# Mantle Structure beneath the Damara Belt in southern Africa Imaged with Adaptively Parameterized Teleseismic Tomography

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## Abstract

Situated between the Congo and Kalahari Cratons, the Damara Belt is southern Africa's youngest Proterozoic mobile belt. Some prior studies have suggested that the Damara Belt is underlain by slow seismic velocities, thought to be associated with temperature perturbations in the upper mantle. However, other studies instead argue that the lithosphere in this region is not thermally perturbed and that it is underlain by fast upper mantle velocities. There are also questions as to how the lithospheric and mantle structure varies along strike, particularly on the eastern side of the Damara Belt where it meets the Irumide belt and the East Africa Rift System (EARS).

In our study, we use adaptively parameterized teleseismic P-wave tomography to further elucidate the mantle structure beneath the Damara Belt and neighboring regions. Our aim is to determine whether the upper mantle beneath this area shows evidence for thermal perturbation and if so, what is the source of this anomalous structure. By employing a comprehensive dataset that includes 1,576 seismic stations from 60 different networks as well as an augmented version of the global International Seismological Centre travel-time catalog, we have generated high-resolution 3-D images of the entire mantle beneath the study area. Our findings show fast upper mantle velocities beneath the Damara Belt with anomalously slow seismic velocities constrained to the lower mantle (below ~1000 km depth). Further to the northeast, the slow seismic velocities ascend through the mantle transition zone, reaching the upper mantle beneath the Irumide belt and the EARS. We attribute this anomalously slow structure to the rise of the African Large-Low Velocity Province (LLVP), which ascends from the core-mantle boundary beneath southern Africa. The Damara Belt itself is not notably influenced by the LLVP, but neighboring tectonic regimes are strongly impacted by the deep-seated mantle anomaly. Interestingly, this interpretation also agrees with surface observations. The region to the northeast of the Damara Belt, where the LLVP structure is closer to the surface, contains numerous hot springs, but no such geothermal activity occurs in the Damara Belt, where the slow seismic anomalies are not observed above the mantle transition zone.

## Introduction

The African Large-Low Velocity Province (LLVP) was initially imaged more than 30 years ago, and since then, new seismic datasets have enhanced our understanding of the LLVP's origin, composition, and extent. Numerous tomographic models suggest a northeastward extension of the LLVP, which may drive rifting in the East African Rift System (EARS); however, debates persist about whether the LLVP also extends to the north or northwest beneath south-central Africa. In particular, the upper mantle structure beneath the Damara Belt (Fig. 1) is uncertain. Some studies (*e.g.*, Yu et al., 2017; Ortiz et al., 2019; Akinremi et al., 2022) suggest a seismically slow upper mantle beneath this region, potentially associated with the LLVP, while others (*e.g.*, Celli et al., 2020; White-Gaynor, 2021; Pandey et al., 2022) argue that there is no evidence for anomalously slow mantle beneath the Damara Belt. Limited resolution in existing tomographic images underscores the need for further exploration to understand the mantle structure beneath this area.

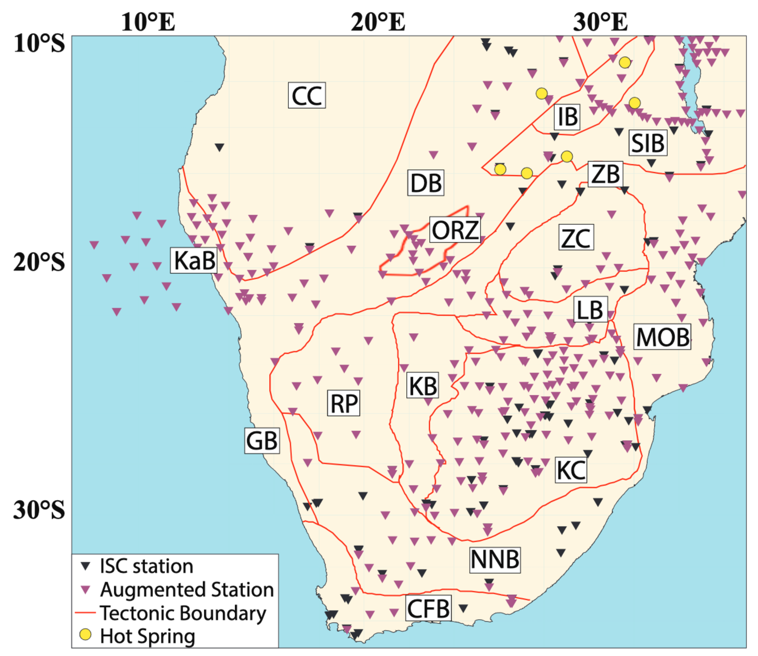


**Figure 1.** Map of southern Africa, showing the locations of seismic stations and the boundaries of tectonic provinces. Black triangles: stations from the global ISC catalog; purple triangles: augmented stations; yellow circles: hot springs. CC: Congo Craton, IB: Irumide Belt, SIB: Southern Irumide Belt, KaB: Kaoko Belt, DB: Damara Belt, ORZ: Okavango Rift Zone, ZB: Zambezi Belt, ZC: Zimbabwe Craton, LB: Limpopo Belt, MOB: Mozambique Orogenic Belt, GB: Gariep Belt, RP: Rehoboth Province, KB: Kheis Belt, KC: Kaapvaal Craton, NNB: Namaqua-Natal Belt, CFB: Cape Fold Belt. Tectonic boundaries are from Begg et al. (2009).

To further investigate the structure beneath the Damara Belt, we use adaptively parameterized teleseismic P-wave tomography and new seismic data to generate a high-resolution image of the mantle beneath south-central Africa. We aim to determine whether the upper mantle beneath the study area shows evidence for thermal perturbation and if so, to determine whether this anomalous structure is associated with the African LLVP. Further, we seek to determine whether the mantle structure beneath south-central Africa may directly influence surface features, such as geothermal activity and continental rifting.

## Adaptively Parameterized P-wave Tomography

A comprehensive collection of P-wave travel-time residuals was used to develop our new model. Much of our data was acquired from a recent version of the International Seismological Center (ISC) catalog, which includes ~562,000 earthquakes that occurred between 1964 and 2016. To further increase our model resolution, data from 60 additional seismic network (1,576 stations; Fig. 1) that are not included in the ISC catalog were used to augmented to the global dataset, similar to that used by Saeidi et al. (2023).

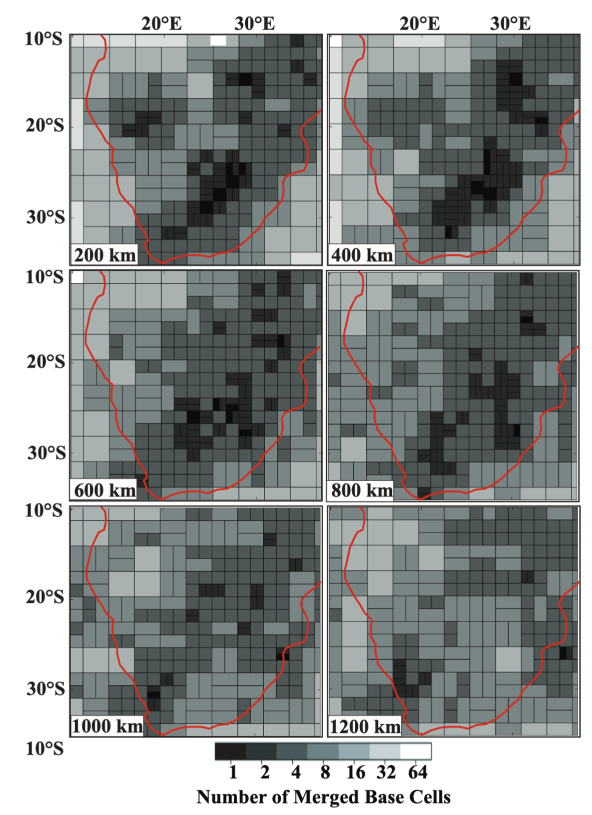


**Figure 2.** Adaptive grid cells from our tomographic model across southern Africa, shown at selected depths. Shading indicates the number of base cells (0.7° x 0.7°) included in each final cell. Darker shading indicates smaller cells, and lighter shading indicates larger cells. A threshold of 900 ray paths is required per cell; therefore, darker (smaller) cells highlight areas with greater ray path coverage and higher resolution.

Model gridding is adapted to variations in the ray path coverage, which prevents regions with poor coverage from becoming over-parameterized and those with dense coverage from losing resolution due to averaging. The smallest grid cells in our model are 0.7° x 0.7°, and our current model contains 764,406 adaptive grid cells (Fig. 2). Together, the adaptive grid and the combined ISC-African travel-time residuals are inverted to calculate P-wave velocity perturbations relative to the AK135 reference model (Fig. 3).

## Results

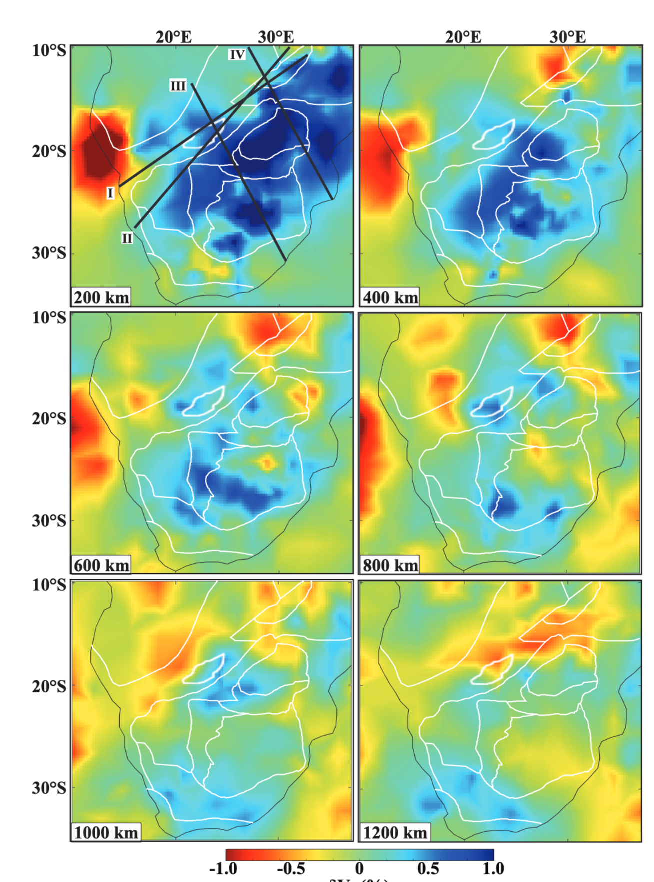


**Figure 3.** Map-view images of our tomographic model across southern Africa, showing P-wave velocity perturbations relative to the AK135 reference model (δVP; Kennett et al., 1995) at selected depths. White lines show the same tectonic boundaries as in Figure 1. Black lines labeled I to IV on the 200 km panel show the locations of the cross-sectional profiles in Figure 4.

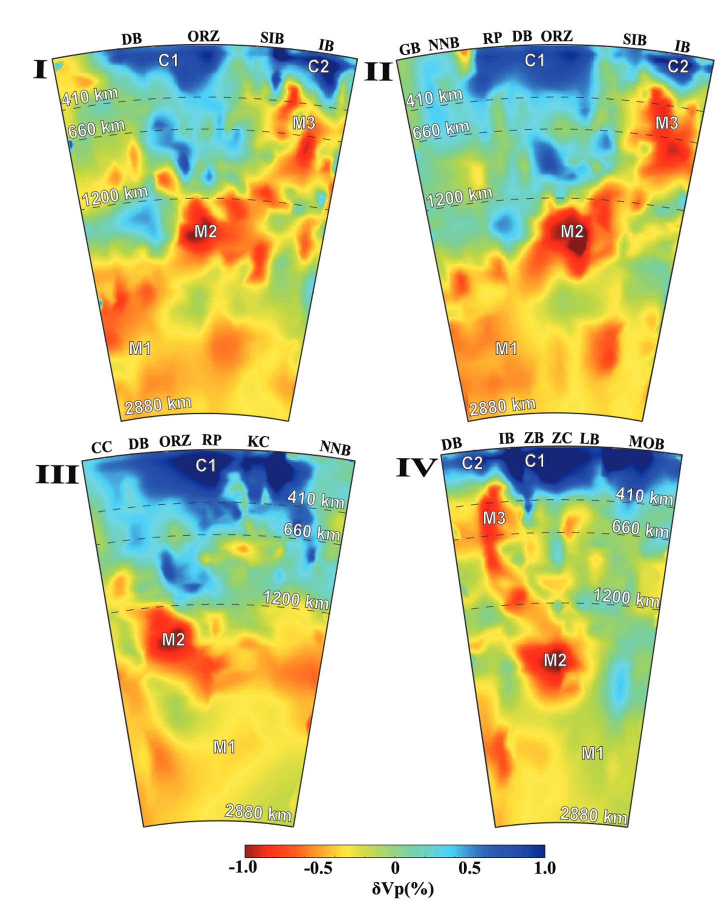


**Figure 4.** Cross-sectional profiles across the study region (locations are shown in Figure 3). Abbreviations for tectonic features are the same as in Figure 1. We note that our profiles I and II are the same as those from White-Gaynor et al. (2020), though our model is plotted to deeper depth.

We observe slow mantle velocities beneath the Damara region, but they are constrained to depths greater than ~1200 km (Figs. 3-4). Additionally, as shown on Profiles I, II, and IV (Fig. 4), the slow velocities ascend to shallower depths on the northeastern side of the study region, crossing the mantle transition zone near the Irumide Belt, and reaching the upper mantle beneath the EARS. Our results also suggest a change in the fast upper mantle seismic velocities from southwest to northeast. Beneath the Damara Belt, fast anomalies extend to ~400-500 km depth (depending on the profile), but beneath the Irumide Belt, the fast velocities are constrained to the upper ~200-300 km of the mantle.

## Resolution Tests

Several types of resolution tests were performed to evaluate our model. Our checkerboard tests (Fig. 5) included 5° x 5° input checkers, with thicknesses of 35 km and +/- 2% P-wave velocity perturbations, centered at different depths in the model space. Targeted resolution tests (Fig. 6) were also designed to assess features of interest in our tomographic results (Figs. 3-4), and synthetic anomalies were varied to match the observed features as closely as possible. All synthetic input anomalies (Figs. 5-6) were projected onto the adaptive grid (Fig. 2).

The synthetic anomalies are generally well recovered, illustrating the high resolution and reliability of our model. The seismically slow structure beneath the study area (Fig. 4) is best-matched by a deep feature (M1) beneath southern Africa that shallows to the northeast (M2 and M3; Fig. 6), and this is interpreted as the rising African LLVP. That said, the Damara Belt is characterized by fast upper mantle velocities, which agrees with prior studies that argue for unperturbed mantle beneath this area. This suggests that the LLVP does not extend into the upper mantle beneath south-central Africa.

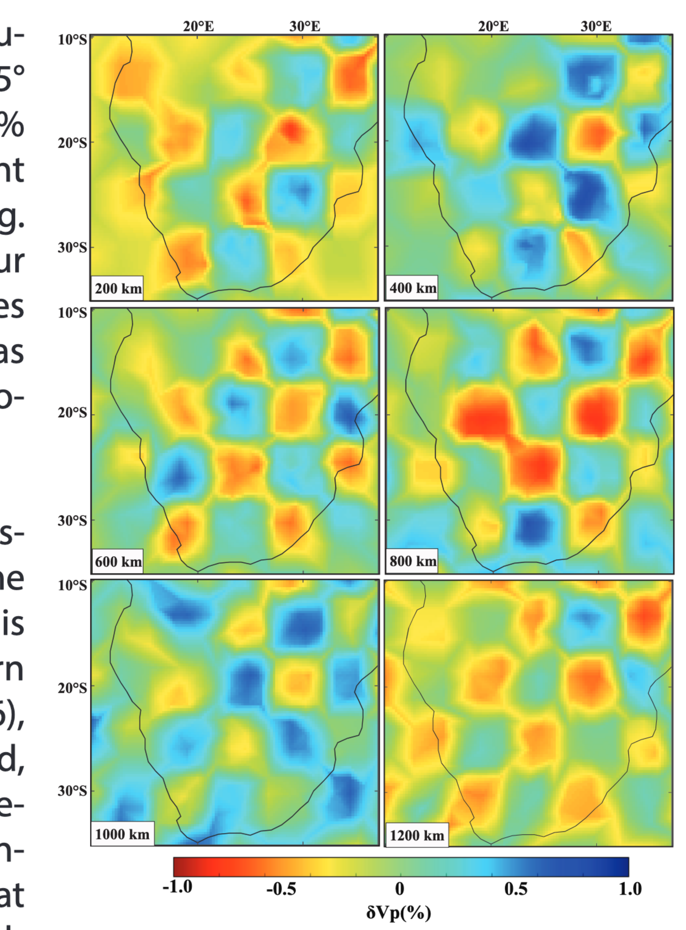


**Figure 5.** Checkerboard resolution tests at selected mantle depths. All models were generated with 5° x 5° input checkers that had +/- 2% P-wave velocity perturbations (δVP) compared to the reference model.

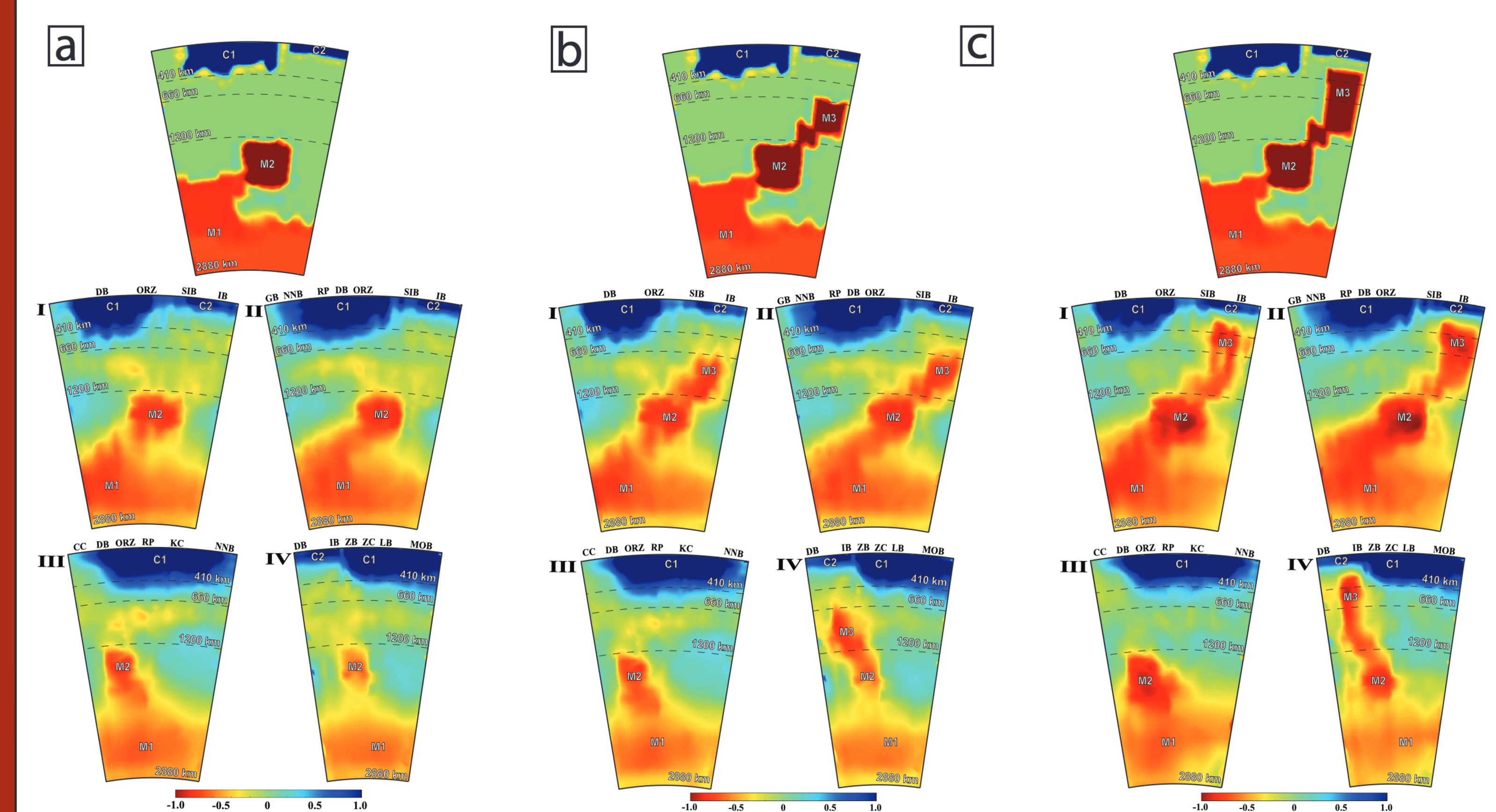


**Figure 6.** Targeted resolution tests. (a) Top panel: input model along Profile II. Fast anomalies C1 and C2 represent the cratonic lithosphere under the Damara region and the Irumide Belt. Slow anomalies M1 and M2 represents the African LLVP, which extends upwards from the core-mantle boundary to just below 1200 km depth. Bottom panels: recovered results along all four profiles (Fig. 4). Abbreviations for tectonic features are the same as in Figure 1. (b) Same as (a) but now including slow anomaly M3, which extends upwards to the bottom of the mantle transition zone. (c) Same as (b) but M3 now extends accross the mantle transition zone and into the upper mantle beneath the northeastern part of the study area.

## Concluding Points

Our new adaptively parameterized teleseismic P-wave tomography model:

- advocates for slow seismic velocities below ~1200 km depth beneath south-central Africa, indicating that the African LLVP does not extend into the upper mantle beneath the Damara Belt.
- disputes a thermally perturbed upper mantle beneath the Damara region.
- suggests the African LLVP rises obliquely toward the northeast, crossing the mantle transition zone near the Irumide Belt, and extending into the upper mantle beneath the EARS
- correlates with surface observations, including areas of heat flow, the distribution of geothermal features, and the locations of rifts.

List of References