TOPOGRAPHY AND TECTONICS

Mike Sandiford

School of Earth Sciences, University of Melbourne, Victoria 3010, Australia.

m.sandiford@earthsci.unimelb.edu.au

http://jaeger.earthsci.unimelb.edu.au

SUMMARY

The Earth is a hot, dense planet in a cold, sparse universe. Many of Earth's psychoses, such as volcanism, earth-quaking and other forms of anti-social behaviour, can be understood in terms of a competition between heat loss, which strives to disperse the thermal energy anomaly, and self-gravitation which holds the mass anomaly together. This competition is manifest as tectonics and is perhaps most spectacularly observed through the topography of the Earth's surface. As is well understood, plate tectonics provides a framework that accounts for most of the large-scale surface topographic features. Increasingly it is able to account for subtle features!

Topography of the ocean basins (pinks are high, blues are low) as measured and estimated from gravity data derived from satellite altimetry and shipboard depth soundings.
Plate tectonics provides a framework for understanding the connection between the processes that facilitate heat loss and the forces that drive plate motion. One of the great successes of plate tectonics lies in its explanation of most of the major surface topographic features of the Earth, particularly in the ocean basins (Figures 1 & 2). In recent years, this success has extended to many subtle aspects of topography at the continental-scale that potentially provide important insights into the dynamics of the hot interior of the planet. This talk discusses the links between topography and tectonics, highlighting recent advances that help relate surface topography to dynamic processes in the mantle.

In recent years large-scale digital databases have revolutionised our approach to Earth sciences. This is particularly true for tectonics where global topographic and gravity datasets provide a level of analysis hitherto unimaginable. This talk will use visualisations based on a number of different datasets including digital terrain models (DTMs) such as GTOPO30, the GEOSAT synthetic topography and gravity datasets. These images are available at my web site: http://jaeger.earthsci.unimelb.edu.au/msandifo/Talks/2000/Selwyn/Selwyn.html.

The many topographies of the plate tectonic world

The lithospheric plates represent the surface manifestation of large-scale flow in the mantle. Much of the surface topography reflects the density distribution within the plates themselves, related to the way in which they grow and age, and contributes to what we term the “isostatic topography”. The isostatic response of the lithosphere reflects the way in which the lithosphere accommodates lateral variations in density by creating topography, not only at the

Figure 1. Shaded relief map of the world from the ETOPOS dataset.

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surface, but also on internal density interfaces such as the crust-mantle boundary. Density variations in the lithosphere represent internal loads and, at length-scales less than several hundred kilometers, such loads flex the lithosphere, resulting in the production of "flexural topography", with the characteristic flexural response depending on the size and age of the load and the strength of the lithosphere. In the deep mantle, the large-scale convective flow involving both upwelling and downwelling deforms the Earth's surface thereby creating "dynamic topography". Dynamic topography is best seen in the "residual topographic" field obtained by removing the isostatic contribution from the observed topography (Figure 3).

Isostatic and dynamic topography in the ocean basins

Plate tectonics finds its greatest success in the ocean basins. The ocean floors are dominated by the mid-ocean ridges, with their symmetrical, gently curved ridge flanks descending into the abyssal plains (Figure 2). To a very good approximation the bathymetry of the ocean floors increases with square root of the age of the ocean floor, at least for ocean lithosphere younger than about 80 Ma. A corresponding decrease in the heat flow with the square root of age gives rise to the remarkable age-bathymetry-heatflow relationship for the ocean floor. This relationship is probably the most profound observation pertaining to the behaviour of the Earth and provides one of the cornerstones of plate tectonics: the ocean lithosphere forms by the conductive cooling of hot mantle! The increase in density as the lithosphere cools causes it to "sink" giving rise to variations in topography that are essentially isostatic in nature. The resulting topography developed around the mid-ocean ridges generates horizontal buoyancy forces, helping to drive flow away from the ridges and consequently stabilising the plate divergence at the ridge axis.

Figure 2. Topographic field of the ocean basins. Note the anomalously low segment of the mid-ocean ridge on the Australian-Antarctic-discordance to the south of Australia.

2 Debate continues as to the nature of the age-bathymetry relation in oceanic lithosphere older than about 80 Ma. The perception that this relation breakdown at about 80 Ma has lead to the thermal plate model e.g. Parsons & Sclater, (1978). For an alternative view see Marty & Cazenave (1989), Davies and Pribac (1993).
The residual topography of the ocean basins is obtained by subtracting the isostatic contributions from the topographic field in Figure 2. This effectively removes the age-dependence of oceanic bathymetry, such that mid-ocean-ridges disappear. Variations in the residual topography reflect dynamic and flexural contributions at long and short wavelengths, respectively. Note the low in the residual topography on the Australian-Antarctic-discordance to the south of Australia, and the high in the western Pacific. Australia is currently in transit from a dynamic topographic low to a dynamic topographic high.

The age-bathymetry-heatflow relationship implies that the ocean lithosphere has a simple structure that changes in a very predictable way with time. Therefore we can easily unroll the effects of time, allowing us to separate the "isostatic topography" from the "residual topography". Variations in residual topography reflect dynamic processes associated with convection deep within the Earth. The buoyancy flux associated with upwelling of hot mantle contributes to broad swells around many hot-spot or plume-related volcanic islands, where the contributions of dynamic and flexural topography are relatively obvious (Figure 4).

One of the most dramatic, large-scale residual topographic features occurs south of Australia on the Australian-Antarctic discordance (Figure 3). The anomalously deep nature of the residual topography in this region suggests the possibility of mantle downwelling, while the apparent slope in the residual topography from the Antarctic to the Australian margin points to large-scale density anomalies in the sub-lithospheric mantle (Figure 5).

The geoid and continental flooding

The geology of the ocean crust is very simple, consisting of a thin layer of sediment (siliceous ooze and red clay) overlying a 5-7 km thick mafic igneous crust consisting mainly of basalt, "sheeted" dyke complexes and gabbro. Simply on the basis of the age we can predict the major geophysical features of the ocean such as its bathymetry and heat flow. In comparison, the continents are much more heterogeneous, and plate tectonics *sensu stricto* has found more difficulty in accounting for the subtleties in continental topography. Many subtle features are however explicable in terms of the links between dynamic topography and sea level as the continents circuit above a "lumpy mantle" (Gurnis et al., 1998).
Figure 4. Line profiles of topography and free-air gravity across Hawaii, showing the flexural response of the lithosphere to the seamount.

Figure 5. Bathymetric profile from Antarctica (left) to Australia (right) across the Southern Ocean. Top panel shows age of ocean floor. Bottom panel shows the observed and residual topography. The residual topography is anomalously low (~ -1 km), with the suggestion of a slight gradient across the Southern ocean.
Variations in the density structure at depth create variations in gravitational potential inducing anomalies in the equipotential surfaces relative to a spherically symmetric Earth. The geoid is a reference equipotential surface that equates to the mean sea level. There is a general correlation between the geoid anomalies and the large-scale pattern of dynamic topography (Figures 3 & 6). If the geoid height changed at exactly the same rate as dynamic topography, then the "lumpy mantle" would have no effect continental sea level. On the other hand, when geoid changes at a different rate to the dynamic topography, the extent of continental flooding should change as the continents transit across the mantle. The ratio of the amplitude of the variation in the geoid to the amplitude in the variation in the dynamic topography (the so-called admittance) is still uncertain but is estimated to be about 0.3 - 0.5 (Gurnis, 1990). The range in the geoid anomalies on the modern Earth is about 150m, suggesting that dynamic topography can readily account for 150-300 m of relative sea-level change.

Over the last 150 Ma, Australia has moved northward over the dynamic topographic low now centered beneath the Australian-Antarctic discordance. It is now moving towards a dynamic and geoid high centered over the western Pacific (Figure 7). The impact of this dynamic topography has left its imprint in the flooding record and drainage systems on the Australian continent. For example, the flooding of the Mesozoic inland seas can be attributed to the passage of the Australian continent over a developing dynamic topographic low associated with downwelling, the remnants of which are now located beneath the Australian-Antarctic discordance (Gurnis et al., 1998). The re-emergence of the continent and the development of the ~1000 km scale west-flowing drainage systems of the Murray-Darling basin can be linked to the changing topography of the eastern sea-board as it exited this dynamic topographic low.

**Figure 6.** Global geoid map. There is general correlation between the geoid highs (light colours) and the residual topographic highs in Figure 3. The total amplitude in the geoid is about 150m from the low of Sri Lanka, to the high near Papua-New Guinea. He ghosted outlines of the continents reflect the fact that sources due to lithospheric density variations are subordinate to deep mantle density anomalies.
Figure 7. The "lumpy mantle" effect illustrated by draping a shaded relief image of the Indian Ocean on the geoid surface. The view is to the east, with north to the left. A broad geoid trough extends from India (lower left) to southern Australia (upper right). Papua-New Guinea (top center) is riding the crest of the western pacific geoid high. The admittance between the geoid and the dynamic topography I estimated to be ~0.3 -0.5 implying that transit across a lumpy mantle will modulate relative sea level.

The role of dynamic topography in the Australian Neogene sea-level record is yet to be satisfactorily elucidated. Nevertheless, it is clear from the current setting of Australia that dynamical processes are likely to have helped shaped this record. The elucidation of the dynamic topographic signal of the continents as distinct from ice, and sea-floor spreading rate, controlled sea-level changes remains a major challenge for the Earth sciences, in part because it will help unravel the dynamic story of the Earth's interior.

REFERENCES


