Hotspots, polar wander, Mesozoic convection and the geoid

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This paper introduced the concept of top-down control on mantle temperature and convection. Insulation of the mantle by supercontinents, and absence of subduction cooling, can raise the temperature of the underlying mantle and cause melting, uplift and true polar wandering. We now know that large plates can insulate the mantle, whether they are continental or not. There is no need to have a large continent in the Pacific in order to insulate and heat the mantle. Although much of the long-wavelength geoid originates in the deep mantle, the dynamic topography appears to originate from density variations in the upper mantle. It is now also known that upper-mantle tomography correlates with past subduction and with the locations of magmatism.

The concept of continental insulation can be extended to large-plate insulation and is particularly important when the mantle is near the melting point. A small increase or decrease in melting temperature in a mantle near the solidus can substantially change the melt content. Although the change in mantle temperature is calculated to be only a few tens of degrees in 100 Myr, this is enough to completely melt any eclogite blobs in the mantle, or to go from a small amount of melt in peridotite to tens of percent of melt. Lateral temperature gradients can also cause mantle convection by the EDGE effect, also known as Elder convection.

Hotspots, polar wander, Mesozoic convection and the geoid

Don L. Anderson

Seismological Laboratory, California Institute of Technology, Pasadena, California 91125, USA

The geoid bears little relation to present tectonic features of the Earth other than trenches and hotspots. The Mesozoic supercontinent of Pangea, however, apparently occupied a central position in the Atlantic–African geoid high. This and the equatorial Pacific geoid high contain most of the world's hotspots[1,2]. The plateaus and rises which are now in the western Pacific formed in the Pacific geoid high and this may have been the early Mesozoic–late Palaeozoic position of a large part of Asia and other fragments of the Pacific rim continents. The major global geoid highs were regions of extensive Cretaceous volcanism and may be the former sites of continental aggregations and mantle insulation and, therefore, hotter-than-normal mantle. The pent-up heat causes rifts and hotspots and results in uplift, magmatism, fragmentation and dispersal of the continents and the subsequent formation of plateaus, aseismic ridges and seamount chains which cause a global rise in sea-level. Convection in the upper mantle caused by such lateral temperature gradients is intrinsically episodic. A geoid anomaly of 50 m can be formed in about 100 Myr by continental insulation. We show here that such geoid anomalies are long-lived and may be used to remove the ambiguity in early Mesozoic–late Palaeozoic plate reconstructions. Geoid highs control the rotation axis of the Earth and, in effect, bring long-lived continental aggregations to the Equator. Many aspects of continental geology such as vertical-tectonics and episodicity of magmatism and transgressions can be explained by continental insulation.

The Earth's largest positive geoid height anomalies are associated with subduction zones and hotspots and bear no simple relationship to other present-day tectonic regions such as continents and ridges. When the subduction-related geoid highs are removed from the observed field the residual geoid shows broad highs over the central Pacific and the eastern Atlantic–African regions[1,2]. Like the total geoid, the residual geoid does not reflect the present-day distribution of continents and oceans and shows little trace of the ocean ridge system. Geoid highs, however, correlate with hotspots[1,2] and with regions of anomalously shallow ocean floor and sites of extensive Cretaceous volcanism.

The Atlantic–African geoid high extends from Iceland through the North Atlantic and Africa to the Kerguelen plateau and from the middle of the Atlantic to the Arabian penninsula and western Europe. Most of the Atlantic, Indian Ocean, African and European hotspots are inside this anomaly. Iceland, Trindade, Tristan, Kerguelen, Reunion, Afar, Eiffel and Jan Mayan form the 20-m boundary of the anomaly and seem to control its shape. The Azores, Canaries, New England seamounts, St Helena, Crozet and the African hotspots are interior to the anomaly. This, plus similar evidence in the Pacific, suggests that geoid highs may be associated with hotter-than-normal mantle.

Although the geoid high cuts across present-day ridges and continents there is a remarkable correspondence of the predrift assemblage of continents with the present location of both the geoid anomaly and hotspots (Fig. 1). Reconstruction of the mid-Mesozoic configuration of the continents[3] reveals, in addition, that most of the large shield areas of the world are contained inside the Atlantic–African geoid high. Most of the Phanerozoic platforms are also in this area, the main exceptions being the Siberian and South-East Asian platforms.

The area inside the geoid high is also characterized by higher-than-normal present elevations, for example, in Africa, the North Atlantic[4] and the Indian Ocean south-east of Africa[4]. This also holds true for the axial depth of oceanic ridges[5]. Most of the continental areas were above sea level from the Permo-Carboniferous to the Triassic, at which time there was subsidence in eastern North and South America, central and southern Africa, Europe and Arabia[6]. The widespread uplift, magmatism, breakup and initial dispersal of the Pangean landmass apparently occurred while the continents were centrally located with respect to the present geoid anomaly. The subsequent motions of the Atlantic bordering plates were largely directed away from the anomaly. This suggests that the residual geoid high, hotspots, the distribution of continents during the late Palaeozoic and early Mesozoic and their uplift and subsequent dispersal and subsidence are all related. The shields are regions of abnormally thick lithosphere. The thickest lithosphere is in eastern and central North America, northeastern South America, northwestern and central Africa and northern Siberia[7]. These regions were all within the area of Fig. 1 at 200 Myr.

The area in Fig. 1 also experienced exceptional magmatism during the Mesozoic. The great flood basalts of Siberia and South Africa were formed during the Triassic and Jurassic, possibly at the sites of the Jan Mayen and Crozet hotspots[3]. The plateau basalt provinces of South-east Greenland and Brazil were formed during the Cretaceous and early Cenozoic, possibly at the sites of the Iceland and Tristan hotspots[3]. The Walvis Ridge, the Rio Grande Rise and the plateaus in the western Indian Ocean are mainly on Mesozoic and Palaeocene crust. A large part of the Pacific also experienced extensive on- and off-ridge volcanism in the Cretaceous[8,9]. This extensive ridge and hotspot volcanism may have caused the rapid rise in sea level during the Jurassic and Cretaceous[9]. If sea level[10] can be used as a guide to the volume of the ocean basins then from the end of the Cretaceous to the end of the Oligocene was a period of less intense oceanic volcanism and subsidence of the oceanic and continental crust. Sea-level variations may therefore indicate that the thermal and geoid anomalies formed in the Palaeozoic and have attentuated since the early Mesozoic.

Much of the Pacific rim appears to be terrain which originated in the Pacific[11,12]. The possibility of a continent centrally located in the Pacific has been discussed for some time[13], but its location has been an enigma and its size uncertain. The central Pacific geoid anomaly, like the Atlantic–African anomaly, may mark the early Mesozoic or late Palaeozoic location of a large continental landmass and, later, the site of extensive Cretaceous ridge crest and midplate volcanism.

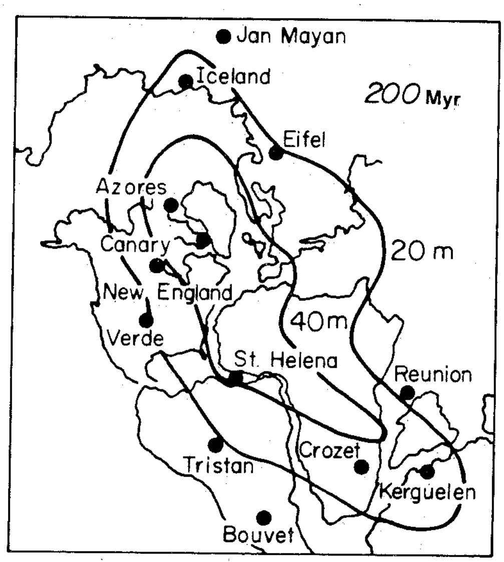

Fig. 1 The Jurassic configuration of the continents, based on Morgan's hotspot-based reconstruction[3], superposed on the Atlantic–African residual geoid high[1,2]. Note that most of the stable shield areas are inside the 20-m contour. Selected hotspots (●) are also shown.

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Palaeomagnetic data indicate that various blocks of Asia such as Kolyma, Sikhote Alin, Sino-Korea, Yangtze, South-east Asia and Japan have moved northwards by up to 32° since the Permian[11]. It is unlikely that they were in the vicinity of Australia or associated with Gondwana[11] and a central Pacific location is likely. Part or all of Alaska and northwestern North America were also far south of their present positions, relative to North America, in the Permian[12]. The same may be true of California, Mexico, Central America and other accreted terrain in the Pacific rim continents.

The central Pacific residual geoid high (>20 m) extends from Australia to the East Pacific Rise and from Hawaii to New Zealand. It encompasses most of the Pacific hotspots and is approximately antipodal to the Atlantic–African anomaly.

The western Pacific contains numerous plateaus, ridges, rises and seamounts which have been carried far to the north-west from their point of origin. The Ontong–Java plateau for example, presently on the Equator, was formed at 33–40°S in the mid-Cretaceous[14]. The Hess rise, Line Islands ridge and Necker ridge were formed in the Cretaceous on the Pacific, Farallon and Phoenix ridge-crests[8] which were, at the time, in the eastern Pacific in the vicinity of the polynesian seamount province. This ridge-crest volcanism was accompanied by extensive deep-water volcanism[8,9] and, possibly, rapid seafloor spreading[15]. The Caribbean and Bering Seas may have formed at the same location and carried northward on the Farallon and Kula plates. It is significant that the Caribbean and the anomalous regions in the Pacific have similar geophysical and geochemical characteristics[16].

The Pacific geoid high also has anomalously shallow bathymetry[4,5]. This shallow bathymetry, the 'Darwin Rise', extends from the East Pacific Rise to the north-west Pacific in the direction of plate motion, and includes the central and southwest Pacific hotspots. The extensive volcanism in the central western Pacific between ~70 and 120 Myr (refs 8, 9, 16) occurred about 60°–100° to the south-east of its present position, in the hotspot frame. This would place the event in the vicinity of the southeastern Pacific hotspots and the eastern part of the geoid anomaly. This suggests that the anomaly dates back to at least early Cretaceous. A similar thermal event in the Caribbean[17] may mean that it was also in this region in the Cretaceous, particularly since the basalts in the Caribbean are similar to those in the western Pacific[16].

Going back even further are the Triassic basalts in Wrangellia[11] of northwestern North America and the Permian greenstones in Japan[13], both of which formed in equational latitudes and subsequently drifted to the north and north-west respectively. We suggest that they also formed in the Pacific geoid high.

Plate reconstructions based on palaeomagnetism or palaeoclimatology have arbitrary longitudinal relationships between the plates. Figure 2 gives a possible late Palaeozoic reconstruction which places Africa, South America, Antarctica and Europe in the Atlantic–African geoid high and Asia in the Central Pacific geoid high. This is similar to previous reconstructions[6,18] in that North America is adjacent to western South America but Asia is placed much closer to North America. The biogeographic similarities between Asia and western North America are well known[19] and the placement of North America provides the continuity between the major land masses which is suggested by some palaeontological data. With this reconstruction Gondwanaland and Asia were the continental aggregations that caused the geoid anomalies and they brought themselves to the Equator, by the Goldreich–Toomre mechanism[20], before their breakup and dispersal. Parts of Alaska, western North America and West Antarctica may also have migrated away from the Pacific geoid high.

We propose that episodicity in continental drift, polar wander, sea-level variations and magmatism are due to the effect of thick continental lithosphere on convection in the mantle and that supercontinents 'insulated' large parts of the mantle for more than 10^8 yr. The excess heat caused uplift by thermal expansion and partial melting and, eventually, breakup and dispersal of the supercontinents. A large geoid high is generated by this expansion and, if this is the dominant feature of the geoid, the spin axis of the Earth would change so as to centre the high on the Equator[20], much as it is today. The continents stand high while they are within the thermal and geoid high and subside as they drift over cooler mantle.

The association of the Atlantic–Africa geoid high with the former position of the continents and the plateau basalt provinces with currently active hotspots suggests that Mesozoic convection patterns in the mantle still exist, as proposed by Menard.[21]. The mid-Atlantic and Atlantic–Indian ridges and the Atlantic, African and Indian ocean hotspots and the East African rift are regions where heat and material is being efficiently removed from the uppermantle in the Atlantic–African geoid high. The East Pacific rise and the Pacific hotspots are serving the same role in the Pacific geoid high. If geoid anomalies and hotspots are due to a long period of continental insulation and if these regions had higher-than-normal heat flow and magmatism for the past 100 Myr, then we might expect that these features will wane with time.

Global isostatic geoid anomalies can be written[22,23]

$$N \cong \frac{2\pi G}{g}\frac{(l+2)}{(2l+1)}\rho h \delta h$$

where G is the gravitational constant, g is the acceleration of gravity, l is degree of spherical harmonic, ρ is density, h is the depth of the anomalous region and δh is the elevation anomaly associated with the mass anomaly. For a coefficient of thermal expansion of 3×10^{-5} °C^{-1}, a temperature excess of 70 °C in the upper 500 km of the mantle gives $\delta h = 1$ km and $N = 50$ m for $l = 3$. A similar effect can be achieved by 1% melting. Some combination of heating and melting is likely.

The average heat loss through oceanic areas is 2.4 μcal cm^{-2} s^{-1} (ref. 24). Continental heat flux is about 0.6 of this in spite of the higher radioactivity of continental crust. If we assume that the oceanic heat flux is available everywhere and that there is a balance between heat production and heat loss under oceans the temperature rise under an extended stationary continent is 0.60 °C Myr^{-1} for a 500-km thick column or, alternatively, 6% melting, using a latent heat of 100 cal g^{-1}. Thus, 100 Myr of continental insulation can give the observed geoid and elevation anomalies. The continental aggregations were relatively stable for at least this long[6,18]. True polar wander is likely while the geoid anomalies are developing.

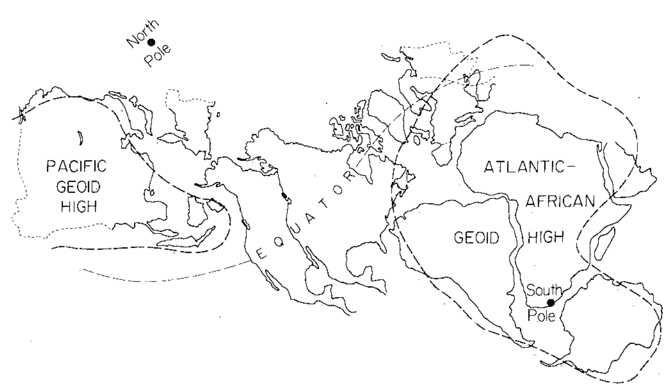

Fig. 2 Possible late Palaeozoic continental configurations relative to the current residual geoid highs and the Palaeoequator. This is similar to previous reconstructions[6,18] except that the Pacific geoid high is used to position eastern Asia. Australia and India are not shown. The dashed lines enclose regions of high elevation (>20 m) of the residual geoid[1,2]. If the geoid highs were generated under Gondwana and Asia they formed in high latitudes and were subsequently brought to the Equator by their affect on the rotation axis of the Earth. The geoid highs are currently centred on the Equator. Parts of western North America may also have been in the Pacific geoid high. This and the eastern migration of North America, relative to South America, during the Palaeozoic are indicated schematically by plotting North America in two positions. Asia is probably also fragmented at this time[11].

After the continents move off the mantle which they have been insulating the thermal and geoid anomalies decay by convection in the mantle and conduction through the newly-formed oceanic lithosphere. The rate of temperature decrease, $\dot{\theta}$, can be written

$$\dot{\theta} = \frac{-\kappa\theta}{h^2}\left(\frac{R}{R_{cr}}\right)^{1/3}$$

where κ is the thermal diffusivity, R is the Rayleigh number and R_{cr} is the critical Rayleigh number. For $R_{cr} = 10^3$, $R = 10^6$, $\kappa = 10^{-2}\ cm^2\ s^{-1}$, $\theta = 10^3 K$ and $h = 500$ km

$$\dot{\theta} = -0.12\ °C\ Myr^{-1}$$

This gives a decrease in elevation of 180 m in 100 Myr. The corresponding geoid height reduction is ~9 m. Thus, geoid anomalies caused by continental insulation are long-lived features.

Horizontal temperature gradients can drive continental drift[25-28]. The velocities decrease as the distance increases away from the heat source and as the thermal anomaly decays. The geoid high also decays. Thick continental lithosphere then insulates a new part of the mantle and the cycle repeats. Periods of rapid polar motion and continental drift follow periods of continental stability and mantle insulation.

The relatively slow motion of the continents[29] or the pole[30], or both, during the Permian and the relative stability of sea level during this period suggest that the geoid anomalies were developing at this time. Continental drift velocities[29] and sea level[10] changed rapidly during the Triassic and Jurassic. This we interpret as the start of extensive rift and hotspot magmatism and the decay of the thermal and geoid anomalies.

The rotation axis was apparently stable from ~200 to 80 Myr (ref. 3) but has shifted with respect to the hotspot reference frame for at least the past 65 Myr (ref. 31). In the framework of our model this shift would represent a growth of the equatorial region of the Atlantic–African high due to continued insulation by Africa, a decay of the South Pacific or North Atlantic portions of the highs due to extensive Cretaceous volcanism, a reconfiguration of the world's subduction zones or some combination.

It is difficult to separate true polar wander and the apparent wander due to continental drift. In the present model they are intimately related. If ridge volcanism is precluded for an extensive period of time, as seems to have been the case in the mantle under Pangea during the early Mesozoic and late Palaeozoic, the mantle will warm up and/or partially melt. In either case a geoid anomaly will develop. This anomaly will affect convection and plate motions in a manner previously suggested[25,32] and will also affect the rotation axis of the Earth[20]. As the thermal anomalies seem to be long-lived and it takes a long time to establish a new thermal regime, major shifts of the rotation axis due to this mechanism will be infrequent and gradual.

Goldreich and Toomre[20] have shown that density inhomogeneities caused by convection in the mantle will control the orientation of the spin axis and that large shifts of the pole, that is, true polar wander, are to be expected in a dynamic Earth. The present orientation of the pole apparently bears no relationship to the present distribution of continents, ridges or trenches[32]. On the other hand, the geoid bears a close relationship to the present distribution of hotspots and to the former distribution of continents and areas of extensive Cretaceous ridge and plateau volcanism.

If our conjecture about the relationship between geoid highs and the former position of continents is correct, then we would conclude that there were two large antipodal continental aggregations in the Permian. The antipodal supercontinents were presumably formed by a previous episode of continental drift which swept buoyant material away from an earlier configuration of thermal and geoid highs. Using sea level as a guide, with high sea-level indicating rifting and extensive sea floor volcanism, the supercontinents were stable from 300 to 150 Myr ago and the previous continental assemblages were dispersing between 500 and 350 Myr. The suggestions that hotspots may be a primary cause of continental breakup[3] and that they affect polar wander[1,2] are not new. What is new is the suggestion that continents cause geoid anomalies and hotspots and, indirectly, control the rotation axis of the Earth.

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Development of earthquake-induced fissures in the Main Ethiopian Rift

Laike M. Asfaw

Geophysical Observatory, Addis Ababa University, PO Box 1176, Addis Ababa, Ethiopia

A series of episodes involving land subsidence along an elongated formation of pits connected by fissures have been observed in various parts of the Main Ethiopian Rift[1-4] over the past 25 yr. Although other workers[1] have proposed a possible relationship between tectonics, subsurface drainage and subsidence no field observations have related earthquakes to such development of fissures. I present here the first observation of the development of fissures following an earthquake swarm with local magnitude, $M_L \leqslant 4$ in the Main Ethiopian Rift north of the Fentale Mountain (Fig. 1) between January and March 1981 (ref. 5). This showed that there could be a variety of developments in the evolution of earthquake-induced fissures depending on geological formation, vegetation cover and drainage; the implication on similar earlier observations is considered.

That the Afar Depression and the Main Ethiopian Rift are regions under tension is well established through geodetic