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Subsidence of “normal” seafloor: Observations do indicate “flattening”

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[1] Seafloor topography is a key observational constraint upon the evolution of the oceanic lithosphere. Specifically, plots of oceanic depth (z) versus crustal age (t) for “normal” seafloor are well explained by depth-age predictions of thermal contraction models such as the half-space and cooling plate model. Old seafloor ($t > \sim 70$ Ma) shallower than that predicted by half-space cooling (i.e., $z \propto \sqrt{t}$), or “flattening,” is a key but debated discriminator between the two models. Korenaga and Korenaga (2008) in a recent paper find normal seafloor depths of all ages to be consistent with a $z \propto \sqrt{t}$ model, thus supporting a cooling half-space model for all ages of seafloor. Upon reevaluation, however, the mean depths of their “normal” seafloor flatten at ages > 70 Ma, e.g., by 723.2 ± 0.5 m (1 standard error) for $t > 110$ Ma. This observed inconsistency with the $z \propto \sqrt{t}$ model is statistically significant ($> 99.9\%$) and remains robust ($> 94\%$) even if the number of effective independent depth observations is argued to be low (e.g., $n = 10$). So, if any statistically significant conclusion can be drawn from the observed depths of rare old normal seafloor, it is that old seafloor flattens, which is incompatible with the cooling half-space model applying to all ages of seafloor but does not preclude a cooling-plate style approximation to lithospheric evolution.

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1. Introduction

[2] Plots of oceanic depth (z) versus crustal age (t) for “normal” seafloor are well explained by depth-age predictions of thermal contraction models such as the cooling half-space model [Davis and Lister, 1974] and cooling plate model [Langseth et al., 1966; McKenzie, 1967]. The key discriminator between these models is the observation, first made in the North Atlantic and North Pacific oceans [Parsons and Sclater, 1977], that the water-loaded depth of old “normal” seafloor (presumed to equate to old lithosphere) is shallower than predicted by the cooling half-space model, often abbreviated to “flattening.” There has been protracted debate [e.g., Schroeder, 1984; Marty and Cazenave, 1989; Stein and Stein, 1993; Carlson and Johnson, 1994; Hillier and Watts, 2005; Crosby et al., 2006; Korenaga and Korenaga, 2008] about the existence, form, and interpretation of flattening because (1) lithospheric evolution is an important geological question, (2) complications exist in rigorously and quantitatively defining “normal” seafloor, and (3) unperturbed “normal” seafloor becomes increasingly rare as seafloor ages, so that the significance of conclusions drawn from this relatively small remnant can be questioned.

[3] “Normal” must be appropriate to the evolution model, i.e., the data under examination must be composed of depths that result from the processes included in the model and those alone. For instance, Smith and Sandwell [1997] examined a model whereby flattening was achieved by using stochastic reheating events, and thus retained hot spot swells as “normal” depths but excluded seamounts, oceanic plateaus, oceanic trenches, and flexural bulges. For the cooling plate model, hot spot swells are also excluded. For both cases, sediments are backstripped [e.g., Schroeder, 1984]. Methods for excluding features are various and may vary by type of feature, e.g., manually delimiting features representing abnormal [e.g., Smith and Sandwell, 1997; Crosby et al., 2006; Zhong et al., 2007], using gravity to identify mantle-derived dynamic topography [Crosby et al., 2006], using statistics [Renkin and Sclater, 1988], using algorithms [Hillier and Watts, 2004, 2005], and using proximity to seamounts [e.g., Heestand and Crough, 1981; Zhong et al., 2007; Korenaga and Korenaga, 2008]. The results of these methods, however, do not necessarily agree, fuelling the debate.

[4] Korenaga and Korenaga [2008] globally estimated “normal” seafloor depths using two different criteria, the results of which were in good accord with each other. Then, with a formalized statistical approach and bootstrap method, they estimated best fitting $z \propto \sqrt{t}$ models for the “normal” seafloor (0–70 Ma) and 68% “confidence zones” associated with the models. These estimates were extrapolated to $t > 70$ Ma. The majority of z - t data (all t) fall within this confidence zone of about ± 500 m from the model.

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Korenaga and Korenaga [2008] state that “age-depth data falling within these bounds can be considered as consistent with half-space cooling,” and thus, “normal seafloor following [the] half-space cooling [model] does exist for almost all ages.” For this argument, however, the sample of n observed depths in Δt must be consistent with the model as a group, for which even the majority of individual data points falling within confidence zones is not sufficient. Inspection of their z versus t scatterplots of normal seafloor illustrates this, showing a majority of the (z, t) data nearer to the shallower confidence limit, suggesting flattening. Thus, the first statement of *Korenaga and Korenaga* [2008] is not correct, so neither is the second. To justify this assertion, this paper reexamines this aspect of the interpretation of *Korenaga and Korenaga* [2008] using their definition and processing of normal seafloor for consistency. The methods, model, and data are briefly stated then their interpretation discussed. Specifically, the question assessed is “Is flattening (or otherwise) indicated by depth observations of ‘normal’ seafloor?” The related, but distinct, question “Is any flattening (or otherwise) indicated by the observations statistically significant?” is also pertinent to the interpretation of *Korenaga and Korenaga* [2008]. It is, therefore, discussed where relevant. A further question, “What are the geophysical implications of any flattening (or otherwise) observed?,” relates primarily to the selection criteria for “normal” seafloor and is not focused upon.

2. Method and Data

[5] To best facilitate a comparison of interpretations, the methods and data used here are as given by *Korenaga and Korenaga* [2008]. Details are given in the following.

[6] *Korenaga and Korenaga* [2008] analyzed “normal” seafloor by excluding abnormal seafloor and perturbed areas around it. Abnormal seafloor was defined as that area, where the age of igneous basement can be estimated [*Muller and Roest*, 1997] and depths are >1 km shallower than the predictions of plate model GDH1 [*Stein and Stein*, 1992] after a 150 km wide Gaussian filter is applied. Perturbed surrounding areas are excluded either according to a “correlation criterion” or a “distance criterion.” In the former, if distance from abnormal seafloor versus residual depth within a 100 km radius plot with a gradient of <-1 m km⁻¹ (ordinary least squares (OLSs) fitting), they are excluded. Radii of 50–150 km were tested and results found to have little sensitivity to this variable. In the latter, data <300 km from abnormal seafloor are excluded [e.g., *Heestand and Crough*, 1981]. For both cases, areas with >2 km of sediment cover [*Divins*, 2006] were excluded, and elsewhere sediment loading was corrected for as *Schroeder* [1984]. Results were found to be insensitive to the choice of reference cooling model in both cases.

[7] Out of the two criteria fewest normal seafloor depths defined by the “distance criterion” plot above the confidence limits [*Korenaga and Korenaga*, 2008, Figure 5]. Since these data are, therefore, the least likely to contain flattening, i.e., support the case for evidence of normal seafloor subsiding as $z \propto \sqrt{t}$ at almost all t presented in that paper, this method is replicated here.

[8] As in *Korenaga and Korenaga* [2008], the bathymetry used is that of *Smith and Sandwell* [1997], sediment

thickness is that of *Divins* [2006], sediment correction equation that of *Schroeder* [1984], and the plate model then used to abnormal seafloor is that of *Stein and Stein* [1992]. The sediment grid (already much interpolated in its construction) was resampled at $2' \times 2'$ to match the bathymetry. In both methods, the region analyzed was 0° – 360° longitude and $\pm 72^\circ$ latitude, although areas without either age or sediment thickness data were masked and not used. Here, GMT [*Wessel and Smith*, 1998] was used to perform the Gaussian filter (grdfilter) and distance evaluation (grdselect). As of *Korenaga and Korenaga* [2008], z - t data are weighted equally despite representing different areas (km²).

3. Results

[9] Figure 1a shows z - t data for “normal” seafloor (gray dots). The confidence zone corresponding to 68% certainty (about ± 500 m) is shown as the thin black lines [*Korenaga and Korenaga*, 2008]. This replicates *Korenaga and Korenaga* [2008, Figure 5b]. The cooling half-space, i.e., $z \propto \sqrt{t}$, model best fitting the young data (0–70 Ma), according to the statistical description and bootstrap analysis of *Korenaga and Korenaga* [2008] is also shown (bold line, $z = 2648 + 336\sqrt{t}$).

[10] For comparison, Figure 1b shows that same z - t data. The bold gray curve is the running mean in 1 Myr bins surrounded by confidence intervals of two standard deviations ($\pm 2s_x$, thin gray lines). The bold line ($z = 2668 + 323\sqrt{t}$) is a simple OLS fit to the 1 Myr means of 0–70 Ma data [e.g., *Stein and Stein*, 1992; *Hillier and Watts*, 2005] an approach which, as achieved by the random bootstrap sampling of *Korenaga and Korenaga* [2008], gives seafloor age intervals equal weight. This is important as there is more young seafloor than old. The thin lines are intervals of ± 500 m around the trend. The means become shallower than the $z \propto \sqrt{t}$ model for $t > 70$ Ma, with the lower confidence interval becoming shallower than the model at about 100 Ma. Sixty three percent of depth $t > 70$ Ma plot within ± 500 m of this model, but 81% are shallower than predicted compared to only 19% being deeper. On average residual (i.e., measured minus model) depths $t > 70$ Ma are 360.1 ± 0.3 m shallower than the model compared to 1.2 ± 0.1 m for ages <70 Ma (errors are $1s$ for the mean).

[11] Figure 1c plots histograms of the difference between observed “normal” seafloor depths and the $z \propto \sqrt{t}$ model (OLS fit). Young seafloor (<70 Ma) depths appear normally distributed about the model with a standard deviation (s_x) of 331.1 m and are almost exactly centered on it with a mean difference of 1.2 ± 0.1 m (error is $1s$ for the mean). Mean depths for older seafloor (increasingly dark grays) have positive residual depths indicating that they are, on average, shallower than the model. Normal, seafloor >110 Ma old, is on average 723.2 ± 0.5 m shallower; however even for seafloor 90–70 Ma old a shallowing many times the error on the mean demonstrates a statistical significance that will be valid even allowing for distributions not being perfectly Gaussian in shape. Note that the 110–90 Ma distribution is the least Gaussian, and that it contains a suggestion of bimodality with the lower amplitude peak centered close to the model.

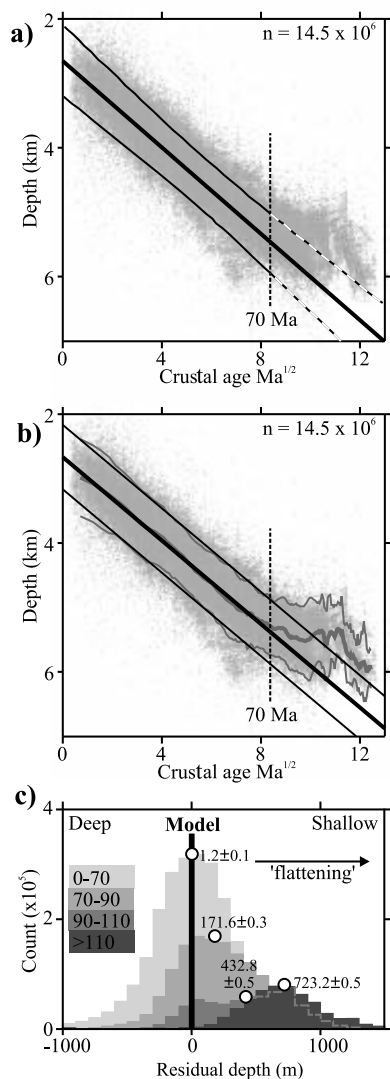


Figure 1. Age-depth data representing normal seafloor generated by replicating the methods of *Korenaga and Korenaga* [2008]. Flattening is present at old ages. (a) Model $z = 2648 + 336\sqrt{t}$ is that of *Korenaga and Korenaga* [2008] (bold black line). Data (gray dots), 68% confidence zone digitized from *Korenaga and Korenaga* [2008] (thin black lines). (b) Data (gray dots), mean $\pm 2s_x$ in 1 Myr bins for the data are gray lines, and the model ± 500 m are black lines. (c) Histograms of residual depths (i.e., observed-model) for age bands shown as darker gray shades with increasing age. Circles indicate mean residual depths, and errors are $\pm 1s$ of the means (i.e., s_x/\sqrt{n}). Histogram of 70–0 Ma is shown at one-fifth of true counts for ease of plotting. Visually, this understates the relative area of young seafloor but has no effect on the key statistic, the mean residual depth for the Δt bins. Residual of 1.2 m for 70–0 Ma seafloor arises because fitting the model gives equal weight to each 1 Myr age bin, while the raw statistics weight each data point equally.

[12] The number of data points in the bins (n), estimated standard deviations (s_x), mean residuals (\bar{x}), standard errors (s_x/\sqrt{n}), and confidence from observations in the bin that flattening exists are given in Table 1. The statistics used are

explained in section 4. Similar figures, but assuming only 10 independent depth observations in each bin are given in Table 2.

[13] These results change little if the model fitted by *Korenaga and Korenaga* [2008] is used except that residual depths (i.e., the shallowing) become larger, e.g., mean depth for $t > 100$ Ma is about 867 m.

4. Interpretation and Discussion

4.1. Is Flattening (or Otherwise) Indicated by Depth Observations of “Normal” Seafloor?

[14] To interpret the z - t data resulting from the extraction of “normal seafloor,” *Korenaga and Korenaga* [2008] describe depth as

$$z = A + B\sqrt{t} + \varepsilon,$$

where ε is an error term with a Gaussian distribution, zero mean, standard deviation σ_ε , as is implicit in any OLS fit of a regression line to depth age data [e.g., *Marty and Cazenave*, 1989]. A 68% “confidence zone” was then determined for seafloor older than 70 Ma (about ± 500 m), and age-depth data points plotting in this zone considered consistent with half-space cooling. Since these appear in a majority, *Korenaga and Korenaga* [2008, Figures 5a and 5b] deduced that seafloor conforming to the half-space cooling model dominates normal seafloor at almost all ages. *Korenaga and Korenaga* [2008], however, also state that after filtering “the signal of seafloor flattening is still present.” In the context of geophysical models of the lithosphere, “flattening” means that the sample of n observed normal seafloor depths in a Δt bin is as a whole shallower than predicted by the cooling half-space model. If variability from nonmodeled sources ε [*Korenaga and Korenaga*, 2008] is allowed for “flattening,” it means that the average of the observed sample is shallower than the average of the population predicted by the cooling half-space model. So, *Korenaga and Korenaga*’s [2008] statements appear to be contradictory. By “the signal of seafloor flattening is still present,” however, they mean that individual data points shallower than the upper confidence bound of their $z \propto \sqrt{t}$ description exist for old seafloor. Referring to individual data points, they make no comment on the observed sample or population. Thus, there is no contradiction, but their statement has no relevance to models in the form ($z = A + B\sqrt{t} + \varepsilon$) [*Korenaga and Korenaga*, 2008], approximating the cooling and contraction of the lithosphere.

[15] The results replicated here agree with *Korenaga and Korenaga* [2008] that the majority of depth data are within ± 500 m of a $z \propto \sqrt{t}$ model, which approximates their “confidence zone.” However, the bulk of data from old seafloor ($t > 70$ Ma) appear above the prediction of the $z \propto \sqrt{t}$ model in [*Korenaga and Korenaga*, 2008, Figures 5a and 5b]. This observation is borne out in Figure 1, which shows the average of depth data ($t > 70$ Ma) to be significantly shallower than the model. *Korenaga and Korenaga* [2008, Figures 7a and 7b] and Figure 1 also show that data from old seafloor outside the confidence interval are almost entirely above it, quantitatively in a ratio of 4:1. Thus, while individual data points might be argued

Table 1. Residual Depth Statistics Assuming Statistical Independence of Depth Observations

Age Bin (Ma)	Number of Depth Data (n)	Standard Deviation s_x (m)	Mean Residual \bar{x} (m)	Standard Error s_x/\sqrt{n} (m)	Confidence
>110	5008	327.4	723.2	0.5	>99.99%
110–90	5951	371.8	432.8	0.5	>99.99%
90–70	11669	302.1	171.6	0.3	>99.99%
70–0	101870	331.1	1.2	0.1	n/a

to be consistent with half-space cooling, ε has a nonzero mean ($t > 70$ Ma) and is skewed toward shallow depths for the data as a whole. From the methods of *Korenaga and Korenaga* [2008], it can, therefore, either be argued that (1) seafloor flattens at old ages (i.e., ε develops and increasingly nonzero mean as seafloor age increases past 70 Ma) or (2) that the definition of normal seafloor was too lax and insufficient “normal” seafloor exists to comment upon the increase in seafloor depth with crustal age ($t > 70$ Ma) from seafloor depth alone [e.g., *Schroeder*, 1984; *Renkin and Sclater*, 1988]. Specifically in the latter case, neither $z \propto \sqrt{t}$ subsidence nor flattening can be argued for and other geophysical properties need to be measured in order to understand lithospheric evolution. The extent to which it is possible to say anything about lithospheric evolution from old seafloor is further considered in section 4.2.

4.2. Is Any Flattening (or Otherwise) Indicated by the Observations Statistically Significant?

[16] *Korenaga and Korenaga* [2008] state about flattening that, after filtering, “The significance of such [a] signal is uncertain” because “the remaining flattening is supported by only a small fraction of the global data.” The uncertainty is justified by noting that their remaining signal (i.e., the normal seafloor) at old ages is sensitive to how they define perturbed seafloor. So, they question the need for “flattening.” Their question, however, should apply to the ability to determine any signal (flattening or otherwise) from normal old seafloor. It is, therefore, not possible to both question “flattening” as they do and state that “normal seafloor following half-space cooling does exist for almost all ages.” The question of the significance of the flattening, therefore, remains open.

[17] For old seafloor ($t > 70$ Ma), the significance of observed flattening is calculated as the probability that the n observations of normal seafloor depth in a bin of width Δt originated by random sampling of a model population representing the predictions of the half-space cooling model ($z = A + B\sqrt{t} + \varepsilon$) defined from young seafloor ($t < 70$ Ma). Subtracting the deterministic model ($z = A + B\sqrt{t}$) from observed depths gives residual depths. Then, within a bin of Δt , there are n measured residual depths x . These have mean \bar{x} and sample variance s_x^2 estimating population mean

μ_x and variance σ_x^2 . The mean depth for the model is μ_m , and mean residual is $\mu_{mr} = 0$. The mean difference between the population of depths on seafloor in the range Δt and the model is $\mu_d = \mu_x - \mu_m = \mu_{mr}$ under null hypothesis $H_0: \mu_d = 0$ (i.e., “flattening” does not exist) versus $H_1: \mu_d > 0$ (“flattening” exists), and the appropriate test statistic under H_0 is

$$Z = \frac{\bar{x}}{\sqrt{s_x^2/n}} \sim N(0, 1),$$

where $\sim N(\mu, \sigma^2)$ indicates distribution of a normal (Gaussian) function. For large n (>30) t_{n-1} tends to $N(0, 1)$, and the central limit theorem states that this is true whatever the parent population of residual depths. If Y , say, is the value of the test statistic the probability of H_0 being rejected when true $P(Z > Y)$ can be found from tables of “Standard Normal” probabilities.

[18] The estimated probabilities that flattening exists are high, i.e., >99.99% (Table 1). This is in accord with the observation (Figure 1) that mean depths of observed seafloor $t > 70$ Ma are many multiples of their standard error (standard deviation of the mean) shallower than the $z = 2648 + 336\sqrt{t}$ model. This treatment, however, assumes that each data point in the bathymetry of *Smith and Sandwell* [1997] is independent, which is unlikely. On the other hand confidences remain at >99.9% until $n < 30$, i.e., less than 120 independent data in the global ocean. While n was reduced, s_x^2 on the basis of all the data was still used as a reasonable estimator of σ_x^2 .

[19] In a worst statistical case, n may be $\ll 30$. Assuming, for example, a dynamic component to bathymetry generated by mantle convection of wavelength (λ), where λ is approximately thousands of kilometers, only depth observations separated by on the order of λ km are effectively independent. This scenario implies one independent observation in an $\sim \lambda^2$ km² area. So, simplistically, the effective number of independent samples n_{eff} could be obtained by dividing the area of seafloor in a Δt bin by λ^2 . This estimates a very small n_{eff} , but probably underestimates n_{eff} as isolated areas of normal seafloor less than this size are likely to exist. The work to determine the number of truly independent bathymetry observations is beyond the scope

Table 2. Residual Depth Statistics Assuming, Globally, Only 10 Independent Observations per Bin

Age Bin (Ma)	Number of Depth Data (n)	Standard Deviation s_x (m)	Mean Residual \bar{x} (m)	Standard Error s_x/\sqrt{n} (m)	Confidence
>110	10	327.4	723.2	103.5	>99.95%
110–90	10	371.8	432.8	117.6	99.7%
90–70	10	302.1	171.6	95.5	94.6%
70–0	10	331.1	1.2	104.7	n/a

of this paper, but the case of $n = 10$ in each Δt bin can be considered.

[20] Statistically, $n = 10$ constitutes a small sample; so, the test statistic is distributed according to t_{n-1} (i.e., $\sim t_{n-1}$ replaces $\sim N(0, 1)$). The roughly Gaussian shape of observations (Figure 1c) means that the statistics remain illustratively valid. Confidence that flattening exists remain high (Table 2). If however, upon determining the independent depth estimates, confidence in disproving H_0 decreases because of small n , this should not immediately be interpreted in favor of the $z \propto \sqrt{t}$ model. A test should be done to compare whether it is more likely that observations come from model representing half-space cooling or a model, say, representing the cooling plate model, i.e., which can be disproved with more confidence. It must be stressed that if it is decided that the sample is too small no comment should be made on trends in the seafloor of $t > 70$ Ma (i.e., flattening or otherwise), and no trend should be favored by statistical arguments.

[21] So, to summarize, if it is possible to say anything about whether or not the seafloor “flattens” at old ages, it must be concluded that it flattens.

[22] Differences resulting from using the model of *Korenaga and Korenaga* [2008] are small and do not affect any of the conclusions. Of course, the selection of normal seafloor must be appropriate to make any inferences, but discussion of this is beyond the scope of this paper.

4.3. Distribution Shapes and Geophysical Parameters

[23] There is a final observation of interest in Figure 1c, the possible bimodality of depths at ages greater than 70 Ma. At all ages residual depths deeper than the $z \propto \sqrt{t}$ model for that age bin appear to remain as half a Gaussian distribution, as for 0–70 Ma, while skew to positive residual depths is introduced in 90–70 Ma, a possible second peak at about +700 m appears in 110–90 Ma, and this dominates for >110 Ma. Perhaps the negative residual depths could be used to guide the fitting of a Gaussian consistent with the $z \propto \sqrt{t}$ model, then a remnant second residual population could be combined with spatial analysis of the depths associated with each population. Work on the way in which the percentage “normal” seafloor conforming to a $z \propto \sqrt{t}$ model decreases with age, the spatial variation in this, and the tightness with which it still conforms to the $z \propto \sqrt{t}$ model might then be used as an additional constraint upon mechanisms invoked to explain the depths of old seafloor. This, however, is beyond the scope of this paper.

[24] Finally, it should be noted that other significant observations of *Korenaga and Korenaga* [2008] are in accord with this paper and previous work. Specifically, up to 70 Ma, at least, the observed increase in mean depth with crustal age is well described by

$$z = A + B\sqrt{t},$$

where z is depth (m) and t is crustal age (Ma). Recent studies of the Pacific have put B lower than the classical value of 354 ± 30 m Myr^{-1/2} (70–0 Ma) [*Parsons and Sclater*, 1977] at 307 ± 25 m Myr^{-1/2} (85–0 Ma fit) [*Hillier and Watts*, 2005; *Zhong et al.*, 2007], 329 m Myr^{-1/2} (from parameters of preferred plate model) [*Hillier and Watts*, 2005], and 315 m Myr^{-1/2} (90–0 Ma) [*Crosby et al.*, 2006]

despite using three radically different approaches to define “normal” seafloor. *Korenaga and Korenaga* [2008] support this growing consensus finding 323 ± 23 and 336 ± 22 m Myr^{-1/2} for their two criteria. Furthermore, they find an effective value of thermal expansivity (α_{eff}) about 10%–20% lower than mineral physics data ($\alpha \approx 3.1$). This is in agreement with a value of $\alpha_{\text{eff}} = 2.77$ required by *Hillier and Watts* [2005] for their preferred model (model X), which they noted as being lower than 3.1. This may be due to viscoelastic effects [*Korenaga*, 2007], although other lithosphere models that also incorporate mineral physics data, where α varies with temperature and/or pressure are able to replicate seafloor subsidence [e.g., *Doin and Flietout*, 1996; *McKenzie et al.*, 2005].

5. Conclusion

[25] From reanalysis of “normal” seafloor depth data produced by the analytical method of *Korenaga and Korenaga* [2008], it is possible to conclude that, while the nature and cause of the observed flattening of “normal” ocean floor is still debated, significant flattening does exist. The cooling half-space is, therefore, not a complete description of the evolution of normal oceanic lithosphere under current definitions (including that of *Korenaga and Korenaga* [2008]) of normality. It must be stressed, however, that this paper makes no argument for or against any data selection criteria applied to select “normal” seafloor, for instance anomalous intraplate topography could be positive (too shallow, as in this paper) or both positive and negative [e.g., *Crosby et al.*, 2006].

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