Comments on 'Comparison of Long-Wavelength Residual Elevation and Free Air Gravity Anomalies in the North Atlantic and Possible Implications for the Thickness of the Lithospheric Plate' by John G. Sclater, Lawrence A. Lawver, and Barry Parsons

C. R. B. LISTER

GL03725

Department of Geophysics and Department of Oceanography, University of Washington, Seattle, Washington 98195

E. E. DAVIS

Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

In their paper, *Sclater et al.* [1975] have extended depth versus age and heat flow versus age relationships for ocean floor from 80 m.y. B.P. to roughly 150 m.y. B.P. From their plots they deduce that the lithosphere is bounded at a fixed depth, even though reasonable fits to the topographic and heat flow data require two quite different lithosphere thicknesses. We would like to point out that their data perusal is not complete and that although we do not claim to make a complete analysis, we can adduce data that could lead to the opposite conclusion: that there is no apparent lower boundary or major new phase change in lithosphere out to an age of 150 m.y. B.P. With the data set as incomplete as it is, however, we would emphasize that neither conclusion can confidently be drawn. Only with more refined heat flow and topographic data can one test adherence to the simple boundary layer model or deviations from it due to convective heat supply from below, radioactive heating in the lithosphere itself, or historical parameter changes.

Davis and Lister [1974] showed that a simple boundary layer model of lithosphere thickening by cooling predicted a linear depth versus square root of age plot for the sea floor. We showed also that data presented by *Sclater et al.* [1971] follow such a linear relationship by major ocean to ages as great as 80 m.y. B.P., within the standard errors of the means. Very shortly thereafter (by submission date), *Yoshii* [1973] extended the empirical relationship, this time by using residual gravity anomaly (RGA) versus $(\mathrm{age})^{1/2}$ and found that his RGA is approximately proportional to the square root of age out to 150 m.y. B.P. The RGA takes into account the effects of sediment cover and of varying crustal thickness on the depth of the sea floor: it is defined as

$$\mathrm{RGA} = \mathrm{FAA} + 2\pi G \sum_i h_i(\rho_m - \rho_i)$$

where FAA is free air anomaly, ρ_m is upper mantle density, and h_i is the thickness of the ith layer whose density is ρ_i. The latter two values were obtained from seismic refraction data and from the *Nafe and Drake* [1957] empirical velocity-density law; ρ_m was taken as 3.4 g cm^{-3} [*Yoshii*, 1973]. The RGA is thus a crustal Bouguer anomaly that removes the effect of any compensated crustal topography or uncompensated mantle bulges and responds directly to changes in mantle density. Yoshii's data are replotted as RGA versus $(\mathrm{age})^{1/2}$ in Figure 1, and the points continue to lower beyond 100 m.y. B.P. even though the scatter is large. It is encouraging that the data lie close to the RGA line (included in Figure 1) that results from a topographic slope of 0.35 km/(m.y.)$^{1/2}$ and Yoshii's ρ_m, in good agreement with the topographic slope determined for the North Pacific [*Davis and Lister*, 1974]. The four oldest points lie closer to this line than they would to a flattening curve, like that suggested by *Sclater et al.* [1975]. It is unfortunate that the three points older than 100 m.y. B.P. have been derived from three anomalous regions: the Emperor seamounts, Japan trench, and Shatsky rise. Nevertheless, if correctly determined, the RGA should still reflect the true lithospheric thickness.

The three depth points that *Sclater et al.* [1975] add to those of *Sclater et al.* [1971] are all taken from one area immediately southwest of the Hawaiian ridge. Datable magnetic anomalies are observed in a basin of relatively smooth sea floor between the Hawaiian ridge and the mid-Pacific mountains [*Chase et al.*, 1971]. The three points are all of the same depth within their standard errors, and the middle point is the deepest, as would be expected from a basin. The corresponding region northeast of the Hawaiian ridge contains the Hawaiian arch, a sea floor bulge of about 400 m. The mid-Pacific mountains are associated with a general sea floor rise of at least 200 m relative to other local depths, and the width of the zone of influence of their cause is not known. One published seismic reflection profile from the area [*Raff*, 1973] does not show convincing basement signatures, either near the mid-Pacific mountains or near Hawaii. Thus the available evidence suggests that *Sclater et al.*'s [1975] data points could be substantially deeper than the superficial depth readings indicate and vindicates the section-correcting method of *Yoshii* [1973].

Regions of old sea floor do exist which are less proximate to obviously disturbed topography, although there is insufficient information on sediment thickness and crustal structure in these areas to calculate a fully corrected RGA. We cite two examples in the northeast Pacific basin which were surveyed and sampled by DSDP leg 20 [*Heezen and Jones*, 1973]. They are the regions around sites 196 and 199. Both areas are topographically smooth and distant from obvious major topographic disturbances. Only a minimum estimate can be placed on the sediment thickness, as basement was not reached by drilling, and reflection profiling in the areas was not able to produce a convincing basement reflection. One of the best records in either area was taken by *Davies* [1973] across site 196. The deepest reflector visible regionally lies beneath 0.8 s of sediment; with values of sediment velocity and density sampled from site 196, a regional basement depth of 6650 m was obtained and corrected for sediment loading. By using an 'average' crustal section [e.g., *Raitt*, 1963] and assuming zero free air gravity anomaly, an RGA of 820 mGal results. The age of the area is not well determined; a rough estimate of 150 m.y. B.P. was obtained by extrapolating from Mesozoic anomalies in the area, described by *Lancelot and Larson* [1975].

The region surveyed around site 199 in the Caroline abyssal plain is older in age than that near site 196, and its age is correspondingly less well determined; an estimate of 170 m.y. B.P. will be used here. Very little of the total sediment section was penetrated by the seismic reflection profiling in the area [*Heezen and Jones*, 1973], but the thickness is likely to be at least as great as that at site 196. The resulting regional sediment-corrected basement depth here is 6580 m, and the RGA is estimated as 814 mGal.

These points have been plotted with those of *Yoshii* [1973] in Figure 1. They may be extreme cases and are not a fair sample of all the data available, but with the points of Yoshii, they agree well with a model of the lithosphere that continues to thicken and subside well beyond the age of 100 m.y. B.P. A more thorough investigation of old ocean crustal depths needs to be made to resolve the problem, and particular attention must be paid to the removal of sediment thickness by a physically correct method such as that of *Yoshii* [1973].

The problem of the heat flow data is more complex than the dispute over topographic data points. We have replotted the data from *Sclater and Francheteau* [1970] against $1/(\text{age})^{1/2}$, as did *Sclater et al.* [1975], but now the original population standard deviations are shown rather than the standard error of the means (Figure 2). This gives a measure of the heat flow variability as a function of age that is independent of sample size. Scatter is large in samples from crust as old as 100 m.y.; this scatter is likely to be caused by circulation of seawater in the crust, and if any circulation is open to the sea, a bias will result in the measured values. Crustal circulation should decrease with age, and the decreasing trend in scatter suggests this. The possibility of open circulation should also decrease with age due to the accumulation of an impermeable sediment cover, so that, in general, measurements from the oldest ocean crust should represent the total heat flux most reliably.

The bias due to hydrothermal leakage of heat from the young crust to the sea can be removed effectively by selecting heat flow sites in well-sedimented areas where open groundwater circulation is not significant. Average heat flow from two young but well-sedimented areas, one on the Juan de Fuca ridge flank [*Lister*, 1972] and one on the Explorer ridge flank [*Davis and Lister*, 1976], is plotted in Figure 2.

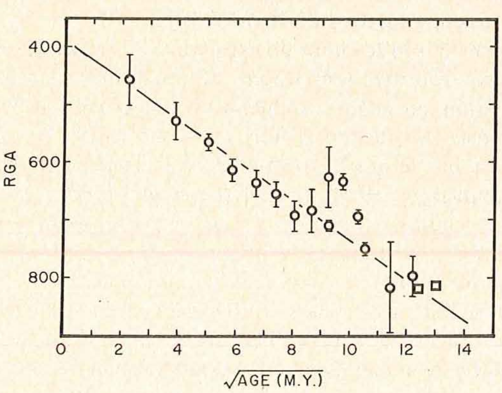

Fig. 1. Residual gravity anomaly (RGA) plotted against the square root of age. Points are from *Yoshii* [1973] (circles) and from estimates discussed in the text (squares). The line is the anomaly expected from the $t^{1/2}$ topography line of the North Pacific in *Davis and Lister* [1974].

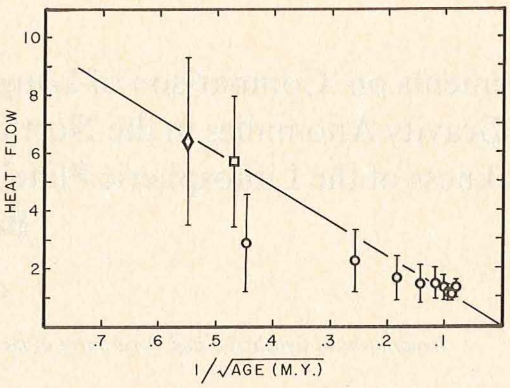

Fig. 2. Sea floor heat flow, in HFU, plotted against $1/(\text{age})^{1/2}$. Points are from *Sclater and Francheteau* [1970] (circles), *Lister* [1972] (diamonds), and *Davis and Lister* [1976] (squares). Standard deviations are plotted to show heat flow variability as a function of age. A line can be drawn through points which are most likely to represent the total geothermal flux and through the origin, which would agree with a simple boundary layer cooling model for the oceanic lithosphere.

The bulk of the data is not on the straight line through the origin that would be expected from a boundary layer cooling model in the absence of significant surficial radioactive heat generation. However, the group of values that is likely to represent the total geothermal flux does follow such a heat flow versus age trend; these values are fitted fairly well, as suggested by *Lister* [1975], by

$$H_F = 12.0/(\text{age})^{1/2}$$

where H_F is heat flow in HFU (1 HFU = 1 $\mu\text{cal cm}^{-2}\text{ s}^{-1}$) and age is in million years. This line is shown in Figure 2.

Sclater et al.'s [1975] final point, that the absolute value of heat flow reached in the oldest lithosphere is too high to agree with the 'model' of *Davis and Lister* [1974], is simply not valid. The 'square root law of ridge topography' is not a 'model' in the sense of specifying parameters: it determines a parameter 'kernel,' $[2/(\pi)^{1/2}]\ \alpha_{\text{eff}} T_1(\kappa)^{1/2}$, that differs over various parts of the global spreading system. The values of the individual parameters quoted in the paper were selected as 'reasonable' without reference to the absolute level of oceanic heat flow. If that is known, another parameter kernel becomes available: $[1/(\pi)^{1/2}]\rho c_p T_1(\kappa)^{1/2}$ (from the slope of heat flow versus $1/(\text{age})^{1/2}$), and the ratio of these allows one to determine $\rho c_p/\alpha_{\text{eff}}$ and nothing more. The line drawn in Figure 2 would suggest a rather high value for this ratio, but one within the range of possible rock parameters, especially as these are not known for high temperatures. It is also important to remember that the relatively low heat flows from the oldest lithosphere may contain a significant component of heat generated by the radioactivity within the surface rocks themselves. Correction for this would reduce the apparent ratio $\rho c_p/\alpha_{\text{eff}}$, and so it will be valuable to obtain realistic estimates of the heat production in upper mantle material.

Just as is the case with the topographic data, a distinction between bounded and unbounded lithospheric cooling cannot as yet be made by means of the heat flow data. Only with an accurate and unbiased estimate of the oceanic heat flow for a wide range of ages may the problem be resolved. In old ocean basins, absolute accuracy is of extreme importance, since the heat flow levels are low and the age gradients of heat flow are extremely small.

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