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Anisotropy of Southern African lithosphere and asthenosphere

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ABSTRACT

Observations of anisotropy, when understood in terms of deformation processes, are critical to illuminating the dynamics of past and present tectonic processes. In particular anisotropy can infer how continents formed, stabilized and interacted with underlying mantle regions in the past, and how they do so today. Seismology and electromagnetic observations of anisotropy are essential if we are to understand the tectonic history of a region. Seismic anisotropy, defined from SKS arrivals, is poorly constrained in depth, whereas electrical anisotropy has inherent depth localization but lower spatial resolution. Given the limitations of both sub-disciplines a more robust characterization of anisotropy is achieved by integrating complementary datasets. Southern Africa has now two rich geophysical databases from the SASE and SAMTEX experiments that can be explored, compared and contrasted for lithospheric anisotropy. Doing so suggests a new model to explain SKS observations which is based on plausible tectonic history. The new model combines the "Silver" lithospheric anisotropy and "Vinnik" asthenospheric anisotropy models, and incorporates their differentiation using electrical anisotropy.

Key words: SAMTEX, SASE, electrical anisotropy, seismic anisotropy.

INTRODUCTION

Our understanding of how the Earth operates, particularly its tectonic history and secular variation of tectonic processes, is severely limited by both our lack of knowledge, and the intrinsic bias in knowledge, at depth. Superb geological mapping yields plausible inferences about subsurface geometries from which reasonable deductions can be made about likely tectonic histories. However, there are very few regions where such models have been tested, and then only to depths of 10 km in deep continental drilling programmes, such as the German Kontinentales TiefBohrung (KTB, see Haak and Jones, 1997 and papers therein). Similarly, inferences based on geochemical, petrological and geochronological analyses of crustal and mantle xenoliths and xenocrysts, brought to the surface by volcanic or tectonic processes, also yield models of subsurface geometries and tectonic histories. However sampling is highly biased, with no material from many key locations, leading to valid questions about generic applicability of those inferences.

In-situ physical properties obtained through seismological and electromagnetic observations yield geometrical information and have the advantage that all regions are sensed, albeit with varying resolution kernels, but with the singular disadvantage that the methods are sensing the properties and geometries of today, not those of the past. It is through relating these geometries and properties either to surface observations, by tracing structures to the surface where they are mapped geologically, or to regions from which reasonably detailed geochemical and petrological information exists through comprehensive xenolith databases, that significant advances can occur in understanding. One excellent example of this is the deductions made of the Neoarchean tectonic history of the Slave craton in northern Canada by Davis et al. (2003), based on comparing and contrasting information from petrology, geochronology, geochemistry, geology and geophysics.

Rock fabrics induced by tectonic processes, particularly, but not exclusively, by lateral plate tectonic translations, provide important clues about petrogenesis and the deformation history of the region. Unfortunately, our direct knowledge of subcontinental lithospheric fabrics is severely limited by the scarcity and bias of mantle samples. This leaves a significant observational gap in our understanding of dynamics of tectonic processes – in particular, how continents formed and interacted with underlying mantle regions in the past, and how they do so today. This gap can be filled by appropriate geophysical observations of lithospheric anisotropy.

Anisotropy – the directional dependence of material properties – is an important manifestation of penetrative tectonic processes. Geophysical observations of anisotropy, particularly seismic and electrical anisotropy, constitute essential data for investigating lithospheric fabrics. Over the past decade increases in sensors deployed, improved observational methods and developments of processing, analyses and inversion techniques are contributing to more refined and realistic Earth models incorporating anisotropy and heterogeneity at various scales. However, the vast majority of these studies have not only been limited to single-discipline analyses, but are often only single-technique within a discipline. Both seismological and electromagnetic methods have their strengths and weaknesses – as well as their proponents and detractors – but unequivocally the whole is greater than the sum of the parts so multi-technique methods of interpretation must be applied.

Continental seismic anisotropy has been studied for two decades, with shear wave splitting analyses of core-traversing teleseismic waves (SKS arrivals) providing the most comprehensive observational dataset (Silver, 1996, Savage, 1999, Park and Levin, 2001). The incident S-wave, upon entering an anisotropic medium is split into two orthogonally polarised S-waves, with different velocities. SKS waves travel through the liquid outer core as compressional (K) waves then are converted at the core-mantle boundary to shear (S) waves. Travel from the earthquake to the core could be either by compressional (P) waves or by shear (S) waves, but PKS arrivals occur at the same time as other strong arrivals in the wavetrain so are more difficult to identify than the later SKS arrivals. The advantage of analysing SKS arrivals is that all "source-side" anisotropy, i.e. anisotropy from the earthquake to the core, is removed on conversion from S to P at the core-mantle boundary. More recently, seismic anisotropy deduced from surface-wave studies and receiver functions are also providing important insights (e.g., Gung *et al.*, 2003). Seismic anisotropy in the lithospheric and sub-lithospheric mantle is readily explained in terms of aligned olivine crystals. However, given our understanding of the likely processes of lithospheric mantle formation, not only today but also in the past (particularly the Archean), that interpretation does test the bounds of credulity, and alternative explanations are urgently needed.

Electromagnetic observations of long-period magnetotelluric (MT) signals provide the best available method to measure electrical anisotropy of the mantle. However, in contrast to seismic anisotropy, electrical anisotropy interpreted from MT observations, from Mareschal et al.'s (1995) key contribution to more recent studies (Simpson, 2001, e.g., Bahr and Simpson, 2002, Leibecker *et al.*, 2002, Gatzemeier and Moorkamp, 2005), is often significantly higher than expected from intrinsic "dry" crystal anisotropy. Without a ready explanation the origin of electrical anisotropy in the lithospheric mantle remains controversial; processes that have been proposed to explain it include melt lenses, conductive films along grain boundaries, and anisotropic diffusion of hydrogen, but none are without considerable objection.

Both SKS and MT methods suffer from significant inherent weaknesses. SKS has no intrinsic depth resolution; the results are generally interpreted in terms of either fossil structures in the lithosphere representative of past formation and deformation processes - the "Silver" school of thought, championed by Paul Silver (Silver and Chan, 1988), or present-day structures in the lowermost lithosphere and underlying asthenosphere resulting from mantle flow - the "Vinnik" school of thought, of Lev Vinnik (Vinnik *et al.*, 1992). A raging debate is occurring between these two schools, often without recognition that both mechanisms are likely at play but to differing degrees at differing depths. Progress on understanding the observations is hindered by this lack of depth resolution.

Equally, MT interpretations are beset by intrinsic limitations. Jones (2006) draws attention to the consequences of the vast range of electrical conductivity in rocks, and that attenuation in anisotropic crustal conductors may severely limit mantle penetration. Crustal attenuation and anisotropy effects in Fennoscandia are severe, and Lahti et al. (2005) call into question the mantle paleoflow interpretation of Bahr and Simpson (2002) based on their MT observations.

Approximate agreement between geoelectric strikes and seismic fast-axis directions in regions as varied as the Grenville belt (Ji *et al.*, 1996), the Great Slave Lake shear zone (Eaton *et al.*, 2004), central Australia (Simpson, 2001), central Germany (Gatzemeier and Moorkamp, 2005), and the São Francisco craton (Padilha *et al.*, 2006), suggests that seismic and electrical anisotropy may often have a common underlying origin, and that taken together greater insight into past and present processes will result.

Southern Africa has now two rich geophysical databases from the SASE and SAMTEX experiments that can be explored, compared and contrasted for lithospheric anisotropy. Figure 1 shows the locations of the SASE (black dots) and SAMTEX (coloured dots) stations. The background is the tectonic subdivision of Southern Africa by Webb (2009, pers. comm.).

Results of seismic and electrical anisotropy have already been published in Silver et al. (2001, 2004) and Hamilton et al. (2006), but the latter was only for the single main NE-SW Kaapvaal craton profile, whereas the former raised queries that warranted re-analysis of the original seismic data.

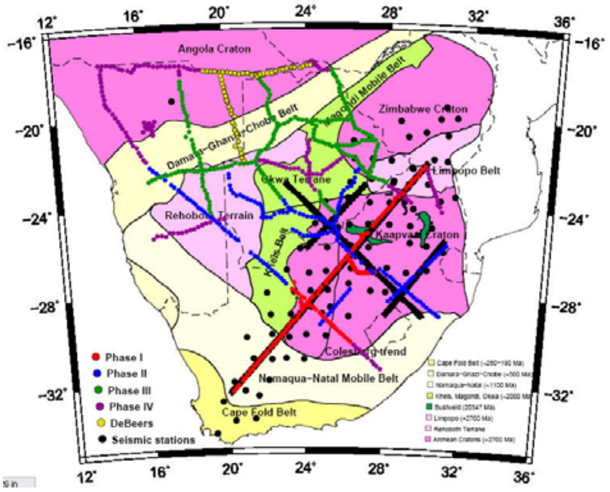

Figure 1: MT and seismic station map.

SEISMIC ANISOTROPY OF SOUTHERN AFRICA

The seismic anisotropy of southern Africa was defined by Silver et al. (2001, 2004) using observations of SKS arrivals at the SASE stations, and are shown on Fig. 2 as coloured bars. The strength of the anisotropy is given by the length of the bar, and the fast direction by the orientation of the bar. The colour coding of the bar represents the correlation between the fast axis direction of the SASE splitting results, and the plate motion model of Gripp and Gordon (1990), with the misfit (0°-90°) indicated by the colour of the bar of the SASE results. Null stations are represented by open circles, and poorly constrained splitting results are plotted with a black outline. These results are overlain on the seismic S-wave tomography model of southern Africa at 200 km depth, from Fouch et al. (2004), with percentage variations (-1.2 to 1.2).

Although there is no reason to suspect that the results of the teleseismic shear wave splitting study (shown in Fig. 2) undertaken by Silver et al. (2001, 2004) were incorrect, it was decided to re-analyse the data from some locations to test whether the assumption of a single layer of anisotropy was appropriate, and also of observations of "null" stations in the SE part of the craton.

The SASE data from representative stations, as well as three permanent stations, were re-analysed for shear wave splitting. This analysis was undertaken using established methodologies and tested codes in order to gain a greater understanding of the results and to search for any indications of more complex anisotropy that may have been missed by the previous studies. Additionally, we have investigated further the correlation of shear wave splitting results with plate motion and mantle flow models, as well as with tomography results from the SASE study. Below are the main results of the seismic re-analysis and investigation:

- Re-analysis of shear wave splitting results provide multi-event measurements statistically consistent, with a few notable exceptions, with those of previous authors.
- We find that while the splitting parameters plotted as a function of backazimuth do not suggest more complex anisotropy than a single horizontal layer, but the data are insufficient to reject this possibility. Waveform inversion that searches for parameters for two layer splitting was inconclusive.
- An important observation established in this study is that regions where there is good correlation between seismic fast axis directions and plate motion or mantle flow directions occur primarily where thick lithosphere is indicated by tomography models. This argues for a component of seismic anisotropy at the lithosphere/asthenosphere boundary, or within the asthenosphere. We suggest that this is a result of increased flow velocity below thick lithosphere.

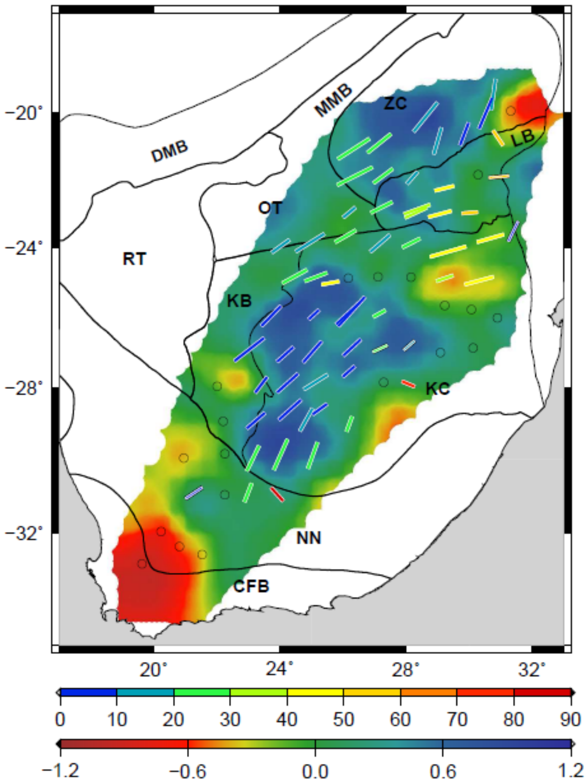

Figure 2: Results of shear wave splitting study overlain on the seismic S-wave tomography model of southern Africa at 200 km depth (see text for details).

ELECTRICAL ANISOTROPY OF SOUTHERN AFRICA

The electrical anisotropy can be defined using a variety of techniques on the MT data. Herein we use the distortion decomposition approach of Groom and Bailey (Groom and Bailey, 1989, Bailey and Groom, 1987), as implemented in the multi-site, multi-frequency code of McNeice and Jones (2001). Typically maps of anisotropy are shown for a specific period of investigation, but this approach makes radical, and in the case of Southern Africa completely inappropriate, assumptions about lateral homogeneity of the Earth. As shown in Hamilton et al. (2006), the penetration depth at each period varies widely across the SAMTEX array, so the data must be analysed in period bands that are consistent with depths.

The electrical anisotropy at lithospheric and asthenospheric depths are shown in Figs. 3 and 4, together with the seismic anisotropy defined by SKS. The figures show the lithospheric mantle (Fig. 3) and asthenosphere (Fig. 4) MT most conductive directions, displayed as red bars, with the length scaled by phase difference, overlain on SKS splitting results of Silver et al. (2001), plotted as green bars parallel to the fast axis splitting direction, with the length scaled by delay time. Light green bars are poorly constrained splits, and blue dots represent null sites.

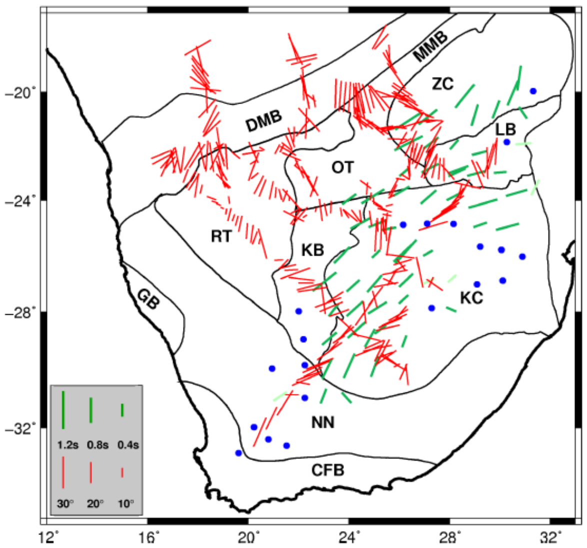

Figure 3: Lithospheric mantle MT most conductive directions and SKS anisotropy.

Our lithospheric mantle results (Fig. 3) show a stark contrast to the seismic results, and exhibit a level of complexity comparable to that of the crustal MT results (not shown). While in some regions, such as the northeastern and southwestern Kaapvaal craton, there appears to be quite a close correlation between the directions of the MT and seismic fast axis directions, there are also regions where this is certainly not the case, such as on the Limpopo belt where the electrically more conducting directions are near perpendicular to the seismic fast axis direction.

Our lithospheric mantle results are clearly different to the SASE fast axis directions, which was not what was anticipated from observations in previous studies, although this was perhaps naive to expect considering the complexity of this region. However, this difference hinted that perhaps the lithosphere is not the source of the seismic anisotropy, and is what prompted us to analyse the regions of the MT data that penetrated to asthenospheric depths. Although we have far fewer stations in which both modes penetrate into the asthenosphere, which is required in order to define anisotropy (Jones, 2006), those that do show a strong orientation correlation with the SASE SKS results (Fig. 4). This may be taken as evidence that in the centres of cratons the seismic anisotropy predominantly lies in the asthenosphere (Vinnik model). The average phase split of 15 degrees can be explained by an order of magnitude difference in electrical anisotropy, which implies aligned hydrated olivine crystals in the asthenosphere.

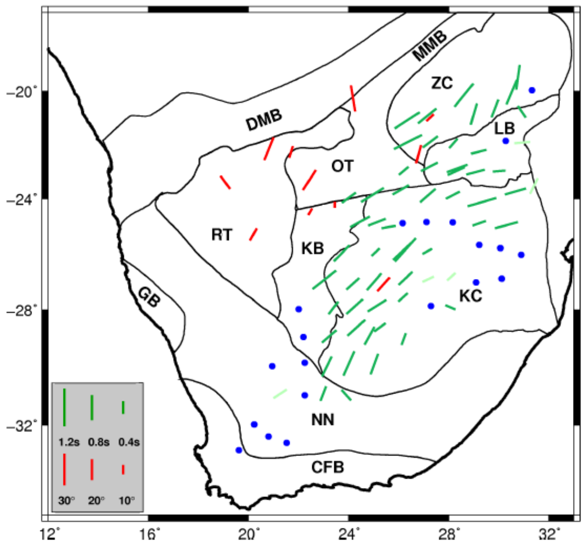

Figure 4: Asthenosphere MT most conductive directions and SKS anisotropy.

NEW MODEL TO DESCRIBE SEISMIC ANISOTROPY OBSERVATIONS

Neither of the two end-member models of Silver (fossil anisotropy in the lithospheric mantle, Fig. 5A) and Vinnik (present-day anisotropy in the asthenosphere, Fig. 5B) explain the SKS observations shown in Fig. 2 and the correlation with the MT results shown in Figs. 3 and 4.

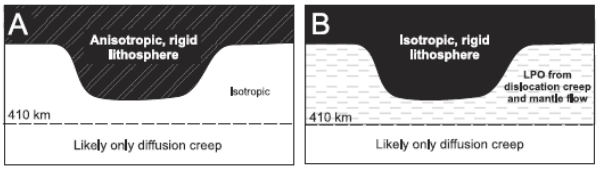

Figure 5: Silver (A) and Vinnik (B) models to explain seismic SKS anisotropy.

We propose a new model to explain seismic anisotropy that takes into consideration likely formation processes, physics of creep mechanisms, correlation with plate flow direction, and correlation with our MT results. This model is shown schematically in Fig. 6, and essentially suggests that for Southern Africa the Silver model is correct off-craton and the Vinnik model is correct on-craton.

On-craton: The lithospheric mantle was formed through processes that resulted in incoherent crystal structure, but asthenospheric flow is strong causing aligned lattice-preferred orientation (LPO) from flow in the dislocation creep regime.

Off-craton: Proterozoic and younger lithospheric mantle was formed through more coherent processes, i.e. plate tectonics, that resulted in well-ordered frozen crystal structure. The asthenosphere is only weakly aligned with present-day plate motion due to the slow movement of Southern Africa.

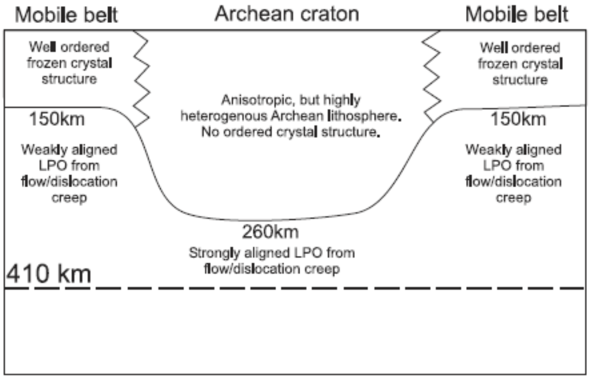

Figure 6: A proposed model for the origin and structure of anisotropy in southern Africa.

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