Complex Anisotropy in the Australian Lithosphere from Shear-wave Splitting in Broad-band SKS Records

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Shear wave splitting of seismic core phases (such as SKS and SKKS) reveals complex azimuthal anisotropy in continental Australia. Using broad-band seismograms recorded at stations deployed for the SKIPPY project we are able to supplement the previously spatially sparse shear-wave splitting measurements from permanent stations. This enables us to study Australian continental anisotropy on an unprecedented scale and to investigate the variation of shear-wave splitting across the continent. Using the broad band width of the seismograms, we demonstrate that differing SKS splitting phenomena are manifested at different frequencies. At a frequency of about 1 Hz, the time difference between fast and slow SKS waves is 0.3-0.6 s, and the polarization directions parallel pre-existing crustal fabric rather than present-day compressional stress axes. Over a broader frequency band, the polarization directions are inconsistent with present-day plate motion direction but can possibly be explained by predominant mineral orientation in the sub-crustal lithosphere.

INTRODUCTION

Shear waves passing through anisotropic material (characterised by direction-dependent elastic properties) split into orthogonally polarised waves with different wave speeds [Crampin, 1985]. The splitting, or birefringence, of core phases such as SKS is now almost routinely used to investigate seismic anisotropy in the Earth's mantle and its relationship to tectonic deformation [Silver and Chan, 1991; Vinnik et al., 1992].

After phase conversion at the core-mantle boundary (CMB) the shear waves propagate nearly vertically to the Earth's surface, forming isolated arrivals beyond 80_, making them ideal for the study of tectonically stable regions. In an isotropic, spherically symmetric Earth, SKS would be observed only on the radial component of the shear-wave field. Significant transverse energy, combined with non-linear particle motion, indicates shear-wave splitting due to anisotropy. Owing to the nearly vertical path to the receiver, any anisotropy inferred from shear-wave splitting is well resolved laterally, but there is little constraint on its depth. The potential source zone is approximately 3000 km, from the CMB to the surface of the Earth, although it is now generally accepted that the strain-induced Lattice Preferred Orientation (LPO) of anisotropic minerals in the upper mantle is the main source region [Mainprice and Silver, 1993]. For an extensive

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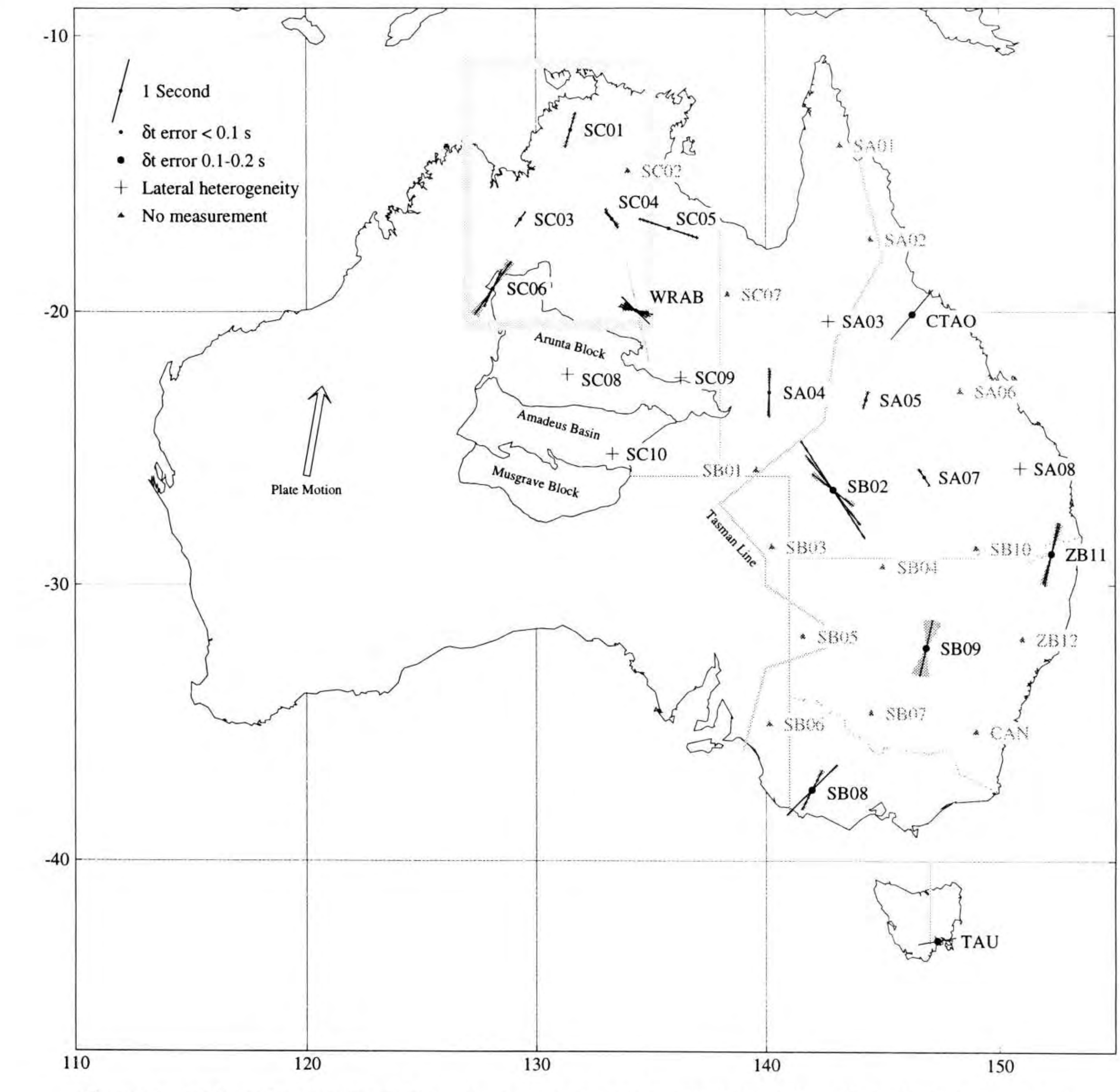

Figure 1. Study region and station locations. Also shown is the present-day motion of the Australian continent relative to Eurasia (DeMets et al, 1990), open arrow, and the outlines of geological features discussed in the text. The measurements at CTAO and TAU are after Vinnik et al, (1992).

review of investigations of anisotropy based on shear wave splitting we refer to Silver [1996].

We investigated azimuthal anisotropy for the central and eastern part of the Australian continent using SKS, SKKS and pPKS phases recorded at permanent stations and at arrays of portable broad-band seismometers of the SKIPPY project [Van der Hilst et al., 1994) (Figure 1). The SKIPPY project was designed to exploit regional seismicity [Van der Hilst et al., 1994; Zielhuis and Van der Hilst, 1996] but also provides data for the construction of an anisotropy map of the Australian continent. The data redundancy to constrain the measurements is limited as a result of the relatively short operation period of each array, but we believe that the spatial coherency of polarization directions provides significant new information on the origin of splitting. In addition, shear-wave splitting manifests itself at different frequencies, depending on site location and seismic phase used. Splitting observed at relatively high frequencies suggests that shear-wave data also carry structural signals about anisotropy in the crust. Our results are consistent with inferences from the splitting of high-frequency shear-waves excited by (sub-) crustal micro-earthquakes [Kaneshima, 1990], or by phase conversion at the crust-mantle interface [e.g., Herquel et al., 1995] and quantitatively agree with results of petrophysical modelling [Barruol and Mainprice, 1993] .

METHOD AND DATA

Shear-wave splitting is usually quantified by the fast polarization direction (ϕ) and the time delay (δt) of the slow wave. Following Silver and Chan [1991], we searched for the pair ($\phi, \delta t$) that most successfully corrects for the effects of anisotropy by minimising (i) the energy, E_t, on the transverse component and (ii) the smaller eigen value, λ_2, of the two-dimensional covariance matrix of corrected horizontal particle motion, which is equivalent to searching for the most linear particle motion. We used (i) to obtain the measurements and (ii) to assess the influence of lateral heterogeneity, if any. For each measurement confidence bounds (σ_ϕ and σ_{dt}, the 1σ uncertainties), defined by ($\phi, \delta t$), are determined from the F probability distribution where E_t/E_{tmin} is less than a critical value. Three additional diagnostics were used to assess the ability of the method to correct for anisotropy (Figure 2, D-G): (i) The radial and transverse components are corrected using the splitting parameters ($\phi, \delta t$); this provides a visual measure of the ability of the method to minimise E_t, the energy on the transverse component (Figure 2, D). (ii) A contour plot of $E_t(\phi, \delta t)$ in multiples of the 95% confidence interval; this allows a check for multiple minima and a check of the uncertainty in each measurement (Figure 2, E). (iii) A check of the particle motion for the corrected fast and slow components (Figure 2, F), this allows an assessment of the degree to which the correction produces linear particle motion (Figure 2, G).

We searched for earthquakes at distances beyond 85_ and at depths larger than 80 km with isolated impulsive SKS or SKKS phases well recorded at permanent observatories and SKIPPY stations. In the case of SKKS it is important to ensure that it is well isolated from SK_3S, otherwise interference between these phases at the CMB may violate the assumption of radial polarisation. For one event, we were able to use pPKS phases. We measured ($\phi, \delta t$) and their uncertainties for all available SKS, SKKS and pPKS phases with a significant transverse signal. Unfortunately, the short deployment period of each array,

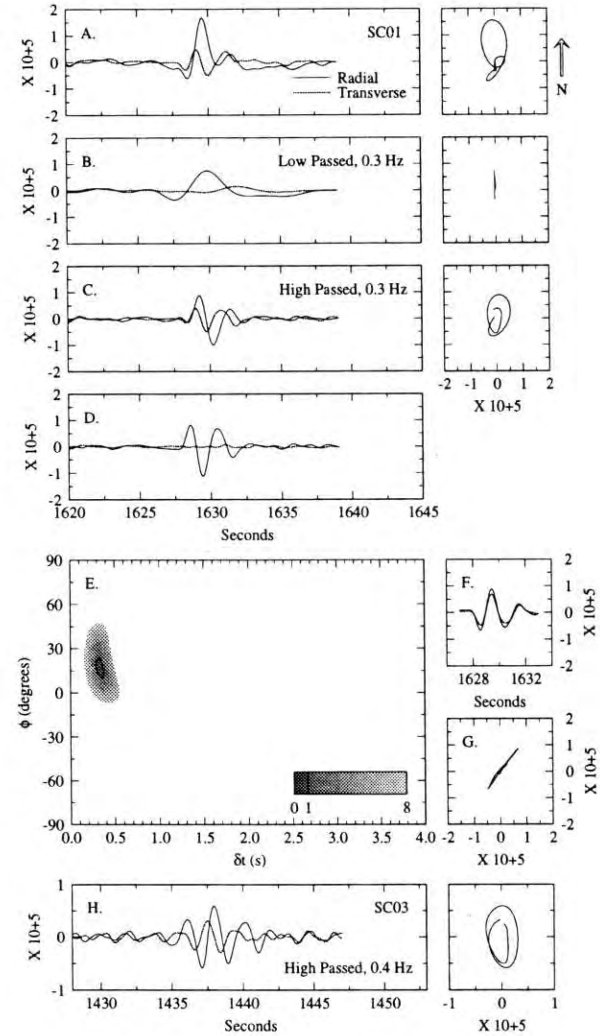

Figure 2 (A-G). SKKS splitting at different frequencies and measurement diagnostics for event 94 231, back azimuth = 160.47°, recorded at SC01.

and the need for deep, large, distant events, limits the number of suitable shear-wave phases recorded at the SKIPPY stations. In total we used 23 shear-wave phases (11 SKS, 7 SKKS, 5 pPKS) from 10 earthquakes recorded on 14 of the 30 SKIPPY stations. We used data from two events with focal depth less than 80 km (Table 1).

We could not determine the splitting parameters unambiguously for all stations. For five SKIPPY stations (SA03, SA08, SC08, SC09, SC10) and for CTAO (Charters Towers, Queensland), ϕ appeared to depend on back azimuth, and the particle motions were linear instead of elliptical. This indicates that the signal on the transverse component was not due to anisotropy but to structural heterogeneity. Of these, SC08, SC09, and SC10 were located near the Arunta and Musgrave Blocks (Figure 1) where

Table 1. List of Events Used in Study.

Date	Lat. (°N)	Long. (°W)	Depth (km)	m_b
93 221	36.436	70.711	204	5.8
93 221	36.379	70.868	215	6.2
93 247	36.429	70.812	195	5.9
93 323	54.290	-164.16	30	6.1
94 010	-13.339	-69.446	596	6.4
94 073	15.994	-92.428	165	5.8
94 119	-28.326	-63.221	571	6.3
94 130	-28.551	-63.070	603	6.4
94 143	18.174	-100.547	59	6.0
94 231	-26.653	-63.378	564	6.0

thrust faults probably dip through the entire crust [Lambeck and Burgess, 1992], and SA03 and SA08 were located in regions of complex surface faulting. For event 94 010 (see Table 1) at SB03, no significant transverse component SKS (or SKKS or pPKS) was observed even though the phase was well recorded on the radial components. This may indicate either the absence of significant anisotropy, or the alignment of event back azimuth with the fast or slow polarization direction. We found no convincing evidence for splitting at NWAO (Narrogin, Western Australia) and the splitting measurements at CAN (Canberra, ACT) are ambiguous. Reported values for CTAO and TAU are not well constrained [Vinnik et al., 1992]. The following SKIPPY stations did not record useful SKS, SKKS, or pPKS phases; SA01, SA02, SA06, SB01, SB06, SB07, SB10, SC02, SC07. At 12 SKIPPY stations and WRAB splitting measurements were made.

Shear-wave splitting is often determined from long-period or broad-band seismograms, with the latter low-pass filtered to suppress noise [Vinnik et al., 1992; Gledhill and Gubbins, 1996]. In the present case such filters were often found to remove the transverse shear-wave energy that was perceptible in the original records. In some cases, it was observed that application of filters that pass energy in different frequency bands revealed shear-wave splitting only at frequencies higher than 0.3 Hz. For an isolated SKKS phase, with clearly observed transverse energy in the record at SKIPPY station SC01, we can observe the following (Figure 2, A). When this data is low-passed at 0.3 Hz (Figure 2, B), there is little energy apparent on the transverse component and particle motion is linear. High passing at 0.3 Hz shows clear transverse energy (Figure 2, C), which has the same form as the unfiltered data. Resultant particle motion is clearly elliptical. Splitting measurements made (by minimising E_t) on the SKKS phase, high-passed at 0.3 Hz, yielded the following splitting parameters: ϕ = 17_ (σ_ϕ = 2), δt = 0.32 s ($\sigma_{\delta t}$ = 0.02) . Using these parameters to correct the radial and transverse components we are able to asses their ability to remove the effects of shear-wave splitting. Using ϕ to rotate to a fast-slow reference frame there is little energy apparent on the corrected transverse component (Figure 2, D). The contour plot of E_t (Figure 2, E) shows a single, well constrained, localised minimum. Using δt to time shift the radial and transverse components (Figure 2, F) yields excellent phase coherence with resultant linear particle motion (Figure 2, G). This indicates that the method is able to correct well for the effects of anisotropy. At high frequencies, scattering may result in transverse energy. Consistency between measurements obtained by minimising E_t and λ_2 confirms that we are observing the effects of anisotropy. This can also be seen visually in the particle motion for the high-passed SKKS phase (Figure 2-C). It is elliptical, moves off in the fast direction, and returns, orthogonally to it, in the slow direction. Shear-wave splitting only at higher frequencies (higher than 0.3 Hz) was observed at SC01, SC03, SC04, SC06 and WRAB. In all cases the data were low-pass filtered at 1.5 Hz to suppress noise.

RESULTS AND DISCUSSION

The measurements along with their uncertainties are summarised in Figure 1. Each ($\phi,\delta t$) is plotted as a line; ϕ is the angle of the line and the length of the line is proportional to δt. Error estimates for each measurement are shown by: i) for σ_ϕ a shaded diabolo (e.g Figure 1. station SB09); in many cases this diabolo is too small to be visible; ii) for $\sigma_{\delta t}$ the size of the station point represents error; $\sigma_{\delta t}$ less than 0.1 s is shown with a small circle, $\sigma_{\delta t}$ 0.1-0.2 s with a large circle. Some measurements overlap. A cross denotes sites where lateral heterogeneity obscures any splitting due to anisotropy. Splitting was observed only at higher frequencies at SC01, SC03, SC06, SC04, and WRAB. These stations and the surrounding region within the grey rectangle are shown in detail in Figure 3. All other measurements (stations mainly in eastern Australia) are made over wider frequency ranges including frequencies below 0.3 Hz (low-passed at 1.5 Hz).

The directions of fast polarization inferred from the high-frequency records at WRAB show a remarkable alignment with macro-scale crustal fabric, in particular with pervasive faulting in the Proterozoic basement, and with the fault planes of the 1988 Tennant Creek earthquakes [Bowman, 1992] (Figure 3, inset). Also for the SKIPPY stations there is a strong correlation between the orientation of crustal features and the ϕ determined at high frequency. For instance, the polarization direction at SC01, SC03, and SC06 coincides with the NNE strike of major shear zones that separate the Kimberley block from the central Australian craton (Figure 3). These observations strongly suggest a relationship between splitting of shear waves with wave lengths λ of the order of 5 to 10 km and crustal structure.

The small magnitude of the delay times, a few tenths of a second, can indeed be explained by crustal anisotropy alone [Barruol and Mainprice, 1993; Alsina and Snieder, 1995], although it does not rule out a larger source of weak anisotropy. Petrophysical analysis demonstrated that several types of crustal rock may produce some amount of anisotropy [Barruol and Mainprice, 1993], and that geological structures, in particular steeply dipping foliation in felsic rocks and amphibolites, can produce significant shear-wave splitting (0.1-0.2 s delay per 10 km). These numbers are in quantitative agreement with our observations: a crustal thickness beneath WRAB of 50 km [Collins, 1991] and a delay δt Å 0.5 s render a delay time of 0.1 s per 10 km of crustal rock, equivalent to ~3.5 % anisotropy, which is also consistent with magnitude of crustal anisotropy inferred for other regions [Kaneshima, 1990; Herquel et al., 1995; Gledhill and Stuart, 1996]. We argue that the anisotropy signal is due to crustal fabric caused by folding and faulting/shearing. At low effective confining pressures or at high pore pressures, such as in the upper crust, anisotropic fabric can also be caused by micro-cracks aligned in the direction of compressional tectonic stress [Crampin, 1985]. The inferred north-south orientation of compressional stress in this region of the Australian continent [Coblentz, 1995] does, however, not support this explanation for our observations.

Tong et al. [1994], using high-frequency SV and SH waves recorded at the Waramanga array after horizontal propagation through the lithosphere, argued that scattering due to heterogeneity may have masked any splitting due to lithospheric anisotropy. However, using waves refracted from the upper-mantle transition zone, they infer 1.4% transverse anisotropy in the asthenosphere. This is not necessarily inconsistent with our inferences, since shear waves do not carry information about this class of transverse isotropy.

In accord with previous observations of shear-wave splitting [Silver and Chan, 1991; Vinnik et al., 1992; Silver, 1996], the splitting of broad-band shear waves (δt Å 1.0-2.0 s) is significantly more pronounced than the signal that we attribute to crustal anisotropy. We remark that waves at frequencies of about 50 mHz, and λ Å 90 km, are less sensitive to 10-km scale crustal fabric. Concurring with other investigators we therefore invoke a larger, deeper anisotropy source to explain the large time delays at the remaining stations. The alignment of ϕ inferred for eastern Australia (Figure 1) could be explained by either

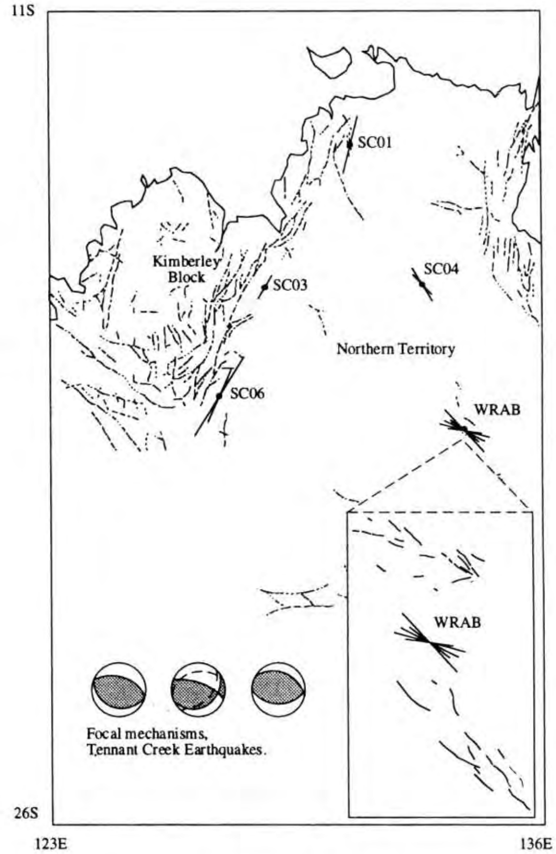

Figure 3. Polarization directions from high-frequency records of WRAB, SC01, SC03, SC04, and SC06 in relation to major crustal features (faults and thrusts). The inset shows detailed structural trends in the vicinity of WRAB and the focal mechanisms of the large Tennant Creek earthquakes of January 1988 (Bowman, 1992).

'fossil' anisotropy [Silver and Chan, 1991] or by asthenospheric flow [Vinnik, 1992]. Fossil anisotropy is supported by the tentative observation that polarization directions in eastern Australia exhibit a curvilinear trend somewhat similar to that of the "Tasman Line", the presumed, but poorly constrained [Zielhuis and Van der Hilst, 1996], eastern boundary of the Proterozoic cratons (Figure 1). Shear-wave splitting possibly indicates anisotropy frozen into the lithospheric mantle during Paleozoic terrane accretion that resulted in, from west to east, the Adelaide, Lachlan, and New England Fold Belts [Collins and Vernon, 1994]. Alternatively, the curvilinear trend of ϕ could be explained by alignment of olivine crystals by asthenospheric flow around the irregularly shaped eastern edge of the deep continental root. A similar model has been proposed to explain the spatial variation in splitting direction observed for the North American continent (Fischer, personal communication, 1996).

CONCLUSIONS

From the broad-band data we infer that shear wave splitting can be manifest at different frequencies. Higher frequency waves (λ Å 5-10 km) are polarised by anisotropic crustal fabric. In the examples given, crustal anisotropy is most likely due to structural features such as pervasive foliation, and our observations are in accord with petrophysical data. In Eastern Australia, the splitting of broad-band shear waves may be due to fossil anisotropy frozen into the lithosphere, or anisotropy induced by flow in the asthenosphere.

At this stage of data processing, we cannot yet state whether splitting occurs exclusively at either high or low frequency, or whether the splitting parameters are a more continuous function of frequency. The former could point to the existence of two anisotropic layers, which can be investigated using the two-layer approach of Silver and Savage [1994]. The latter would point to a more complex source of anisotropy, which calls for rather different analysis tools that exploit the broad-band nature of splitting, and perhaps provide a stochastic characterisation of the anisotropic medium [Gaherty et al., 1996]. We aim to investigate the effect of depth- and scale-dependent anisotropy on shear-wave splitting with wave-form modeling. Upon completion of the remaining three deployments of SKIPPY, we may also be able to infer the typical length scale of LPO and thus constrain stochastic anisotropy models proposed for the Australian lithosphere [Gaherty and Jordan, 1995].

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