Comment on "Mantle Flow Drives the Subsidence of Oceanic Plates"

Marcel B. Croon[1*], John K. Hillier[2] and John G. Sclater[1]

[1]Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Drive, California 92093-0220, USA. [2]Department of Geography, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK.

[*] To whom correspondence should be addressed. E-mail: mcroon@ucsd.edu

Abstract

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

Main Text

Sea-floor depth (*z)* yields important information on how the lithosphere cools, thickens with age (*t)*, and interacts with the asthenosphere. *Adam & 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 'asthenospheric 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 1,000s of km in length. Complications include (a) the effects of mantle plumes (e.g., 'hot-spot swells'), large volcanic features, seamounts, flexural bulges and fracture zones, (b) the dramatic decrease of ocean floor area with age and (c) visual compression at older ages when plotting $z \propto \sqrt{t}$ or $\sqrt{x}$. Here, we highlight some of the major shortcomings in the analysis of *Adam & 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 since the six trajectories by *Adam & Vidal* (*1*) cannot fit a single rotation pole. The misfit is the largest for profiles aa', bb' (Fig. 1B1) and ff' (Fig. 1B2). Second, *Adam & 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

$$z = z_R + a\sqrt{x} \quad (1)$$

where z_R 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 cc', dd' 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 Ma seafloor spreading was comparatively fast (*9*). *Adam & Vidal* (*1*) projected these low a values to older ages along the profiles. This resulted in a low z-$\sqrt{x}$ gradient that passes through shallow features, which are unassociated with the plate-scale z-$\sqrt{x}$ model and were inappropriately retained in the analysis leading to an apparent but biased fit. Profile cc' crosses the Tuamotu and Manihiki Plateaus, dd' the Mid-Pacific Mountains, and ee' the Hess Rise. Sea-floor in these areas of thickened crust is up to ~one 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 100s of km wide, up to ~one km high (*12*) and they are only included for models with plumes, e.g. (*13*). Profiles aa' and ff' 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 $\sqrt{x} = 1150$ $m^{1/2}$ where sea-floor age increases ~20 Myr 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.

As single profiles are easily misinterpreted, we calculated the median z from the data of the six profiles presented by *Adam & 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 since 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 & Vidal* (*1*) is the lack of a physically justifiable model: even if $z \propto \sqrt{x}$ 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 $z \propto \sqrt{x}$ trends due to conductive cooling (*15*). They (*1*) propose that temperature variations at the base of the lithosphere modulate subsidence, which is neither controversial nor novel, 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 $z \propto \sqrt{x}$ implies some relationship between asthenospheric temperature and x. However, the mechanism for this has not been explained by *Adam & Vidal* (*1*). To demonstrate a serious problem with currently

accepted models of ocean lithospheric subsidence they would have to show that a robustly extracted $z \propto \sqrt{x}$ relationship can be applied to the entire Pacific, Atlantic and Indian oceans. They have not done this.

Even though *Adam & Vidal* (*1*) 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 favors flattening at old ages consistent with recent analyses of the $z \propto \sqrt{t}$ relation for the Pacific Plate (*2, 4, 5*).

Figures

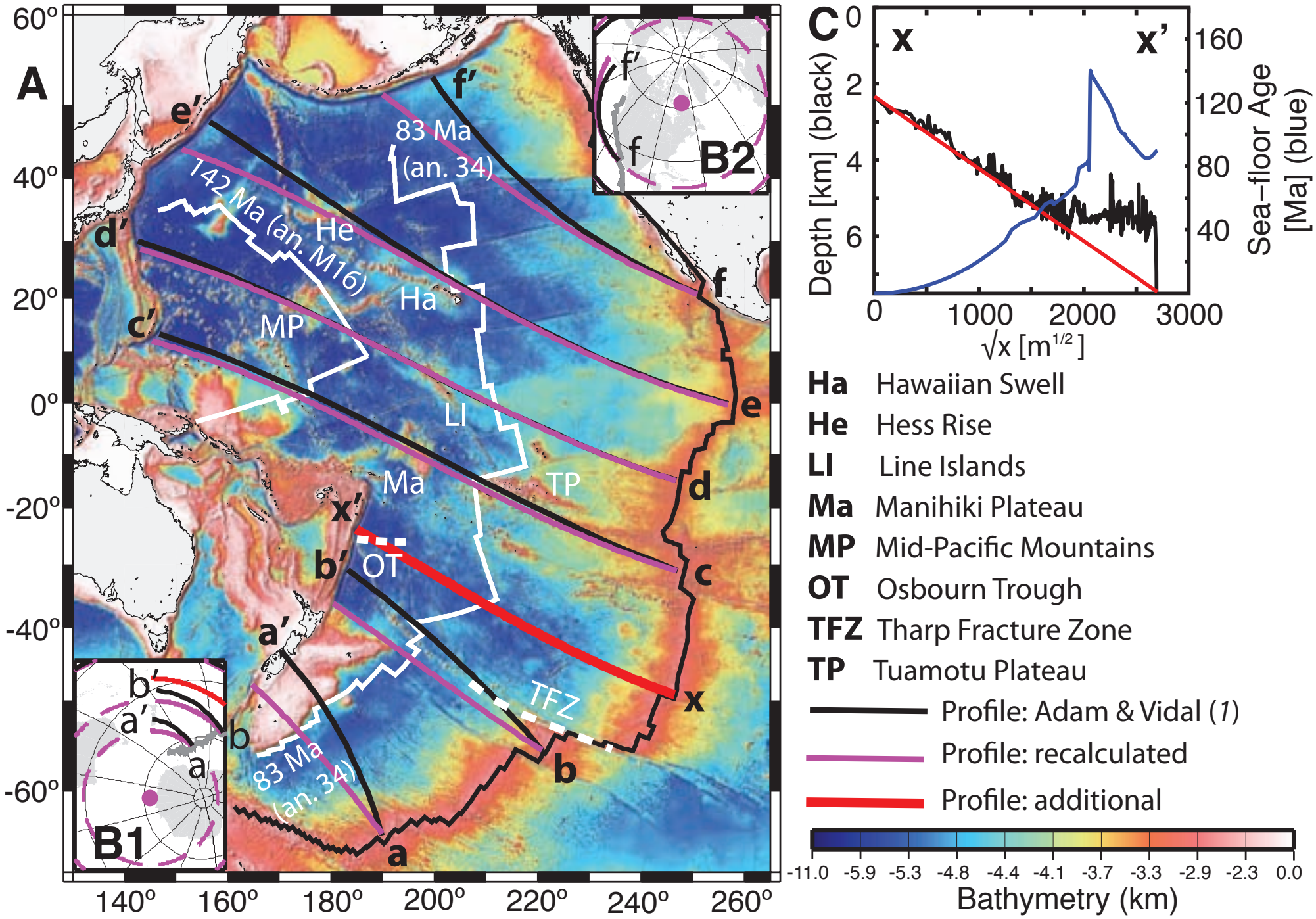
Fig. 1. (A) Predicted bathymetry of the Pacific plate (*13*) with profiles from (*1*) (black lines) and recalculated (purple lines), profile xx' (red line) and isochrons for illustrative magnetic anomalies (white lines). **(B1 and B2)** Lambert azimuthal equal-area projection of profiles aa', bb' and ff' from (*1*) (black lines) and recalculated profiles (purple lines), which are part of small circles (dashed purple lines) calculated for the NUVEL-1A model in the No Net Rotation reference frame for the pole of the Pacific plate (Lon: -72.6°, Lat: 63.0, purple dots) (*8*). **(C)** Profile xx', $z \propto \sqrt{x}$ (black), linear trend (red), *sea-floor age* $\propto \sqrt{x}$ (blue). Sediment loading correction as (*16*).

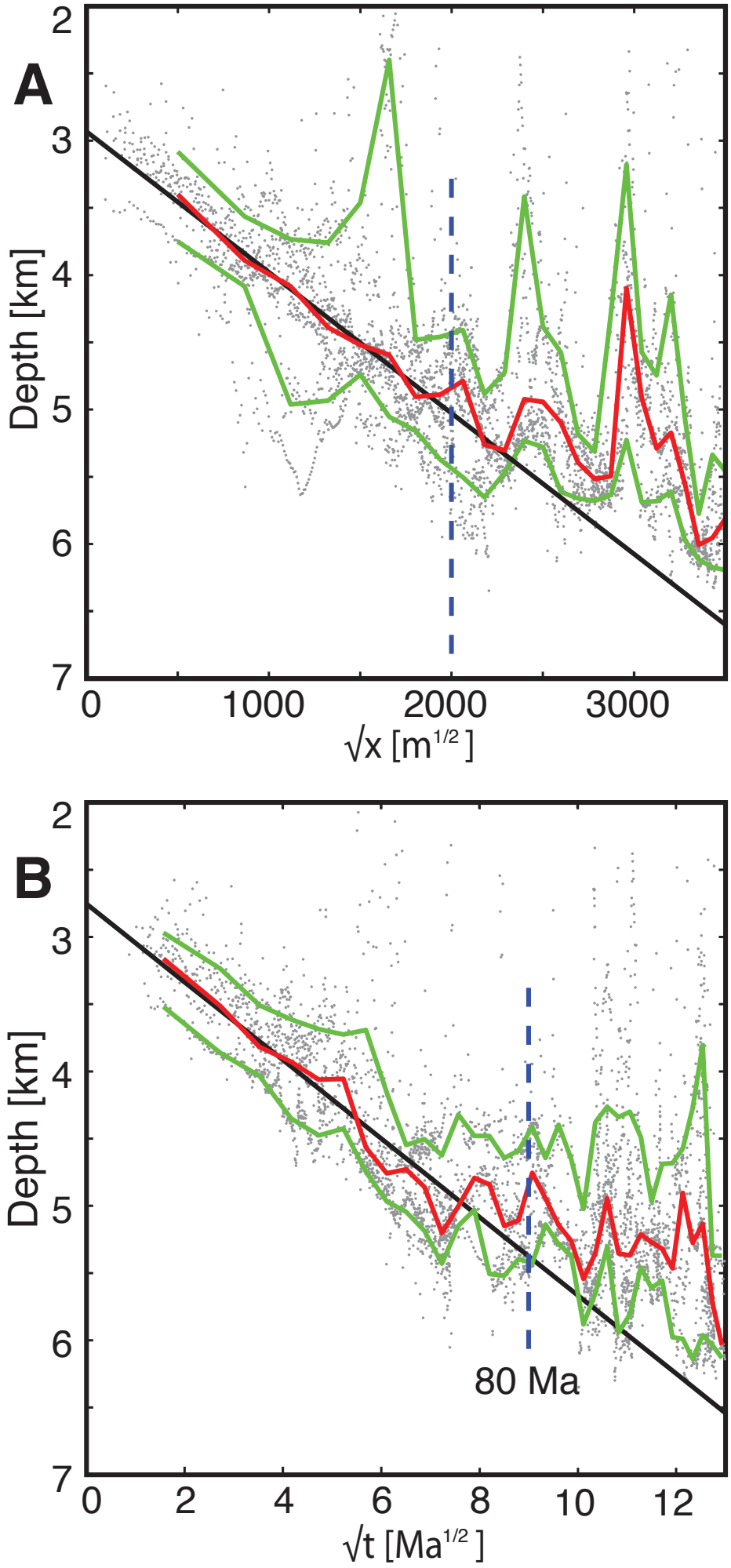
Fig. 2. (A) $z \propto \sqrt{x}$ data (grey dots) for the six profiles (*1*), median (red line), ±34% percentiles contours (green lines) and ordinary least squares (OLS) trend line (black) for median (calculated for x = 0 to 2000 $m^{1/2}$). Bins: depth 200 m, distance

500 km. Sediment loading correction as (*16*). **(B)** Data as Fig. 2A but presented as $z \propto \sqrt{t}$. OLS fit to 80 Ma. Bins: depth 200 m, age 5 Myr.

References

1. C. Adam, V. Vidal, in *Science*. (2010), vol. 328, pp. 83.
2. A. G. Crosby, D. McKenzie, J. G. Sclater, in *Geophysical Journal International*. (2006), vol. 166, pp. 553.
3. R. L. Heestand, S. T. Crough, in *Journal of Geophysical Research*. (1981), vol. 86, pp. 6107.
4. J. K. Hillier, in *Journal of Geophysical Research-Solid Earth*. (2010), vol. 115, pp. B03102.
5. J. K. Hillier, A. B. Watts, in *Journal of Geophysical Research-Solid Earth*. (2005), vol. 110, pp. B02405.
6. T. Korenaga, J. Korenaga, in *Earth and Planetary Science Letters*. (2008), vol. 268, pp. 41.
7. J. C. Marty, A. Cazenave, in *Earth and Planetary Science Letters*. (1989), vol. 94, pp. 301.
8. C. DeMets, R. G. Gordon, D. F. Argus, S. Stein, in *Geophysical Research Letters*. (1994), vol. 21, pp. 2191.
9. R. D. Müller, M. Sdrolias, C. Gaina, W. R. Roest, in *Geochemistry Geophysics Geosystems*. (2008), vol. 9, pp. Q04006.
10. J. K. Hillier, A. B. Watts, *Journal of Geophysical Research-Solid Earth* **109**, B10102 (Oct 21, 2004).
11. M. Patriat *et al.*, in *Geophysical Research Letters*. (2002), vol. 29, pp. 1656.
12. S. T. Crough, in *Geophysical Journal of the Royal Astronomical Society*. (1978), vol. 55, pp. 451.
13. W. H. F. Smith, D. T. Sandwell, in *Science*. (1997), vol. 277, pp. 1956.
14. D. P. McKenzie, *Journal of Geophysical Research* **72**, 6261 (1967).
15. E. E. Davis, C. R. B. Lister, in *Earth and Planetary Science Letters*. (1974), vol. 21, pp. 405.
16. W. Schroeder, in *Journal of Geophysical Research*. (1984), vol. 89, pp. 9873.


A
B1
B2
C
60°
40°
20°
0°
-20°
-40°
-60°
140°
160°
180°
200°
220°
240°
260°
a
a′
b
b′
e′
f′
d′
c′
x
x′
83 Ma (an. 34)
142 Ma (an. M16)
He
Ha
MP
LI
Ma
TP
OT
TFZ
Depth [km] (black)
Sea–floor Age [Ma] (blue)
√x [m^1/2]
Ha Hawaiian Swell
He Hess Rise
LI Line Islands
Ma Manihiki Plateau
MP Mid-Pacific Mountains
OT Osbourn Trough
TFZ Tharp Fracture Zone
TP Tuamotu Plateau
Profile: Adam & Vidal (1)
Profile: recalculated
Profile: additional
-11.0 -5.9 -5.3 -4.8 -4.4 -4.1 -3.7 -3.3 -2.9 -2.3 0.0
Bathymetry (km)


A
Depth [km]
2
3
4
5
6
7
0
1000
2000
3000
√x [m^1/2]
B
Depth [km]
2
3
4
5
6
7
0
2
4
6
8
10
12
√t [Ma^1/2]
80 Ma