape' (derived from bathymetric data), but also raises challenges to the community, i.e., by highlighting the need to better integrate supporting data (e.g.

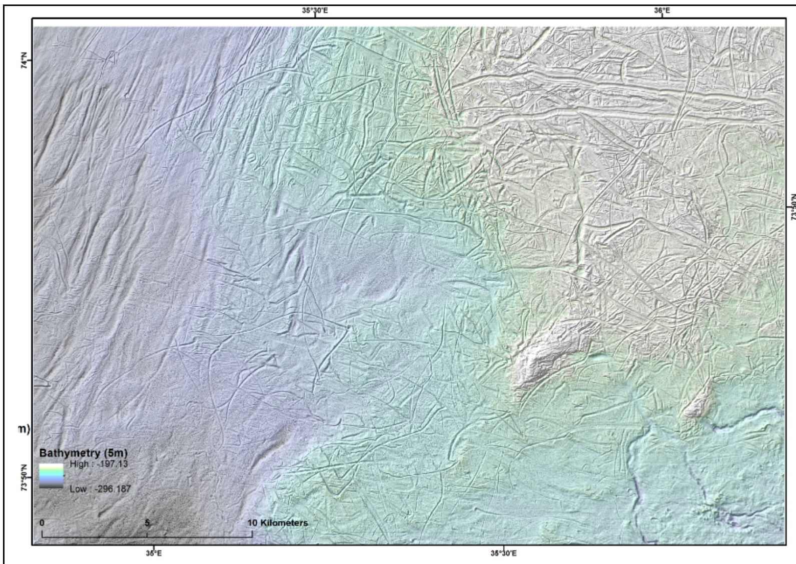
acoustic backscatter, shallow seismic, hydrodynamic and sediment models) to inform comprehensive marine geomorphic maps.

Workshop structure

To facilitate a discussion-oriented workshop, the day focused on two interactive exercises, separated by three contextual talks (Appen. 1). **Exercise 1** was a manual 'traditional' mapping activity (e.g., paper maps, pens, and transparent film) intended to introduce fundamental considerations of mapping: source data resolution and quality, spatial scale, intended map audience, specific features of interest, objective mapping vs. 'expert' interpretation, symbology, etc…

Exercise 2 introduced participants to a number of innovative geospatial mapping tools developed to implement various forms of geomorphological mapping. The developers of these geospatial tools come from academia, the survey industry, software development, and government agencies, who volunteered to demonstrate their methods at the workshop. ***These tools/methods are the subject of the individual case-studies presented in the next section.*** Workshop participants rotated around interactive mapping demonstration tables where they had a chance to see how each tool performed, and ask questions of the tool developers. To assist this process, several of the demonstrators made use of two common-datasets of multibeam bathymetry and backscatter provided by the Geological Survey of Norway (NGU) (Fig. 1).

**We note that while participants enjoyed these demonstrations, we scheduled insufficient time for discussion. Nevertheless, participants were able to pursue discussions through the remainder of the conference week.*



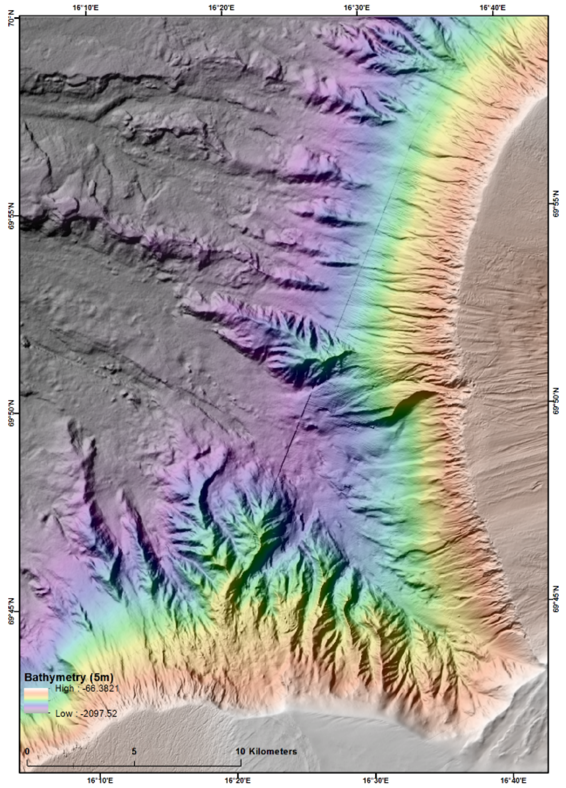


Figure 1: Common data set bathymetry from Norwegian Continental Shelf (Above); and Continental Slope (Right). Both MBES bathymetry datasets provided courtesy of NGU at 5m and 50m resolution, together with MBES ackscatter data. (http://www.mareano.no/en/download-data/the-geological-survey-of-norway-ngu)

Workshop organisers: MIM-GA

MIM-GA, which stands for Mareano (Norway), INFOMAR (Ireland), MAREMAP (UK), and Geoscience Australia (GA), is a collaboration between marine mapping programs, aimed at addressing common challenges. Marine geomorphic mapping is a key focus of all participant groups, who universally acknowledged the lack of a robust classification framework that we could consistently apply. This initially led to the development of the 'Two-part' classification approach presented in Dove et al. (2016), and more recently has instigated improved methods for producing accurate, efficient and consistent maps using that incorporate semi-automation. These common interests and challenges led to this Geomorphology Workshop, and its applied focus.

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Geospatial tools - Exercise 2 demonstrations

These self-contained case studies provide brief summaries of the function of the various tools and methods presented at the workshop. The case studies provide links to more in-depth information, which may include publications, source-code/downloadable software, or example applications of the tools/methods. Please keep in mind that none of these tools are promoted as one-stop-shop ‘black boxes’ for conducting geomorphological mapping, so as always users should investigate the tools themselves, understand how they are parameterised, and be aware of what biases, ‘noise’, and uncertainties may persist through to the final products.

Table 1: Geospatial tool demonstrations (Exercise 2): List of developers and associated tools/methods

1	Marc Roche (SPF Economie)	Osculatory Surfaces Extraction applied to Monitoring of Sub-marine Sand Material
2	Vincent Lecours (Univ. of Florida)	Terrain Attribute Selection for Spatial Ecology (TASSE) toolbox
3	Shaun Walbridge and Drew Stephens (ESRI)	ArcGIS Benthic Terrain Modeler (BTM)
4	Tim Le Bas (National Oceanography Centre, Southampton (NOCS)	Remote Sensing Object Image Analysis (RSOBIA)
5	Rada Khadjinova (Fugro)	4D Satellite Seafloor Morphology (4DSSM) - Satellite data to improve nautical charts and maritime boundaries
6	Massimo Di Stefano (CCOM – Univ. New Hampshire)	Open source GIS (GRASS and QGIS) for applications of general and specific geomorphometry
7	MIM-GA group: Lilja Bjarnadottir (NGU)), Janine Guinan (GSI), Dayton Dove (BGS), Rachel Nanson (GA)	Two-part Geomorphology Classification - approach, applications, and methods

Demonstrator 1

Improving the extraction of morphological patterns by using osculatory surface derived from Digital Bathymetric Model

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Overview

Osculatory surfaces are smooth virtual surfaces giving access to the envelop surface of the top or bottom of any Digital Bathymetric Model (DBM). Originally, the method was developed to extract the active dune portion of the fossil part of sandbanks in order to assess the volume of sand involved in the dune dynamics (Debese et al., 2018ab and 2019).

The algorithm is composed of two building blocks. The first one performs the partition of the whole geographic area of the DBM into connected patches of equal area. Since the partitioning criterion is based on a stochastic process, several partitions of the same domain can be generated. The second core building block of the algorithm makes use of an asymmetric robust norm to fit a local osculatory surface on a patch, or a set of patches. The global osculatory surface is then built on the whole domain through a Monte-Carlo procedure. This iterative scheme performs the recombination of local osculatory surfaces based on stochastic partitions while managing the partial overlapping of their respective patches – the results discussed in this work require fewer than five iterations. The two main parameters of the algorithm are thus: (i) the average diameter of any stochastic patch (referred to the scale-space parameter); and (ii) the corresponding maximum degree of the local surfaces.

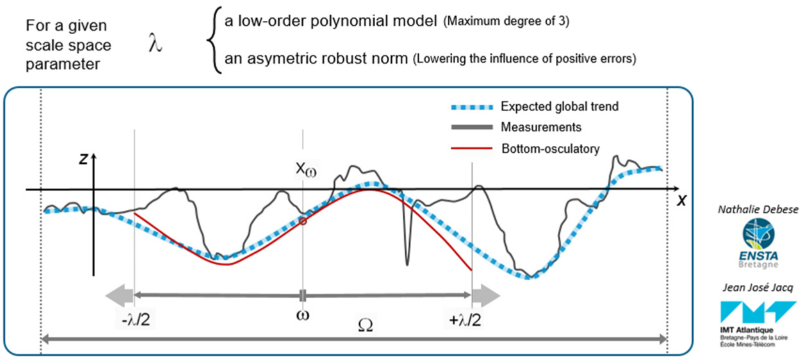

Figure 1: Principle of extraction of a bottom osculatory surface.

Demonstration

As part of the Seafloor Geomorphology Workshop GeoHab Workshop, the extraction of the top osculatory surface at different scale parameters of the continental shelf feature of the common dataset (Cont_shelf_50m.tif) was demonstrated. The usefulness of this concept to extract the erosive morphological pattern after subtraction of the osculatory surfaces from the different scale parameters with the original DBM was highlighted.

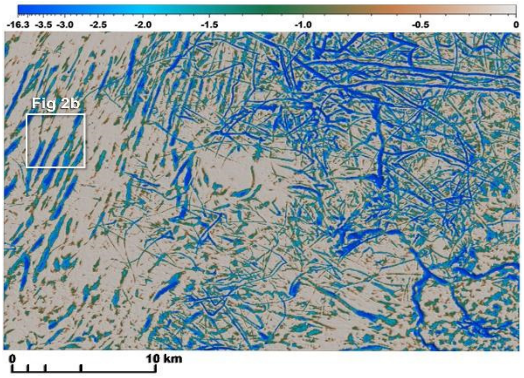

Figure 2a: Delta DBM - Top osculatory surface (scale space = 1500 m); scale in m.

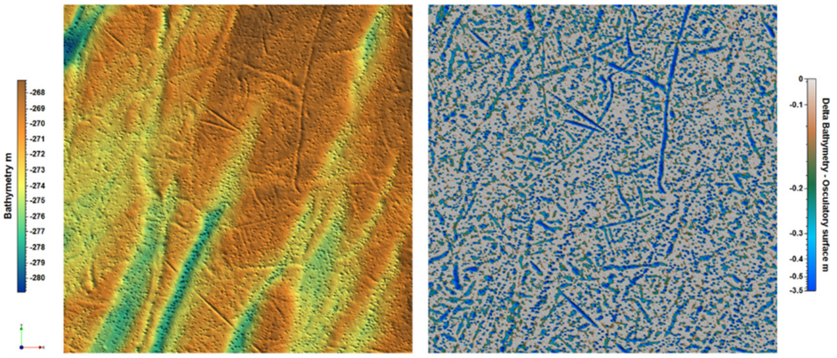

Figure 2b: Original DBM (Cont_shelf_50m.tif) and Delta DBM - Top osculatory surface (scale space = 150m); scales in m.

An osculatory surface can be derived from any initial surface. The key and relevance of this approach lies in the interpretation that the geomorphologist can give to the derived osculatory surface. In the case of the common dataset (Cont_shelf_50m.tif), the upper osculatory surface can be seen as a paleosurface that precedes the glacial erosion.

An all-in-one shell command is under development and testing. To this end, new datasets with challenging objectives are welcome. In the near future, the binary versions (MacOS, Windows) of the command are expected to be made available on request.

For any additional information and/or requests, please contact: *nathalie.debese@ensta-bretagne.fr*

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Demonstrator 2

TASSE – Terrain Attribute Selection for Spatial Ecology (v. 1.1)

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Overview

The Terrain Attribute Selection for Spatial Ecology (TASSE) toolbox for ArcGIS automatically derives a set of six terrain attributes from digital terrain models (DTM; *i.e.*, digital bathymetric or elevation models), which can then be integrated into any geomorphological or habitat mapping analysis. The selection of terrain attributes that are derived by the tools in this toolbox was determined by the analysis of the correlative structure among 230 terrain attribute algorithms offered by 11 different open source and proprietary software (see Lecours *et al.*, 2017). The 230 algorithms were applied on nine artificial terrain surfaces of different complexity levels. Principal component analyses, variance inflation factor analyses, and mutual information matrices analyses were performed to identify a suite of algorithms that were extracting different information from a surface (Lecours *et al.*, 2017). The appropriateness of the selection, determined in a theoretical context using artificial surfaces, was confirmed in a practical application using unsupervised and supervised approaches to habitat mapping: when compared to other comparable selections, it provided the most generalizable and robust results (Lecours *et al.*, 2016).

The six terrain attributes are statistical mean, slope, easterness, northerness, standard deviation, and relative deviation from mean value. Figure 1 shows an example of six terrain attributes derived from bathymetry using the TASSE toolbox.

- Depending on the scale at which it is computed, statistical mean is often highly correlated with the initial DTM, and thus should only be used when the DTM is not. For instance, it can be useful when the original DTM is noisy as the statistical mean will smooth out the DTM and potentially remove local errors. The units of statistical mean are those of the DTM, most often meters (DTMs must be projected in order to provide accurate measurements in geomorphometry, *i.e.*, not be in geographic coordinates). In Lecours *et al.* (2017), statistical mean was found to be highly correlated to other statistical terrain attributes such as maximum, minimum, and median.
- Slope, in degrees, is measured using Horn's (1981) algorithm.
- Easterness and northerness are derivatives of aspect (*i.e.*, the orientation of the slope). Easterness indicates the deviation of the slope from East, and northerness indicates the deviation of the slope from North. They range between -1 (due West or due South) and 1 (due East or due North). Both measures are derived from aspect (in degrees) that is computed using Horn's (1981) algorithm. Aspect is then converted into radians before calculating its sine (for easterness) and cosine (for northerness).
- Standard deviation is a measure of rugosity/ruggedness/roughness. If all the elevation or depth values are the same within a window of analysis, then the standard deviation is zero and there is no rugosity. If the elevation or depth values within a window of analysis are very different, the standard deviation is higher, highlighting a higher level of rugosity. Units of standard deviation are those of the initial DTM, most often meters. In Lecours *et al.* (2017), standard deviation was correlated with terrain ruggedness indices, surface ratio, Melton ruggedness index, roughness and range.
- Relative deviation from mean value(RDMV) is a measure of relative position that identifies peaks (positive values) and pits (negative values). It is unit-less and computed using a combination of focal statistics: rdmv = -(local mean – initial value of elevation or depth)/(local range). In Lecours *et al.* (2017), RDMW was found to be correlated to relative position indices such as Topographic Position Index (TPI) and Bathymetric Position Index (BPI) and several types of curvature (general, plan, minimum, maximum, mean curvatures).

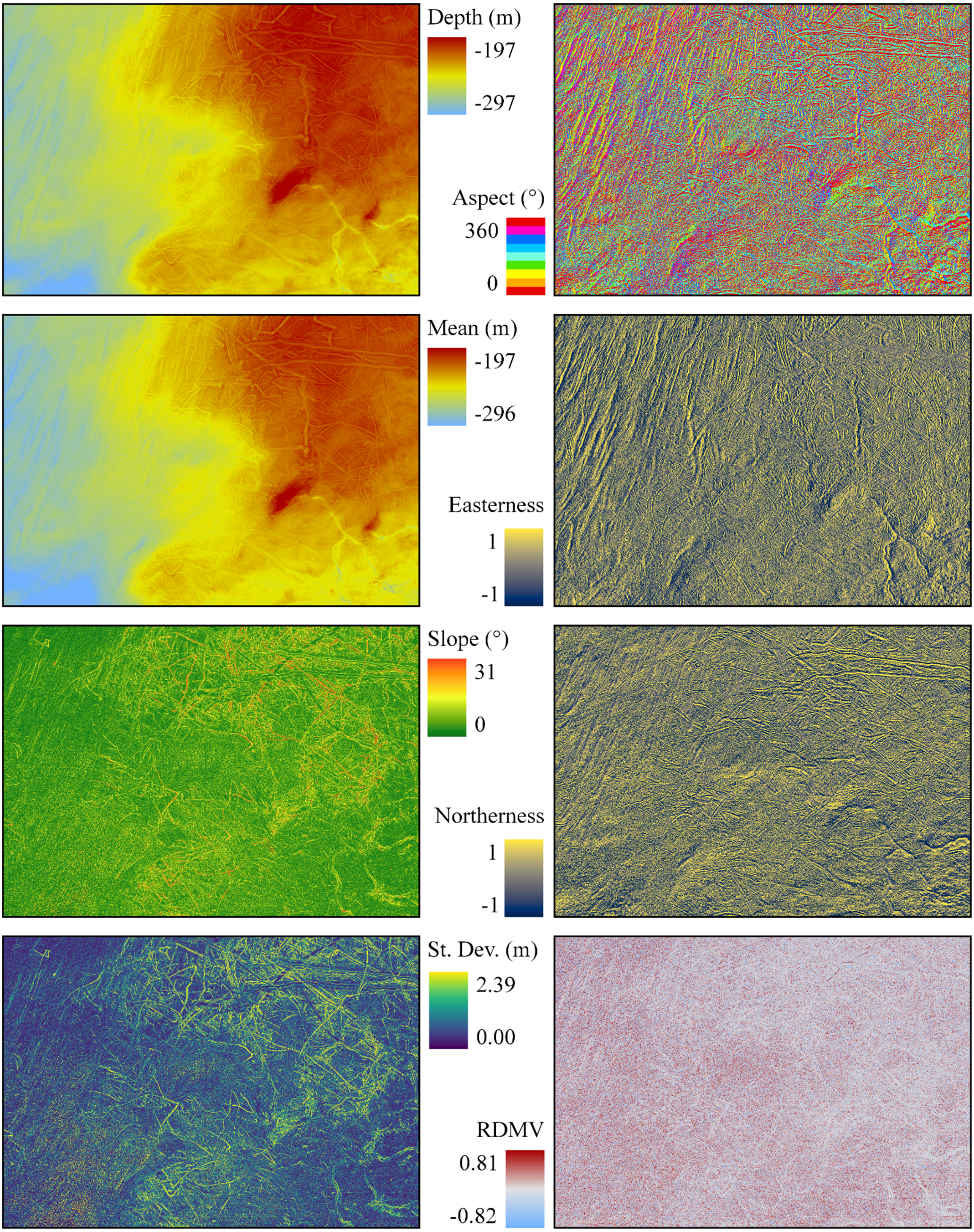

Figure 1: The "Geomorphometry for Ecology" tool of TASSE applied to the workshop common dataset (shelf).

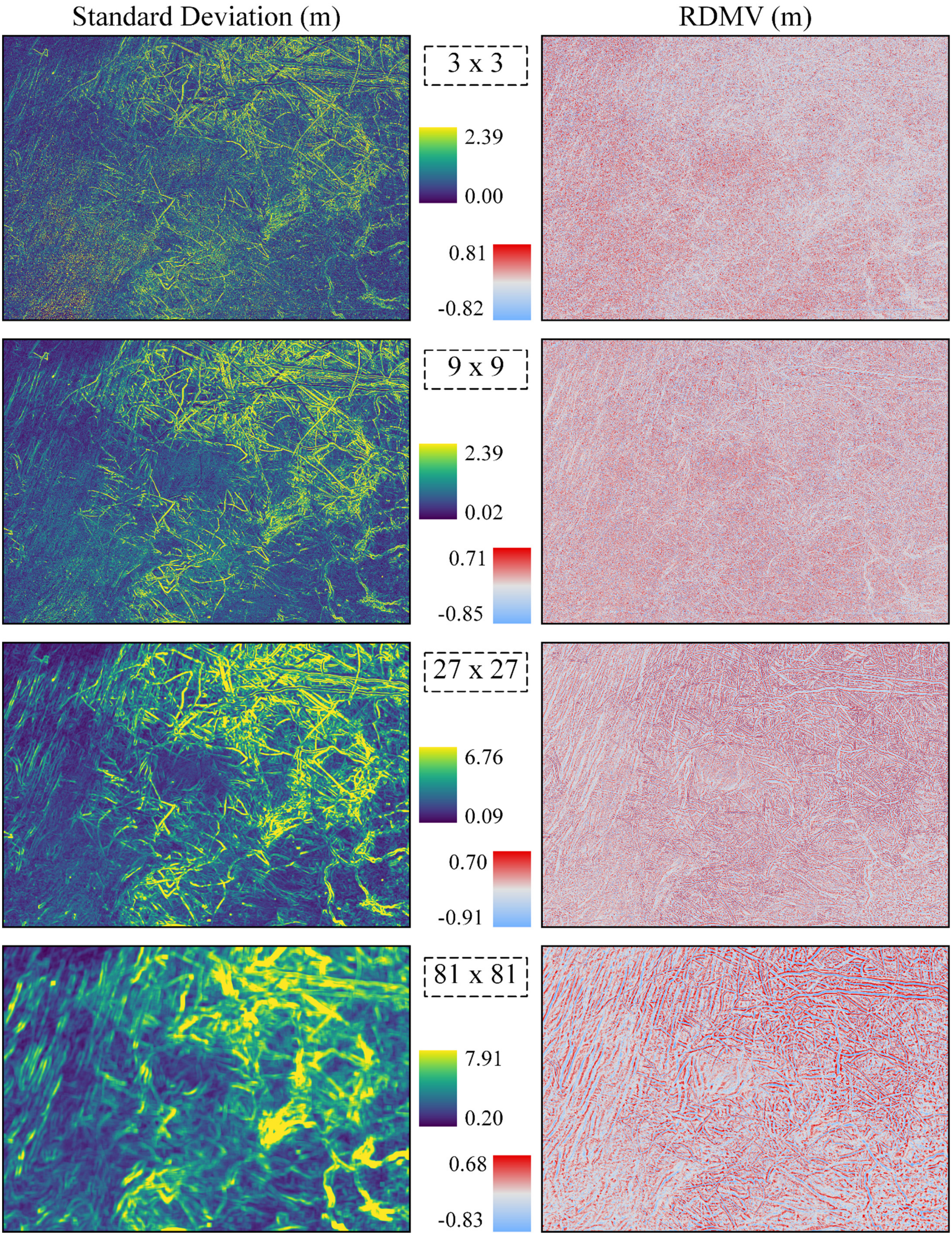

Figure 1 (cont.): The "Alternative Analysis Window" tool of TASSE applied to the common dataset (shelf) with standard deviation and RDMV.

The toolbox has 4 tools within 2 toolsets: 1 toolset that is optimised to use if you have Ascii (".asc") files (it is faster), and 1 toolset for any raster types that are compatible with ArcGIS, including Ascii files (".bil", ".bip", ".bmp", ".bsq",

".dat", ".gif", ".img", ".jpg", ".jp2", ".png", ".tif", ".asc"). There are two tools within each toolset: "Geomorphometry for Ecology", and "Alternative Analysis Window". "Geomorphometry for Ecology" uses a default 3x3 window of analysis, thus extracting relatively local characteristics (depending on the spatial resolution of the DTM). "Alternative Analysis Window" is a tool that can compute terrain attributes at different scales using different types (*e.g.*, rectangle, circle) and sizes of analysis windows. Figure 1 shows an example at four different scales, or window of analysis, using standard deviation (*i.e.*, rugosity) and RDMV. The example, particularly with RDMV, shows how different features are captured at different scales. Because of limitations of ArcGIS regarding the use of a different window size for measurements of slope and aspect, some alternative options are suggested for those two attributes, based on Dolan (2012).

The four tools require at least one DTM as input, but there is no limit of number of DTMs that can be used as input at the same time. The different input DTMs do not have to be in the same projection nor spatial resolution. The tool will simply read each DTM, identify its projection and resolution, and derive the six terrain attributes from it before moving on to the next one. The tools automatically set up a logical folder structure to save the attributes from each DTM independently. Each tool has an option to save all outputs as Ascii files to facilitate sharing. As shown in Figure 1, each tool also has the option to save aspect in addition to easterness and northerness, which are automatically saved. While it is not recommended to use aspect in any statistical, spatial or modelling analyses because of its circular nature (0-360 degrees), aspect is still useful for geovisualization purposes. For any other purposes, it is recommended to use both easterness and northerness instead of aspect. Each tool also has the option to apply a mask to all outputs, for instance to remove edge effect along the margins of the DTM and its derived terrain attributes, or if only a sub-area of the DTM is of interest to the user.

The tools can also be used in a model within ModelBuilder. They can also be run directly in a Python script or called through the Python window in ArcMap, ArcCatalog, or ArcGIS Pro. The python script is also provided with the toolbox so that it can be integrated into bigger workflow scripts or adapted for different GIS software that use Python.

TO DOWNLOAD AND CITE:

Lecours, V. (2017) Terrain Attribute Selection for Spatial Ecology (TASSE), v.1.1, URL https://www.researchgate.net/publication/314300617_TASSE_Terrain_Attribute_Selection_for_Spatial_Ecology_Toolbox_v_11

The toolbox requires a valid "Spatial Analyst" extension to work. The toolbox (.tbx file) can be located anywhere on your computer and can be accessed through ArcMap, ArcCatalog, or ArcGIS Pro to run the tools. To add the toolbox to the ArcToolbox menu in ArcMap, right click (in ArcMap) on "ArcToolbox" → Click "Add Toolbox" → Browse to the TASSE toolbox → Click "Open".

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Demonstrator 3

Benthic Terrain Modeler - tools for understanding and classifying the benthic environment.

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The Environmental Systems Research Institute (Esri) contributions to the GeoHab Seafloor Geomorphology Workshop included:

(i) using the common datasets to demonstrate BTM look and feel;
(ii) A discussion on implementation options between ArcMap and ArcGIS Pro;
(iii) An overview of functionality and analysis basics.

The Benthic Terrain Modeler (BTM) is a collection of tools for ocean and coastal scientists and resource managers to use in concert with bathymetric data to classify and understand the benthic environment. The BTM was initially developed as a desktop extension for ArcGIS versions 8.x through 9.2SP3. This updated release of BTM for ArcGIS 10.1+ presented here is comprised of a series of ArcPy scripts combined in a custom toolbox that allows the user to run the individual processes as separate functions. The BTM toolbox contains a set of tools that allow users to create grids of bathymetric position index (BPI), standardised BPI's, slope, and terrain ruggedness from an input bathymetric data set. Additionally, two terrain classification tools give users the freedom to create their own zone and structure classifications and define the relationships that characterise them. BTM is now at version 3.0 for ArcGIS for Desktop. A full tutorial with sample data is included with the download (found in 'tutorial' directory). This self-paced training module introduces the benthic terrain modeling concepts used in the BTM, and steps users through sample analyses.

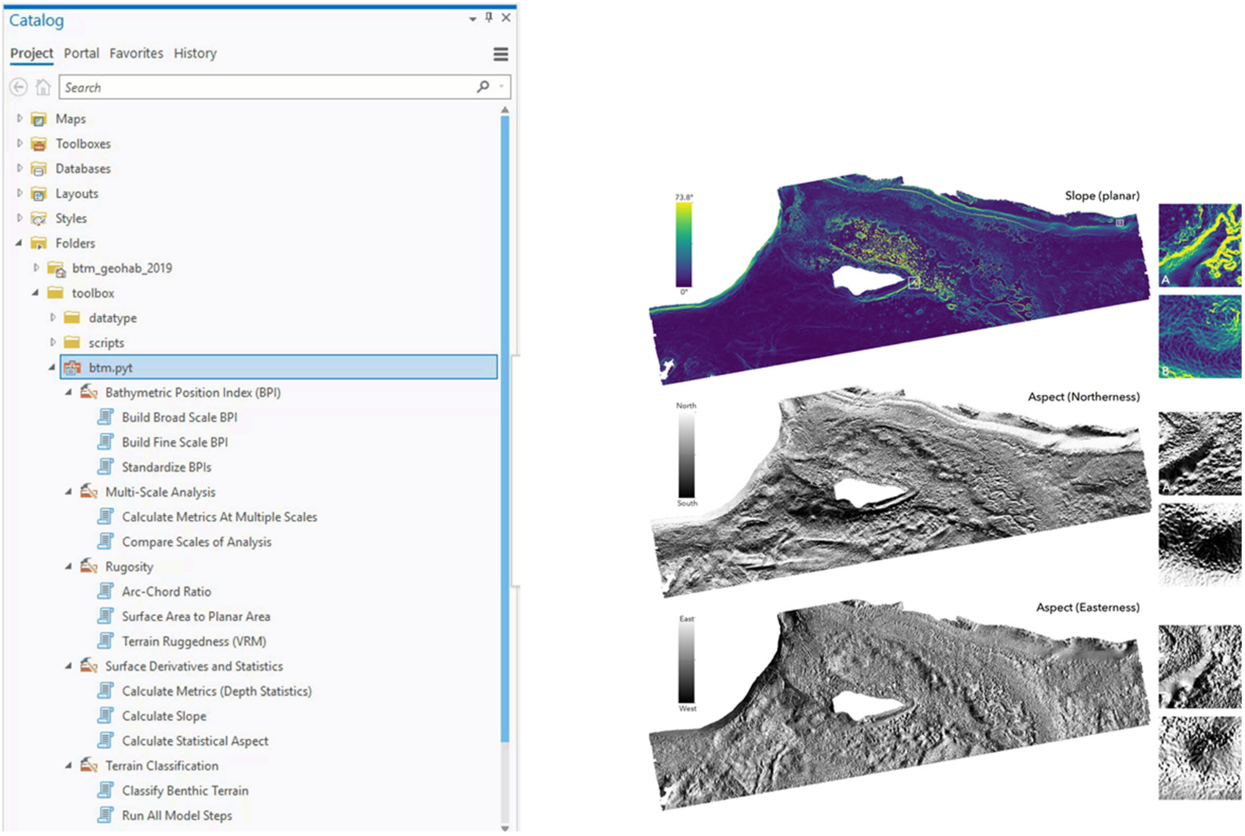

Figure 3: BTM interface and example BTM output. BTM is an Open Source toolbox for Marine Geomorphometry, begun at Oregon State University by Dawn Wright and students. It was developed for simplicity of use for faculty, students, and researchers, and is now maintained and supported by Esri.

Updates: BTM architecture has been redesigned to support Python 3, so the tools are now available in ArcGIS Pro as a toolbox. Block based processing has also been implemented for large raster calculations using the NumPy and SciPy scientific libraries.

New tools include:

- Comparison of Scales of Analysis
- Slope-corrected Surface Area to Planar Area (SAPA)
- Arc Chord Ratio based on the work of DuPreez (2015)
- New depth statistics such as kurtosis and interquartile range
- Excel classification dictionaries
- Surface Area to Planar Area roughness tool
- Statistical Aspect tool

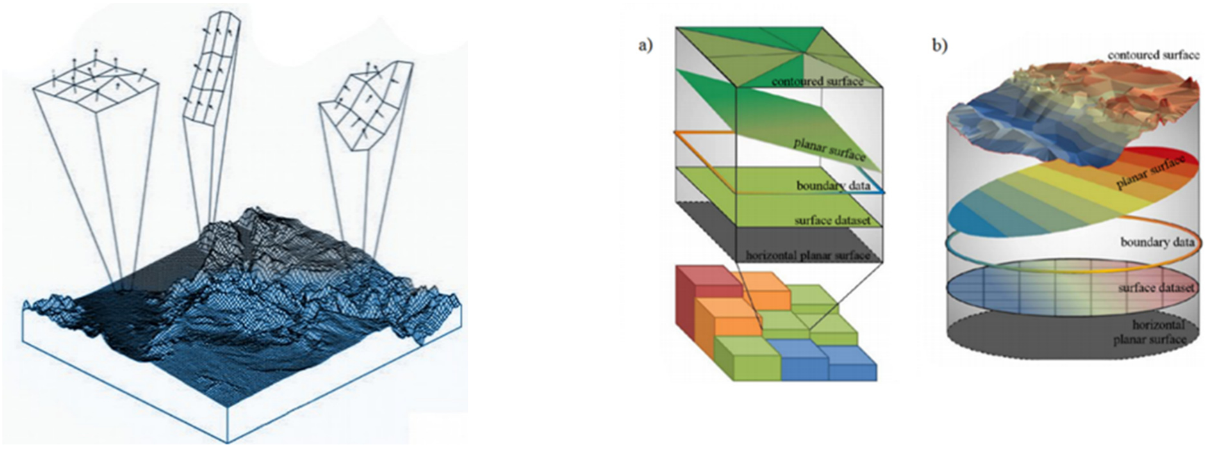

Figure 4: Vector Ruggedness Measure (VRM) (left), and Arc-Chord Ratio (ARC), DuPreez (2015) (Implements Slope Corrected SAPA, and an AOI plane of best-fit method) (right).

Additional resources:

- BTM Download: http://4326.us/btm-install
- BTM on GitHub: https://github.com/EsriOceans/btm
- 2018 Geosciences paper: https://www.mdpi.com/2076-3263/8/3/94
- Noah Slocum technical presentation: https://tinyurl.com/y2ws89us

For further information or questions, please contact:

Shaun Walbridge - swalbridge@esri.com, or Noah Slocum - nslocum@esri.com

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Walbridge, S.; Slocum, N.; Pobuda, M.; Wright, D.J. Unified Geomorphological Analysis Workflows with Benthic Terrain Modeler. *Geosciences* **2018**, *8*, 94. doi:10.3390/geosciences8030094

Du Preez, C., 2015. A new arc–chord ratio (ACR) rugosity index for quantifying three-dimensional landscape structural complexity. Landscape ecology, 30(1), pp.181-192

Demonstrator 4

RSOBIA - Remote Sensing Object Based Image Analysis in ArcMap – a quick and easy toolset

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A new toolbox for ArcMap 10.1 to 10.6 was presented that segments the data layers into a set of polygons. Each polygon is defined by a K-means clustering and region growing algorithm, thus finding areas, their edges and any lineations in the imagery (Bunting et al. 2014). Attached to each polygon are the characteristics of the imagery such as mean and standard deviation of the pixel values, within the polygon. The segmentation of imagery creates a jigsaw of polygons and has the advantage that the human interpreter does not need to spend hours digitising the boundaries.

Input to the segmentation process is a multi-layered raster image, for example; satellite imagery, or any set of raster datasets made up from derivatives of topography. For marine habitat mapping the slope, roughness and backscatter are suggested as important defining data layers to assist interpretation. The minimum size and number of clusters are set by the user and are dependent on the imagery used.

The advantage of having OBIA within the ArcGIS environment is that it can become part of the workflow, either separately or in models. Such integration speeds analysis and allows easier manipulation of data. Comparison with datasets of different provenance was demonstrated and the OBIA segmentation software was presented and results shown.

Meaningful classification of the polygons using their numerical characteristics can be very dependent on the data subject. Many classification systems are available and tailored to the data available. A simple classification tool is provided as a paint function, but it is expected that functionality within ArcMAP is already being used to undertake complex classification rules.

There are two ways use the toolbox: one is to create derivatives manually from the user's data and to layer these datasets together in a multi-layered raster image, or to use a simple wizard which takes bathymetry grid and backscatter imagery and will calculate the segmentation according to predefined criteria.

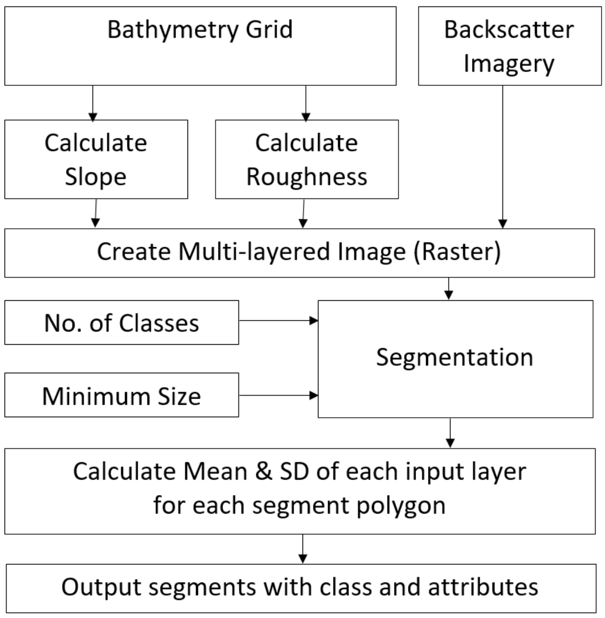

Figure 1: Basic workflow for RSOBIA multibeam bathymetry wizard for habitat mapping

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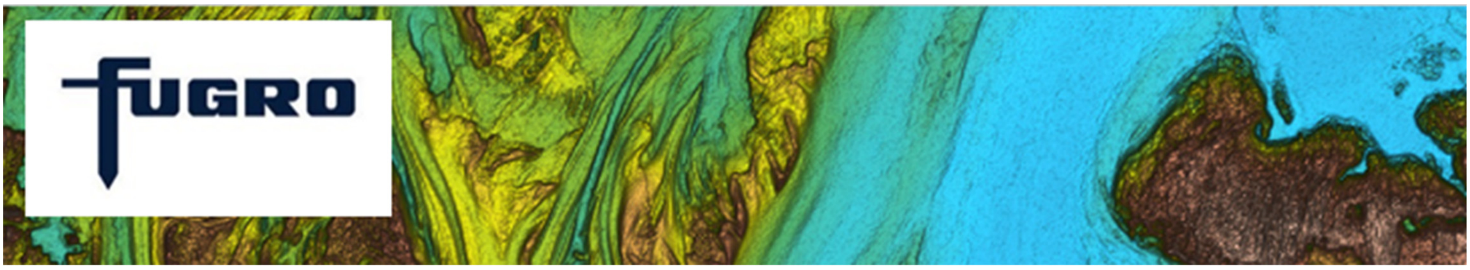
Demonstrator 5



Dynamic Shallow Water Risk Assessment

Rada Khadjinova, Fugro - *ask@fugro.com*

Nearshore and foreshore coasts, estuaries, and riverbed environments are dynamic and can evolve on time scales from weeks to years. Fugro's 4D Satellite Seabed Morphology (4DSSM) provides up-to-date imagery in the vicinity of your shallow water (<25 mwd) development area, helping to mitigate risks in this rapidly changing environment. This low cost, rapid turn-around assessment can help you reduce project demands and costs and improve overall project safety.

Geomorphological surveys in coastal areas quickly become outdated by the installation of coastal and subsea infrastructure, natural and man-made changes to coastlines, and variation in sediment loads due to a constantly evolving environment. As an extension of our Law of the Sea investigations and mapping services, Fugro uses Landsat optical imagery as source data and applies a series of proprietary and customised tools to provide 15-m-resolution images for any dynamic shallow water area of interest in the world. With imagery available from February 2013 to the present day, we produce near-real time, visually intuitive datasets for understanding changes over time in dynamic shallow water environments. The global coverage extent is 85°N to 85°S and 180°W to 180°E. All landmasses, shorelines, nearshore, and shallow water offshore areas are covered. Extensive testing and ground truthing suggest derived results are robust, and reveal near-present-day seabed morphology (skin of the earth beneath the water) useful for preliminary project site planning. Present-day results can be compared to images up to six years old, to evaluate both natural and man-made modifications to the seabed that may present hazards, thus helping ensure proper risk identification and mitigation for any shallow-water project.

Benefits of 4DSSM:

✓Reduce costs - inexpensive, provides key early information

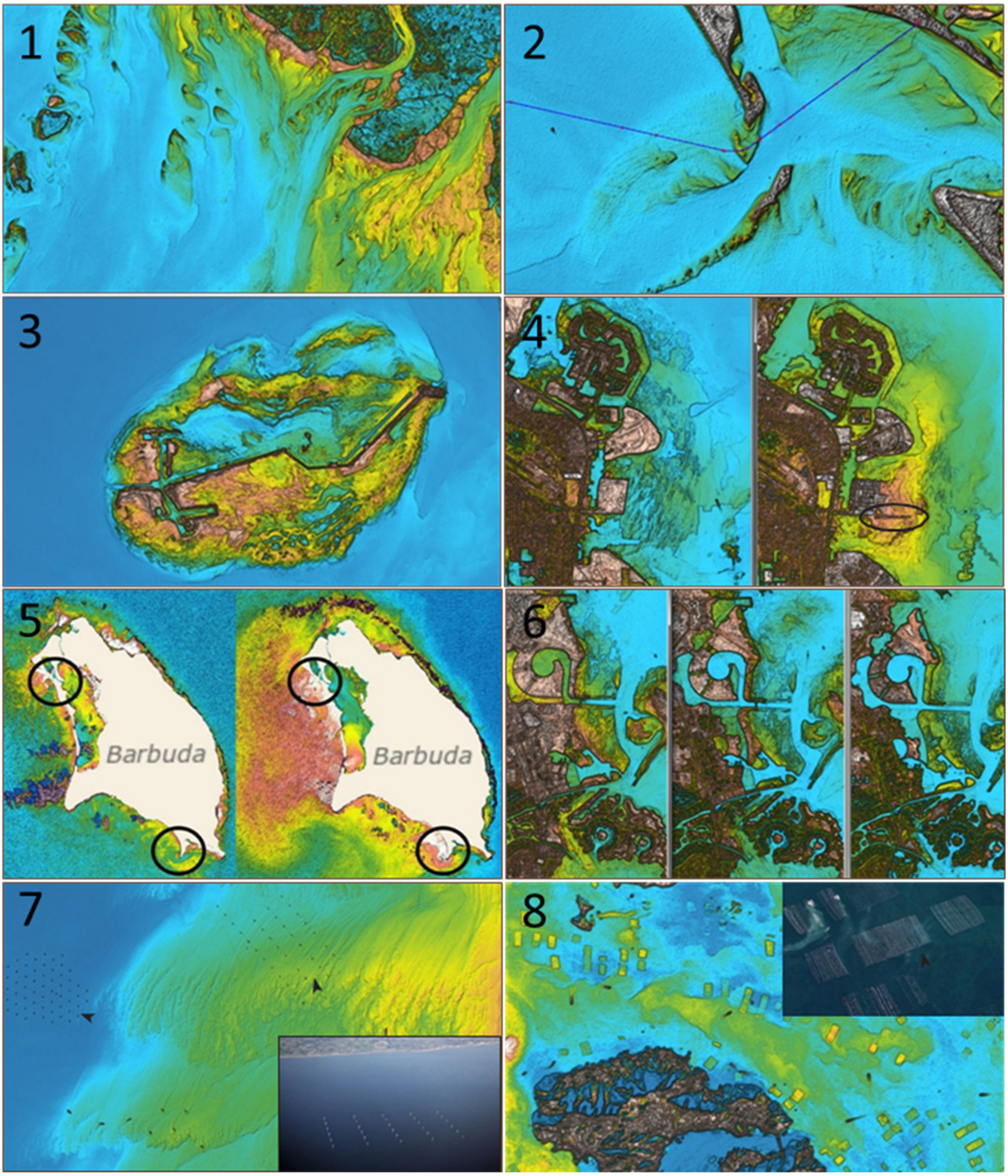
✓Reduce risks - Identify and mitigate shallow water risks for project planning

✓Accelerate project planning - rapid turn-around service

✓Identify and understand a rapidly changing environment over time

Example applications*

1. Shallow water preliminary site investigations
2. Pipeline or telecom cable landing site analysis
3. New infrastructure installations
4. Dredging activities, harbor planning and works, and channel evaluation
5. Damage assessment after significant events (e.g., storms, earthquakes)
6. Fast look at seabed conditions where prior surveys may be outdated, including review of nautical charts
7. Renewables site planning (windfarms, seabed cable infrastructure, etc.)
8. Identification of uncharted temporary manmade structures (construction barges, aquaculture rafts, etc.)



4DSSM application examples: *1. Shallow water preliminary site investigations. Example from Guinea-Bissau. 2. Proposed pipeline route analysis. Shoaling near the pipe bend required additional design work. Example from Mexico. Example from Mexico. 3. New infrastructure installations. Example from the United Arab Emirates. 4. Dredging activities, harbor planning and works, and channel evaluation. Example from Bahrain March 2013 (left) and March 2019 (right), note the new pier circled in 2019 image. 5. Initial Damage assessment after significant events. Example is from the Caribbean island of Barbuda, pre- (left) and post- (right) category 5 Hurricane Irma, Nov 2017. 6. Fast look at seabed conditions where prior surveys may be outdated, including review of nautical charts. Examples from Qatar (left to right): March 2013, March 2016, March 2019. 7. Renewable energy site development planning (black dots are installed windmills). Example from the Netherlands; inset photo shows the grid layout of a windfarm. 8. Identification of uncharted manmade structures (construction barges, aquaculture rafts, dredged channels, etc.). Example oyster farms in South Korea; inset is photo of the farms.*

Email ask@fugro.com for more information on 4DSSM services.

Demonstrator 6

An open source GIS approach for application of generic and specific geomorphometry

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Geomorphometry is the quantitative description of a form (morphometry) when applied to the Earth's surface (Thomas, 2016). Geomorphometry can be divided into 1) general geomorphometry, which analyzes the land surface as a continuous surface described by local attributes; and 2) specific geomorphometry, which relates to a specific surface's features and deals with their quantitative description. Specific geomorphometry can be further described as the process of using a segmentation process to subdivide terrain into landforms and to characterise of the resulting segments based on their relationship to one another (Evans, 1980).

Here we describe open-source tools developed for the quantitative description of terrain attributes, which are fully integrated into a GIS environment. Two different methods, both integrated into the GRASS GIS (GRASS Dev. Team, 2017), are considered:
1) ***r.param.scale*** - based on differential geometry principles (Wood and Snell, 1960; Wood, 1996; Dragut et al., 2009), and
2) ***r.geomorphon*** **-** based on pattern recognition principles (Stepinkski and Jasiewicz, 2011).

In ***r.param.scale***, terrain features are determined by analyzing the slope and curvature of each grid cell by running a fixed-size focal window operator on the whole surface; while ***r.geomorphon*** performs an elevation difference between a focus pixel and other pixels at a known distance (search radius) in eight principal directions (N, NE, E, SE, S, SW, W, NW). Starting from the east and proceeding counterclockwise, the algorithm produces a ternary operator that identifies a specific topographic pattern (geomorphon) that can be then be associated with a particular landform element (Jasiewicz, 2013).

Table 1: *Descriptive list of the bathymetric derivatives provided as output layers by the 'r.param.scale' routine.*

Output	**Description**
slope	The magnitude of the maximum gradient (steepest slope angle)
aspect	The direction of the maximum gradient (steepest slope direction=flow direction)
profc	Profile curvature (curvature intersecting with the plane defined by Z-axis and maximum gradient direction). Positive values describe convex profile curvature, negative values concave profile curvature.
planc	Plan curvature (horizontal curvature, intersecting with the XY plane)
longc	Longitudinal curvature (profile curvature intersecting with the plane defined by the surface normal and maximum gradient direction)
crosc	Cross-sectional curvature (tangential curvature intersecting with the plane defined by the surface normal and a tangent to the contour - perpendicular to maximum gradient direction)
maxic	Maximum curvature (can be in any direction)
minic	Minimum curvature (in direction perpendicular to the direction of maximum curvature)
feature	Morphometric features: peaks, ridges, passes, channels, pits and planes

Table 2: Descriptive list of the bathymetric derivatives provided as output layers by the 'r.geomorphon' routine.

Output	**Description**
form	geomorphic map with 10 most popular terrestrial forms. Legend for forms, its definition by the number of + and - and its idealized visualization are presented at the image.
pattern	code of one of 498 unique ternary patterns for every cell. The code is a decimal representation o 8-tuple minimalized patterns written in the ternary system. A full list of patterns is available in the source code directory as patterns.txt. This map can be used to create alternative form classification using a supervised approach
positive and negative	codes binary patterns for zenith (positive) and nadir (negative) line of sights. The code is a decimal representation of 8-tuple minimalized patterns written in binary system. Full list of patterns is available in source code directory as patterns.txt

intensity	average difference between the central cell of geomorphon and eight cells in visibility neighborhood. This parameter shows local (as is visible) exposition/abasement of the form in the terrain
range	difference between the minimum and maximum values of visibility neighborhood.
variance	variance (the difference between particular values and mean value) of visibility neighborhood.
extend	area of the polygon created by the 8 points where line-of-sight cuts the terrain.
azimuth	orientation of the polygon constituting geomorphon. This orientation is currently calculated as an orientation of the least square fit line to the eight vertices of this polygon.
elongation	proportion between sides of the bounding box rectangle calculated for geomorphon rotated to fit the least square line.
width	length of the shorter side of the bounding box rectangle calculated for geomorphon rotated to fit the least square line.

For more details about the two tools, refer to the GRASS GIS manual [9] [10] and to a wiki page dedicated to terrain analysis in GRASS GIS [11].

Both methods offer a wide range of input parameters, allowing the detection of many terrain features at different scales (Specific Morphometric Measurements), and producing many terrain derivatives (Generic Morphometric Measurements). The complete list of outputs and their corresponding descriptions are listed in Table 1 (r.param.scale), and Table 2 (r.geomorphon). However, such flexibility comes with a cost. It has been observed that for different values of the input parameters, the two methods can return completely different results [12]. Thus, it is crucial for users to have a good understanding of how the algorithms behave in response to parameter adjustments, and their combinations [12].

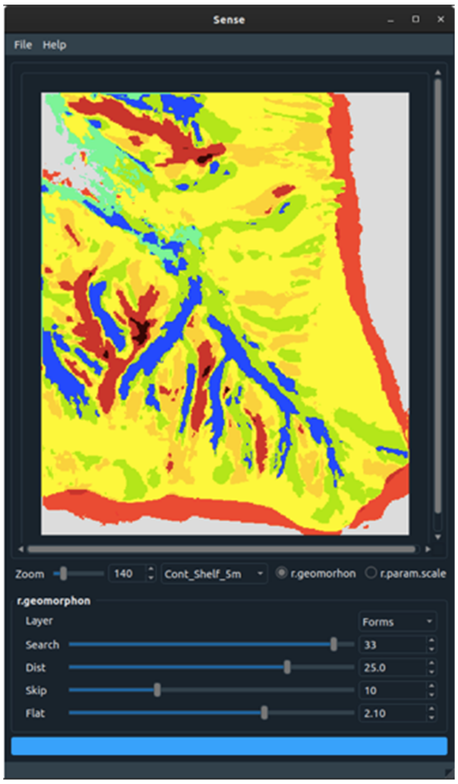

Figure 1: User interface developed to visually explore the behavior of the algorithms in response to input parameter adjustments.

Table 3: Summary list of parameters and the ranges used in the simulation analysis.

Method	**Parameter**	**Range**	**Step**
r.param.scale			
	Size of processing window	3 - 25	2
	Curvature tolerance that defines 'planar' surface	0.0001 - 0.01 0.01 - 0.1	0.001 0.01

	Exponent for distance weighting	0 - 5	1
	Z scale	0 - 3	0.5
	Slope tolerance that defines a 'flat' surface (degrees)	0 - 3	0.1
r.geomorphon			
	Outer search radius	5 - 35	1
	Inner search radius	0 - 33	1
	Flatness threshold (degrees)	0.1 - 3.0	0.1
	Flatness distance	7 - 33	1

For the reasons above, the experiment proposed during the **GeoHab2019** workshop on geomorphometry focused on:

1. Presenting the results of a sensitivity analysis of the two methods = The analysis consisted of visually exploring the outputs of several runs of each tool with a wide range of input parameters;
2. A discussion on how to utilise the specific geomorphometry output, to further identify and quantitatively characterise various element of the seascape like sand waves, ripple fields, and pock-marks.

We explored the results of the sensitivity analysis, an ad-hoc application was presented (Figure 1) which allowed users to visualise in near real-time the effect on outputs resulting in small variations of each input parameter. By exploring the specific geomorphometric outputs, it was shown how the results of each method can be considered as a starting point for further segmentation and characterization of the bathymetric surfaces.

We further discussed how, through using different values of the input parameters, and by combining the results of multiple runs of each method, it is possible to identify different terrain features at different spatial scales.. This capability supports the development of complex geospatial-analysis routines that enable the quantitative and automated identification of specific landform elements on the seafloor. With this understanding, an approach for the detection and quantitative characterization of large and isolated bedforms was presented Figure 2 [12]. Lastly, it is important to emphasise the importance of having such tools fully integrated into a GIS environment, which by combining already existing raster and vector geoprocessing routines, can speed-up the development of complex models for the quantitative characterization of the seascape

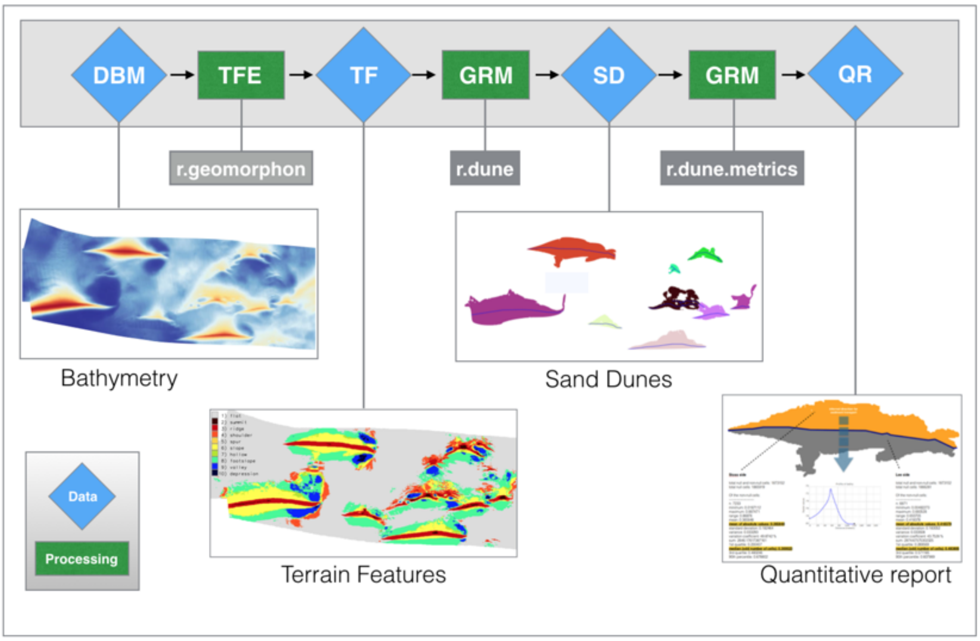

Figure 2: *Schematic describing a procedure for the quantitative characterization of bedform.*

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Demonstrator 7

MIM-GA: Seafloor Geomorphology classification framework; applications and novel mapping methodologies

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Mareano (Norway), INFOMAR (Ireland), MAREMAP (UK), and Geoscience Australia (GA) (MIM-GA) is a collaboration between several marine mapping groups who share similar goals and challenges. A key challenge has been to more effectively (accuracy, detail, consistency, efficiency) characterise the geomorphology of the seafloor. The first significant MIM-GA activity towards this aim has been to develop a classification framework to support geomorphological mapping. Prior to establishing MIM-GA, several of us were independently realizing that we were undertaking more and more geomorphological mapping (i.e. due to the availability of high-quality data; and varied applications of geomorphic mapping), but the absence of a robust classification approach impeded producing consistent, and where required, standardised map products. The first output from this effort was v. 1 of the new 'Two-part geomorphological classification system' (Dove et al., 2016 - (http://nora.nerc.ac.uk/id/eprint/514946/). The classification approach has since been applied to a range of UK and Australian marine settings. In this case-study we describe the attributes of the classification approach and how it is being improved, show several mapping examples, and then present several semi-automated mapping tools that MIM-GA members have employed to detect and delineate geomorphic features, prior to classification. This is a significant point; the 'Two-part' classification scheme provides a framework of target units to map, but does not stipulate or require any particular mapping method (e.g. manual, unsupervised, model-based prediction).

'Two-part geomorphological classification system'

Basic principles (see Fig. 1; Appen. 3; and Dove et al. (2016) for further detail):

- Independent assessment of 'Morphology' and 'Geomorphology' (robust/flexible approach to characterise seafloor features)
    - Morphology: Fundamental physical shape of feature (objective); (e.g. 'Bathymetric High > Mound > Streamlined Mound');
    - Geomorphology: Interpreted origin, process association of feature (subjective) (e.g. 'Glacial > Subglacial Landform > Streamlined landform > Drumlin';
- All features mapped should have 'Morphology' class; the Geomorphology class is attributed as an interpretation, with confidence levels recorded.
- Hierarchical scheme allows features to be described to varying levels of detail.
- With v.2 of the Two-part scheme, all features will have an associated glossary definition. We anticipate this will be a useful resource for the community;
    - 'Morphology' glossary, with associated schematics, is near publication;
    - 'Geomorphology' glossary anticipated for early 2020.

MIM-GA are currently preparing V.2 of the Two-part classification approach based on practical experiences thus far, which will include glossary entries for 'Morphology' and 'Geomorphology' features.

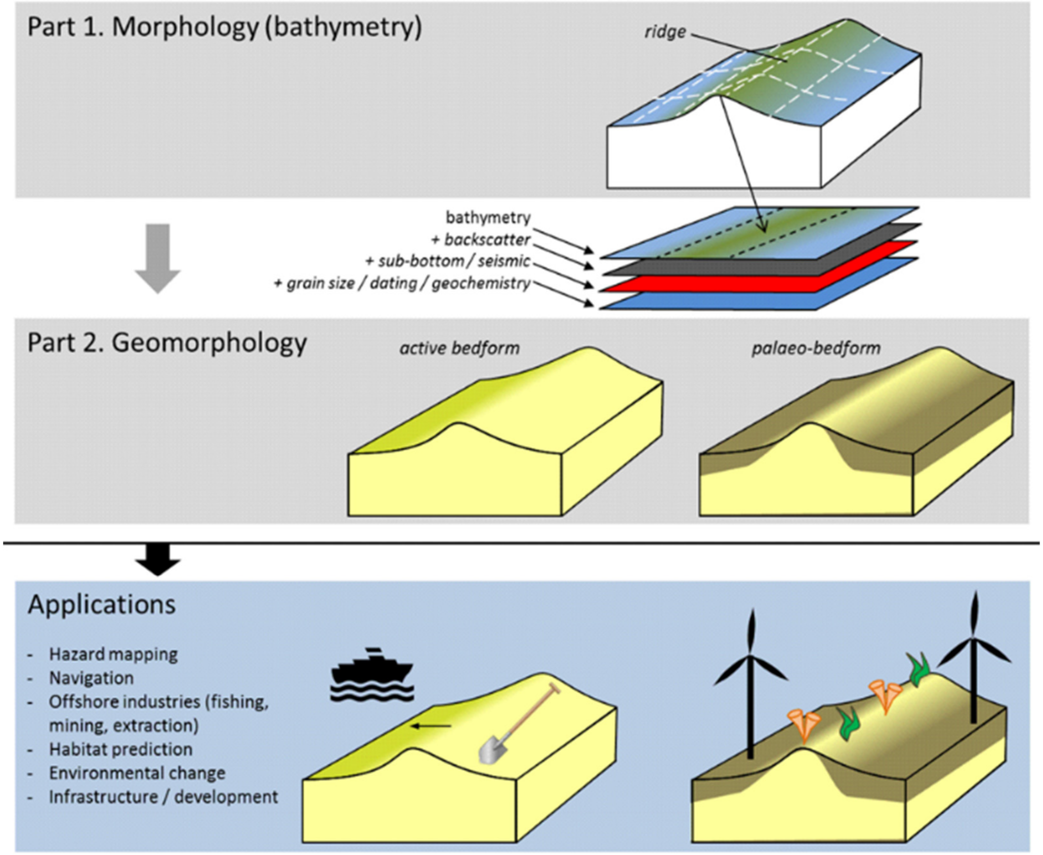

Figure 1:Two-part classification: The bathymetry of the seafloor can be used to map feature Morphology (Part 1), however, additional datasets may be used to interpret the feature genesis, and predicted sub-surface composition (i.e. the Geomorphology – Part 2) (Dove et al., 2016; Nanson and Nichol, 2018). The implications of alternative Geomorphological (Part 2) interpretations of a Morphological (Part 1) Ridge are illustrated in the Applications panel. V.1 of the classification structure, with the full suite Morphology and Geomorphology terms is presented in Appen.3.

Applications of the 'Two-part' classification approach

Orkney Islands, UK continental shelf

- An area (~7,000 km²) east of Orkney Islands represents the first formal application of the 'Two-part" approach in UK Waters (Fig. 2- *Dove et al., in prep*).
    - Maps produced using a semi-automated approach, and GIS implementation (Marine SIGMA - https://www.bgs.ac.uk/research/sigma/home.html) of the two-part scheme (Fig. 2). In short, this method merges relative bathymetric highs and lows at multiple spatial resolutions (Lecours, 2017) together with unsupervised clustering to identify the most pronounced high, or low at any location. Bulk attribution of classes employs 'expert' knowledge. This approach allows the user to exploit computational efficiency to produce detailed linework, but saves the interpretation and classification of features for the mapping scientist;
    - Map products and the accompanying report will soon be released via: http://mapapps2.bgs.ac.uk/geoindex_offshore/home.html

Common dataset, Continental shelf of Norway

- The method applied in the Orkney example above was also applied to the common-data set (Figs. 1, 3). The full mapping process took ~4 hours (i.e. Assembling data layers, calculating bathymetric derivatives (*majority of time*), and tentative feature classification).
    - The semi-automated approach identified both Pock Marks (Morph=Depressions), and iceberg ploughmarks (Morph=Grooves) (Fig. 3). A simple area threshold was used to differentiate and bulk classify the two features, which will have caused some misclassifications (e.g. very large pockmarks, very small ploughmarks).

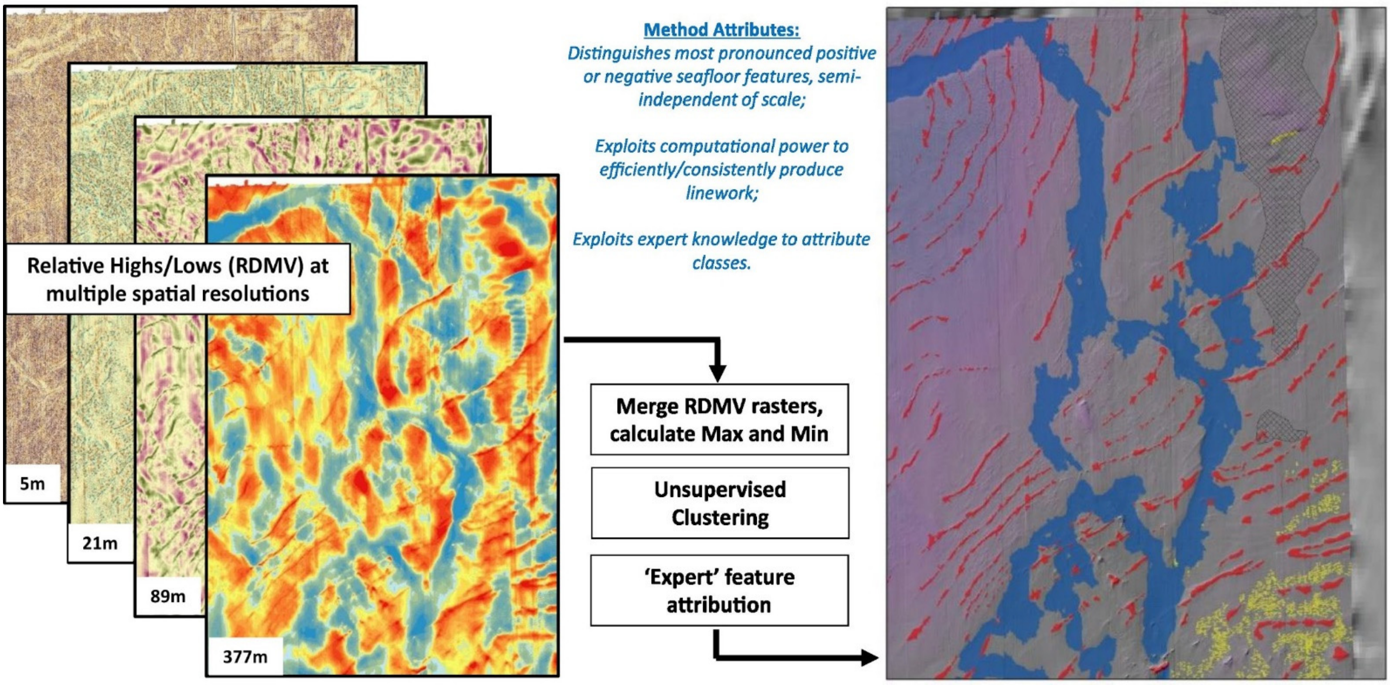

Figure 2: Left panel) Semi-automated procedure to detect, delineate, and classify ('Two-part' approach) features. Right panel) Draft Geomorphology map from Orkney Islands shows features of different scale being captured by method (i.e. sediment waves, moraines, and sub-glacial channels).

Figure 3: Two-part classification approach showing independent Morphology, and Geomorphology classes. Mapping method employed semi-automated detection and delineation of common data set (Norwegian continental shelf). Classification over hillshade bathymetry.

Evolution of the two-part approach and applications in Australia

Geoscience Australia (GA) have been advancing the Dove et al. (2016) two-part scheme through discussion with their stakeholders at a National Seafloor Geomorphology Mapping workshop (NSGM: Nanson and Nichol, 2018a). The method has been successfully applied to a diverse range of Australian marine settings, including Perth Canyon (Western Australian continental slope; Nanson et al, 2018b), Gifford Guyot (Lord Howe Rise; Nanson et al., 2018) and Darwin and Bynoe Harbours (continental shelf; Nicholas et al., in press). Figure 4 provides an example glossary term for a targeted Morphological unit. Mapping was semi-automated, and comprised three sequential steps:

(1) Running the 10 m bathymetry grid through Benthic Terrain Modeller (BTM: Walbridge et al., 2018);
(2) Generalising these shapes using ArcGIS Majority Filter and Aggregation tools;
(3) User-defined reclassification of these output to match the revised (Part 1) Morphology (Dove et al. 2016) target features.

An example of these results is presented in Figure 4b, which illustrates a mapped portion of each of the two largest channels in the region, and the adjacent and overlapping Knolls, Ridges, Bedforms (field) and Slope. Subsequent interpretations of the backscatter, Optically Stimulated Luminesence dating, extensive sediment sampling and sub-bottom profiling were used to interpret the Geomorphology of these shapes (Figure 1 Part 2; Dove et al, 2016). Notably, the Ridge schematic in Figure 1 above was devised on the basis of relict Ridges (Morphology) that were mapped in Darwin Harbour, and subsequently interpreted using sub-bottom, backscatter and dating to be relict aeolian dunes. This case emphasises the need for a two-step approach, whereby geomorphic interpretations are undertaken as a secondary step where expertise and data can support it.

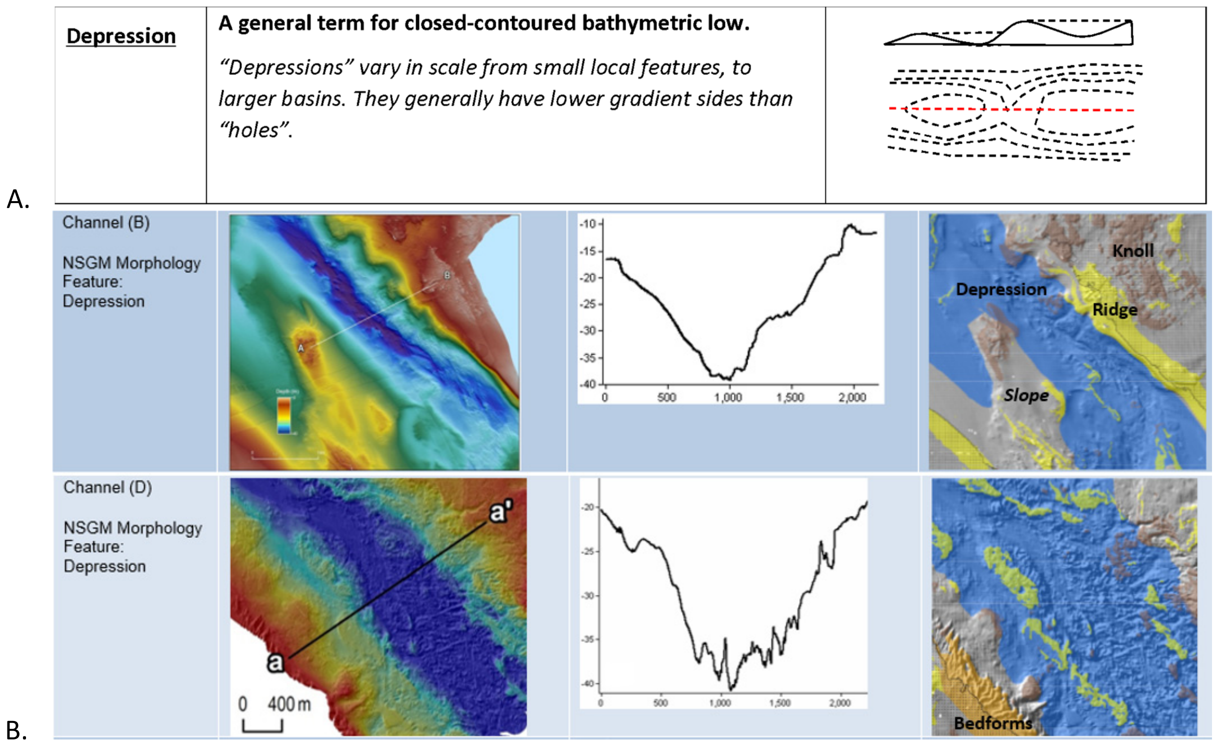

Figure 4: A) Morphology Glossary Example: 'Depression' feature targeted in Darwin Harbour. B) Example mapping of BTM-derived depressions (Morphology; Geomorphology: Channel), Knolls, Ridges, Bedforms and Slope in Darwin and Bynoe Harbours (Australia).

Semi-automated mapping tools for geological map products, examples from NGU

NGU have been expanding their use of semi-automated tools for geological mapping in recent years. The main driver for this move towards semi-automated workflows is a need for efficient, objective and repeatable workflows which address the demands of extensive seafloor mapping tasks using large volumes of data and deliver products in keeping with user expectations. Different approaches, of varying complexity, have been tried over the past few years. In some cases, these have been ad-hoc developments, arising from immediate needs for solutions. For example, GIS-analyses have been used for the generation of terrain attributes such as slope and BPI to aid the delineation of various geomorphic features. Similarly, area thresholds have been used to delineate large iceberg ploughmarks for the purpose of mapping the distribution of different sediment classes. Another example is the use of Geographic Object Based Image Analysis (GEOBIA) to classify the distribution of bedrock, based on a range of bathymetric data and derivatives and by combining image segmentation with the results of classification trees that can be translated into classification rule-sets in GEOBIA. In other cases, method development has been defined as specific projects with in-depth work and well-defined deliverables. An example of this is a recent method development study aimed at constructing a method for delineating cold-water coral carbonate mounds on the seafloor. In this project a methodology for deriving maps of coral mounds was developed, including an associated spatially-explicit confidence measure. The approach includes a combination of image segmentation and random forest spatial prediction, applied to multibeam bathymetry data. Presence and absence of mounds was predicted with high accuracy and confidence, with image-object mean planar curvature as the most important predictor. This method is described in detail by Diesing and Thorsnes (2018).

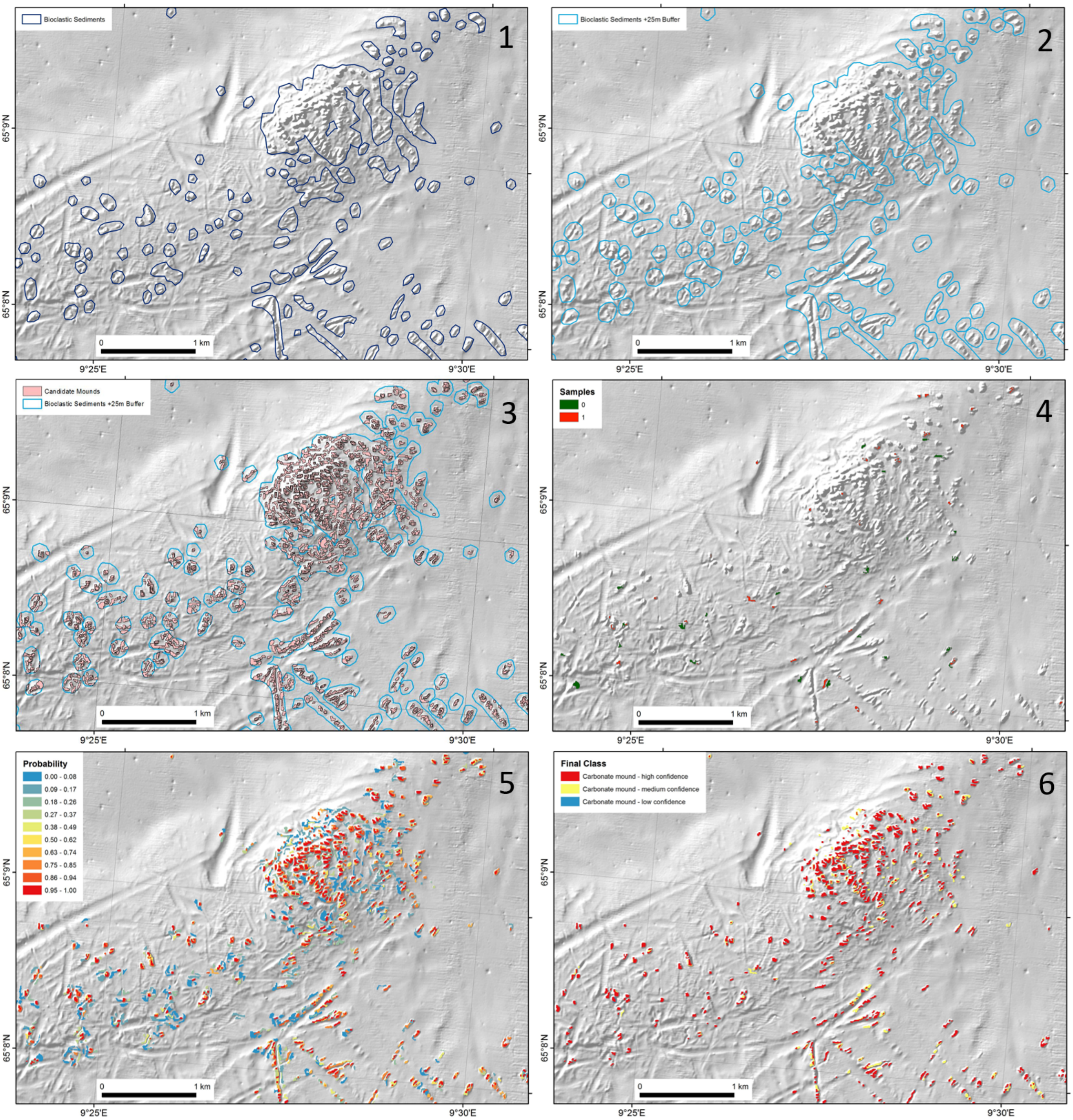

Fig. 5: Cold-water coral carbonate mounds. 1) Manually mapped bioclastic sediments. 2) 25 m buffer around bioclastic sediments used as a constraint for further mapping. 3) Candidate mounds defined within constrained area based on geomorphometry ('positive relief'). 4) Presence/absence 'samples' of mounds, derived by expert interpretation of randomly selected image objects. 5) Random Forest prediction showing probability of mounds. 6) Final class with confidence. See Diesing & Thorsnes (2018) https://doi.org/10.3390/geosciences8020034 for details.

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Key themes - Future challenges

- ### Seafloor Geomorphology is commonly a key 'means to an end', and less an 'end in itself'

  This idea was borne out of the presentations and discussions during the workshop, as well as from the results of the Questionnaire (Appen. 2). Many participants indicated that geomorphic mapping is required for their work, but there is less demand (currently) for Geomorphology maps as an end-product. So in this sense, Geomorphology may be viewed as a tool kit that is regularly used (if not required) to address a diverse range of applications (habitat mapping, resource development, palaeo-environmental science, and marine spatial planning);

- ### What are you mapping? Communication is key

  As discussed under the 'Geomorphology is a broad church' heading, there has been significant recent progress in developing new mapping/analysis methods that approach Geomorphology from different angles, e.g. quantitative 'morphometry' vs. subjective interpretations of formative environmental process/dynamics. Both have their value (and may at times be most effective when used together), but one important discussion point was that to ensure geomorphic maps/analysis are used appropriately and effectively, the pertinent attributes and uncertainties of the maps/analysis must be clearly communicated. This might include information on source data (e.g. spatial resolution), automated vs. 'expert' interpretation method applied (and limitations of each approach), scale dependence of features mapped (e.g. are features of a particular size range emphasised over others), and whether one makes inferences on bedform mobility, sub-surface geotechnical properties, etc..;

- ### An aspirational group

  The questionnaire results indicated that a significant number of people who don't currently use these methods, plan to employ more quantitative analysis methods in the near future (and undertake less manual 'expert' mapping). Key challenges were identified however, including access to appropriate software, the requirement to develop further skills, and/or establish collaborations with others who already possess these skills;

- ### The inevitability of automation?

  Each of the case studies presented above, to varying degrees, employs mathematical criteria and automation in the production of geomorphic maps. These methods offer efficient analysis, with transparent repeatable methods, where rules are applied consistently across the map/analysis area. With increasing volumes of high-resolution data, the appeal of such methods is obvious. The workshop common-dataset (continental shelf data set at 5m), for example, included at least 100,000 pockmarks. Capturing this detail using manual 'expert' mapping would be labour intensive and simply not be effective. Yet, each of the automated approaches will vary in what is mapped, depending on different physical rules and morphological thresholds, and do not (currently) characterise what 'type' of feature is present. For example, a purely automated approach could easily result in a similar classification for an unconsolidated sediment drift and a glacial drumlin, but because these features of similar morphology result from very different formation mechanisms, they will comprise significantly different sediment characteristics (and geotechnical properties), and will behave differently over time (e.g. potential substrate for benthos, or modification from storm/wave events under changing climate). An ongoing question to the community will be to what extent we require expert knowledge in the process of mapping geomorphology (accepting implicit biases), vs. how well new methods can be 'trained';

- ### Requirement for classification standards; or available standards are not currently fit for purpose

  Many participants listed that lack of Seafloor Geomorphology classification standards as a key obstacle for effective, consistent mapping. A challenge to the community will be to develop classification approaches that are fit-for-purpose for a broad range of applications (or perhaps application/discipline specific). And further challenges/questions will be whether these classification approaches will be applicable to a range of geomorphic/geographic environments, and whether they'll effectively handle spatial scale, i.e. accommodate the characterisation of seafloor features of highly variable size and morphology.

Appendices

Appendix 1: Workshop Agenda

Seafloor Geomorphology Workshop;

GeoHab Pre-Conference Workshop (13 May, 2019)

'Big Conference Hall', VSEGEI – Russian Geological Research Institute

Agenda

- ***9:00-9:30 – Registration (and coffee?);***
- ***9:30-9:40 –Host welcome and workshop introduction;***
- ***9:40-9:55 – Invited presentation: 'Merits of geomorphological mapping and applications to ecosystem science' - Peter Harris (GRID –Arendal);***
- ***9:55-10:00 – Questionnaire Results;***
- ***10:00-10:50 – Workshop exercise #1: Manual mapping and fundamental principles;***
- ***10:50-11:10 - Coffee Break;***
- ***11:10-11:20 – Exercise #1 results and discussion;***
- ***11:20-11:35 – Invited presentation: 'Morphometrics and quantitative applications within geomorphological mapping' - Vincent Lecours (Univ. of Florida);***
- ***11:35-12:20 - Workshop Exercise #2: Demonstration of geospatial tools for geomorphological mapping;***
    - ***Introduction to exercise, and sample results from volunteer demonstrators;***
- ***12:20-13:20 – Lunch;***
- ***13:20-15:15 – Exercise #2 cont.*** *(*list of demonstrators on following page)*
    - ***13:20-14:30: Organised group rotation around interactive mapping tables;***
    - ***14:30-15:15: Coffee, and interactive mapping tables – free to roam;***
- ***15:15-15:30: Invited presentation: 'Future considerations regarding geomorphological mapping, and challenges for the community' - Geoffroy Lamarche (NIWA / Univ. of Aukland);***
- ***15:30-15:45: Exercise #2 discussion, and final remarks.***

Workshop Organisers: *Dayton Dove (BGS), Lilja Bjarnadottir (NGU), Janine Guinan (GSI), Tim Le Bas, (NOCS), Rachel Nanson (GA), Kim Picard (GA), Margaret Dolan (NGU), Peter Harris (GRID-Arendal), Aaron Micallef (Univ. Malta)*

Exercise #2 Interactive mapping tables: Volunteer Demonstrators

- *Marc Roche (SPF Economie) - Osculatory Surfaces Extraction applied to Monitoring of Sub-marine Sand Material.* *https://www.tandfonline.com/doi/abs/10.1080/01490419.2018.1509161*
- *Vincent Lecours (Univ. of Florida) - Terrain Attribute Selection for Spatial Ecology (TASSE) toolkit:* *https://www.researchgate.net/publication/314300617_TASSE_Terrain_Attribute_Selection_for_Spatial_Ecology_Toolbox_v_11*
- *Shaun Walbridge and Drew Stephens (ESRI): ArcGIS Benthic Terrain Modeler (BTM):* *https://www.arcgis.com/home/item.html?id=b0d0be66fd33440d97e8c83d220e7926*
- *Tim Le Bas (National Oceanography Centre, Southampton (NOCS)) – Remote Sensing Object Image Analysis (RSOBIA):* *https://www.oceanwise.eu/software/rsobia-remote-sensing-object-based-image-analysis/*
- *Rada Khadjinova (Fugro) - 4D Satellite Seafloor Morphology (4DSSM) - Satellite data to improve nautical charts and maritime boundaries:* *https://www.fugro.com/*
- *Massimo Di Stefano (CCOM – Univ. New Hampshire): Open source GIS (GRASS and QGIS) for applications of generic and specific geomorphometry:* *https://github.com/epifanio*
- *MIM-GA: (MAREANO, Infomar, MAREMAP, Geoscience Australia) – 2 part classification approach, applications, and methods:* *https://www.researchgate.net/publication/309475889_Seabed_geomorphology_a_two-part_classification_system*

Lilja Bjarnadottir (Geological Survey of Norway (NGU)), Janine Guinan (Geological Survey Ireland (GSI)), Dayton Dove (British Geol. Survey (BGS)), Rachel Nanson (Geoscience Australia)

APPENDIX 2 – Questionnaire

A questionnaire was circulated via Survey Monkey to the workshop participants in advance to help set the context for the workshop and gauge the challenges, issues and interests most relevant to the attendees.

The questionnaire consisted was completed by 49 participants.

Question 1 - What is your motivation for attending the workshop?

Answer choices	Responses %	Number
To learn about what other people / institutions / programmes / countries are doing	34.69	17
To make contact with other geomorphological mappers	12.24	6
To learn how to use automated / semi-automated methods	28.57	14
To learn about software	0	0
To learn about new and upcoming advances	24.49	12
As part of attendance at GeoHab	0	0
Just killing time before the ice-breaker	0	0
		49

Question 2 - What is your primary field of work?

Answer choices	Responses%	Number
Geological mapping	51.02	26
Habitat mapping	30.61	16
Species distribution modelling	8.16	4
Technical development	2.04	1
Management	4.08	2
Other (see below)		
		49

Other
Management and control of sand extraction Geophysical survey

Question 3 - How would you rate the demand (1-10) for geomorphic mapping in your field (1 = highest; 10 = lowest)?

Score = 3.5 (medium high)

Question 4 - To which applications do you apply geomorphological mapping? (Select those most relevant)

Answer choices	Responses%	Number
As a step towards modeling habitat / species distributions etc	61.22	30
To support commercial development of the seabed	14.29	7
To support Marine Spatial Planning	36.73	18
For the production of a geomorphological map	61.22	30
Characterising geomorphological features and assemblages for purposes of paleo environmental science	32.65	16
None of the above	0	0
This question is not relevant to me	0	0

Question 5 - How would you rate the importance of geomorphic information and / maps to your work?

Average score = 76%

Question 6 - What data types do you use for geomorphological mapping?

Answer choices	Responses%	Number
Multibeam bathymetry	89.8	44
Single beam bathymetry	2.04	1
Lidar	0	0
Multi-spectral satellite data	0	0
Nautical charts	2	1
Structure from motion (e.g. drone / uw footage	2	1
None of the above	2	1
The question is not relevant to me	2	1
		49

Question 7 - Do you map to the full resolution of your data i.e. all significant features that can be resolved are mapped

Answer choices	Responses%	Number
Always	14.29	7
More often than not	34.7	17
Sometimes depending on the scope of the work	40.82	20
Usually not	8.16	4
Never	0	0
The question is not relevant to me	2.04	1
		25

Question 8 - Do you assess the limitations of your data (i.e. quality / uncertainty linked to acquisition / processing)

Answer choices	Responses%	Number
Always	24.49	12
More often than not	28.57	14
Sometimes, depending on the scope of the work	36.73	18
Usually not	4.08	2
Never	0	0
The question is not relevant to me	6.12	3
		49

Question 9 - Which mapping methods do you use regularly?

Answer choices	Response%	Number
Manual (expert driven digital / analogue mapping i.e. polygons / lines are drawn)	31.25	16
Semi-automated (expert attribution of auto polygon / line features)	20.83	10
Object Based Image Analysis (OBIA)	8.33	4
Unsupervised classification (pixel based)	18.75	9
Supervised classification (pixel baed)	4.17	2
Model based classification (i.e. prediction)	6.25	3
None of the above	6.25	3
This question is not relevant to me	4.17	2

		49

Other
Pixel based unsupervised reasonably often to, supervised pixel base less often Also models, unsupervised and supervised MVA Manual and unsupervised Beginning the use of automatic and semi-automatic classifications although not regularly yet e.g. BTM, OBIA and manual interpretations

Question 10 - Select the mapping methods you plan to use within the next year, or that you would like to learn or plan to test over the next year

Answer choices	Response%	Number
Manual (expert driven digital / analogue mapping i.e. polygons / lines are drawn)	8.33	4
Semi-automated (expert attribution of auto polygon / line features)	20.83	10
Object Based Image Analysis (OBIA)	18.75	9
Unsupervised classification (pixel based)	18.75	9
Supervised classification (pixel baed)	16.67	8
Model based classification (i.e. prediction)	14.58	7
None of the above	0	0
This question is not relevant to me	2.08	1

Comments

- Will begin the use of automatic and semi-automatic classifications, although not yet regularly. Ex: BTM, OBIA and also manual interpretation.
- Will test a variety of them supervised and unsupervised pixel based. I will also have a student working on OBIA, and will most likely use manual on small projects.
- Machine learining based classification
- Osculatory surface extraction
- Would like to learn also about model based classification
- Would like to develop a kind of backscatter model, but also including the use of an unsupervised classification
- Supervised classification
- Semi-automated classification
- Manual. Model based

Question 11 - In terms of software do you use commercial or open source or both?

Answer choices	Response%	Number
Commercial	22.45	11
Open-source	20.41	10
Both commercial and open source	57.14	28
		49

Comments
▫ ArcGIS ▫ CARIS HIPS, FMGT, SonarWiz, RSGISlib, PRISM ▫ ArcGIS, Rstudio ▫ ArcGIS & Fledermaus ▫ MBsystem, QPS ▫ CARIS HIP/SIPS, FMGT, Sonarwiz ▫ QPS package (QINSy, QIMERA, Fledermaus, FMGT) Caris, ArcGIS ▫ Hypack, Qgis, Global Mapper

Question 12 - In your opinion what are the 3 biggest challenges in mapping / analysing seafloor geomorphology associated with each below;

A. Data quality
B. Skills set
C. Technical limitations
D. Lack of guidelines
E. Classification standards
F. Transparent work flow
G. Communication

A. Data quality

	Responses%	Number
Insufficient data quality, resolution, or coverage	55.51	24
Inconsistent data quality, resolution or coverage	44.19	19
		43

B. Skills set

	Responses	Number
Not trained in relevant methods	22.50	9
Methods are difficult for non-specialists	20	8
Need to expand multidisciplinary knowledge and / or collaborate	57.50	23
		40

C. Technical limitations

	Responses	Number
Do not have the required software	65.22	18
Available software not suitable for my data	34.78	8
		23

D. Lack of guidelines

	Responses	Number
Difficult to choose the best mapping approach	40.74	11
Require field specific guidelines	7.41	2
Require data specific guidelines	22.22	6
Require resolution specific guidelines	11.11	3
Difficult to choose appropriate mapping and presentation scale	18.52	5
		27

E. Classification standards

	Responses	Number

Lack of universal classification standard	66.67	30
Available classification approaches are not fit for purpose	33.33	10
		33

F. Transparent work-flow

	Responses	Number
Reducing bias during map production	14.29	4
Documentation and reproducible results	21.43	6
Ensuring consistency between different areas and different mappers	46.43	13
Provide confidence information relevant for onward user	17.86	5
		28

G. Communication

	Responses	Number
Making my map applicable and relevant to end users	33.33	9
Communication of limitations including confidence assessment	25.93	7
Presenting the map products in ways that are useful to the end user	25.93	7
Incorporate misuse of necessary information to avoid misuse of maps	7.41	2
Publicising significant results	7.41	2
		27

Appendix 3: Seabed Geomorphology - Classification

V.1 of the two-part classification scheme developed by MIM-GA (Dove et al., 2016), and applied in Case Study 7 above.

Report: http://nora.nerc.ac.uk/id/eprint/514946/1/Seabed_Geomorpholgy_classification_BGS_Open_Report.pdf