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Adaptively Parameterized P- and S-wave Tomography in Africa: Assessing Deep Mantle Influence on Surface Geology

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Abstract

Various seismic investigations in Africa have tried to assess the potential connection between surface geology and the African Large Low Velocity Provinces (LLVP); however, numerous questions still exist regarding how lower mantle processes influence those seen at the surface. Using adaptively parameterized teleseismic travel-time tomography, we are expanding such studies, particularly to improve imaging at mid- to lower mantle depths, which are critical to assess mantle dynamics. Data from the International Seismological Center catalog as well as from temporary deployments throughout Africa have been combined, leading to the largest collection of travel-time residuals recorded across the continent to date. These data have been used to develop new P- and S-wave velocity (V_P and V_S) models that provide strong evidence for connections between the LLVP and features in both western and eastern Africa, including the Cameroon Volcanic Line and the East African Rift System. Further, results from both models are being combined to develop self-consistent V_P/V_S estimates, which will allow us to assess the thermal versus chemical structure of the LLVP. Ultimately, our work will further elucidate how surface features in Africa depend on deep mantle influence.

Introduction

One of the main challenges in geology is connecting processes occurring inside our planet to those we observe at the surface. Africa displays a wide variety of tectonic features, including continental rifting, linear volcanic chains, and plateau uplift, and is therefore an ideal natural laboratory to investigate geodynamic processes (Fig. 1). However, despite numerous prior investigations, there are still unanswered questions about many features across the African continent.

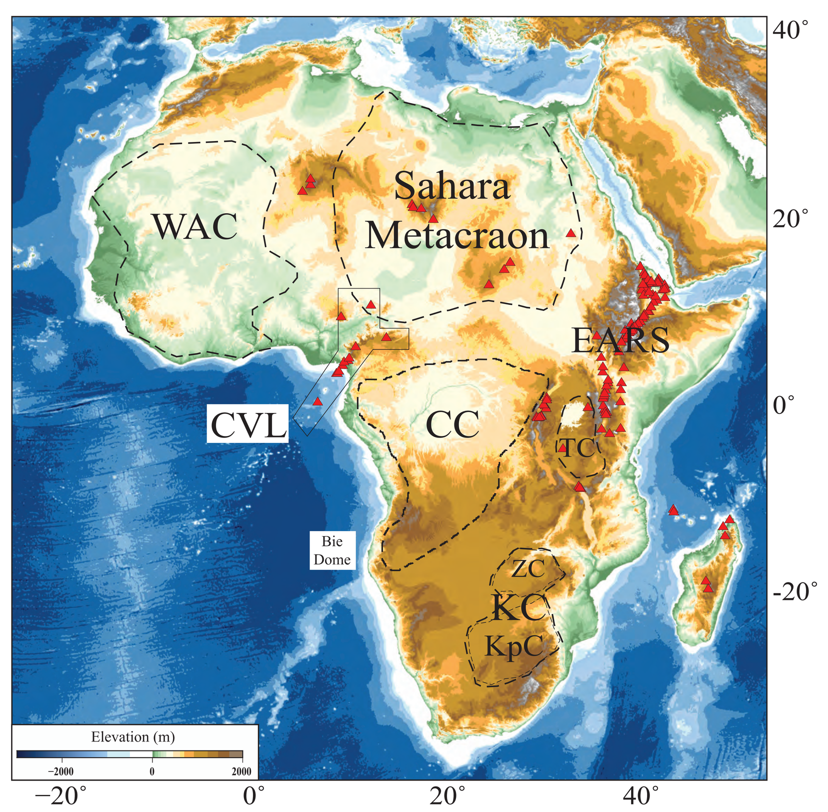
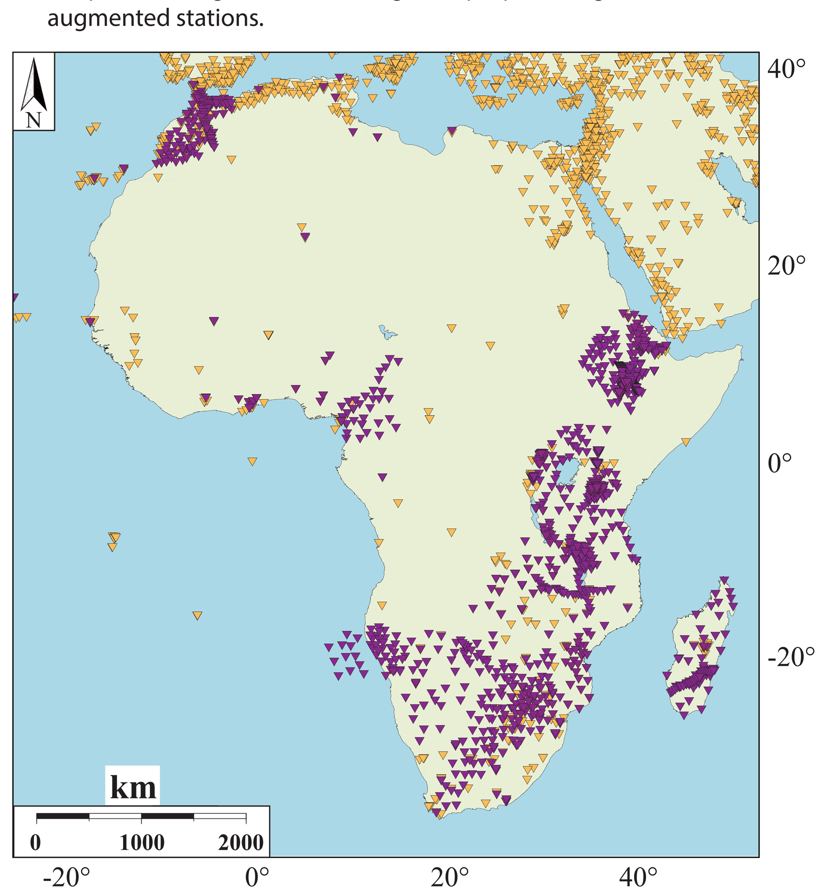


Figure 1. Tectonic map of Africa, based on ETOPO1 (Amante & Eakins, 2009), that highlights the cratonic boundaries and other tectonic features of interest. Red triangles indicate the locations of Quaternary volcanoes reported by the Global Volcanism Program (Smithsonian Institution, 2022). CVL: Cameroon Volcanic Line; CC: Congo Craton; EARS: East African Rift System; KC: Kalahari Craton; KpC: Kaapvaal Craton; TC: Tanzanian Craton; WAC: West African Craton; ZC: Zimbabwe Craton.

While teleseismic body wave tomography is a common tool to investigate Earth structure, the non-uniform distribution of seismic stations and earthquakes prevents uniform sampling of the Earth's interior. Despite this, most traditional tomographic methods use a regularly-spaced grid to parameterize the model space, which can lead to resolution issues.

Figure 2. Map of Africa showing the distribution of seismic stations used in this study. Orange triangles denote stations that are part of the global ISC catalog, and purple triangles denote augmented stations.



Our investigation instead uses an approach where the model grid is adapted to the ray path coverage, thereby improving resolution at critical mid- and lower mantle depths that are generally poorly resolved in regional and global models. Our tomographic results are developed using data from both the global International Seismological Center (ISC) catalog (Engdahl et al., 1998; Weston et al., 2018) as well as from other stations throughout Africa (Fig. 2).

Collectively, our applied method and our large seismic dataset allow us to develop new P- and S-wave velocity models for the structure beneath Africa and to further assess potential connections between deep mantle processes and surface tectonics.

Adaptive Grids for P- versus S-wave Tomography

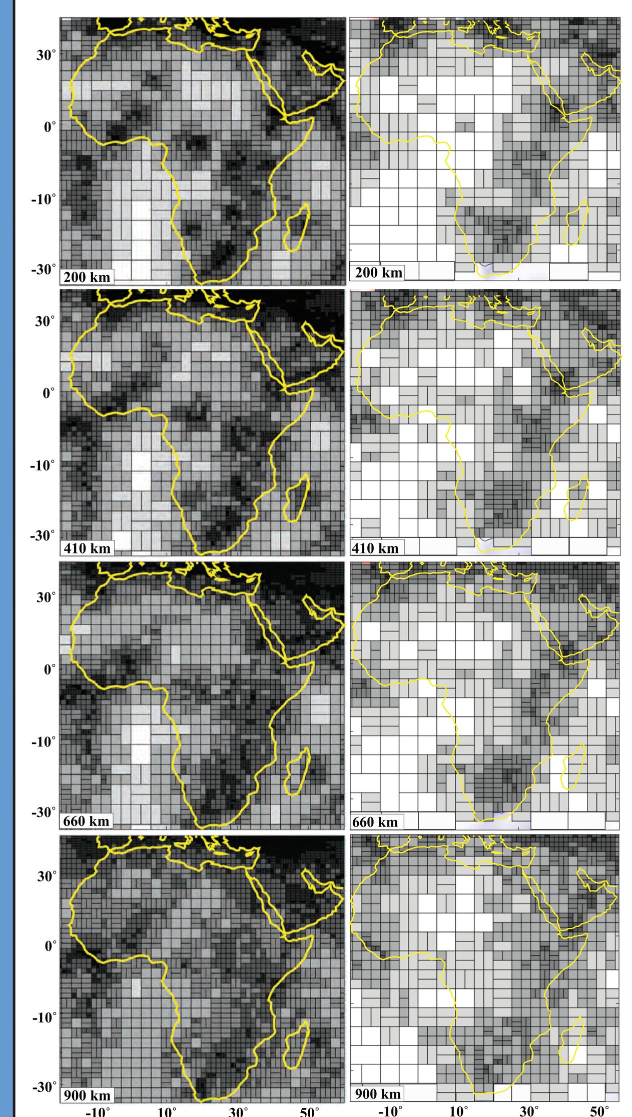
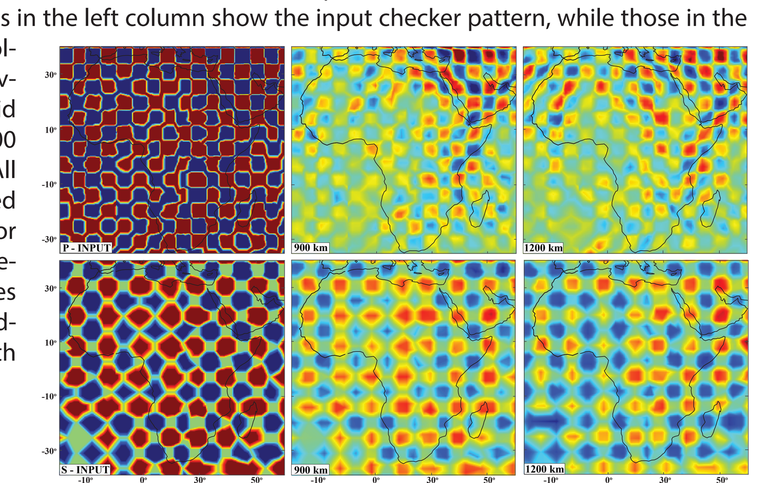


Figure 3. Adaptive grids for both P-wave (left) and S-wave (right) models, shown at selected mantle depths. All adaptive cells are required to have a ray count of at least 900 for the P model and 500 for the S model. Darker (smaller) cells are associated with areas of greater ray path coverage and higher resolution. Our model resolution is better at mid- to lower mantle depths compared to the shallow mantle.

The global ISC P-wave catalog includes more than 30 million travel-time residuals from over 550,000 earthquakes; however, the ISC S-wave catalog is smaller, containing about half a million travel-time residuals from about 44,000 events (Engdahl et al., 1998; Weston et al., 2018). We augment the global catalogs with ~102,000 P-wave and ~43,000 S-wave travel-time residuals from data recorded by temporary African seismic networks (Fig. 2).

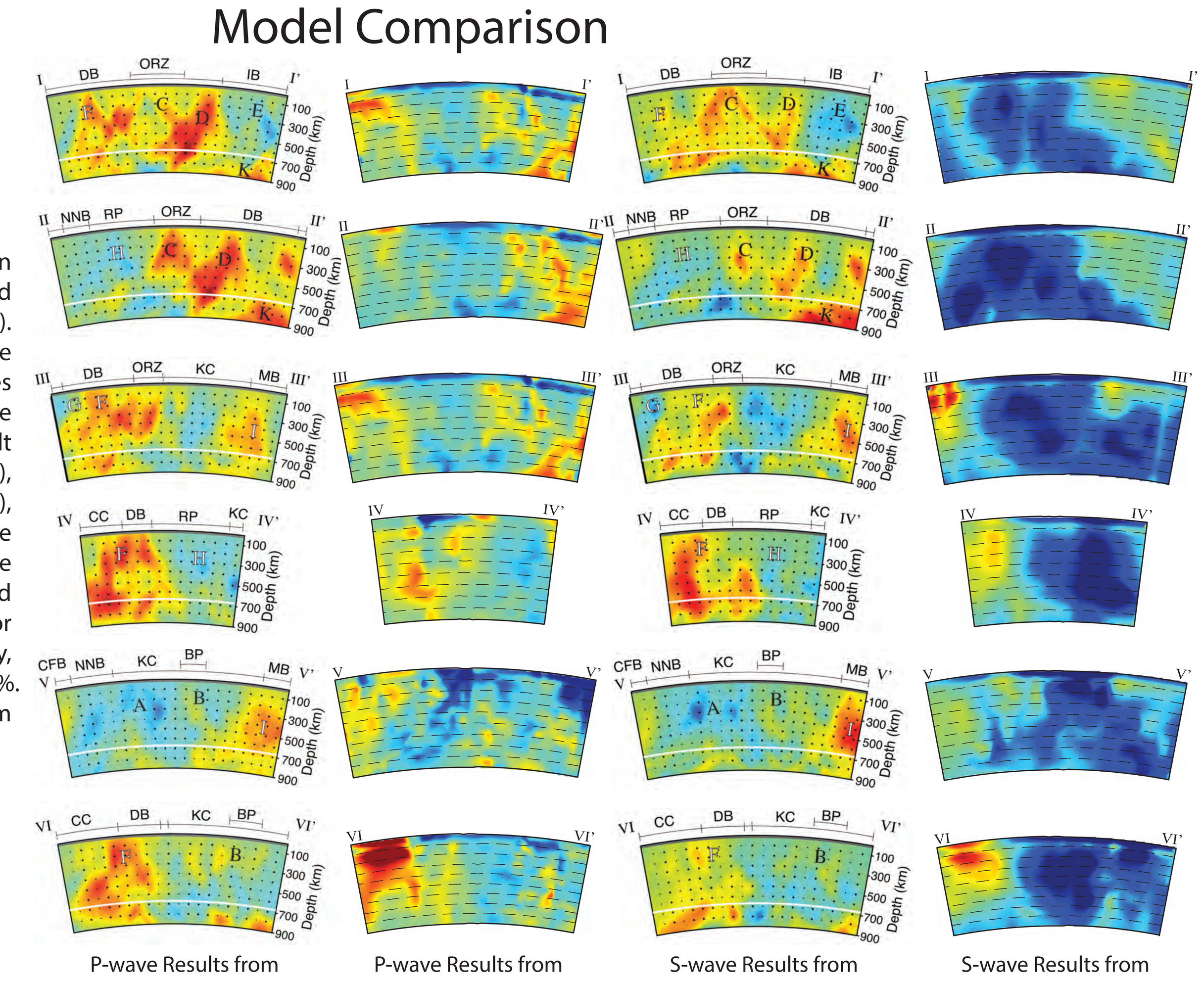
Since the number of S-wave travel-time residuals is vastly lower than the P-wave dataset, our S-wave model has lower resolution (Figs. 3-4). That said, both models have acceptable resolution when compared to other global models, and both display smaller, local anomalies that are similar to those observed in regional models. Further, the new adaptively parameterized P- and S-wave models have reliable resolution at mid- to lower mantle depths, thereby allowing us to potentially fill the resolution gap between global and regional tomographic studies.

Figure 4. Checkerboard resolution tests for the (top row) P-wave model and (bottom row) S-wave model. Panels in the left column show the input checker pattern, while those in the middle and right columns show the recovered pattern at mid mantle depths (900 and 1200 km). All models are plotted with a ± 1% color scale. Amplitude recovery varies (~30-50%), depending seismic ray path density.



Model Comparison

Figure 5. Cross-section comparison between our P- and S-wave results and those from White-Gaynor et al. (2020). Anomalies labeled A-K in the White-Gaynor et al. (2020) images highlight the Kaapvaal Craton (A), the Bushveld Complex (B), the Damara Belt (C, D, & F), the Irumide Belt (E, J, & K), the Etendeka magmatic anomaly (G), the Rehoboth Province (H), and the Mozambique Belt (I). Note that the White-Gaynor et al. (2020) P- and S-wave models are plotted with color scales of ± 1% and ± 1.5%, respectively, while our results are all plotted at ± 1%. Dashed or dotted lines indicate 100 km depth increments on each panel.



Our results show good agreement with recent regional tomographic models for Africa, such as that from White-Gaynor et al. (2020; Fig. 5). This comparison illustrates that our adaptively parameterized models can help to resolve local-scale features while also providing improved resolution for mid- to lower mantle structures (Figs. 3-4), thereby allowing us to better assess connections between the deep mantle and surface phenomena.

Results and Interpretations

Similar to many other tomographic models, both our P- and S-wave results show slow velocities in the lower mantle beneath southern Africa, which are attributed to the African LLVP: a large-scale, thermo-chemical anomaly that originates near the core-mantle boundary. Our models also indicate that slow velocities in the upper mantle beneath the Cameroon Volcanic Line (CVL) are connected to the LLVP through the mid-mantle (Fig. 6). This suggests that CVL volcanism is driven by a deep mantle source.

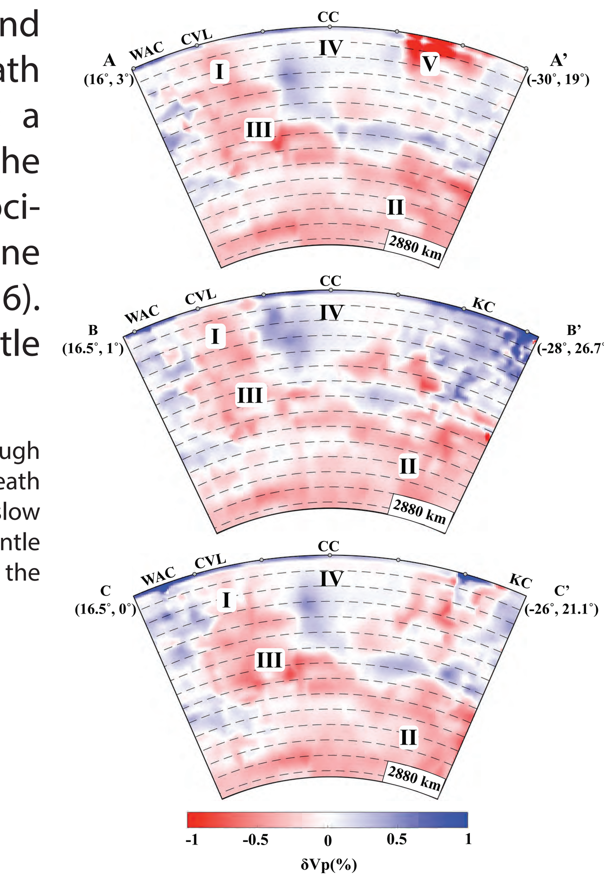


Figure 6. Cross-sectional profiles extending between western and southern Africa, passing through the center of the CVL. Dashed lines mark the depth in 200 km increments. Slow velocities beneath the CVL (I) and those in the African LLVP (II) are connected across the mid-mantle (III). The slow anomaly near the southern end of profile A-A' (V) is located near Bie Dome. Fast, upper mantle anomalies are associated with the Congo Craton (IV; CC), the West African Craton (WAC), and the Kaapvaal Craton (KC).

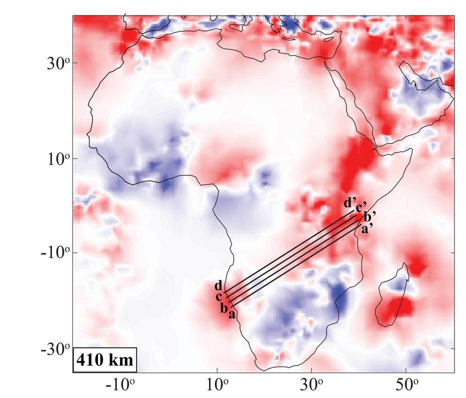
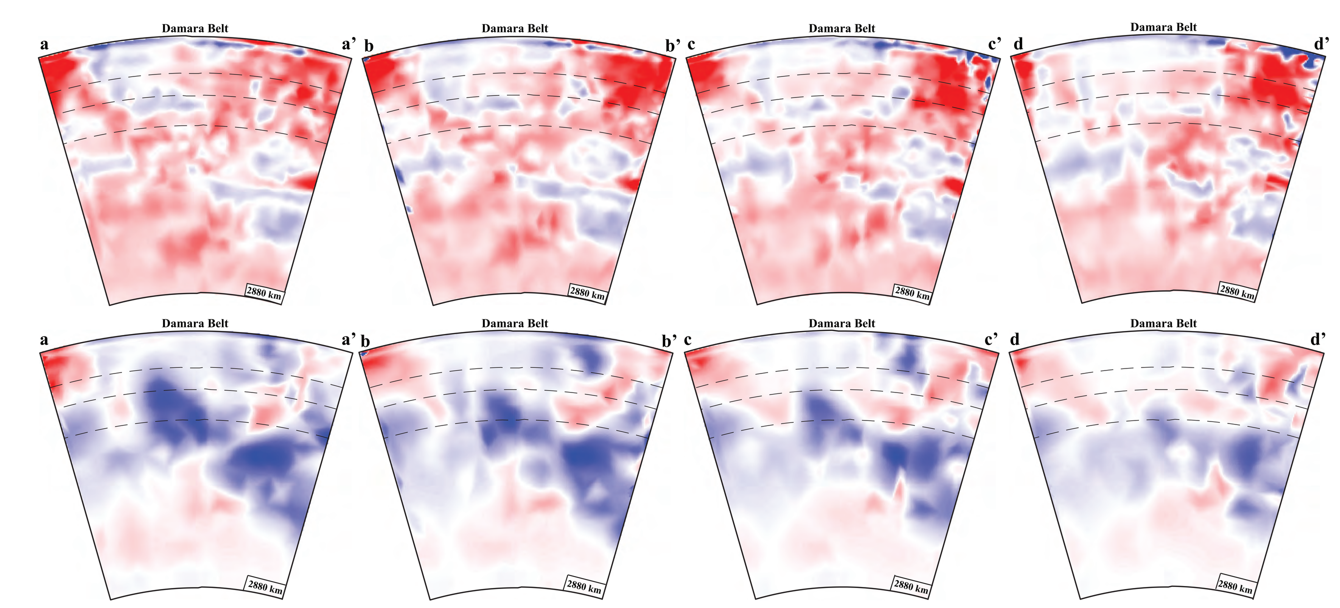


Figure 7. Map view of our new P-wave tomography model at 410 km depth. Black lines show the locations of the profiles in Figure 8.

Cross-sections through both our P- and S-wave models also suggest that the slow LLVP anomaly may be connected to slow velocity structures in the shallow mantle beneath the EARS and the Damara Belt. The hot buoyant LLVP material may be directed by topography on the base of the lithosphere, directing this material beneath thinner regions between the cratons. Further resolution tests are needed to investigate this structure in central and eastern Africa and the potential connection between the lower mantle LLVP anomaly and surface tectonics.

Figure 8. Cross-sections through our new (top row) P-wave and (bottom row) S-wave velocity models, extending from the south-central coast of Africa, near Bie Dome, through the Damara Belt, and into the southern EARS (locations shown on Figure 7). Dashed lines denote depths of 410, 660, and 1000 km. All panels are plotted with a ± 1% color scale.



Concluding Points and Future Work

We have developed new P- and S-wave tomography models for the African continent to further assess tectonic structure and the potential connection between deep Earth processes and surface tectonics. Our adaptive parameterization allows us to resolve regional-scale features while also providing high-resolution imaging at critical mid- and lower mantle depths. Key features indicated by our new models include:

- deep mantle influence on the Cameroon Volcanic Line
- a potential connection between the LLVP and structures in both East Africa and in the Damara Belt

Future work will include:

- Additional resolution tests
- Further assessment of V_P/V_S
- Associated receiver function analysis