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Coupled Crust-Mantle Evolution for > 2 Gy in Southern Africa from Exceptionally Strong Crustal Anisotropy

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An enigmatic feature of Precambrian continental lithosphere is its long-term stability, which depends on the degree of coupling between the crust and mantle since cratonisation. Earlier studies infer deformation of the lower lithosphere by mantle flow with fast direction of seismic anisotropy being parallel to present plate motion, and/or report anisotropy frozen into the lithospheric mantle. We demonstrate coupled crust-mantle evolution in southern African cratons for more than 2 billion years based on unexpectedly strong crustal azimuthal anisotropy (Thybo et al., 2019). The direction of the fast axis is uniform within tectonic units and parallel to orogenic strike in the Limpopo and Cape fold belts. It is further parallel to the strike of major dyke swarms which indicates that a large part of the observed anisotropy is controlled by lithosphere fabrics and macroscopic effects. Parallel fast axes in the crust and in the mantle indicate coupled crust-mantle evolution. These conclusions have implications for the rheology of the lower lithosphere and the effects of mantle flow on lithosphere deformation.

The long-term stability (Sleep, 2003) of Precambrian continental lithosphere after formation more than 2 billion years ago is enigmatic. Lithosphere stability depends primarily on the rheology of the lithospheric mantle (Karato, 2009) and the crust-mantle coupling since cratonisation. A natural laboratory for studying cratons and their stability for billions of years is found in the Archaean cratons in southern Africa. This cratonic crust formed and stabilised in the Archaean (Moser et al., 2001) and was reworked by Proterozoic and Phanerozoic tectonomagmatic events (Carlson et al., 2000).

Estimates of lithosphere thickness in southern Africa vary from 175 km from isotropic surface wave inversion (Priestley et al., 2006), 250 km from, ray-theory body wave inversion (James et al., 2001), and 350 km from teleseismic, finite-frequency methods (Youssof et al., 2015). Surface wave inversion indicates that the upper crust is highly anisotropic in the Limpopo Belt and that the mantle lithosphere and the asthenosphere in general are anisotropic with different directions of the fast axes (Adam and Lebedev, 2012). Anisotropy implies that seismic velocity depends on propagation direction. The popular SKS-splitting method has no depth control, as it determines the accumulated traveltime difference between the SH and SV waves between the core and the surface. However, it is often assumed that the anisotropy primarily resides in the lithospheric or asthenospheric mantle (Silver, 1996). Earlier observations of strong crustal anisotropy have been restricted to tectonically young areas (Chen et al., 2013).

Possible causes of anisotropy include alignment of joints or microcracks filled with water or melts, foliated metamorphic rocks, alternating isotropic layers with different elastic properties, and lattice preferred orientation of anisotropic minerals. We present the first observation of strong anisotropy in cratonic crust. Our analysis of seismic data from southern Africa shows that the fast axes of the crustal anisotropy are homogeneous within the main tectonic units and parallel to the fast axes determined by SKS analysis, to orogenic strike in the Limpopo and Cape fold belts, and to the strike of major dyke swarms. The parallel crust and mantle fast axes indicates strong rheology of the lithosphere and coupled crust- mantle since cratonisation at 2 Ga.

Strong crustal anisotropy observed from seismic observations

We apply the receiver function (RF) technique for determination of crustal anisotropy based on data from the SASE experiment (Southern African Seismic Experiment, Fig. 1). Our results show that the crustal contribution to the total anisotropy is significant at all stations reaching > 50% of the total SKS-splitting at some stations. The direction of the fast axis is uniform within tectonic blocks (Fig. 1). Our analysis is based on 6198 RFs from 220 teleseismic events (Mw ≥ 5.5) with broad distribution of azimuth and distance. We observe strong transverse phases and traveltime differences between radial and transverse RFs (Fig. 2), which demonstrates that earlier assumptions of an isotropic crust (Silver et al., 2001) cannot explain the data. The calculated RFs show azimuthal periodic amplitude variation of the Ps phase, polarity reversals, and Ps delay undulation. These observations require the

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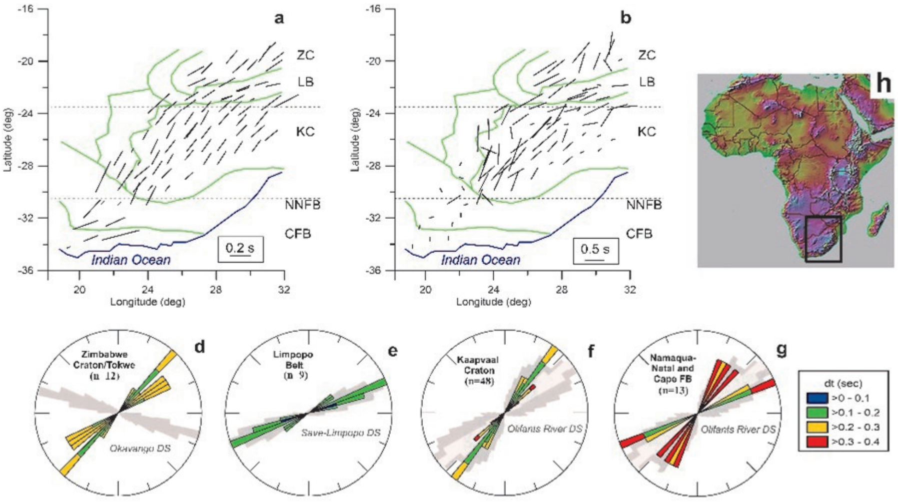

Fig. 1. Anisotropy variation in southern Africa.

Fast polarisation direction for (a) crustal anisotropy from from surface to Moho based on RFs. (b) total anisotropy determined from SKS-splitting (another scale than in a). (d–g) Rose diagrams of observed fast directions for all analysed stations in the various tectonic provinces, colour coded for delay time dt, superimposed on directions of individual dykes (grey shading30) in major dyke swarms (DS) for four main areas; Fold Belt is abbreviated FB. (h) Map shows the study area. Abbreviations: ZC: Zimbabwe Craton, LB: Limpopo Belt, KC: Kalahari Craton, NNFB: Namaqua-Natal Fold Belt, CFB: Cape Fold Belt.

presence of crustal anisotropy (Eckhardt and Rabbel, 2011).

The time delay (δt) between the radial (SV) and transverse (SH) converted waves generated at the base of the lower cratonic crust is 0.19 s for the Archaean cratonic areas and 0.34 s in the Cape and Namaqua-Natal post-Archaean fold belts (Fig. 2). These crustal delay times correspond to at least 30–55% of the S-wave splitting in the cratons (Silver et al., 2001). This is remarkable as crustal anisotropy is usually considered negligible in shear wave splitting interpretations (Silver et al., 2001). Our observation suggests that this assumption may not be true, not even in cratonic regions.

By calculation of synthetic RFs we show that the relative velocity difference between the fast and slow axes is very high (10%) in Kaapvaal lower crust with fast axis direction 40º ± 20º for the lower crust and 100º ± 20º for the upper crust, and 7% in the whole crust of the Limpopo Belt. The fast polarisation axis directions are between 50 and 70º in western Zimbabwe Craton and 70º ± 20º for the crust in the Limpopo Belt and the Cape Fold Belt (Fig. 1a).

We observe characteristic change in the shear wave splitting: The transverse PSH component arrives earlier than the radial PSV component in the Limpopo Belt and western Zimbabwe Craton, whereas the opposite is the case in other areas (Fig. 2). This observation can be explained by the dip of the fast axis, which we model to be 50º from vertical in most of Kaapvaal and 35º in the Limpopo and Cape fold belts.

The fast directions for the crustal and the SKS anisotropy are generally parallel (Figs. 1, 3) although the anisotropy is much less coherent in the SKS-splitting results than in our crustal results from RF (Fig. 1a, b), particularly in the Cape and Namaqua–Natal fold belts and western Kaapvaal.

The observed coherence is surprising because the SKS fast-propagation direction may not necessarily be the same in all depth intervals of the crust, and the lithospheric and sublithospheric mantle. The similar anisotropy directions in the Kaapvaal and Zimbabwe cratons indicates that the anisotropy was frozen into the lithosphere during the collision between these cratons at ca. 2.7 Ga when the Limpopo belt was deformed such that it today has different anisotropy fast axes. This conclusion is further supported by the observations of a surprising coherence between the crustal anisotropy directions in the cratons and the orientations of major dykes swarms except for the Zimbabwe Craton (Fig. 1), and between the crustal and SKS anisotropy directions in the intervening Limpopo Belt where the fast directions are subparallel to the strike of the collisional belt (Fig. 3).

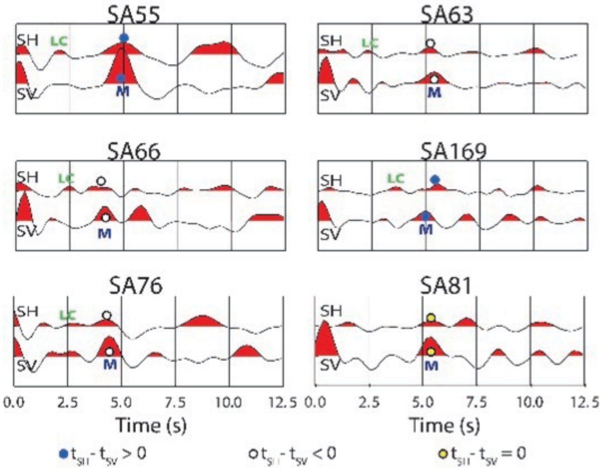

Fig. 2. Stacked transverse and radial receiver functions.

M and LC denote conversions from the Moho and top of the lower crust, respectively. Notice the change in relative arrival times of the transverse PSH- and the radial PSV-RFs between the two cratons and the Limpopo Belt. The examples are from Kaapvaal Craton (SA63), Limpopo Belt (SA55, 169), Zimbabwe Craton (SA66, 76), and Namaqua-Natal Belt (SA81).

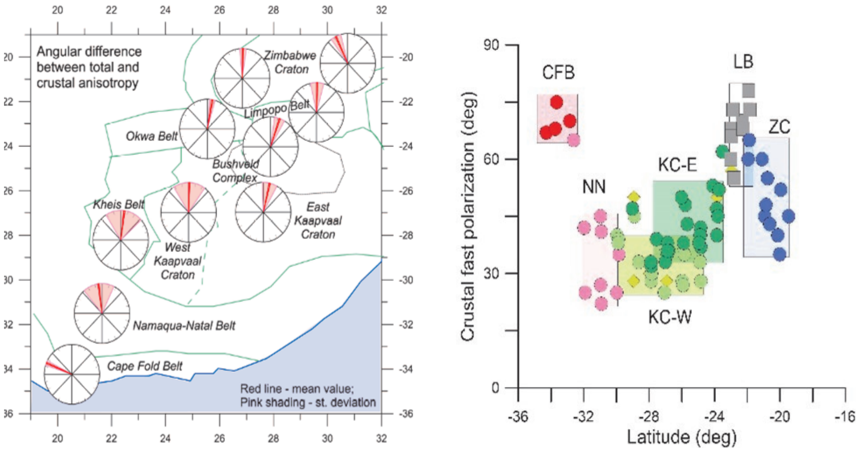

Fig. 3. Difference between fast axis directions for SKS and RF-determined anisotropy (left) and Fast polarization axes for the crustal anisotropy latitude and versus tectonic province (right).

Left: Red lines mark average difference, and pink shading marks standard deviation in the rose diagrams, where zero difference corresponds to the north direction. Right: The fast axes shows systematic variation between the tectonic provinces. Abbreviations: See Fig. 1, and GD – Zimbabwe Craton around the great Dyke.

Lattice-preferred orientation (LPO), alignment of anisotropic minerals, and structural anisotropy (SPO) associated with dyke intrusions may explain the observed anisotropy in the crust. The causes for crustal anisotropy may be more complex than for mantle anisotropy, which is believed to primarily originate from lattice-preferred orientation of olivine aggregates (Adam and Lebedev, 2012). We suggest that the azimuthal anisotropy observed in the brittle upper crust may be related to upper crustal fine layering or aligned cracks (confined to depths < 5–10 km), but this mechanism usually is weak (Crampin and Chastin, 2003) (up to 5%). However, we observe that the fast axes are parallel to the large dyke swarms in the Limpopo Belt, Kaapvaal Craton, and the Namaqua-Natal and Cape fold belts (Fig. 1). This indicates a generic connection. The swarms each consist of many individual thin dykes which may generate a structural type of anisotropy (SPO) with fast axis parallel to the dyke direction 42. The seismic velocity of mafic dykes in the upper crust is usually much higher than in the surrounding host rock of granitic origin (Thybo and Artemieva, 2013).

We suggest that pre-existing lithosphere weakness fabric both determine the fast anisotropy direction and also may have guided the direction of the dykes. The overall weakness fabric determines anisotropy to large depths. The dykes contribute to the total anisotropy with fast axis parallel to the horizontal component of the original fast axes, thereby contributing constructively to the crustal anisotropy amplitude. The initial anisotropy in the host rock is maintained with a dip component of the fast direction. Therefore, our modelled dip of the fast axis may be more horizontal than the initial direction of the fast axis due to the effect of the later dyke swarms.

We have demonstrated the presence of unexpected, strong crustal anisotropy which indicates that the anisotropy in the depleted Archaean cratonic mantle may be up-to 30–55% weaker than previously believed. The effect of the strong crustal anisotropy is both to rotate the observed fast axis in SKS-splitting studies towards the crustal direction and to weaken the strength of the total anisotropy. Therefore, the total mantle anisotropy may be relatively larger than indicated by this upper limit if the orientations deviate substantially, but the close agreement in fast axes orientation determined from RF and SKS-splitting suggests that the difference between fast axes in the crust and mantle lithosphere is small. We find that the similar fast polarization direction between the anisotropy determined from SKS-splitting (Silver et al., 2001) and the crustal anisotropy of the cratons (this study), indicates that the crust and mantle have been coupled since the anisotropy formed. Therefore, the lithosphere must have been stable since the time of the last tectono-magmatic events, which provides support to xenolith studies for long term stability of the upper 150 km of the lithosphere in the Kalahari Craton.

Previous studies based on the same seismic data did not recognize or model the crustal anisotropy, probably because the authors assumed that it is a negligible component of the total anisotropy. Our findings suggest that much of the crustal anisotropy was acquired during craton formation and evolution involving collisional tectonics, magmatic activity, and thermal recycling. Reworking processes may have changed the chemistry of the lower crust to increase the anisotropy and produce metamorphosed bands (mica-foliated gneiss) with intermediate (granitoid gneiss) composition.

Our analyses show strong anisotropy in the crust in the Cape Fold Belt and the Namaqua–Natal Fold Belt, whereas SKS-splitting results (Silver et al., 2001) indicate very weak anisotropy (Fig. 1). We speculate that the weak SKS anisotropy may be due to a highly heterogeneous depth distribution of the fast direction in the mantle. It also indicates that plate motion parallel anisotropy in the asthenosphere may not be dominant in southern Africa because, otherwise, strong SKS-splitting would be observed also in these fold belts.

The parallel fast axes for the crust and from SKS-splitting analyses indicates that the major part of the measured SKS-splitting originates in the lithosphere, whereas the contribution from the asthenosphere is smaller. Our interpretation is further supported by the observation that the SKS-splitting directions (Silver et al., 2001) deviate substantially from the plate motion direction in the Limpopo Belt and the Cape Fold Belt. The overall coincidence in fast axes between the crustal and the SKS-splitting anisotropy within each tectonic block indicates long-term coupling between crust and mantle lithosphere. Our findings therefore support interpretations that the crust and mantle lithosphere have remained one solid entity since cratonisation. This conclusion has fundamental implications for the degree to which mantle flow can affect lithosphere deformation, for the rheological structure at the lithosphere–asthenosphere transition, as well as for the strength of the lithospheric crust and mantle.

Key words: cratonisation, anisotropy, coupled crust-mantle lithosphere

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References

Adam, J.M.C., and Lebedev, S., 2012. Azimuthal anisotropy beneath southern Africa from very broad-band surface-wave dispersion measurements. Geophysical Journal International, 191: 155–174.

Carlson, R.W., Boyd, F.R., Shirey, S.B., and Janney, P.E., 2000. Continental Growth, Preservation, and Modification in Southern Africa. GSA Today, 10: 1–7.

Chen, Y., Zhang, Z.J., Sun, C.Q., and Badal, J., 2013. Crustal anisotropy from Moho converted Ps wave splitting analysis and geodynamic implications beneath the eastern margin of Tibet and surrounding regions. Gondwana Research, 24: 946–957.

Crampin, S., and Chastin, S., 2003. A review of shear wave splitting in the crack-critical crust. Geophysical Journal International, 155: 221–240.

Eckhardt, C., and Rabbel, W., 2011. P-receiver functions of anisotropic continental crust: A hierarchic catalogue of crustal models and azimuthal waveform patterns. Geophysical Journal International, 187: 439–479.

James, D.E., Fouch, M.J., Van Decar, J.C., van der Lee, S., and Kaapvaal Seismic Group, 2001. Tectospheric structure beneath southern Africa. Geophysical Research Lettera, 28: 2485–2488.

Karato, S.I., 2009. Rheology of the deep upper mantle and its implications for the preservation of the continental roots: A review. Tectonophysics, 481: 82–98.

Moser, D.E., Flowers, R.M., and Hart, R.J., 2001. Birth of the Kaapvaal tectosphere 3.08 billion years ago. Science, 291: 465–468.

Priestley, K., McKenzie, D., and Debayle, E., 2006. The state of the upper mantle beneath southern Africa. Tectonophysics, 416: 101–112.

Silver, P.G., 1996. Seismic anisotropy beneath the continents: Probing the Depths of Geology. Annual Review Earth Planet Sciences, 24: 385–432.

Silver, P.G., Gao, S.S., Liu, K.H., and Kaapvaal Seismic Group, 2001. Mantle deformation beneath southern Africa. Geophysical Research Letters, 28: 2493–2496.

Sleep, N.H., 2003. Survival of Archean cratonal lithosphere. Journal of Geophysical Research, 108(B6): 2302.

Thybo, H., and Artemieva, I.M., 2013. Moho and magmatic underplating in continental lithosphere. Tectonophysics, 609: 605–619.

Thybo, H., Youssof, M., and Artemieva, I.M., 2019. Southern Africa crustal anisotropy reveals coupled crust-mantle evolution for over 2 billion years. Nature Communications, 10: 5445.

Youssof, M., Thybo, H., Artemieva, I.M., and Levander, A., 2015. Upper mantle structure beneath southern African cratons from seismic finite-frequency P- and S-body wave tomography. Earth Planetary Science Letter, 420: 174–186.

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