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Mantle deformation beneath southern Africa

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Abstract. Seismic anisotropy from the southern African mantle has been inferred from shear-wave splitting measured at 79 sites of the Southern African Seismic Experiment. These data provide the most dramatic support to date that Archean mantle deformation is preserved as fossil mantle anisotropy. Fast polarization directions systematically follow the trend of Archean structures and splitting delay times exhibit geologic control. The most anisotropic regions are Late-Archean in age (Zimbabwe craton, Limpopo belt, western Kaapvaal craton), with delay times reduced dramatically in off-craton regions to the southwest and Early-Archean regions to the southeast. While thin lithosphere can account for weak off-craton splitting, small or vertically incoherent anisotropy is a more likely explanation for the Early-Archean region. We speculate that this difference in on-craton anisotropic structure is the result of two different continent-forming processes operating.

Introduction

How ancient continents form and how they evolve, remain two of the most basic questions facing Earth scientists. It has become increasingly clear over the last few decades that the mantle plays a significant, if not dominant, role in these processes [*e.g., Jordan,* 1988*; Fei et al.,* 1999]. Southern Africa is an ideal locale for studying this mantle component. It contains some of the largest intact terrains of Late- and Early-Archean ages, as well as an abundance of kimberlite-derived mantle nodules that provide a direct sampling of the mantle. One fruitful approach to studying the subcontinental mantle is to analyze its seismically-inferred history of deformation [e.g., *Silver and Chan,* 1988, 1991*; Silver and Kaneshima,* 1993*; Silver,* 1996*; Silver et al.,* 1999]. That the mantle portion of continental plates is pervasively deformed is well documented by the mantle nodules [*Mainprice and Silver,* 1993*; Ben Ismail et al.,* this issue]. These same nodules also exhibit strain-induced lattice preferred orientation (LPO). Through LPO, this deformation is manifested macroscopically as seismic anisotropy, defined as the dependence of wave speed on both propagation and polarization directions. Seismic anisotropy is thus an important measure of mantle deformation, past and present, with the nodules providing a key interpretative link.

Using teleseismic shear waves with near-vertical paths through the upper mantle beneath the station, shear-wave splitting, a direct manifestation of anisotropy, is particularly valuable in studying subcontinental mantle deformation because it provides excellent lateral resolution. The two splitting parameters, fast polarization direction, ϕ, and delay time, δt, are measures of the orientation and magnitude of mantle deformation, respectively. δt in turn depends on three factors: the intrinsic anisotropy, the thickness of the anisotropic region, and the vertical coherence of mantle deformation.

In this report, we utilize the more than 80 sites of the Southern African Seismic Experiment (SASE) to measure the anisotropy of the southern African upper mantle, and address the causes of the inferred deformation. Two candidate processes are expected to dominate subcontinental mantle deformation: vertically coherent deformation of the plate, and deformation due to the differential motion between the plate and a presumed stationary mantle [*Silver,* 1996]. The former hypothesis predicts that ϕ should be parallel to the dominant deformational structures produced by the last tectonic event, be it Archean, as in southern Africa, or present-day, as in Tibet [*Silver,* 1996*; McNamara et al.,* 1994*; Holt,* 2000]. The latter predicts that $\phi = \phi_{APM}$, an orientation that is parallel to the absolute motion (APM) of the African plate. The issue of which process dominates has been controversial; both have been invoked for southern Africa based on data from 8 sites on the southern Kaapvaal craton [*Vinnik et al.,* 1995*; Silver,* 1996]. The order-of-magnitude more data available to us permits the resolution of this issue.

The Kaapvaal craton is the oldest continental mass from which shear-wave splitting measurements have been made. It is an ideal location because there are significant variations in the directions of structural features, and numerous kimberlite nodules [*Kaapvaal Working Group,*this issue]. Based on previous studies of its tectonic history, southern Africa can be divided into seven subdomains [*de Wit et al.,* 1992*; Tankard et al.,* 1982*; de Beer and Stettler,* 1988*; de Wit and Roering,* 1990] (Figure 1). Area A: Zimbabwe craton near the Great Dyke. Area B: southwestern corner of the Zimbabwe craton. Area C: western half of the Kaapvaal craton. Area D: Limpopo belt, formed by the collision between Zimbabwe and Kaapvaal cratons. Area E: southeastern Kaapvaal craton. Area F: Namaqua–Natal mobile belt. Area G: Cape fold belt. Areas A-D are Late-Archean in age (2.5-3 Ga), E is Early-Archean (3.0-3.7 Ga), and F and G are younger than 2.0 Ga.

Data and Method

The shear-wave splitting data set consists of 473 records of SKS and 142 SKKS phases recorded by 79 broadband seismic stations from 91 events, which cover a broad back azimuthal range (Figure 1). We use a multi-event stacking procedure [*Wolfe and Silver,* 1998] to search for the optimum values of ϕ and δt and their uncertainties. Of the

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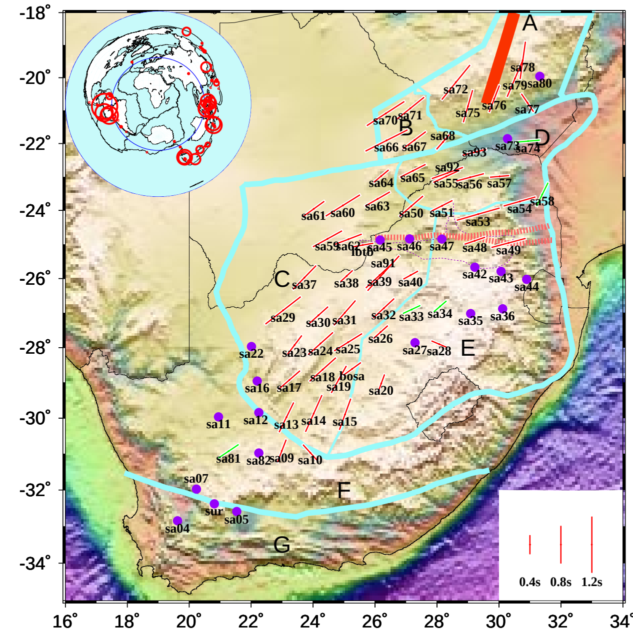

Figure 1. Shear-wave splitting measurements. Orientation, length of bars give fast polarization direction, splitting delay time, respectively, for Type I (red, high-quality) and III (blue, low-quality) stations. Purple dots denote undetectable splitting (Type II). Also shown, tectonic domains. Area A: Zimbabwe craton near Great Dyke. Area B: southwestern corner of Zimbabwe craton. Area C: western half of Kaapvaal craton. Area D: Limpopo belt. Area E: southeastern Kaapvaal craton. Area F: Namaqua–Natal mobile belt. Area G: Cape fold belt. Ages: A-D, Late-Archean; E, Early-Archean; F, G younger than 2.0 Ga (see text). Solid red line (Area A) denotes Great Dyke. Dashed red line denotes Murchison Lineament. Small inset, top-left: Events used in study. Circle size proportional to number of records used from event.

85 sites occupied by SASE and three permanent broadband stations (SUR, BOSA, LBTB) used, only six of them failed to record data suitable for splitting analysis (sa01, sa02, sa03, sa08, sa52, sa69) due to instrumental or other problems. Results from the remaining 79 sites can be divided into three types: Type I stations are well-constrained when all the events available for a station are stacked. Type II stations do not exhibit detectable splitting (corresponding to $\delta t \leq 0.25$ s), and will be referred to as 'null' stations. Type III stations are poorly constrained, primarily due to the lack of clear SKS or SKKS arrivals. Overall, the splitting is somewhat weak; for stations with detectable splitting, delay times average 0.62 ± 0.02 s for the entire area, a value that is significantly smaller than the global average of 1.0 s [*Silver,* 1996] (Figure 2). Areas E, F, and G contain mostly null stations (Figure 1).

Discussion

There are three useful constraints on the depth of anisotropy. First, it is dominantly of mantle origin. To isolate the crustal component, we measured crustal splitting parameters ($\phi_c, \delta t_c$) from P-to-S phases converted at the Moho, employing the same multievent stacking procedure used for the core phases. About half of the stations possessed usable arrivals. The median crustal delay time $\bar{\delta t}_c$ is small, 0.15 s, or a quarter of the average for the core phases. The values of ϕ_c were not well-constrained, primarily due to the small delay times. While individual crustal splitting measurements are sometimes difficult to interpret [*e.g., Savage,* 1998], this value of $\bar{\delta t}_c$ is expected to be more robust. At this magnitude, mantle anisotropy should dominate the splitting measurements. If the crust provided a significant contribution, then we expect to observe backazimuthal variation in splitting parameters characteristic of vertical heterogeneity [*Silver and Savage,* 1994; *Rumpker and Silver,* 1998; *Saltzer et al.,* 2000]. With the favorable backazimuthal coverage, we have systematically searched for, but were unable to detect signs of this heterogeneity. Second, the observation of abrupt changes in splitting parameters for nearby stations (~100 km apart) constrains the top of the anisotropic layer to be no deeper than about 50-100 km, based on the Fresnel-zone arguments of *Rumpker and Ryberg* [2000]. Finally, a surface wave study in the same region [*Freybourger et al.,* this issue] places the anisotropy well within the lithosphere, as defined by the seismic tomography [*James et al.,* this issue] for most of the areas.

We can test for the influence of present-day flow by comparing to predicted values. Based on the APM model HS2-NUVEL1 for the African Plate [*Gripp and Gordon,* 1990], ϕ_{APM} is expected to have smooth latitudinal dependence, decreasing from an azimuth (clockwise from north) of 50° to 20°, going from south to north. The observed values do reveal a clear latitudinal dependence, but it is distinctly different from that predicted by the APM model (Figure 3). ϕ increases from 20° in the southwest to a maximum

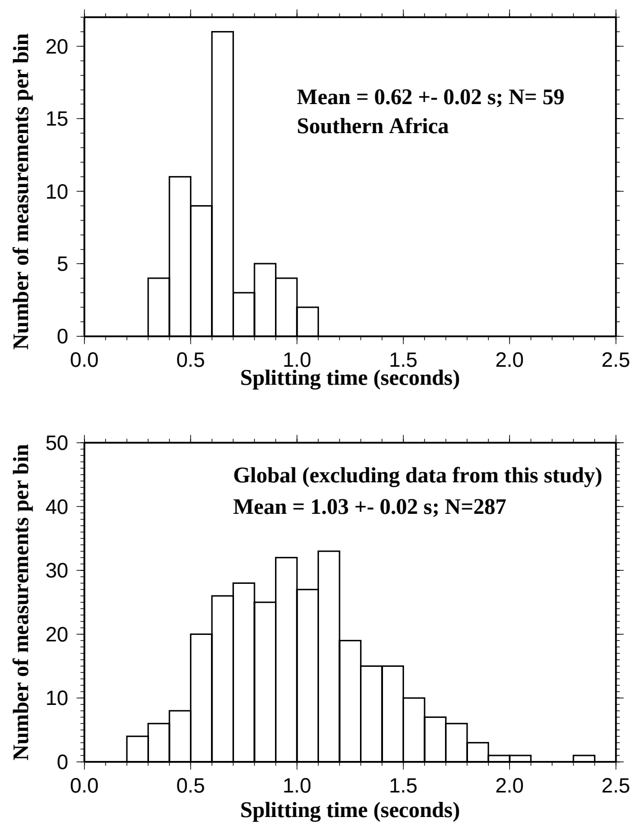

Figure 2. Histograms for δt. Top: this study (excluding the 20 null stations). Bottom: Global measurements [*Silver,* 1996] (excluding null stations).

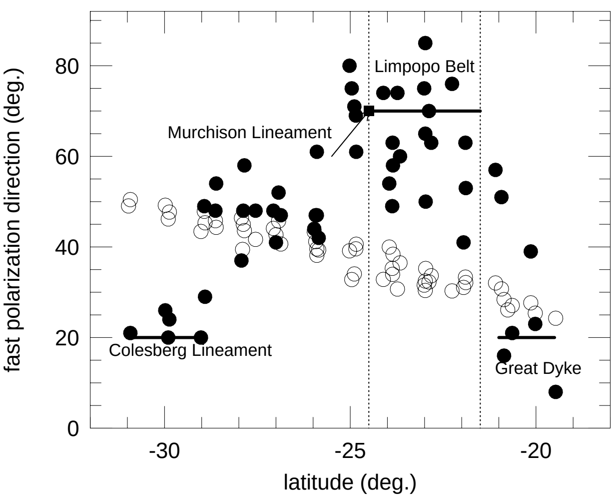

Figure 3. Observed values of ϕ (Type I, filled circles), excluding three outlyers (sa10, sa28, sa77 with latitude/ϕ of -30.97°/-42°, -27.90°/-67°, -20.76°/-34°), and predicted values, ϕ_{APM}, from HS2-NUVEL1 (open circles). Also shown, prominent geologic features and boundaries. Note that data closely track geologic features but not APM-predicted trend.

of 80° at the latitude of the Limpopo belt and then drops abruptly back to 20° towards the very north within the Zimbabwe craton. A newer model HS3-NUVEL1A [*Gripp and Gordon,* 2001] is even less successful in explaining the data, since $\phi_{APM} \sim 100^o$ for the whole region. Thus APM-related flow does not explain the observed values of ϕ. Furthermore, if an 'APM' layer were present beneath the 'geologic' layer, it would lead to clear signs of vertical heterogeneity, which, as noted above, are not found in the data.

The areas showing the clearest evidence for geologic involvement are A, B, and D. Area D, the Limpopo belt, is where the orientation of large-scale geologic structures is best known. The average value of ϕ is 71° and virtually parallel to the strike of the belt. Crossing north into the Zimbabwe craton, ϕ abruptly rotates by over 50° (Figures 1, 3) to a value that is parallel to the most prominent feature in the Zimbabwe craton, namely the Great Dyke. Note that this rapid change occurs across a major geologic boundary, and in both regions the values of ϕ are parallel to large-scale geologic structures. Also, the values of ϕ within the Zimbabwe craton exhibit spatially coherent variations (area A vs. B). These characteristics suggest that the mantle retains the history of Archean deformational structures. Another geologic feature that appears closely tied to mantle anisotropy is the Murchison Lineament [*McCourt and Vearncombe,* 1992*; Good and de Wit,* 1997]. This 500 km-long ENE-WSW trending shear zone, active since the Late-Archean, is thought to mark the actual boundary between the southern margin of the Limpopo belt and Kaapvaal craton [*Good and de Wit,* 1997]. It coincides with the north-south transition between strong and weak splitting (Figures 1, 3), suggesting that it is a fundamental structural boundary in the mantle as well.

Like the fast polarization directions, the delay times reveal striking geologic control. For example, the craton boundary to the southwest marks an abrupt transition from detectable splitting on-craton (area C) to weak splitting off-craton (F,G). There are also significant within-craton variations. In particular, Early-Archean region E exhibits negligible splitting compared to the Late-Archean areas directly to the west and north. As noted above, there are three variables that control the delay time: intrinsic anisotropy, path length, and vertical coherence of deformation. The overall weakness of southern African anisotropy is apparently due to weak intrinsic anisotropy. Taking the measurements of *Ben Ismail et al.* [this issue], and assuming a vertical foliation plane (appropriate for geologically-related deformation), the average intrinsic anisotropy is 1.7%. Coherent deformation and a delay time of 0.6 s yield a mantle layer thickness of 160 km, consistent with the depth of anisotropy inferred from the nodules.

As indicated by seismic tomography [*James et al.,* this issue], the particularly weak splitting in the off-craton regions (Areas F, G) is associated with thinner lithosphere. Taking off-craton subcrustal lithosphere to be 60 km thick gives a predicted δt of less than 0.25 s. The weak anisotropy in the southeastern Kaapvaal (Area E), however, cannot be easily explained by thin lithosphere, since it, like Area C, is underlain by a relatively thick root. A difference in the vertical coherence of deformation [*Rumpker and Silver,* 1998*; Saltzer et al.,* 2000] or intrinsic anisotropy [*Ben Ismail et al.,* this issue] between the two regions is a more likely cause.

The splitting data from SASE provide particularly dramatic confirmation that mantle deformation is preserved as far back as the Earth's earliest continents, in the form of mantle anisotropy. Where splitting is detected, major geologic structures at the surface possess clear counterparts in mantle anisotropy, and point to the close relationship between surface and mantle deformation in most of southern Africa. The style of mantle deformation consequently provides a means of studying the processes that created and modified these early continental terrains.

We are particularly struck by the systematic difference in the magnitude of mantle anisotropy between the Early- and Late-Archean regions, and the possible role of vertical deformational coherence. A global survey of the hundreds of splitting observations [*Silver,* 1996] provides a useful context for the present measurements. The largest delay times and strongest correlation with geologic features are found in areas of large-scale, convergent-margin deformation, such as the Tibetan Plateau [*McNamara et al.,* 1994*; Holt,* 2000]. Undetectable splitting is by contrast a rare occurrence, accounting for only about 10% of the global data set. Given these characteristics, we speculate that the delay-time variations between the Late- and Early-Archean southern African regions reflect a difference in continent-forming environments: a plate-tectonic, convergent-margin setting for the Late Archean, and a distinctly different setting for the Early Archean, which failed to produce the same level of vertically coherent mantle deformation. Plumes have been proposed as one possible Early-Archean environment [*Boyd,* 1989*; Haggerty,* 1994], yet such environments do appear to produce detectable splitting today [*Bjarnason et al., (in preparation); Schutt et al.,* 1998*; R. Russo, personal communication*]. Another possibility is the internal deformation of unsubductable oceanic lithosphere. *Davies* [1999] argues that it is difficult to subduct oceanic plates in the past, because higher temperatures would produce a thicker crust and thinner plate, both of which would make the oceanic lithosphere more buoyant. Indeed, it has been argued that

Early-Archean continental crust is the result of the thrust-faulting and melting of this material [*de Wit,* 1998]. Such a process, in the absence of the large-scale organization provided by subduction, would account for our observations.

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References

Ben Ismail, W., G. Barruol, and D. Mainprice, The Kaapvaal craton seismic anisotropy: A petrophysical analysis of upper mantle kimberlite nodules, *Geophys. Res. Lett.*,(this issue), 2001.

Bjarnason, I., P. G. Silver, G. Rumpker, and S. C. Solomon, Shear wave splitting across the Iceland Hotspot: Results from the ICEMELT experiment, *J. Geophys. Res.*, in preparation.

Boyd, F. R., Compositional distinction between oceanic and cratonic lithosphere, *Earth Planet. Sci. Lett., 96*, 15-26, 1989.

Davies, G. F., *Dynamic Earth*, Cambridge University Press, 1999.

de Beer, J. H., and E. H. Stettler, Geophysical characteristics of the southern African continental crust, *J. Petrol. Spec. Vol.*, 163-184, 1988.

de Wit, M. J., On Archean granites, greenstones, cratons and tectonics: does the evidence demand a verdict? *Precambrian Res., 91*, 181-226, 1998.

de Wit, M. J., C. Roering, R. J. Hart, R. A. Armstrong, C. E. J. de Ronde, R. W. Green, M. Tredoux, E. Peberdy, and R. A. Hart, Formation of an Archean continent, *Nature, 357*, 553-562, 1992.

de Wit, M. J., and C. Roering, *The Limpopo Belt: A Field Workshop on Granulites and Deep Crustal Tectonics, extended abstr.*, J. M. Barton (Ed.), Rand Afrikaans Univ., Johannesburg, 1990.

Fei, Y., C. Bertka, and B. O. Mysen, Eds., *Mantle Petrology: Field Observations and High Pressure Experimentation. A Tribute to Francis R. (Joe) Boyd*, The Geochemical Society, Houston, 1999.

Freybourger, M., J. B. Gaherty, T. H. Jordan, and the Kaapvaal Seismic Group, Structure of the Kaapvaal craton from surface waves, *Geophys. Res. Lett.*,(this issue), 2001.

Good, N., and M. J. de Wit, The Thabazimbi-Murchison Lineament of the Kaapvaal craton, South Africa; 2700 Ma of episodic deformation, *J. Geol. Soc., London, 154*, 93-97, 1997.

Gripp, A. E., and R. G. Gordon, Current plate velocities relative to the hotspots incorporating the NUVEL-1 global plate motion model, *Geophys. Res. Lett., 17*, 1109-1112, 1990.

Gripp, A. E., and R. G. Gordon, Young tracks of hotspots and current plate velocities relative to the hotspots, *Geophys. J. Int.*, submitted, 2001.

Haggerty, S. E., Superkimberlites - A geodynamic diamond window to the Earth's Core, *Earth Planet. Sci. Lett., 122*, 57-69, 1994.

Holt, W. E., Correlated crust and mantle strain fields in Tibet, *Geology, 28*, 67-70, 2000.

James, D. E., M. J. Fouch, J. C. VanDecar, S. van der Lee, and the Kaapvaal Seismic Group, Tectospheric structure beneath southern Africa, *Geophys. Res. Lett.*,(this issue), 2001.

Jordan, T. H., Structure and formation of the continental tectosphere, *J. Petrology*, special lithosphere issue, M. A. Menzies (Ed.), 11-37, 1988.

Kaapvaal Working Group, The Kaapvaal Project, *Geophys. Res. Lett.*, (this issue), 2001.

Mainprice, D., and P. G. Silver, Interpretation of SKS-waves using samples from the subcontinental lithosphere, *Phys. Earth. Planet. Int., 78*, 257-280, 1993.

McCourt, S., and J. R. Vearncombe, Shear zones of the Limpopo belt and adjacent granitoid-greenstone terranes; implications for late Archean collision tectonics in Southern Africa, *Precambrian Res., 55*, 553-570, 1992.

McNamara, D. E., T. J. Owens, P. G. Silver, and F. T. Wu, Shear wave anisotropy beneath the Tibetan Plateau, *J. Geophys. Res., 99,* 13,655-13,665, 1994.

Rumpker, G., and T. Ryberg, New 'Fresnel-zone' estimates for shear-wave splitting observations from finite-difference modeling, *Geophys. Res. Lett., 27*, 2005–2008, 2000.

Rumpker G., and P. G. Silver, Apparent shear-wave splitting parameters in the presence of vertically-varying anisotropy, *Geophys J. Int., 135*, 790-800, 1998.

Saltzer, R. L., J. B. Gaherty, and T. H. Jordan, How are vertical shear wave splitting measurements affected by variations in the orientation of azimuthal anisotropy with depth?, *Geophys. J. Int., 141*, 374–390, 2000.

Schutt, D., E. D. Humphreys, and K. Dueker, Anisotropy of the Yellowstone Hot Spot wake, eastern Snake River plain, Idaho, *Pure Appl. Geophys., 151*, 443-462, 1998.

Savage, M. K., Lower crustal anisotropy or dipping boundaries? Effects on receiver functions and a case study in New Zealand, *J. Geophys. Res., 103*, 15,069–15,087, 1998.

Silver, P. G., Seismic anisotropy beneath the continents: Probing the depths of geology, *Ann. Rev. Earth. Planet. Sci., 24,* 385-432, 1996.

Silver, P. G., and W. W. Chan, Implications for continental structure and evolution from seismic anisotropy, *Nature, 335,* 34-39, 1988.

Silver, P. G., and W. W. Chan, Shear wave splitting and subcontinental mantle deformation, *J. Geophys. Res., 96,* 16,429-16,454, 1991.

Silver, P. G., and S. Kaneshima, Constraints of mantle anisotropy beneath Precambrian North America from a transportable teleseismic experiment, *Geophys. Res. Lett., 20,* 1131-1134, 1993.

Silver, P. G., and M. Savage, The interpretation of shear-wave splitting parameters in the presence of two anisotropic layers, *Geophys J. Int., 119*, 949-963, 1994.

Silver, P. G., D. Mainprice, W. Ben Ismail, A. Tommasi, and G. Barruol, Mantle structural geology from seismic anisotropy, in *Mantle Petrology: Field Observations and High Pressure Experimentation. A Tribute to Francis R. (Joe) Boyd*, Y. Fei, C. Bertka, and B. O. Mysen, Eds., The Geochemical Society, Houston, 1999.

Tankard A. J., M. P. A. Jackson, K. A. Eriksson, D. K. Hobday, D. R. Hunter and W. E. L. Minter, *Crustal Evolution of Southern Africa: 3.8 billion years of earth history*, Springer-Verlag, New York, 1982.

Vinnik, L. P., R. W. E. Green, and L. O. Nicolaysen, Recent deformations of the deep continental root beneath Southern Africa, *Nature, 375*, 50-52, 1995.

Wolfe, C. J., and P. G. Silver, Seismic anisotropy of oceanic upper mantle: shear wave splitting methodologies and observations, *J. Geophys. Res., 103*, 749-771, 1998.

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