Comment on “Mantle Flow Drives the Subsidence of Oceanic Plates”

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Adam and Vidal (Reports, 2 April 2010, p. 83) reported sea-floor depth increasing as the square root of distance from the ridge along “mantle flow lines.” However, their data actually support a depth-age relationship and “flattening” at older ages. We argue that no plausible physical mechanism supports their proposal that mantle flow drives subsidence.

Sea-floor depth (z) yields important information on how the lithosphere cools, thickens with age (t), and interacts with the asthenosphere. Adam and Vidal (1) took a different approach from previous z-t studies (2–7) and demonstrated an apparent relationship between z and the square root of distance (\(\sqrt{x}\)) along “mantle flow lines” away from the spreading ridge for the Pacific plate. In such studies, which make inferences about physical models of oceanic lithosphere from empirical relationships (e.g., z-t), it is critical that the “normal” analyzed depths only reflect the physical processes in the model. These plate-scale processes are thousands of kilometers in length. Complications include (i) the effects of mantle plumes (e.g., hot-spot swells), large volcanic features, seamounts, flexural bulges and fracture zones, (ii) the dramatic decrease of ocean floor area with age, and (iii) visual compression at older ages when plotting \(z \propto \sqrt{t}\) or \(\sqrt{x}\). Here, we highlight some of the shortcomings in the analysis of Adam and Vidal (1) and discuss why they draw incorrect conclusions about the physical implications.

First, flow lines computed with the NUVEL-1A model in the No Net Rotation reference frame for the Pacific plate (8), as described in the supporting online material accompanying (1), do not match the trajectories of their illustrative profiles (Fig. 1A). The source of the discrepancy is not known because the six trajectories by Adam and Vidal (1) cannot fit a single rotation pole. The misfit is the largest for profiles a', b' (Fig. 1B1), and f' (Fig. 1B2). Second, Adam and Vidal (1) fit \(z \propto \sqrt{x}\) trend lines visually without modeling or quantitative criteria. Hence, their profile trends are subjective, and no objective reproduction is possible. Third, parameters in their empirical model \(z = z_0 + a \sqrt{x}\) [equation 1 in (1)], where \(z_0\) is ridge depth and \(a\) is subsidence rate, are not determined by fitting sea-floor topography data unaffected by crustal-scale processes. This leads to the incorrect appearance of a single \(z \propto \sqrt{x}\) trend to fit sea-floor depths along several of their presented profiles. The younger parts of profiles c', e', and ee' have a low \(a\) value because (i) they follow trajectories at a relatively high (~40°) angle to the direction of most-rapidly increasing sea-floor age (9) and (ii) 60 to 0 million years ago (Ma), sea-floor spreading was comparatively fast (9). Adam and Vidal (1) projected these low \(a\) values to older ages along the profiles. This resulted in a low \(z \propto \sqrt{x}\) gradient that passes through shallow features, which are unassociated with the plate-scale \(z \propto \sqrt{x}\) model and were inappropriately retained in the analysis, leading to an apparent but biased fit.

Profile c' crosses the Tuamotu and Manihiki Plateaus, d' the Mid-Pacific Mountains, and ee' the Hess Rise. Sea floor in these areas of thickened crust is up to ~1 km shallower than normal (10, 11). Profile dd' crosses the Line Islands Swell, and ee' crosses the Hawaiian Swell. These isolated hot-spot swells are hundreds of kilometers wide, up to ~1 km high (12), and they are only included for models with plumes, for example, (13). Profiles a'' and f'' best avoid these problems. They end at sea floor younger than 85 Ma and are equally well fit by both \(z \propto \sqrt{t}\) and \(z \propto \sqrt{x}\) trends. Profile bb' crosses the Tharp Fracture Zone at \(\sqrt{x} = 1150\,\text{m}^{1/2}\), where sea-floor age increases ~20 million years (My) and depth increases ~500 m, producing an apparent \(z \propto \sqrt{x}\) fit. However, our profile xx' (Fig. 1), which is not biased by such discontinuities, initially exhibits a \(z \propto \sqrt{x}\) trend but then shallows and deepens where the age varies as it crosses the Osbourn Trough, a Cretaceous fossil spreading center. This demonstrates that age is a major factor in the subsidence of oceanic lithosphere at old ages.

Because single profiles are easily misinterpreted, we calculated the median \(z\) from the data of the six profiles presented by Adam and Vidal (1). Median \(z\) increases as \(\sqrt{x}\) up to ~2700 m\(^{1/2}\) and thereafter “flattens” (Fig. 2A). However, such an approach is misleading because (i) most data that represent the flattening are “abnormal” [e.g., as “distance criterion” of (4, 6)] and (ii) \(\sqrt{x}\) cannot be simply translated to \(\sqrt{t}\) to address heat input. Plotting \(z \propto \sqrt{t}\) (Fig. 2B) presents clear evidence of flattening for ocean floor older than 80 Ma. Therefore, if any valid inference is possible, their data selection requires heat flow into...
old lithosphere (14) or some other way of counteracting the effects of a conductively cooling half-space (15).

The fundamental omission of Adam and Vidal (1) is the lack of a physically justifiable model: Even if \( z \propto \sqrt{t} \) trends were to be accepted, they do not demonstrate causally that “mantle flow drives the subsidence of oceanic plates.” For instance, “asthenospheric flow trajectories,” where \( z \) increases linearly with \( \sqrt{t} \) (e.g., profiles cc', dd', and ee'), will exhibit \( z \propto \sqrt{t} \) trends due to conductive cooling (15). Adam and Vidal propose that temperature variations at the base of the lithosphere modulate subsidence, which is neither controversial nor novel [see, e.g., (12)]. Specifically, they argue that a 47- to 50-Ma rearrangement of the mantle convection has provided the Pacific plate sufficient time to adapt to new thermal conditions. This appears inconsistent with their claim that “no additional heat supply is required at the base of the lithosphere.” Moreover, plotting \( z \propto \sqrt{t} \) implies some relationship between asthenospheric temperature and \( x \). However, the mechanism for this has not been explained by Adam and Vidal. To demonstrate a serious problem with currently accepted models of ocean lithospheric subsidence, they would have to show that a robustly extracted \( z \propto \sqrt{t} \) relationship can be applied to the entire Pacific, Atlantic, and Indian oceans. They have not done this.

Even though Adam and Vidal made an ambitious attempt to propose a different approach to the topic of ocean lithospheric subsidence, we do not believe that they have demonstrated an absence of sea-floor flattening. Rather, we show that their combined data favor flattening at old ages, consistent with recent analyses of the \( z \propto \sqrt{t} \) relation for the Pacific plate (2, 4, 5).

References

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