Are large oceanic depth anomalies caused by thermal perturbations?

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"All models are approximations. Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind."
George Box, statistics pioneer

ABSTRACT

The average depth and heat flow of oceanic lithosphere as functions of age are well described by cooling plate models in which old lithosphere approaches an asymptotic thermal structure, causing average depth and heat flow to flatten. However, some areas are significantly shallower or deeper than the global average for their age. One possibility is that the deviations reflect variations in lithospheric temperature structure. Another is that the deviations reflect processes including excess volcanism or dynamic effects of mantle flow. The first hypothesis assumes that the average flattening reflects thermal perturbations to halfspace cooling, so the temperature structures of areas that are unusually deep for their age reflect continued halfspace cooling and thus should have lower heat flow. Although this hypothesis predicts lower heat flow at deeper sites in old lithosphere, the deep sites are divided approximately evenly between ones with high and low heat flow. Instead, the anomalously deep sites occur primarily at passive continental margins, perhaps because of dynamic topography due to sublithospheric mantle processes and in only a few cases thinner crust formed at slow spreading rates immediately after rifting. Similarly, preferentially high heat flow is essentially not observed at anomalously shallow sites, primarily on hotspot swells, indicating that the swells do not result from hotspots significantly reheating the lithosphere. Thus, in general, neither shallow nor deep areas reflect primarily perturbed lithospheric thermal structure. Hence a plate model is more useful than a halfspace model in describing how ocean depth and heat flow vary with lithospheric age, and excluding the vast majority of the seafloor while ascribing significance to the small fraction matching the halfspace model is pointless.

INTRODUCTION

A major feature of Earth's topography is the systematic deepening of the ocean basins away from the mid-ocean ridges. This deepening and the corresponding decrease in seafloor heat flow reflect the cooling and thickening of oceanic lithosphere with increasing age as it moves away from the spreading centers where it formed.

To first order ocean depth increases as the square root of age and heat flow decreases inversely with the square root of age (Figure 1). This behavior can be described by treating the oceanic lithosphere as a conductively cooling halfspace. The primary perturbation observable in the data is the flattening of the depth and heat flow curves for ages older than about 70 Ma. The resulting average depths are significantly shallower than predicted by a halfspace model.

The flattening is thought to result from pervasive heat addition from below, making the normal thermal state of old lithosphere warmer than a cooling halfspace (Doin and Fleitout, 1996; Goutorbe, 2010; Huang and Zhong, 2005; Parsons and McKenzie, 1978; Sleep, 2011). The simplest description of the observed variation in depth and heat flow are plate models in which the addition of heat from below is modeled by an isothermal boundary condition at a depth defined as the thermal thickness of the oceanic lithosphere. Such plate models (Goutorbe and Hillier, 2013; Hasterok et al., 2011; Hillier, 2010; Parsons and Sclater, 1977; Stein and Stein, 1992) are used as reference models to characterize the average depth and heat flow as a function of age and predict them in areas where they have not been measured. Depth and heat flow data scatter about the average behavior with age. Relative to a reference model, sites whose depths or heat flow deviate significantly are traditionally termed "anomalous." Hence plate models yield smaller anomalies than halfspace models.

The causes of deviations from the average behavior remain under discussion. Hydrothermal circulation in younger crust transports heat at very shallow crustal depths, giving rise to both high and low seafloor heat flow values (Fisher et al., 2003; Stein and Stein, 1994a; Williams et al., 1974). Heat flow data in old lithosphere are less scattered, and extremely low values are rare, showing that relatively little heat is transported this way (Embley et al., 1983; Stein and Stein, 1994a; Von Herzen, 2004), except perhaps in areas of recent intraplate volcanism where such flow has been suggested (Harris and McNutt, 2007).

Other causes of scatter include effects of rapid sedimentation reducing surface heat flow (Hutchison, 1985). Variations in crustal thickness either from ridge crest processes or hotspot volcanism give rise to depth variations (Coffin and Eldholm, 1994; White et al., 2001). Some studies have explored whether the flattening of the depth-age curve could reflect the integrated effect of local excess volcanism (Hillier and Watts, 2005; Korenaga and Korenaga, 2008; Zhong et al., 2007).

The above hypotheses fall in two broad classes. In one, deviations from average behavior reflect variations in lithospheric temperature structure. In the other, the deviations reflect processes including excess volcanism or dynamic effects of mantle flow. The two classes of explanations differ in their predictions. The first predicts coupled variations in depth and heat flow with age that jointly, with some time lag for the latter, reflect the perturbed thermal state of oceanic lithosphere relative to the global average. In the second, depth and heat flow perturbations would be largely independent. For example, uplift or subsidence due to mantle flow would have little thermal effect (Stein and Stein, 1994b). Hence our goal here to examine these variations and their possible correlations.

DATA

We analyzed heat flow and depth data at sites older than 80 Ma to minimize the effects of hydrothermal circulation (Stein and Stein, 1994a; Von Herzen, 2004). We characterized site depths using depth anomalies (Müller et al., 2008) relative to the GDH1 plate model (Stein and Stein, 1992). These anomalies were determined by removing the Airy isostatic effect of the sediment from the seafloor depths and then subtracting the GDH1-predicted depth. Heat flow sites from the recent compilation of Hasterok et al. (2011) were winnowed by excluding poor quality measurement sites. Sites near trenches whose depth appeared to be perturbed by flexure were also excluded. This selection yielded 2659 sites.

Histograms of the site ages and depth anomalies are shown in Figure 2 (a and b). Heat flow data were compared to the depth anomaly in two ways. The first is via the heat flow anomaly, the measured value minus the GDH1-predicted value for that crustal age (Figure 2c). The second is via the heat flow fraction, the ratio of the measured heat flow to the GDH1-predicted value (Figure 2d). Essentially the same trends are observed for both approaches.

PERTURBATIONS

The location of the sites and oceanic depth anomalies with respect to GDH1 are shown in Figure 3. Most sites with positive depth anomalies greater than 500 m are located in areas of excess volcanism or hotspots. Most sites with depth anomalies deeper than -1000 meters are located near continental margins.

Although the sites come from different surveys and do not uniformly sample the oceans, they show general trends. For this purpose, we averaged sites within 1° squares to reduce the effect of dense heat flow surveys. As shown in Figure 4 (top), approximately equal numbers of the resulting 1158 areas have positive and negative depth and heat flow anomalies, because the GDH1 plate model seeks to characterize average behavior as a function of age.

Median and mean anomaly values are shown for the areas binned by depth in Figure 5 (top). Within the ± 1000 m range, measurements are binned every 200 m. ±(1000-2000 m) data are in 500 m bins, ±(2000-4000 m) data are in 1000 m bins, and ±(4000-7000 m) data are in a single bin.

If the depth anomalies reflect variations in lithospheric temperature structure relative to the global average, heat flow anomalies at these sites should correlate with the depth anomalies. We thus examined possible correlations between the depth and heat flow anomalies.

Deep Perturbations

A proposed thermal explanation for anomalously deep sites is that halfspace cooling continues for all ages, but localized heat sources below the lithosphere perturb the temperature structure, giving rise to shallower depths and higher heat flow than otherwise expected (Heestand and Crough, 1981). Thus the deepest seafloor at a given age would be the least perturbed from halfspace cooling and should have the lowest heat flow (Nagihara et al., 1996a). Studies starting from this view often seek to find these “true” areas by excluding the vast majority of the seafloor in search of the small fraction matching the halfspace model.

This hypothesis predicts that sites with large negative depth anomalies should have negative heat flow anomalies and thus plot in the lower left quadrant of Figure 4 (top). However, contrary to this prediction, the deep sites divide approximately evenly between those with high (upper left quadrant) and low (lower left quadrant) heat flow. Similarly, as shown in Figure 5 (top) the deep sites show no significant decrease in heat flow with decreasing depth.

Figure 4 (bottom) and Figure 5 (bottom) show the same analysis, for anomalies relative to a cooling halfspace model with the same thermal parameters. As expected, most areas are too shallow and have too-high heat flow, because of the model’s bias (Figure 1). However, the too-deep sites still divide approximately evenly between those with high (upper left quadrant) and low (lower left quadrant) heat flow.

Thus the behavior of the shallow areas (right side) favors a plate model over a halfspace model. The left side shows that areas that are deep with respect to either model are no more likely to have low heat flow, contrary to the behavior expected from the hypothesis that the deepest areas are those least affected by a thermal perturbation to halfspace cooling. Similar behavior would occur for other plate models derived from similar datasets (Goutorbe and Hillier, 2013; Hasterok, 2013), whereas ones fit to preferentially deep data would tend more toward a halfspace.

This hypothesis further predicts that areas with deep depth anomalies due to halfspace cooling would define a downward-dipping linear region in depth anomaly/heat flow anomaly space as a function of age. Figure 6 shows sites with negative depth anomalies less than 2000 m, corresponding to the yellow box in Figure 4 (top). These are the areas whose excess depth relative to a plate model could be due to halfspace cooling (Figure 1). Sites exactly following halfspace cooling would plot on the line shown. These areas do not cluster around the linear trend or show the expected age dependence, and so do not appear to reflect continued halfspace cooling at old ages.

Instead, the deepest sites reflect their tectonic settings. As shown in Figure 7, most sites with negative depth anomalies greater than -1000 m are adjacent to passive margins. Those with negative anomalies greater than -2000 m are largely in the Gulf of Mexico or on the western European margin.

A natural question is whether the deepest sites are at passive margins because of the margin-forming processes or processes acting at the continental margins today. One possibility is that slow spreading immediately following rifting caused thinner crust, as might be expected if young crust formed at the slowest spreading rates (less than 20 mm/yr full rate) is thinner due to low magma production (White et al., 2001). As shown by the yellow band in Figure 8, the Gulf of Mexico and parts of the European margin, which have depth anomalies deeper than -2000 m, formed at slow spreading rates. In contrast, NW Africa and the Bay of Bengal have deep depths but formed at higher spreading rates.

Similarly, passive margin sites with smaller negative depth anomalies, between -1000 and -2000 m, occur for a range of spreading rates. Moreover, many sites formed by slow spreading do not have deep depth anomalies. Thus, spreading rate may be a factor but cannot be the only factor.

Other regional effects, both past and present, seem likely to be acting as well (Louden et al., 2004). The Gulf of Mexico sites, which represent almost all of the very deepest depth anomalies (Figure 7b), may reflect the fact that this small thickly sedimented (~8 km) basin is surrounded by cold continental margins. It is worth noting that uncertainties in the density profile of these thick sediments make the inferred values of the depth and heat flow anomalies more uncertain (Nagihara et al., 1996b).

Shallow Perturbations

As shown in Figure 3, some areas - primarily hotspot swells - are shallow relative to the global average. The size of this effect depends on the reference model, in that using a model that predicts widespread depth anomalies will enhance those inferred at swells (King and Adam, 2014; Stein and Stein, 1993). It was thus originally suggested that thermal rejuvenation of the ocean lithosphere by hotspots could account for the shallow depths of the broad swells (Crough, 1978; 1983). If so, shallow depth anomalies would correlate with positive heat flow anomalies.

However, contrary to this prediction, the shallow sites in Figure 4 (top) divide approximately evenly between those with high (upper right quadrant) and low (lower right quadrant) heat flow. We see at most a weak preference for anomalously shallow sites having anomalously high heat flow, and thus little evidence for lithospheric reheating.

This result for our dataset, which contains sites on many swells, is consistent with results from individual swells. Detailed heat flow measurements for Hawaii (Von Herzen et al., 1982; 1989) and other swells do not support the reheating model (DeLaughter et al., 2005; Hasterok, 2013; Stein and Stein, 1993). Heat flow measured on the swells is about that expected or at most slightly high for its crustal age, implying that the swells are primarily dynamic. Within the broad swell, some of the shallowing also reflects constructional volcanism. Similarly, some of the somewhat higher heat flow measured near the younger parts of swells (Harris et al., 2000) may reflect transient cooling of igneous rocks emplaced during hotspot formation (Stein and Von Herzen, 2007).

SUMMARY

Analysis of a global data set of heat flow sites shows no preference for deep sites to have anomalously low heat flow, as would be expected if halfspace cooling continued for old ages. Similarly, preferentially high heat flow is essentially not observed at anomalously shallow sites, primarily on hotspot swells, indicating that the swells do not result from significant reheating of the lithosphere. Hence in general neither shallow nor deep areas reflect primarily perturbed lithospheric thermal structure.

Thus a significant component of the unusually deep (Whittaker et al., 2010) and unusually shallow (Cadio et al., 2012) topography may be due to dynamic processes below the lithosphere (Conrad and Husson, 2009; Forte et al, 2010; Kido and Seno, 1994), rather than thermal processes within it. The Gulf and Argentine basin sites may be deepened by mantle flow due to nearby subduction zones (Shepard et al., 2012). Mantle flow may also have effects at continental margins (Japsen et al., 2012; King, 2007; King and Anderson, 1998; Ramsay and Pysklywec, 2011; Winterbourne et al., 2009). Depth and heat flow anomalies thus can be used to explore and test models of the effects of mantle flow (Colli et al., 2014; Nerlich et al., 2013; Stein and Stein, 1994b; Winterboune et al., 2014).

Most crucially, in the spirit of the paper's epigram, both plate and halfspace models are approximations, but the plate model more usefully describes how ocean depth and heat flow vary with lithospheric age. Hence, in our view, excluding the vast majority of the seafloor while ascribing significance to the few unrepresentative areas matching the halfspace model is pointless. It is more useful to view these few sites as outliers perturbed relative to the norm, than as the norm from which almost everything else has been perturbed.

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REFERENCES:

Cadio, C., Ballmer, M.D., Panet, I., Diament, M., Ribe, N., 2012, New constraints on the origin of the Hawaiian swell from wavelet analysis of the geoid to topography ratio, Earth and Planetary Science Letters: v. 359-360, p. 40-54, doi: 10.1016/j.epsl.2012.10.006.

Coffin, M.F., and Eldholm, O., 1994, Large igneous provinces: Crustal structure, dimensions, and external consequences: Reviews of Geophysics, v. 32, p. 1-36, doi:10.1029/93RG02508.

Colli, L., Stotz, I., Bunde, H.-P., Smethurst, M., Clark, S., Iaffaldano. G., Tassara, A., Guillocheau, F., Bianchi, M.C., 2014, Rapid South Atlantic spreading changes and coeval vertical motion in surrounding continents: Evidence for temporal changes of pressure-driven upper mantle flow: Tectonics, v. 32, p. 1-18, doi:10.1002/2014TC003612.

Conrad, C.P., and Husson, L., 2009, Influence of dynamic topography on sea level and its rate of change, Lithosphere, v. 1, p. 110-120, doi: 10.1130/L32.1.

Crough, S.T., 1978, Thermal origin of mid-plate hot-spot swells: Geophysical Journal of the Royal Astronomical Society, v. 55, p. 451–469.

Crough, S.T., 1983, Hotspot swells: Annual Reviews of Earth and Planetary Sciences, v. 11, p. 165–193, doi: 10.1146/annurev.ea.11.050183.001121.

DeLaughter, J., C. A. Stein, and S. Stein, 2005, Hotspots: a view from the swells, in Foulger, G. R., J. Natland, D. C. Presnall, and D. L. Anderson (eds.), Plates, plumes, and paradigms, Geological Society of America Special Paper 388, p. 257-278, doi: 10.1130/2005.2388(16).

Doin, M.P., and Fleitout, L., 1996, Thermal evolution of the oceanic lithosphere: an alternative view: Earth and Planetary Science Letters, v. 142, p. 121-136.

Embley, R.W., Hobart, M.A., Anderson, R.N., and Abbott, D., 1983, Anomalous heatflow in the northwest Atlantic: A case for continued hydrothermal circulation in 80-m.y. crust: Journal of Geophysical Research, v. 88, p. 1067– 1074.

Fisher, A. T., Stein, C.A., Harris, R.N., Wang, K., Silver, E.A., Pfender, M., Hutnak, M., Cherkaoui, A., Bodzin, R., and Villinger, H., 2003, Abrupt thermal transition reveals hydrothermal boundary and role of seamounts within the Cocos Plate: Geophysical Research Letters, v. 30, doi 10.1029/2002GL016766.

Forte, A.M., Moucha, R., Simmons, N.A., Grand, S.P., and Mitrovica, J.X., 2010,
Deep-mantle contributions to the surface dynamics of the North American continent, Tectonophysics, v. 481, p. 3-15, doi:10.1016/j.tecto.2009.06.010.

Goutorbe, B., 2010, Combining seismologically derived temperature with heat flow and bathymetry to constrain the thermal structure of oceanic lithosphere: Earth and Planetary Science Letters, v. 295, p. 390-400, 2010, doi:10.1016/j.epsl.2010.04.013.

Goutorbe, B. and Hillier, J.K., 2013, An integration to optimally constrain the thermal structure of oceanic lithosphere: Journal of Geophysical Research, v. 118, p. 432–446, doi:10.1029/2012JB009527.

Harris, R.N., and McNutt, M.K., 2007, Heat flow on hot spot swells: Evidence for fluid flow, Journal of Geophysical Research, v. 112, 14 pp., B03407, doi:10.1029/2006JB004299, 2007.

Harris, R.N., Von Herzen, R.P., McNutt, M.K., Garven, G., and Jordahl, K., 2000, Submarine hydrogeology of the Hawaiian archipelagic apron, 1: Heat flow patterns north of Oahu and Maro Reef: Journal of Geophysical Research, v. 105, p. 21,353–21,369, doi: 10.1029/2000JB900165.

Hasterok, D., Chapman, D., and Davis, E.E., 2011, Oceanic heat flow: Implications for global heat loss: Earth and Planetary Science Letters, v. 311 p. 386–395, doi: 10.1016/j.epsl.2012.10.036.

Hasterok, D., 2013, A heat flow based cooling model for tectonic plates: Earth and Planetary Science Letters, v. 361, p. 34–43, doi: 10.1016/j.epsl.2012.10.036.

Heestand, R.L., and Crough, T., 1981, The effect of hot spots on the oceanic age-depth relation: Journal of Geophysical Research, v. 86, p. 6107 – 6114, doi:10.1029/JB086iB07p06107.

Hillier, J. K., 2010, Subsidence of ‘‘normal’’ seafloor: Observations do indicate ‘‘flattening’’: Journal of Geophysical Research, v.115, B03102, doi:10.1029/2008JB005994.

Hillier, J.K., and Watts, A.B., 2005, Relationship between depth and age in the North Pacific Ocean: Journal of Geophysical Research, v. 110, B02405, doi:10.1029/2004JB003406.

Huang, J., and Zhong, S., 2005, Sublithospheric small-scale convection and its implications for the residual topography at old ocean basins and the plate model: Journal of Geophysical Res, v. 111, B05404, doi:10.1029/2004JB003153.

Hutchison, I, 1985, The effects of sedimentation and compaction on oceanic heat flow: Geophysical J. R. Astron. Soc., v. 82, no. 3, p. 439–459, doi: 10.1111/j.1365-246X.1985.tb05145.x

Japsen, P., Bonow, J.M., Green, P.F., Cobbold, P.R., Chiossi, D., Lilletveit, R., Magnavita, L.P., and Pedreira, A., 2012, Episodic burial and exhumation in NE Brazil after opening of the South Atlantic: GSA Bulletin, v. 124, p. 800–816, doi: 10.1130/B30515.1.

Kido, M. and Seno, T., 1994, Dynamic topography compared with residual depth anomalies in oceans and implications for age-depth curves: Geophysical Research Letters, v. 21, p. 717-720.

King, S., 2007, Hotspots and edge-driven convection: Geology, v. 35, p. 223-226, doi: 10.1130/G23291A.1.

King, S.D., and Adam, C., 2014, Hotspot swells revisited, Physics of the Earth and Planetary Interiors, v. 235, p. 66–83, doi:10.1016/j.pepi.2014.07.006.

King, S.D., and Anderson, D.L., 1998, Edge-driven convection: Earth and Planetary Science Letters, v. 160, p. 289–296.

Korenaga, T., and Korenaga, J., 2008, Subsidence of normal oceanic lithosphere, apparent thermal expansivity, and seafloor flattening: Earth and Planetary Science Letters, v. 268, no. 1–2, p. 41–51.

Louden, K., Tucholke, B.E., and, Oakey, G.N., 2004, Regional anomalies of sediment thickness, basement depth and isostatic crustal thickness in the North Atlantic Ocean: Earth and Planetary Science Letters, v. 224, no. 1–2, p. 193–211.

Müller, R. D., Sdrolias, M., Gaina, C., and Roest, W.R., 2008, Age, spreading rates and spreading asymmetry of the world's ocean crust: Geochem. Geophysical Geosyst., v. 9, Q04006, doi:10.1029/2007GC001743.

Nagihara, S., Lister, C.R.B., and Sclater, J.G., 1996a, Reheating of old oceanic lithosphere: deductions from observations: Earth and Planetary Science Letters, v. 139, no. 1–2, p. 91–104.

Nagihara, S., Sclater, J.G., Phillips, J.D., Behrens, E.W., Lewis, T., Lawver, L.A., Nakamura, Y., Garcia-Abdeslem, J., and Maxwell, A.E., 1996b, Heat flow in the western abyssal plain of the Gulf of Mexico: Implications for thermal evolution of the old oceanic lithosphere: Journal of Geophysical Research, v. 101, p. 2895– 2913.

Nerlich, R., Clark, S. R. , and Bunge, H.-P., 2013, The Scotia Sea gateway: No outlet for Pacific mantle: Tectonophysics, v. 604, p. 41–50, doi:10.1016/j.tecto.2012.08.023.

Parsons, B., and McKenzie, D. P., 1978, Mantle convection and the thermal structure of the plates, Journal of Geophysical Research, v. 83, p. 4485-4496.

Parsons, B., and Sclater, J.G., 1977, An analysis of the variation of ocean floor bathymetry and heat flow with age: Journal of Geophysical Research, v. 82, p. 803-827.

Ramsay, T., and Pysklywec, R., 2011, Anomalous bathymetry, 3D edge driven convection, and dynamic topography at the western Atlantic passive margin: Journal of Geodynamics, v. 52, p. 45-56, doi:10.1016/j.jog.2010.11.008.

Shephard, G.E., Liu, L., Müller, R.D., Gurnis, M., 2012, Dynamic topography and anomalously negative residual depth of the Argentine Basin: Gondwana Research, v. 22, p. 658–663, doi:10.1016/j.gr.2011.12.005.

Sleep, N.H., 2011, Small-scale convection beneath oceans and continents: Chinese Science Bulletin, v. 56, no. 3, p. 1292-1317, doi: 10.1007/s11434-011-4435-x.

Stein, C., and Stein, S., 1992, A model for the global variation in oceanic depth and heat flow with lithospheric age: Nature, v. 359, p. 123-128.

Stein, C. and Stein, S., 1993, Constraints on Pacific midplate swells from global depth-age and heat flow-age models: in Pringle, M., W. Sager, W. Sliter, and S. Stein (eds), The Mesozoic Pacific, Geophysical Monograph 76, 53-76, American Geophysical Union.

Stein, C., and Stein, S., 1994a, Constraints on hydrothermal flux through the oceanic lithosphere from global heat flow: Journal of Geophysical Research, v. 99, p. 3081-3095.

Stein, C. and Stein, S., 1994b, Comparison of plate and asthenospheric flow models for the evolution of oceanic lithosphere: Geophysical Research Letters, v. 21, p. 709-712.

Stein, C.A., and Von Herzen, R. P., 2007, Potential effects of hydrothermal circulation and magmatism on heat flow at hotspot swells: in Foulger, G. R., and Jurdy, D. M. (eds.), Plates, Plumes, and Planetary Processes, Geol. Soc. Am. Sp. Paper. 430, p. 261-274, doi: 10.1130/2007.2430(13).

Von Herzen, R.P., 2004. Geothermal evidence for continuing hydrothermal circulation in older (60 m.y.) ocean crust, in Davis, E.E., and Elderfield, E.H., eds., Hydrogeology of the oceanic lithosphere: Cambridge, Cambridge University Press, p. 414–447.

Von Herzen, R.P., Detrick, R.S., Crough, S.T., Epp, D., and Fehn, U., 1982, Thermal origin of the Hawaiian swell: Heat flow evidence and thermal models: Journal of Geophysical Research, v. 87, p. 6711–6723.

Von Herzen, R.P., Cordery, M.J., Detrick, R.S., and Fang, C., 1989, Heat flow and the thermal origin of hotspot swells: The Hawaiian swell revisited: Journal of Geophysical Research, v. 94, p. 13,783–13,799.

White, R.S., Minshull, T.A., Bickle, M.J., and Robinson, C.J., 2001, Melt generation at very slow-spreading oceanic ridges: constraints from geochemical and geophysical data: J. Petrology, v. 42, no. 6, p. 1171-1196, doi: 10.1093/petrology/42.6.1171.

Whittaker, J.M., Müller, R.D., and Gurnis, M., 2010, Development of the Australian-Antarctic depth anomaly: Geochemistry, Geophysics, Geosystems, v. 1, Q110066, doi:10.1029/2010GC003276.

Williams, D. L., Von Herzen, R. P., Sclater, J. G., and Anderson, R. N., 1974, The Galapagos spreading centre: lithospheric cooling and hydrothermal circulation: Geophysical J. R. Astron. Soc., v. 38, p. 587-608.

Winterbourne, J., Crosby, A., and White, N., 2009, Depth, age and dynamic topography of oceanic lithosphere beneath heavily sedimented Atlantic margins: Earth and Planetary Science Letters, v. 287, no. 1–2, p. 137–151.

Winterbourne, J., N. White, and A. Crosby, 2014, Accurate measurements of residual topography from the oceanic realm: Tectonics, v. 33, p. 982–1015, doi:10.1002/2013TC003372.

Zhong, S., Ritzwoller, M., Shapiro, N., Landuyt, W., Huang, J., and Wessel, P., 2007, Bathymetry of the Pacific plate and its implications for thermal evolution of the lithosphere and mantle dynamics: Journal of Geophysical Research, v. 112, B06412, doi:10.1029/2006JB004628.

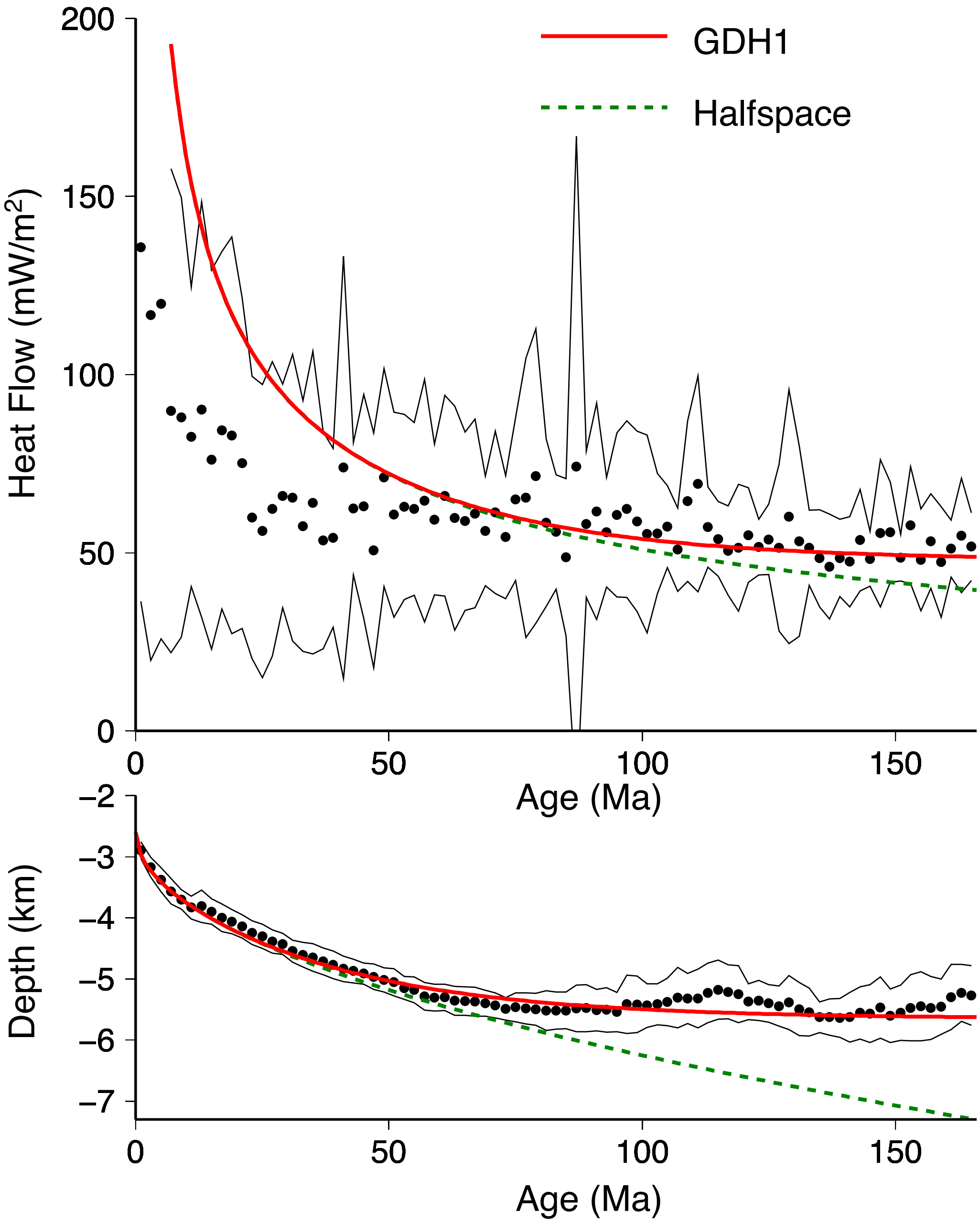

Figure 1. Data and models for (top) heat flow and (bottom) depths as a function of age. The average depth increases and the average heat flow decreases with crustal age. The scatter of data about the means primarily reflects spatial variability due to secondary processes, rather than errors of measurement. Closed circles are two-million year means. The thin lines are the one standard deviation values. Reference curves are for the Stein and Stein (1992) GDH1 plate model (thick red line) and a halfspace model (dashed green line) with the same thermal parameters.

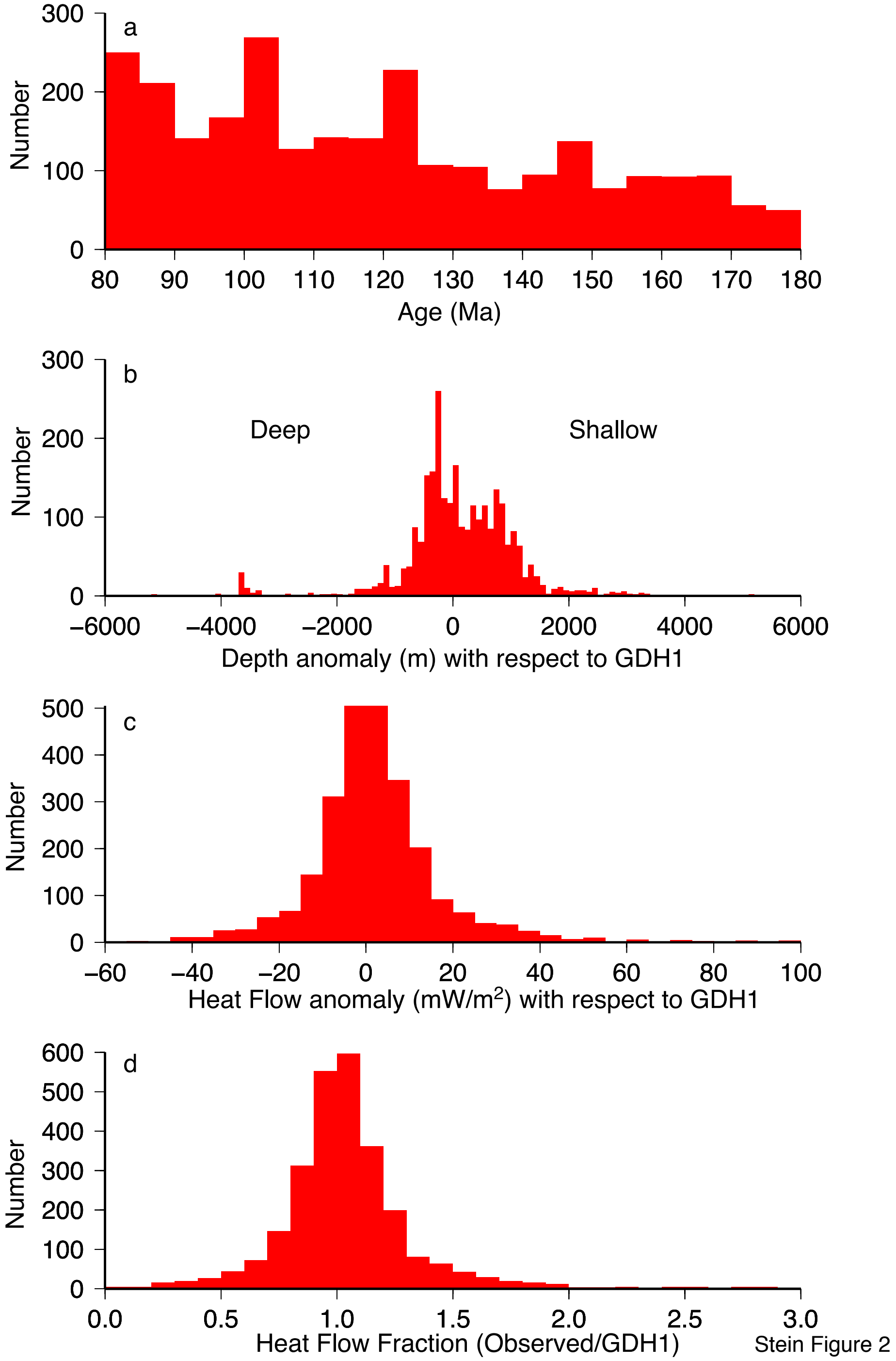

Figure 2. Histograms for the data set used in this paper. a) Number of heat flow sites binned in 5 million year age intervals. b) Depth anomalies at these sites with respect to the GDH1 reference model binned in 100 m intervals. c) Heat flow anomalies at these sites binned in 5 mW/m^2 intervals. Thirteen values greater than 160 mW/m^2 are not shown. d) Heat flow fraction values binned in 0.1 intervals. Eight values greater than 3.0 are not shown.

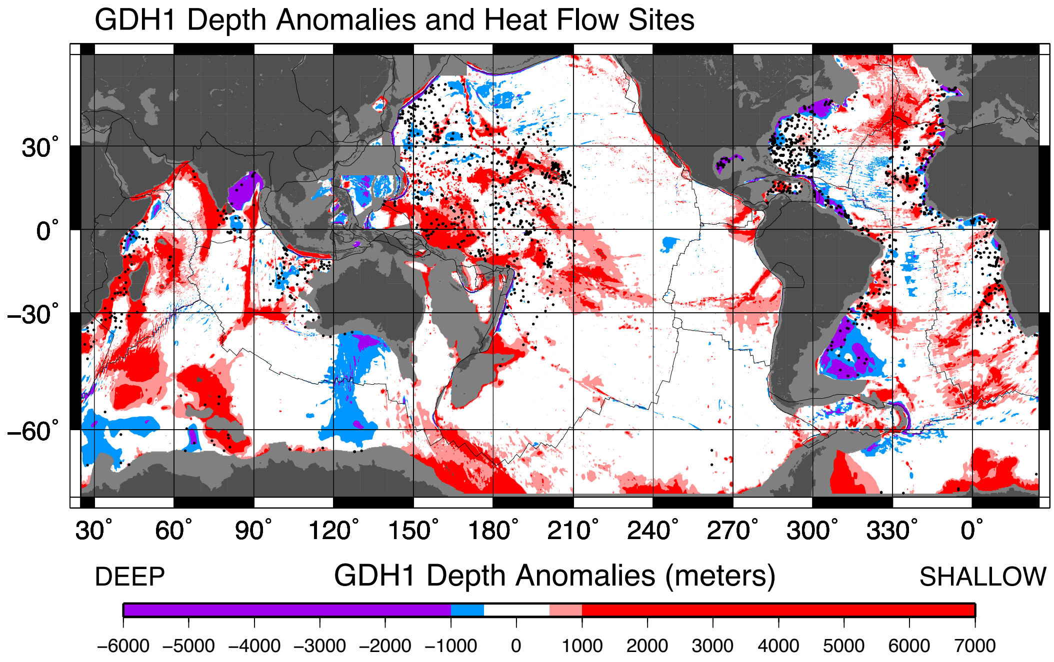

Figure 3. Seafloor depth anomalies (Müller et al., 2008). Dots show locations of heat flow sites used in this study.

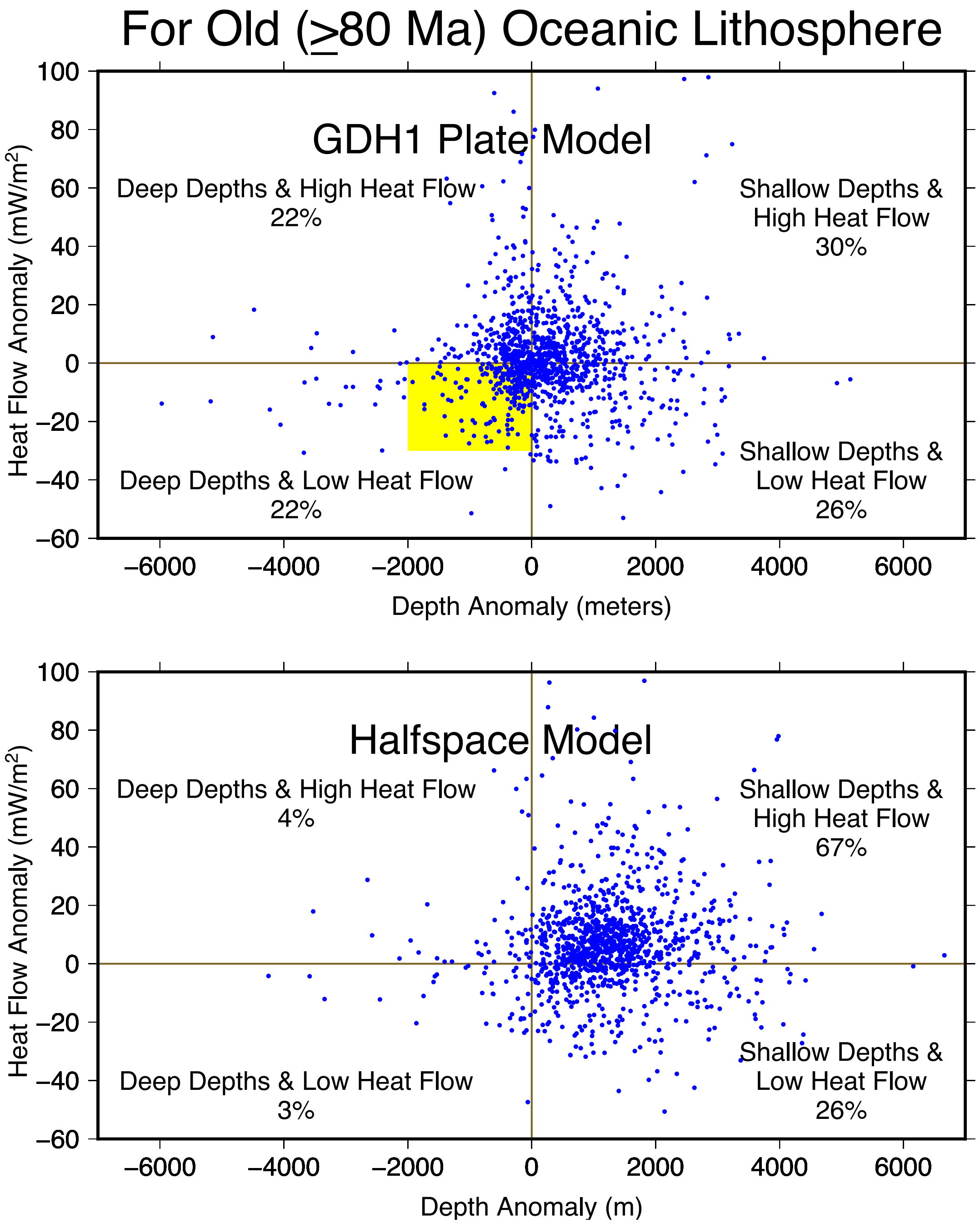

Figure 4. *Top:* Comparison of depth and heat flow anomalies with respect to the GDH1 reference model at areas in Figure 3. There is little evidence for thermal perturbations that would cause deep areas to have preferentially low heat flow, or shallow areas to have preferentially high heat flow. Moreover, the deep areas with low heat flow (yellow box) do not show behavior expected for halfspace cooling, as discussed in Figure 6. Eight measurements with heat flow fractions greater than 3 are not shown. *Bottom:* Same analysis for a cooling halfspace model with the same thermal parameters. Most areas are too shallow and have too-high heat flow, because of the model's bias (Figure 1).

However, the too-deep sites still divide approximately evenly between those with high (upper left quadrant) and low (lower left quadrant) heat flow.

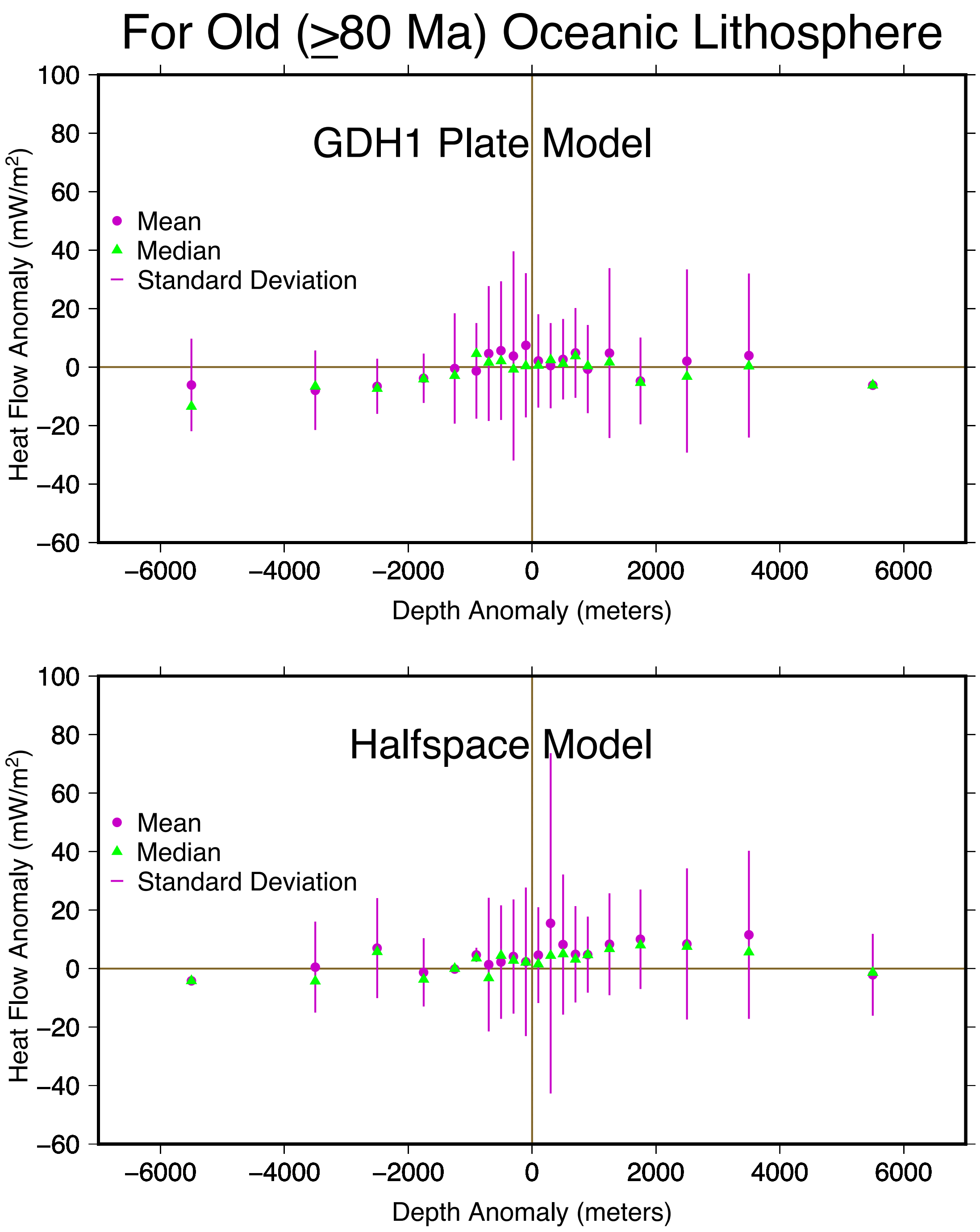

Figure 5. Binned area values in Figure 4. The deep areas show no significant decrease in heat flow with decreasing depth.

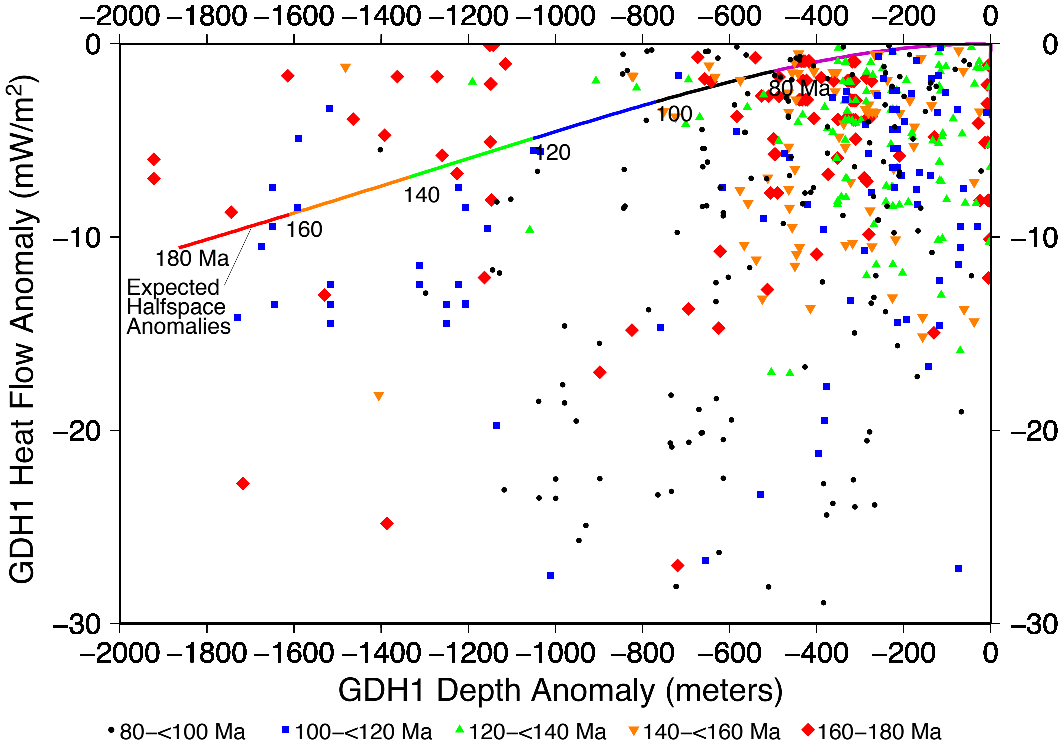

Figure 6. Comparison of areas with negative depth and heat flow anomalies whose excess depth relative to a plate model could be due to halfspace cooling (yellow box in Figure 4, top). These areas do not cluster around the linear trend for halfspace cooling or show the expected age dependence, and so do not appear to reflect continued halfspace cooling at old ages.

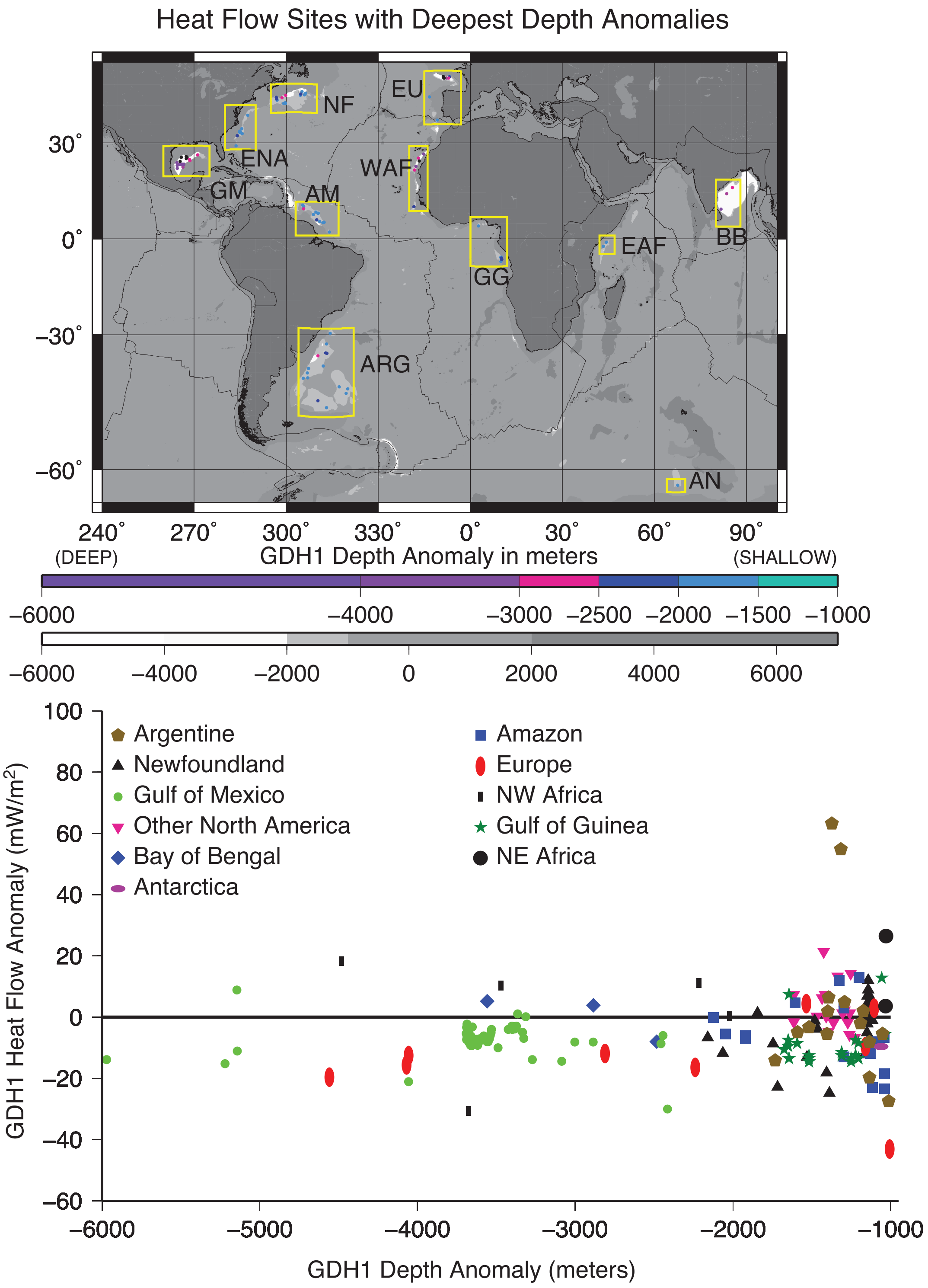

Figure 7. (top) Location of heat flow areas with depth anomalies deeper than 1000 m. (bottom) Heat flow anomalies compared to depth anomalies for areas with anomalies deeper than -1000 m.

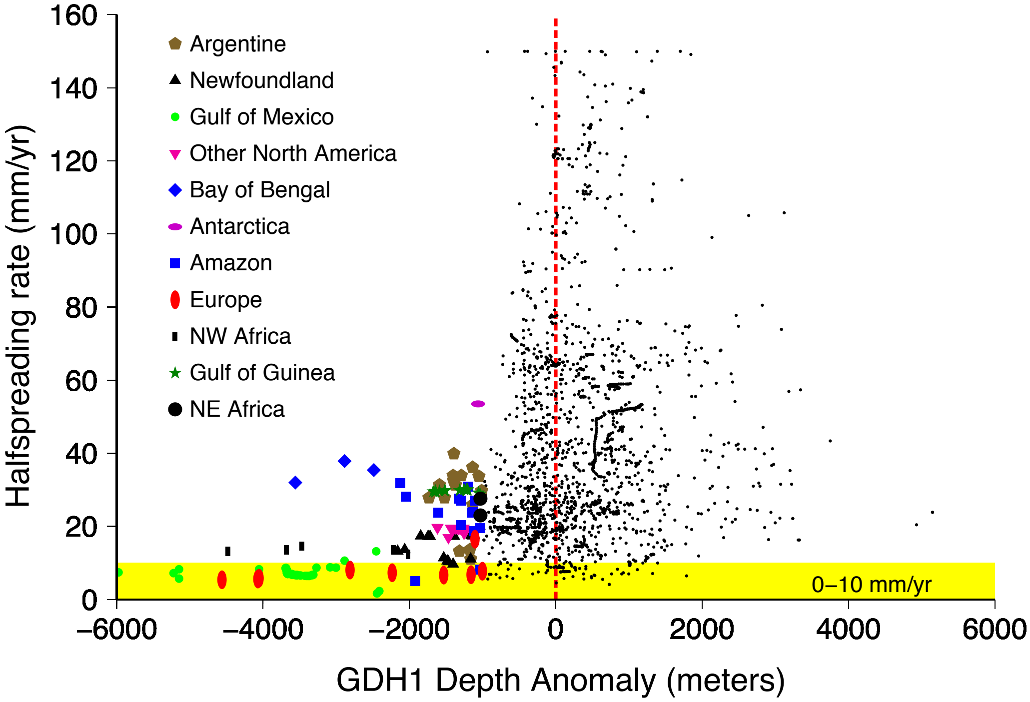

Figure 8. Depth anomaly versus half spreading rates (Müller et al., 2008) for the heat flow areas. Passive margins ones are identified and dots show others.