Sizes and Ages of Seamounts Using Remote Sensing: Implications for Intraplate Volcanism

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Satellite altimetry is used to identify and characterize Pacific intraplate seamounts. The gravimetric amplitudes of seamounts appear to be related to the age difference between seafloor and seamounts; by inverting this relationship pseudo ages can be obtained for undated seamounts. These pseudo ages imply that excursions in seamount volcanism generally correlate with times of formation of large oceanic plateaus.

The Pacific plate may support more than 50,000 seamounts taller than 1 km, yet ~50% of these undersea volcanoes are uncharted because of sparse bathymetric coverage (1, 2). Even fewer (<1%) have been sampled for radiometric dating (3), making assessment of temporal fluctuations in intraplate volcanism uncertain. Because electromagnetic sensing devices cannot penetrate the oceans, we are unable to image the seafloor remotely and instead must rely on surface ships equipped with sonar. At the present rate of data acquisition, complete bathymetric coverage may take centuries. However, the density contrast between sea water and the seafloor basalt gives rise to gravity anomalies. These minute variations in the Earth gravitational pull cause sea water to be attracted to seamounts, leading to a sea surface (which approximates the geoid) whose shape reflects these underlying features (4). Thus, since the early 1980s, satellite altimetry has provided broad coverage of the sea surface or geoid undulations (5). Early attempts to map the seamount distribution were largely limited by the coarseness of the satellite coverage [the typical track spacing was more than 100 km (6)], and many seamounts went undetected. Because seamounts are typically much smaller than 100 km, it was difficult to estimate what part of the seamount had been traversed by the satellite, leading to large uncertainties in estimates of seamount height and diameter (7).

Recently, the U.S. Navy declassified its Geosat satellite altimetry, which has been combined with the European Space Agency ERS-1 altimetry to provide a detailed (~10 km resolution) view of all ocean basins (8). Traditionally, statistical studies of seamount distributions have focused on assessing the spatial variability of volcanism (9). Yet, it is the temporal aspect of intraplate volcanism that is the most important to understand, but most seamounts have not been dated. Given the cost (in time and money) of sample acquisition it is doubtful that we ever will obtain a dramatically improved database of radiometric ages, making it imperative to explore alternatives to radiometric dating of seamounts.

On the basis of 59 seamounts for which size and age information were known, a vague but tantalizing relationship emerged that seamount size increased with square-root of the age contrast between seamount and seafloor (that is, the seafloor age at the time of seamount formation (10)); this trend could be related to the simple and systematic effects of seafloor maturation (11). Here, I document the existence of such a relationship using a fully automated characterization of seamount shapes on the entire Pacific plate from satellite

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altimetry to yield pseudo-ages for uncharted and unsurveyed seamounts and assess the temporal aspects of intraplate volcanism on a large scale.

Fig. 1. Theoretical VGG over an isostatically compensated seamount. The amplitude $v_0$ and zero-crossing distance $d$ are the two clearest characteristics of the anomaly.

Rather than using the gridded gravity anomalies (8) my starting point was the gridded vertical gravity gradient (VGG, with units of Eötvös = 0.1 mGal/km), also known as the curvature of the geoid or sea surface (12). Use of VGG provides for reduced sensitivity to the elastic thickness of the lithosphere and the density of sediments, and better spatial separation of overlapping seamounts (13). I preprocessed the VGG grids by removing the longer length-scales using robust median filters and determined local maxima in the residual data; these are the potential sites of seamounts. Theoretical modeling indicates that VGG anomalies over a Gaussian seamount should have a pronounced zero-crossing somewhat inside the actual seamount radius (14; Fig. 1). However, because of random noise in the data, the zero-contour meanders and rarely encloses a seamount. I therefore determined the 25-Eötvös contour instead and used it to evaluate the potential maxima that fell inside this contour (15). When two or more maxima were contained by the same closed contour I estimated the individual zero-crossings by evaluating the "volume" under the VGG surface within the contour and distributing this volume among the contained volcanoes, assuming that all the volcanoes inside the contour have the same height/radius aspect ratio (16). Finally, I excluded all features within 25 km of a known fracture zone or trough, leaving a total of 8882 seamounts on the Pacific plate (Fig. 2). The spatial distribution of small (blue), intermediate (green), and large (red) seamounts generally confirms earlier results obtained with lower resolution data (17), but adds more higher-order details.

Fig. 2. Equal-area Hammer projection showing all 8882 seamounts found on the Pacific plate; the sizes of crosses reflect the VGG amplitudes. Blue crosses are small seamounts (30-60 Eötvös, generally < 2.5 km tall), red crosses are large seamounts (> 120 Eötvös, generally > 3.5 km tall), whereas green crosses are of intermediate size.

Given the dense coverage available, I also estimated the actual bathymetric size of each seamount. For example, by examining a 10° by 10° area in the central Pacific the observed VGG (Fig. 3A) can be processed to isolate the seamount signatures only (Fig. 3B). By use of forward modeling of seamount VGG of all sizes allowed, I created a numerical look-up table that relates the observed VGG amplitude and zero-crossing distance to actual seamount radius and height (18). Although gravimetric estimates closely correspond to the VGG residual maxima, the bathymetric predictions exhibit uncertainties up to 25% (19; Fig. 3C). A comparison with available bathymetry (Fig. 3D) shows that in general the poor bathymetric coverage gives overly smooth bathymetry that in many cases overestimates the size of individual seamounts, and many features are missing entirely (20). Although the predicted sizes of individual seamounts may have significant errors, the robust gravimetric estimates are more than adequate for a variety of purposes, including but not limited to studies of spatial seamount distributions (9), absolute motion plate tectonic reconstructions (21), hot spot flux estimates (22), stress and elastic thickness (23), and determination of hot spot locations (24).
Fig. 3. Comparison between observed VGG (A) and VGG shapes of seamounts isolated by our technique (B) for a segment of the Marshall-Gilbert-Ellice chain. The zero-crossing distances and VGG amplitudes were then used with the lookup-table to predict seamount radius and heights (C). For comparison, the ETOPO5 bathymetry is shown (D). The regional depth variations evident in the ETOPO5 have been filtered out in the other images.

Of the 8882 seamounts detected, 6306 are located on seafloor of known age (25). A plot of all VGG estimates versus crustal age give a scatter plot with an upper envelope (Fig. 4). This envelope implies that there is a simple relationship between VGG and \( \Delta t \) and occurs because the VGG over seamounts sitting on seafloor of a given age should be less than or equal to the VGG of the youngest seamount on seafloor of that age; older seamounts will have progressively smaller VGG since they formed when the seafloor was younger and less able to support a large volcano. This model assumes all volcanoes grow to their limiting size. The VGG amplitudes for all seamounts of known age contrast (open circles (3)) generally agree with the simple envelope relation. The regression fit to the envelope may thus be inverted to give predictions of seamount age given VGG and seafloor age (26). It is clear that the prediction of an individual seamount’s age will involve large uncertainties. For example, the horizontal distances from each open circle to the regression line (Fig. 4) represent the misfit between known radiometric ages and the corresponding pseudo age. However, when the large data set is averaged into age categories, the

uncertainties decrease substantially. The age predictions are completely decoupled from the bathymetric predictions.

![Graph showing scatter plot of seamount VGG versus crustal age](attachment:image)

**Fig. 4.** The envelope of maximum values in the scatter plot of seamount VGG versus crustal age reflects a simple square-root relationship between seamount size and $\Delta t$, which can be inverted to give predictions of pseudo-age. For example, the observed VGG value inside the circle (116.6 Eötvös) was measured over a seamount on 69 m.y. crust. Inversion gives a $\Delta t$ of 25.6 m.y., implying a seamount (pseudo) age of 43.4 Ma.

Using the bathymetric predictions and isostatic modeling I estimated the total seamount volume (extrusive plus moat infill) for all 8882 seamounts (27; Fig. 5). The data reveals that a large cumulative volume of younger seamounts sit on mid-Cretaceous crust (110-120 Ma), as evidenced by the shift toward lower age-ranges between pseudo ages and crustal ages. I find that seamounts on the oldest crust actually have pseudo ages that are much younger (Fig. 5). The satellite-derived volumes are almost twice as large as volumes estimated from the available ship bathymetry data sets (28, 29). In view of seamount volumes for both crustal and pseudo ages, larger than average seamounts appear to have formed in the time-spans 70-80 Ma, 90-100 Ma, and perhaps 140-150 Ma. These periods are generally associated with the formation of several large igneous provinces in the Pacific ocean (30), although it is not possible to discern whether the seamount production predates, was synchronous with, or postdates plateau formation.
Fig. 5. (A) Number of seamounts versus pseudo age (narrow solid columns) or crustal age (wide gray columns). Seamount production seems to have been higher in the 90–120 Ma range. (B) Same graph except showing total seamount volumes, indicating higher volumes in the 80–120 Ma period. The solid line is comparable results obtained from bathymetry (29). (C) Average seamount volume (total volume divided by seamount count) peaked during the 70–80 Ma, 90–100 Ma, and 140–150 Ma intervals. Unlike histograms versus crustal ages, the histograms for pseudo ages cannot be normalized by the proportions of crust of different ages.

Because of the scatter of the data about the regression line in Fig. 4, the age predictions are neither unique nor necessarily accurate. If factors such as local magma supply or regional stress variations do affect seamount size then our pseudo ages become upper age bounds. The general correlation between peaks in the average seamount volume

versus pseudo age distribution (Fig. 5C) and formation of oceanic plateaus, however, implies that the pseudo-age histogram should reflect the actual temporal aspects of Pacific intraplate volcanism. While radiometric dating will continue to be the only accurate dating method, pseudo ages are useful in identifying areas where additional radiometric dates would be most influential.

**References and Notes**

4. Sea surface (or geoid) undulations over seamounts are small: a 4 km tall seamount may give rise to an anomaly of a few meters spread over a few hundred kilometers, making it imperceptible to human observers but easily detectable by satellite altimetry.
9. D. Chapel and C. Small, *Eos (Fall Suppl.)* 77, F770 (1996); also see (2).
12. Vanicek, P. and E. Krakiwsky, in *Geodesy: the concepts* (North-Holland, New York, 1982.) The gravity anomalies (8) are derived from a VGG grid via a Fourier transform; the VGG was obtained by algebraic manipulation of observations and does not contain spectral edge effects. Walter Smith kindly provided the VGG grid used herein.
13. Large seamounts depress the crust, reaching an isostatic equilibrium. The shape of such flexural deformation depends on the elastic thickness of the lithosphere and the density of the sediment in the moats [A. B. Watts, *J. Geophys. Res.* 83, 5989 (1978)]. Because the VGG strongly attenuates long-wavelength signals, the gravitational effect of flexural subsidence beneath a seamount is largely eliminated, making the attraction of the seamount itself the dominant component of the VGG anomaly.
14. I follow Craig and Sandwell (2) and approximate all seamounts by Gaussian shapes. The radial VGG signal over such features can be approximated by

\[
VGG = \frac{\nu_0}{2} \left[ 1 - \left( \frac{r}{d} \right)^2 \right] + \exp \left[ -\frac{9}{2} \left( \frac{r}{d} \right)^2 \right]
\]

where \(\nu_0\) is the maximum VGG amplitude and \(d\) is the zero-crossing distance where \(VGG(d) = 0\). VGG has a steep slope at \(r = d\), making it much easier to detect the zero-crossing than comparable features in the geoid, free-air anomaly or deflection of the vertical (1, 6).
15. I account for this adjustment by using the same contour in model calculations.

16. With height proportional to radius the volume of a single seamount is proportional to \( r^3 \). Equating the sum of these volumes to the numerically integrated volume inside the contour allows estimation of individual radii.

17. I find numerous linear seamount chains indicative of hot spot volcanism and a much higher density of seamounts in the Central and Western Pacific; the latter also has most of the largest seamounts detected. The lowest seamount densities are found south of the Udintsev fracture zone and in the equatorial Eastern Pacific.

18. I used forward modeling of plate flexure caused by Gaussian seamounts of all sizes, low-pass filtered the results to make them spectrally similar to the observed data, and estimated zero-crossings and maximum amplitudes using the same procedures as applied to the data. The results were compiled into a 2-D look-up table that relates maximum VGG and \( d \) to seamount height and flank slope, which combine to yield radius.

19. The observed and predicted volumes appear to agree to within 10–15%, but the requirement of a Gaussian shape leads to larger errors in the seamount height and radius estimates.


24. P. Wessel and L. W. Kroenke, Nature 387, 365 (1997). In fact, it was the compilation of the data presented here that facilitated their discovery.


26. Robust regression of the envelope in Fig. 3 gives \( VGG(\Delta t) = 61.8 + 10.8 \sqrt{\Delta t} \). This is inverted to yield the empirical relationship

\[
\text{pseudo age} = \text{seafloor age} - \left( \frac{VGG(\Delta t) - 61.8}{10.8} \right)^2
\]

27. The flexural modeling also allowed us to numerically estimate moat volumes.


30. The Ontong Java plateau was emplaced during two distinct episodes at ~121 Ma and ~89 Ma [D. Bercovici and J. Mahoney, Science 266, 1367 (1994)]; the Manahiki plateau also formed ~123 Ma, while Hess rise (90–100 Ma) and the Mid-Pacific Mountains (75–130 Ma) have longer ranges or ages. The oldest plateau is Shatsky rise (138–145 Ma) [R. Larson and P. Olson, Earth Planet. Sci. Lett. 107, 437 (1991)].

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