2 The geophysical observables

The basic constraints on the first order geodynamic processes that have shaped the modern Earth are provided by the observed long-wavelength variations in topography, the geoid (which contains information about the distribution of potential energy), heat flow, seismicity and the *in-situ* stress field. The main features of each of these *geophysical observables* at the global scale is summarised below.

2.1 Topography

At the global-scale the distribution of topography is strongly bimodal (Figure 2.1) with continental topography having a mean elevation of several hundred m and ocean bathymetry having a mean depth of about -4 km.
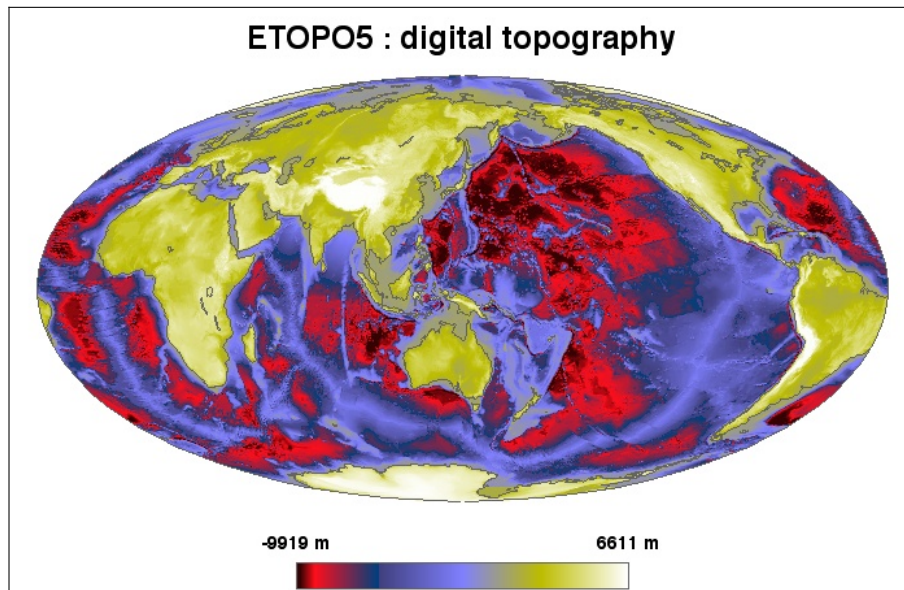

Figure 2.1   Global topography derived from the ETOPO5 database.

2.1.1 Morphology of the ocean floor

The floors of the ocean basins have a relatively simply morphology (at least when considered at long wavelengths, being dominated by narrow ridges (the mid-ocean ridges), abyssal plains and trenches. The mid-ocean ridges represent submerged volcanic mountain ranges, with an average depth beneath sea level of 2–3 km. Broad

swells in the elevation of the ridges occur along their length and locally the ridges are exposed, as is the case in Iceland. The depth of the ocean floor increases systematically away from the ridges, corresponding to time dependent changes in the density structure of the upper mantle beneath the ageing oceanic lithosphere, as reflected for example in the geoid (see Section 7.1). The depth beneath the ridges above 40 Ma oceanic crust is about 2 km, while for 80 Ma old oceanic crust it is about 3 km. The average depth of the ocean waters is therefore clearly related to the age of the oceanic lithosphere, which in turn is related to the rate of generation (spreading rate) of new oceanic lithosphere at ridges (see Section 5.2). In trenches, which mark the sight of subduction of old oceanic lithosphere water depths may reach 10 km.

This regular pattern of oceanic bathymetry is disturbed by:

- *Guyots and sea-mounts* From the point of view of the history of understanding seafloor evolution, now submerged, but once exposed, oceanic seamounts termed *guyots* are an important morphological feature of the ocean basins.[7] These features show, unequivocally, that the change in bathymetry of the mean sea-floor with distance form the ridge corresponds to a temporal sequence of subsidence, and thus coroborates the interpretation of sea-floor spreading based on the observed symmetrical magnetic striping of the ocean floors.

- *Fracture zones*

2.1.2 Continental topography

The continents have a mean elvation of several hundered meters above sea-level with a range from about 300 meters below sea-level (at the break in the continental shelf) up to about 8 km at Mt. Everest. At the 100 km - scale,the highest average elevation is only 5 km.

Continental landscapes provide one of the most dramatic of natural fractal surfaces. The characteristic feature of the fractal is the statitiscal scale-invariance, that is the general character of the surface looks the same independent of the scale of observation. For landscapes this is strictly true only over a limited range of scales (10^{-1}m – 10^5 m). The invariance of landscapes on this range of scales suggests that the processes operating to sculpt the landscape (i.e., erosion, mass wastage and deposition) are either scale-invariant themselves or that when acting together produce the scale-invariant effect. Erosion acts to roughen landscape at a wide range

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[7] Menard provides an excellent first hand account in his book *An ocean of truth* of the significance of these drowned-islands on the development of sea-floor spreading hypotheses.

of scales while both mass wastage and deposition act to smooth the landscape, at the short and long-wavelength, respectively.[8]

2.2 The geoid

Because of the inviscid nature of water (when viewed at geological time-scales) the mean sea-level represents gravitational equipotential surface in the earths gravitational field and therefore its elevation can be related to the density distribution at depth (as well as the the orbital dynamics of the Earth which cause an ellipticity in mass distribution and hence in the equipotential surfaces). The observed geoid height, as determined from the mean sea-level elevation, is expressed in terms of an anomaly relative to some fixed elevation (i.e., the predicted geoid for an idealised sphercially symmetric, hrotating mass distribution).
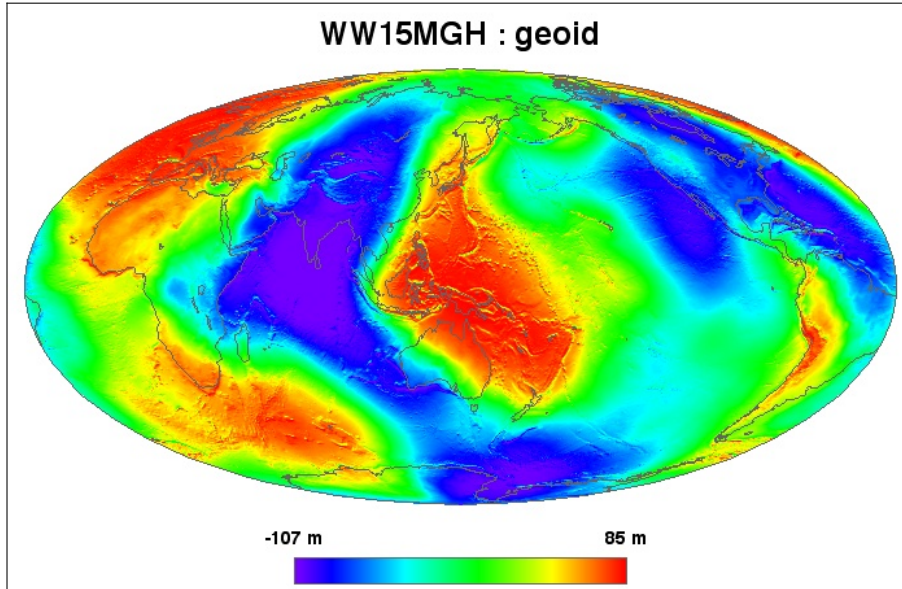

Figure 2.2   Global topography. ETOPO5 database.

Variations in the gravitational potential energy of the lithosphere, ΔU_l, correlate with the dipole moment of the near-surface density distribution and therefore they can be directly related to the lithospheric component of the observed geoid anomalies, ΔN_l :

$$\Delta U_l = \frac{g^2}{2\,\pi\,G}\,\Delta N_l \tag{2.1}$$

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[8] See Chase (1992),*Geomorphology.*

where g is the gravitational acceleration, and G is the gravitational constant (note that the potential energy varies with the geoid anomaly as approximately 0.23 x 10^{12} N m^{-1} per meter). The main problem with using this relationship is resolving the lithospheric contribution of the geoid anomalies from the much larger amplitude anomalies associated with the dynamic processes of plate tectonics and mantle convection.

Positive geoid anomalies of up to 10 – 15 m associated with a number of mid-ocean ridge segments, as well as age-correlated geoid offsets across fracture zones imply that ageing of the ocean lithosphere is accompanied by a decline in potential energy. The geoid anomaly predicted for the cooling half-space model (as well as the thermal plate model) for young ocean lithosphere is about $d\left(\Delta N_o\right)/dt = -0.15$ m/Ma, which compares favourably with the observed geoid anomaly over the Mid-Atlantic Ridge at 44.5$^\mathrm{o}$N, and elsewhere, as well as with the geoid offsets across fracture zones. The total geoid anomaly of -12.7 m over 84 Ma corresponds decline in U_l of 2.9 x 10^{12} N m^{-1}.

In comparison with the mid-ocean ridges, the geoid anomalies associated with continental margins and the interior of continents are far less clear. On the basis of averages taken over large areas there appears to be no systematic difference in the geoid height between old ocean basins (older than Cretaceous) and continental masses. Such an interpretation implies that the mean potential energy of the continental lithosphere is equivalent to old ocean basins. However, the data show very substantial differences between continents, with the mean geoid of the African continent some 40 m higher than the North American continent and 10 m higher than the mean for the Atlantic and Pacific ocean basins older than Cretaceous. This observed intercontinental variation far exceeds the plausible lithospheric contributions to geoid anomalies and therefore must reflect long-wavelength sub-lithospheric contributions. Moreover, a number of continental margins are characterized by distinct positive anomalies of the order 6 m across the transition from the ocean basin to sea-level continent and imply that a continental lithospheric column supporting sea level elevation has the potential energy equivalent to ocean lithosphere of age about 44 Ma.

Since the lithospheric contribution to the geoid anomaly reflects the dipole moment of the near-surface density distribution, the observed geoid anomalies across continental margins can also be used to constrain the continental lithospheric density structure. A lithospheric thickness of 125 km and a crustal density of 2750 kg /m^3 is consistent with a continental marginal geoid anomaly of + 6 m. Moreover, such a density structure is consistent with the interpretation that an isostatically compensated continental lithospheric column supporting about 1 km of surface elevation above sea level is in potential energy balance with the mid-ocean ridges. While the

generally poor resolution of the geoid in mountainous regions precludes definitive correlation between topography and potential energy within the continents, some evidence of the correlation is provided by the lithospheric contribution to the geoid anomaly of 24 – 27 m for the Andean Altiplano. Such inferences are consistent with a geoid that varies with continental topography as 6 – 7 m/km, corresponding to a potential energy variation of about 1.3×10^{12} N m^{-1}. For a continent with an average elevation of 500 m, this correlation suggests a mean continental potential energy of $0.997 \times U_{MOR}$

2.3 Heat flow

Since the lithosphere represents a conductive lid to mantle convection the variation in heat flow measured at the surface provides insight into the vertical structure of the lithosphere.

In the ocean lithosphere, the highest heat flow regions are associated with mid-ocean ridges, where absolute values are very variable (50-300 mW m^{-2}) due to intense, but localised, hydrothermal activity. In older, deeper lithosphere the heat flow measurements become less variable and gradually decline. The decline in heat flow approximates the same dependence on $t^{0.5}$ as bathymetry. This *age-bathymetry-heatflow* law for ocean lithosphere which provides one of the most profound insights into the structure of the lithosphere (see Chapter 7).

2.4 Active seismicity

Earthquakes are generated during rupture events associated with the small relative motions (typically less than several metres) of rock masses across faults. The distribution of seismicity in the lithosphere therefore provides a direct "snapshot" of the active deformation, with the intensity of seismicity in any region providing a indicator of the relative rate of deformation.

Seimic activity in plate boudaries accounts for about 95% of the global seismic moment release. Implying hat the great majority of relative motion in the lithosphere is accommodated in the plate boundaries. Indeed it was this very observation that provide the understanding that the earths lithosphere could be separated into a relatively few large, essentially rigid plates, with the belts of seismicity marking out the plate boundaries.

Nevertheless, there is significant earthquake activity in some areas of the continents away form plate boudaries, in areas of so-called diffuse deformation, such
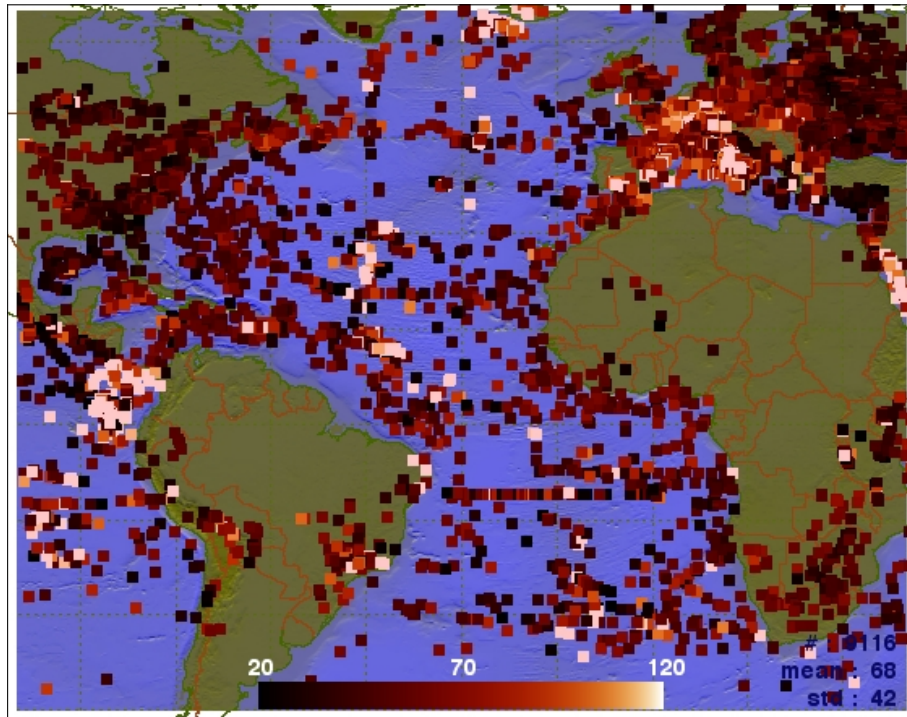
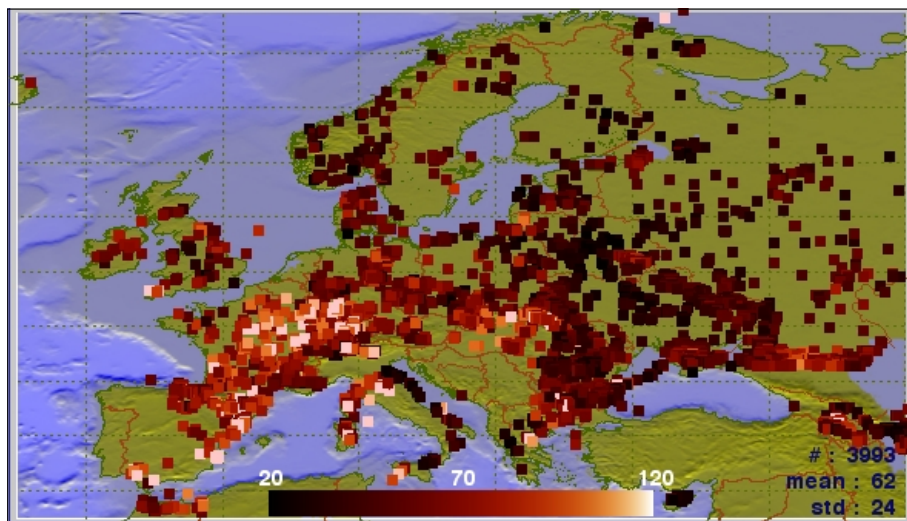Figure 2.3 Heat flow measurements from the Atlantic Ocean from the NOAA database. Units in mWm^{-2}.

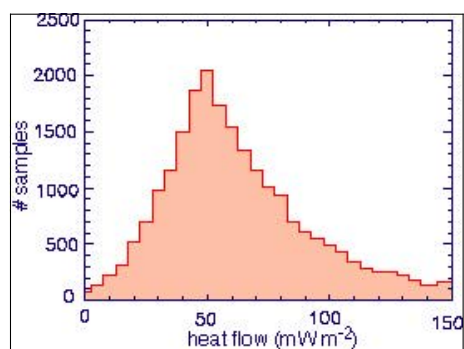Figure 2.4 Heat flow measurements from Europe from the NOAA database. Units in mWm^{-2}.

Figure 2.5 Global heat flow measurements. NOAA database.

as central Asia, and the western USA, and to a less extent, in stable continental interiors such as Australia.

2.5 Gravity field

2.6 Crustal thickness

2.7 Deep seismic velocity strutcure

2.8 Plate velocity field

2.9 The *in-situ* stress field

Stress in th lithosphere is created by internal variations in matterrial propoerties such as density and elastiicity, as well as by tractions exrted form plate boundaries
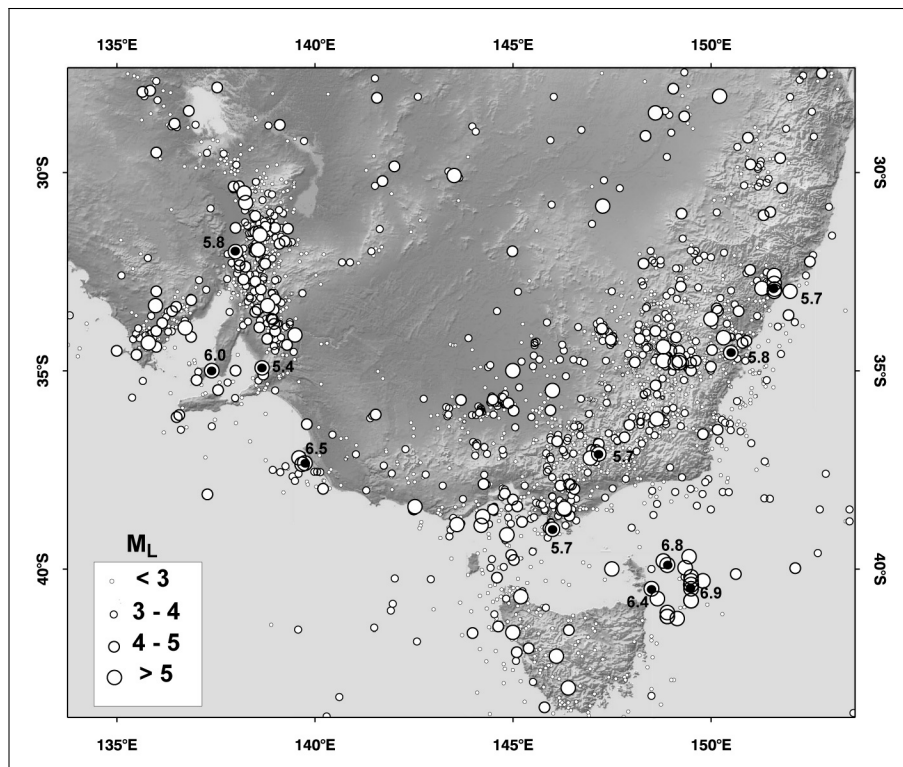

Figure 2.6   Earthquakes in SE Australia.

and along that base of he plate. The pttern of stress witin plates should therrefore reflect the way in which

The orientation of the stress field in the lithosphere provides an important constraint on mechanisms driving plate motion (see Chapter 10).
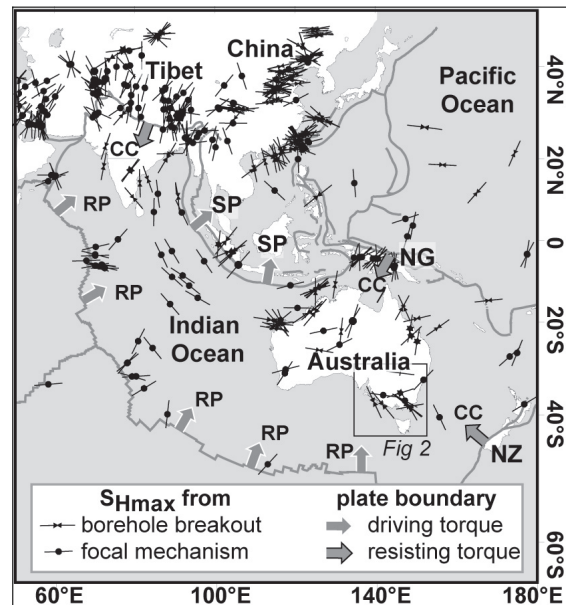

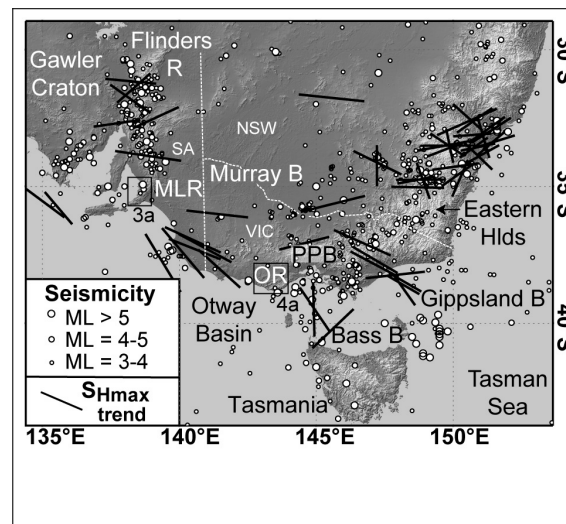Figure 2.7   Stress field in the Indo-Australian Plate.

Figure 2.8   Stress field in SE Australia.
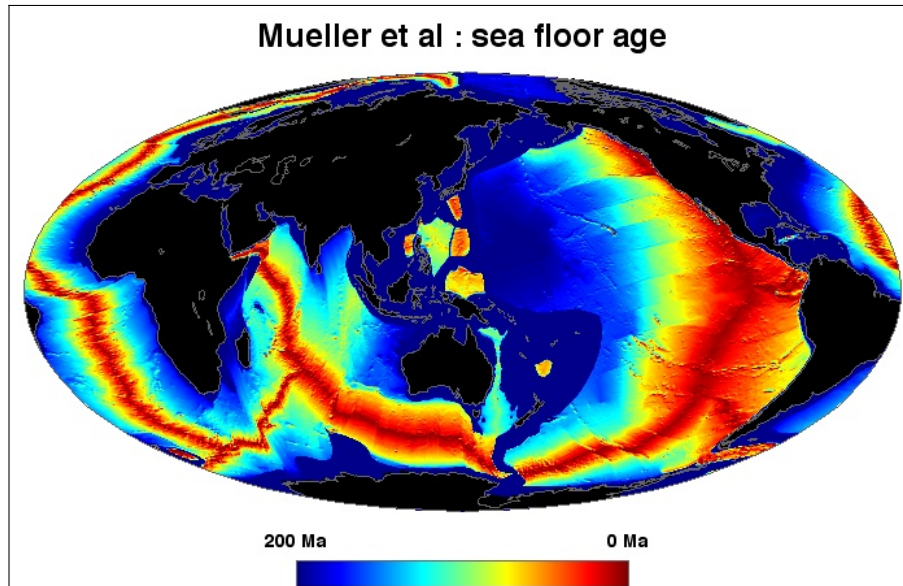
2.10   Age

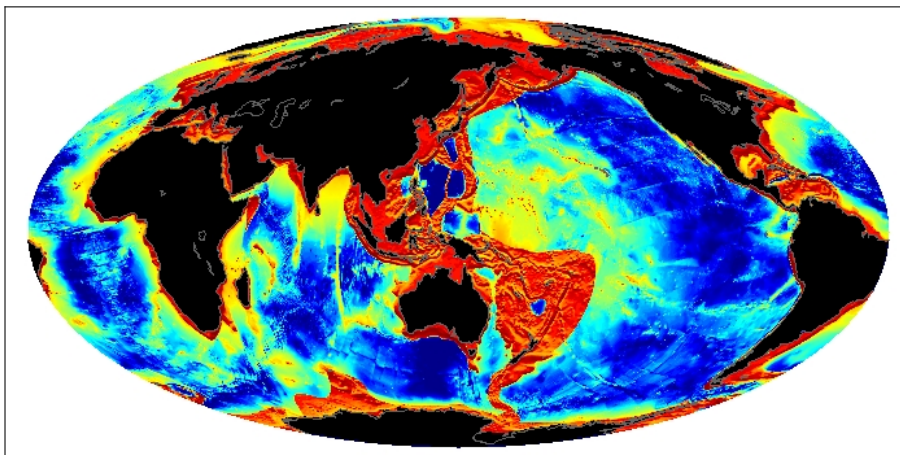Figure 2.9   Age of the ocean lithosphere.

Figure 2.10   The *residual* bathymetry obtained by subtracting the age dependant cooling from observed ocean floor bathymetry. Note the positive residual anomalies in the western Pacific and around southern Africa.