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Prominent thermal anomalies in the mantle transition zone beneath the Transantarctic Mountains

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ABSTRACT

The Transantarctic Mountains (TAMs), Antarctica, exhibit anomalous uplift and volcanism and have been associated with regions of thermally perturbed upper mantle that may or may not be connected to lower mantle processes. To determine if the anomalous upper mantle beneath the TAMs connects to the lower mantle, we interrogate the mantle transition zone (MTZ) structure under the TAMs and adjacent parts of East Antarctica using 12,500+ detections of P-to-S conversions from the 410 and 660 km discontinuities. Our results show distinct zones of thinner-than-global-average MTZ (~205–225 km, ~10%–18% thinner) beneath the central TAMs and southern Victoria Land, revealing throughgoing convective thermal anomalies (i.e., mantle plumes) that connect prominent upper and lower mantle low-velocity regions. This suggests that the thermally perturbed upper mantle beneath the TAMs and Ross Island may have a lower mantle origin, which could influence patterns of volcanism and TAMs uplift.

INTRODUCTION

One outstanding question about the tectonic evolution of Antarctica is the origin of thermally perturbed upper mantle along the western geographic margin of the West Antarctic Rift System and its influence on Cenozoic volcanism within the Transantarctic Mountains (TAMs). Mantle plumes have commonly been invoked to explain volcanism in the Victoria Land segment of the TAMs (LeMasurier and Landis, 1996), though alternate mechanisms have also been proposed (Rocchi et al., 2002). Furthermore, while seismic tomography indicates low velocities in both the upper and mid-lower mantle (e.g., French and Romanowicz, 2015; White-Gaynor et al., 2019), limited resolution of the mantle transition zone (MTZ) leaves open the possibility that upper and lower mantle anomalies are connected. As a result, the origin of the volcanism and underlying thermally perturbed upper mantle along the TAMs is still debated.

Further, elucidating the origin of thermally perturbed upper mantle is important for understanding uplift of the TAMs, which exhibit a spatially variable and episodic history of uplift during the Cretaceous and the Cenozoic (e.g., Wilson, 1995; Fitzgerald, 2002). Multiple mechanisms have been proposed to explain the TAMs uplift (e.g., Stern and ten Brink, 1989; Wannamaker et al., 2017; Shen, et al., 2018), with some possibilities invoking flexure due to lithospheric heating (e.g., Brenn et al., 2017, and references therein) and dynamic uplift due to mantle convection (Faccenna et al., 2008). A mantle plume, if present, might contribute to lithospheric heating or dynamic uplift mechanisms.

One of the best ways to probe for a connection between thermal anomalies in the upper and lower mantle is to interrogate the structure of the MTZ. Prior MTZ P-wave receiver function (PRF) analysis found no evidence for thinning beneath Ross Island and concluded that only upper mantle processes were active (Reusch et al., 2008). However, more data are now available (~450% more), spanning much of the TAMs and East Antarctica; we use this full ensemble of data to search for connections between the upper and lower mantle.

DATA AND METHODS

Data were collected from several broadband seismic deployments and long-term stations in Antarctica (Fig. 1; Appendix S1 in the Supplemental Material[1]). The PRF processing steps are identical to those of Emry et al. (2015); however, because longer-period filters provide better detection of MTZ Ps converted phases at the 410, 520, and 660 km discontinuities, we limit analysis to one Gaussian filter of width 0.5 (≤0.24 Hz). We also correct for three-dimensional (3-D) seismic velocity variations in this analysis.

The PRFs were stacked using the method of Owens et al. (2000); each stack was bootstrap resampled 200 times, and 95% confidence bounds were created from the resampled PRFs. Peaks near 410 and 660 km (discontinuities hereafter referred to as 410′ and 660′, respectively) with a lower confidence bound above zero amplitude were interpreted as MTZ discontinuities, and the resampled stack peaks

[1]Supplemental Material. Additional information about methods and results (Appendices S1 and S2, Figures S1–S8, and Datasets S1 and S2). Please visit https://doi.org/10.1130/GEOL.26213S.12218282 to access the supplemental material, and contact editing@geosociety.org with any questions.

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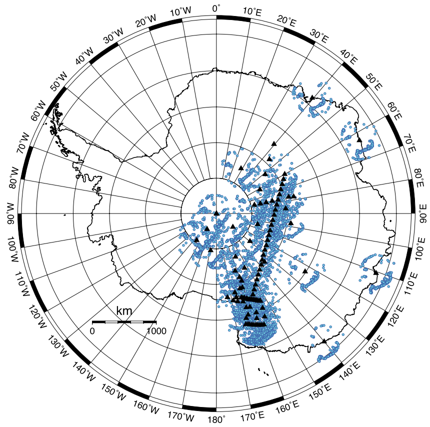

Figure 1. Antarctic seismic stations (black triangles) used in this study, and Ps conversion points at 660 km depth (cyan dots) based on ak135 one-dimensional global velocity model (Kennett et al., 1995).

were used to find depth uncertainties (Fig. 2; Appendix S1).

Following initial individual station (i.e., "single-station") stacking, higher-resolution common conversion point (CCP) stacks were created, assuming a one-dimensional velocity model (ak135; Kennett et al., 1995), where Ps conversions from multiple stations overlapped (Fig. 1). The CCP bin radius was 2° in East Antarctica, 1.5° in the central TAMs, and initially 1.0° in Victoria Land, with additional 1.25° stacks calculated for the southern Victoria Land (SVL) region. Subsequently, where MTZ thinning was found, we migrated the CCP stacks using three different P- and S-wave tomography models (Simmons et al., 2010; Brenn et al., 2017; Lloyd et al., 2019; Appendices S1 and S2).

RESULTS

Our results provide new higher-resolution estimates of MTZ thickness in East Antarctica, Victoria Land, and the central TAMs (Fig. 2). Initial results from single-station stacking and subsequent CCP stacks migrated with the ak135 velocity model (Kennett et al., 1995) show an MTZ thickness of ~190–240 km (±~15 km) in several central TAMs and SVL stacks (Data Set S1 in the Supplemental Material). When we incorporate depth uncertainties, a statistical measurement based on the variation of the stacked PRFs, our most conservative estimates for the thickness of the MTZ are still <225 km for ~12% of the central TAMs and ~11% of the SVL stacks. This robustly suggests a hotter-than-average MTZ, assuming that an average dry, pyrolitic Earth would have a ~250-km-thick MTZ (Bina and Hellfrich, 1994). Furthermore, depending on which 3-D tomographic model is used to migrate the PRFs, 12%–15% of the central TAMs stacks and 3%–8% of the SVL stacks still indicate that the most conservative MTZ thickness estimates are <225 km (Data Set S1; Fig. S1).

In addition to MTZ thickness, we observe a depression of both the 410′ and 660′ in the western Ross Sea stacks (longitude >160°E), regardless of whether a thinned MTZ was identified. This apparent downward shift indicates that the upper mantle Vp/Vs ratio in the tomographic models may not represent the true anomalies (Emry et al., 2015; Appendix S1) and suggests that MTZ thickness is a more robust indicator of mantle temperature. We also observe that the SVL anomaly (Fig. 2, region C) overlaps with an area previously studied by Reusch et al. (2008),

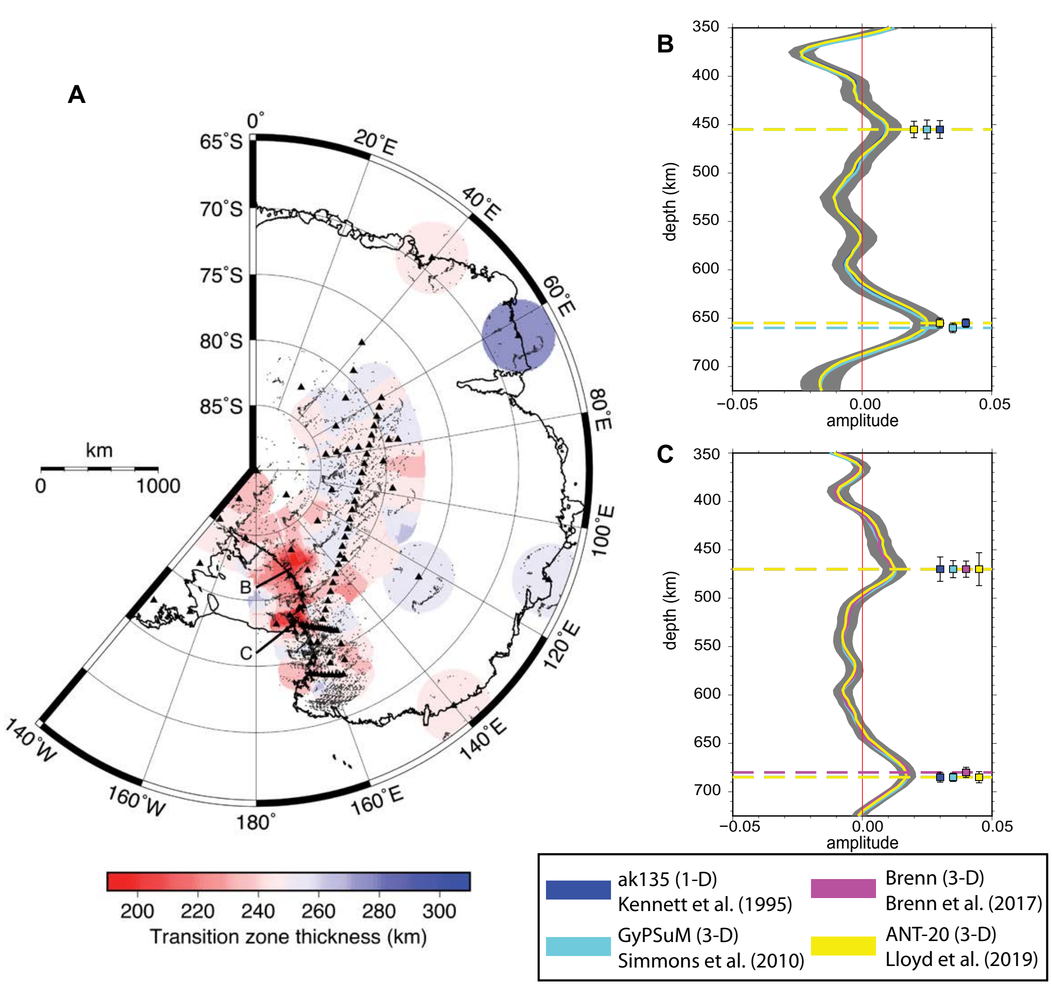

Figure 2. (A) Mantle transition zone (MTZ) thickness using ak135 model (Kennett et al., 1995). Isolated seismic stations show MTZ thickness from single-station stacks. Common conversion point (CCP) stacks in East Antarctica (longitude <135°E) have 2.0° bin radius; in central Transantarctic Mountains (TAMs) (south of 79°S), bin radius is 1.5°; and in Victoria Land (north of 79°S), bin radius is 1.0°. Black triangles show seismic stations. Black dots show Ps conversion locations at 660 km depth. Regions of prominent MTZ thinning are labeled B and C. (B) Comparison between P-wave receiver function (PRF) CCP stacks for region B (82°S, 160°E, central TAMs), migrated with velocity models described in legend; here, CCP stacks have 1.5° bin radii. (C) Same as B, except showing PRF CCP stacks for region C (79°S, 165°E, beneath southern Victoria Land). In B and C, gray shading shows stack uncertainty for one-dimensional (1-D) model. Peak depths and depth uncertainty (2σ) are shown by squares and horizontal, dashed lines with colors that correspond to legend. 3-D—three dimensional.

who found no MTZ thinning using ~20% of our PRFs; however, many of their stacks showed complex 410′ and 660′ peaks, which we also find on the edges of our anomalous regions. This complexity simplifies near the center of our anomalies, suggesting a localized anomaly; we expect that our expanded data set has improved our resolution (Appendix S1).

DISCUSSION

MTZ Thermal Structure

Our results provide evidence for MTZ thinning beneath the central TAMs and SVL. Although hydration or other compositional effects may thicken the MTZ (e.g., Weidner and Wang, 2000; Bina, 2003), heat is the only clear cause of MTZ thinning (Bina and Hellfrich, 1994). As in Emry et al. (2015), we use deviations from global average MTZ thickness (i.e., 250 km; Bina and Hellfrich, 1994) to estimate anomalous temperature, incorporating our depth uncertainties and a range of 660′ Clapeyron slopes (see Data Set S2, and references therein). Corresponding predicted excess temperature beneath SVL and the central TAMs is 100–500 K and 100–600 K, respectively.

Beneath SVL, some tomographic models indicate slower-than-average velocities at MTZ depths (~400–700 km; e.g., French and Romanowicz, 2015), though recent results (Lloyd et al., 2019) suggest only a moderate velocity decrease (~1%). At first glance, this seems to contradict our findings. However, studies of temperature effects on elastic parameters suggest that at increasing depth, temperature variations produce smaller changes than at shallower depths. For example, a 100 K anomaly at the top of the MTZ only produces a 0.3%–0.7% change in seismic velocity (Karato, 2011; Núñez-Valdez et al., 2013). Our lower-end temperature estimates are ~100–200 K; if we assume these temperature derivatives, our estimates do not contradict models showing ~1% velocity decreases in the MTZ. Additionally, velocity anomaly amplitudes in tomography are commonly under-recovered due to regularization-imposed bias and should be considered as a lower bound on a localized, true velocity anomaly (e.g., Rawlinson and Spakman, 2016).

In the central TAMs, we similarly note pronounced MTZ thinning, but we also observe more prominent negative peaks above the MTZ, similar to prior results from Marie Byrd Land in West Antarctica (Emry et al., 2015). Negative peaks above the 410′ have been attributed to a 410-km-depth low-velocity layer (410-LVL; e.g., Emry et al., 2015; Fig. S2), and recent tomography also images a nearby region of low velocities at 500 km (Lloyd et al., 2019). The 410-LVL is thought to be either a compositionally distinct or a partial-melt layer produced by current or prior MTZ hydration (Bercovici and Karato, 2003; Saki et al., 2019). While MTZ hydration or compositional variations would lower seismic velocity, if substantial, they would also thicken the MTZ (Weidner and Wang, 2000; Bina, 2003). Together, these observations suggest that a hotter-than-average MTZ exists beneath the central TAMs, but that past and present MTZ hydration might also be a factor. Such considerations may help to reconcile apparent discrepancies between MTZ thicknesses and seismic anomalies throughout Antarctica (e.g., Hansen et al., 2014; Emry et al., 2015; Lloyd et al., 2019).

Mantle Dynamics beneath the TAMs

The patterns of MTZ thinning indicate hotter temperatures beneath portions of the TAMs. As described above, clear topography is imaged on both the 410′ and the 660′, though both are also depressed beneath the western Ross Sea (Fig. 3; Data Set S1). Because of the overall apparent

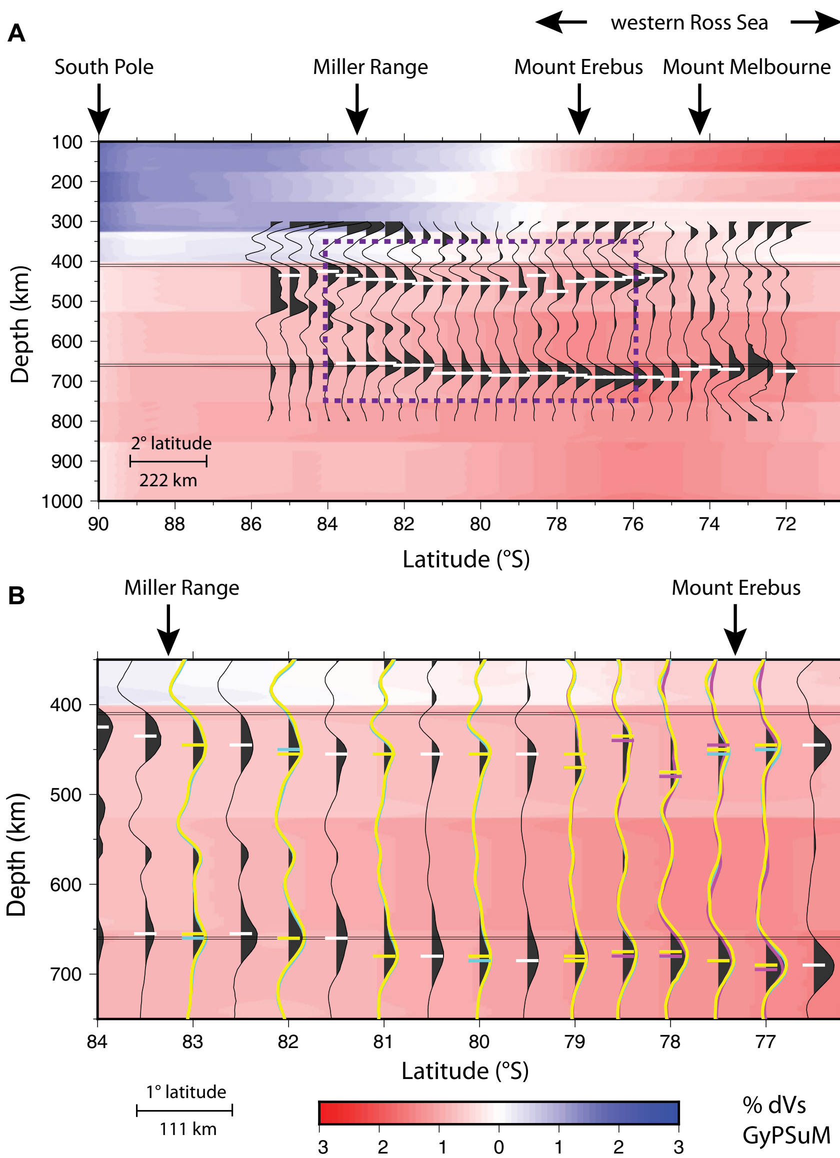

Figure 3. (A) P-wave receiver functions (PRFs) (black traces) plotted in cross-section for southern Victoria Land (SVL) and central Transantarctic Mountains (TAMs), Antarctica. White dashed lines show robust PRF peaks (above uncertainty). GyPSuM Vs model (Simmons et al., 2010) is plotted in background along 165°E longitude. Thin black horizontal lines mark depths of 410 and 660 km, where mantle transition zone boundaries would be located if mantle structure were equal to global average. Box (dashed purple lines) indicates region magnified in B. (B) Magnified region stretching from central TAMs (Miller Range) to SVL (Mount Erebus). Plot is same as in A, except PRFs migrated with GyPSuM (cyan lines; Simmons et al. 2010), Brenn et al. (2017; magenta lines), and ANT-20 (yellow lines; Lloyd et al., 2019) models are also plotted, along with their 410′ and 660′ peak depths.

depression of both, likely due to residual tomographic uncertainty, it is less reliable to interpret absolute peak depths than MTZ thickness (e.g., Bina, 2003). An edge-driven convection (EDC) model could feasibly perturb the MTZ thickness and the 410′, but not the 660′ (Kaislaniemi and van Hunen, 2014). To assess whether this could also explain our findings, we compare the locations of thinned MTZ with the edge of thick East Antarctic lithosphere (Lloyd et al., 2019). We find that the depressed 410′ and thinned MTZ is closer (<200 km) to the edge of the East Antarctic lithosphere than is predicted by an EDC model (Fig. S4).

Therefore, given that many tomographic models image low velocities (~1%–2% less than ak135; Kennett et al., 1995) at 800–1000 km depth beneath the TAMs (Figs. S5–S8; e.g., French and Romanowicz, 2015) and that regional models image low velocities in the upper mantle of the western Ross Sea (e.g., Lloyd et al., 2019), a more consistent explanation for the MTZ anomaly is a thermal upwelling from the lower mantle (Fig. S4). The SVL MTZ anomaly is located beneath the active volcanoes of the Erebus Volcanic Province (Kyle, 1990). Although disagreement exists as to whether the high μ (HIMU) signatures in the Erebus Volcanic Province come from lower mantle material or from metasomatized lithospheric melts (Panter et al., 2018, and references therein), our results showing a hot MTZ beneath SVL best fits with a lower mantle contribution, which agrees with the geochemical evolution of Erebus lavas over the last few million years (Phillips et al., 2018).

In contrast to the SVL MTZ, the central TAMs anomaly underlies a volcanic gap that stretches from Ross Island to Mount Early (LeMasurier, 1990). This area is located near a recent TAMs-crossing magnetotelluric study (Wannamaker et al., 2017), which identified thick resistive lithosphere beneath the TAMs and conductive material in the upper mantle beneath the Ross Sea. In this case, for the central TAMs anomaly to have an influence on volcanism, it may require that the proposed upwelling flow around a thick, central TAMs lithosphere, as proposed for other continents (Emry et al., 2019), toward adjacent regions of thinned lithosphere. This interpretation appears plausible given shear-wave splitting results (Accardo et al., 2014) that suggest variable flow directions beneath the central TAMs.

The SVL and central TAMs anomalies are laterally separated by ~600 km, and the anomalies' proximity to each other suggests that the localized upwellings could be sourced from a common, ponded, lower mantle plume (e.g., Civiero et al., 2015; Fig. S4). Further away from the TAMs front, several distinct low-velocity anomalies were recently imaged in the upper mantle of the Ross Sea (White-Gaynor et al., 2019). While it is possible that additional MTZ anomalies could exist beneath the Ross Sea, our data cannot resolve this region.

Uplift of the TAMs

Thermal plumes could promote uplift along the TAMs, either by providing heat to the lithosphere (e.g., Brenn et al., 2017) or by invoking flow that produces dynamic uplift (e.g., Faccenna et al., 2008). While a narrow mantle plume upwelling might contribute to dynamic uplift, we expect that the effect would be minor, unlike the effects predicted by earlier, large-scale models for the northern TAMs (Faccenna et al., 2008). Furthermore, lateral flow, as may exist beneath the central TAMs (e.g., Accardo et al., 2014), might further diminish any dynamic uplift contribution.

Rather, our MTZ anomalies may have a stronger influence on lithospheric heating. Prior models of a narrow, thermal plume scenario suggested localized heating beneath Marie Byrd Land (Seroussi et al., 2017); similarly, lithospheric heating could occur locally above our upwellings. However, we also expect that any low-viscosity thermal upwelling could be diverted by a thick central TAMs lithosphere (Wannamaker et al., 2017) or spread laterally along thinner lithosphere (Emry et al., 2019); therefore, we suggest that the thermal influence of a localized upwelling might have a geographically larger influence on lithospheric heating and uplift than on dynamic uplift. However, future 3-D geodynamical models of the region might further elucidate this matter.

CONCLUSIONS

We utilized a greatly expanded seismic data set in East Antarctica and the TAMs to search for indications of thinner (hotter)–than–average MTZ structure associated with mantle plumes. Our results show strong evidence for localized MTZ thinning beneath SVL and the central TAMs. We propose that these anomalies are due to MTZ-crossing thermal plumes, and we expect such plumes to contribute to patterns of Ross Island volcanism and TAMs uplift by transporting hot material into the upper mantle.

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REFERENCES CITED

Accardo, N.J., Wiens, D.A., Hernandez, S., Aster, R.C., Nyblade, A., Huerta, A., Anandakrishnan, S., Wilson, T., Heeszel, D.S., and Dalziel, I.W.D., 2014, Upper mantle seismic anisotropy beneath the West Antarctic Rift System and surrounding region from shear wave splitting analysis: Geophysical Journal International, v. 198, p. 414–429, https://doi.org/10.1093/gji/ggu117.

Bercovici, D., and Karato, S.-i., 2003, Whole-mantle convection and the transition-zone water filter: Nature, v. 425, p. 39–44, https://doi.org/10.1038/nature01918.

Bina, C.R., 2003, Seismological constraints upon mantle composition, *in* Carlson, R.W., ed., Treatise on Geochemistry, Volume 2: The Mantle and Core: Amsterdam, Pergamon, p. 39–59, https://doi.org/10.1016/B0-08-043751-6/02002-8.

Bina, C.R., and Hellfrich, G., 1994, Phase transition Clapeyron slopes and transition zone seismic discontinuity topography: Journal of Geophysical Research, v. 99, p. 15,853–15,860, https://doi.org/10.1029/94JB00462.

Brenn, G.R., Hansen, S.E., and Park, Y., 2017, Variable thermal loading and flexural uplift along the Transantarctic Mountains, Antarctica: Geology, v. 45, p. 463–466, https://doi.org/10.1130/G38784.1.

Civiero, C., et al., 2015, Multiple mantle upwellings in the transition zone beneath the northern East-African Rift system from relative P-wave travel-time tomography: Geochemistry Geophysics Geosystems, v. 16, p. 2949–2968, https://doi.org/10.1002/2015GC005948.

Emry, E.L., Nyblade, A.A., Julià, J., Anandakrishnan, S., Aster, R.C., Wiens, D.A., Huerta, A.D., and Wilson, T.J., 2015, The mantle transition zone beneath West Antarctica: Seismic evidence for hydration and thermal upwellings: Geochemistry Geophysics Geosystems, v. 16, p. 40–58, https://doi.org/10.1002/2014GC005588.

Emry, E.L., Shen, Y., Nyblade, A.A., Flinders, A., and Bao, X., 2019, Upper mantle Earth structure in Africa from full-wave ambient noise tomography: Geochemistry Geophysics Geosystems, v. 20, p. 120–147, https://doi.org/10.1029/2018GC007804.

Faccenna, C., Rossetti, F., Becker, T.W., Danesi, S., and Morelli, A., 2008, Recent extension driven by mantle upwelling beneath the Admiralty Mountains (East Antarctica): Tectonics, v. 27, TC4015, https://doi.org/10.1029/2007TC002197.

Fitzgerald, P., 2002, Tectonics and landscape evolution of the Antarctic plate since the breakup of Gondwana, with an emphasis on the West Antarctic Rift System and the Transantarctic Mountains: Royal Society of New Zealand Bulletin, v. 35, p. 453–469.

French, S.W., and Romanowicz, B., 2015, Broad plumes rooted at the base of the Earth's mantle beneath major hotspots: Nature, v. 525, p. 95–99, https://doi.org/10.1038/nature14876.

Hansen, S.E., Graw, J.H., Kenyon, L.M., Nyblade, A.A., Wiens, D.A., Aster, R.C., Huerta, A.D., Anandakrishnan, S., and Wilson, T., 2014,

Imaging the Antarctic mantle using adaptively parameterized P-wave tomography: Evidence for heterogeneous structure beneath West Antarctica: Earth and Planetary Science Letters, v. 408, 66–78, https://doi.org/10.1016/j.epsl.2014.09.043 .
Kaislaniemi, L., and van Hunen, J., 2014, Dynamics of lithospheric thinning and mantle melting by edge-driven convection: Application to Moroccan Atlas mountains: Geochemistry Geophysics Geosystems, v. 15, p. 3175–3189, https://doi.org/10.1002/2014GC005414.
Karato, S.-i., 2011, Water distribution across the mantle transition zone and its implications for global material circulation: Earth and Planetary Science Letters, v. 301, p. 413–423, https://doi.org/10.1016/j.epsl.2010.11.038.
Kennett, B.L.N., Engdahl, E.R., and Buland, R., 1995, Constraints on seismic velocities in the Earth from travel times: Geophysical Journal International, v. 122, p. 108–124, https://doi.org/10.1111/j.1365-246X.1995.tb03540.x.
Kyle, P.R., 1990, Erebus Volcanic Province: Summary, *in* LeMasurier, W.E., et al., eds., Volcanoes of the Antarctic Plate and Southern Oceans: American Geophysical Union Antarctic Research Series 48, p. 80–89.
LeMasurier, W.E., 1990, Late Cenozoic volcanism on the Antarctic plate: An overview, *in* LeMasurier, W.E., et al., eds., Volcanoes of the Antarctic Plate and Southern Oceans: American Geophysical Union Antarctic Research Series 48, p. 1–17, https://doi.org/10.1029/AR048p0001 .
LeMasurier, W.E., and Landis, C.A., 1996, Mantle-plume activity recorded by low-relief erosion surfaces in West Antarctica and New Zealand: Geological Society of America Bulletin, v. 108, p. 1450–1466, https://doi.org/10.1130/0016-7606(1996)108<1450:MPARBL>2.3.CO;2.
Lloyd, A.J., et al., 2019, Seismic structure of the Antarctic upper mantle imaged with adjoint tomography: Journal of Geophysical Research: Solid Earth, v. 125, https://doi.org/10.1029/2019JB017823.
Núñez-Valdez, M., Wu, Z., Yu, Y.G., and Wentzcovitch, R.M., 2013, Thermal elasticity of $(Fe_x,Mg_{1-x})_2SiO_4$ olivine and wadsleyite: Geophysical Research Letters, v. 40, p. 290–294, https://doi.org/10.1002/grl.50131.
Owens, T.J., Nyblade, A.A., Gurrola, H., and Langston, C.A., 2000, Mantle transition zone structure beneath Tanzania, east Africa: Geophysical Research Letters, v. 27, p. 827–830, https://doi.org/10.1029/1999GL005429.
Panter, K.S., Castillo, P., Krans, S., Deering, C., McIntosh, W., Valley, J.W., Kitajima, K., Kyle, P., Hart, S., and Blusztajn, J., 2018, Melt origin across a rifted continental margin: A case for subduction-related metasomatic agents in the lithospheric source of alkaline basalt, NW Ross Sea, Antarctica: Journal of Petrology, v. 59, p. 517–558, https://doi.org/10.1093/petrology/egy036.
Phillips, E.H., Sims, K.W.W., Blichert-Toft, J., Aster, R.C., Gaetani, G.A., Kyle, P.R., Wallace, P.J., and Rasmussen, D.J., 2018, The nature and evolution of mantle upwelling at Ross Island, Antarctica, with implications for the source of HIMU lavas: Earth and Planetary Science Letters, v. 498, p. 38–53, https://doi.org/10.1016/j.epsl.2018.05.049.
Rawlinson, N., and Spakman, W., 2016, On the use of sensitivity tests in seismic tomography: Geophysical Journal International, v. 205, p. 1221–1243, https://doi.org/10.1093/gji/ggw084.
Reusch, A.M., Nyblade, A.A., Benoit, M.H., Wiens, D.A., Anandakrishnan, S., Voigt, D., and Shore, P.J., 2008, Mantle transition zone thickness beneath the Ross Island, the Transantarctic Mountains, and East Antarctica: Geophysical Research Letters, v. 35, L12301, https://doi.org/10.1029/2008GL033873.
Rocchi, S., Armienti, P., D'Orazio, M., Tonarini, S., Wijbrans, J.R., and Di Vincenzo, G., 2002, Cenozoic magmatism in the western Ross Embayment: Role of mantle plume versus plate dynamics in the development of the West Antarctic Rift System: Journal of Geophysical Research, v. 107, 2195, https://doi.org/10.1029/2001JB000515.
Saki, M., Thomas, C., Cobden, L., Abreu, R., and Buchen, J., 2019, Causes for polarity reversals of PP precursor waves reflecting off the 410 km discontinuity beneath the Atlantic: Physics of the Earth and Planetary Interiors, v. 286, p. 111–126, https://doi.org/10.1016/j.pepi.2018.11.007.
Seroussi, H., Ivins, E.R., Wiens, D.A., and Bondzio, J., 2017, Influence of a West Antarctic mantle plume on ice sheet basal conditions: Journal of Geophysical Research: Solid Earth, v. 122, p. 7127–7155, https://doi.org/10.1002/2017JB014423.
Shen, W., et al., 2018, Seismic evidence for lithospheric foundering beneath the southern Transantarctic Mountains, Antarctica: Geology, v. 46, p. 71–74, https://doi.org/10.1130/G39555.1.
Simmons, N.A., Forte, A.M., Boschi, L., and Grand, S.P., 2010, GyPSuM: A joint tomographic model of mantle density and seismic wave speeds: Journal of Geophysical Research, v. 115, B12310, https://doi.org/10.1029/2010JB007631.
Stern, T.A., and ten Brink, U.S., 1989, Flexural uplift of the Transantarctic Mountains: Journal of Geophysical Research, v. 94, p. 10,315–10,330, https://doi.org/10.1029/JB094iB08p10315.
Wannamaker, P., et al., 2017, Uplift of the central Transantarctic Mountains: Nature Communications, v. 8, 1588, https://doi.org/10.1038/s41467-017-01577-2.
Weidner, D.J., and Wang, Y., 2000, Phase transformations: Implications for mantle structure, *in* Karato, S.-I., et al., eds., Earth's Deep Interior: Mineral Physics and Tomography from the Atomic to the Global Scale: American Geophysical Union Geophysical Monograph 117, p. 215–235, https://doi.org/10.1029/GM117p0215.
White-Gaynor, A.L., et al., 2019, Heterogeneous upper mantle structure beneath the Ross Sea Embayment and Marie Byrd Land, West Antarctica, revealed by P-wave tomography: Earth and Planetary Science Letters, v. 513, p. 40–50, https://doi.org/10.1016/j.epsl.2019.02.013.
Wilson, T.J., 1995, Cenozoic transtension along the Transantarctic Mountains–West Antarctic rift boundary, southern Victoria Land, Antarctica: Tectonics, v. 14, p. 531–545, https://doi.org/10.1029/94TC02441.

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