

Change report

Manuscript # hess-2016-73

Reviewer #1 – Dr. Neil Mitchell

#	Comment	Revision and Comments
1	“This article sets out to review efforts to quantify different aspects of shape of the ocean floors. It has ambitious intent, covering data collection, processing and analysis. A purpose of the article is to highlight the growth of the subject (hence justifying its inclusion in a discussion forum such as HESS).”	We thank Dr. Mitchell for acknowledging the relevance of including our manuscript in HESS and for his helpful comments.
2	“I found the graphs in Figure 1 interesting. However, the terms ‘geomorphometry’ and ‘geomorphometric analysis’ are not widely used in marine geology and geophysics, so the shapes of the graphs in Figure 1b, as the authors acknowledge, strongly reflect how these terms have been adopted, rather than representing the rise in practice in this subject area. Researchers began frequently measuring aspects of ocean floor shape from at least the 1960s onwards if not earlier, e.g., the work in characterizing how the seabed subsides with crustal age (some of the original articles cited by Parsons and Sclater (1977)).”	<p>With this comment, the reviewer introduced an aspect that we realize we had neglected in the initial version of our paper: the temporal aspect of marine geomorphometry. With the temporal aspect comes the different ways that the field was defined through time. This review addresses what Minar and Evans (2008, Geomorphology 95) called “modern geomorphometry”, a science that is comprehensively reviewed in Hengl and Reuter (2009, Developments in Soil Science 33).</p> <p>To avoid confusing readers in terms of timeline and definitions of geomorphometry, we added a section (1.2) in which we defined our scope more clearly and put our review into historical context. We acknowledged the important contribution that was made to the field by the qualitative study of seafloor morphology from DTMs as early as the 1960s, but our review, like in Hengl and Reuter (2009), addresses geomorphometry as known since the theoretical developments of the 1970s and their implementation in computers in the 1980s. We did not consider in our review works that defined depth values and thus modelled the seafloor, but did not extract any additional quantitative measurements to characterize seafloor morphology.</p>

3	<p>“There is a lot of text in this new article devoted to data collection and processing, which is fine (and important), though I thought distracting and left little room for meaningful insight into marine geomorphometry, considering the term in its general sense. The later discussion I therefore found disappointing, focusing on largely practical issues. The authors have already invested significant effort in generating the present version of the article, so they may not wish to invest much further time, though I thought the basic practical steps and data issues (for sonar methods, for example) could be strongly reduced and relevant sources for this information cited, leaving more space for developing insight into how the analysis of bathymetry has evolved.”</p>	<p>We agree with the reviewer that the details on the different techniques may have been distracting. We thus reduced this section to focus on the elements from these techniques that dictate data characteristics and are thus still very relevant to geomorphometry. The details about the theories behind the different techniques were moved to an appendix in order to leave this information available for readers that may want to deepen their understanding of these techniques. We also added a list of relevant reviews and discussions in Figure 1.</p>
4	<p>“I would also like to encourage the authors to repeat Figure 1b after attempting to find out how many articles measured shape characteristics from bathymetry in practice. This may take some effort, but the tables presented suggest they have already got part of the way. I have suggested some articles at the end of this review from my own experience. I suspect there are many more, sponsored in part by the US navy (Office of Naval Research). The results would hopefully show how efforts compare with the history of instrument development and number of research vessels. There are at least data on the history of geophysical research cruises to compare against (Wessel & Chandler, 2011) and there may be other information on, for example, the sales of multibeam sonars available from the sonar companies.”</p>	<p>We have attempted to find a better source of information to revise Figure 1 (Figure 2 in the revised article). It was however difficult to establish a consistent and valid methodology for the meta-analysis. For instance, we felt that including research funded by the US Navy but not from other navies or government agencies (e.g. British, Italian, Spanish and Norwegian) would induce a strong bias in the analysis. We encountered the same issue when looking into instrument development and problems with companies that do not exist anymore or that got bought by others.</p> <p>In order to still attempt to provide a better figure, we broadened the range of terms queried in the Scopus database, which gave a better estimate of the work that has been done in marine geomorphometry than the previous version.</p>
5	<p>“As the term "geomorphometry" is not widely used, it may be better to use the title to clarify the meaning for readers not familiar with it (as the aim of the article stated in the conclusions section is to raise awareness). I suggest: "A review of marine geomorphometry, the quantitative study of the shapes of seabed features"”</p>	<p>We modified the title to make it clearer to readers that are not familiar with the topic.</p>

6	<p>“It is of course an author’s decision what style to choose to write in. The text to me seems too exaggerated. It is almost in the style of a research grant proposal rather than in the dry style of a serious research article. This is important because the text tends to distract the reader from the facts presented. I recommend Strunk and White (ref below), which may help in making the text more succinct. The logic in the text needs to be tightened - some examples below, though I have not captured all problem text.”</p>	<p>We thank the reviewer for the examples provided. We made the modifications where appropriate according to the comments below, in addition to have modified the text in other parts. We also tried to limit our use of the passive voice in new sections.</p>
8	<p>“Page/line # 1/10 ...the science of quantitatively describing terrains... (science doesn’t do anything strictly speaking, its the humans that do things in using the scientific method)”</p>	<p>We changed it to “the science that helps quantitatively describe terrains”, according to the definitions provided by Chorley et al. (1957) and Pike et al. (2009).</p>
9	<p>“1/12 ... (GIS) and other software”</p>	<p>This was reviewed and now reads “(GIS) and spatial analysis software”</p>
10	<p>“1/15 ... investigate the characterization of -> characterize”</p>	<p>This was reviewed and now reads “characterize seabed terrain “</p>
11	<p>“1/19 delete "the science and application of””</p>	<p>This was deleted.</p>
12	<p>“1/19 ...we learn from experiences in terrestrial geomorphometry.”</p>	<p>This was modified at line 20 to read “we learn from experiences in terrestrial studies. “</p>
13	<p>“1/20 This sentence is too vague. The issues need to be spelt out.”</p>	<p>We added three examples of issues but preferred not to elaborate further considering it is still only the abstract.</p>
14	<p>“1/23 This paragraph is the only description of the content of the article (the preceding text is background). In my opinion, this needs to be more extensive and the preceding text greatly reduced.”</p>	<p>We elaborated on the different sections to give the reader a better idea of the elements that are reviewed and discussed in the paper. We also reduced the preceding text (e.g. lines 1/11-1/14 of the original manuscript).</p>
15	<p>“2/2 Geomorphological studies have improved”</p>	<p>This has been changed at lines 1/30 to read “To ensure that geomorphometry is used and developed to its full potential.....”</p>
16	<p>“2/3 Morphology - and quantitative measures of topography - are considered... components”</p>	<p>The suggested change was made from line 2/7 This has been changed to read “Morphology and quantitative measures of topography are considered the most important components of geomorphology because they represent the age and origin of the landscape (Speight, 1974; Minár and Evans, 2008;</p>

		Bishop et al., 2012). The shape of the landscape influences many Earth systems across a range of scales.”
17	“2/4 ...because the interpretation of the origins of geomorphological features and their ages necessarily follow it/them”	The proposed change was made at lines. “because they represent the age and origin of the landscape”.
18	“2/5 The shapes of terrestrial landscape are important for”	The change was made at line 2/9.
19	“2/11 Geomorphology also plays a fundamental role beneath sea level. I’m not sure the following sentence is correct - we always collect samples or data within the water column (depends what we define as the surface exactly).”	This sentence was ambiguous and unnecessary, and was thus removed in an attempt to reduce the length of the introduction (cf. comment #3).
20	“2/14 ...for many subjects (the following list does not contain questions)”	This is right; we made the suggested change at line 2/15.
21	“2/18 ... can affect the efficacy of model predictions of marine species dispersion.... (delete "of different elements")”	This sentence was modified at line 2/18 and “different elements” was deleted.
22	“2/20 ...that 90% of the oceans are”	Changed at line 2/20 to read “90% of the global ocean is unexplored”.
23	“2/23 ...explaining what is meant by "explored". Delete: "The fact is that ""	These words were deleted.
24	“2/25 an estimate of global bathymetry, which revealed”	This sentence was modified at line 2/24 to read “The entire ocean floor has been mapped to a resolution of a few kilometres using satellites, which has created an estimated surface of global bathymetry (Smith and Sandwell, 1994).”
25	“2/29 were all identified as requiring -> require”	The change was made (line 2/27).
26	“2/29 Delete the sentence "It is therefore .." and instead specify resolution in previous sentence.”	The sentence was removed and the resolution was added to the previous sentence (line 2/28).
27	“3/3 as above, a subject area does not measure, rather humans measure. Later in the sentence, we use the methods of these disciplines.”	The sentence was modified to “Geomorphometry is defined as the science on which quantitative measurements of terrain morphology are based, with foundations in geosciences, mathematics, and computer sciences (Chorley et al., 1957; Mark, 1975; Pike et al., 2009).”

28	“3/6 Sentence "Methods in ..." includes citations to recent articles - wouldn't this provide better historical context if the text started out with more original articles? Also, what is meant by "Methods" - this seems a bit too vague to me.”	Reference to recent articles were added (e.g. Qin et al. 2013, Podobnikar and Székely, 2015, Rigol-Sanchez et al., 2015). The sentence including “methods” was modified to be more specific (line 3/8).
29	“3/10 What "differences"?”	Two examples were added as an introduction to what is discussed later in the manuscript (lines 3/10-12).
30	“3/22 I would not say the field is recent, only the use of the term "geomorphometry" is recent”	We set our review in a temporal context in Sect. 1.2 and supported it with appropriate referencing (cf. comment #2). Since modern terrestrial geomorphometry is considered young, we believe that it is appropriate to say that marine geomorphometry is “recent”. In order to avoid ambiguity, we elaborated on this in Section 1.2 and modified “recent” for “relatively recent” where appropriate.
31	“4/15. There have been attempts to reconstruct bathymetry from wave refraction, using the effect of water depth on wave celerity. To my knowledge, nobody has analyzed the results in the way considered here, however.”	We shortened and simplified this sentence, simply stating an example and the appropriate reference.
32	4/23 I wouldn't say the data were used to 'define' the geoid, rather they have been used to derive the marine geoid. The geoid is not 'relative' to sea level, it is sea level in the absence of any ocean currents (dynamic effects). The sea is an equipotential (almost).	This section was moved to an appendix. We removed “define”, kept the previous mention of “derive”, and removed “relative to mean sea level”.
33	“4/27 Here 'gravitational field' is mentioned, but previous sentences talk about the geoid.”	This section is now in an appendix. The link between geoid and gravitational field was made explicit in line 3 of this section.
34	“5/1 I wouldn't say that thick sediments are a problem. Rather, the method relies on using a single density value for the seabed in a given area, but in practice density varies.”	This was removed from the text in the appendix.
35	“5/7-9 This is vague - needs to be more explicit about what the data products contain. The Shuttle radar dataset was collected over land using interferometry, so the other data were needed to fill in marine areas.”	We specified that these datasets also include terrestrial data (line 6/7).

36	“5/25 ...in uniformly attenuating water”	The change was made in the appendix as suggested.
37	“5/30 I would just say that the attenuation rate is obtained by correlating log10(local water depth measurements) with optical amplitude, if that is how it is done. The ground truth measurements don’t ‘verify’ the relationships as such, rather they are used to derive them.”	This sentence, now moved to the appendix, was modified.
38	“6/13 These methods do not rely on attenuation (please specify)?”	This comment is no longer relevant since the methods were moved to the appendix but the description of the types of data remained in the main text. Adding details on attenuation would involve bringing back the details on methods from the appendix to the main text. We added references to adequate review papers that describe these principles in detail, both in the appendix and the main text, and in Figure 1.
39	“6/16 bottom types vary with depth.”	This sentence, now in the appendix, was ambiguous and we modified it. Bottom types do not necessarily vary with depth. Bottom reflectance is one of the main sources of error in bathymetric estimation from optical remote sensing. By extracting the spectral signature of the different bottom types, it is possible to correct for these errors by “removing” the effect of bottom reflectance and thus keep only the spectral return relevant to estimating depth.
40	“6/19 how shallow?”	Specifications were added at lines 6/24-28.
41	“7/1 Please do not use words like ‘vector’ that have specific meanings in science. The velocity of sound in water is not increased by density (acoustic velocity actually decreases with density if occurring in isolation), rather water has a much higher bulk rigidity and that dominates velocity.”	The word “vector” was removed in this section of the appendix.
42	“7/7- 8 also knowing the speed of sound in the water.”	This was added in the appendix.
43	“7/13 ...seafloor, water depth can only be measured from the first echo in SSS amplitude data, the remaining parts of the data provide only indirect	This was specified in the appendix.

	information on water depth.”	
44	“7/15 ... by combining data from two receiving ... This is a similar form of bathymetry to that derived using multibeam sonars (e.g., the Kongsberg systems, which use the split beam method do compare phase between pairs of split beams).”	This was modified at lines 7/21-22.
45	“7/18 how? This is too vague. This section is missing a couple of methods (unless contained in the cited literature, which is unclear from the text given) - relief of objects from acoustic shadow lengths (which has been used for many years, e.g., in military applications (mine assessments)) and shape-from-shading (I think illustrated in Blondel and Murton).”	We added details on this at lines 7/23-26. Since all three reviewers found that section too long and technical, most of its content was moved to the appendix and we did not describe in more details the different methods.
46	“7/27 many early systems were not narrow beam. The multibeam sonar is arguably the most important instrument used for marine surveying - it is a shame that it is described in such a limited way here. There is no adequate description of the sounding geometry and no mention of motion sensors and sound velocity issues (although some of these do appear later on). I suggest referring to one of the review articles on these instruments, such as by de Moustier.”	As the three reviewers agreed that this section was too long and technical, we decided not to elaborate on the description of MBES. However, we added references to Lurton (2010) that describe in details principles of MBES, including sounding geometry, motion sensors and sound velocity, and references to de Moustier (1988). These references were also added to Figure 1 and the appendix.
47	“8/18 This still doesn't quite say how these systems derive water depth from the data (e.g., time of flight and velocity of light, but time of flight from the laser or through the water (detection of sea surface and seabed)?)”	We added a reference to the appendix and elaborated on this in it to avoid getting too long and technical in the main manuscript.
48	“9/7- No system generates truly continuous bathymetry, they all provide samples. Some systems effectively filter the bathymetry by imposing a resolution (e.g., acoustic beam width in the case of multibeams) before sampling. Other systems you might say sub-sample the bathymetry without first filtering, hence 'alias' the bathymetry (widely spaced single beam soundings, for example).”	The reviewer is right. We corrected this at line 7/13 to read- swath coverage.
49	“9/26 Also see Smith & Wessel (1990) for interpolation issues.”	A sentence referring to the conclusions of Smith and Wessel was added at lines 10/2-4.
50	“10/4 Is it the technique that is sensitive to errors or the DBM that is produced using it?”	It is the technique; we specified it at lines 10/7-8.

51	“11/6 They are surely not the "principles" of radar altimetry that limit resolution, rather the beam width and noise characteristics of the data? This is too vague.”	This section was removed (cf. comment #8 of Reviewer #2), but this particular sentence was moved and modified at lines 5/11-13.
52	“11/7 not the platform as such, but the distance of the platform from the seabed or sea surface.”	This was clarified at line 5/13.
53	“11/11 I think why sampling density increases needs to be explained (because of the cycle time of sounding systems limited by the speed of sound in water and beam widths, etc).”	This is now explained at lines 11/5-7.
54	“11/28 .. and may be amplified in some attributes computed from them.”	This was changed as suggested.
55	“12/30 This is an obscure sentence. I think what is meant here is that there are no other data to check whether a feature is an artifact or not.”	This was clarified at line 12/26-29.
56	“14/5 This is rather trivial and I’m not so sure that grids of bathymetry ought to be negative always (water depth is positive downwards) - a negative depth implies terrain above sea level.”	We agree with this comment and have removed the sentence.
57	“15/29 and 31. I would stick to either ‘variability’ or ‘rugosity’ rather than use both terms.”	As summarised in Table 1 there are several measures of terrain variability, including rugosity, VRM etc. It is incorrect to replace the collective term variability with any one of these sub-terms throughout this paragraph. We have, however replaced ‘rugosity’ with ‘terrain variability’ in the generic sentence at line 15/31. The following sentences give detail on sub-methods where individual terms need to be retained for clarity.
58	“16/1 Is meant here comparing depths with a planar surface fitted to the data?”	No, the rugosity measure compares the surface area and planar area. We have revised the wording to make this clearer.
59	“16/3,4 alternative measures of rugosity that are less affected by gradient.”	We did not implement the suggested change here because we felt that it would have changed the meaning of the claim that is made.
60	“16/6 between them (what exactly?)”	‘them’ was changed to ‘these attributes’ – refers to slope and variability at the start of the sentence.

61	“16/11-12 Not in marine geophysics. For example, the subsidence of the seabed with age was first looked at in the 1960s as far as I am aware (references in Parsons and Sclater, 1977).”	See responses to comments #2 and #30, and Section 1.2. Specific geomorphometry is used here in terms of (semi)automatic extraction rather than qualitative description of landforms based on terrain characteristics.
62	“18/2,3 Is it bathymetry that is influencing the biology or rather a number of other properties vary with water depth (light because of attenuation, waves, etc)?”	Yes it is the bathymetry influencing the biology- line clarified to read “Bathymetry is known to have a first order influence on species distribution, largely because many properties that directly affect benthic habitat vary with depth (e.g. light, temperature).”
63	“19/16 What is meant here exactly by scale invariance in terms of statistics and morphology?”	This sentence was changed to “This kind of approach has been applied to slope instability offshore Norway, demonstrating the fractal characteristics of submarine mass movement morphology and statistics.”
64	“20/1 I think references need to be cited for these, e.g., Fox et al or Malinverno for the spectral method.”	We agree with the reviewer. However, in order to address comment #3 of Reviewer #2, we added a reference to Table 2 in which the reader can find the relevant citations.
65	“24/32 I wouldn’t say they are more affordable, rather the oil and gas industry has invested an enormous amount (with often dubious success) to acquire these datasets. Academic and government researchers have benefitted from access to these data.”	This sentence has been changed to “The development of seismic geomorphometry is a natural consequence of increasing computer power, which enables the rapid manipulation, visualisation and interpretation of 3D seismic reflection data, and the enormous investment in this technology by the oil and gas industry, with academics and government researchers benefitting from access to these data.”
66	“26/27 Figure 1 only shows the uptake of the word ‘geomorphometry’, not practice.”	This reference to Figure 1 was removed.
67	“27/7 If >50 years can be described as infancy, I am an infant!”	This was addressed in responses to comments #2, #30 and #61.
68	“p 55. Table 2 contains only a selection, so I would make that clear in the table title.”	The title of the table was modified accordingly.
69	“Figure 2 - surely "pre-processing" should occur before interpolating the data onto a grid? Or am I misunderstanding what pre-processing means here (an iterative stage of binning and gathering statistics before filtering the data and forming a final	The term “pre-processing” correspond to the term that is accepted within the geomorphometry literature (cf. Hengl and Reuter, 2009; Bishop et al., 2012), thus making us reluctant to use a different term. We however understand that there may be

	grid)? A better term might be needed.”	confusion for readers that for instance are used to bathymetric data processing. To prevent this, we define and clarified the meaning of “pre-processing” in this context in the introduction of the paper, when referring to this figure (lines 3/26-28).
70	“Figure 3 caption. The last sentence does not really inform us of what is in the figure. Standard deviation is presumably computed within each cell. It is really not clear what is meant by "hypotheses" - I would not use that kind of term here for what I think is meant a working grid of the data. This kind of language is only going to confuse readers.”	This sentence was removed.
71	“Figure 4. I understood the GEBCO charts to contain information from the hydrographic agencies that is not freely available. The caption needs to say where these data were taken from (geographically) for the discussion to have much meaning. I suspect the remaining data were not only obtained from altimetry measurements.”	The GEBCO digital dataset is now freely available, including a software to extract sub-areas of the global dataset, online at www.gebco.net . It is characterized on the website as “the most authoritative, publicly-available bathymetry data set for the world’s oceans.”
72	“axis -> direction We don’t know the survey direction, ship track etc, so difficult to read the middle panel. Hence, "are mainly caused by the roll motion" - I suspect this is not roll motion exactly, rather a roll motion that is not compensated by the motion sensor used. Striping can arise because of other errors caused by bubbles passing over transducers in bad weather.”	The mention of roll was removed.
73	“Figure 6 is really not very useful, given that the sample set is effectively censored by the limited use of the terms searched.”	Figure 6 was removed.
74	<p>“Suggested additional articles within the field of geomorphometry (only a small sub-set from my personal experience):</p> <p>Czarnecki, M.F., Bergin, J.M., 1986. Characteristics of the two-dimensional spectrum of roughness on a seamount. Naval Research Laboratory.</p> <p>Goff, J.A., 1991. A global and regional stochastic analysis of near-ridge abyssal hill morphology. J. Geophys. Res. 96, 21,713-721,737.</p> <p>Goff, J.A., 1992. Quantative Characterstics of</p>	<p>We thank the reviewer for these references. The following ones were added in the text:</p> <p>Blondel and Murton (1997) →lines 7/15 and 7/26</p> <p>De Moustier (1988)→line 7/16 and Figure 1</p> <p>Czarnecki and Bergin (1986) → line 4/14</p> <p>Goff (1991) →line 27/30</p> <p>Goff (1992) →lines 4/15 and 27/30</p>

<p>Abyssal Hill Morphology along flow line in the Atlantic Ocean. <i>Jour. Geophys. Res.</i> 97, 9183-9202.</p> <p>Goff, J.A., 2001. Quantitative classification of canyon systems on continental slopes and a possible relationship to slope curvature. <i>Geophys. Res. Lett.</i> 28, 4359-4362.</p> <p>Herzfeld, U.C., 1993. A method for seafloor classification using directional variograms, demonstrated for data from the western flank of the Mid-Atlantic Ridge. <i>Math. Geol.</i> 25, 901-924.</p> <p>Malinverno, A., 1990. A quantitative study of the axial topography of the Mid-Atlantic Ridge. <i>J. Geophys. Res.</i> 95, 2645-2660.</p> <p>Malinverno, A., 1991. Inverse square-root dependence of mid-ocean-ridge flank roughness on spreading rate. <i>Nature</i> 352, 58-60.</p> <p>Malinverno, A., 1993. Transition between a valley and a high at the axis of mid-ocean ridges. <i>Geology</i> 21, 639-642.</p> <p>Malinverno, A., Cowie, P.A., 1993. Normal faulting and the topographic roughness of mid-ocean ridge flanks. <i>J. Geophys. Res.</i> 98, 17921-17939.</p> <p>Malinverno, A., Gilbert, L.E., 1989. A stochastic model for the creation of ocean floor topography at a slow spreading center. <i>J. Geophys. Res.</i> 94, 1665-1675.</p> <p>Menard, H.W., 1984. Origin of guyots: the Beagle to Seabeam. <i>J. Geophys. Res.</i> 89, 11117-11123.</p> <p>Mitchell NC (1995) Diffusion transport model for pelagic sediments on the Mid-Atlantic Ridge. <i>J. Geophys. Res.</i> 100(B10):19,991- 920,009</p> <p>Mitchell NC, Huthnance JM (2007) Comparing the smooth, parabolic shapes of interflues in continental slopes to predictions of diffusion transport models. <i>Mar. Geol.</i> 236:189-208</p> <p>Mitchell, N.C., Stretch, R., Oppenheimer, C., Kay, D., Beier, C., 2012. Cone morphologies associated with shallow marine eruptions: east Pico Island, Azores. <i>Bull. Volcanol.</i> 74, 2289-2300.</p>	<p>Goff (2001) → line 4/15</p> <p>Herzfeld (1993) → line 4/16</p> <p>Malinverno (1990) → line 4/15</p> <p>Malinverno and Cowie (1993) → line 27/32</p> <p>Malinverno and Gilbert (1989) → line 27/31</p> <p>Parsons and Scalter (1977) → line 4/12</p> <p>Shaw (1992) → line 14/17</p> <p>Shaw and Lin (1993) → line 27/32</p> <p>Shaw and Smith (1987) → line 4/14</p> <p>Shaw and Smith (1990) → line 4/15</p> <p>Smith and Wessel (1990) → line 10/4</p> <p>Wessel and Chandler (2011) → line 4/12</p>
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<p>Shaw, P.R., 1992. Ridge segmentation, faulting and crustal thickness in the Atlantic Ocean. <i>Nature</i> 358, 490-493.</p> <p>Shaw, P.R., Lin, J., 1993. Causes and consequences of variations in faulting style at a Mid-Atlantic Ridge. <i>J. Geophys. Res.</i> 98, 21839-21851.</p> <p>Shaw, P.R., Smith, D.K., 1987. Statistical methods for describing seafloor topography. <i>Geophys. Res. Lett.</i> 14, 1061-1064.</p> <p>Shaw, P.R., Smith, D.K., 1990. Robust description of statistically heterogeneous seafloor topography through its slope distribution. <i>J. Geophys. Res.</i> 95, 8705-8722.</p> <p>Smith, D.K., 1988. Shape analysis of Pacific seamounts. <i>Earth Planet. Sci. Lett.</i> 90, 457-466.</p> <p>Smith, D.K., 1996. Comparison of the shapes and sizes of seafloor volcanoes on Earth and "pancake" domes on Venus. <i>J. Volcanol. Geotherm. Res.</i> 73, 47-64.</p> <p>Smith, D.K., Jordan, T.H., 1988. Seamount statistics in the Pacific Ocean. <i>J. Geophys. Res.</i> 93, 2899-2918.</p> <p>Other cited references:</p> <p>Blondel, P., Murton, B.J., 1997. Interpretation of sidescan sonar imagery. John Wiley, Chichester.</p> <p>de Moustier, C., 1988. State of the art in swath bathymetry survey systems. <i>Internat. Hydr. Rev.</i>, Monaco 65, 25-54.</p> <p>Parsons, B., Sclater, J.G., 1977. An analysis of the variation of ocean floor bathymetry and heat flow with age. <i>J. Geophys. Res.</i> 82, 803-827.</p> <p>Smith, W.H.F., Wessel, P., 1990. Gridding with continuous curvature splines in tension. <i>Geophysics</i> 55, 293-305.</p> <p>Strunk, W., White, E.B., 1972. The elements of style, 2nd Ed. MacMillan Publishing, New York.</p> <p>Wessel P, Chandler MT (2011) The spatial and temporal distribution of marine geophysical surveys.</p>	
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Reviewer #2 – Anonymous

#	Comment	Revision and Comments
1	The paper presents an exhaustive list of research dealing with marine geomorphometry. In this sense, it represents a thorough effort and a very complete picture of what has been done in the topic. I put forward the following suggestions which I think may help to improve the manuscript.	We thank the reviewer for recognising the effort that was put in reviewing the existing literature, and for its helpful comments.
2	I would try to reduce the overall length of the manuscript. As it is now, the paper is not easy to read, it is too long, but especially, sometimes there is a lack of context to the referencing, and all the effort to compile the literature may be partially lost when reporting results of the search.	We tried to reduce the overall length of the manuscript. For instance, the second section was significantly reduced to keep the focus on data characteristics that may impact marine geomorphometry. We also removed the section on spatial scale. However, the other reviewers also asked to add some sections, e.g. in terms of emerging applications and the temporal context of marine geomorphometry. We thus do not think that it resulted in a net length reduction, although we hope to have greatly improved the flow of the manuscript, which should make it easier to read.
3	I think that the chapters are fine, but I would create tables with the references, avoiding what may be regarded as a long list of literature. Using tables, where the most important papers are reported, section by section, and using the text to discuss the importance of those findings may be more convenient, and a context may be built for the references; thus the listing would be avoided, the text would be more readable, and most of the references would be included in tables.	To address this comment, we expanded Table 2 to re-organize the references used as examples of work performed in marine geomorphometry, and modified Figure 1 to include relevant reviews or discussions related to the different topics. We also tried to reduce the list of literature by removing some references in places where more than two references were given to support a claim. We however preferred not to remove all the references from the text: since each reference usually supports a claim or an argument, removing them from the text would prevent the association of the reference with the appropriate claim.
4	Having said this, I think the authors should report on their thinking as derived from lessons learned from the literature. As the paper is now, that task is partly derived to the reader, and it is hinted at in the conclusions with the 5	We included some insights on the lessons learned from past work on marine geomorphometry (particularly the limitations) and how these could be addressed in the future in Section 7. We also welcome specific suggestions based on the experience of the reviewer.

	major points highlighted by the authors.	
5	The introduction would benefit to the references to the most recent reviews about high resolution data and earth surface processes, specifically (Passalacqua et al., 2015; Tarolli, 2014). This would also hint to the current limits or merits in marine geomorphometry as related to this wider context of earth surface processes.	A comparison with the more recent work in terrestrial geomorphometry was added in Section 7 to highlight the merits/limits of marine geomorphometry.
6	As stated above, the manuscript as of now is a bit on the long side. There is a lot of pages focused on data collection and processing. While this is transversally useful, it hinders the part of the paper which is specific to the theme of the review (marine geomorphometry). Currently, chapter 2 appears more as a technical report on the different techniques. The basic technical descriptions could be strongly reduced and referred to relevant sources, focusing more on the merits and limits of the different technologies, underlining the areas where there is still room for progress specifically for the field of marine geomorphometry.	We agree with the reviewer that the technicalities associated with the remote sensing techniques shifted the focus away from the main theme of the review. We thus reduced this section to focus on how each technique dictates data characteristics that are relevant to geomorphometric analyses. We moved the technical parts to an appendix in order to still inform readers that may have limited understanding of the theories behind the different techniques.
7	All the softwares reported in the article could be nicely organized and referenced in a table, so that a reader can have quick access to their name and location, and eventually reporting also the works that used one software or the other.	<p>We agree that a list of software relevant to each step of geomorphometry may be a useful addition to a manuscript focusing just one or two steps of geomorphometry, where the emphasis is on methods/algorithms. However, we feel that a list of software is not appropriate for this review for the following reasons:</p> <ul style="list-style-type: none"> -A list of software would not add anything to the paper unless we made it a comprehensive list of all available software for each of the 5 steps of geomorphometry, not just the few examples of commonly used software we have mentioned to date in certain sections. Such a list would quickly approach 100 software/scripts/tools covering diverse aspects of data processing and analysis. -Such a list would be overwhelming in the present manuscript which only provides an overview of all 5 steps of geomorphometry. We feel it would detract from the focus the

		<p>paper and existing tables.</p> <p>-Listing of software relevant in 2016 would also quickly give grounds for the paper to become outdated since software are under continuous development both in the commercial and open-source sector.</p> <p>We appreciate that software reviews have been useful in publications such as Hengl & Reuter (2009) but these were in-depth chapters on software where the functionality could be described in detail. Such detail is beyond the scope of the current review, but would be worth considering for future papers focussing on more technical aspects of just one, or possibly two steps of geomorphometry.</p>
8	Chapter 3 feels somehow not linked to the review. The chapter about scale could be merged to the different technique described in chapter 2, again highlighting the difference in scale as merit or limit of each technique, for example.	We removed the section on spatial scale and included the relevant parts in Section 2. We however kept Section 3 as the generation of a surface model plays a crucial role in the geomorphometric approach and involves decisions from the user regarding spatial resolution, data quality, interpolation characteristics, sampling, and intended use. We modified this section to link it better to the rest of the review.
9	Chapter 5 and 6 seems redundant. They could be merged together explaining what technique was used in the different studies.	We kept the description of the techniques separated from the discussion of the application of geomorphometry, partly to enable addressing a comment from Reviewer #3 regarding the addition of a sub-section in the applications section that would not have fit well if Sections 5 and 6 were merged.
10	I found table 2 very interesting, but surprisingly this is reported only in reference to chapter 6.2, while it could be reorganized grouping the works also according to the aim, not just the technique.	We agree with the reviewer that this table is more useful when used in reference to many applications. We modified the table by classifying the references according to the main theme of the study.

Reviewer #3 – Anonymous

#	Comment	Revision and Comments
1	This paper aims at providing a timely review of marine geomorphometry. The intention is to raise awareness of the science of geomorphometry in marine environments, to review the existing literature on marine geomorphometry, to highlight differences from terrestrial geomorphometry, and to outline and recommend future research directions	N/A

	within marine geomorphometry. Overall the paper is structured according to the five steps outlined by Pike et al. (2009) in chapter 1 of the seminal book on geomorphometry edited by Hengl and Reuter.	
2	As I was invited to review the paper after two other reviews were already available, I have tried not to repeat the comments and suggestions of the two other referees which both agree with. I instead try to focus on other issues of the paper. Overall I very much agree with the authors that there is a need for a review on marine geomorphometry. It is a discipline which is blooming immensely in these years, and this will for sure be the case in several years to come.	We appreciate that the reviewer finds this review timely.
3	RE Structure: The five steps in geomorphometry outlined by Pike et al. (2009) are highly pedagogical in relation to teaching and learning geomorphometry as a discipline. However, the choice of structuring the paper according to these five steps and combining this with the aim of attempting an exhaustive review is very challenging, and more or less a Sisyphus task, as each of the five steps would be worthy of its own review. The result is that the review/analysis of each of the five steps tends to become surficial and to some extent rather being a listing of earlier studies. Consider an alternative structure with a clear alignment between the aim and objectives of the paper and the findings and recommendations based on the analysis of the authors. In this regard the aims and objectives could be even more precisely formulated, also in order to highlight the focus of the review. Referee #2 provides many good suggestions of how to alternatively structure the paper.	<p>We agree with the reviewer that each section would be worthy of its own review. Our objective was not to write a review of each of these steps, but to review how they integrate together to form a typical marine geomorphometry workflow.</p> <p>Reviewer #2 thought that “the chapters are fine”. We have discussed the matter and decided to keep the current structure of the manuscript based on Pike et al. (2009). It is often observed in the community of end-users that there is a lack of understanding of the fact that each of the five steps has implications for the derivation of terrain attributes or extraction of terrain features, and consequently implications for the final application. By structuring the review following these steps, we hope that end-users can realize the role of each step in determining their quantitative terrain characteristics, something that we emphasized on in lines 24-26 of page 27.</p> <p>To address this comment, we made some sections, e.g. section 2 on the remote sensing techniques and section 3, shorter and shifted their focus towards data characteristics and how they impact the final application. We believe that this make the manuscript flow better. We also made it clearer in the introduction why we picked that structure, and why it is important to consider each of these steps when using geomorphometry. In doing so, we hope that it made the review less surficial and</p>

		<p>more focused on the importance of each step for the final application. We also added specifications throughout the manuscript that it is meant to be an overview and not a comprehensive review of each steps. For instance: “Clearly there is room in the literature for more detailed reviews of each of these five steps and relating to many of the sub-disciplines, however we hope that this review will serve as a solid foundation for further, more detailed reviews on these sub-topics.” (lines 3-5 of page 29)</p>
4	<p>RE Technologies: The section on sampling technologies (section 2) could be excluded from the review. Despite the dedication of five pages to the section it remains surficial, as it attempts to encompass a very broad range of technologies, including technologies like SBES which will not play a key role in the future. The data quality is fundamental for the DEM quality, and consequently for all DEM derivatives, and the final interpretations. However, this could be described and explained more generically by focusing on the general characteristics and properties of point data, which in essence is integrated areal information, as all points are related to a footprint. I very much agree with the authors that one of the key dangers in the future application of DEMs and geomorphometry in planning and management is that the planners, managers and decision makers are not aware of the properties of the data foundation of the DEMs. Hence, consider highlighting data properties and not different technologies.</p>	<p>We did not fully exclude this section from the review. As mentioned in the responses to other comments, we found important to individually address each of the five steps that impact geomorphometric applications. In addition, Reviewer #1 had many comments (#31 to 48) that suggested specifications and extension of this section, thus challenging the idea of excluding this section.</p> <p>We however agree with the reviewer that this section was too technical and too detailed, so we shifted the focus away from the technologies and towards the data. Regarding SBES, we indicated that its use is likely to dwindle, but we also mention a recent study that demonstrated that previously collected SBES data can be combined together and offer much potential for applications.</p> <p>We highlighted the reviewer’s last thought on awareness of data foundation in lines 24-26 of page 27.</p>
5	<p>RE Terminology: From a reader’s point of view, the impression arises that the authors stress the importance of the differences between terrestrial and marine geomorphometry, as if the identification of differences would make the field of marine geomorphometry more relevant. This even leads to the suggestion of different terminologies for DEMs. In my opinion this is contra productive and merely confusing. The acronyms DEM, DSM and DTM are generic and sufficient for all environments. A more uniting approach with suggestions for a joint terminology and vocabulary across environments</p>	<p>We agree with this comment and consequently tried to highlight the similarities between terrestrial and marine geomorphometry rather than solely the differences. We added some elements on this, for instance in Section 7.</p> <p>Regarding terminology, the reviewer seems to suggest that we came up with the different terms for DTMs. Since this is review, the different terms that are discussed in the manuscript are those found in the literature. The difference between DEM and DBM was clearly defined in Section 3,</p>

	<p>would be much more meriting. One of the major potentials of geomorphometry, as for geomorphology, is that it interacts with many disciplines. Within the geomorphometry community we should aim at aligning our terminology in order to foster and ease the coupling with other disciplines. Therefore, consider highlighting both similarities and differences between terrestrial and marine geomorphometry, and aim to unite the two disciplines wherever it is possible.</p>	<p>thus avoiding confusion. We agree that the generic terms DSM and DTM are sufficient for all environments (although they mean different things), and as suggested by the reviewer, we clarified this issue and added to our recommendations the adoption of a joint terminology across environments (cf. Section 7.2).</p>
6	<p>RE Domain: The exact spatial domain of the review is unclear. There is a strong bias towards deep water environments with practically no review of the shallow water coastal environment. Nevertheless, the authors seem to use the coastline as the perimeter of their domain. Many studies, especially within the last decade, have used high resolution DEMs in shallow water coastal environments to quantify sediment transport, sediment transport pathways, morphology and morphodynamics. These studies are practically absent in the present review. Many of these studies are available in relation to the line of international conferences of MARID, RCEM and ICS, and in the journals JGR Earth Surface, Geomorphology, ESPL and more recently ESurf (I will not mention any specific studies here, as the list is long). Moreover, the authors mention the bridging of terrestrial and marine environments as one of the key future challenges (and actually a paper in the special issue is addressing this), but this without having reviewed the shallow water environments in the first place. Hence, the present analysis is simply too superficial. This was also highlighted by referee #1 although not in relation to shallow water. Consider defining the exact domain of the review, and then either fully include or exclude shallow water coastal environments. Specifically it even leads to erroneous information, e.g. when the authors discuss tidal corrections which are rarely used in high-precision and high-resolution shallow water environments where high-precision positioning is available and applied.</p>	<p>Our spatial domain does extend to the coastline. Our reference list already included many articles focusing on the coastal waters and the continental shelf/shallow waters. To make this clearer, we added the spatial domain to the list of articles cited in Table 2.</p> <p>We also do not feel the need to specifically review the shallow water environment as suggested by the reviewer since we do not specifically review the deep water environment. We define our spatial domain as the marine environment, which encompasses shallow and deep waters. We believe, as demonstrated in Table 2, that we cover both depth ranges in a reasonable fashion that do not justify excluding one or the other.</p> <p>Bridging terrestrial and marine environments is a challenge in terms of integrating and fusing datasets from multiple sources for regional to global-scale analysis, rather than actually bridging the environments at a local-scale with LiDAR. We agree that this may not have been clear, and thus modifications were made to Sect. 6.4.3 to review the current literature on LiDAR, and made more explicit that the challenge for the future is in combining different datasets for geomorphometry at a broader scale.</p> <p>We also note that we did not provide erroneous information regarding tidal corrections. Acoustic surveys do require tidal corrections, and references are made to published peer-reviewed literature to support this claim. The reviewer also mentioned the paper in this special issue that</p>

		addresses the littoral gap using LiDAR; a quick look at it confirmed that the authors of this paper did account for tides (-1m DVR90), using a tidal gauge 20km away from the study site (which confirms a claim made in our paper), and that they needed to correct for the “continually changing water level in the study area due to tides”. This highlight the fact that many applications still do not have access to the latest positioning technologies mentioned by the reviewer and still require proper calibration of their system.
7	RE Applications: A range of applications is listed. However, the descriptions of the applications are strongly biased towards habitat mapping, and to some extent also hydrography in relation to safety of navigation. The enormous potential of geomorphometry is that it has a vast amount of applications, and some not yet realised. It would suit the review if the analysis of the authors would lead to suggestions of new areas where geomorphometry has not yet been introduced and tested or highlight areas where present applications could be further developed.	The bias towards habitat mapping and geomorphology is in line with the fact that these are the two most common applications of marine geomorphometry, as illustrated in one of the figures that was removed from the initial submission. However, we agree with the reviewer that it would suit the review to suggest new areas of application. We thus extended Section 6 to suggest new areas where marine geomorphometry may be applied with success in the near future. We also welcome specific examples that the reviewer would like to see included.
8	I have not included any specific comments to the separate sections and also no comments for technical corrections. Due to the somehow fundamental character of the general comments from all three referees, it seems more relevant to initially restructure and refocus the paper, before more detailed corrections are suggested.	N/A.
9	I sincerely hope that the authors will take up the challenge to revise the paper. Marine geomorphometry is a blooming field and we need an overview within the community, and we need this paper to ease communication with other disciplines that could benefit from marine geomorphometry.	We thank the reviewer for recognising that this review paper is timely.

~~Characterising the ocean frontier:~~ A review of marine geomorphometry, the quantitative study of the seafloor

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Abstract. Geomorphometry, the science ~~that quantitatively describes terrains~~of quantitative terrain characterization, has traditionally focused on the investigation of terrestrial landscapes. However, the dramatic increase in the availability of digital bathymetric data and the increasing ease by which geomorphometry can be investigated using Geographic Information Systems (GIS) and spatial analysis software has prompted interest in employing geomorphometric techniques to investigate the marine environment. Over the last decade or so, a ~~suitemultitude~~ of geomorphometric techniques ~~have been applied~~ (e.g. terrain attributes, feature extraction, automated classification) have been applied to investigate the characterisation of~~characterize~~ seabed terrain from the coastal zone to the deep sea. Geomorphometric techniques are, however, not as varied, nor as extensively applied, in marine as they are in terrestrial environments. This is at least partly due to difficulties associated with capturing, classifying, and validating terrain characteristics underwater. There is, nevertheless, much common ground between terrestrial and marine ~~geomorphology~~geomorphometry applications and it is important that, in developing ~~the science and application of~~ marine geomorphometry, we ~~build on the lessons learned~~learn from experiences in terrestrial studies. ~~We note, however, that~~However, not all terrestrial solutions can be adopted by marine geomorphometric studies since the dynamic, four-dimensional nature of the marine environment causes its own issues, ~~boosting throughout the geomorphometry workflow. For instance, issues with underwater positioning, variations in sound velocity in the water column affecting acoustic-based mapping, and our inability to directly observe and measure depth and morphological features on the seafloor are all issues specific to the application of geomorphometry in the marine environment. Such issues fuel~~ the need for a dedicated scientific effort in marine geomorphometry.

This ~~contribution~~review aims to highlight the relatively recent growth of marine geomorphometry as a distinct discipline, and offers the first comprehensive ~~review~~overview of marine geomorphometry to date. ~~It addresses~~We address all the five main steps of geomorphometry, from data collection to the application of terrain attributes and features. We focus on how these steps are relevant to marine geomorphometry and also highlight differences and similarities from terrestrial

geomorphometry. We conclude with recommendations and reflections on the future of marine geomorphometry. To ensure that geomorphometry is used and developed to its full potential, there is a need to increase awareness of (1) marine geomorphometry amongst scientists already engaged in terrestrial geomorphometry, and of (2) geomorphometry as a science amongst marine scientists with a wide range of background and experience.

5 **Keywords:** Geomorphometry, terrain analysis, marine habitat mapping, marine geomorphology, bathymetry, GIS.

1 Introduction

1.1 Background

Studies of geomorphology have improved our understanding of many of the Earth's systems and surface processes (Smith et al., 2011; Bishop et al., 2012). Morphology ~~—and topography in its quantitative form—~~is measures of topography are considered the most important ~~component~~components of geomorphology because they represent the ~~interpretation of other components (e.g. genetics, chronology) often starts with the characterization of morphology~~ age and origin of the landscape (Speight, 1974; Minár and Evans, 2008; Bishop et al., 2012). The ~~shapes~~shapes of the terrestrial landscape ~~impacts~~are important for many Earth systems ~~at all~~across a range of scales. For instance, broad-scale features such as mountains and valleys may dictate weather patterns (Dimri et al., 2013), vegetation and biodiversity patterns (Anderson and Ferree, 2010), and hydrological processes (Iordanishvili, 2000), while fine-scale features such as local slope may influence soil stability (Buscarnera and Di Prisco, 2013) or influence nest-site selection by certain bird species (Whittingham et al., 2002). Overall, topography is known to influence gradients in moisture, energy and nutrients across the landscape (Hengl and MacMillan, 2009).

~~The~~ Likewise, the oceans ~~also~~ play a fundamental role in the Earth system at multiple scales. ~~An important part of ocean-related work addresses the physical, chemical and biological patterns and processes of the water surface and, to a lesser extent, the water column. . By contrast, seafloor research has been less spatially extensive, except for research on global, broad-scale geomorphology and processes (e.g. Ma et al., 1998).~~ Knowledge of seafloor topography is also crucial for many ~~questions~~subjects (Smith, 2004). For example, seafloor topography, or bathymetry, influences surface currents (Gille et al., 2004), near-bottom currents (White et al., 2007), and ocean mixing rates (Kunze and Llewellyn Smith, 2004). Lack of knowledge on factors influenced by bathymetry can ~~impact modelling and forecasting~~affect the efficacy of ~~different elements, from model predictions, for example models of~~ marine species distributions (McArthur et al., 2010) ~~to~~ climate (Jayne et al., 2004) ~~to~~ or the paths of floating objects like marine debris (Smith and Marks, 2014).

It is commonly stated that 90% of the oceans are 90% ~~global ocean is~~ unexplored (e.g. Gjerde, 2006) and that more is known about the surface of Earth's Moon ~~(e.g. Li et al., 2014)~~, Mars ~~(e.g. Carr et al., 1977; Stepinski and Vilalta, 2005)~~, Mercury

(e.g. Zuber et al., 2012) or Venus (e.g. Ford and Pettengill, 1992) than about the ocean floor (Sandwell et al., 2002; Smith, 2004; Smith and Marks, 2014). However, such statements mean little without further specification or elaboration on their real meaning. The facts are that the in relation to objectives, data types and spatial resolution. The entire ocean floor has been mapped to a resolution of a few kilometres using satellites, which generatedhas created an estimationestimated surface of the underwater landscape and revealed features of the Earth's crust beneath seafloor sedimentsglobal bathymetry (Smith and Sandwell, 1994; Smith, 1998). However, these coarse-resolution data are often inadequate for many scientific, economic, public safety and management purposes. Applications such as tsunami hazard assessment, submarine cable and pipeline route planning, resource exploration, habitat mapping, territorial claims, navigation, and ocean circulation and climate studies, and navigation were all identified as requiringrequire more reliable, fine-scale bathymetric data (i.e. finer than 5 km) (Sandwell et al. 2002). It is therefore imperative to extract the most useful information that can be retrieved from the seafloor data available at resolutions finer than 5 km.

Fuelled by advancements in remote sensing and Geographic Information Systems (GIS) (e.g. Grohmann, 2004), the field of geomorphometry has entered a new era in recent decades (Evans and Minár, 2011; Florinsky, 2012). Geomorphometry is defined as the science that quantitatively measureson which quantitative measurements of terrain morphology usingare based, with foundations in geosciences, mathematics, and computer sciences (Chorley et al., 1957; Mark, 1975; Pike et al., 2009). It can be divided into two sub-fields: general geomorphometry (e.g. Minár et al., 2013), and specific geomorphometry (e.g. Drăguț and Blaschke, 2006). General geomorphometry deals with continuous surfaces in order to extract terrain attributes (e.g. slope, aspect, rugosity), while specific geomorphometry aims at characterizing or extracting discrete landforms (Evans, 1972). Methods inThe science of geomorphometry were, including its theories, methods, algorithms, and tools, was mainly developed and tested on artificial (e.g. Jones, 1998; Qin et al., 2013), terrestrial (e.g. Grohmann, 2015; Rigol-Sanchez et al., 2015) and extra-terrestrial settings (e.g. Li et al., 2014Bue and Stepinski, 2006; Podobnikar and Székely, 2015). These methods are relevant for underwater applications and have been increasingly used in the last decade (Lecours et al., 2015a), but differences in the input data nature of the input data (e.g. no need to hydrologically correct the surface model, little to no ability to validate measurements on the terrain) can sometimes produce different results than expected from land-based studies, creating the additional need for a dedicated scientific effort in marine geomorphometry—. To our knowledge, no review on the state-of-the-art of marine geomorphometry has ever been written.

This contribution aims to raise awareness of the relatively recent field of marine geomorphometry by providing an overview of current practices and application areas and summarising the relevant literature to date. We first discuss the gradual rise in the application and development of marine geomorphometry (Sect. 1.2), from the first marine geophysical applications to the latest developments in marine habitat mapping and geomorphology. The paper then addresses the five main steps of geomorphometry identified by Pike et al. (2009) and adopted by the community (Bishop et al., 2012), with a focus on how these steps are relevant to marine geomorphometry and different from traditional, terrestrial geomorphometry (Fig. 1). Section 2 reviews the first step of the geomorphometry workflow, which is to sample the surface. The characteristics of

bathymetric data collected from four types of remote sensing techniques are described: satellite radar altimetry, optical remote sensing, acoustic remote sensing, and LiDAR (Light Detection And Ranging). Section 3, addressing the step in which we need to generate a surface model from the sampled heights, discusses elements that have implications on how the seafloor is represented as data, including the interpolation methods used to create models and the spatial scale (i.e. spatial resolution and extent) at which to generate them. Section 4 addresses the pre-processing step that corresponds to making the surface model ready for the next step, surface analysis, which is reviewed in Sect. 5. The pre-processing of the surface model involves the correction for errors, artefacts and erroneous data in the surface model. The analysis of the surface is the core of the geomorphometric workflow and consists in deriving terrain attributes and terrain features (or objects). Finally, the last step of this workflow is the use of the derived terrain attributes or features for a particular problem or application. The main disciplines in which marine geomorphometry has been applied and developed are examined in Section 6, and we also suggest other fields of research and applications that could benefit from the integration of marine geomorphometry in their practices. We conclude this review with recommendations and reflections on the future of marine geomorphometry.

1.2 The rise of marine geomorphometry

The science of geomorphometry has roots in morphography, hypsometry, cartometric, geophysics, and geomorphology (Pike et al., 2009; Evans and Minár, 2011; Evans, 2013). Following the increase in digital terrain models (DTM) availability in the 1960s, the underlying theories and mathematical developments of modern geomorphometry (i.e. based on quantitative measurements rather than qualitative observations derived from DTMs) started to be developed in the early 1970s (e.g. Carson and Kirby, 1972; Evans, 1972; Krcho, 1973; Schabber et al., 1979). These methods and algorithms were slowly automated in the 1980s as computers became more available (e.g. Horn, 1981; Imhof, 1982; Pike, 1988). However, constraints in computing power (Burrough, 1986) delayed the rapid expansion of geomorphometry until the early 1990s (Pike et al., 2009). As mentioned in recent reviews (e.g. Gessler et al., 2009; Evan and Minár, 2011, p. 105), the field of modern geomorphometry is a “young field” that is “still forming, with many concepts, methods and applications.”

In the marine environment, early geophysical research that studied the link between the shape of the seafloor and elements such as global tectonics (Parsons and Scalter, 1977; Wessel and Chandler, 2011; references therein) led the way to the more recent marine applications of modern geomorphometry. The first applications of quantitative measurements derived from marine DTMs came from the field of marine geomorphology (e.g. Czarnecki and Bergin, 1986; Shaw and Smith, 1987, 1990; Malinverno, 1990; Goff, 1992, 2001), and was sometimes known as mathematical morphology or geology, or simply seafloor classification (Herzfeld, 1993). Then, the realization that different characteristics of seabed morphology was often linked to species distribution and biodiversity (e.g. Burrows et al., 2003; Giannoulaki et al., 2006), combined with the increase availability of higher-resolution bathymetric data (Smith and McConnaughey, 2016), opened a wide range of possibilities for marine habitat mapping in the mid-2000s (Bakran-Petriocili et al., 2006; Lundblad et al., 2006; Wilson et al., 2007). As discussed in Sect. 6, these two applications are still leading research areas in marine geomorphometry, as new

applications slowly emerge. Despite the important amount of literature available on the qualitative description of terrain morphology from DTMs, for instance from the geophysical literature, the current review focusses on modern geomorphometry, i.e. the extraction from depth models of additional quantitative information describing terrain characteristics.

Figure 42 compares the increase in publications in both marine and terrestrial (and potentially extra-terrestrial) geomorphometry over time. The numbers illustrate that marine applications of geomorphometry are more recent and less numerous than their terrestrial counterparts. However, we note that the ~~low~~lower number of published marine applications indicated in Fig. 42 may be biased by the fact that the researched terms (~~i.e.g.~~ geomorphometry and terrain analysis) are not always used in marine studies, even where geomorphometric techniques have been employed. Consequently, Figure 2 may be a reflection of how these terms have been adopted rather than a representation of the actual evolution of the practice. For instance, in Harris and Baker (2012a), an authoritative volume in marine habitat mapping, all of the 57 case studies used bathymetry, 33 of them generated slope, 23 of them measured rugosity, and 14 of them calculated a topographic position index, amongst other terrain attributes (Harris and Baker, 2012b). Despite this high use of general geomorphometry techniques, the term “geomorphometry” was not once used ~~once~~ in the 900 pages of the volume, and “terrain analysis” was only mentioned twice.

~~To our knowledge, no review on the state of the art of marine geomorphometry has ever been written. The aims of this contribution are therefore to raise awareness of this relatively recent field and to lay the basis of marine geomorphometry practices by reviewing the relevant literature to date. As illustrated in Fig. 2, this manuscript addresses the five main steps of geomorphometry identified by Pike et al. (2009) with a focus on how these steps are relevant to marine geomorphometry and different from traditional, terrestrial geomorphometry. The five steps are: sample the surface (Sect. 2), generate a surface model from the sampled heights (Sect. 3), preprocessing, i.e. correct for errors and artefacts in the surface model (Sect. 4), surface analysis, i.e. derive terrain attributes and terrain features (or objects) (Sect. 5), and apply the terrain attributes and features to a specific problem (Sect. 6). We conclude with recommendations and reflections on the future of marine geomorphometry.~~

2 Sampling the depth of the seafloor

For centuries, the lead line was the main instrument used to determine the depth ~~to of~~ the seafloor, until remote sensing technologies revolutionized the way we could measure bathymetry. This section introduces ~~the principles of~~ four types of remote sensing technology that are currently used to collect depth information: ~~acoustic remote sensing, and found in the~~ geomorphometry literature: satellite radar altimetry, optical remote sensing, acoustic remote sensing, and bathymetric LiDAR (light detection and ranging). Radar altimetry and optical. From an application perspective, the survey methodology

or methodologies dictate the spatial scale (i.e. resolution and extent) of the final surface model. First, the fundamental technical limitations of the remote sensing technique that is used to collect bathymetric data will define the scale (resolution) of the surface model (Kenny et al., 2003; Van Rein et al., 2009). ~~both collect depth information in an indirect way~~ For instance, radar altimetry data limits models constructed with them to coarse, usually kilometre-scale resolution, while ~~acoustic remote sensing~~ other methods can achieve up to centimetre-scale resolution models. Second, by defining the distance between the platform and bathymetric LiDAR ~~measure the seafloor directly~~. Radar ~~the target~~, the characteristics of the latter may also influence the scale (extent) of the final model; a remotely sensed image collected from a satellite will usually have a coarser resolution and cover a larger area than an image collected from an aircraft or an unmanned aerial vehicle. While radar altimetry and acoustic remote sensing are limited to deeper waters ~~while~~ and optical remotely sensed and bathymetric LiDAR data are limited to shallower waters, ~~although~~ there is some degree of overlap between the depths in which the various methods can be applied. ~~A global scale~~ In terms of effort, systematic bathymetric survey could be performed with satellite-based methods within a few years at a global scale (Sandwell et al., 2002), compared to the estimated 600 years (Carron et al. 2001) that it would take using acoustic remote sensing technologies. The different techniques are discussed in the perspective of using the information they collect to generate ~~Digital Terrain Models (DTM)~~ DTMs and perform geomorphometric analyses. DTMs using bathymetric data are hereafter referred to as Digital Bathymetric Models (DBM) to distinguish them from Digital Elevation Models (DEM), a term usually reserved for terrestrial elevation data ~~though sometimes including bathymetric data for global datasets~~. Other techniques can be used to measure depth but are less common in the literature. ~~For instance, (e.g. ground-penetrating radar can be used to detect the thickness of the water by measuring the difference between the radar echoes from the air-water and water-seafloor interfaces~~ (Feurer et al., 2008). More details on the underlying theories of these four techniques can be found in Appendix 1.

2.1 Satellite radar altimetry

In the 1970s, satellite-based radar altimeters were developed (cf. Appendix 1) as a method to study the oceans on a global scale (Douglas et al., 1987), which was a significant improvement over the extent covered by very narrow ship tracks. ~~Radar altimeters emit microwaves that bounce on the sea surface and return to the receiver, giving the altitude of the satellite over the sea surface. The topography of the surface can then be deduced and used to derive ocean circulation patterns (Fu, 1983) or define geoid models (e.g. Fernandes et al., 2000). The geoid represents the gravitational equipotential surface of the Earth relative to the mean sea level; gravity varies in space, and the anomalies in its distribution were found to be correlated with bathymetry (McKenzie and Bowin, 1976; Watts 1979). Despite initial reports stating that it was impossible to derive reliable bathymetry from satellite altimeter (Keating et al., 1984; Watts and Ribe, 1984), Dixon et al. (1983) were the first to demonstrate its feasibility using real data. Several algorithms and methods to estimate and predict bathymetry from the gravitational field have since been developed (reviewed in Calmant and Beaudry, 1996 and Sandwell and Smith, 2001).~~

However, it remains a complex process (Calmant and Beaudry, 1996) that still requires acoustic data for calibration (Smith and Sandwell, 1997).

Consequently, the applications of altimetry-derived bathymetric data are limited to the study of broad-scale patterns, processes and features as they only provide low resolution estimates of the bathymetry (Goff et al., 2004); ocean waves create a lot of noise that prevents the collection of fine resolution data (Smith, 1998), and rough seafloor geology and thick sediments affect data accuracy (Smith and Sandwell, 1994). Technological constraints and satellite orbits also prevent data collection close to the poles and the coastline (Sandwell et al., 2002). Some authors identified weaknesses in the method and warned that predicted depths from altimetry may not be reliable and should not be used for geodynamics studies (Smith, 1993), navigation, or hazard identification (Smith and Sandwell, 1994). The main advantages of altimetry-derived bathymetry are speed of collection and uniformity of coverage (Mackenzie, 1997).

Two main altimetry-derived datasets are currently used in applications of marine geomorphometry: the General Bathymetric Chart of the Oceans (GEBCO, 2014) and the Shuttle Radar Topography Mapping 30-arc second database (SRTM30_PLUS, Becker et al., 2009). They are both free datasets that combine together elevation and bathymetric data. The bathymetric parts were created by filling the gaps between publicly available datasets from different sources with radar altimetry (Smith and Sandwell, 1994, 1997; Becker et al., 2009). These datasets have been used for instance in habitat mapping and predictive modelling (e.g. Davies et al., 2008; Knudby et al., 2013), conservation (e.g. Ross and Howell, 2013), search and rescue operations (Smith and Marks, 2014), and geomorphology (e.g. Harris et al., 2014). Many works have found these datasets to be too coarse for their purposes (e.g. Davies et al., 2008; McNutt, 2014). For instance, Vierod et al. (2014) stated: “At present, the availability of bathymetric data at a resolution sufficient to inform reliable terrain attribute predictors is a major limitation to the ability of deep-sea species distribution models to make accurate predictions of the distributions of benthic organisms.” For many applications, quality can also be just as important as resolution (e.g. Sect. 4 and Sect. 6).

2.2 Optical remote sensing

Of the four remote sensing methods presented in this section, optical passive-remote sensing is the least common in the marine geomorphometry literature. However, it presents a cheaper alternative to LiDAR data for collecting depth information in very shallow coastal areas (Su et al., 2014), as satellites can cover large areas in less time (Lafon et al., 2002; Wang and Philpot, 2007). Two main passive optical remote sensing techniques groups of methods are presented usually used to estimate bathymetry from optical remote sensing: one based on the interactions of electromagnetic radiations with water and one based on principles from stereoscopy- (see Appendix 1).

Methods based on electromagnetic radiations are limited to shallow waters because of light attenuation within the water column (Jawak et al., 2015). In theory, based on light penetration in coastal waters, depths down to 50 m could be retrieved (Speight and Henderson, 2010). However, the practical limit varies with local sea conditions. A maximum of 30 m deep is

usually achieved when local conditions are exceptionally good (Collet et al., 2000; Jawak et al., 2015), and most often a depth of 15 m is reported as being the performance limit of optical remote sensing for bathymetry retrieval (e.g. Stumpf et al., 2003). The ability to derive depth estimates from imagery comes from the optical Beer Lambert law of light absorbance, which describes light absorption as it goes through a transparent medium (Serway and Beichner, 1983). In water, light gets absorbed exponentially as depth increases (Lyzenga, 1978). The Beer Lambert law allows the mathematical derivation of depth estimates from the brightness values of pixels in an image, when the absorption characteristics of an area are known (Mobley et al., 2005; Carbonneau et al., 2006). Since the absorption rate of an area is dependent on water turbidity and the characteristics of the incoming energy (e.g. the intensity, angle and wavelength of sunlight), calibration with ground truth data verifying depth colour relationships (i.e. local light absorption characteristics) is a key step in the application of this method. However, calibration is made difficult by temporal variations in the illumination characteristics of an area (Carbonneau et al., 2006); the calibration data would ideally need to be collected at the same time as the remotely sensed data to ensure identical environmental conditions. Since reliable calibration data are particularly challenging to obtain in marine waters (Lafon et al., 2002; Dekker et al., 2011), some methods have been proposed to estimate bathymetry without ground truth data (e.g. Fonstad and Marcus, 2005), however these are not yet widely adopted (Feurer et al., 2008). Rather than using the level of absorbed energy to derive bathymetry from imagery, some authors, e.g. Maritorena et al. (1994), have used bottom reflectance, which is the level of reflected energy.

Photogrammetry applied to pairs of stereo images can also be used to build DBMs in a similar method to the technique applied on land (2003). Optical methods Although possible (e.g. Stojic et al., 1998), through water photogrammetry is challenging due to the need to correct for the air water interface (Feurer et al., 2008). Underwater photogrammetry (i.e. active remote sensing) has, however, been successfully applied at a fine scale to reconstruct the digital terrain (e.g. Johnson Roberson et al., 2010; Kwasnitschka et al., 2013). The work by Friedman et al. (2012) is noteworthy as they derived multi-scale measures of rugosity, slope and aspect from underwater stereo image reconstructions.

All types of imagery have been used to derive marine bathymetry: hyperspectral (e.g. Mobley et al., 2005; Ma et al., 2014), multispectral (e.g. Lyzenga et al., 2006; Pacheco et al., 2015), broadband colour (e.g. Westaway et al., 2003) and grayscale images (e.g. Winterbottom and Gilvear, 1997). Multispectral images enable refined depth estimates by extracting information on the bottom types from non visible spectral bands and linking the bottom types with depth (Winterbottom and Gilvear, 1997). The red band of the electromagnetic spectrum is particularly successful in detecting depth variations (Legleiter et al., 2004; Carbonneau et al., 2006).

All methods from optical passive remote sensing are limited to shallow waters and are sensitive to errors caused by waves, turbidity, sunglint from specular reflection, heterogeneous and complex seafloors, and the presence of shadow that artificially increases depth estimates (Lafon et al., 2002; Louchard et al., 2003; Holman and Haller, 2013; Eugenio et al., 2015). Some of these elements can be corrected or accounted for. For instance, Knudby et al. (2010) applied 'deglinting'

(Hedley et al., 2005; Kay et al., 2009) and water column corrections (Lyzenga, 1978), in addition to the common geometric and atmospheric corrections (Jensen, 2005), to IKONOS satellite images. From these images to create a 4 m resolution DBM ~~was created and rugosity from which~~ was derived measures of seafloor rugosity. The authors indicated, however, that noise prevented the use of bathymetry at depths deeper than 15 m as rugosity values were artificially increased. ~~That depth (15 m) is often reported as being the performance limit of optical remote sensing for bathymetry retrieval (e.g. Stumpf et al., 2003), although the practical limit will vary with local sea conditions.~~

For stereoscopy-based methods, photogrammetry applied to pairs of stereo images can be used to build DBMs in a similar way than what is done on land. Although possible (e.g. Stojic et al., 1998), through-water photogrammetry is challenging due to the need to correct for the air-water interface (Feurer et al., 2008). However, underwater photogrammetry (i.e. active remote sensing) has been successfully applied at a fine scale to reconstruct the digital terrain (e.g. Johnson-Roberson et al., 2010; Kwasnitschka et al., 2013). The work by Friedman et al. (2012) is noteworthy as they derived multi-scale measures of rugosity, slope and aspect from underwater stereo image reconstructions.

2.3 Acoustic remote sensing

The development of acoustic technologies has fuelled marine exploration probably more than any other method, by providing reliable, ~~continuous, swath coverage~~ and relatively high-density data at ever-decreasing price per line kilometre. ~~Acoustic waves are the most practical vector of information in the submarine environment; since water is denser than air, acoustic vibrations propagate through water four to five times quicker (see Lurton, 2010). Sound also travels greater distances underwater as there is less attenuation in the water compared to air (Lurton, 2010).~~

for review). Three ~~tools~~ types of active sonars (Sound Navigation and Ranging) can be used to collect depth estimates and/or backscatter information using sound waves: (see Appendix 1): sidescan sonars (SSS; reviewed in Blondel and Murton, 1997), single-beam echosounders (SBES), and multibeam echosounders (MBES). ~~These tools are all active sonars (Sound Navigation and Ranging) that transmit a characteristic and controlled signal; reviewed in de Moustier, 1988). Backscatter data is effective in direction of the seafloor. The two-way travel time, which is the time taken for acoustic waves to travel between the source and the seafloor and back to the source again, can be measured to estimate the range between the target and the sonar and thus deduce depth. The intensity of this return (i.e. backscatter) can also be measured to provide~~ providing information on the seafloor properties ~~of the seafloor~~ (e.g. sediment composition). These ~~three~~ tools can be pole-mounted on the side of vessels, or mounted on the hull of vessels, on remotely operated vehicles (ROV), on autonomous underwater vehicles (AUV), or on a towed platform.

SSS ~~were developed for military applications in the 1940s. They provide an acoustic image of the seafloor made from backscatter measurements. Despite their ability to provide information on the~~ that can inform on topographic roughness ~~of the seafloor, SSS cannot measure seafloor relief directly. However, similarly to what is done with interferometric synthetic~~

~~aperture radar, interferometry can be used to create estimates of bathymetry by combining. They can only provide bathymetric measurements when data from two receiving antennas-SSS are combined and principles from interferometry are applied. SSS are a commonly used seafloor technology because they are easy to deploy and cheaper than other acoustic technologies (Harris and Baker, 2012c), but not often used to collect bathymetry as they are usually mounted). The acoustic image quality of SSS images are very high resolution, and characteristics (e.g. length and shape) of the acoustic shadows, which are the areas on a towed platform that is difficult to accurately locate in space-SSS image that have null intensity values because the sound was blocked by an object of feature higher than its surroundings, enable the estimation of the height and size of these objects or features (Blondel and Murton, 1997).~~ Collier and Humber (2012) provide an example of the use of sidescan-derived bathymetry to identify geomorphic features on the seafloor. Some techniques from specific geomorphometry are used on backscatter data to identify specific bedforms or depositional units on the seafloor based on their unique acoustic signature (Greene et al., 1999; Huvenne et al., 2005; Martorelli et al., 2012) and to detect differences in reflectivity and texture patterns on the seafloor (van Lancker et al., 2012). We also recognize the potential to generate ~~centimetre-higher~~ resolution (centimetre-scale) bathymetric data using modern synthetic aperture sonar systems such as the HISAS 1030 (Kongsberg Maritime, 2015) from a stable AUV platform (e.g. ~~Thorsnes et al., in press~~). ~~Synthetic aperture sonars differ from traditional SSS by utilising data from several consecutive pings to synthesize a longer sonar array capable of measuring at higher resolution.~~Ludvigsen et al. 2014). There are many potential benefits to this approach although, at present, the processing of bathymetric data is very computationally demanding and therefore best suited to mapping of small areas.

SBES, or fathometers, collect both depth and backscatter data by transmitting a ~~narrow~~single sound beam at nadir. The mapped extent is thus limited to a single track directly below the supporting platform. ~~Some modifications to SBES were suggested to increase their performance. For instance, the split beam echosounder uses interferometry to improve the accuracy of the data and was used to determine slope directly (Fosså et al., 2005). The dual beam echosounder uses two beams of different aperture oriented in the same direction to locate targets more accurately. Finally, the sweep sounder is a combination of several SBES mounted on a horizontal support to increase the number of soundings.~~ Although they remain standard for ships navigation, SBES are less and less used for mapping purposes since MBES became more affordable, ~~but~~ However, recent applications can still be found, particularly where compiled SBES data are available; a SBES bathymetric dataset of the English Channel was used by Coggan and Diesing (2012) for the broad-scale analysis of an exposed rock ridge system, by Elvenes et al. (2014) for surficial sediment and habitat mapping, and by James et al. (2012) to identify geomorphic features in a paleo-valley.

MBES provide a relatively fast, high-resolution and wide coverage measurement of the seafloor, ~~both in terms of depth and backscatter.~~ They sweep a large swath of the seafloor by emitting a fan of narrow sound beams, and are currently the most efficient and accurate tool available to collect bathymetric and backscatter data (Costa et al., 2009; Schimel et al., 2010a, 2010b). In recent years, advancement in MBES technology has further enhanced a valuable source of seafloor data. These

advances have come out of traditional user groups extending the application of the data to meet new requirements and from the motivation of new user groups wanting to employ the technology. This wide ranging and ever growing community of MBES users are adapting and extending the potential of MBES data to address unique applications. MBES users have traditionally included hydrographers, navigators, engineers, marine geologists and military planners, but now we see the extension of the technology to meet the needs of maritime explorers, archaeologists, fisheries biologists, geomorphologists and ecosystem modellers, to name a few. MBES is currently the main source of bathymetric data for applications of marine geomorphometry-, although these data are limited in terms of coverage: “Multibeam soundings are the gold standards, but such mapping has been concentrated in coastal zones, along shipping lanes, and in regions harboring hydrocarbon or mineral deposits” (Normile, 2014, p. 964).

2.4 Bathymetric LiDAR

Bathymetric LiDAR is an adaptation of the more traditional airborne topographic LiDAR (~~Irish and Lillyerop, 1999; Guenther et al., 2002, see Appendix 1~~) and has become increasingly common in the literature in the last two decades (Brock and Purkis, 2009). ~~The main difference between the two types of systems is the wavelengths used; the laser from Recently, they have been combined into topo-bathymetric LiDAR—uses a wavelength in the green spectrum, compared to the red/infrared wavelength of the topographic LiDAR. Recent systems, sometimes called topo bathy LiDAR,—, which are multispectral LiDAR and combines systems that enable data collection both types of laser, which enables the surveying of both above~~ land and water ~~in one flight~~; when flying over the water, ~~the~~ green laser ~~— characteristic of bathymetric LiDAR —~~ penetrates the sea surface and collects information on the water column and the seafloor, while the red/infrared laser ~~— characteristic of topographic LiDAR —~~ collects information on the sea surface. LiDAR can also collect intensity values that, like acoustic backscatter, provide information on the characteristics of the seafloor (Costa et al., 2009; Kashani et al., 2015).

Bathymetric LiDAR is the only technique that can collect high-resolution data in very shallow waters, which makes it especially relevant for coastal applications requiring fine-scale data (<1 m resolution) (Brock and Purkis, 2009). The efficiency of bathymetric LiDAR systems is greatly limited by turbidity, wave action, depth (up to 50-70 m in very exceptionally good conditions), steep slopes, and rocky substrate (Costa et al., 2009; Chust et al., 2010; Jalali et al., 2015). Current geomorphometric applications on bathymetric LiDAR data are mainly related to the exploration of coastal ecosystems (e.g. Wedding et al., 2008; Zavalas et al., 2014) and geomorphology (e.g. Arifin and Kennedy, 2011; Kennedy et al., 2014), but are likely to extend to other applications such as marine archaeology and natural hazards assessment (e.g. Solsten and Aitken, 2006). In 2015, LiDAR data represented 4.5% of the coastal data collected for the Continually Updated Shoreline Product (CUSP) compiled by the National Oceanic and Atmospheric Administration (NOAA) and the National Geodetic Survey (NGS) of the United States (Graham et al., 2015).

3 Generating a surface model from sampled depths

~~By nature, geomorphometric analyses necessitate spatially continuous data, but not all remote sensing techniques used to collect depth samples create continuous surfaces. For instance, bathymetric LiDAR and MBES collect point data that need to be cleaned and then interpolated in order to create a full coverage, and SBES collect data in narrow lines that sometimes need to be interpolated to fill in between the survey lines. This section describes the different interpolators that are available for DBM generation and the question of spatial scale of DBMs.~~ A detailed account of the various approaches to processing (i.e. georeferencing and applying system and environment related corrections) and cleaning of data (i.e. removal of spurious depth soundings) are beyond the scope of this paper and are specific to the sensors used for data acquisition as well as industry and application-related standard practices. We do, however, in this section, we focus on the interpolation of data and only touch briefly on data cleaning ~~in Sect. 3.2 where~~when we present a method where uncertainty algorithms are used to aid data cleaning, and where the interpolation of data is intrinsically linked to the calculation of uncertainty of the bathymetric surface.

3.1 Interpolation

By nature, geomorphometric analyses necessitate spatially continuous data, but no remote sensing techniques used to collect depth samples create truly continuous surfaces. Hengl and Evans (2009) identified several techniques used to generate gridded DTMs from height samples for geomorphometric purposes, including inverse distance-weighting (IDW), minimum curvature, spline, kriging, polynomial regression, moving average, and many others. The same methods can all be used to generate DBMs from depth samples. For instance, Ezhova et al. (2012) created a DBM from SBES data using the natural neighbour interpolation method, and Ramillien and Cazenave (1997) combined altimetry and ship-based data into a single DBM using bilinear interpolation. More rarely, triangulated irregular networks (TIN) are created from depth samples; for example, Heyman and Kobara (2012) generated a TIN from SBES data, and Foster et al. (2009) computed TINs from SBES and bathymetric LiDAR from which volumetric attributes were computed.

The choice of interpolator varies depending on the type of data and the spatial arrangement of the depth samples. For instance, MBES or LiDAR data can collect very dense point clouds that require little interpolation between points, resulting in limited interpolator influence in the final DBM. On the other hand, creating a DBM for a big area from SBES data requires more interpolation as SBES only sample very narrow tracks and have a high density of points along the survey line but no data between the survey lines. This has implications for geomorphometry as the interpolated DBM may miss important geomorphological features (depending on the distance between the survey lines), similarly to what happens with the interpolation of contour lines (Wise, 1998). Also, some methods (e.g. IDW) do not extrapolate and are hence less accurate in cases of sparse sampling. The choice of an appropriate interpolator to generate a surface model is critical as some

[interpolators may produce erroneous depth values that do not adequately represent the real bathymetry \(Smith and Wessel, 1990\).](#)

There are no optimal interpolation methods (Li et al., 2005), and it is well known that each technique has different sensitivity to errors and sample distribution and that the quality of DTMs can be improved when making the appropriate choice of interpolator (Carrara et al., 1997; Hengl and Evans, 2009). [For instance, some techniques will consider all samples while other will ignore outliers or smooth out their effect.](#) By being different in nature, sampled depths may not require the same characteristics from an interpolator than sampled elevations; for instance, DBMs do not need to be hydrologically corrected as drainage analyses are futile underwater. This is why techniques were developed in recent years to address the particular characteristics of depth sampling. Here we examine on such technique, the CUBE (Combined Uncertainty and Bathymetric Estimator) algorithm (Calder, 2003), which accounts for different errors specific to acoustic remote sensing (e.g. geometric and acoustic) and is incorporated in several of the most widely used bathymetric processing software used by the hydrographic survey industry and scientific community. Although not yet universally accepted as data cleaning method by the hydrographic survey industry and hydrographic agencies, who have a particular need to preserve shoal soundings and comply with strict quality control procedures to ensure safety of navigation, CUBE is widely used and of special interest to more applied bathymetric data users and the related scientific community. According to Schimel et al. (2010b), CUBE could be more appropriate than traditional gridding methods to compute precise bathymetry and associated terrain attributes. CUBE is based on the spatially explicit quantification of the total propagated uncertainty (TPU) for each data point (Calder and Mayer, 2003), enabling the rejection of samples that are outside a certain uncertainty confidence level (e.g. 95% for Calvert et al., [2014](#)[2015](#)). When creating the DBM, the algorithm provides vertical error estimates and statistically assigns, to each pixel, the most likely depth value based on the uncertainty of each sounding within the pixel (see Dolan and Lucieer, 2014). In several bathymetric processing software offering CUBE, users can visualize not only the most probable depth for each pixel, but also the subsequent most probable depths (e.g. second or third most likely) and select the one they think is the most appropriate based on their knowledge of an area. For example, this can allow correction for occurrences when the sonar detects fish close to the seafloor instead of the seafloor itself and data cleaning did not appropriately remove these soundings. Figure 3 shows some of the information that can be extracted and visualised from the application of the CUBE algorithm. When interpolating the soundings to create a DBM, the bathymetry and the horizontal and vertical components of uncertainty can be stored in a BASE (Bathymetry Associated with Statistical Errors) surface. The BASE format allows multi-attributes surface models. CUBE's main inconvenience is that it requires a lot of ancillary data to be collected in order to compute TPU, but it is very reliable in defining the spatial pattern of errors, their importance, and helping to identify their sources (Passalacqua et al., 2015). In addition to the bathymetry, a map of uncertainty can be computed, which can become very important when making decisions using the bathymetry and for onward geomorphometric analysis.

3.2 Spatial scale

Spatial scale is a term used to summarise data resolution and extent and is an important component of the interpolation of depth data to generate DBMs. Both resolution and extent of a given DBM are dictated by the survey methodology or methodologies. First, the fundamental technical limitations of the remote sensing technique that is used to collect the bathymetric data will define the scale (resolution) of the DBM (Kenny et al., 2003; Van Rein et al., 2009). For instance, principles of radar altimetry limits DBMs generated with these data to coarse, usually kilometre scale resolution, while other methods can achieve up to centimetre scale resolution data (c.f. Sect. 2). Second, the platform that supports the system may also influence the scale (extent) of the final DBM; a remotely sensed image collected from a satellite will usually have a coarser resolution and cover a larger area than an image collected from an aircraft or an unmanned aerial vehicle.

Unlike systems used in optical remote sensing, radar altimetry and bathymetric LiDAR, acoustic systems do not sample the seafloor uniformly, which influences the spatial scale of the resulting DBM. The sampling density of these systems is directly dependent on depth, or more specifically on the sensor-to-seafloor distance (Lecours and Devillers, 2015). As this distance between a MBES and the seafloor increases, it takes longer for the sound to reach the seafloor, the system's footprint increases and related beam widths increase, leading to a lower sampling density for a greater area sampled at a coarser resolution. Since the seafloor is rarely perfectly flat and at a constant depth, the sampling density is almost never uniform across survey areas, which can make it challenging to determine the appropriate spatial resolution of DBMs for interpolation.

Ultimately, the spatial scale of a DBM will be dictated by its intended use (see Sect. 6) which then influences the choice of the data collection method, typically following hydrographic standards (IHO, 2008) which ensure the appropriate data are acquired to ensure safety of navigation. Besides DBMs created directly from one source of survey data, we are increasingly seeing DBMs generated, or pooled together from several surveys and/or sensor technologies (e.g. EMODnet, 2015). These datasets can be a valuable resource but impose additional challenges for DBM creation and geomorphometric analysis (e.g. Sect. 6.4.3).

4 Correcting errors and artefacts in digital bathymetric models

In terrestrial applications, it is well known that all DEMs, regardless of the techniques used to collect and generate data, are influenced by uncertainty and errors (Fisher and Tate, 2006; Gessler et al., 2009). This is also true for marine applications, but the properties and dynamic nature of the ocean makes DBMs more prone to errors and artefacts than DEMs (Hughes–Clarke et al., 1996). As illustrated in Fig. 4, this has significant implications for marine geomorphometry, which shows as

widely recognized in the terrestrial literature (Florinsky, 1998; Zhou and Liu, 2004; Oksanen and Sarjakoski, 2005) that errors and artefacts in a DTM propagate to ~~terrain attributes~~ and may be amplified in ~~subsequent analyses~~ terrain attributes.

As with DEMs (Harrison et al., 2009; Sofia et al., 2013), errors and artefacts in DBMs can be caused by the interpolation method (Erikstad et al., 2013), movement and positioning of the supporting platform (Hughes–Clarke et al., 1996), and a temporal (Lecours and Devillers, 2015) or spatial (Hughes–Clarke, 2003a, 2003b) misalignment between the different elements of the surveying system. Data from radar altimetry are the least sensitive to platform motion (Smith and Sandwell, 1994). However, large artefacts resulting from fine-scale noise in the gravity field (Goff et al., 2004) and the algorithms used to convert gravity data into bathymetric estimates (Dixon et al. 1983; Calmant and Beaudry, 1996) are often characteristic of these data. Similar large linear artefacts can sometimes be found in satellite images (e.g. Klemas, ~~2011~~2011a). The level of error in bathymetric data from optical remote sensing is known to directly depend on water depth as a result of light attenuation in the water column (e.g. Liceaga-Correa and Euan-Avila, 2002). Recent studies (Leon et al., 2013; Hamylton et al., 2015) have demonstrated that the integration of the spatial structure of errors improves bathymetric estimates derived from satellite images. Data collected with acoustic methods are the most susceptible to artefacts for several reasons. First, they are collected from surface vessels/platforms or underwater vehicles that can be strongly affected by environmental conditions such as waves and wind. Furthermore acoustic waves need to be corrected for sound velocity. Without this correction the data will exhibit artefacts broadly similar to those caused by an inappropriate correction of the atmospheric conditions in optical remote sensing (Li & Goldstein, 1990). Sound velocity varies with temperature, salinity and pressure and the failure to correct for these variations can induce refraction artefacts in the DBM (Yang et al., 2007). This is particularly challenging as water column properties vary both spatially and temporally, especially in the coastal zone where there is the additional complication of freshwater input from rivers, and are less predictable than atmospheric conditions (Cushman-Roisin and Beckers, 2011). Tidal corrections are generally applied using data from locally installed tide gauges, or modelled tides, depending on the accuracy required. Finally, since the surveying system is underwater, direct positioning using the Global Positioning System (GPS) is not possible (Roman and Singh, 2006). The level of error in the data is thus strongly influenced by the accuracy of the different instruments that provide ancillary data to estimate the position of the system's underwater components; ~~the positioning error is known to directly increase with depth~~ (Rattray et al., 2014; Lecours and Devillers, 2015).

Figure 4 illustrates different types of errors and artefacts that can be found in bathymetric data of different types and at different scales, and their propagation to derived terrain attributes. Artefacts commonly found in bathymetric data and that often cannot be corrected using existing methods include gridding and interpolation artefacts (e.g. in the top panels), motion artefacts (e.g. middle and bottom panels), refraction artefacts, and artefacts caused by the temporal or spatial uncertainty associated with ancillary data (e.g. bottom panels)→

1) Artefacts in DBMs are difficult to handle properly as ~~they cannot~~^{depth} generally ~~cannot~~ be ground-truthed, ~~thus preventing verification of whether or not a feature is natural or the result of an artefact~~ (Li and Wu, 2006). Most marine environments are not easy to access and the collection of ground-truth data is often limited by technological and logistical constraints (Solan et al., 2003; Robinson et al., 2011). Consequently, ground-truthing of DBMs is not standard practice. We note however that ground-truthing is often performed for backscatter data to attempt matching sediment types with acoustic reflectivity characteristics. As illustrated in Fig. 4, artefacts in DBMs may be present at all scales and persist, or are sometimes amplified in derived terrain attributes. For instance, artefacts in the GEBCO [dataset](#) are common (Lecours et al., 2013; GEBCO, 2014; Fig. 4), arising mostly from the merging of datasets of different quality. When the artefacts are ~~too~~ ^{big}~~large~~ they [dominate the surface and](#) cannot be removed with traditional filtering methods (e.g. Gaussian filtering) as this considerably affects the overall quality of the surface (Passalacqua et al., 2015), and the artefacts are also difficult to overcome when deriving terrain attributes even by using multi-scale methods (Sect. 5.1). At a finer scale, Yang et al. (2007) developed an algorithm to correct refraction artefacts, although this was only partially successful. When the artefacts are smaller, it can be difficult to distinguish them from real fine-scale features such as sandwaves or iceberg scourings (Hughes–Clarke et al., 1996), especially when no underwater video data are available to confirm the geomorphology of an area. This is particularly challenging for marine geomorphometry as analyses are likely to capture both the real features and the artefacts (Wilson et al., 2007). Currently, the main ways to address artefacts in DBMs are to apply filtering techniques, resample the data to coarser resolutions, manually correct the data based on visual interpretation, and to use algorithms like CUBE that account for errors and uncertainty. Most marine geomorphometry applications simply disregard the presence of the remaining artefacts, excluding them for practical purposes by expert judgement.

5 Deriving terrain attributes and terrain features

Bathymetric data, particularly full coverage multibeam, or LiDAR data, are well suited for the generation of quantitative terrain attributes and terrain features. These attributes and feature classifications can be very useful in describing, interpreting and classifying geomorphology in the marine environment, just as their terrestrial equivalents are on land. These derived datasets can also be of further use in [many applications \(cf. Sect. ~~geological interpretation and habitat mapping and modelling-6~~\)](#). With bathymetric data now available in many areas at comparable resolutions to terrestrial DEMs, depending on the survey equipment used (~~e.g.~~^{cf.} Sect. 2), we can extract a similar level of information to that obtainable from terrestrial DEMs. Elsewhere, global (e.g. GEBCO, 2014) and regional (e.g. IBCAO (Jakobsson et al., 2012); EMODnet, 2015) bathymetric datasets combining information from many sources have become an impressive resource and are being used routinely for many marine science applications, not least those including high seas areas which, as yet, have little detailed coverage. This section reviews both the use of general (i.e. terrain attributes) and specific (i.e. terrain features) marine geomorphometry.

5.1 General geomorphometry (terrain attributes)

The calculation of terrain attributes (synonymous with terrain/topographic variables) first requires some method for mathematically representing the bathymetric surface. This surface representation is then used to calculate the required terrain attribute, and is typically achieved by either using neighbourhood analysis of raster pixels, or by fitting a polynomial expression to describe the surface. ~~A review of terrain attributes was provided by Wilson et al. (2007) in the context of marine benthic habitat mapping and updated by Dolan et al. (2012). In addition, Brown et al. (2011) offer a useful summary of the extent to which many of these various terrain attributes have been employed within published habitat mapping studies in the period 2000 to 2011.~~ The computations performed on DBMs, and the range of applications that these derived terrain attributes are used for, are common to many of those performed on DEMs for terrestrial applications. ~~The key quantitative difference in the underlying data is that DBMs have negative values and this has led to modification of some terrain attributes to suit bathymetric data. Besides this, differences~~ Differences in analysis of bathymetric DBMs versus DEMs are often more related to the meaning or application of the information from the analysis. For instance, deriving a watershed network underwater may be useful e.g. for delineating potential sediment pathways on the continental slope, but is a deviation from the original intended purpose. ~~A review of terrain attributes was provided by Wilson et al. (2007) in the context of marine benthic habitat mapping and updated by Dolan et al. (2012). In addition, Brown et al. (2011) offer a useful summary of the extent to which many of these various terrain attributes have been employed within published habitat mapping studies in the period 2000 to 2011. Habitat mapping is currently one of the largest application areas for these techniques. To our knowledge no equivalent reviews on the use of general geomorphometry exist for more general marine geomorphological or other application areas.~~

Terrain variables can be grouped into four main types describing different properties of the terrain – slope, orientation, curvature/relative position, and terrain variability (Fig. 5). It is beyond the scope of this paper to provide details on all the various options for computation, however, we provide an overview of some of the most commonly used terrain attributes in marine-based studies, as well as an indication of some common calculation approaches ~~(Tables~~ ~~Table 1).~~ (Table 1). Here we note the geomorphological relevance and ecological relevance of the various types of terrain attributes in the context of seabed mapping. Whilst the effects on geomorphology are more direct, the popularity of terrain attributes in benthic habitat mapping is, to a large extent, due to their function as a surrogate (or proxy) in explaining the distribution of benthic fauna. In the absence of better, or alternate information (e.g. gained from high resolution oceanographic data), proxy information such as whether a given location is sheltered or exposed to dominant currents as ~~indicate~~ indicated by its position relative to neighbouring terrain, can be useful in determining suitable habitat for a given species or community. An elevated position for example may be advantageous for suspension feeding organisms and act as a surrogate for the direct need for food supply. Other terrain attributes may capture a proxy for shelter or other ecological

advantage. This topic is discussed further by Lecours et al. (2015b) including the all-important effect of scale which is linked both to data resolution and the scale at which geomorphometric analysis is conducted.

For GIS based calculation of terrain attributes, extending the analysis window beyond the basic 3 x 3 neighbourhood is particularly useful in ~~benthic habitat mapping~~ [marine geomorphometry](#) as it facilitates the identification of spatial scales that are relevant to ~~the~~ benthic communities ([Lecours et al., 2015b](#)) or to [geomorphological interpretation \(Shaw, 1992\)](#) and may also help to overcome artefacts in the DBM (Wilson et al., 2007). The multi-scale analysis methods developed by Wood (1996), which built on the work of Evans (1972, 1980), have been fundamental in establishing an appreciation of scale in marine and terrestrial geomorphometry alike. The associated software package Landserf (Wood, 2009) puts multi-scale analysis within easy reach of marine scientists and the use of Landserf for DBM analysis took off following the early applications of the software to bathymetric data (e.g. Wilson et al., 2007). Although Landserf 2.3 is still used by many scientists requiring a standalone programme for geomorphometric analysis, Wood's algorithms are now perhaps more widely used among the marine community through the GRASS module `r.param.scale`. The newly released ArcGeomorphometry toolbox (Rigol-Sanchez et al., 2015) offers a means to access the Wood-Evans (and other) algorithms for geomorphometric analysis, ~~this~~ [and](#) has the potential to provide a long awaited, convenient multi-scale analysis option for ArcGIS users.

One terrain attribute that is specifically tailored to analysis of bathymetric data is the bathymetric position index (BPI) (Lundblad et al., 2006), which is an adaptation of Weiss' (2001) topographic position index (TPI) and a useful measure of relative position that is simple to calculate over different neighbourhood sizes. Although a relatively simple algorithm to implement (Lundblad's BPI indices can be performed through the raster calculator (e.g. Wilson et al., 2007) or scripting), many marine scientists make use of the Benthic Terrain Modeler (BTM) Toolbox, which was first developed following Lundblad's (2006) study. The current version of BTM (Wright et al., 2012) for ArcGIS 10.1 and later has seen around 4000 downloads in the period 2012-2015 ~~and this, a figure~~ [that](#) gives a conservative estimate of how many scientists are actually using the tool (S. Walbridge, ESRI, pers. comm.). The BTM toolbox relies on ArcGIS Spatial Analyst and includes tools for calculating slope, aspect and terrain variability (rugosity, VRM) as well as methods for combining these into geomorphic zones. It was launched for the scientific community at a time when multibeam data was becoming widely available and modern marine geomorphometry was becoming established. The BTM toolbox quickly became popular as a one-stop shop for terrain analysis and classification of bathymetric data, offering a slightly more tailored solution, and the ability to handle larger datasets, than Landserf, with at least the BPI index being computable at different scales ~~ever~~ since the first release (now joined by VRM). The utility of the BTM tool has been augmented in recent years through updating of the terrain variability and aspect indices, and by providing the tools as both an AddIn and as a standalone ArcToolbox, providing greater flexibility to users who may wish to benefit from all, or just part of, the functionality.

Several bathymetric data processing software (e.g. CARIS HIPS and SIPS, QPS-Fledermaus) also have built in tools for calculation of basic indices such as slope and rugosity, bringing the functions directly to the bathymetric data user and removing the need to search for and select from the vast array of available methods. This has advantages of convenience for some bathymetric data users, but in most applied projects the computation of terrain attributes and further analysis will be conducted in some generic GIS software. Although many of the commercial software are currently limited to single scale analysis (3 x 3 rectangular neighbourhood) it has become easier to find tools for multi-scale analysis, either directly in open source software (e.g. GRASS), through additional toolboxes (e.g. SEXTANTE for QGIS), or via scripting. Many of these also give alternative choices for computation algorithms, the effects of which are investigated by Dolan and Lucieer (2014) using slope as an example.

Terrain variability has been a particularly popular terrain attribute in relation to benthic habitat mapping. This is largely due to the generally accepted link of terrain variability with biodiversity, which has, however, not yet been fully established with regard to spatial scale (Lecours et al., 2015b). Several measures of [rugosity/terrain variability](#) have been applied to DBMs ([Table 1](#)) with some proving suitable for multi-scale analysis and others becoming problematic at larger analysis scales (Wilson, 2006). A rugosity index [comparing which is the ratio of](#) surface [area](#) to planar area (Jenness, 2004) remains perhaps the most widely applied method in marine studies and this was implemented in early releases of BTM. Both the vector ruggedness measure (VRM; Sappington et al., 2007) now incorporated in BTM, and the more recent Arc_Chord Rugosity measure (Du Preez et al., 2014) [offers/offer](#) alternatives that are better decoupled from slope. Where slope and a terrain variability measures are to be used in further analysis e.g. as predictor variables for habitat modelling, it is particularly important that the user is aware of any autocorrelation or covariation between [them/these attributes](#), so they can be handled appropriately. Du Preez et al. (2014) lists several marine studies among those who have ignored the need for decoupling. However, with methods like VRM and Arc-Chord rugosity, or toolboxes like BTM and TASSE (Lecours, 2015) now readily available, we trust that future studies will make a conscious choice of the best geomorphometric analysis [to use](#) for their particular application.

5.2 Specific geomorphometry (terrain features/objects)

Compared to general geomorphometry and the use of terrain attributes, applications of [computer-based](#) specific geomorphometry are still relatively rare in the marine environment. Calculation of terrain features generally relies on the combined properties of several terrain attributes. For instance, Lecours et al. (2013) used Troeh's landform classification (Shary et al., 2005), which uses different types of curvatures to identify zones of relative deflection or accumulation and transit zones, on bathymetric data. The authors also adapted Weiss' (2001) landform classification, which combines slope with TPI measures at different scales to identify up to 16 landform classes, for application within the marine environment using BPI measures.

Terrain features such as crests, ~~and~~ troughs ~~etc.~~ can be extracted through the use of pixel based analysis (e.g. Blaszczyński, 1997; Wood and Dragicevic, 2007), but ~~recently~~ object-oriented methods for landform classification have recently become increasingly popular and are beginning to make their mark on marine studies (e.g. Lawrence et al., 2015) driven by an opportunity to analyse the DBM in conjunction with acoustic backscatter data (an indicator of seabed sediment type) rather than analysing the DBM alone, which offers several advantages for seabed classification. Geographic ~~object-based image analysis~~ (Geobia, ObiaObject-Based Image Analysis (GeOBIA, OBIA)) has been gaining some traction in the seabed mapping community as the spatial resolution of acoustic backscatter data ~~improves~~ (Diesing et al., 2014). The basic processing units in object based image analysis are objects which are represented by textural changes in the acoustic backscatter image and are constrained by derived topographic variables (Benz et al., 2004). ~~Geobia~~GeOBIA allows for the quantitative extraction of image textures and features to be identified in the backscatter data and the ability to relate these spatially to topographic variability (Costa and Battista, 2013). Multi-resolution segmentation is one of the most popular segmentation algorithms to delineate homogeneous seabed segments (Lucieer, 2008; Lucieer and Lamarche, 2011; Hasan, 2012; Eisank et al., 2014) and in the terrestrial literature stands out as the most successful method to delineate homogeneous terrain segments rather than landforms *per se* (e.g. Drăguț and Blaschke, 2006; Drăguț et al., 2011; Blaschke et al., 2014). This has been successfully demonstrated by Ismail et al. (2015) to identify and classify submarine canyons. By combining both the spatial derivatives of the DBM with ~~Geobia~~GeOBIA variables, the authors were able to perform an automated multiple scale terrain analysis to discriminate local and broad scale geomorphic features in the marine landscape. This information was used not only to delineate geomorphic seafloor features but also to identify properties that might influence biodiversity in a complex terrain. Specific geomorphometry is currently not used to its full potential in the marine environment.

6 Applications of marine geomorphometry

~~This section introduces some of the most common applications of geomorphometry in the marine environment: habitat mapping, marine geomorphology and geohazards, change detection, and hydrodynamics and modelling. Other applications of marine geomorphometry can also be found in the literature (e.g. underwater archaeology; Passaro et al., 2013) but are not discussed here. Figure 6 illustrates the proportion of the marine studies represented in the lower graph of Fig. 1 that could be classified in any of the types of applications that are presented in this section.~~

6.1 Marine habitat mapping

~~Benthic habitat mapping is one of the major applications areas where the use of marine geomorphometry has grown in recent years. Linked to the rise in the use of multibeam data for benthic habitat mapping (Brown et al., 2011) the vast majority of habitat mapping studies with access to good bathymetry data are now using, or at least testing, some form of terrain attribute~~

or feature classification in their habitat mapping activities, even though we note that many of these are not yet reflected in the peer-reviewed literature. Among the habitat mapping community several approaches to habitat mapping are common, many of which directly incorporate biological data, such as modelling species (e.g. Davies et al., 2008) or biotope distributions (e.g. Elvenes et al., 2014) and others which are primarily based on physical attributes deemed relevant for the distribution of benthic fauna (e.g. Micalef et al., 2012; Ismail et al., 2015). Geomorphometry is equally useful for both these approaches and those that combine both aspects (e.g. Tempera et al., 2012) and this discussion is relevant to an all-encompassing definition of habitat mapping (Lecours et al., 2015b). Figure 7 illustrates how terrain attributes are typically used in the production of predictive seabed habitat maps, providing an invaluable suite of full coverage predictor variables which are used together with point samples of observed habitat as the input data to modelling.

Harris and Baker (2012b) provide a summary of surrogate variables used for habitat mapping studies in the volume ‘Seafloor Geomorphology as Benthic Habitat: GeoHAB Atlas of Seafloor Geomorphic Features and Benthic Habitats’ including many terrain attributes that have been applied across a multitude of approaches to habitat mapping worldwide. The issue of surrogacy is also discussed in this volume as well as by Lecours et al. (2015b) and McArthur et al. (2010). The case studies presented in the GeoHAB Atlas, and other published studies, vary in the degree to which they have established the ecological relevance of the terrain attributes and/or feature classifications used. For geomorphological variables to really be useful predictors of seafloor habitat, the relationship between habitat and specific variables first needs to be established. Apart from depth, which all of the geomorphological variables are derived from, different shapes or attributes of the seafloor will be relevant to different species at different scales over different bathymetric and biogeographic zones. Bathymetry is known to be a first order influence on species distribution. There are a number of recent papers describing the potential of terrain attributes to act as surrogates of species distribution (Lucieer et al., 2013; Hill et al., 2014). The relationships are validated using several different statistical methods that either test terrain attributes against biological or ecological data, or combine terrain attributes with other environmental data and perform classifications to differentiate between the different habitats (Thiers et al., 2014).

In an example by Rengstorf et al. (2013), habitat suitability models for the cold water coral *Lophelia pertusa* were developed based on full coverage multibeam bathymetry on the Irish continental margin. Maximum entropy modelling was used to predict *L. pertusa* reef distribution at a spatial resolution of 0.002° (250 m). Coral occurrences were assembled from public databases, publications and video footage, and filtered for quality. Environmental predictor variables were produced by re-sampling of global oceanographic data sets and a regional ocean circulation model. Multi scale terrain parameters were computed from multibeam bathymetry at 50 m resolution. In a related study, Rengstorf et al. (2012) examined the effect of bathymetric data resolution on terrain attributes used to predict coral distribution, resampling the original 50 m resolution bathymetry from the Irish National Seabed Survey at successively coarser intervals up to 1 km. They concluded that terrain attributes derived from higher resolution bathymetry are required to adequately detect the topographic features relevant to corals. In a further related study Rengstorf et al. (2014) examined the relative importance of terrain attributes and

hydrodynamic variables (e.g. current speed, vertical flow, temperature etc.) on models of cold water coral distribution, concluding that combining the environmental information from these two sources leads to improved predictions over the spatial scales in question.

At a much finer resolution (~ 1 m) species-habitat relationships were examined across a marine reserve on the south-eastern coast of Tasmania using boosted regression tree analyses (Cameron et al., 2014). The most important explanatory variables of community diversity were those describing the degree of reef aspect deviation from east and south (seemingly as a proxy for swell exposure), reef bathymetry (depth), low rugosity and slope. These models could account for up to 30% of the spatial variability in measures of species diversity. As biological data at scales relevant to acoustic or remote sensing data such as that from AUVs, ROVs and diver surveys become available on national or international databases such as the Census for Marine Life and the Ocean Biogeographic Information System (OBIS) the ability to extend species distribution models into the wider ocean at finer scales will enhance the utility and value of marine geomorphology variables for marine biodiversity assessment.

Pike et al. (2009) listed current and potential applications of marine geomorphometry, including oceanography, coastal geomorphology, geophysical analysis of global tectonics, ocean currents, mineral exploration, fisheries managements, navigation, and concealment of nuclear submarines. While performing the meta-analysis that enabled the making of Fig. 2, we were able to classify marine geomorphometry articles into four main research areas: geomorphology, geophysics and geohazards, habitat mapping, biogeography and ecology, hydrodynamics and modelling, and others. This section thus introduces the most common applications of geomorphometry in the marine environment, and discusses in Sect. 6.4 the least common uses in addition to potential future applications of marine geomorphometry. A selection of published works that have utilised geomorphometric techniques in their study of seafloor morphology is provided in Table 2.

6.1 Marine geomorphology, geophysics and geohazards

Early geomorphometric studies of seafloor morphology in the 1960s were limited by the one-dimensionality and the low resolution of the bathymetric data that were available at the time (e.g. Krause and Menard, 1965; Neidell, 1966). In the last three decades, improvements in seafloor surveying technologies have resulted in a renewed interest in employing geomorphometric techniques to study seafloor geomorphology. ~~A list of some works that have utilised geomorphometric techniques in their study of seafloor morphology is provided in Table 2.~~ Similar techniques have also been utilised in the interpretation of sidescan sonar data (e.g. Blondel et al., 1998; Carmichael et al., 1996; Huvenne et al., 2002; Mitchell and Somers, 1989).

Geomorphometric techniques have generally performed well in submarine environments. The use of specific geomorphometric techniques, where features of interest are identified prior to analysis, has involved examining how different morphological parameters change spatially and with each other. They have been amongst the most successful

techniques, particularly with regard to the study of submarine mass movements, canyons and volcanoes. In the study of submarine mass movements, the general approach has been the prior identification of the boundaries of the landslides, the measurements of a series of morphometric parameters and their spatial and statistical analyses. This kind of approach has been applied to slope instability offshore Norway (Haflidason et al., 2005; Issler et al., 2005; Micallef et al., 2008), demonstrating ~~scale invariance in terms of~~ the fractal characteristics of submarine mass movement morphology and statistics ~~and morphology~~, which has important implications for submarine landslide modelling and hazard assessment. It has also been employed on a finer scale (Casalbore et al., 2011; Rovere et al., 2014) and a broader scale (Hühnerbach et al., 2004; McAdoo et al., 2000; Moernaut and De Batist, 2011) to identify tsunamigenic landslides and to provide interesting insights into failure frequency, preconditioning factors, triggers and controls of submarine mass movements in a wide range of environments, including lakes. In submarine canyons, specific geomorphometric analyses of submarine landslides has shown that landslides can be the most efficient process removing material from canyons and that their influence becomes more significant as the canyon matures (Green and Uken, 2008; Micallef et al., 2012). Geomorphometric investigations of submarine canyon form have generally focused on using morphological data to propose model of canyon erosion by turbidity currents (Mitchell, 2004, 2005; Vachtman et al., 2013). More recently, specific geomorphometric techniques have been used to demonstrate how canyons in passive, progradational margins develop into geometrically self-similar systems that approach steady state and higher drainage efficiency (Micallef et al., 2014b), and how canyons in active margins fail to reach steady-state because of continuous adjustment to perturbations associated with tectonic displacements and base-level change (Micallef et al., 2014a). The geomorphometric study of volcanoes has been useful in determining the key processes constructing and modifying volcano flanks and specifying the conditions that lead to slope instability (Mitchell, 2003; Mitchell et al., 2002; Stretch et al., 2006).

Initially, the techniques of general geomorphometry used in the study of submarine landscapes were less numerous and varied than those used in the study of subaerial landscapes. The majority of studies where geomorphometry was applied to the study of submarine landscapes have involved either spectral analyses of the bathymetric data or the statistical analysis of morphometric attributes- (see Table 2 for examples). More recently, general geomorphometric studies have made wider use of morphometric attributes and their statistical analyses and feature-based quantitative representation, most of which were specifically developed for submarine landscapes. Micallef et al. (2007a), for example, developed a methodology for the quantitative analysis of seafloor data, which was shown to exploit the full potential of these data sets and significantly improve the mapping and characterisation of submarine landslides. This methodology was applied to the submarine mass movements offshore Norway to elucidate the evolution dynamics of a multi-phase submarine landslide (Fig. 87), while emphasising the potential role of gas hydrate dissociation and contourite deposition in controlling the location and extent of submarine slope failure (Micallef et al., 2009), and to improve understanding of the mechanics and triggers of spreading, also while using limit-equilibrium and mechanical modelling (Micallef et al., 2007b). The automated and objective mapping of submarine landscapes is indeed an important application of general geomorphometry, and specific techniques have been

developed for the characterisation of pockmarks (Harrison et al., 2011; Gafeira et al., 2012), terraces (Passaro et al., 2011) and canyons (Ismail et al., 2015). Others have used general geomorphometric techniques to classify submarine landscapes (e.g. fjords (MosalikMoskalik et al., 2014a; MosalikMoskalik et al., 2014b), continental shelf and slope (Elvenes, 2013), and global (Harris et al., 2014)), identify the various styles and scales of deformation across submarine landslides (Mountjoy et al., 2009), and infer the evolution of seamounts (Passaro et al., 2010), mid-ocean ridge scarps (Mitchell et al., 2000) and faults in active continental margins (Kukowski et al., 2008).

6.2 Marine habitat mapping, biogeography and ecology

Benthic habitat mapping is one of the major applications areas where the use of marine geomorphometry has grown in recent years. Linked to the rise in the use of multibeam data for benthic habitat mapping (Brown et al., 2011; Smith and McConnaughey, 2016) the vast majority of habitat mapping studies with access to good bathymetry data are now using, or at least testing, some form of terrain attribute or feature classification in their habitat mapping activities, even though we note that many of these are not yet reflected in the peer-reviewed literature. Among the habitat mapping community several approaches to habitat mapping are common, many of which directly incorporate biological data, such as modelling species (e.g. Davies et al., 2008) or biotope distributions (e.g. Elvenes et al., 2014) and others which are primarily based on physical attributes deemed relevant for the distribution of benthic fauna (e.g. Micallef et al., 2012; Ismail et al., 2015). Geomorphometry is equally useful for both these approaches and those that combine both aspects (e.g. Tempera et al., 2012) and this discussion is relevant to an all-encompassing definition of habitat mapping (Lecours et al., 2015b). Figure 6 illustrates how terrain attributes are typically used in the production of predictive seabed habitat maps, providing an invaluable suite of full coverage predictor variables which are used together with point samples of observed habitat as the input data to modelling.

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that either test terrain attributes against biological or ecological data, or combine terrain attributes with other environmental data and perform classifications to differentiate between the different habitats (Thiers et al., 2014).

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At a much finer resolution (~1 m) species-habitat relationships were examined across a marine reserve on the south-eastern coast of Tasmania using boosted regression tree analyses (Cameron et al., 2014). The most important explanatory variables of community diversity were those describing the degree of reef aspect deviation from east and south (seemingly as a proxy for swell exposure), reef bathymetry (depth), low rugosity and slope. These models could account for up to 30% of the spatial variability in measures of species diversity. As biological data at scales relevant to acoustic or remote sensing data such as that from AUVs, ROVs and diver surveys become available on national or international databases such as the Census for Marine Life and the Ocean Biogeographic Information System (OBIS) the ability to extend species distribution models into the wider ocean at finer scales will enhance the utility and value of marine geomorphology variables for marine biodiversity assessment.

6.3 Hydrodynamics and modeling

The interaction of bottom currents with seafloor sediments results in a wide range of erosional and depositional morphologies – e.g. scours, furrows, ripples, dunes, lineations, contouritic drifts – the morphology and dimensions of which depend on flow velocity and sediment grain size (Stow et al., 2009). Detecting change in bedform morphology is of great interest to geologists, physical oceanographers and climatologists, and many others with the applied interest in such features. Bedforms determine basic flow patterns of ocean circulation at coarse and fine scales; even small perturbations in seafloor topography can influence the pathway and velocity of major shallow and deep current flows, heat transport and

ultimately climate (Gille et al., 2004; Kunze and Llewellyn Smith, 2004; Metzger and Hurlburt, 2001; [Palomino et al., 2011](#)). In turn, bedforms are also excellent archives of current and past bottom flow patterns (Sandwell et al., 2002). Port managers are also interested in bedforms and their evolution, particularly where they constitute a hazard to navigation in coastal waters. Detecting change in bathymetry and its impact on oceanography is therefore important, and local geomorphometric attributes, such as aspect, curvature and rugosity, have been used to develop hydrodynamic models or as proxies for local and regional currents (Lecours et al., 2015a). Seafloor topographic proxies are also fundamental in the predictive mapping of suspension-feeders (Lucieer et al., 2013; Hill et al., 2014), such as cold-water corals (Rengstorf et al., 2012; Tong et al., 2013), because their distribution is inextricably linked to current flow strengths and patterns (Mohn et al., 2014). More recently, understanding the link between seafloor morphometry and currents has been shown to be essential in forecasting the path of floating debris from tsunamis and air disasters and assist in search and rescue operations (Mofield et al., 2004; Normile, 2014; Smith and Marks, 2014).

6.4 Emerging and future applications

Other applications of marine geomorphometry can also be found in the literature. We anticipate that the number of application areas will grow substantially over the next few years as awareness of data and analysis techniques expands, and high-resolution data become more widely available.

6.4.1 Change detection

A number of studies have described temporal morphological dynamics of the seafloor using acoustic bathymetry (e.g. Duffy & Hughes-Clarke, 2005; Smith et al., 2007). However, assessments of biological change beyond the range of optical sensors have been based primarily on ground sampling methods. Rattray et al. (2013) investigated approaches to quantify temporal change in benthic habitats from a spatially explicit perspective using acoustic techniques. [Their methods \(1\)](#) quantified change in terms of gains and losses in the extent of habitat at a site on the temperate southeast Australian continental shelf; (2) they could distinguish between systematic and random patterns of habitat change; and (3) were able to assess the applicability of supervised acoustic remote sensing methods for broad-scale habitat change assessment. Change detection in temperate bedrock reefs were identified through morphological characterisation by Storlazzi et al. (2013). They delineated the classes using a multivariate classification routine (Dartnell and Gardner, 1999) based on acoustic backscatter and rugosity (surface-planar area ratio).

There have also been several examples in the literature of repeat multibeam surveys being used to detect change, many of which are summarised by Schimel et al. (2015). Analysis is generally focussed on differences in depth values detected and often aided by a visual assessment of the changes in morphology. There are fewer studies that have explicitly used terrain attributes or features in their assessments, but we recognise the potential for geomorphometric techniques to be more widely

applied in this type of study. For example, Bøe et al. (2015) used geomorphic feature detection (Wood, 1996) to identify crests and ridges in a sandwave field on the continental slope, and assess movement between surveys based on the change in position of these features. We note also that Schimel et al. (2015) incorporate measures of bathymetric uncertainty in their assessment of volume change and also recommend guidelines on thresholds which can help to improve the confidence of such assessments.

~~6.4 This manuscript has discussed the current practices in marine geomorphometry, from data collection to the applications. Through all aspects of this discussion it is apparent that the use of geomorphometric techniques in the marine realm is relatively nascent, having begun only over a decade ago. The dramatic increase in DBM availability, combined with the increasingly accessible and user friendly GIS tools, is currently fuelling the amount and diversity of applications of marine geomorphometry. However, this availability can become a double edge sword. As noted by Dolan and Lucieer (2014), "Although a [DBM] is a model of the seabed surface, it is often not treated as a model but rather is accepted as a true representation of the seabed". Furthermore, as highlighted in Fig. 1, the end users of geomorphometric techniques are not always aware that they are actually "doing" geomorphometry, but rather think of the steps they are performing as simply using GIS tools for data analysis. As the amount of applications increases, some of the fundamental issues associated with marine geomorphometry are not being addressed quickly or broadly enough. This can increase the risk of unsuspecting end users misusing data or techniques, and to the misinterpretation of results. For instance, due to a lack of awareness of the impact of artefacts in DBMs and their propagation to terrain attributes, artefacts are often disregarded, or assumed to be obvious. In habitat mapping, the consequences of artefacts are often apparent to geomorphometry aware users in the final maps (e.g. Zieger et al., 2009; Lucieer et al., 2012), but this can become problematic if the maps are being used in conservation and management decision making if the effect of the artefacts is not appreciated by the end user. We recognise a critical need for a dedicated scientific effort in marine geomorphometry that will address, and raise awareness of the fundamental issues related to marine geomorphometry. This effort does not necessarily have to come solely from the marine science community, indeed it may well benefit from the expertise of many of those scientists already engaged in terrestrial geomorphometry. The main objectives of this effort would be to learn from the lessons of terrestrial geomorphometry, ensure that studies of geomorphometry become more widespread in the marine literature, and respond to the challenges and opportunities for a wider adoption of marine geomorphometry as a key tool in marine sciences, whilst improving and upholding scientific standards.~~

~~This section first examines the issues associated with two key growth areas where we recognize particular potential for marine geomorphometry to contribute to our understanding of the seafloor. Following this, we reflect on the current and future trends of the field as a whole, highlighting recommendations to improve practices and set standards for future work.~~

7.1 The littoral gap: implications for coastal geomorphometry

This paper has shown how geomorphometric techniques developed mostly in terrestrial settings can be applied to the marine environment or adapted to enable quantification of the seafloor terrain. The boundary between the land and the sea, however, is not easily mapped or delineated and has always represented a challenge for both marine and terrestrial scientists (Klemas, 2011). Due to the inability of satellite remote sensing to collect data in deep waters and the limitations of acoustic systems to collect data in shallow waters, there is often a gap in terrain data where land meets sea. This littoral gap, sometimes referred to as ‘the white zone’ because the lack of data in this area between available DBM and DEM data appear white on maps, often complicates the study of nearshore environments and can have important implications for applications such as navigation and geohazard assessment. For instance, in their attempt to assess the effectiveness of a marine protected area in a Canadian sub-arctic fjord with habitat maps generated from a combination of terrain attributes and other data, Copeland et al. (2013) were only able to map 32 km² of the total 82 km² of the area. They highlighted the laborious nature of shallow water survey (i.e. time and cost consuming MBES surveys), the need for a continuous coverage because of the large littoral gap, and indicated that interpolation and extrapolation of results in the littoral gap were inappropriate because of the heterogeneous nature of coastal fjord environments (Copeland et al., 2013).

Several examples of investigations of the coastal environment using geomorphometry can be found in the literature (e.g. Purkis et al., 2008; Pittman et al., 2009). However, most coastal studies are limited to small areas either above the water (e.g. dunes or emergent features) or submerged (e.g. coral reefs) (Brock and Purkis, 2009). To our knowledge, there are no geomorphometric applications that span the terrestrial and underwater landscapes in a continuous way over large areas, despite many efforts to collect topo bathymetric data that span the coastal environment (e.g. National Coastal Mapping Program of the Joint Airborne Lidar Bathymetry Technical Center of Expertise in the United States). For instance, Dunkin et al. (2011) and Dunkin and McCormick (2011) used bathymetric LiDAR datasets to characterise changes in geomorphic and bathymetric features, respectively to assess consequences of storm events, and for monitoring and shore protection purposes. However, these studies did not explicitly use geomorphometric techniques. Several fields could benefit from seamless geomorphometric analysis. For instance, inter tidal rocky shores are known to shelter a lot of biodiversity (Kostylev et al., 2005) and linking quantitative terrain attributes to measures of biodiversity could improve scientific understanding of ecological patterns and processes in these important areas of the land sea boundary (e.g. Collin et al., 2012). Observations of underwater and terrestrial landforms have shed light on how glaciers retreated in Atlantic Canada during the last deglaciation (Shaw et al., 2006); the investigation of landforms that overlap both realms could help refine this type of analysis.

At a broader scale, a seamless analysis of terrestrial and marine environments requires the combination of terrestrial DTMs, bathymetric data from acoustic systems, and bathymetric LiDAR or optical remotely sensed data to fill the littoral gap and create a Coastal Terrain Model (CTM) (Hogrefe et al., 2008; Leon et al., 2013). The challenges encountered with merging

datasets from different sources makes such an approach still nascent in the general literature (Macon et al., 2008; Quadros et al., 2008; Collin et al., 2012), and very rare, if not fully absent, in the marine geomorphometry literature. Data fusion is the process of acquiring, processing and synergistically combining multi-source datasets both geometrically (i.e. in space) and topologically (i.e. in terms of their attributes or information content) (Usery et al., 1995; Samadzadeghan, 2004; Mohammadi et al., 2011). Despite constant developments in data fusion (Pohl and van Genderen, 1998; Dong et al., 2009; Zhang, 2010), it presents particular challenges for geomorphometry. First, despite improvements in edge matching algorithms, artefacts from merging and surveying can appear when deriving terrain attributes from the fused dataset (Stoker et al., 2009). Data fusion often requires the different datasets to overlap slightly in order to be combined. In theory, the overlapping areas should yield very similar values, within their uncertainty and error ranges. However, important inconsistencies (up to 6.5m) have been reported between depth measurements of the same areas using bathymetric LiDAR and MBES (Quadros et al., 2008; Costa et al., 2009; Chust et al., 2010; Shih et al., 2014). This has implications for geomorphometry since terrain attributes will capture and classify these mismatches as features, especially as the differences usually occur locally (Chust et al., 2010). Also, coastal environments can be very dynamic; artefacts could appear in the DTM if the multi-source data are not collected at the same time and changes occurred between the data collections. Another issue concerns vertical datums (Hogrefe et al., 2008); terrestrial surveys are usually referenced to a local geoid model based on the GPS, while underwater surveys (acoustic and LiDAR) are usually referenced to the mean sea level at the time of survey, which is referenced to a local or regional tidal gauge that is itself referenced to a local datum. Calls for a consistent and unified vertical datum have been made but this issue is still unresolved (Hogrefe et al., 2008; Quadros et al., 2008). Finally, data quality and uncertainty may complicate the fusion of the different datasets. For instance, the inability of bathymetric LiDAR systems to collect reliable data in turbid or cloudy waters and in breaking wave conditions, in addition to their difficulties to distinguish the seafloor from the water surface in waters shallower than 30 cm (Quadros et al., 2008) may create a smaller littoral gap called the “dead zone” (Nayegandhi et al., 2009) and prevent proper fusion. Bernstein et al. (2011) recommend a customized survey design to minimise the challenges associated with creating a seamless DTM.

Regular problems of data fusion, for instance related to merging multi-resolution datasets or to software and format compatibility/interoperability, also apply to the development of DTMs for coastal geomorphometry. Terrestrial terrain models may have a Digital Elevation Model format (.dem), while bathymetric LiDAR data can be recorded with a Laser File format (.las) and finally, acoustic data can be save as a Bathymetric Attributed Grid format (.bag); all these file formats have different structure and characteristics. Impediments to the fusion of multisensor data to build seamless elevation and depth surfaces include, but are not limited to, inconsistent spatial and temporal scales, incompatible formats, and differences in levels of reliability, uncertainty and completeness. Despite these impediments, data fusion has been identified as a promising technique for geomorphometry (Bishop et al., 2012). Some authors (e.g. Quadros et al., 2008) argue that the different types of datasets cannot be readily integrated, but the main challenges will likely be addressed with improvements in data fusion techniques and ease of implementation of these techniques for non-expert users (Zhang, 2010) for geomorphometry. Current

~~work includes detection and correction of differences in geoid models, consideration of uncertainties, and improvement in edge matching algorithms (Quadros et al., 2008; Dong et al., 2009; Stoker et al., 2009). Developments in data fusion will likely allow better integration of different data to create seamless coverage for complete geomorphometric analysis and identification of overlapping landforms between the different realms. This will be useful for a wide range of coastal applications, including the investigation of coastal morphodynamics and land sea exchange modelling, dredging and the identification of hazards due to sea level rise and severe storms, coastal archaeology, resource management and marine spatial planning, anthropogenic sensitivity and environmental status assessment, and other scientific research.~~

7.2 Seismic geomorphometry

Seismic geomorphology is a rapidly evolving discipline. It comprises the application of geomorphological principles and analytical techniques to study palaeo-landscapes as imaged by 3D seismic reflection data (Carter, 2003; Posamentier and Kolla, 2003; Posamentier, 2003). More recently, 3D seismic reflection data have also provided a good alternative source of bathymetric data when the latter are absent (e.g. broad scale geomorphic mapping in the MAREANO project – <http://www.mareano.no/>). The development of seismic geomorphometry is a natural consequence of ~~the advent of high quality and increasingly more affordable 3D seismic reflection datasets, and of~~ increasing computer power, which enables the rapid manipulation, visualisation and interpretation of 3D seismic reflection data, ~~and the enormous investment in this technology by the oil and gas industry, with academics and government researchers benefitting from access to these data.~~

The integration of seismic geomorphology with seismic stratigraphy currently represents the state-of-the-art approach to extracting geological information from 3D seismic reflection data to understand large-scale basin evolution. Seismic geomorphological studies have addressed a broad range of geological problems, ranging from sedimentary to igneous geology, from lithology distribution to large-scale tectonic analysis (e.g. Fachmi and Wood, 2003; Miall, 2003; Wood, 2003).

Up to the present, most studies have focused on the qualitative recognition of broad scale features (e.g. Posamentier et al., 1996; Posamentier et al., 2000; Peyton and Boettcher, 2000; Posamentier, 2003; Zeng and Hentz, 2004). Quantitative seismic geomorphology, or seismic geomorphometry, is the most recent development of seismic geomorphology (Carter, 2003; Posamentier, 2003; Posamentier and Kolla, 2003). Seismic geomorphometry has been defined as the “*quantitative analysis of the landforms, imaged in 3D seismic data, for the purposes of understanding the history, processes and fill architecture of a basin*” (Wood, 2003). Seismic geomorphometry encompasses techniques that use 3D seismic data to investigate the nature and architecture of reservoirs through extraction and analysis of quantitative morphometric information.

Great opportunities exist for applying a more quantitative approach in seismic geomorphology. Seismic geomorphometric techniques provide statistical and mathematical insight into the morphological and dimensional characteristics of geologic

systems that are difficult to derive through qualitative investigations of outcrop exposures and 2D seismic reflection data. Seismic geomorphometric studies provide a deep and spatially extensive understanding of how morphology develops through time, providing insight into the historical evolution of a basin and the possibility of developing predictive models. Quantitative relationships derived from seismic geomorphological studies can decrease our uncertainty in predicting the nature and location of reservoirs in deep-water settings by testing cause-and-effect relationships in a variety of settings. Computer-assisted seismic geomorphometry, in particular planform pattern recognition, is a powerful addition to the seismic geomorphological approach. It allows the interpreter to identify geologically significant features in plan view automatically. The ability to exploit the full potential of large seismic data sets is currently hindered by the lack of tools in existing software packages, coupled with the limited knowledge of how morphometrics can be used in the analytical process. It is the development of such tools that should be a main focus for researchers of marine geomorphometry in the near future.

7.36.4.3 Broad-scale coastal geomorphometry

This paper has shown how geomorphometric techniques developed mostly in terrestrial settings can be applied to the marine environment or adapted to enable quantification of the seafloor terrain. For a long time however, the boundary between the land and the sea was not easily mapped or delineated and represented a challenge for both marine and terrestrial scientists (Klemas, 2011a). This was due to the inability of satellite remote sensing to collect data in deep waters and the limitations of acoustic systems to collect data in shallow waters, which often creates a gap in terrain data where land meets sea. This littoral gap, sometimes referred to as ‘the white zone’ because the lack of data in this area between available DBM and DEM data appear white on maps, often complicates the study of nearshore environments and can have important implications for applications such as navigation and geohazard assessment. For instance, in their attempt to assess the effectiveness of a marine protected area in a Canadian sub-arctic fjord with habitat maps generated from a combination of terrain attributes and other data, Copeland et al. (2013) were only able to map 32 km² of the total 82 km² of the area. They highlighted the laborious nature of shallow water survey (i.e. time and cost-consuming MBES surveys), the need for a continuous coverage because of the large littoral gap, and indicated that interpolation and extrapolation of results in the littoral gap were inappropriate because of the heterogeneous nature of coastal fjord environments (Copeland et al., 2013).

In the last 15 years, developments in bathymetric LiDAR surveying (cf. Sect. 2.4) slowly helped fill the littoral gap. Consequently, efforts to map the littoral using bathymetric LiDAR have spread across the globe (e.g. the National Coastal Mapping Program of the Joint Airborne Lidar Bathymetry Technical Center of Expertise in the United States), and several examples of investigations of the coastal environment using geomorphometry can now be found in the literature (e.g. Purkis et al., 2008; Pittman et al., 2009). This body of literature used to be mostly characterized by the study of small areas either above the water (e.g. dunes or emergent features) or submerged (e.g. coral reefs) (Brock and Purkis, 2009), but there are now more and more efforts targeting the collection of topo-bathymetric data that span the coastal environment (e.g. Dunkin et al., 2011; Dunkin and McCormick, 2011). Several fields can benefit from seamless coastal geomorphometric analysis. For

instance, inter-tidal rocky shores are known to shelter a lot of biodiversity (Kostylev et al., 2005) and linking quantitative terrain attributes to measures of biodiversity could improve scientific understanding of ecological patterns and processes in these important areas of the land-sea boundary (e.g. Collin et al., 2012). So far, limitations of LiDAR systems (e.g. inability to collect data in deeper waters, costs associated with airborne surveys) however restricted these efforts to local, sometimes regional scales. To our knowledge, there are no geomorphometric applications that span the terrestrial and underwater landscapes in a continuous way over very large areas, which would require the integration or fusion of datasets from different sources (e.g. LiDAR, terrestrial DTMs and acoustic surveys).

At a broader scale, a seamless analysis of terrestrial and marine environments requires the combination of terrestrial DTMs, bathymetric data from acoustic systems, and bathymetric LiDAR or optical remotely sensed data to fill the littoral gap and create what has been called in the literature a Coastal Terrain Model (CTM) (Hogrefe et al., 2008; Leon et al., 2013). The challenges encountered with merging datasets from different sources makes such an approach still nascent in the general literature (Macon et al., 2008; Quadros et al., 2008; Collin et al., 2012), and very rare, if not fully absent, in the marine geomorphometry literature. Data fusion is the process of acquiring, processing and synergistically combining multi-source datasets both geometrically (i.e. in space) and topologically (i.e. in terms of their attributes or information content) (Usery et al., 1995; Samadzadeghan, 2004; Mohammadi et al., 2011). Despite constant developments in data fusion (Pohl and van Genderen, 1998; Dong et al., 2009; Zhang, 2010), it presents particular challenges for geomorphometry. First, despite improvements in edge matching algorithms, artefacts from merging and surveying can appear when deriving terrain attributes from the fused dataset (Stoker et al., 2009). Data fusion often requires the different datasets to overlap slightly in order to be combined. In theory, the overlapping areas should yield very similar values, within their uncertainty and error ranges. However, important inconsistencies (up to 6.5m) have been reported between depth measurements of the same areas using bathymetric LiDAR and MBES (Quadros et al., 2008; Costa et al., 2009; Chust et al., 2010; Shih et al., 2014). This has implications for geomorphometry since terrain attributes will capture and classify these mismatches as features, especially as the differences usually occur locally (Chust et al. 2010). Also, coastal environments can be very dynamic; artefacts could appear in the DTM if the multi-source data are not collected at the same time and changes occurred between the data collections. Another issue concerns vertical datums (Hogrefe et al., 2008); terrestrial surveys are usually referenced to a local geoid model based on the GPS, while underwater acoustic surveys are usually referenced to the mean sea level at the time of survey, which is referenced to a local or regional tidal gauge that is itself referenced to a local datum. Calls for a consistent and unified vertical datum have been made but this issue is still unresolved (Hogrefe et al., 2008; Quadros et al., 2008). Finally, data quality and uncertainty may complicate the fusion of the different datasets. For instance, the inability of bathymetric LiDAR systems to collect reliable data in turbid or cloudy waters and in breaking wave conditions, in addition to their difficulties to distinguish the seafloor from the water surface in waters shallower than 30 cm (Quadros et al., 2008) may create a smaller littoral gap called the “dead zone” (Nayegandhi et al., 2009) and prevent proper fusion. Bernstein et al. (2011) recommend a customized survey design to minimise the challenges associated with creating a seamless DTM.

Regular problems of data fusion, for instance related to merging multi-resolution datasets or to software and format compatibility/interoperability, also apply to the development of DTMs for broader-scale coastal geomorphometry. Terrestrial terrain models may have a Digital Elevation Model (.dem) format, while bathymetric LiDAR data can be recorded with a Laser File (.las) format and finally, acoustic data can be save as a Bathymetric Attributed Grid (.bag) format; all these file formats have different structure and characteristics. Impediments to the fusion of multisensor data to build seamless elevation and depth surfaces include, but are not limited to, inconsistent spatial and temporal scales, incompatible formats, and differences in levels of reliability, uncertainty and completeness. Despite these impediments, data fusion has been identified as a promising technique for geomorphometry (Bishop et al., 2012).

Some authors (e.g. Quadros et al., 2008) argue that the different types of datasets cannot be readily integrated, but the main challenges will likely be addressed with improvements in data fusion techniques and ease of implementation of these techniques for non-expert users (Zhang, 2010) for geomorphometry. Current work includes detection and correction of differences in geoid models, consideration of uncertainties, and improvement in edge matching algorithms (Quadros et al., 2008; Dong et al., 2009; Stoker et al., 2009). Recently, Leitão et al. (2016) proposed a new method to merge different DTMs developed specifically for geomorphometry. Future developments in data fusion will likely allow better integration of different data to create seamless coverage for complete geomorphometric analysis and identification of broad-scale overlapping landforms between the different realms. This will be useful for a wide range of coastal applications. For instance, observations of underwater and terrestrial landforms have shed light on how glaciers retreated in Atlantic Canada during the last deglaciation (Shaw et al., 2006); the investigation of landforms that overlap both realms could help refine this type of analysis. Other potential applications include the investigation of coastal morphodynamics and land-sea exchange modelling, dredging, the identification of hazards due to sea-level rise and severe storms, the assessment of consequences of such storm events, monitoring and shore protection, coastal archaeology, resource management and marine spatial planning, anthropogenic sensitivity and environmental status assessment, and other scientific research.

6.4.4 Underwater archaeology

In the last 25 years, terrestrial archaeology has largely benefitted from remote sensing tools and methods (McCoy and Ladefoged, 2009). Radar and LiDAR data have helped reveal archaeological features of interest in many areas of the world (e.g. Meylemans et al., 2015), or detect anomalies that could be linked to sites of interests that cannot be seen from the ground (e.g. Lin et al., 2011). Geomorphometry has been used on radar and LiDAR data to identify such patterns (Kvamme, 1999) or to describe particular areas (Turrero et al., 2013). Similarly to what happens in marine geomorphometry, its use is often not being recognised as geomorphometry or terrain analysis.

The remote sensing techniques described in Sect. 2 have also been used in underwater archaeology to collect bathymetric and backscatter data that were used for instance in initial investigations of wreck sites location and extent before divers or

ROVs deepen the actual archaeological investigation (e.g. Jones et al., 2005; Masetti and Calder, 2012). Similarly to terrestrial archaeology, these types of data enable both the direct identification of the features on the seafloor or anomalies that may indicate potentially buried artefacts (Papatheodorou et al., 2005). Geomorphometry has yet to gain traction in underwater archaeology, but is not completely absent. Using MBES data, Stieglitz (2012) documented an area of seafloor off Australia that had a conspicuous arrangement of over 1,200 shallow holes, and wide (up to 10 m) and deep (up to 1.5 m) holes. They classified these holes using local slope measurements, and found that the systematic distribution of these seafloor features was related to their distance from a shipwreck and likely caused by bioturbation. In another application, Passaro et al. (2013) extracted archaeological features related to Italian sunken cities using curvatures and the `r.param.scale` command from GRASS GIS (cf. Sect. 5.1). Slopes values were used by Solsten and Aitken (2006) to assess the risk of disturbance of archaeological sites by mass movement and marine flooding in Nunavut, Canada. The application of techniques from geomorphometry to underwater archaeology is likely to increase in the future, and we note the potential of seismic geomorphometry to assist in the investigation of buried artefacts.

7 The future of marine geomorphometry

7.1 Current and future trends in marine geomorphometry

Current developments in the marine geomorphometry literature are primarily focussed on the data acquisition end of the workflow. Technology and equipment for surveying the seafloor are improving in quality, accuracy and cost-effectiveness, which will allow an increase in data availability and quality. In coastal environments, ongoing research is focused on improving the extraction of depth information in the littoral gap in order to create seamless DTMs from the seafloor to land, and developments in data fusion should soon enable broad-scale geomorphometric analyses of coastal environments. As the pressure on coastal environments increases, such information will become crucial for many applications. From an ecosystem point of view, coastal environments are also very rich in biodiversity. Studies of the topographic structure that can be identified from CTMs using geomorphometric techniques are likely to facilitate a better scientific understanding of these ecosystems. In the deep-sea, extensive use of AUV and ROV-based MBES and other technologies means we are now able to collect high-resolution bathymetric data of environments never explored before at such level of detail. The knowledge that has been gained from using these data in combination with different techniques, including geomorphometry, has revolutionized scientific understanding of many marine environments. It was initially thought that the deep-sea was mostly flat, muddy and lifeless, but the last twenty years of research have proven otherwise. Nevertheless, exploration is far from complete; there are still wide gaps in the scientific knowledge of deep-sea patterns, processes and ecosystems. High quality bathymetric data is fundamental to the success of revealing this knowledge and its limited availability is currently a barrier to effective protection and management of vulnerable species (Vierod et al., 2014; Ross et al., 2015).

As the marine geomorphometry community moves forward, it will rapidly need to start addressing issues other than those associated with data acquisition. The availability of tools that streamline the workflow from data collection to analysis will be key in making a more complete science of marine geomorphometry accessible to marine scientists with a wide range of background and experience. Repositories of comprehensive and freely available datasets and tools, such as Digital Coast that provide free coastal and marine bathymetric data and analytical tools (NOAA, 2016), are the way forward to improve accessibility to the wider scientific community, and this may well mean that bathymetric data gain the attention of those currently engaged in developing geomorphometric methods for terrestrial data. We also acknowledge that easily accessible GIS tools and readily available data can also bring hidden dangers from non-critical use by users with limited appreciation of data collection and processing methods which to the expert clearly reflect the limitations in the utility of particular bathymetric datasets. To prevent this danger of inappropriate use, tools and datasets need to be accompanied by complete metadata that include information on data provenance, survey, scale, error and uncertainty quantification, and any other information relevant to further use of the tools and datasets. Metadata are crucial to create a “quality-aware” community (Devillers et al., 2007; Lecours and Devillers, 2015; Lecours et al., 2015b). The use of the CUBE algorithm to create BASE surfaces is one way to carry over a measure of quantified uncertainty of the data, but such information is not readily available for the majority of publicly available datasets. This type of information needs to become more accessible to marine scientists with a broad range of scientific backgrounds.

As indicated in ~~It~~ Fig. 1, it is becoming critical to raise awareness of geomorphometry in the marine science community. Methods from specific geomorphometry demonstrate a lot of potential for marine ~~geomorphometry~~ applications and should be used more extensively. At the same time, it is opportune to improve practices by setting standards and protocols for the application of ~~marine~~ geomorphometry. Methods and interpretations need to be standardised, particularly in view of issues specific to the marine environment, or where data and analyses behave differently underwater than on land. Amongst these, the influence of scale and data resolution on the results, and the consideration of spatial uncertainty should be prioritised. End-users should be explicit about which algorithms or methods they use and at which scale in order to enable proper comparison among studies. Since geomorphometric analyses are more and more performed within GIS environments, devising a GIS-based standard methodology and symbology for marine geomorphological mapping using geomorphometry would be a very useful goal for the marine geomorphometry community. Ultimately, the type of standards and protocols a marine geomorphometry community could develop should encourage wider applications of bathymetric data and allow marine scientists optimise the use of their expensive datasets.

7.2 Reuniting efforts in geomorphometry

This manuscript has discussed the current practices in marine geomorphometry, from data collection to the applications. Through all aspects of this discussion it is apparent that the use of modern geomorphometric techniques in the marine realm is relatively nascent, having begun only over a decade ago in application areas outside of marine geomorphology. The

dramatic increase in DBM availability, combined with the increasingly accessible and user-friendly GIS tools, is currently fuelling the amount and diversity of applications of marine geomorphometry. However, this availability can become a double-edge sword. As noted by Dolan and Lucieer (2014), “*Although a [DBM] is a model of the seabed surface, it is often not treated as a model but rather is accepted as a true representation of the seabed*”. Furthermore, as highlighted in Fig. 2, the end-users of geomorphometric techniques are not always aware that they are actually “doing” geomorphometry, but rather think of the steps they are performing as simply using GIS tools for data analysis. As the amount of applications increases, some of the fundamental issues associated with marine geomorphometry are not being addressed quickly or broadly enough. This can increase the risk of unsuspecting end-users misusing data or techniques, and to the misinterpretation of results. For instance, due to a lack of awareness of the impact of artefacts in DBMs and their propagation to terrain attributes, artefacts are often disregarded, or assumed to be obvious. In habitat mapping, the consequences of artefacts are often apparent to geomorphometry-aware users in the final maps (e.g. Zieger et al., 2009; Lucieer et al., 2012), but this can become problematic if the maps are being used in conservation and management decision making if the effect of the artefacts is not appreciated by the end user. It is thus crucial for end-users, planners, managers and decision-makers to become aware and understand the properties of their data that result from each of the five steps of geomorphometry, and how these properties influence their particular application.

In addition to end-users not being aware of geomorphometry as a science, scientists engaged in more terrestrial and extra-terrestrial geomorphometry are rarely aware of marine geomorphometry, its differences and its similarities with their field of expertise. For example, at the turn of the millennium, Pike (2000) identified the study of seafloor abyssal hills as a prospect topic for the application of geomorphometry. However, many examples can be found of marine geophysics and geomorphology studies dating from the 1980s-1990s that have used geomorphometry in abyssal hills (e.g. Malinverno and Gilbert, 1989; Goff, 1991, 1992; Malinverno and Cowie, 1993; Shaw and Lin, 1993). A decade later, Pike et al. (2009) tried to suggest using Digital Depth Models (DDM) to characterize surface models of the seafloor, despite the wide acceptance of DBM as an appropriate term in the marine geomorphometry literature.

We recognise a critical need for a dedicated scientific effort in marine geomorphometry that will address, and raise awareness of the fundamental issues related to marine geomorphometry. This effort does not necessarily have to come solely from the marine science community, indeed it may well benefit from the expertise of many of those scientists already engaged in terrestrial geomorphometry. The main objectives of this effort would be to learn from the lessons of terrestrial geomorphometry, ensure that studies of geomorphometry become more widespread in the marine literature, and respond to the challenges and opportunities for a wider adoption of marine geomorphometry as a key tool in marine sciences, whilst improving and upholding scientific standards. Since sub-fields of geomorphometry dealing with different types of environments are ultimately parts of the same science and share more similarities than have differences, these standards should become common to all these sub-fields. For example, geomorphometry is a field recognized for its ambiguous terminology, particularly in terms of terrain attributes (Bishop et al., 2012). The field of geomorphometry should move

towards a more uniting terminology and vocabulary across environments that would reduce some of that ambiguity. For instance, the use of the terms DEM, DBM, CTM, and DDM should be abandoned in favour of the more neutral, all-encompassing term DTM. Moving towards a joint terminology is just an example of how we can reunite all sub-fields of geomorphometry together, with common goals and approaches. For instance, many of the issues and future challenges mentioned in this overview (e.g. uncertainty and error propagation and modelling, scale, change detection) have been discussed in recent reviews about terrestrial high-resolution topographic data and Earth surface processes (Tarolli, 2014; Passalacqua et al., 2015), highlighting the similarities in challenges and opportunities that marine and terrestrial geomorphometry are facing. Reuniting efforts in geomorphometry will likely result in more effective research and development and facilitate the coupling with other disciplines, including different fields of marine sciences.

8 Conclusions

Relative to the “young” and “still forming” modern terrestrial applications of geomorphometry, which can be traced back to the nineteenth century, (Evan and Minár, 2011, p. 105), the use of geomorphometry in the marine realm is still in its infancy. Ever since the first coarse-scale DBMs were generated, marine geomorphometry has helped improve scientific understanding of the oceans, from the relatively thin border where land meets sea to the deepest waters. This paper is timely because it ~~reviews~~provides an overview of the state of the art in the field and discusses standards for the applications of marine geomorphometry. ~~We have reviewed~~By following Pike et al.’s (2009) five main steps of geomorphometry we have reviewed marine geomorphometry in a way that can easily be compared with terrestrial geomorphometry. We have provided an overview of the different methods to sample the depth of the seafloor, the interpolation methods and issues of spatial scale associated with the generation of a DBM, as well as discussing the different errors and artefacts that are ~~characteristic~~characteristic of DBMs ~~and~~but different from those common in DEMs, ~~and~~Further, we have discussed how general and specific geomorphometry are applied underwater. ~~We also introduced four common and two cutting edge, provided~~ applications of marine geomorphometry, ~~and discussed the outlined~~ future trends ~~of~~in the field. Clearly there is room in the literature for more detailed reviews of each of these five steps and relating to many of the sub-disciplines, however we hope that this review will serve as a solid foundation for further, more detailed reviews on these sub-topics.

Based on this review, we provide the following recommendations that ~~will lead to~~should help establish more ~~efficient~~productive practices in marine geomorphometry: (1) errors and spatial uncertainty should be quantified so that they are able to be considered in the geomorphometric analyses and in the interpretation of results; (2) metadata should consistently be associated with datasets to explicitly indicate data provenance, quality (i.e. quantification of uncertainty), and the spatial scale at which the dataset was intended to be used; (3) data, metadata and tools should be made available for a wider applications of bathymetric data; (4) standardisation of methods and interpretations for each field of application should

be documented, particularly in view of the influence of [algorithms](#), scale and data resolution on the results; [and](#) (5) a GIS-based standard symbology for marine geomorphological mapping based on geomorphometry should be devised.

~~By raising~~Through raised awareness [of each other's disciplines](#), we hope that both marine scientists and geomorphometry practitioners will [be better placed to](#) work together in addressing the fundamental issues of marine geomorphometry, whilst upholding ~~the~~[scientific](#) standards ~~of the discipline of~~[in](#) marine spatial analysis. Building a dedicated effort in marine geomorphometry that can draw ~~from~~[from](#) lessons learned in terrestrial geomorphometry ~~and will not only~~ encourage marine applications [and continued scientific development, but](#) will ensure that [the science of](#) geomorphometry ~~as a science is~~ [able](#)used to ~~fulfil~~ its [full](#) potential [for studying the topography of the whole planet](#).

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Tables

Table 1: Summary of the most commonly used terrain attributes in marine-based studies, as well as an indication of some common calculation approaches. Modified after Dolan et al. (2012). The term ‘multiple scale’ refers to terrain attributes derived in turn using analysis windows of different sizes. ‘Multiscale’ refers to indices derived simultaneously over a range of window sizes. The more general term ‘multi-scale’ is used in this paper to refer to both types of analysis as well as geomorphometric analysis using data of different resolutions.

	<i>Slope</i>	<i>Orientation</i>	<i>Curvature</i>	<i>Terrain Variability</i>
<i>Ecological relevance</i>	Stability of sediments (ability to live in/on sediments) Local acceleration of currents (food supply, exposure, etc.)	Degree of exposure to dominant and/or local currents from a particular direction (food supply, sedimentation, larval dispersion, etc.)	Index of exposure/shelter e.g. on a peak or in a hollow (food supply, sedimentation, predators, etc.)	Index of degree of habitat structure, shelter from exposure/predators (link to life stages) Structural diversity linked to biodiversity
<i>Geomorphological relevance</i>	Stability of sediments (grain size). Local acceleration of currents (erosion, movement of sediments, creation of bedforms)	Relation to direction of dominant geomorphic processes	Flow, channelling of sediments/currents, hydrological and glacial processes. Useful in the classification of landforms	Terrain variability and structures present reflect dominant geomorphic processes
<i>Commonly computed terrain attribute and example marine-based reference</i>	Slope (Lundblad et al., 2006; Lanier et al., 2007; Micallef et al., 2012; Dolan and Lucieer, 2014)	Aspect (Galparsoro et al., 2009), northness/northernness and eastness/easterness (Monk et al., 2011)	Mean curvature (Dolan et al., 2008) Profile curvature (Guinan et al., 2009) Plan/planimetric curvature (Ross et al., 2015) Bathymetric Position Index (BPI) (Monk et al., 2010; Pirtle et al., 2015)	Rugosity (Dunn and Halpin, 2009) Vector Ruggedness Measure (VRM) (Tempera et al., 2012) Relative Relief (Elvenes, 2013) Fractal Dimension (Wilson et al., 2007)

<i>Commonly used terrain attribute and software (algorithm reference)</i>	Single scale: Slope: ArcGIS Spatial Analyst (Horn, 1981)	Single scale: Aspect: ArcGIS Spatial Analyst (Horn, 1981) Statistical Aspect (northness/eastness) BTM toolbox (Wright et al., 2012)	Single scale: Mean, Profile and Plan curvature ArcGIS Spatial Analyst (Zevenbergen and Thorne, 1987)	Single scale: Rugosity (surface area/planar area ratio) (Jenness, 2004)
	Multi-scale: Multiple scale slope: r.param.scale, Landserf (Wood, 1996) Multiscale slope: Landserf (Wood, 1996)	Multi-scale: Multiple scale aspect: r.param.scale, Landserf (Wood, 1996) Multiscale aspect: Landserf (Wood, 1996)	Multi-scale: Several measures of multiple scale curvature: r.param.scale, Landserf (Wood, 1996) Multiple scale BPI (Lundblad et al., 2006) Multiscale curvature Landserf (Wood, 1996)	Multi-scale: Multiple scale VRM (Sappington et al, 2007) Multiple scale relative relief (Erikstad et al., 2013 and references therein) Multiple and multiscale fractal dimension - Landserf (Wood, 1996)

Table 2: [ListSelection](#) of studies published in the last three decades that applied geomorphometric techniques to [submarine landscapes](#) the marine environment. A particular focus is given to marine geomorphology studies, as a few other documents (e.g. McArthur et al., 2010; Brown et al., 2011; Harris and Baker, 2012; Rengstorf et al., 2012; Lecours et al., 2015b) already summarized the extent to which many of these techniques have been employed in habitat mapping studies, and many of these techniques have yet to be employed in other contexts.

Technique	Reference	Spatial Domain	Broad Theme
General geomorphometry			
Morphometric attributes/ basic Basic geometrical analysis	(Adams and Schlager, 2000)	Continental slope	Geomorphology and geohazards
	(De Moustier and Matsumoto, 1993)	General	
	(Teide Group, 1997)	Volcanic islands	
	(Coggan and Diesing, 2012)	Continental shelf	Habitat Mapping and ecology
	(Ezhova et al., 2012)	Coastal and continental shelf	
	(Mofield et al., 2004)	Continental slope and rise, abyssal hills	Hydrodynamics
	(Passaro et al., 2013)	Coastal	Others
Morphometric attributes and their statistical analyses	(Berkson and Matthews, 1983)	General	Geomorphology and geohazards
	(Booth and O'Leary, 1991)	Continental slope and upper rise	
	(Chakraborty et al., 2001)	Mid-ocean ridge, abyssal plain, seamounts	
	(Goff and Jordan, 1988)	General	
	(Kukowski et al., 2008)	Continental slope	
	(Micallef et al., 2007a)	Continental slope	
	(Mitchell et al., 2000)	Mid-ocean ridge	
	(Mosalik Moskalik et al., 2014a)	Coastal and inner shelf	
	(Passaro et al., 2010)	Seamount	
	(Passaro et al., 2011)	Seamount, volcanic island	
	(Passaro et al., 2011)	Abyssal hills	
	(Smith and Shaw, 1989)		
	(Lucieer et al., 2013)	Coastal to inner shelf	Habitat Mapping and ecology
	(Hill et al., 2014)	Coastal to inner shelf	
	(Rengstorf et al., 2012)	Continental slope	
	(Tong et al., 2013)	Outer shelf	
	(Micallef et al., 2012)	Coastal to inner shelf	
	(Tempera et al., 2012)	Seamounts	
	(Rengstorf et al., 2013)	Shelf to abyssal plain	
	(Rengstorf et al., 2014)	Continental slope	
	(Mohn et al., 2014)	Continental slope	Hydrodynamics
	(Tong et al., 2013)	Outer shelf	Others
	(Solsten and Aitken, 2006)	Coastal	
	(Stieglitz, 2012)	Coastal	
Spectral analysis	(Fox and Hayes, 1985)	General	Geomorphology and geohazards
	(Fox, 1996)	Mid-ocean ridge	
	(Gilbert and Malinverno, 1988)	General	
	(Goff and Tucholke, 1997)	Mid-ocean ridge	
	(Mosalik Moskalik et al., 2014b)	Coastal and inner shelf	
Geostatistical methods	(Herzfeld, 1989)	Continental slope	Geomorphology and geohazards
	(Herzfeld and Higginson, 1996)	Mid-ocean ridge	

	(Ismail et al., 2015)	Continental slope	
	(Diesing et al., 2014)	Coastal to inner shelf	Habitat Mapping and ecology
	(Hillman et al., 2015)	Continental slope	Hydrodynamics
Feature-based quantitative representation	(Harrison et al., 2011)	Outer shelf	Geomorphology and geohazards
	(Micallef et al., 2007a)	Continental slope	
	(Micallef et al., 2007b)	Continental slope	
	(Mitchell and Clarke, 1994)	Continental shelf	
	(Pratson and Ryan, 1996)	Continental slope	
	(Calvert et al., 2015)	Coastal	Habitat Mapping and ecology
	(Bøe et al., 2015)	Continental slope	Others
Neural networks	(Jiang et al., 1993)	Mid-ocean ridge	Geomorphology and geohazards
	(Marsh and Brown, 2009)	Continental shelf	
Other techniques	(Mountjoy et al., 2009)	Continental slope	Geomorphology and geohazards
	(Preston et al., 2001)	Coastal to inner shelf	
<i>Specific geomorphometry</i>	(Casalbore et al., 2011)	Volcanic island	Geomorphology and geohazards
	(Gee et al., 2001)	Volcanic island	
	(Green and Uken, 2008)	Continental slope	
	(Haflidason et al., 2005)	Continental slope	
	(Hühnerbach et al., 2004)	Continental slope and volcanic islands	
	(Issler et al., 2005)	Continental slope	
	(McAdoo et al., 2000)	Continental slope	
	(Micallef et al., 2008)	Continental slope	
	(Micallef and Mountjoy, 2011)	Continental slope	
	(Micallef et al., 2012)	Continental slope	
	(Micallef et al., 2014b)	Continental slope	
	(Micallef et al., 2014a)	Continental slope	
	(Mitchell and Searle, 1998)	Mid-ocean ridge	
	(Mitchell et al., 2002)	Volcanic island	
	(Mitchell et al., 2003)	Volcanic island	
	(Mitchell, 2003)	Volcanic island	
	(Mitchell, 2004)	Continental slope	
	(Mitchell, 2005)	Continental slope	
	(Moernaut and De Batist, 2011)	Continental slope	
	(Rovere et al., 2014)	Coastal to inner shelf	
	(Roy et al., 2015)	Volcanic island	
	(Stretch et al., 2006)	Continental slope	
	(Vachtman et al., 2013)		
	(Costa and Battista, 2013)	Coastal	Habitat Mapping and ecology
	(Diesing et al., 2014)	Coastal to inner shelf	ecology

Figures

~~Fig. 1: Geomorphometry is commonly implemented in five steps (Pike et al., 2009; Bishop et al., 2012).~~
~~Fig. 1: Cumulative number of publications (articles or reviews) listed in the Scopus database mentioning specific keywords (see legends) in their title, abstracts of keywords, by the end of 2015. For the applications, the keywords “topographic variable*”, “topographic attribute*”, “terrain attribute*” or “terrain variable*” were used, without “marine” (top) or with “marine” (bottom).~~

~~Fig. 2: According to Pike et al. (2009), geomorphometry is commonly implemented in five steps, here adapted to the application of geomorphometry to the marine environment (left). The panels on the right describe the structure and elements addressed in Sect. 2 to Sect. 6 of this paper, and list reviews and important discussion papers on these elements.~~

~~Fig. 2: Cumulative number of publications (articles or reviews) listed in the Scopus database mentioning specific keywords in their title, abstract of keywords, by the end of June 2016 for land-based (top) and marine (bottom) geomorphometry publications. For the “Geomorphometry” curves, the keywords “geomorphometry” and “geomorphometric” were queried. The keyword “terrain analysis” was researched for the “Terrain Analysis” curves. For the terrestrial applications, the following terms were used to query the database: “topographic variables”, “topographic attributes”, “topographic derivatives”, “terrain variables”, “terrain attributes”, “terrain derivatives”, and “terrain morphology”. These terms were also used for marine applications, in addition to “bathymetric variables”, “bathymetric attributes”, “bathymetric derivatives”, “seafloor morphology” and “seabed morphology”. The queries were all performed to exclude (for land-based publications) or include (for marine publications) the terms “marine”, “ocean” and “underwater”. We note that some common terms in the field (e.g. surface parameters, seafloor characterization) were not included because of their parallel use and different meaning in other fields that do not involve geomorphometry.~~

~~Fig. 3: Example of elements that can be extracted and visualised when using the CUBE algorithm, using the ROV-based dataset from Fig. 4 (source: Lecours and Devillers, 2015). On top, the components contributing to the horizontal and vertical TPUs can be studied. Other marginal contributioncontributions to the vertical TPU includeincluded the roll and pitch of the platform, timing of the inertial measurement unit, and uncertainty associated with the sonar system (range and angle). The combination of the GPS and delta draft provides the three-dimensional position of the soundings (x, y, z); in ROV-based research, the positional accuracy decreases with depth (Lecours and Devillers, 2015). On the bottom, it is possible to visualise how the uncertainty and the density of soundings vary spatially. Other spatial information that CUBE provides include the standard deviation on estimated depth values based on the hypotheses generated by CUBE, and information on the hypotheses count and strength.~~

~~Fig. 4: Examples of errors and artefacts found in different datasets and their impact on derived terrain attributes. The top panels represent data from GEBCO (2014), which uses radar altimetry to fill in the gaps between higher-resolution, freely available bathymetric data. The main artefacts that can be observed are caused by the interpolation method that was used to combine the different datasets. For instance, a linear artefact following a Southwest to Northeast axis can be observed as a result of the combination of one SBES acoustic survey line with radar altimetry data. Similarly, some “spots” can be seen in the middle of the panels (South to North direction). These artefacts, especially apparent in the curvature, are caused by the~~

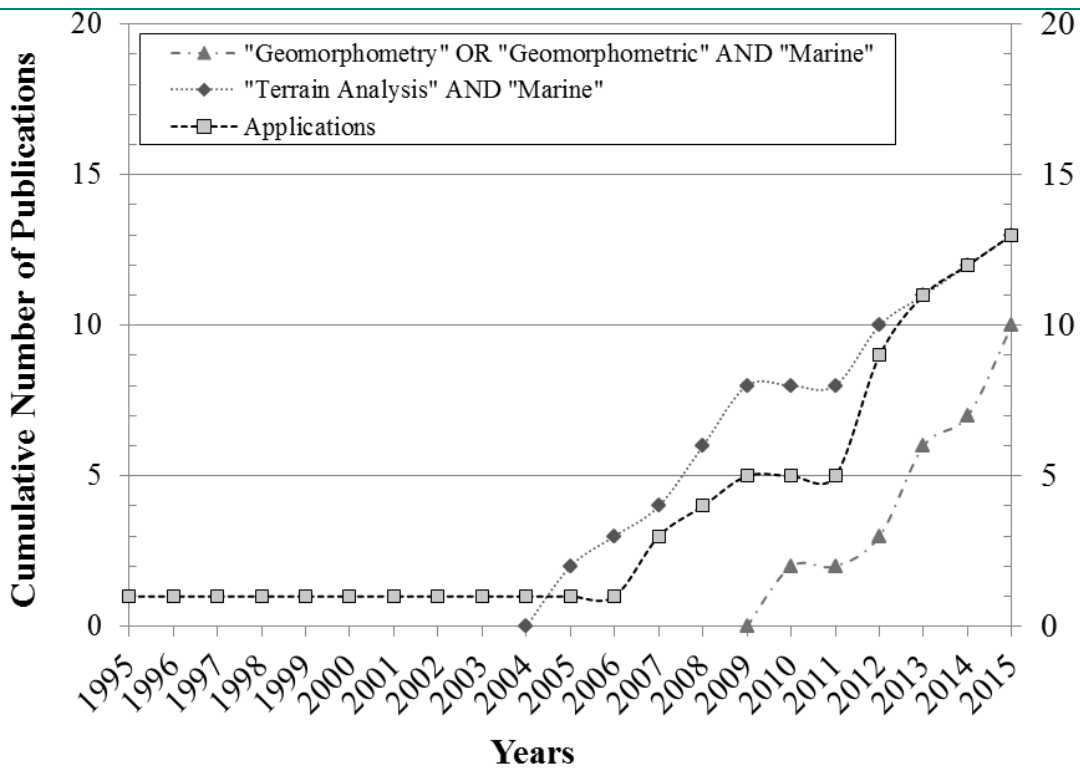
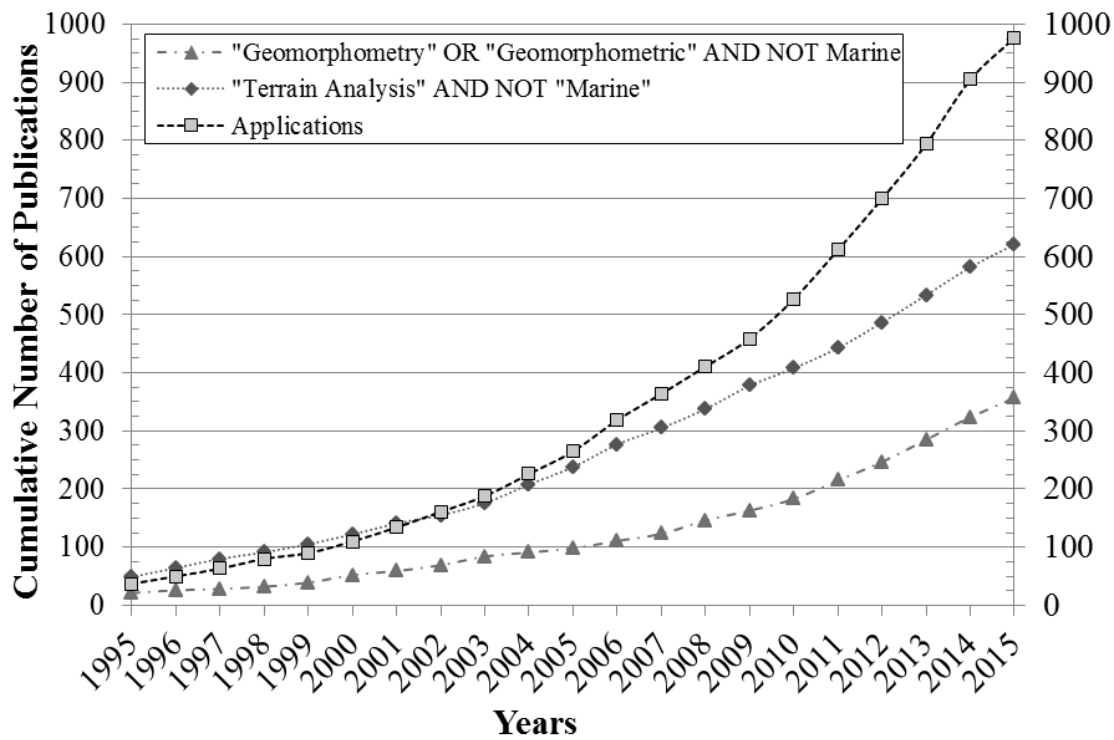
merging of punctual lead line measurements with the radar altimetry data. Finally, a slight gridding artefact can be observed in the curvature (i.e. thin vertical and horizontal linear features). The middle panels show ship-based MBES data (Brown et al., 2012). The obvious artefacts follow the surveying pattern of the vessel, and are mainly caused by ~~the roll motion of the vessel during the survey~~. vessel motion that was not compensated properly by the motion sensor. Finally, the bottom row of panels corresponds to ROV-based MBES collected from 20 m above the seafloor in the deep sea (Lecours et al., 2013). In this case, the artefacts are caused by a combination of heave and other platform motions; the ancillary data collected to account for this motion are too uncertain at this depth to appropriately correct for the errors (Lecours and Devillers, 2015). The “spots” observed in the bottom and top of the derived terrain attributes are spurious soundings that can be removed in bathymetric software during post-processing of the data. Note differences in spatial resolutions (left axis) and cartographic scales. Depth values of the top left panel range from 60 to 4,275 m deep, those of the middle left panel range from 20 to 105 m deep, and those of the bottom left panel range from 2,345 to 2,425 m deep. Lighter blue is shallower.

Fig. 5: Illustration of the main types of terrain attributes that can be derived from bathymetry data. Modified after Wilson et al. (2007).

~~Fig. 6: Proportion of the marine geomorphometry articles or reviews compiled in Fig. 1 that corresponds to each of the types of applications presented in Sect. 6.~~

Fig. 76: Indicative workflow showing the use of terrain attributes in predictive habitat mapping. Generally following some pre-selection of variables the observed habitat points (response variable) are combined with full coverage predictor variables selected from bathymetry, terrain attributes and other environmental variables as available to form the input to a habitat model which will be used to predict a full-coverage habitat map. The choice of habitat model will depend on the study in question but is typically either a statistical (e.g. GLM) or machine-learning based model (e.g. Random Forest). Observed habitat points are classified from visual or physical samples of the seabed. Terrain attributes are typically multi-scale and may include general and/or specific geomorphometry. Other environmental variables may include, for example, oceanographic data (temperature, salinity, current speed etc.) ~~and~~ and geological data (e.g. grain size). A similar workflow applies to modelling of single species or communities, where the output will be a continuous map indicating the probability of occurrence within the study area, rather than a categorical map as shown here.

Fig. 87: Example of the use of marine geomorphometry to semi-automatically map the components of mega-scale submarine landslide offshore Norway (adapted from Micallef et al. (2009)). Figures a-c show the trough depth, ridge length and ridge spacing extracted from a multibeam echosounder map of the north-eastern Storegga Slide using ridge characterisation techniques (Micallef et al., 2007b). Figure d is a classification map generated by using these ridge characteristic maps as input layers in an unsupervised clustering algorithm (ISODATA). Figure e is an interpretative map of the range of spreading events based on figures a-d. Other mass movements and geological processes and structures have been interpreted using geomorphometric mapping (Micallef et al., 2007a).



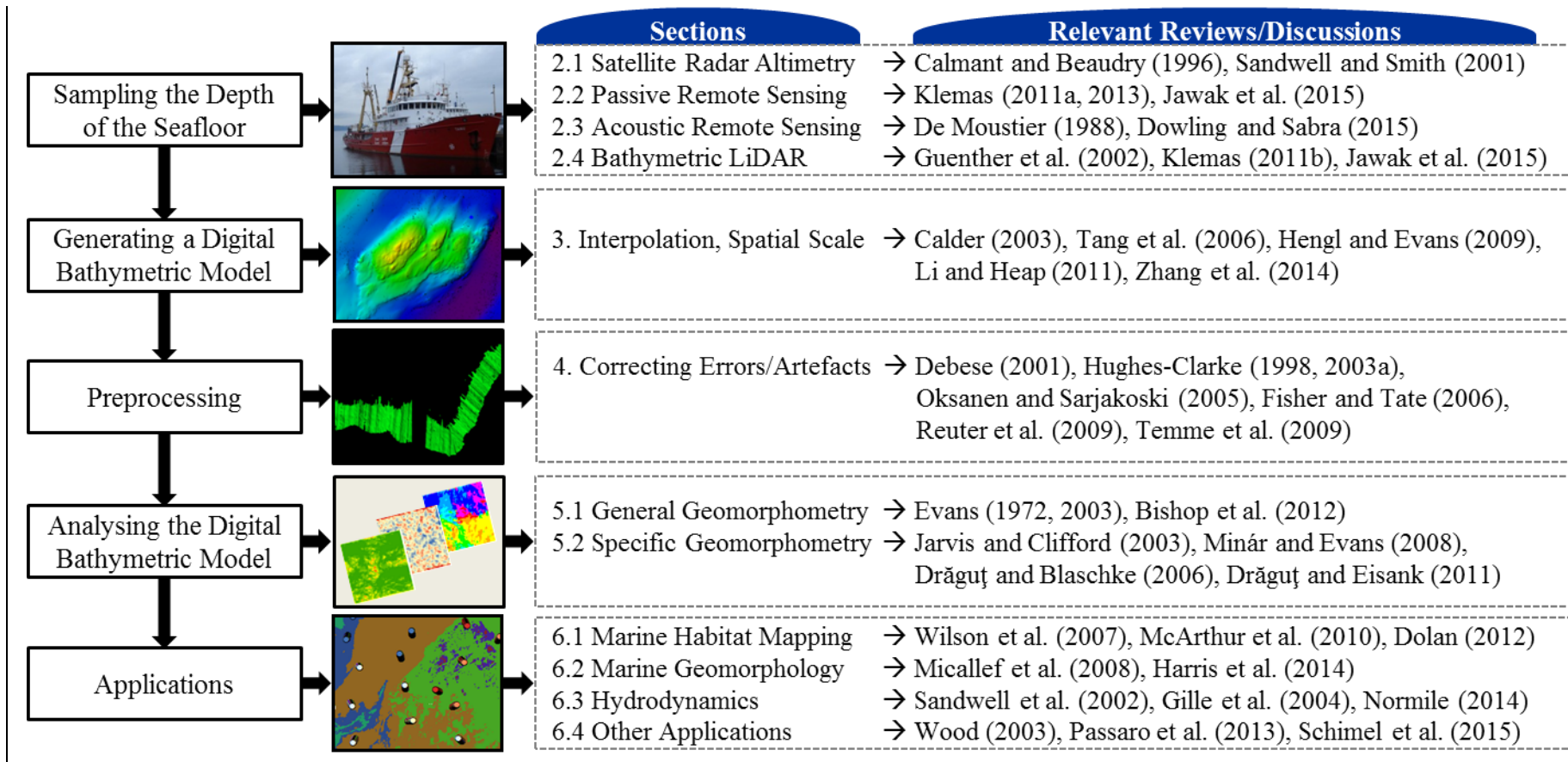
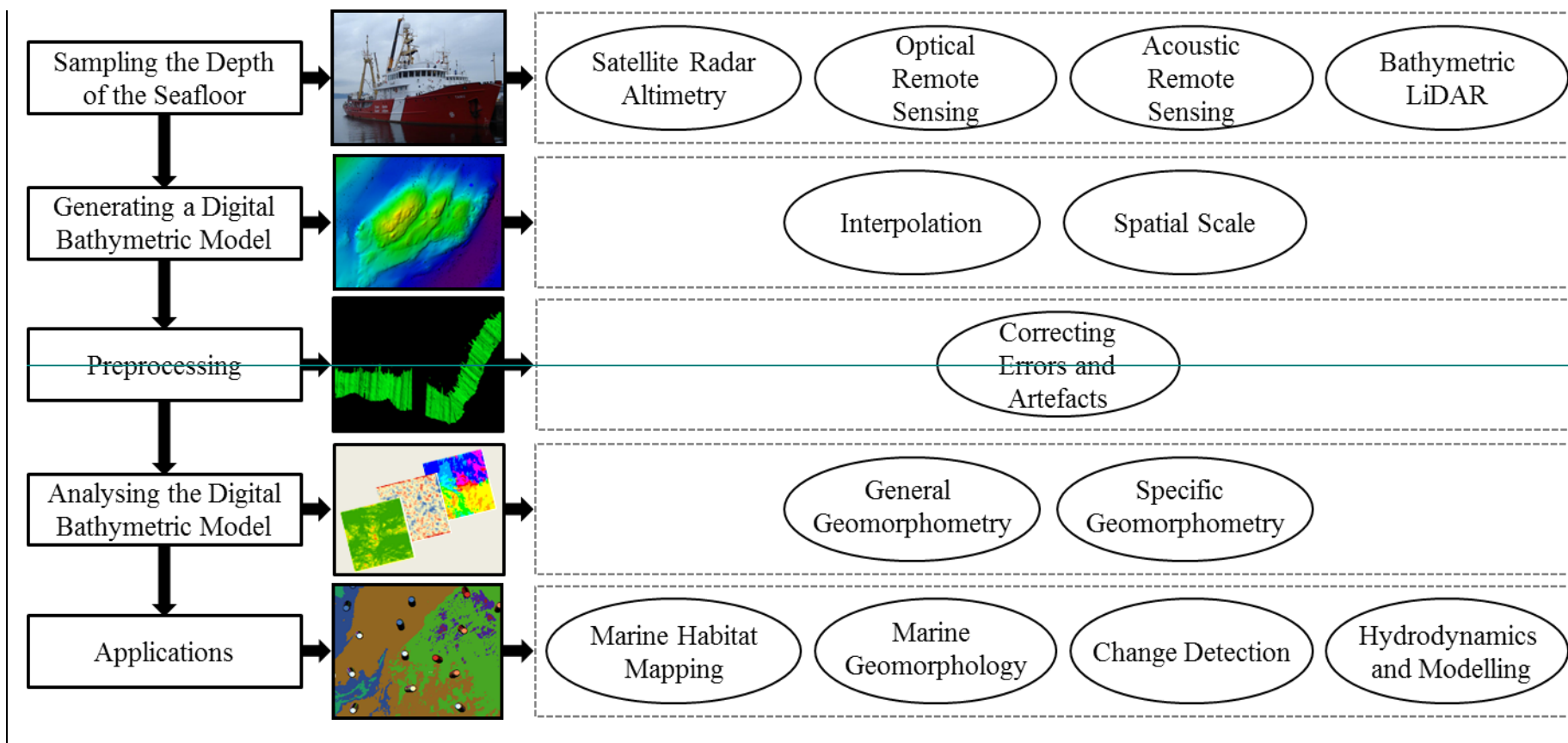


Figure 1



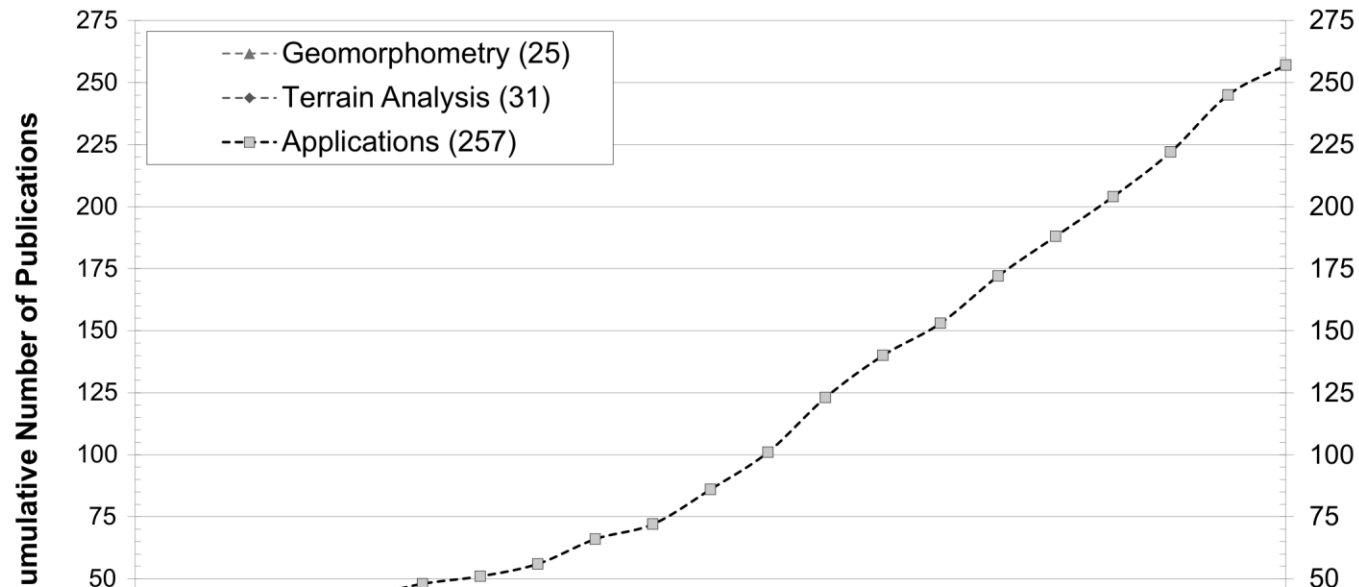
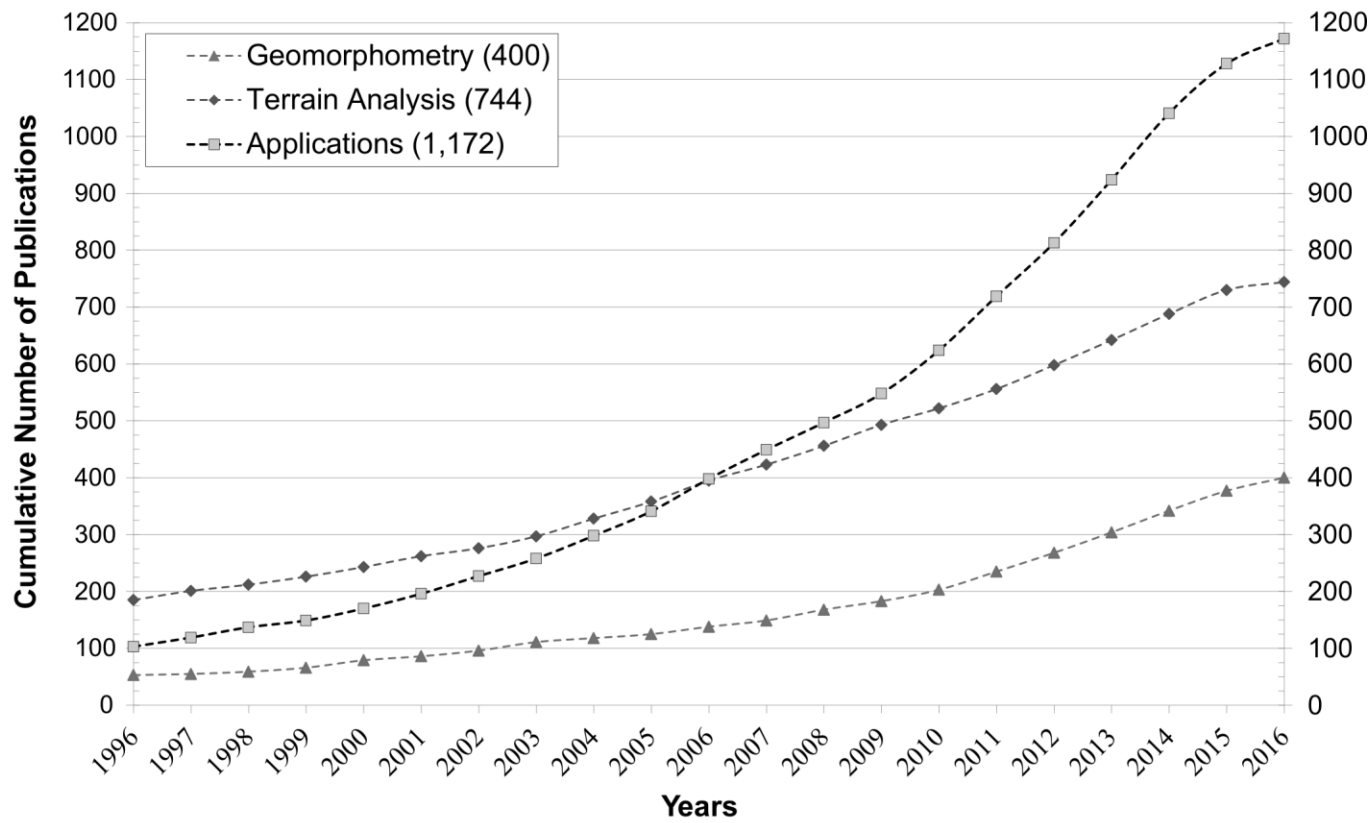
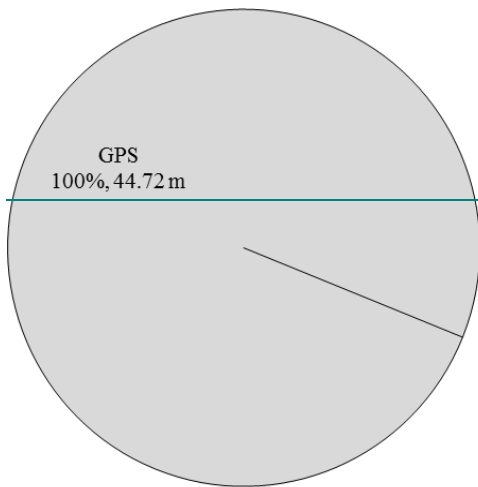


Figure 2

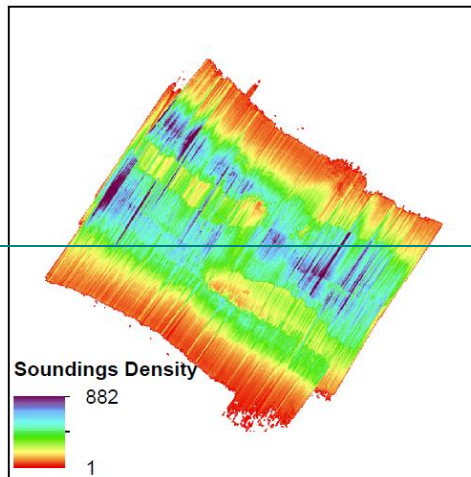
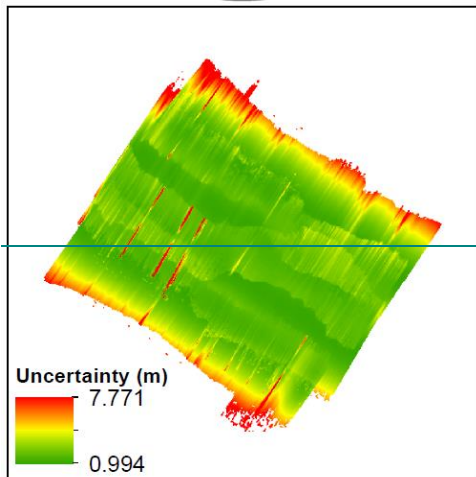
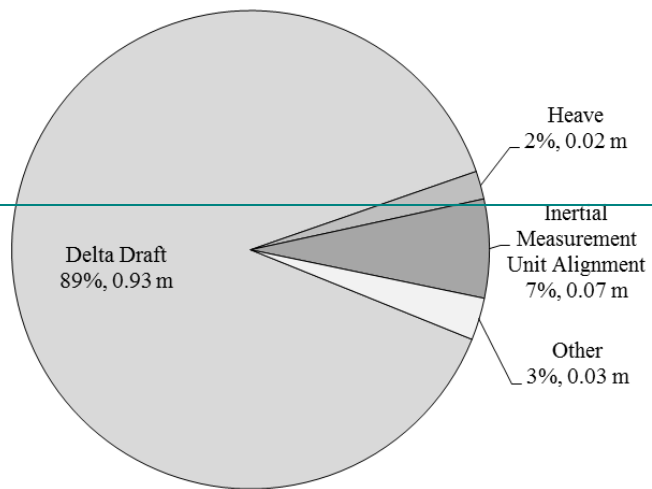
Horizontal Total Propagated Uncertainty

Averaged over 1,482,971 soundings:
44.72m



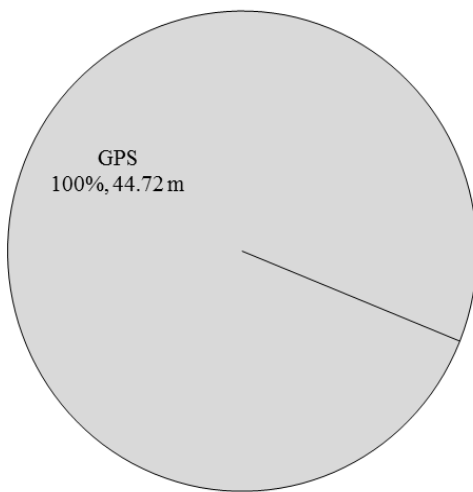
Vertical Total Propagated Uncertainty

Averaged over 1,482,971 soundings:
1.05m



Horizontal Total Propagated Uncertainty

Averaged over 1,482,971 soundings:
44.72m



Vertical Total Propagated Uncertainty

Averaged over 1,482,971 soundings:
1.05m

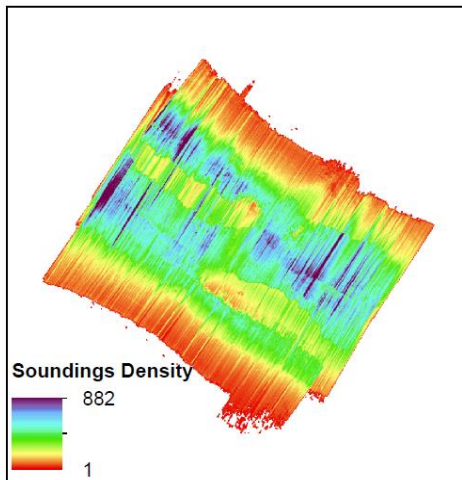
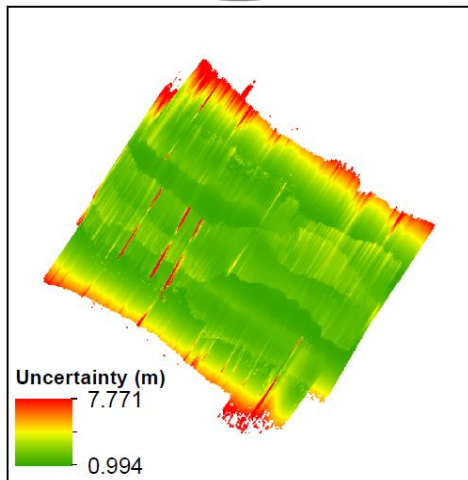
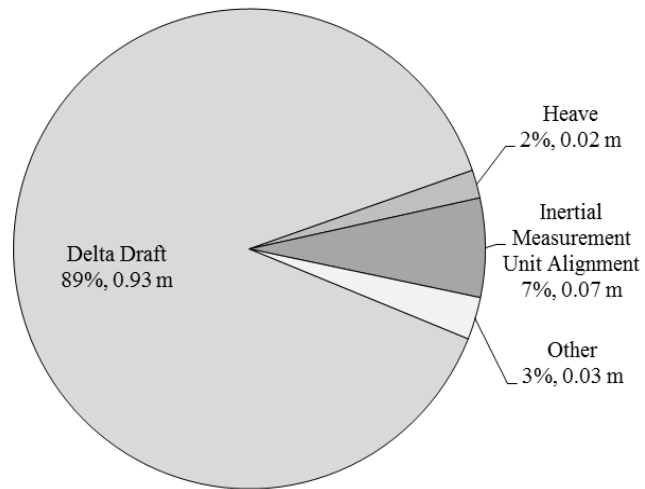
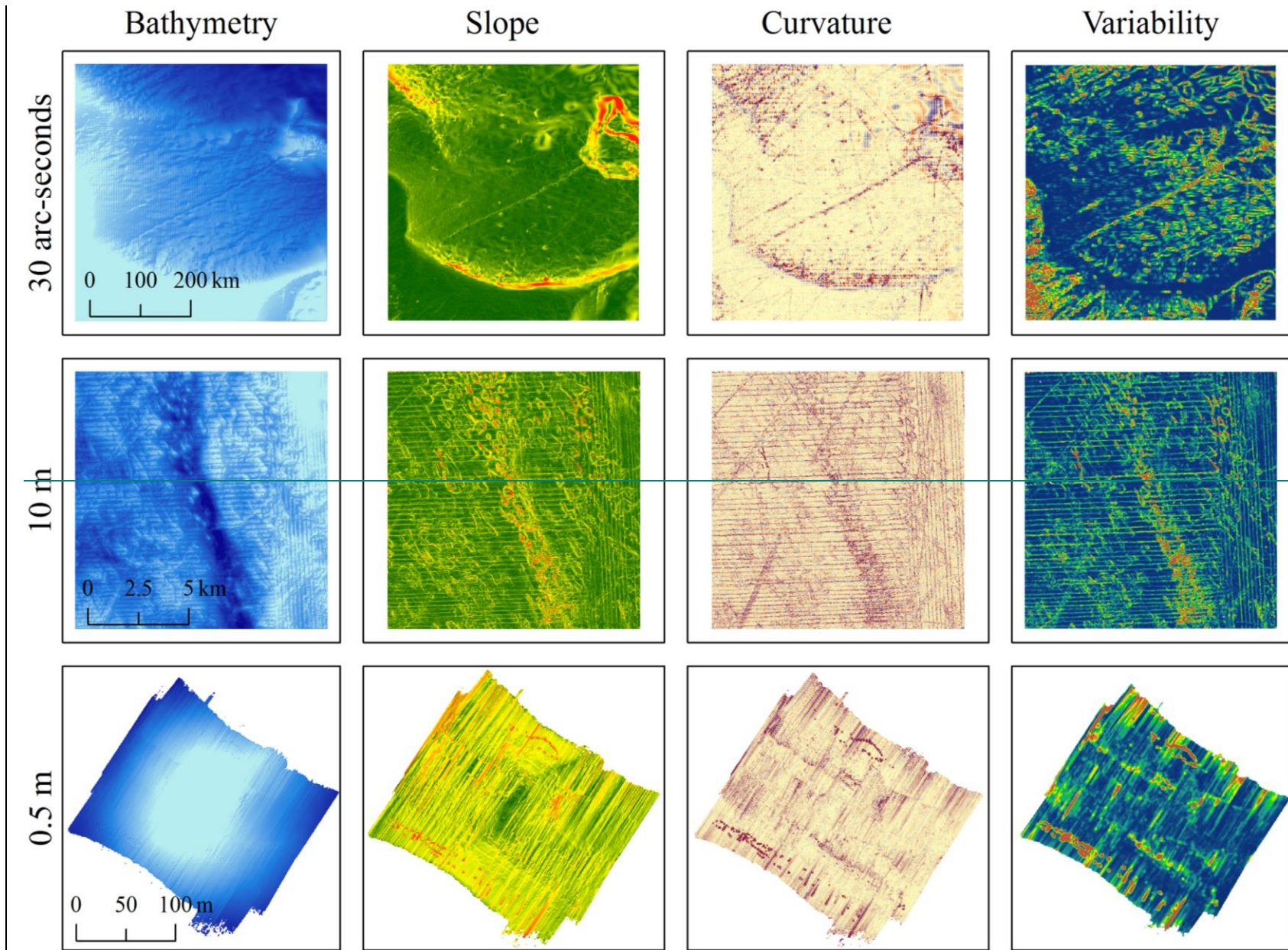


Figure 3



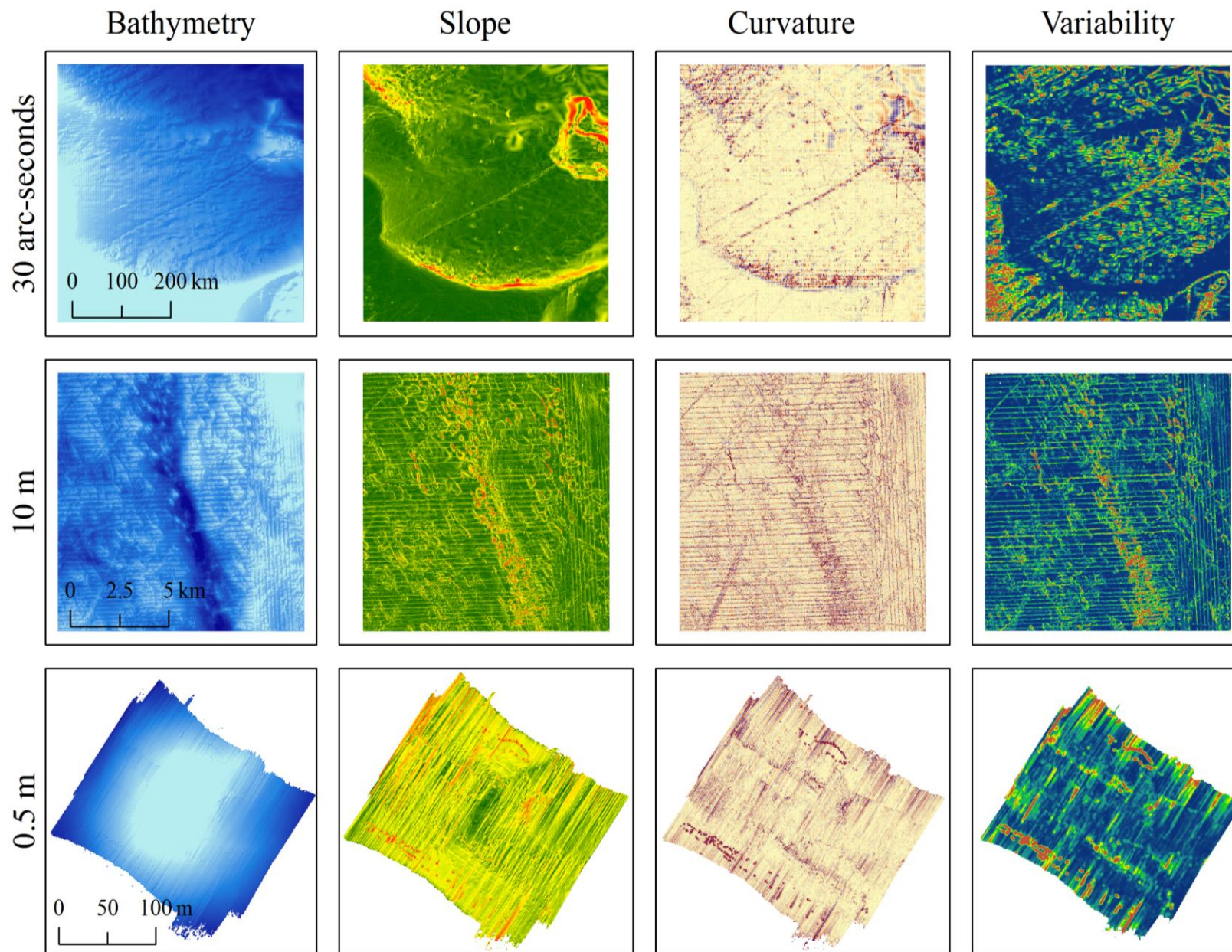
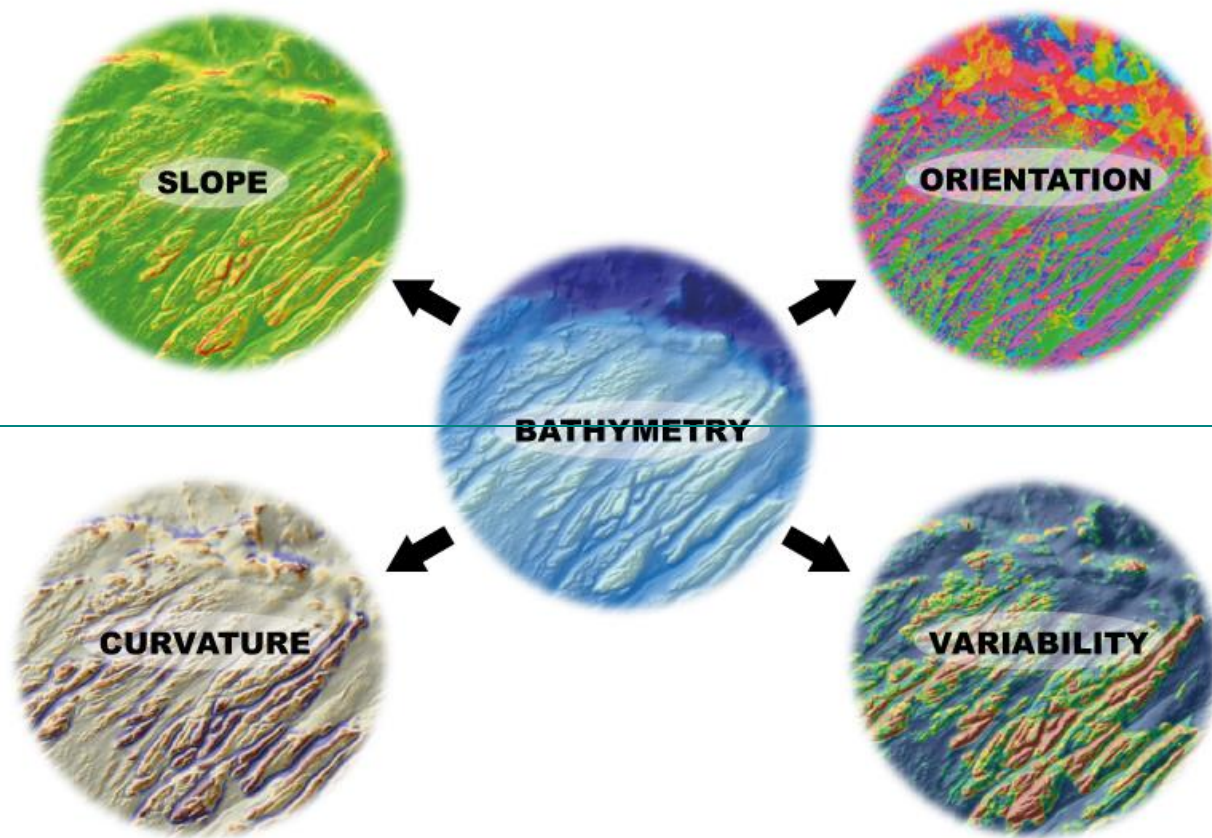


Figure 4



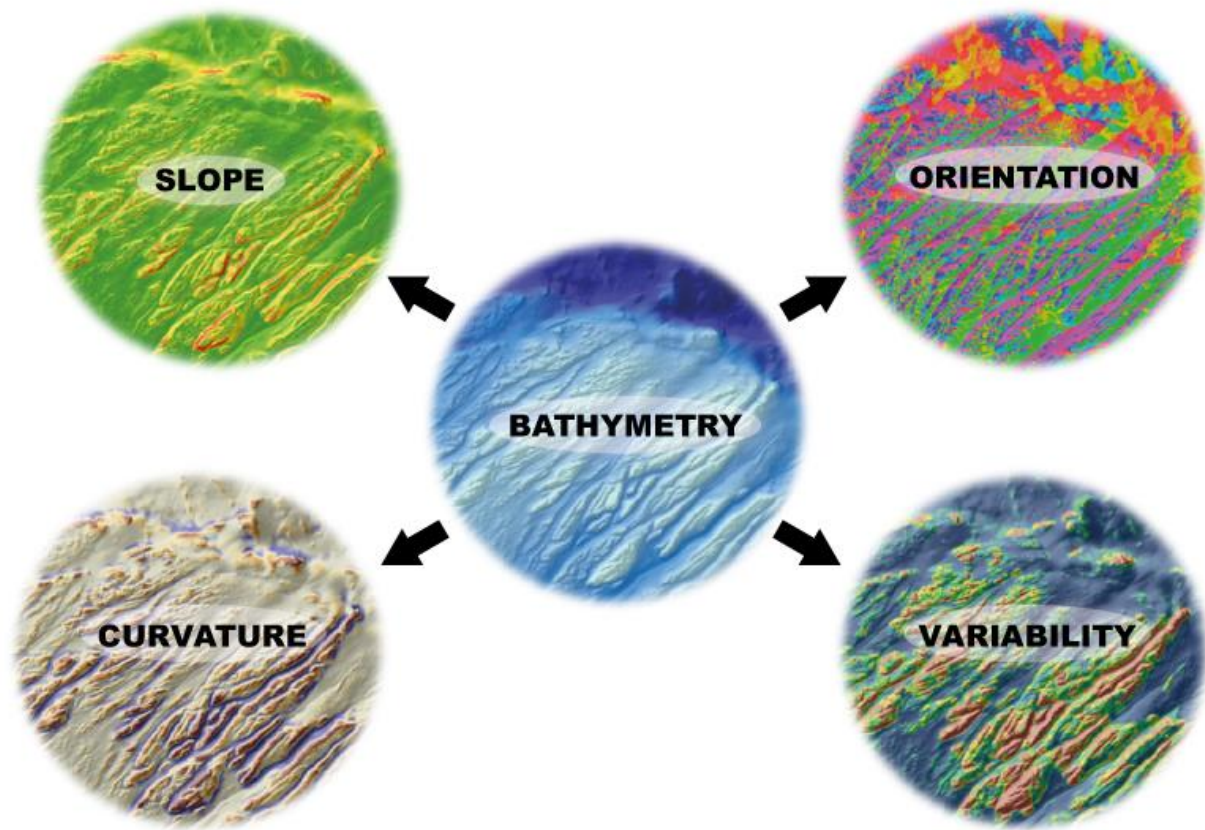


Figure 5

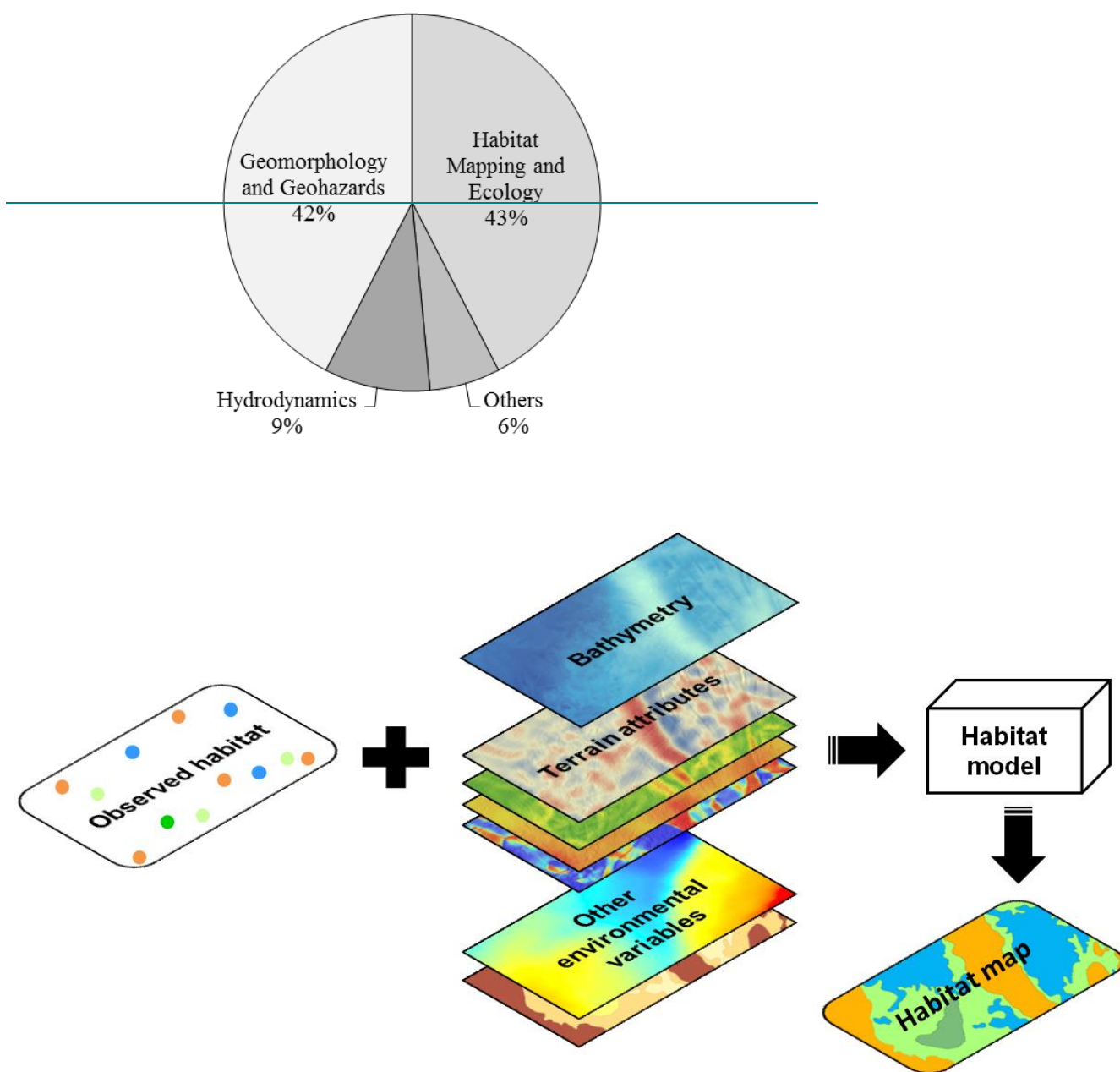
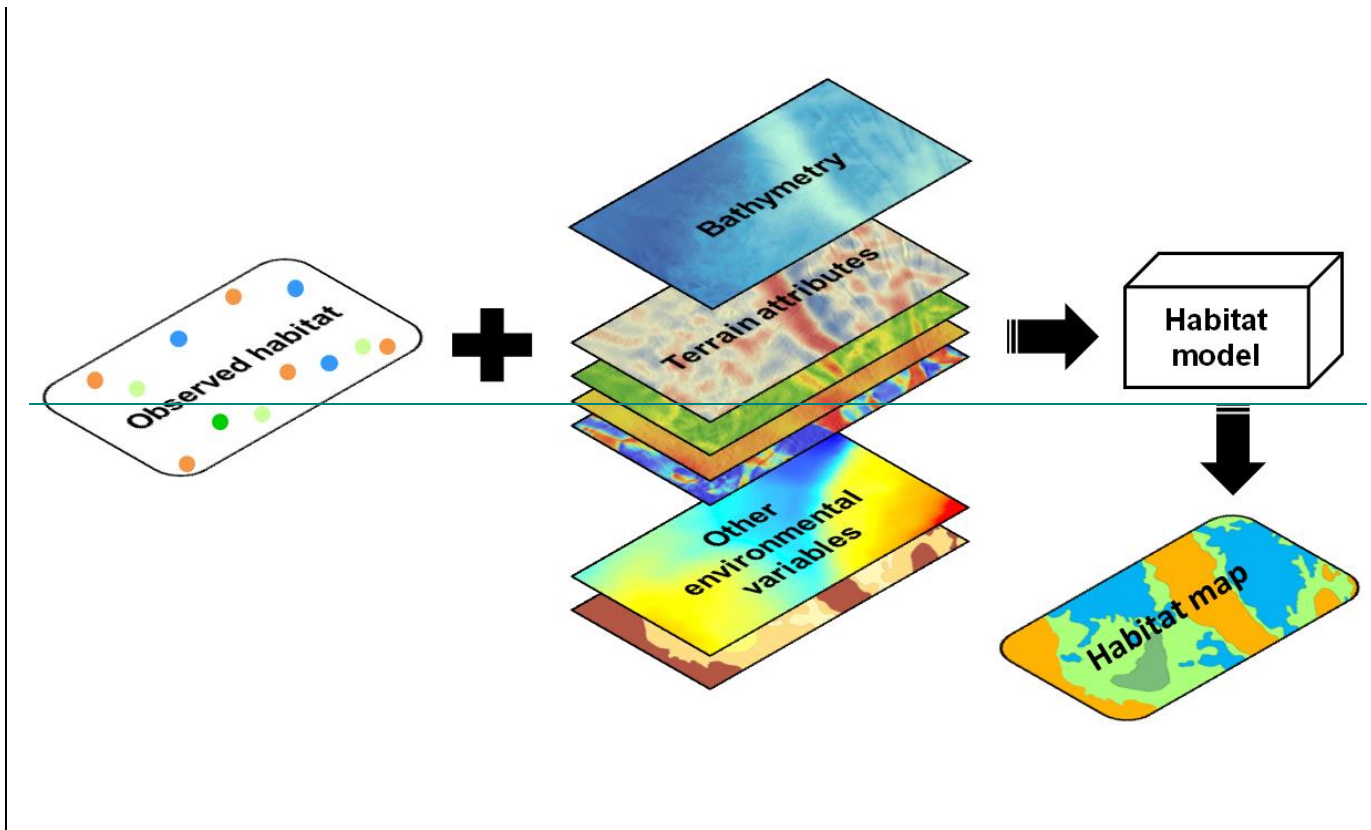
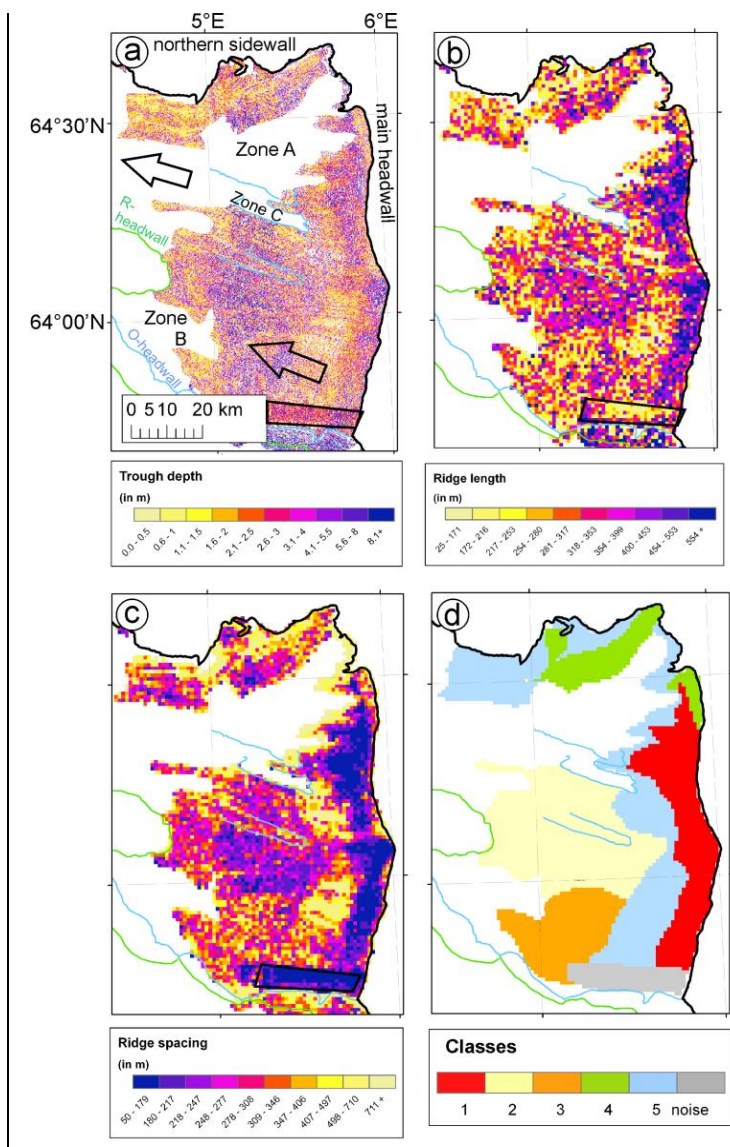


Figure 6





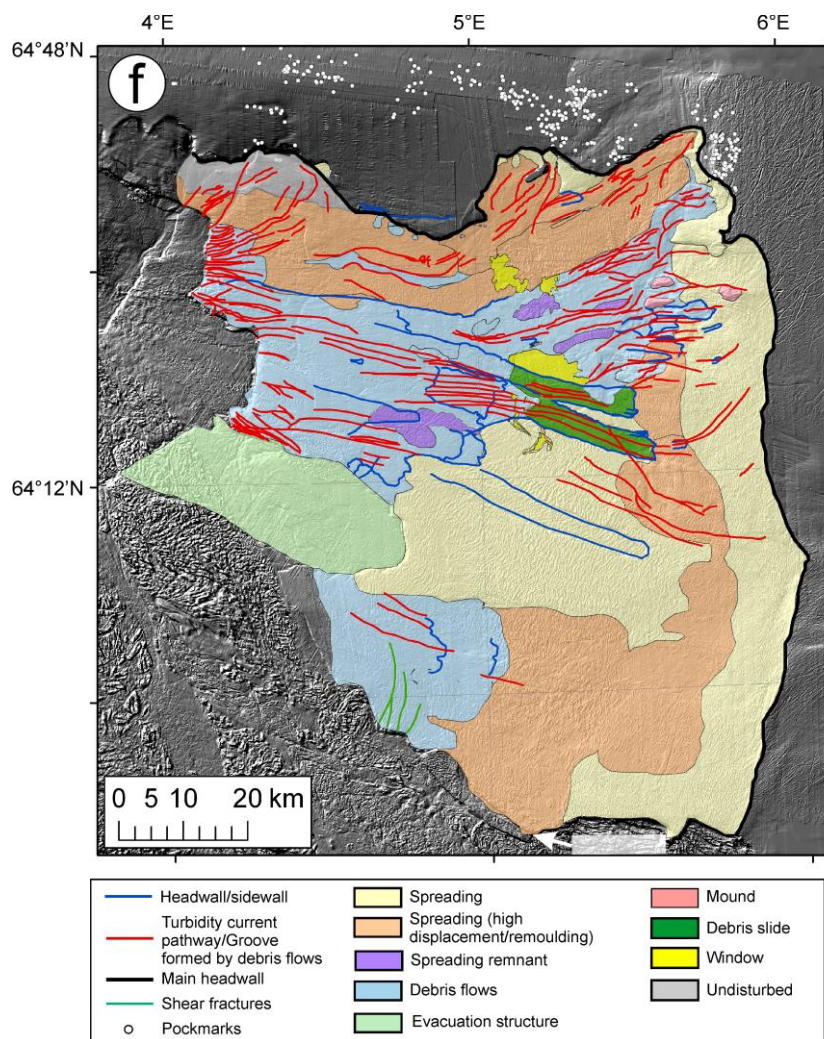


Figure 7

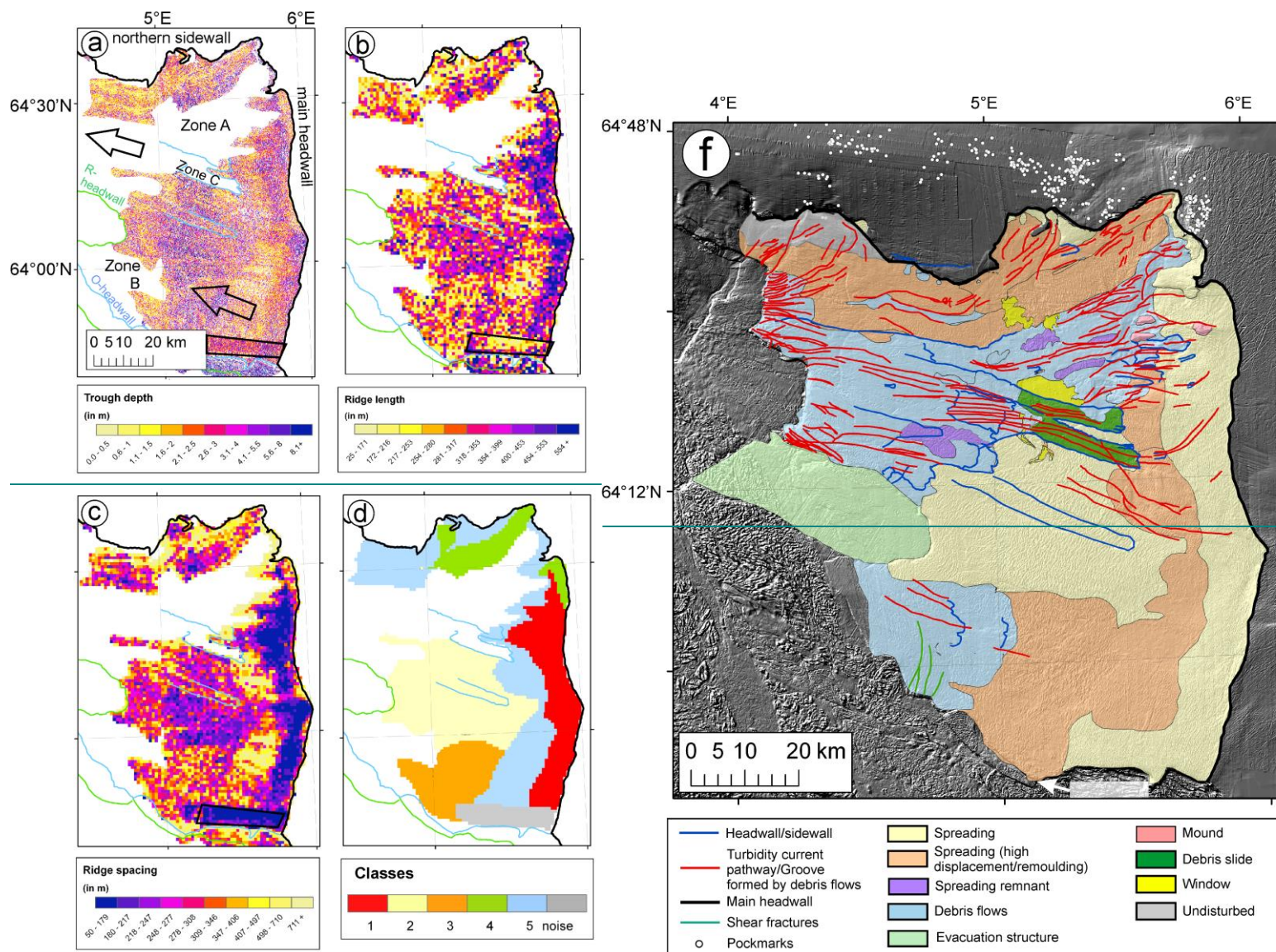


Figure 8