Submarine Geomorphology: Quantitative Methods Illustrated With The Hawaiian Volcanoes

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Abstract

Submarine geomorphology, like sub-aerial geomorphology, is the study of the Earth's surface in order to better understand tectonic and geomorphic processes. Such processes include volcanism, neo-tectonics (i.e. the activity of geological faults), the escape of hydrocarbons, and submarine erosion (e.g. by channel cutting or landslides). Furthermore, submarine geomorphology can provide valuable input into other fields, such as indicating likely fisheries or habitats for corals.

This case study illustrates quantitative methods in submarine geomorphology with '*Regional-Residual Relief Separation*', which splits landscapes (Digital Elevation Models) into two components, isolating features of interest in one component for visualization or analysis as desired: here, isolating Hawaiian volcanoes. Separating the volcanoes enhances mapping and facilitates their accurate quantification via descriptive properties such as height and volume which are vital to constrain our understanding of how the Earth melts and volcanoes erupt. Key future opportunities in submarine geomorphology using quantitative methods are illustrated by, but not limited to, those highlighted here.

Key words: submarine, quantitative, DEM, residual, regional

1 Introduction

Humans cannot directly observe the vast majority of the seafloor as seawater absorbs nearly all light by a depth of a few hundred metres, which 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. Electronic geophysical equipment is therefore necessary to measure the deep ocean at any level beyond the most cursory and crude. Observation and analysis of seafloor relief has therefore been strongly linked to geophysics. Bathymetry (depth) measurement has improved in line with geophysical equipment and has historically been measured on research vessels alongside the gravitational and magnetic fields. Digital Elevation Models (DEMs), although they were not called that, and quantitative analyses have predominated since the early 1970s [e.g. Watts, 1976] in a strand of submarine geomorphology based in "blue skies" geophysics research. This strand of geomorphology continues to the present, although at some degree of separation from "conventional" techniques. Based on quantitative criteria methods in this strand tend to be strictly reproducible, can be automated, and focus on locating and optimally evaluating the properties (e.g. height, volume) of a number of, sometimes very many (>10,000 [Wessel, 2001]), features as a constraint upon physical processes. Ideas and methods in this strand are complementary to conventional geomorphology and can provide a number of interesting "alternative" approaches to analysing landscapes.

Common in this "alternative" strand of geomorphology is the concept of *Regional-Residual Separation*. Originating in the treatment of gravity and magnetic field data this is the idea that the signals of two objects can be present in the same location on a map, but can be separated, and once separated both parts better examined: In geomorphology for 'signal' read 'shape'. By convention the *regional* component is the larger scale of the two components because, in older methods, it was calculated first and then subtracted to leave the *residual*. In newer, more computationally demanding, methods however either the *regional* or *residual* component can be calculated first. As an illustration, using a glacial landscape, the larger-scale *regional* could be gently rolling hills whilst the *residual* could be the drumlins superimposed upon those hills. Clearly, once a component is isolated individual features within it can better be mapped or visualized. Note that components are not 'terrain units', areas of similar properties in a conventional geomorphological map. Components contain height relating to a class of feature across the whole map area, several components may have non-zero height at any map location, and summing the components recreates the terrain.

Section 1.1 describes the historical developments leading towards the strand of geomorphology in which *Regional-Residual Relief Separation* arose. Section 1.2 then documents the development of digital bathymetric data, culminating in the recent convergence of both submarine and sub-aerial topography data towards high resolution DEMs. This also serves to place this case study in a wider context. Section 1.3 introduces *Regional-Residual Separation*, leading into the Hawaii case study. Submarine volcanoes are difficult to isolate accurately, so the Hawaiian volcanoes are ideal to illustrate, and have indeed driven, the development of quantitative techniques. Equally the Hawaiian region is chosen because the mapping and geomorphological quantification of that region's features has been critical to improving our understanding of volcanism and its causes. To conclude, the final section draws together wider opportunities and lessons about quantitative analysis in submarine geomorphology.

1.1 **Historical Development**

Knowledge of water depth has long been critical for navigation, with depth measured by 'soundings' using a variety of techniques. Initially sounding used a long pole; from the 1870s hemp rope with a lead weight attached was used (e.g. the steamer *Albatross*) until the early 20th century when a wire cable method began to be used. These soundings were, however, neither quick nor cheap to obtain, so only a few thousand were available in the deep oceans. Further substantial progress was not made until 1935 when *USS Ramapo* of the US Navy took some of the first 'sonic soundings', measuring the return time of a sound pulse, at relatively closely spaced intervals [Menard, 1964]. So, whilst many local detailed sub-aerial observations were made, submarine geomorphology resolved features at scales of 100s or even 1000s of km. Depth data, however, was electronically collected.

Using sonic soundings Betz & Hess [1942] produced one of the earliest bathymetry maps of the Pacific, or indeed any ocean, with 'many' soundings [Menard, 1964] i.e. >> 10,000. 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. Broad features were, however, represented '*with a fair degree of accuracy*'; for instance, they noted and named the '*Hawaiian Swell'* (Figures 1a & 5c). Subsequently this feature's morphology has been the inspiration for, and is still a critical constraint upon, many theories about the processes driving the vigorous flows within the planet, how the Earth melts, and volcanism [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 verify the hypsometric curve (i.e. area *vs* depth) of Murray and Hjort [1912] and discuss modes of formation of the deep oceans. This is a form of analysis recently reinvigorated for sub-aerial [e.g. Willgoose & Hancock, 1998; Montgomery *et al.*, 2001] and planetary [e.g. Rosenblatt *et al.*, 1994] geomorphology.

Perhaps because of the electronic nature of data collection, a digital global seafloor depth map called SYNBAPS was created in the 1970s [Van Wyckhouse, 1973]. This was, indeed still is, a DEM. With many electronically stored data quantitative, and even computational, analyses of the shapes of different classes of feature on the seafloor became common from this time in "blue skies" geophysical investigations [e.g. Menard, 1969; Sclater, 1971; Watts, 1976; Parsons & Sclater, 1977; Watts, 1978, McKenzie *et al*, 1980]. These papers are early examples of the regional-residual analysis of relief. As other strands of geomorphology, this strand has evolved as data has developed.

1.2 Data Development

Ocean wide digital bathymetry maps (e.g. GEBCO [2003], ETOPO-5 [N.O.A.A., 1988]) from soundings now contain ~40×10^6 km of measurements along ship tracks [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 e.g. RMBS [2009]. 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 types 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], and lava flows [e.g., White *et al.*, 2000]. Concurrently, this increase in data resolution (commonly to < 100m grid cells) has started to permit quantitative geomorphological investigation of features more usually associated with sub-aerial processes (e.g. landsliding [e.g. Mitchell, 2001; Watts & Masson, 2001] and canyon formation). In the oil and gas industry, higher data resolutions have permitted conventional sub-aerial style study of processes for longer on the continental margins. Analyses are used for the likes of seabed oil and gas field planning and development, and data resolutions can be very high e.g., <5 m grid spacing. So, submarine geomorphology started, out of necessity, quantitatively at a large scale and as data resolution increased has been able to study in a way more akin to sub-aerial geomorphology.

Sub-aerially, it has been possible to create quantitative maps and study local detail for a considerable time. However, global gridded data at a resolution to be considered useful is a more recent development, for example satellite-derived digital elevation models (DEMs): NASA's SRTM data with 90 × 90 m grid spacing became available in 2001. Complementing this, very high resolution data are locally available, for example LIDAR data. These data drive the need for quantitative automated approaches in sub-aerial geomorphology. In submarine geomorphology it is common to integrate surface (e.g. side-scan sonar) and subsurface data (e.g. reflection seismic). Similarly, satellite data (e.g. multi-spectral data) are assimilated in sub-aerial geomorphology. So, now sub-aerial and submarine data are at similar resolutions, permitting similar quantitative analyses of the same processes, making this an ideal time for cross-fertilization of ideas. In this spirit, the following section describes *regional-residual separation*.

1.3 Regional-Residual Relief Separation

To better understand processes that affect the Earth's surface, landforms (or 'features') are divided into classes or categories, based on some similarity of form, or *a priori* knowledge that they relate to the physical process under investigation. Implicit in this categorisation is the notion that landscapes are composed of, and can be divided into, meaningful classes, or 'components', of features related to a process. If H is height, $H\_DEM = H_1 + H_2 + \ldots\ldots H_n$, where n is the number of components. Regional-residual separation methods [e.g. Sclater, 1975; Wessel, 1998] aim to divide the landscape, so that all features of interest are completely and uniquely in one component. The features in, and the process represented by, the component may then be more easily quantified, analysed and investigated. Although regional-residual separation allows features to be more clearly seen, by whatever visualisation technique is chosen (see Smith, 2010), it must be emphasised that such separation is conceptually very different from visualisation alone and has the benefit that numerical analyses can be separately performed for each class of feature even where they are superimposed.

Nature is complex, so regional-residual separation is often difficult. Features within components may be separate or overlapping, and may vary in shape and size. For example submarine volcanoes range from < 100 m to 6.7 km in height [e.g. Hillier & Watts, 2007]. Features in different components may be superimposed on each other, e.g. 200 m wide drumlins superimposed on 10 km wide rolling hills. As the last example suggests, the skill is identifying a distinctive difference such as 'width-scale' [e.g. Hillier & Smith, 2008] between components. Most simply, but effectively, features of interest can be identified manually and a trend extrapolated underneath them [e.g. Smith *et al*, 2009]. Usually, the aim is automated and objective determination of the larger scale regional from which the smaller residual features can be derived [e.g. McKenzie *et al*, 1980; Hillier & Smith, 2008], but it is also possible to devise methods to directly isolate (i.e. identifying and determining accurate spatial limits for) of all individual features of a certain type within landscapes [e.g. Hillier & Watts, 2004] leaving the regional trend.

In short, geophysics has a long history, using various techniques, of dividing the seafloor into components. Techniques vary with the task in hand. For more regional-residual separation techniques, references, and background the reader is referred to Wessel [1998]. The case study below illustrates the development of geomorphological techniques as applied to Hawaii and geological insights gained. The older techniques are good first approximations here, and remain excellent solutions in some situations [e.g. Hillier & Smith, 2008]. The desire, however, for more accurate observations (e.g. of height and volume), preferably of many volcanoes and without the possibility of influencing the result through subjective choice separation parameters (e.g. width-scale), has driven the development of methods. In a wider context, these methods have application in many analogous situations.

2 Case Study: Hawaii

Figure 1a shows Hawaii, a large ~250 km diameter volcano in the Pacific Ocean, at the SE end of the Hawaiian Island Chain. The volcanoes in the chain get progressively younger towards Hawaii [H] [e.g. Clouard & Bonneville, 2005], a current 'hot-spot' [Christofferson, 1968] of volcanic activity. Figure 1b(iv) is a simplified profile across the chain: Hawaii is dark grey and older, smaller volcanoes are black. Hawaii sits atop an ~1000 km wide 'super-Gaussian' shaped [Wessel, 1993] bulge or swell, also shown on Figure 1b(iii). Hawaii is immediately surrounded by a trench then, farther away, a bulge. The scars of old fracture zones (large inactive fault systems) are also present (Figure 1a).

The paragraph above describes the geomorphology of the seafloor in the region of Hawaii, but what can this usefully tell us about our planet? What do the shapes mean? To interpret this window into the Earth's interior, geomorphological techniques and mapping must be used. The paragraph below illustrates the spectrum of what geomorphology can tell us, and then the case study focuses on the mechanics of isolating volcanoes into a 'residual' component.

Through isolating the various features and using them as constraints in physical models we now much better understand the main processes acting to cause this fascinating array of geomorphological features. The swell is probably caused (directly or indirectly) by an upward flowing jet of hot material that is also feeding the volcanism [e.g. Wilson, 1963; Morgan, 1971]. The volume of the volcanoes constrains, for example, the temperature of the jet, which limits how vigorously it can push up and how much it can re-heat the tectonic plate; both of these processes could cause the swell [Crough, 1978; Ribe & Christensen, 1999]. The volcano volumes also record the waxing and waning of this jet through time: its dynamics [e.g. White, 1993; Ark & Lin, 2004]. Seafloor warping (i.e. bulge and trench) is due to Hawaii's weight [e.g. Vening, 1941; Watts, 2001: *Eqn* 3.25], so these shapes are indicative of the strength of the tectonic plates. Lastly, the shape of the Hawaiian Swell is a further constraint upon possible origins of both itself and the volcanoes [e.g. Wessel, 1993]. It is therefore important to isolate geomorphic components in the DEM.

Volcanoes are the most striking component of the DEM but, since key to successful regional-residual separation is identifying a distinctive difference between the component of interest and others, there are a number of difficulties in isolating them. This, however, makes them ideal to illustrate the progression of techniques. The main complications are:

- Volcanoes are numerous: Globally, there are 40±10 thousand of them taller than 1 km [Hillier & Watts, 2007], which strongly favours the use of automated techniques.
- Volcanoes' heights range from < 0.1 km to 10 km, and their diameters from < 1 km to 250 km [e.g. Wessel, 2001; Behn, 2004], which limits the use of a 'width-scale' or a size related distinction.
- Approximately conical, volcanoes' shapes vary enormously [e.g. Jordan *et al*, 1983], so there is no distinctive defining shape for pattern matching.
- Volcanoes overlap, are superimposed, and some have been tilted.
- Volcanoes occur on slopes, in trenches, and sometimes in very high spatial densities, which complicates (and biases) attempts to compute large-scale regional trends.

Initial processes for regional-residual separation involved the definition of a regional larger-scale trend from which the "residual" containing small features (i.e. volcanoes) could be calculated. The earliest efforts were manual [e.g. Menard, 1973; Sclater, 1975]. Computationally, early methods used efficient 'frequency domain' filters [e.g. Watts & Daly, 1981, Casenave *et al*, 1986] to retain long wavelengths (λ), e.g. $400 < \lambda < 4000$ km, but these '*are not a good quantitative translation of 'regional' in a seamount province*' [Smith, 1990]. Alternatively, regional depth can be estimated from a 'linear combination' of data within an area, the simplest of which is the mean [e.g. Watts, 1976]. A mean computed within a window and output to the window's central point is a sliding mean or 'boxcar' filter. Figure 2a illustrates the (equal) weights assigned to the data within the window for a mean; variants include using a Gaussian weighting [e.g. McKenzie *et al*, 1980]. These work well with an appropriately selected filter width where residual topography is both positive and negative around the regional, and work reasonably where 'normal' flat seafloor overwhelmingly dominates. Figures 3a and 4a, however, show the computed output on simplified and observed volcano topographies respectively, which highlight Smith's [1990] point. Because all volcanoes stick upwards, height is never removed, just spread around. In both cases the width, height and volume of edifices are underestimated, and smaller volcanoes isolated in Figure 4b are completely missed. 'Robust' statistics can mitigate this [Smith, 1990].

Robust statistics such as the median and mode ignore 'outliers' (e.g. volcanoes if flat seafloor is the statistical norm) when computed in windows along profiles or in areas. So, such statistics better estimate regional depth in the presence of volcanoes [e.g. Smith, 1990; Levitt and Sandwell, 1996] (Figure 3a). Consequently, the number and dimensions of the volcanoes themselves are better estimated. Techniques such as identifying the deepest of multiple modes [Crosby *et al*, 2006], or using directional medians on gridded data [Kim & Wessel, 2008], have improved results further. Problems, however, remain; mainly i) 'spectral overlap' or the sharing of width-scales with other seafloor features [Wessel, 1998], which prevents simple approaches that can succeed in isolating some superimposed landforms [Hillier & Smith, 2008] ii) width-scale selection, which has not been automated as would be necessary for optimally separating each individual edifice in a large population. Additionally, conceptually proceeding down this route, one must consider how *a priori* the existence and location of every edifice is known for a separation to be optimised.

An alternative approach is to directly isolate (i.e. identify and determine accurate spatial limits for), by their own descriptive characteristics, all individual features of a certain type within a landscape. For multi-scale seamounts, the challenge is to isolate them computationally whatever their shape with no *a priori* knowledge of where they are or how big they are. Hillier [2008] details the history of such attempts, criteria for evaluating methods, and proposes a method based on a 'Spatial Wavelet Transform' (SWT).

A 'wavelet', as its name suggests, is a small wave that grows and decays over a limited range of distance [Percival & Walden, 2000]. The wave consists of weights to create a weighted average of another function (e.g. a depth profile such as Figure 4a) *at a given scale and location*, and can be designed (Figure 2b) to be a maximum at the scale and location of a volcano (e.g. Figure 3b) [Hillier, 2008]. Conceptually, the wavelet in Figure 2b is simply the difference in mean heights on the central and edge sections of the wavelet. Once wavelet coefficients are computed across a grid of distances and scales (Stage 1), the largest 'best-fitting' one can be found giving a location and scale for each feature (Figure 4c). Then, completing Stage 2, other features such as the flexural bulge (star) are distinguished in size-scale space as they are much less tall than volcanoes at that width scale. Finally, in Stage 3, using the derived widths and locations and in conjunction with the original bathymetry the limits of the volcanoes are determined. Figure 4b clearly shows that the SWT method works accurately for the whole size-range of volcanoes, even in the presence of several other topographic components.

Figure 5 shows the application of the SWT method to gridded data, isolating Hawaii from its swell. Currently, the SWT method is only coded to work along profiles, so this result is produced using a mesh of profiles across the grid. Scatter, produced by differences between profiles, is random about the desired regional, so a 100 km wide median filter was applied before computing components for display. The components in Figure 5b and Figure 5c sum together to make the DEM in Figure 1a, and the success of the separation can be judged by absence of seamounts in Figure 5c and absence of swell in Figure 5b. With the regional-residual separation complete visualization, mapping (manual or automated), or any other analysis could be performed on either of the components.

The 3 stages used by Hillier [2008] provide an analytical framework and are entirely interchangeable with any equivalent preferred by a future investigator. For instance, the 'spatial wavelet' does not conform to some mathematical strictures usually taken to define wavelets and so has great flexibility. For example, to eliminate large artefacts at the edge of trenches the coefficient was reduced to zero if either edge was above the centre; this is not easily possible with formal wavelets, however, depending upon the task, one may prefer a readily available wavelet such as a 2D 'Mexican Hat' [e.g. Gonzalez-Huevo *et al*, 2006]. Likewise, rules to distinguish features of interest in the size-scale space of the WT can be customised, as can the translation of this information into outlines of features.

The SWT is also relatively computationally efficient. For the 750 data spaced at 2 km intervals across the Hawaiian chain (Figure 4a,b) a 1.33-GHz ibook with 512-MB RAM took 0.8 s to find the 38 features. Analysis of gridded data is considerably slower: the 844 profiles took 22 min 43 s to analyse, compared to 13 min 57 s for the traditional 480 km wide median filter (grdfilter of GMT).

For full details of the SWT algorithm, the reader is directed to Hillier [2008]. The SWT code is in the CD accompanying this book.

A major advantage of performing a regional-residual separation by finding the smaller features (e.g. volcanoes using the SWT) first, then deriving the regional, is that the smaller features are effectively already mapped. Such automated detection and isolation of seamounts has permitted work on the geophysical dating of ~2000 Pacific volcanoes [Hillier, 2007], and the refinement of the estimate of the global volcano population taller than 1 km from 10 – 100 thousand to 40±10 thousand [Hillier & Watts, 2007]. Additionally, however, the automated isolation permitted a large, self-consistent and morphologically parameterised catalogue of seamounts to be created, which has generated interest in diverse communities such as those studying fisheries and habitats for corals [e.g. Tittensor *et al*, 2009]. Similar large (e.g. 100,000 entries), self-consistent, and parameterised catalogues of features could assist in sub-aerial geomorpohology such as the study of drumlins and their formation processes. These opportunities exist as part of a wider context, summarised below.

3 Discussion and Conclusions

Quantitative analysis of DEMs of the seafloor has existed since the early 1970s, and this case study illustrates the concept of *regional-residual separation* and some of the techniques used to perform it by focusing on the important region around Hawaii. The techniques divide the submarine landscape into 'components' containing features representing processes. Such division is extremely valuable. From the Hawaii example it can be concluded that regional-residual separation permits better visualization and mapping of features, but more importantly the features and thus the processes can be quantitatively analysed (e.g. via volcano volume). The mapping and subsequent analysis of the Hawaiian region's morphology has been a major contributor to our understanding of how, why and when the Earth melts, rises, and erupts to the surface.

Always, the skill in performing a successful regional-residual separation is determining a property that makes the features you wish to isolate distinctively different. If, for instance, features of interest are ~100m wide and have a complex morphology but lie on a gently undulating regional topography with undulations of 1 km in width, then determine the shape of the simple component, the regional: a sliding mean may be appropriate. If, however, both regional and residual topographies have complex and varied morphologies but the features of interest are known to be constructional (i.e. *always* build upwards) then use this: a wavelet detecting areas that rise above their surroundings may be appropriate.

Once a component is separated, the features within it can be mapped, but regional-residual separation dictates no conclusion about whether this mapping is best done manually or automatically. Automated methods are fast to run, reproducible, and therefore arguably more objective, but currently take longer to set up than manual methods. So, the appropriate method depends upon the task in hand. It is also noteworthy, however, that when a regional-residual relief separation technique that finds the smaller-scale component first (e,g., SWT for volcanoes) features in this component are effectively already mapped.

Automated mapping methods include i) mimicking the mapping method of a manual interpreter in an automated and reproducible way (e.g. Hillier, 2004) ii) proposing robust statistics and objective metrics to optimally isolate individual features (e.g. Wessel, 1998) iii) using algorithms that search a landscape for a class of feature using scale-invariant or multi-scale parameters (e.g. Behn, 2004; Wessel, 2001) iv) simultaneously using multiple Land Surface Parameters (LSPs) in order to categorize areas within a landscape into classes with distinctive properties that relate to a type of feature. Method iv) is typically used in subaerial geomorphology. SWT, when used to map features, falls into method type iii).

By dint of how submarine and sub-aerial relief has to be measured, the available data have differed. Now, however, as data in both environments tend to high resolution DEMs, a re-merging of submarine and sub-aerial geomorphology is occurring. This study seeks to emphasise the great opportunity for exchange of knowledge about processes, technical expertise, and thus opportunities for improving our understanding of our planet.

Drawing on work presented in the session on *'Seafloor expression of tectonic and geomorphic processes'* at the 2007 EGU General Assembly, Hillier *et al* [2008] identify key future opportunities in submarine geomorphology. They promote 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 and geodynamics) ii) strives to progress beyond qualitative methods and embrace quantitative approaches iii) integrates bathymetry with standard marine techniques that readily image sub-surface structures. Although the opportunities highlighted are from the academic sphere, analogous possibilities will exist in other areas.

Methodological progress will have a significant impact. Several areas for progress are:-

- Increasingly quantitative analysis.
- Time-lapse studies, for instance repeated multibeam studies [e.g. Smith *et al.*, 2005], to reveal the kinematics and link a feature with its formational process. Possible targets: Coastal erosion by wave cutting; how does material disperse after a sea-cliff fails? How do sedimentary dunes migrate?
- Further integration of bathymetry information with seismic and other techniques that image the sub-surface in a similar way to combining data from multiple satellites.

Four prospective or emergent areas of study highlighted to have great potential are:-

- The interaction between submarine erosional or mass wasting processes (e.g. landsliding & turbidity flows) and tectonics, which has proved fruitful on land [e.g. Montgomery *et al.*, 2001].
- Quantitative comparison between sub-aerial and submarine analogues, such as slope-area scaling relations and channel morphology [e.g. Ramsey *et al.*, 2006], using the same techniques.
- Insight into the way earthquakes create landscapes by examining the evolution of a surface expression through time as recorded in the morphology of surface and subsurface layers. Reflection seismic data is routinely recorded at sea, whilst fully excavating a structure on land using trenches is rarely done.
- Understanding the processes of landform creation by resolving their interior structures and relationship to bedrock e.g. drumlins formed during the last ice-age that are now drowned and are visible on OLEX data [Spangolo & Clark, 2009], or possible signatures of catastrophic floods [e.g. Gupta *et al.*, 2007].

4 Software & Data

GMT (Generic Mapping Tools) is an open source collection of ~60 tools for manipulating Cartesian and geographic data sets, and producing simple x-y scatter plots to artificially illuminated perspective views. GMT is downloaded from *http://gmt.soest.hawaii.edu/* (Windows, UNIX, Linux, & Mac OSX). Code, c-shell scripts, and compliation checks for MiMIC [Hillier & Watts, 2004] and SWT [Hillier, 2008] as used in the production of the papers are, without any guarantee whatsoever, supplied on the CD attached to this volume. If used or altered, the appropriate reference should be cited. Data used here are also on the CD.

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6 Figures

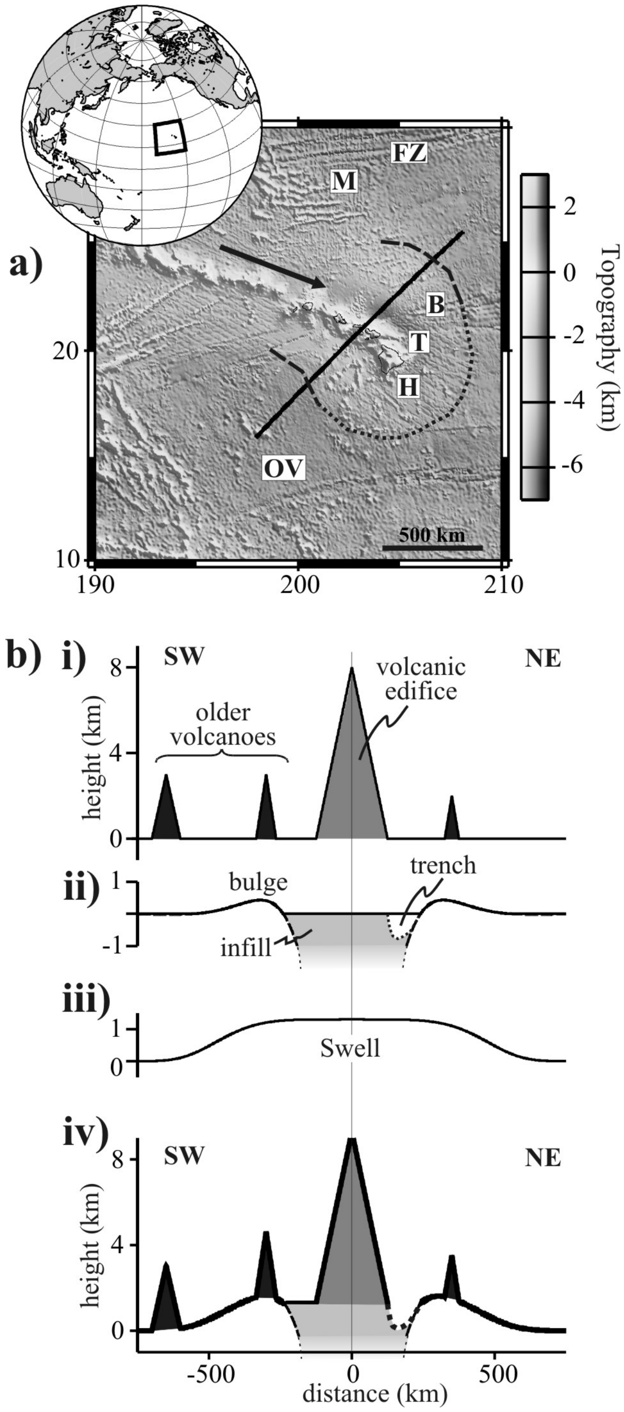

Figure 1: a) 2' x 2' relief-shaded topography [Smith & Sandwell, 1997] of the Hawaiian Region as Hillier [2008], located on inset. Thin lines are coastlines. H, Hawaii; T, Trench; B, Bulge; FZ, fracture zone; M, Musicians Seamounts; OV, older volcanoes. Dashed and dotted lines illustrate limit of SE end of the '*Hawaiian Swell*' [e.g. Betz & Hess, 1942; Wessel, 1993]. Solid line locates profile (Figure 4), selected proximal to those of Watts [1978]. b) Schematic illustration of interaction between i) a volcanic edifice ii) seafloor warping due to the volcano's weight and iii) an ~1000 km wide swell. i) to iii) are components of, and sum to, the total bathymetry in iv). Colour version on DVD.

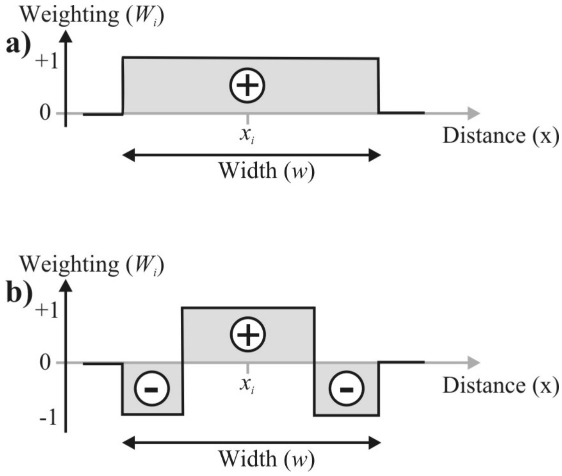

Figure 2: Weightings creating a) sliding mean filter (e.g. GMT [Wessel & Smith, 1998]) b) spatial wavelet transform [Hillier, 2008].

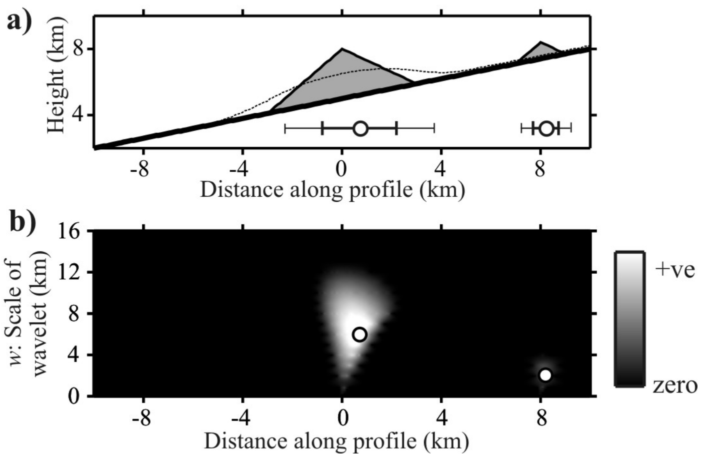

Figure 3: Wavelet transform of two synthetic seamounts, one small and one large on a sloping regional bathymetry a) Bathymetry profile (thin line) overlies the seamounts (grey shades). White circles outlined in black locate the highest amplitude coefficients in b): the associated bold horizontal bars indicate the span of the central part (i.e. $x_i \pm w/4$) of the best-fitting wavelets, and the thin bar the whole width (Figure 2b). Thick black line is the regional bathymetry (i.e. pre-existing seafloor before seamount was added) as estimated by the SWT method [Hillier, 2008] (see text for details). Thin dotted line is a 6 km wide mean filter. b) WT of the profile. Coefficients $C_{x,w}$ at each scale w centred on distances x_i along the profile are grey-shaded with large $C_{x,w}$ light coloured. White circles outlined in black are the highest amplitude best-fitting coefficients. SWT, Spatial Wavelet Transform.

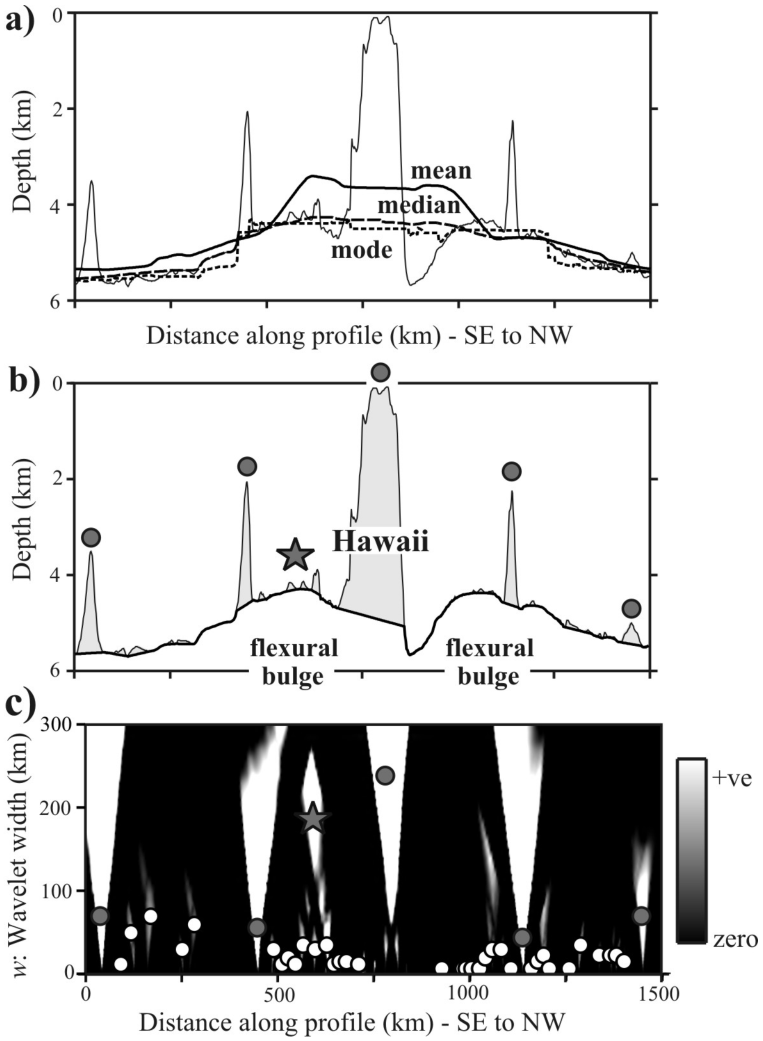

Figure 4: Comparison of windowed filters and the SWT method on a bathymetric profile across the Hawaiian Chain, as in Hillier [2008]. Profile located on Figure 1. a) Bathymetry profile (thin line) and regional bathymetries estimated by optimal [Wessel, 1998] 480 km wide mean (thick line), median (dashed line), and mode (dotted line) filters. b) Regional bathymetry estimated by the SWT method (bold line) by extrapolating under detected seamounts (light grey). WT of the bathymetry profile. Circles are the coefficients best fitting the seamounts, $w > 20$ km only for clarity. Illustratively, grey circles are linked to seamounts in b). Another, scale-invariant, MiMIC technique produces very similar results [Hillier & Watts, 2004]. Star indicates coefficients relating to the flexural bulge; eliminated and not used to create regional in b). c) WT of the profile. Colour version on DVD.

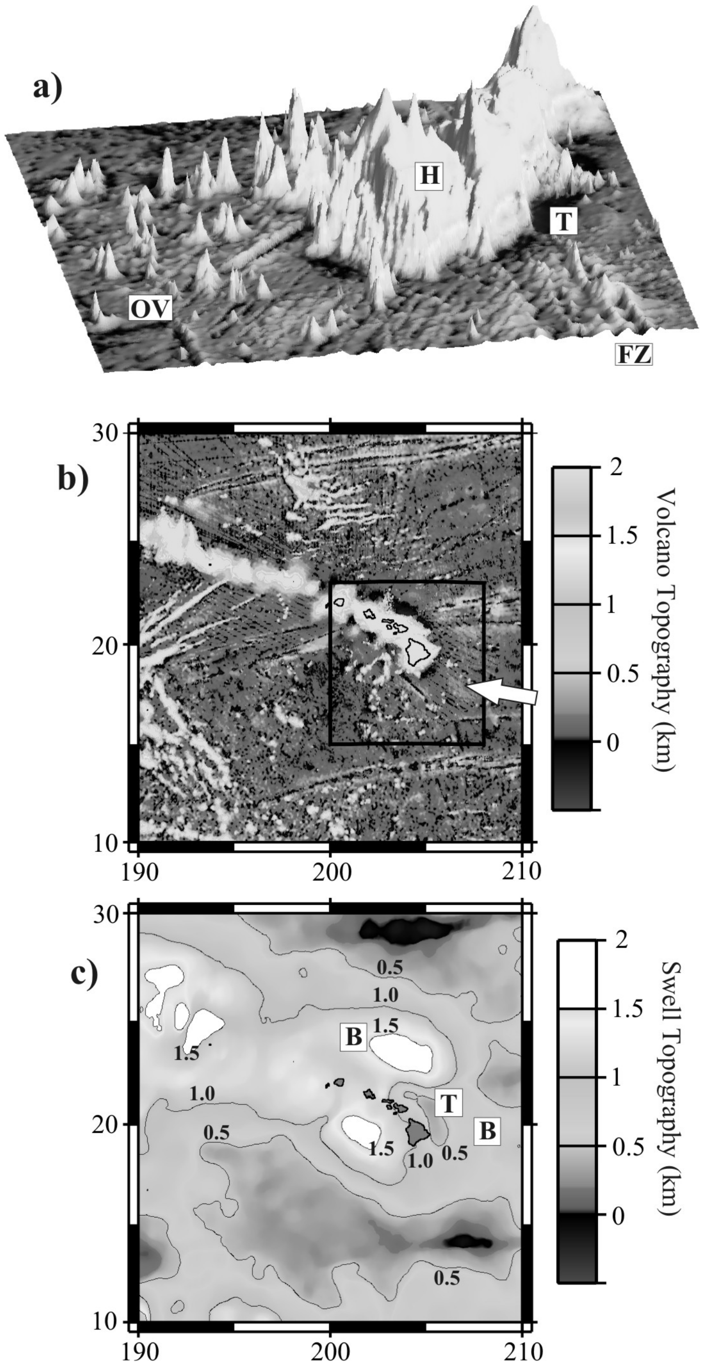

Figure 5: Application of the SWT method applied to gridded data (Figure 1a) in the region of Hawaii. b) & c) Volcano and swell topography above a 6 km deep baseline respectively. Letters as Figure 1. Coastline shown for reference in b) & c), land shaded dark grey in c). a) 3D view relief-shaded view of estimated volcano component of bathymetry near Hawaii i.e., in box in b). View from 100/25, white arrow. Relief is coloured as in b). Note that features within both components are much more evident than in Figure 1, and that any desired visualization technique may now be used on the components. Colour version on DVD.