

determining the balance between Si and N uptake by the biological community. □

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## Anisotropic structures at the base of the Earth's mantle

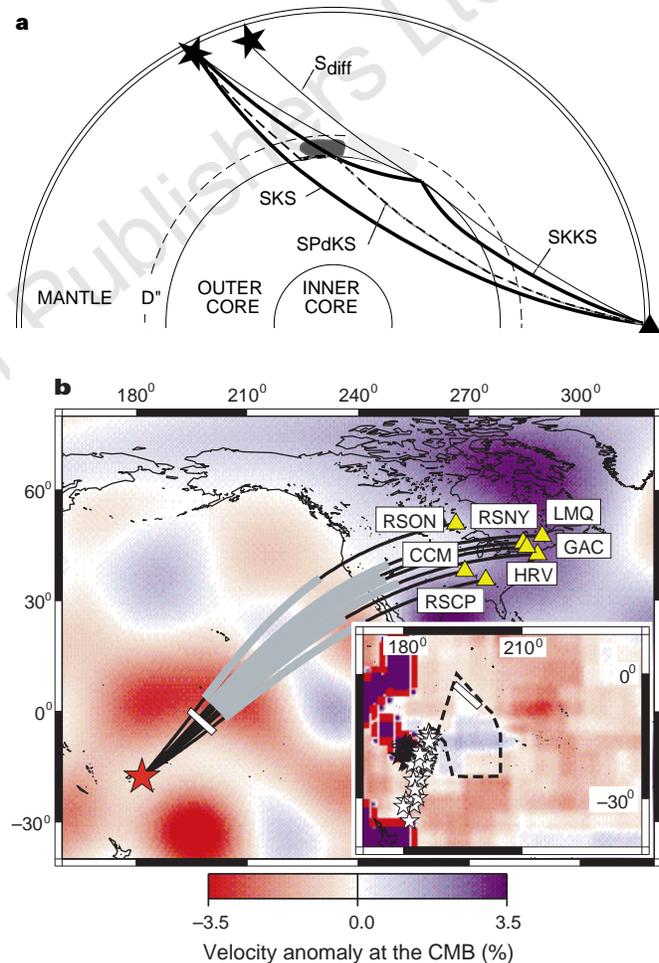
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The D'' shell at the base of the Earth's mantle is thought to be a thermal and compositional boundary layer where vigorous dynamical processes are taking place<sup>1–4</sup>. An important property of D'' is its seismic anisotropy, expressed as different velocities for horizontally and vertically polarized shear waves that have been diffracted or reflected at the core–mantle boundary<sup>5,6</sup>. The nature of this anisotropy has been the subject of debate<sup>7–11</sup>.

Here we present an analysis of various seismic phases, generated in the Kermadec–Fiji–Tonga zone and recorded at stations in North America, which reveal a region at the base of the mantle beneath the southwest Pacific Ocean where horizontally propagating vertically polarized waves are slower (by at least 10 per cent) than horizontally polarized waves. This observed anisotropy is an order of magnitude larger than that previously thought to exist in the lower mantle, and corresponds to lateral variations in horizontally polarized shear-wave velocity which are also of about 10 per cent. We speculate that this anisotropy may be the result of the mixing and shearing of strongly heterogeneous material in the boundary layer.



**Figure 1** Geometry of the data set considered. **a**, Schematic representation of the wave paths of SKS, SKKS, S<sub>diff</sub> and SPdKS. The wave paths of S<sub>diff</sub> for two different positions of the source (stars) differ only at the source side. The lightly shaded area indicates the region where SH is slow, as discussed in the text. The darker, hatched area is the region where SH velocity is elevated or normal, but SV is much slower than SH. **b**, Surface projections of wave paths superimposed on a tomographic model of SH velocity in D'' (ref. 15). The light-grey zone of the wave path indicates approximately the D'' leg of S<sub>diff</sub> for the shortest distances considered. The white bar corresponds to the kink for SH<sub>diff</sub>–SKS residuals, discussed in the text. Red star is location of earthquake source region; yellow triangles and 3/4-letter codes indicate station locations and names, respectively. Inset, close-up look at the source side of the wave-paths. Epicentres of deep Fiji–Tonga events and of shallow Kermadec–Fiji–Tonga events are shown by filled and open stars, respectively. The background tomographic model of S-wave velocity in D'' is from ref. 16. The polygon indicates the zone of ultra-low P-wave velocity in D'' (ref. 18). The barcode indicates amplitudes of shear velocity anomalies at the core–mantle boundary (CMB) in the tomographic models<sup>15,18</sup>.

The first part of our analysis is based on the residuals of differential travel times between seismic phases  $SH_{diff}$  and SKS/SKKS relative to those for the standard Earth model PREM<sup>12</sup>. ( $SH_{diff}$  are horizontally polarized S waves that have been diffracted at the core–mantle boundary; SKS/SKKS are shown in Fig. 1.) Differential travel times are helpful because they are not sensitive to errors in focal parameters of seismic events and structural complexities in the source region. Contrary to earlier studies<sup>13,14</sup>, we consider (1) not the absolute values of the residuals, but rather the slopes of the resulting time–epicentral distance plots; (2) not the average residuals for many stations, but the individual slope for every station; and (3) not only the residuals for deep events, but also for intermediate and shallow events. For the given source–receiver geometry (Fig. 1) and a fixed station, changes of the wave path occur practically only at the source side of the wave path.

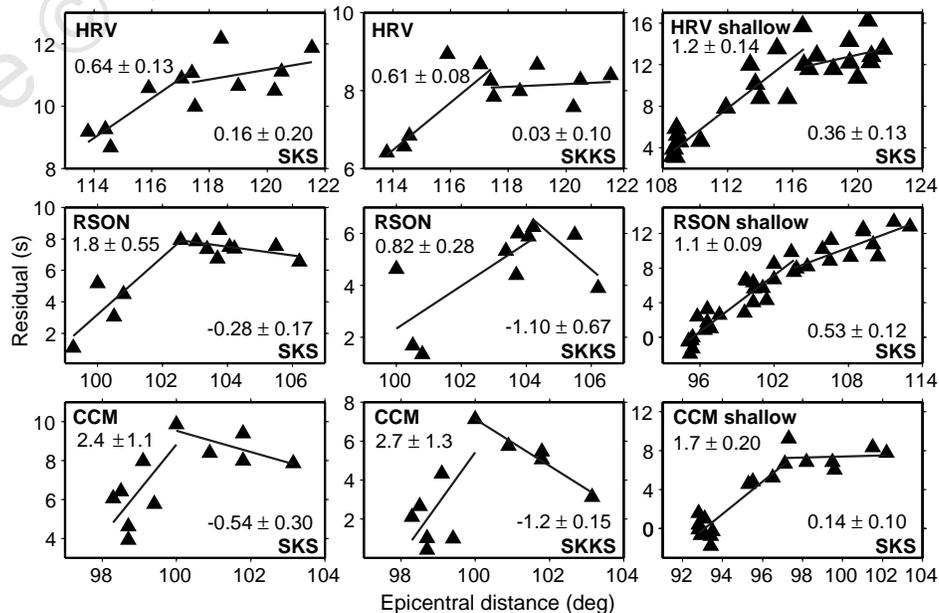
The residuals as a function of epicentral distance show a remarkable trend, consistent from station to station, for shallow and deep events and whether SKS or SKKS is used as reference phase. Figure 2 shows examples for the three best stations. Each panel can be divided into two parts, with rapidly increasing residuals at shorter distances, and slowly rising (or decreasing) residuals at larger distances. To make this trend more visible, we divide each set of measurements into two subsets corresponding to epicentral distances smaller than or equal to, and greater than or equal to, a variable cut-off distance. When the best-fitting position of the cut-off and linear fits on both sides of it are obtained by regression, the average variance reduction is twofold with respect to a single regression line. We note that the epicentral distance of the change of slope (the ‘kink’) varies (for example, 116–117° at HRV; 103–104° at RSON), depending on the epicentral distance range of the Kermadec–Fiji–Tonga seismic zone to the given station. Comparable results are obtained for the other stations where a similar analysis was performed: RSCP, LMQ, RSNY and GAC (Fig. 1).

The features in Fig. 2 cannot be explained by mantle complexity immediately beneath the seismic foci, because the change of slope is

present in the data for both deep and shallow events. Therefore, our preferred explanation for the kink is a first-order change in the properties of the lowermost mantle at the source side of the wave-path. Moreover, SKS and SKKS ray-paths are separated in  $D''$  by a distance exceeding 10°, and a similar trend in the residuals in Fig. 2 with respect to SKS and SKKS implies that the effect is mainly in the travel times of  $SH_{diff}$ . If the position of the kink for every station is inverted for the position of the corresponding border in the  $D''$  layer, assuming that SH enters  $D''$  at a height of 300 km above the core–mantle boundary, the estimates for different stations are mutually consistent and correspond to the white bar in Fig. 1b. In experiments with synthetic seismograms, the anomaly of slowness of 1.1 s per degree corresponds to S-wave velocity in  $D''$  reduced by ~10% with respect to PREM. The region of anomalously low SH-wave velocity is located to the northeast of the bar (Fig. 1b), whereas SH velocity to the southwest of the bar is either slightly elevated or normal. Qualitatively, this division is confirmed by two recent tomographic models<sup>15,16</sup> (Fig. 1b), but the magnitude of the low-velocity anomaly in both models is ~3 times smaller than in our data. Robustness of our technique is confirmed by other data<sup>17</sup>.

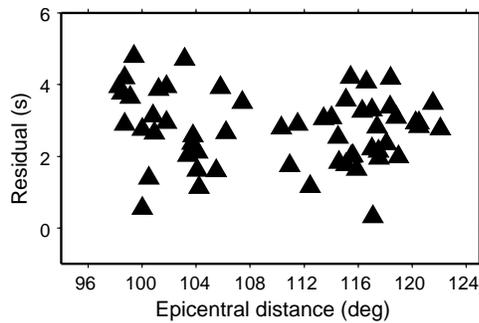
The residuals of SKKS–SKS differential travel times relative to PREM, derived from our data (Fig. 3) are positive, with an average value of around 2–3 s. As argued in ref. 18, these positive residuals can only be explained by anomalously low S-wave velocity in the lowermost mantle on the source side, due to the longer paths of SKKS relative to SKS. Our data, however, indicate that, on the source side, SKS and SKKS propagate in a region of  $D''$  with normal SH velocity (Fig. 1b). As SKS and SKKS are SV polarized, to explain the discrepancy at least partly, we suggest that although SH velocity is normal, SV velocity in the lowermost mantle on the source side is anomalously low. (SV indicates vertically polarized S waves.)

To obtain quantitative estimates of this anisotropy, we assume that the lowermost mantle is intrinsically isotropic, finely layered and horizontally stratified. For long waves, it behaves like a homogeneous transversely isotropic medium with a vertical axis of



**Figure 2** Residuals of  $SH_{diff}$ –SKS and  $SH_{diff}$ –SKKS differential travel times with respect to those for PREM<sup>12</sup>, for HRV/WFM, RSON and CCM, and corresponding regression lines. The data labelled ‘shallow’ are for shallow and intermediate events; all others are for deep events. Shallow events broaden the distance interval available for SKS. The slopes of the plots are controlled mainly by the slowness of  $SH_{diff}$  and, consequently, by SH velocity at the source side of  $D''$ . The slope is negative, positive or equal to zero, if SH velocity is higher, lower or similar

to that in PREM. Numerical values of the slopes of the regression lines with their respective confidence intervals are shown in the upper left and lower right corners of each panel. Confidence intervals are usually around  $\pm 0.1$ – $0.3$  s per degree, but they exceed  $\pm 1.0$  s per degree for deep events at CCM, left of the kink. If the latter data are excluded, the average values of the slopes are  $1.12 \pm 0.2$  and  $-0.21 \pm 0.2$  s per degree, left and right of the kink, respectively.



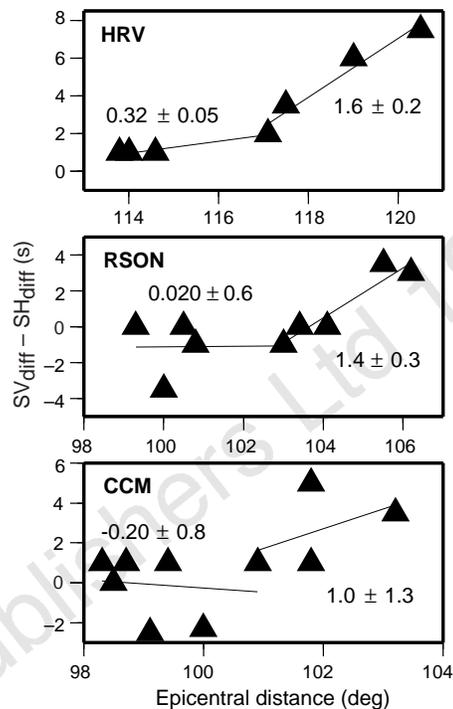
**Figure 3** SKKS-SKS residuals for all paths in Fig. 1b. Comparable residuals were reported for similar wave-paths in earlier studies<sup>13,18,24</sup>. For other paths beneath the Pacific and America, the residuals are close to zero<sup>18,24</sup>.

symmetry<sup>19–21</sup>. In this medium,  $SH_{diff}$  and  $SV_{diff}$  propagate independently, with the former faster than the latter, which is consistent with the seismic observations<sup>5</sup>. To explain residuals of  $\sim 2$  s, SKS and SKKS velocities in a layer 300 km thick should be  $\sim 10\%$  lower than standard velocity. For the angles of incidence characteristic of SKS and SKKS, the SV velocities are larger than for horizontal propagation. Then the difference between SH and SV velocities for horizontal propagation can be even higher than 10%. This prediction can be tested by observing propagation of  $SH_{diff}$  and  $SV_{diff}$ .

The seismic phase  $SV_{diff}$  is usually weak, and can be easily distorted by effects of azimuthal anisotropy in the mantle outside  $D''$  and side refraction of  $SH_{diff}$ . To eliminate these effects and to pick arrivals of  $SV_{diff}$  accurately, we have devised a special technique<sup>22</sup>, illustrated in ref. 22 for the records of HRV/WFM and RSON. For the present study, a search for  $SV_{diff}$  has been conducted in the records of the deep Fiji-Tonga events at seismograph stations shown in Fig. 1b. The best data set has been obtained at HRV/WFM, RSON and CCM. Remarkable features of the detected  $SV_{diff}$  signals are their distance-dependent delays relative to  $SH_{diff}$  (Fig. 4). At shorter distances, the slopes of the plots are close to 0 s per degree, whereas at larger distances they are in the range 1.0–1.6 s per degree. Then anisotropy is weak (not more than a few per cent) in the region of very low SH velocity (northeast of the white bar in Fig. 1b), and  $\sim 15\%$  in the region of normal SH velocity, southwest of the bar. Anisotropy of  $\sim 15\%$  is stronger by about an order of magnitude than reported elsewhere.

Additional data on the properties of  $D''$  beneath the southwest Pacific are provided by the observations of SPdKS (Fig. 1a). This phase propagates as  $P_{diff}$  in  $D''$  and as SKS elsewhere<sup>23</sup>.  $P_{diff}$  beneath the southwest Pacific is anomalously slow<sup>18,24</sup>, with a remarkable correlation between the anomalous delays of SPdKS relative to SKS and positive SKKS-SKS residuals, similar to those shown in Fig. 3. An explanation for this phenomenon is partial melting<sup>25</sup>. The anomalously slow  $P_{diff}$ , however, propagates on the source side in a medium with normal SH velocity (Fig. 1b), which is hard to reconcile with a strong reduction of S velocity, expected in the case of partial melting. Because, as we have demonstrated, the SKKS-SKS residuals can be related to anisotropy, the correlation between them and SPdKS delays suggests that the delays are affected by anisotropy as well. Moreover, east of the white bar in Fig. 1b, where (according to our data) anisotropy is weak, the layer of low P-wave velocity, if present, is very thin<sup>26</sup>. Assuming that the SPdKS delays are related to anisotropy, we note that the low horizontal P-wave velocity in a fine-layered horizontally stratified medium is possible if the variations of S-wave velocity between the layers are much stronger than those of P-wave velocity<sup>20</sup>. Another possibility to be considered is lattice preferred orientation<sup>27</sup>.

For normal distribution of random variations of S-wave velocity in the stack of thin horizontal layers with mean  $m$  and standard



**Figure 4** Delays of  $SV_{diff}$  with respect to  $SH_{diff}$  as a function of epicentral distance for stations HRV/WFM, RSON and CCM. The slope of any of the plots is the difference in slowness between  $SV_{diff}$  and  $SH_{diff}$  at the source side of the wave-path. Magnitude of anisotropy can be determined as the ratio between these slopes, and the standard slowness of 8.4 s per degree. Each data set is approximated by two regression lines. The boundaries between the corresponding distance intervals are taken from Fig. 2. Numerical values of the slopes of the regression lines with their respective confidence intervals are shown adjacent to the corresponding portions of the plots.

deviation  $\sigma$ , the SH/SV velocity ratio for horizontal propagation is expressed<sup>20</sup> as  $SH/SV \approx \sqrt{1 + 4(\sigma/m)^2}$ . For S-wave anisotropy of 15%,  $\sigma$  thus evaluated is 28% of  $m$ . It is not possible to explain the variations exceeding a few per cent solely by temperature variations<sup>28</sup>. S-wave velocity can be significantly lowered by partial melting or/and by accumulation of crystalline iron-alloy products of chemical reactions between iron of the outer core and mantle perovskite<sup>29</sup>. Among these possibilities, relatively weak variations of P-wave velocity favour partial melting. The layered structure in  $D''$  could be generated by convective mixing and shearing. Then, strong anisotropy in  $D''$  should be accompanied by strong wave scattering. The anomalous region of  $D''$ , if projected on the surface of the Earth, is close to Polynesia, a region of unusual thermal agitation, where a large-scale thermochemical plume may be present at the top of the lower mantle<sup>30</sup>. The anisotropic region in  $D''$  could somehow be related to the same plume.

Comparable magnitudes of lateral heterogeneity and anisotropy suggest that lateral variations of anisotropy can be mistaken for lateral velocity variations, when the models are derived under the assumption of isotropy. Whatever its origin, the observations of strong and laterally variable anisotropy add a new dimension to the question of properties and processes in the  $D''$  layer.  $\square$

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## Ediacara-type fossils in Cambrian sediments

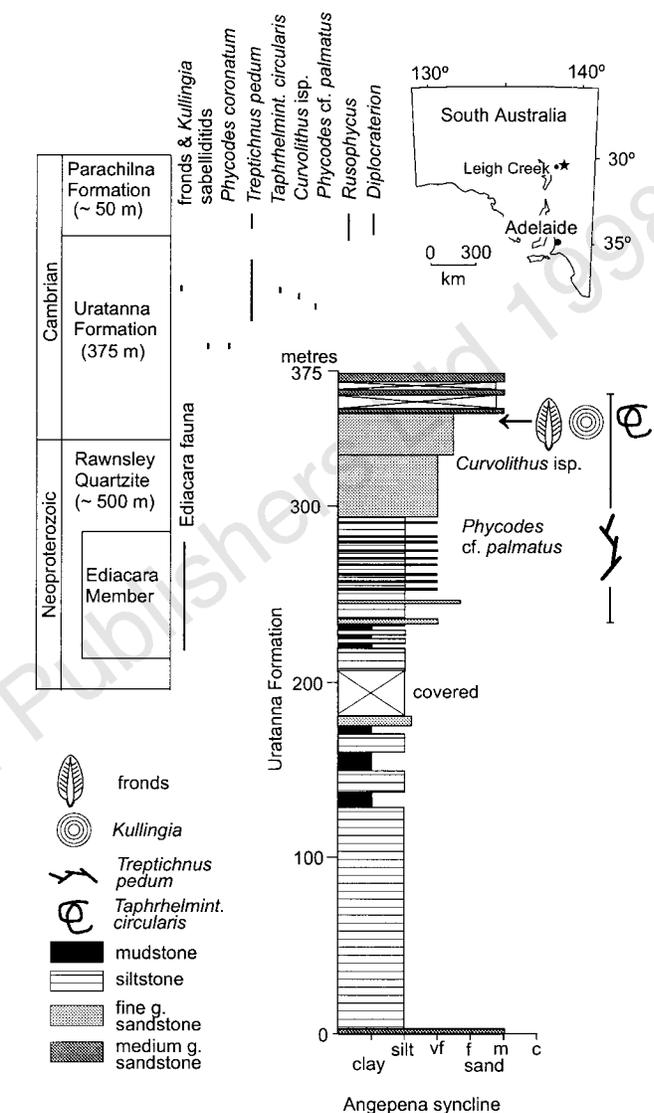
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Fossil assemblages that preserve soft-bodied organisms are essential for our understanding of the composition and diversity of past life. The worldwide terminal Proterozoic Ediacara-type fossils (from ~600–544 Myr BP) are unique in consisting of soft-bodied animals, which are typically preserved as impressions in coarse-grained sediments<sup>1–4</sup>. These Lagerstätten are also special because they pre-date the major burst of skeletonization, which occurred near the start of the Cambrian period<sup>3</sup>. Most Ediacara-type fossils are interpreted to be cnidarians, but higher metazoans such as annelids and molluscs may also be represented<sup>1–4</sup>. However, the unique style of preservation and difficulties in finding convincing



**Figure 1** Location (marked by an asterisk, top right) and stratigraphic context of Ediacara-type fronds from the Uratanna Formation, in the Angepena syncline, northern Flinders Ranges. The simplified lithological log (bottom left and right) shows the occurrence of fronds and *Kullingia* and the distribution of selected trace fossils. The stratigraphical context of the Uratanna Formation and a range of selected faunal elements is shown schematically (top left). g, grained; vf, very fine; f, fine; m, medium; c, coarse.

morphological homologies with definite animals have led some specialists to prefer non-metazoan interpretations, such as Vendobionta<sup>5</sup>. In addition, the rarity of Ediacara-type fossils in younger sediments has led to suggestions of a terminal Proterozoic mass extinction<sup>6</sup>. Here we report typical Ediacara-type frond-shaped fossils that occur together with an assemblage of Cambrian-type trace fossils in unequivocally Cambrian-aged sediments of the Uratanna Formation, South Australia. This occurrence bridges the apparent divide between the terminal Proterozoic and Cambrian fossil assemblages, and also suggests that closure of a taphonomic window (an interval of time with unique preservational conditions) was as important as extinction in the disappearance of Ediacara-type organisms.

One of the great controversies in animal evolution concerns the significance of the worldwide terminal Proterozoic soft-bodied Ediacaran fauna<sup>1–5</sup>. The traditional interpretation of these fauna as including early representatives of Phanerozoic phyla such as