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## **ISSUE TITLE: Seafloor Expression of Tectonic and Geomorphic Processes**

### **Submarine Geomorphology: New Views on an ‘Unseen’ Landscape**

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#### **1. Abstract**

Geomorphology, one of the oldest disciplines in the geosciences, is undergoing a rebirth in the submarine environment. 2D (i.e. gridded) high-resolution bathymetry data offers exciting views of ever more of this hidden landscape, allowing a much improved understanding of both the solid Earth and Earth surface processes that shape the seabed. Such geomorphology is particularly powerful when convolved with geophysical techniques that image the sub-seafloor to form 3D studies.

This journal issue promotes a vision where submarine geomorphology i) unites processes typically studied in sub-aerial geomorphology (e.g. landsliding & channel erosion) and marine geophysics (e.g. volcanism, tectonics & geodynamics) ii) strives to progress beyond purely qualitative methods and to employ quantitative approaches in analyses and iii) integrates bathymetry with other surface or subsurface data to enhance the analysis. The aim in bringing together work on the various causes and consequences of the underwater landscape is to endorse interaction and knowledge transfer between disciplines and study areas.

This editorial highlights the links between submarine geomorphology, geophysics, Earth surface processes and bathymetry. Questions from the issue reviewed here include: How does the Earth melt? How does seafloor morphology affect the size of subduction earthquakes? What is the interconnection between submarine mass-wasting and tectonic environment?

#### **2. Submarine Geomorphology & Geophysics, a Historical Perspective**

Practically, it is not possible for humans to directly observe the vast majority of the seafloor. This is in direct contrast to the sub-aerial landscape. Contrast, for example, a pilot looking down from an aircraft and a sailor looking over the side of his craft. Even in the best conditions seawater is opaque to visible light beyond a few hundred metres penetration. Because it cannot be viewed, or indeed easily walked around upon, the seafloor can be thought of as an ‘unseen’ landscape that is in some ways less accessible to us than the surface of Mars. Electronic geophysical equipment is necessary to measure the deep ocean at any level beyond the most cursory and crude. Developments in submarine geomorphology have therefore been intrinsically linked to developments in geophysics. This is simply not true for sub-aerial geomorphology where less sophisticated equipment (e.g. a plane table) can produce accurate data, and this contrast probably explains the differential and disparate development of geomorphology on land and underwater.

Long before geophysics, however, water depth was critical information for the purposes of navigation, so ‘soundings’ have been taken, firstly using a long pole. From the 1870s hemp rope with a lead weight attached was used by *HMS Challenger* and *USS Tuscarora*, continued with the United States Fish Commission steamer *Albatross* from 1888 until the early 20<sup>th</sup> century when a wire cable method began to be used. Soundings taken by these methods were neither quick nor cheap to obtain, so only a few thousand soundings were available in the deep oceans, even the relatively well-explored North Pacific. Further substantial progress was not made until 1935 when

the US Navy diverted ships to unsounded areas and the *USS Ramapo* took some of the first ‘sonic soundings’, measuring the return time of a sound pulse) at relatively closely spaced intervals [Menard, 1964].

Consequently, Betz & Hess [1942] were able to produce one of the earliest bathymetry maps of the Pacific, or indeed any ocean, with many soundings. They likened its resolution to a map of North America created from an airplane flown at 200 m.p.h. across the continent 100 times taking soundings every 10 minutes. In this, however, broad features are represented ‘with a fair degree of accuracy’. For instance, they noted a gentle rise 600 miles wide by 1900 miles long that they called the ‘*Hawaiian Swell*’. This feature is now well known and has been the constraint on, and inspiration for, many theories about mantle convection, volcanism and geodynamics [e.g. Crough, 1978; McKenzie *et al.*, 1980; Wessel, 1993; Ribe & Christensen, 1999; Watts & Zhong, 2002]. Similarly, using echo-sound data Menard & Smith [1966] were able to firm up the hypsometric curve of Murray and Hjort [1912] and discuss modes of formation of the deep oceans. This is a form of analysis now more commonly associated with sub-aerial [e.g. Willgoose & Hancock, 1998; Montgomery *et al.*, 2001] or planetary [e.g. Rosenblatt *et al.*, 1994] geomorphology.

### 3. Recent Developments & Future Opportunities

Ocean wide bathymetry maps (e.g. GEBCO [I.O.C., 2003], ETOPO-5 [N.O.A.A., 1988]) from soundings now contain  $\sim 40 \times 10^6$  km of ship track [e.g. Hillier & Watts, 2007]. Interpolation between these sparse soundings has been improved by using bathymetry predicted, via a derived gravity field, from satellite altimetry [e.g. Smith & Sandwell, 1997]. Additionally, high-resolution data has been collected. Even though all publicly available data only cover a small fraction (i.e. few percent) of the deep ocean [Smith & Sandwell, 2004] swath bathymetry has allowed the morphology of many other sorts of smaller feature to be examined; for example seamounts [e.g. Smith & Cann, 1992; Scheirer & MacDonald, 1995], abyssal hills [e.g. Mitchell & Searle, 1998; Behn *et al.*, 2002], lava flows [e.g., White *et al.*, 2000; Mitchell *et al.*, 2008], and tectonic fabrics [e.g. Mitchell *et al.*, 2000, Combi *et al.*, 2008].

Concurrently, this increase in data resolution (commonly to  $< 100$ m grid cells) has started to permit quantitative geomorphological investigation of features more usually associated with sub-aerial processes (e.g. landsliding and canyon formation) in a manner similar to that developed for the now ubiquitous sub-aerial digital elevation models (DEMs) (e.g. NASA’s SRTM data with  $90 \times 90$  m grid spacing). Parallels between processes on land and under water have been drawn for some time [e.g. Chough and Hesse, 1976], but improved data is giving progressively clearer insight into erosive processes sculpting the submarine landscape; landslides [e.g. Mitchell, 2001; Watts & Masson, 2001], submarine canyons and channel networks [e.g. Ramsey *et al.*, 2006], and possible signatures of catastrophic floods [e.g. Gupta *et al.*, 2007].

Possible investigations with the analysis of seafloor bathymetry at their core unite study areas from the shallow continental shelf all the way through progressively deeper water to the mid-ocean ridges. Four prospective or emergent areas of study that we believe to have great potential are:-

- The interaction between mass wasting processes (e.g. landsliding & turbidity flows) and tectonics. Work to understand feedbacks and controls in this area has proved fruitful on land [e.g. Montgomery *et al.*, 2001], and could prove equally illustrative for understanding the mechanics and evolution of subducting sedimentary wedges. Work building on an increasing awareness of submarine erosion [e.g. Mitchell *et al.*, 2003] to understand nascent mountain ranges when they are generated underwater such as Taiwan [e.g. Ramsey *et al.*, 2006] would be included here.

- Comparison between sub-aerial and submarine analogues aided by application of protocols of topographic analysis developed on land. This has been started on processes such as hill-slope diffusion [e.g. Mitchell & Huthnance, 2007], channel knick-points [e.g. Mitchell, 2006], slope-area scaling relations and channel morphology [e.g. Ramsey *et al.*, 2006], but much research on the submarine continental slope remains to be done. By comparison, and with the advantage of detailed structure and stratigraphy afforded sub-surface data, submarine study can contribute to understanding the mechanics of the fundamental processes involved both on land and under water.
- Insight into neo-tectonics (e.g. in the Central Adriatic or on the SW Iberian Margin). Topography sustained by ongoing tectonic activity such as faulting or rising salt diapirs can best be understood by integrating analysis of surfaces up to and including the present-day seafloor. In depositional environments this approach gives insight not only into the current expression of tectonic activity, but also into the evolution of this expression over time. Geophysical techniques have the potential to fully determine sub-surface structure, whilst in practice fully excavating a structure on land using trenches is rarely done.
- Insight into the interior structure of landforms, in particular those that formed during the last ice-age and are now drowned. Where it is technically difficult to image the interiors of such landforms whilst they are sub-aerial, techniques are readily available with which to probe in high resolution the shallow subsurface (e.g. <100m depth penetration) of the marine environment. This is related to ‘seismic geomorphology’ (i.e. study of the shape of surfaces observed in seismic data) [e.g. Davies *et al.*, 2007], but with an emphasis on tie-ins with the current (or a recently preserved) seafloor in order to understand processes. Sub-glacial processes are ripe for this type of examination, for instance the mode of drumlin formation [e.g., Boulton & Hindmarsh, 1987]. Drumlins formed during the last ice-age, some of which are now drowned. Seismically derived internal structures of drumlins will give a potentially crucial dimension to this analysis that would be difficult to obtain on land. Furthermore, Holocene erosion tends to be less severe and pervasive underwater (e.g. OLEX data [Bradwell *et al.*, 2008]) and the relationship between till and bedrock could be determined. Other, now submarine, sub-aerial processes might be open to similar treatment.

Ever improving and expanding data acquisition and more effective internet-based dissemination (e.g. RMBS [2008] or the Seamount Catalog [Earthref, 2008]) will continue to drive submarine geomorphology. Methodological progress, however, will also have a significant impact. In general, robust characterization and reproducible quantification of the morphologies of seafloor features are vital in testing and substantiating theories of earth system dynamics and landform evolution. Where ‘looks like’ has often sufficed in geomorphological discourse, analyses should move towards a quantitatively robust analysis, interpretation and explanation of the seabed and its details. We see several areas for progress.

- Increasingly quantitative analysis. Geophysics has a history of quantitative analysis of seafloor morphology [e.g. Murray & Hjort, 1912; Renkin & Sclater, 1988; Malinverno, 1991; Smith & Sandwell, 1997; Behn *et al.*, 2004], as does geomorphology for sub-aerial DEMs [e.g. Lave & Avouac, 2001; Montgomery *et al.*, 2001]. Some methods are common to both. Occasional note is made of this [e.g. Pike, 2000], but one of the biggest challenges in studies of the seafloor is to integrate and share available geophysical and geomorphological techniques and approaches. For instance, quantifications relating landforms to fluvial mechanics are more advanced in sub-aerial geomorphology. Using these would benefit the marine community [e.g. Ramsey *et al.*, 2006]. On the other hand,

regional-residual separation is commonly applied in marine geophysics. This emphasises classes of physically meaningful features by treating the DEM as a landscape and dividing it up into geological features (e.g. isolating volcanoes from the hot-spot swells upon which they sit [Wessel, 1998]) rather than just using visualization methods [e.g. Smith & Clark, 2005]. The original DEM is then the sum of the regional and residual DEMs, which has the benefit that numerical analyses can be separately performed for each class of feature even where they are superimposed. Work on automated and objective isolation (i.e. identifying and determining accurate spatial limits for) of all individual features of a certain type within landscapes [e.g. Hillier & Watts, 2004] is an extension of such work permitting large (e.g. 100,000 entries), self-consistent, and parameterised catalogues of features to be created. Different types of feature such as mud volcanoes, pockmarks or drumlins may benefit from this type of quantification routine. Morphological sub-classes of drumlin, for example, may exist with each relating to a different formation mechanism. These, however, are not resolved by present morphometrics, i.e. visually determined length and width. After length and width measurements are made reproducible, new parameters (e.g. skew) could be added to investigate formation mechanisms.

- Time-lapse studies. It is notoriously difficult to link with certainty a morphological form to the process that created it using only a single ‘snapshot’ of a landscape. Time series reveal the kinematics of a feature’s evolution, providing a useful bridge to the dynamics of processes at work. In the submarine setting time series are created by repeated, time-separated multibeam surveys. These have been used to examine eruptions on the Juan-de-Fuca Ridge [Chadwick *et al.*, 1995], deposition and erosion in canyons [e.g. Smith *et al.*, 2005], and other sedimentary processes. Schmitt *et al.* [2008] have reviewed this approach and refine the processing methodology involved. Studies including true repeat surveys, however, are not numerous. Suggestions of other targets for time-lapse multibeam bathymetry include: Coastal erosion by wave cutting; how does material disperse after a sea-cliff fails? How do sedimentary dunes migrate? How do individual turbidity currents affect the shape of submarine channels, and how does the surface of a submarine fan evolve over time? In neo-tectonics, how does a fault scarp evolve after a submarine earthquake, and how does oceanic sedimentary structure deform as the result of an earthquake on a blind thrust? Of special interest are locations where a recent perturbation has affected the ‘normal’ state of the surface. The relaxation phase after a perturbation contains much information about the processes that operate on a landscape, and on the controls on their rates. Ideally to study relaxation, and critically in the other suggestions, the *a priori* state of the site is known. This raises the challenge of anticipating seismic or other perturbations in space and time. As more and more sites are surveyed, the number of useful, ongoing perturbations for which *a priori* information exists will increase. The community must look for, and recognise the potential of such perturbations, and invest in the documentation and analysis of their aftermath
- Integration of bathymetry information with seismic and other techniques that image the sub-surface. For instance, at a larger spatial scale, and for deeply-buried oil bearing sediments, seismic data is commonly used to infer depositional environment but it is less commonly used to link deep structure, gas pathways (e.g. some faults) and related features on the seafloor (e.g. pockmarks) which often indicate ongoing or very recent activity. This, however, has recently become more popular [e.g. Cartwright & Huuse, 2005]. Side-scan sonar can assist in this endeavour, often giving resolutions much better than multibeam data. This approach can be likened to multi-attribute analysis in seismic reflection data or a classification algorithm for DEMs [Iwahashi & Pike, 2007], but would perhaps distinguish a feature in parameter space by a combination of its surface shape, seafloor roughness, side-scan sonar character and sub-seafloor echo character.

The key routes to continued progress are developing quantitative methods and integrating methodological expertise.

#### 4. This Issue

This journal issue seeks to promote a vision of a discipline that unites the protocols and practice of quantitative sub-aerial geomorphology targeting processes such as landsliding and channel erosion, and the statistical and algorithm-based surface quantification techniques used in marine geophysics to study, for instance, volcanism and tectonics. The papers exemplify several of the areas in which we see great potential such as an increasingly quantitative approach, and the integration of surface and sub-surface data types. Together, the papers span traditional boundaries between geophysics and geomorphology, tackling questions such as: How is melt distributed underneath the oceanic lithosphere? What relationship, if any, exists between the rupture zones of great subduction earthquakes and the bathymetry of the subducting plate? How do feedbacks between tectonic and mass wasting processes operate under water? The papers are ordered by a progression from the edges of the continents to the centre of the oceans, and are briefly put in context below.

##### 4.1 Near Continental Tectonics, Erosion & Mass Wasting

Geletti *et al.* [2008] investigate gas seeps and salt tectonics in the Central Adriatic Sea. The combination of swath bathymetry, chirp sub-bottom echo-sounder and multi-channel seismic data with well control allows them to establish a link between seepages evidenced at the surface as pockmarks, fracture systems and the deeper salt tectonics. They have also succeeded in assigning timings to the salt tectonics, and establishing how these tectonics divide the Adriatic into separate sedimentary depo-centres, demonstrating the power of combining data types within a bathymetric framework.

Mitchell & Lofi [2008] quantify channel profiles in order to compare rates of submarine and sub-aerial erosion on volcanic islands. This forms part of an emerging body of work relating the mechanics of sub-aerial and submarine mass wasting. Chiu & Liu [2008] also consider mass wasting, this time using chirp sub-bottom profiles in conjunction with swath bathymetry in order to compare neighbouring active and passive margins to illustrate an exciting link between tectonics, landslides and canyon-forming processes.

##### 4.2 Subduction, Earthquakes & Critical Wedges

Kopp *et al.* [2008] use multibeam bathymetry and seismic profiles to both qualitatively and quantitatively understand the morphotectonic response of the upper plate to the subduction of lower plate fabric. Their use of critical taper analysis and its relationship to mass wasting is again looking at the mechanistic relationships between submarine tectonics and mass wasting.

Morgan *et al.* [2008], on the other hand, demonstrate how existing bathymetry alone can yield new results with a robust, quantitative analysis. In general, seafloor roughness can be characterized using power-spectra [e.g. Bell, 1979; Hillier & Watts, 2005], fractals [e.g. Goff & Jordan, 1988] or slopes [e.g. Bell, 1979; Shaw & Smith, 1990]. Here, Morgan *et al.* [2008] apply a fractal approach to characterising the roughness of the seafloor on the downgoing and overriding plates in subduction zones and relate observed characteristics to the magnitudes of the ruptures of great subduction earthquakes. This fits with other recent work considering how topography on subducting plates can affect the rupture [Robinson *et al.*, 2006] and rupture areas [Sparkes *et al.*, 2008] of large subduction earthquakes.

### 4.3 Oceanic Volcanism

Moving to the centre of the oceanic tectonic plates, Hirano *et al.* [2008] combine multibeam bathymetry with side-scan sonar images to investigate volcanism. How the Earth melts beneath the oceans is currently the subject of debate, not insignificantly contributed to by the petit-spot volcanoes first identified by Hirano *et al.* [2001]. These monogenetic edifices seem to be a response to flexure of the lithospheric plate which, significantly, suggests that although volumetrically small sub-lithospheric melting may be ubiquitous. This adds an intriguing alternative end member model to melt supplied by large thermal plumes (e.g. at Hawaii) [Morgan, 1971].

Hillier [2008] proposes a methodology that contributes to the collection of morphological data across all sizes of seamount (mainly volcanoes) such that theories involving ‘plumes’, ‘plumelets’ [Janney & Castillo, 1999], and ‘mini-plumes’ [Shen *et al.*, 1993] might be assessed, perhaps by characterizing the seamounts’ size-frequency distributions. Significantly, Hillier looks at roughness in a different way, proposing an automated method to objectively isolate all individual seamounts from the background bathymetry. This exemplifies methods applicable to both submarine and sub-aerial data that could be applied to more of the Earth’s surface as data quality improves [e.g. NEXTmap, OLEX], and to different classes of topographic feature e.g. mud volcanoes (Earth or Mars [Kite *et al.*, 2007]), drumlins [e.g. Hillier & Smith, 2008], or sub-aerial volcano fields.

### 4.4 Mid-ocean tectonics

Fournier *et al.* [2008] examine possibly the largest type of volcanic feature on Earth, the mid-ocean ridge, but to answer a significant question in plate kinematics; Do ridge-ridge-fault (RRF) triple junctions exist on Earth? Their main data is multibeam bathymetry, but it is complemented by gravity, magnetic and sub-bottom seismic profiles. In demonstrating that Aden-Owen-Carlsberg is in fact a transient on the way to a RRF configuration they conclude that no RRF junctions currently exist, again illustrating the power of combining bathymetry with other data sets. So, alongside the body of work on plate reconstruction from magnetic anomalies, Fournier *et al.* [2008] show that bathymetry can help us to understand the detailed organisation of plate boundaries and provides hints of the underlying dynamics.

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NOTE: no doi yet for Hillier, Kopp *et al*, or Chiu and Liu in this issue.