Geophysical Research Abstracts
Vol. 14, EGU2012-5745, 2012
EGU General Assembly 2012

Inferring Properties of the Hawaiian Plume from the Hawaiian Swell

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The most prominent geophysical signature associated with the Hawaiian island chain is a broad topographic anomaly ('swell') some 1000 km wide and 2500 km long. Isostasy requires the swell to be compensated by a layer of low-density material at depth whose shape in mapview is similar to that of the swell itself. That shape can be predicted using a simple 2-D thin-layer flow model in which buoyant fluid with constant viscosity is supplied at a volumetric rate Q by a fixed mantle plume and spreads laterally over the base of a plate moving at speed U. A more realistic 3-D version of the model involves a hot thermal plume in a fluid with temperature- and pressure-dependent viscosity that interacts with the shear flow generated by the plate motion. Comparison of the predictions of these models with observations of the Hawaiian swell yields several important inferences about the Hawaiian plume:

(1) Plume buoyancy flux B. The observed height and width of the swell imply $B \approx$ 3000 kg s^{-1}, much less than earlier estimates $B =$ 6300-8700 kg s^{-1} based solely on the horizontal flux of (negative) swell buoyancy carried by the moving plate. The reason for the discrepancy is that the horizontal flux calculation neglects (a) the contribution of the buoyant residue of partial melting to the swell topography, and (b) the fact that the mean speed of downstream transport of the buoyant material by the shear flow is less than the plate speed.

(2) Depth of compensation. The 3-D model predicts a geoid/topography ratio (GTR) $\approx$ 7-8 m/km for the Hawaiian swell, in apparent contradiction with earlier estimates $\approx$ 4-5 m/km based on the observed geoid and bathymetry alone. However, an extended version of the 3-D model including volcanic loading and lithospheric flexure reveals that the low values GTR$\approx$ 4-5 m/km are artifacts of incomplete removal of the shallowly compensated volcanic islands and the surrounding flexural moat. The GTR of the swell itself is therefore $\approx$ 7-8 m/km, implying a compensation depth $\approx$ 70-80 km.

(3) Rheology of the plume material. The young ($\approx$ 5 Ma) and old ($\approx$ 20 Ma) parts of the Hawaiian swell have very nearly the same amplitude and width, implying that the swell decays very slowly downstream from the hotspot. An extended version of the thin-layer model with a power-law rheology (strain rate proportional to the power n of the stress) predicts that the swell should decay as the power $-1/(3n+2)$ of the downstream distance. The slow decay of the Hawaiian swell requires the plume material to have a dislocation-creep rheology with $n \approx 3.5$.