# LETTERS

# The rapid drift of the Indian tectonic plate

Prakash Kumar[1], Xiaohui Yuan[2], M. Ravi Kumar[1], Rainer Kind[2,3], Xueqing Li[2] & R. K. Chadha[1]

**The breakup of the supercontinent Gondwanaland into Africa, Antarctica, Australia and India about 140 million years ago, and consequently the opening of the Indian Ocean, is thought to have been caused by heating of the lithosphere from below by a large plume whose relicts are now the Marion, Kerguelen and Réunion plumes. Plate reconstructions based on palaeomagnetic data suggest that the Indian plate attained a very high speed (18–20 cm yr$^{-1}$ during the late Cretaceous period) subsequent to its breakup from Gondwanaland, and then slowed to ~5 cm yr$^{-1}$ after the continental collision with Asia ~50 Myr ago[1,2]. The Australian and African plates moved comparatively less distance and at much lower speeds of 2–4 cm yr$^{-1}$ (refs 3–5). Antarctica remained almost stationary. This mobility makes India unique among the fragments of Gondwanaland. Here we propose that when the fragments of Gondwanaland were separated by the plume, the penetration of their lithospheric roots into the asthenosphere were important in determining their speed. We estimated the thickness of the lithospheric plates of the different fragments of Gondwanaland around the Indian Ocean by using the shear-wave receiver function technique. We found that the fragment of Gondwanaland with clearly the thinnest lithosphere is India. The lithospheric roots in South Africa, Australia and Antarctica are between 180 and 300 km deep, whereas the Indian lithosphere extends only about 100 km deep. We infer that the plume that partitioned Gondwanaland may have also melted the lower half of the Indian lithosphere, thus permitting faster motion due to ridge push or slab pull.**

The term lithosphere, commonly understood as describing Earth's rigid outer shell floating on a viscous asthenosphere, originally evolved in a mechanical sense[6] to explain the post-glacial rebound phenomenon. Since then, several usages of this term have evolved, such as thermal, chemical and seismic lithospheres[7]. Traditionally, seismologists refer to this boundary as the Gutenberg discontinuity after the discovery of low-velocity zones in regions underlying oceanic basins by Gutenberg[8]. Old and stable continental regions are understood to be underlain by a thick lithosphere[9], as demonstrated by the presence of numerous diamondiferous regions located within their interiors. Results from seismic tomography show the presence of deep roots in old continents such as Africa where the lithospheric thickness exceeds 250 km (ref. 10).

Alterations of the primordial lithospheric configuration due to passage over hotspots in areas covered by vast regions of basalt on the continent (large igneous provinces) are also shown by thinning of the lithosphere and by the presence of low-velocity uppermost mantle. Because the thickness of the lithosphere has a prominent role in shielding the mantle attrition processes that are vital for determining the stability factor for the survival of the Precambrian crust, its precise determination is important. In addition, imprints of major tectonic events such as passage over hotspots (plume–lithosphere interaction), rifting due to continental breakup, and continental collision are expected to be manifested as alterations in the deep lithospheric architecture.

We apply a recently developed seismic method (shear-wave (S) receiver functions) to determine with high accuracy the depth of the lithosphere/asthenosphere boundary (LAB) in the region of the Indian Ocean and the surrounding fragments of Gondwanaland. Figure 1 and Supplementary Fig. 1 show the distribution of the seismic stations used. This method uses S-to-P converted waves from the LAB beneath a seismic station. Details of the technique and examples of applications in other regions have been given in several papers[11–18]. The observed S receiver functions are shown in Fig. 2a for each station. These data are summation traces of several tens of records at each station. Two prominent phases are clearly visible at all stations, marked Moho and LAB. To verify our observations of the LAB, we show in Supplementary Fig. 3 synthetic S receiver functions and their relation to possible anisotropy in the mantle and to compressional-wave (P) receiver function observations. Individual S receiver functions of HYB and three other Indian stations are shown in Supplementary Figures 4 and 5.

Conversions from the Moho and the LAB have different signs because they result from discontinuities with velocities that increase (Moho) and decrease (LAB) downwards. The times for the Moho vary between ~2 s and 8 s, and those for the LAB vary between about 4 s and 32 s. The Moho and LAB times, along with their corresponding depths (using the global reference model IASP91), are given in Supplementary Table 1. The stations in Fig. 2a are sorted in order of increasing LAB time. The depth of the LAB varies between 30 and 300 km. There is no obvious correlation between crustal thickness and LAB depth. Theoretical receiver functions are shown in Fig. 2b for the models in Fig. 2c. The agreement between computed and observed seismograms is very good. A simple model with a homogeneous crust and a homogeneous lithosphere above the asthenosphere can explain most features of the observations. Only the depths of the Moho and of the LAB need to be varied. In this study we have not attempted to model the sharpness of the discontinuities, but the relative amplitudes of the Moho and LAB phases with respect to their corresponding direct S phases clearly reveal that the amplitude at Moho is twofold to threefold that for LAB. An interesting feature of Fig. 2d is that the cratonization of the lithosphere is reflected in a decrease in the LAB amplitudes, whereas the Moho amplitudes remain nearly stable from oceanic regions to cratons.

For verification that a large LAB time corresponds to a thick high-velocity mantle lid, we examined the arrival times of the P-to-S converted waves from the discontinuity at 410 km, which roughly sample the average velocity above 410 km depth. The existence of a thick high-velocity lid can cause the converted waves to travel faster, at a rate proportional to the lid thickness. Consequently, the times of the P-to-S converted waves from the 410-km discontinuity should anti-correlate with the times of the S-to-P conversions from the LAB. In Fig. 3, we show the measured times from the LAB and from the 410-km and 660-km discontinuities. The waveform data of the conversions of the data from the 410-km and 660-km discontinuities are shown in Supplementary Fig. 6. Figure 3 shows clearly that the times from the LAB and the 410-km discontinuity are anticorrelated,

[1]National Geophysical Research Institute, Hyderabad 500 007, India. [2]GeoForschungsZentrum, 14473 Potsdam, Germany. [3]Freie Universität, Berlin 12249, Germany.
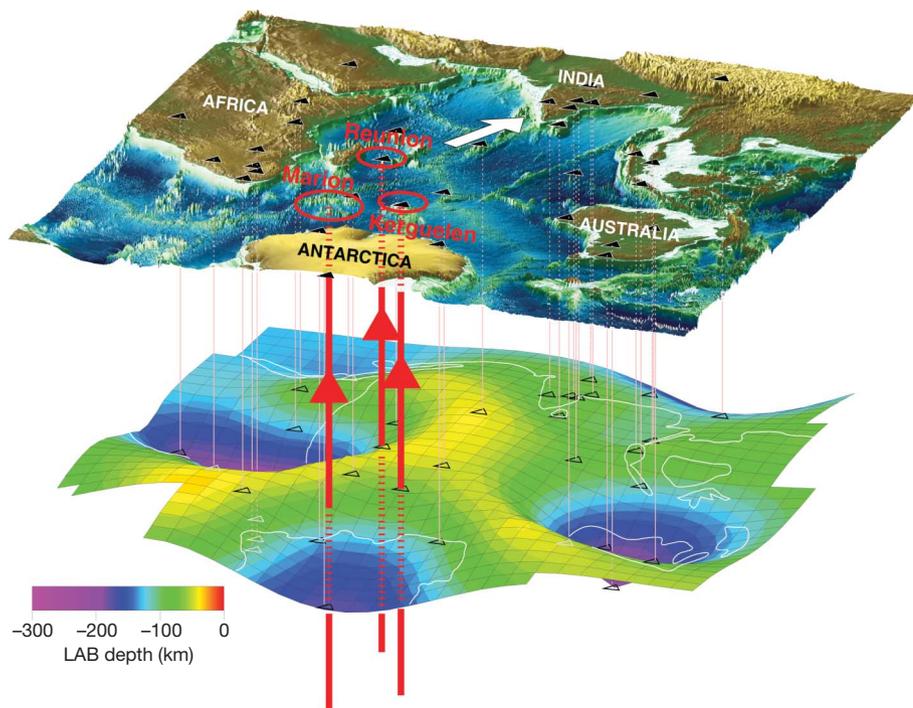
**Figure 1 | Topography of the surface and the LAB in the region of the Indian Ocean and the fragments of Gondwanaland surrounding it.** The Indian lithosphere is exceptionally thin compared with the other fragments of Gondwanaland. Black triangles denote seismic stations. The station locations are also shown in Supplementary Fig. 1, with station codes. Red circles mark the surface locations of the mantle plumes whose conduits are illustrated by the thick vertical lines.
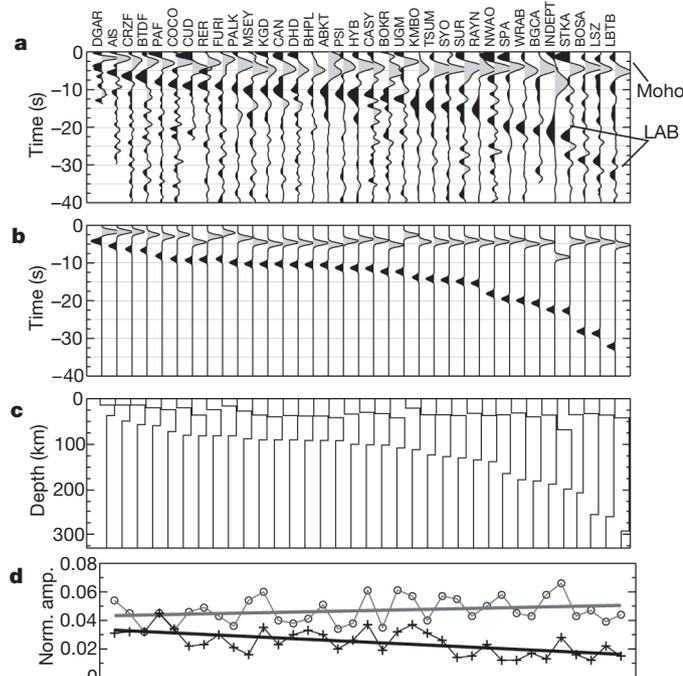


**Figure 2 | S-receiver function data and modelling. a,** Stacked S-receiver function traces from all stations used. Converted signals from the Moho and the LAB are clearly visible. The traces are arranged with increasing LAB time from left to right. The vertical axis measures the time differences between the S-to-P converted phases and the corresponding reference S phases. Time is negative because the S-to-P converted waves travel faster than the S waves. **b,** Synthetic seismograms[33], which model the observed waveforms very well. **c,** Simple models used for the computation of the theoretical seismograms. The models consist of a homogeneous crust, mantle lithosphere and asthenosphere. Velocities are fixed for all the models ($V_s$ for the crust is 3.58 km s$^{-1}$, $V_s$ for the lithospheric mantle lid is 4.5 km s$^{-1}$ and $V_s$ for the asthenosphere is 3.9 km s$^{-1}$). Only the depths of both discontinuities are varied to fit the travel times. **d,** Variation in normalized amplitudes (norm. amp.; with respect to the direct S phase) of the Moho (open circles) and the LAB (plus signs) with respect to the amplitude of the direct S phase. The grey and black lines are trend lines from a least-squares fit.

whereas those of the 410-km discontinuity and the 660-km discontinuity are correlated. Small LAB depths correlate with low average velocities above the 410-km discontinuity. The correlation of the times from the 410-km and 660-km discontinuities suggests that most of the time variations can be attributed to mantle velocity variation above 410 km depth. The possible influence of the topography of the 410-km discontinuity on this conclusion is small[19].

As shown in Fig. 1, on the basis of the data given in Fig. 2a and Supplementary Table 1, the lithosphere is very thin in the young regions of the mid-oceanic ridges and is very thick (more than 180 km) below the cratons of South Africa, Antarctica and Australia. The Indian lithosphere is ~100 km thick or less, although it was a part of the same Gondwanaland. Six stations on the Indian shield, namely DHD (situated on the western Dharwar craton), HYB and CUD (situated on the Eastern Dharwar craton), KGD (situated within the Godavari rift zone), and BHPL and BOKR in northern India, indicate a lithospheric thickness of 80–100 km. Such a thin lithosphere for the Indian shield is unexpected, because all these stations are sited on Archaean basement, away from the coast. Earlier studies of the lithospheric thickness in India do not lead to a homogeneous picture. Surface-wave tomography studies reveal that the lithosphere could be ~100 km (ref. 20) or 150 km (ref. 21) thick. Lithospheric thickness estimates based on temperature–depth profiles[22] yield an average thickness of 104 km for the Indian shield region. Studies based on temperature data constrained by pressure–temperature estimates from xenoliths lead to a thickness of 200–250 km (ref. 23) or 160 km (ref. 24) (adding S velocity data). Our estimates of lithospheric thickness are based purely on the seismic body-wave observations, yielding the present-day lithospheric thickness. We also consider that the resolution of our body-wave data is higher than that of the long-period surface-wave data. The lithosphere in the south Indian shield must originally have been thick, in view of the presence of diamond-bearing kimberlites[24] close to HYB. There is now an increasing use of structural and metamorphic pressure–temperature data, precise dating measurements and comparison of subsurface geophysical models to aid in palaeocontinent reconstructions with respect to Gondwanaland and Rodinia[25]. Diamonds originate in the deep roots of ancient continental blocks that extend into the diamond stability field beneath ~140 km and more. Ar–Ar dating of the kimberlites in the Indian shield constrains their age to the Proterozoic era (~1,091 ± 20 Myr (ref. 26)). Because
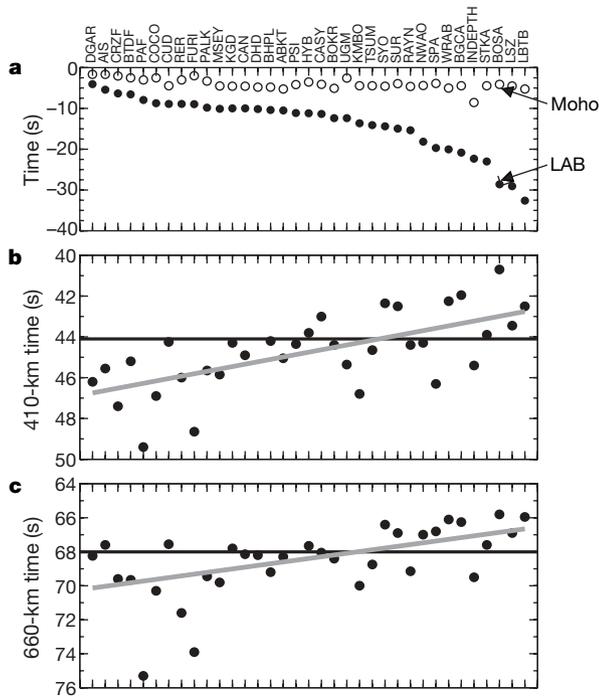
**Figure 3 | Comparison of different upper mantle seismic phases. a,** Filled circles show times for the S-to-P conversions at the LAB arranged in increasing order; open circles are those for the Moho. **b,** Times for the P-to-S converted waves at the 410-km discontinuity. **c,** Times for the P-to-S converted waves at the 660-km discontinuity. As the LAB times (**a**) increase, the corresponding times for the 410-km (**b**) and 660-km (**c**) discontinuities decrease. This observed anticorrelation confirms the interpretation of the LAB pulses as originating from the LAB. Scatterings in **b** and **c** are due to time picking error and to the presence of local heterogeneities within the upper mantle.

the diamonds are older than the kimberlites that transport them to the surface, the lithosphere in this region must have been thicker before the breakup of Gondwanaland.

The high speed attained by India during the Cretaceous period coupled with the present-day estimates prompts us to argue that the originally thick lithosphere beneath India seems to have been preferentially thinned by a large plume either during or immediately after the Gondwana breakup ~130 Myr ago[2]. Subsequently, the Indian plate could have been further degenerated by the influence of its passage over the hotspots and the large-scale magmatic extrusions such as the Deccan and Rajmahal traps, although their role in thinning of the lithosphere cannot be ascertained. Osmium isotopic studies suggest a lack of evidence for the involvement of the subcontinental mantle lithosphere in Rajmahal basalts[27], which seem to share an origin with the Kerguelen lavas[28]. Figure 4 shows a reconstruction of Gondwanaland with the present-day lithospheric thickness, which is exceptionally small beneath India and east Africa. The loss of the lithospheric roots might have been the reason that the Indian plate attained a very high velocity of 20 cm yr$^{-1}$, which is unusual for any continental lithospheric plate[29]. The plate speed, resulting from either a push caused by a hot mantle source or a trench pull due to a cold downwelling slab, increases with decreasing root depth[30].

In the present study, the thickest lithosphere (~300 km) is found in the oldest continental nuclei in the Kaapvaal craton (Supplementary Fig. 2), which is diamond bearing, implying that the lithosphere is preserved over Archaean times. The other stations in the Archaean Kaapvaal craton also indicate a lithosphere thicker than 250 km. This result is supported by independent studies of seismic tomography[10]. As expected, the thickness of the lithosphere found by seismic tomography[31] is also greater than 200 km in the Australian and Antarctic
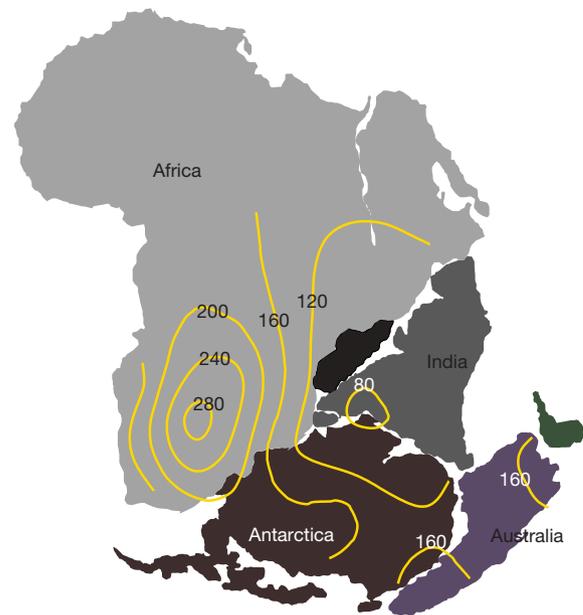


**Figure 4 | Reconstruction of Permian Gondwanaland.** The contours show the present-day continental lithospheric thicknesses.

shield regions. Tomographic inversion of teleseismic P and S travel times indicates that high-velocity lithosphere beneath the Tanzania craton extends to a depth of at least 200 km and possibly to 300 or 350 km (ref. 32). In addition, the lithosphere tends to get thinner in regions closer to the coast as a result of the effect of rifting due to the breakup of Gondwanaland.

1. Klootwijk, C. T., Gee, J. S., Peirce, J. W. & Smith, G. M. An early India–Asia contact: Paleomagnetic constraints from Ninetyeast Ridge, ODP Leg 121. *Geology* **20**, 395–398 (1992).
2. Gaina, C., Müller, R. D., Brown, B. & Ishihara, T. Breakup and early seafloor spreading between India and Antarctica. *Geophys. J. Int.* **170**, 151–169 (2007).
3. Veevers, J. J. Breakup of Australia and Antarctica estimated as mid-Cretaceous (95 ± 5 Ma) from magnetic and seismic data at the continental margin. *Earth Planet. Sci. Lett.* **77**, 91–99 (1986).
4. Cande, S. C. & Mutter, J. C. A revised identification of the oldest sea-floor spreading anomalies between Australia and Antarctica. *Earth Planet. Sci. Lett.* **58**, 151–160 (1982).
5. Jacoby, W. R. in *Landolt-Bornstein, New Series, Group V* Vol. 2b (eds Fuchs, K. & Soffel, H.) 298–369 (Springer, Berlin, 1985).
6. Barrell, J. The strength of the Earth's crust. *J. Geol.* **22**, 655–683 (1914).
7. Anderson, D. L. Lithosphere, asthenosphere, and perisphere. *Rev. Geophys.* **33**, 125–149 (1995).
8. Gutenberg, B. *Physics of the Earth's Interior.* (Elsevier, New York, 1959).
9. Jordan, T. H. The continental tectosphere. *Rev. Geophys. Space Phys.* **13**, 1–13 (1975).
10. James, D. E., Fouch, M. J., VanDecar, J. C. & van der Lee, S. Tectospheric structure beneath southern Africa. *Geophys. Res. Lett.* **28**, 2485–2488 (2001).
11. Li, X., Kind, R., Yuan, X., Wölbern, I. & Hanka, W. Rejuvenation of the lithosphere by the Hawaiian plume. *Nature* **427**, 827–829 (2004).
12. Kumar, P. *et al.* The lithosphere–asthenosphere boundary in the North West Atlantic Region. *Earth Planet. Sci. Lett.* **236**, 249–257 (2005).
13. Kumar, P., Yuan, X., Kind, R. & Kosarev, G. The lithosphere–asthenosphere boundary in the Tien Shan-Karakoram region from S receiver functions—evidence of continental subduction. *Geophys. Res. Lett.* **32**, L07305, doi:10.1029/2004GL022291 (2005).
14. Kumar, P., Yuan, X., Kind, R. & Ni, J. Imaging the colliding Indian and Asian lithospheric plates beneath Tibet. *J. Geophys. Res.* **111**, B06308 10.1029/2005JB003930 (2006).
15. Sodoudi, F., Yuan, X., Liu, Q., Kind, R. & Chen, J. Lithospheric thickness beneath the Dabie Shan, central eastern China from S receiver functions. *Geophys. J. Int.* **166**, 1363–1367 (2006).
16. Angus, D. A., Wilson, D. C., Sandvol, E. & Ni, J. F. Lithospheric structure of the Arabian and Eurasian collision zone in eastern Turkey from S-wave receiver functions. *Geophys. J. Int.* **166**, 1335–1346 (2006).
17. Landes, M., Ritter, J. R. R. & Readman, P. W. Proto-Iceland plume caused thinning of Irish lithosphere. *Earth Planet. Sci. Lett.* **255**, 32–40 (2007).

18. Li, X., Yuan, X. & Kind, R. The lithosphere–asthenosphere boundary beneath the western United States. *Geophys. J. Int.* **170,** 700–710 (2007).

19. Li, X. *et al.* Seismic observation of narrow plumes in the oceanic upper mantle. *Geophys. Res. Lett.* **30** (6), 1334, doi:10.1029/2002GL015411 (2003).

20. Polet, J. & Anderson, D. L. Depth extent of cratons as inferred from tomographic studies. *Geology* **23,** 205–208 (1995).

21. Mitra, S., Priestley, K., Gaur, V. K. & Rai, S. S. Shear-wave structure of the south Indian lithosphere from Rayleigh wave phase–velocity measurements. *Bull. Seism. Soc. Am.* **96,** 1551–1559 (2006).

22. Pandey, O. P. & Agarwal, P. K. Lithospheric mantle deformation beneath the Indian cratons. *J. Geol.* **107,** 683–692 (1999).

23. Artemieva, I. M. Global 1 degree × 1 degree thermal model TC1 for the continental lithosphere: Implications for lithosphere secular evolution. *Tectonophysics* **416,** 245–277 (2006).

24. Priestley, K. & McKenzie, D. The thermal structure of the lithosphere from shear velocities. *Earth Planet. Sci. Lett.* **244,** 285–301 (2006).

25. Mezger, K. & Cosca, M. A. The thermal history of the Eastern Ghats belt (India) as revealed by U–Pb and $^{40}$Ar/$^{39}$Ar dating of metamorphic and magmatic minerals: implications for the SWEAT correlation. *Precambr. Res.* **94,** 251–271 (1999).

26. Kumar, A., Padma Kumari, V. M., Dayal, A. M., Murty, D. S. N. & Gopalan, K. Rb–Sr ages of Proterozoic Kimberlites of India: evidence for contemporaneous emplacement. *Precambr. Res.* **62,** 227–237 (1993).

27. Ingle, S., Scoates, J. S., Weis, D., Brügmann, G. & Kent, R. W. Origin of Cretaceous continental tholeiites in southwestern Australia and eastern India: insights from Hf and Os isotopes. *Chem. Geol.* **209,** 83–106 (2004).

28. Coffin, M. *et al.* Kerguelen hotspot magma output since 130 Ma. *J. Petrol.* **43,** 1121–1139 (2002).

29. Jurdy, D. M. & Gordon, R. G. Global plate motions relative to the hotspots 64 to 56 Ma. *J. Geophys. Res.* **89,** 9927–9936 (1984).

30. Gurnis, M. & Torsvik, T. H. Rapid drift of large continents during the late Precambrian and Paleozoic: Paleomagnetic constraints and dynamic models. *Geology* **22,** 1023–1026 (1994).

31. Gaherty, J. B., Mamoru, K. & Jordan, T. H. Seismological structure of the upper mantle: a regional comparison of seismic layering. *Phys. Earth Planet. Inter.* **110,** 21–41 (1999).

32. Ritsema, J., Nyblade, A. A., Owens, T. J., Langston, C. A. & VanDecar, J. C. Upper mantle seismic velocity structure beneath Tanzania, east Africa: Implications for the stability of cratonic lithosphere. *J. Geophys. Res.* **103** (B9), 21201–21214 (1998).

33. Frederiksen, A. W. & Bostock, M. G. Modelling teleseismic waves in dipping anisotropic structures. *Geophys. J. Int.* **141,** 401–412 (2000).