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Carbonatite melt pathways connect the deep mantle to Archean craton margins

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Abstract

Earth's deep carbon-cycle has been active since subduction of carbon-rich oceanic crust began in the Paleoproterozoic. Petrological evidence for carbonatite melts suggests they are a significant part of the mantle carbon reservoir and act as a highly efficient, volatile-rich transporting agent that dissolve, mobilise, and transfer rare earth and sulphur-bearing elements from deep mantle into the crust at craton margins. However, direct geophysical imaging of carbonatite melts in the mantle are ambiguous as electrical resistivity and shear-wave velocity anomalies can also be ascribed to hydrous silicates in solid or small melt fractions. In this paper we use long-period MT data to image an electrically anisotropic and conductive ($\sim 1 \text{ Ohm.m}$) lower lithosphere (180 km depth) beneath the Archean core of the Gawler Craton in southern Australia. We interpret these features as metasomatically modified and channelised structures, potentially associated with carbon-bearing melts, where small fractions ($\sim 0.05 \text{ vol\%}$) of carbonatite melt account for observed low resistivity. Additionally, low resistivity ($< 100 \text{ Ohm.m}$) regions are imaged at Moho depths in an arcuate belt around the Archean Craton, coincident with a shear-wave velocity decrease. Such low

resistivity regions are interpreted to be the signature of carbon exsolved as graphite from upward migrating deep-mantle carbonatite melts.

199 words

Introduction

It is well established that both organic and inorganic carbon is sequestered into the mantle by transport of oceanic sediment at subduction zones¹⁻⁴, with some fraction returned at island arc volcanics early in the subduction cycle⁵. However, a significant but unknown amount is transported deeper into the upper mantle in the form of carbonatites.^{1,6}, that have implications for mantle melting⁷, lithospheric metasomatism^{8,9}, redox state¹⁰, sulphur mobilisation¹¹⁻¹⁵, and rare earth element partitioning^{2,16}. Carbon is eventually returned to the oceans and atmosphere at continental¹⁷ and oceanic rifts¹⁸. The carbon cycle has been active since the Paleoproterozoic^{19,20}, but has changed with time²¹ depending on the configuration of plate boundaries and fluctuations in carbon sequestration into the mantle.

From petrological studies, it has been shown that carbonatite melting in the mantle lowers the melting temperature of surrounding peridotite mantle by several hundred degrees and generates highly mobile, reactive melts that facilitate deep carbon cycling and promote chemical enrichment of the Earth's interior^{13,22-24}. There is laboratory geophysical evidence that carbonatite melts at very small fractions (0.02-0.08 vol%) reduce the seismic shear-wave velocity²⁵ and significantly reduce (by up to three orders of magnitude compared to hydrous silicate melts of similar melt volume fraction) electrical resistivity²⁶⁻²⁸. However, direct geophysical observation of deep lithosphere shear-wave velocity and electrical

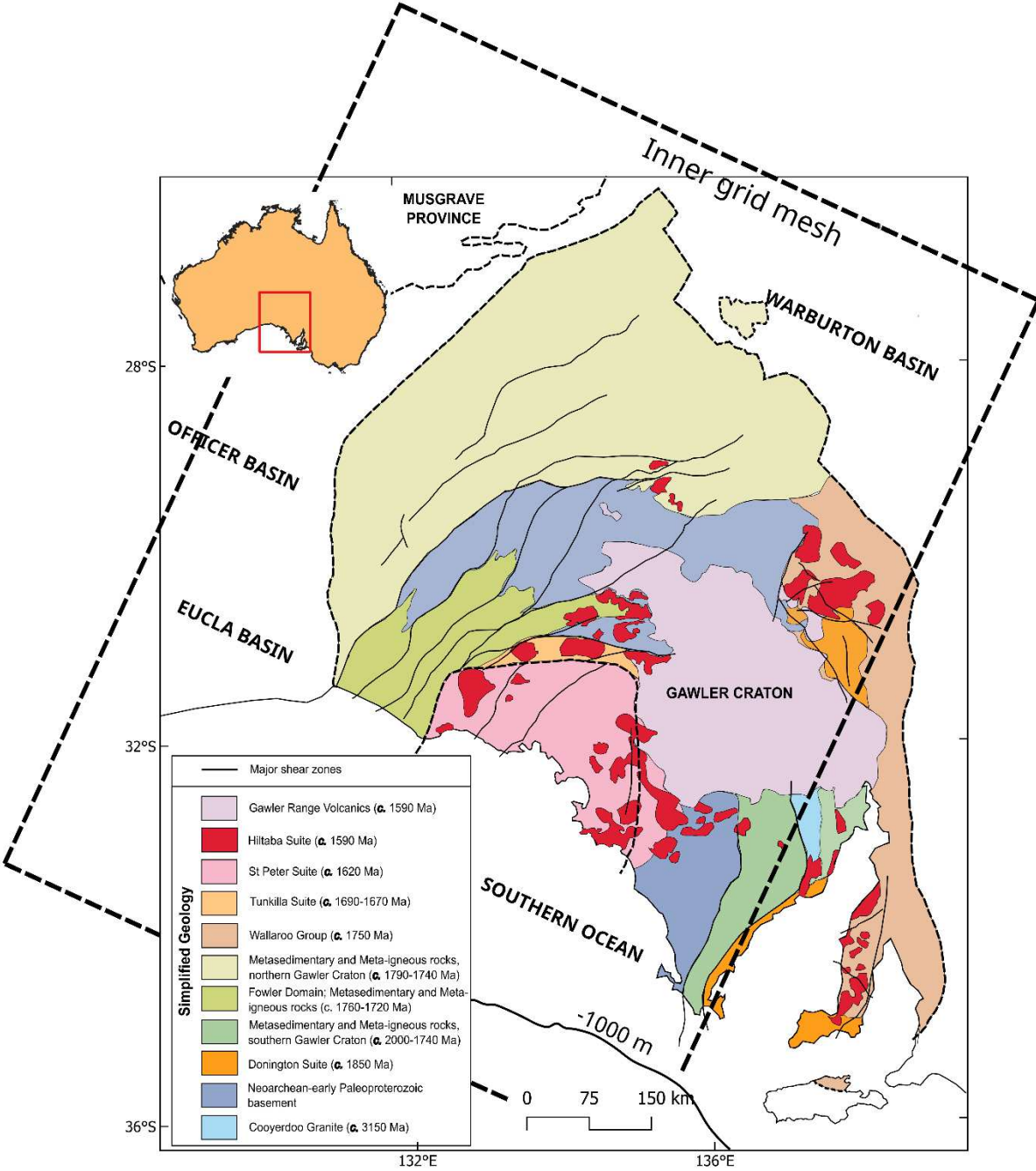
resistivity remains ambiguous as hydrous mantle phases, particularly phlogopite minerals that are fluorine rich, can also reduce shear wave velocity and electrical resistivity at comparable depths.^{29,30}

In this paper we consider the causal mechanisms for low resistivity at the base of the Gawler Craton lithosphere and the case for carbonatite melt that has remained in situ since emplacement ~1.6 Ga. Previous studies have imaged a region of low electrical resistivity (< 100 Ohm.m) beneath the Archean part of the Gawler Craton, but the depth and vertical extent were not well resolved with only partial MT site coverage³¹. Forward model studies also suggest that the conductor potentially has anisotropic resistivity properties, but the degree and extent of anisotropic properties is not constrained³². Here we invert 200 long-period MT sites covering an area 640,000 km² over the Gawler Craton and Musgrave Province to reassess the resistivity, depth and geodynamic setting.

Geological and Geophysical Setting

The Gawler Craton is the major component of the South Australian Craton³³, as shown in **Figure 1**. The central part of the craton is Archean³⁴⁻³⁶, surrounded by Paleoproterozoic orogenic belts³⁷⁻⁴⁰. The most significant tectonic event was the 1595 Ma Mesoproterozoic-aged eruption of the Gawler Range Volcanics^{33,41,42}, and the initial deposition of several iron-oxide copper gold (IOCG) deposits, most notable at Olympic Dam^{41,43-45} at 1590 Ma. It has been suggested that both the Gawler Range Volcanics and the IOCG deposits are linked to an early Paleoproterozoic subduction event (1620 Ma) to the southwest of the current craton location. Initial arc-related melting occurred in the St Peter Suite⁴⁶⁻⁴⁸, with the slab subducting beneath the Archean core of the Craton (comprising the Mulgathing and Sleaford

67 Complexes³⁴). Several authors^{43,49} have suggested that with high thermal fluxes in the
 68 Paleoproterozoic, subduction would have been shallow dipping and potentially the source of
 69 melt for the Gawler Range Volcanics and the thermal flux driving the IOCG formations.



71 **Figure 1.** Broad-scale geological map of the Gawler Craton and Musgrave Province. The
 72 inner grid of the 3D model is shown by the dashed line, aligned 25° clockwise from

geographic north. The broader mesh extends 500 km beyond the inner grid as padding cells.

Figure adapted from⁴⁷, re-drawn using Inkscape v1.2.1 (<https://inkscape.org>).

Understanding of the structure of the Archean core of the Gawler Craton is primarily defined by petrology of mantle xenoliths^{50,51}, and the geophysical imaging methods of seismic tomography⁵²⁻⁵⁴, and magnetotellurics^{31,43,55}. Analysis of >3000 mantle xenoliths across the craton suggested the lithosphere can be divided into a shallow Gawler Craton (60-130 km) representing the original cratonic core, and a deeper lithosphere (>160 km) that was added to the original core of the craton by Archean mantle plume interactions⁵⁰. With high volumes of melt segregating volatiles, the lithosphere would initially be depleted lherzolite but has subsequently been metasomatized and refertilised by high temperature melts from the asthenosphere.

Seismic tomography⁵⁴ suggests that the lithosphere is about 180-200 km thick. From shear-wave splitting there is evidence^{53,56} of anisotropy within the mid-lithosphere with a strike angle $68^{\circ} \pm 19^{\circ}$ with a mean splitting time of 0.80 ± 0.29 s, almost perpendicular to the current plate motion⁵⁶. A preliminary electrical resistivity model of the Gawler Craton using a long-period MT array prior to the establishment of the AusLAMP program highlighted a region of low resistivity of <100 Ohm.m at >80 km depth^{31,43}. Further analysis using additional AusLAMP data across the southern Gawler Craton placed the conductor at >120 km, and forward modelling suggested that it is likely anisotropic, with a strike of about 130° ⁵⁷. The cause of low electrical resistivity in the upper mantle was suggested to be hydrated phlogopite, possibly enhanced by fluorine to be stable at higher temperatures^{55,58,59}.

96 **Results**

97 Magnetotelluric data were acquired at approximately 200 sites across the study region. Most
98 sites form part of the Australian Lithospheric Architecture Magnetotelluric Project
99 (AusLAMP) dataset^{32,55}, supplemented by additional legacy stations^{31,60}. The data typically
100 span periods from 10 to 10,000 s and include measurements of both impedance tensor and
101 vertical magnetic field transfer functions.

102 Figure 2a shows phase tensors at a period of 21 s, coloured by minimum phase; additional
103 data plots are shown in the Supplementary section Fig. S1 and Fig. S2. Black lines indicate
104 major crustal boundaries⁶¹. At these relatively short periods, pronounced spatial variations
105 in the phase response are evident across the study area. The Officer and Eucla Basins in the
106 west are generally characterised by lower phase angles than the Musgrave Province to the
107 north, whereas the Gawler Craton exhibits a more heterogeneous response.

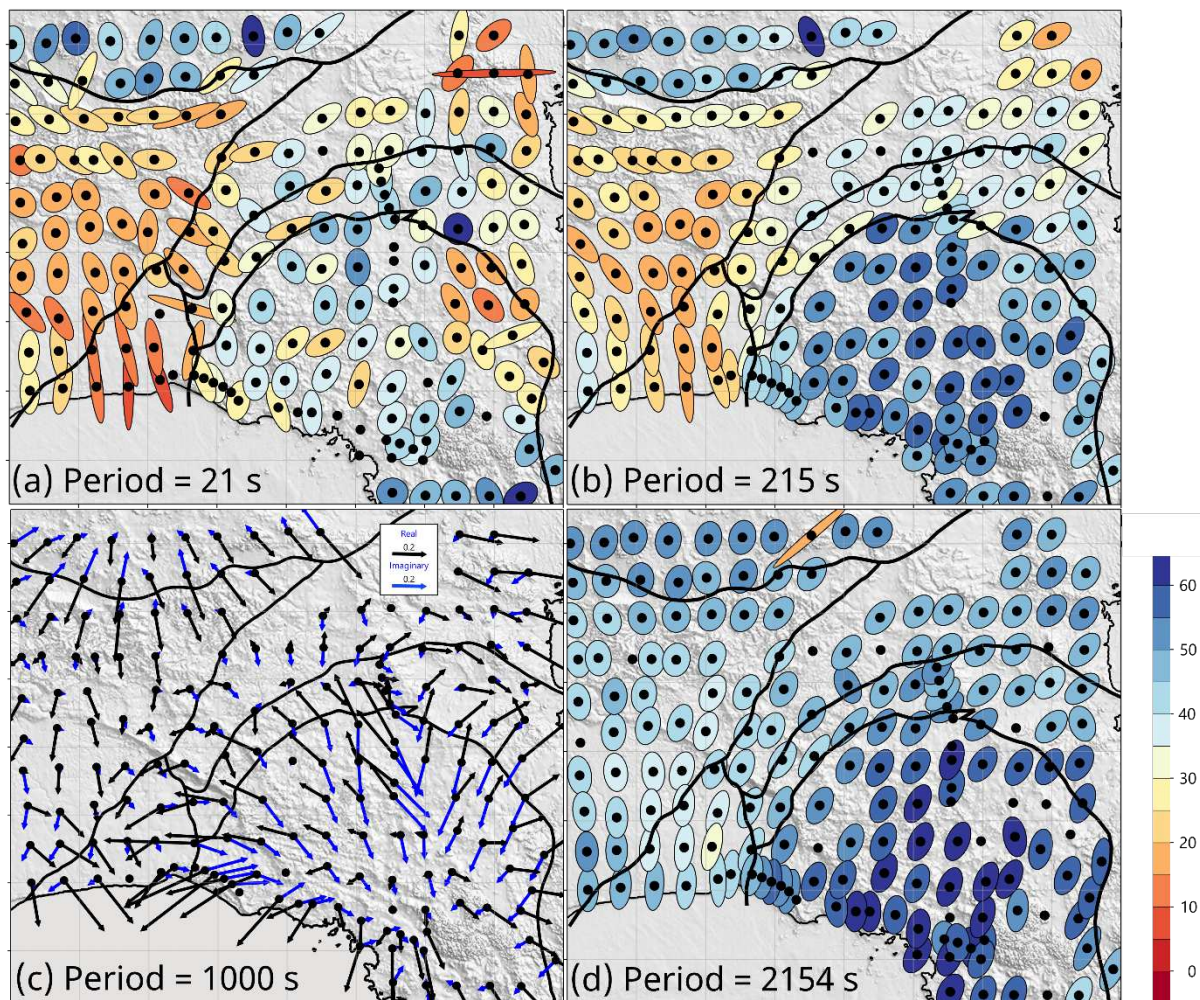
108 At a longer period of 215 s (Fig. 2b), the phase tensors define a more spatially coherent
109 pattern. The Musgrave Province and Gawler Craton are characterised by relatively high
110 phase angles, contrasting with the lower phase angles observed across the Officer, Eucla and
111 Warburton basins. Pronounced and systematically aligned phase-tensor ellipticity occurs
112 along several major crustal boundaries, particularly the margins of the Gawler Craton and
113 Musgrave Province. These patterns indicate strong lateral resistivity gradients associated
114 with the boundaries between the major crustal domains⁶¹.

115 The vertical magnetic field response at a period of 1,000 s is shown in Fig. 2c. Black induction
116 arrows represent the real (in-phase) component and are reversed according to the Parkinson
117 convention such that they point towards regions of low resistivity. Blue arrows represent the
118 imaginary (quadrature-phase) component. The real induction arrows generally point away

119 from the comparatively resistive Musgrave Province and Gawler Craton, towards the
120 surrounding Proterozoic belts, as well as towards the ocean to the south. The induction-
121 arrow pattern is, however, spatially complex, reflecting substantial lateral variations in
122 electrical resistivity along and across the major crustal boundaries.

123 At the longest period shown (2,154 s; Fig. 2d), the phase-tensor response becomes more
124 spatially homogeneous, consistent with sensitivity to greater mantle depths. Nevertheless,
125 the Gawler Craton remains characterised by relatively high phase angles, indicating a distinct
126 deep resistive structure compared with the surrounding regions. Systematic alignment of the
127 phase tensors with major crustal boundaries remains evident, particularly around the
128 margins of the Gawler Craton, although this relationship is less pronounced around the
129 Musgrave Province. Collectively, the phase-tensor and vertical-field responses demonstrate
130 that the major crustal domains and their boundaries exert a strong influence on the regional

131 electrical structure over a broad range of depths.



132

133 **Figure 2.** Phase tensors across the study area, coloured by minimum phase, at periods of (a)
134 21 s, (b) 215 s, and (d) 2,154 s. Induction arrows in the Parkinson convention, are shown for
135 a period of 1,000 s. Thicker black lines represent major crustal boundaries⁶¹. All figures
136 were produced using Viridien Geotools v.4.0.6.12598
137 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) and Inkscape
138 v1.2.1 (<https://inkscape.org>).

139

140 All MT data were inverted to obtain a 3D model of electrical resistivity across the study
141 region. The model grid was oriented 25° clockwise from geographic north as shown in Fig. 1,

142 extending farther south to incorporate the continent–ocean boundary. Details of the
143 inversion procedure, model parameterisation and assessment of model fit are provided in
144 the Methods section.

145 At 5 km depth (Fig. 3a) the model shows a clear distinction between the comparatively
146 resistive Gawler Craton and Musgrave Province and the more conductive Eucla, Officer and
147 Warburton basins. This contrast broadly follows the boundaries of the major crustal domains
148 and demonstrates the strong influence of shallow sedimentary basins on the regional
149 electrical structure. At 15 and 25 kms depth in Fig. 3b and 3c, the Gawler Craton becomes
150 substantially more resistive, locally reaching values $>10,000$ Ohm.m. More conductive
151 structures are locally evident within the middle crust, including beneath the IOCG Cairn Hill,
152 Prominent Hill and Olympic Dam mines, consistent with conductive crustal features
153 identified in previous MT studies^{55,62}.

154 In the lower crust, at 35 km depth (Fig. 3d) two major conductive regions are evident,
155 parallel to the margin of the northeastern Gawler Craton, and additionally to the west of the
156 Archean core of the Craton. Both conductors are within the wider Paleoproterozoic margin
157 of the Craton. Conductive features remain evident at approximately 45 km depth (Fig. 3e),
158 extending to depths near or below the Moho which is approximately 35-40 km⁶³ under the
159 Gawler Craton.

160 In contrast, the upper mantle at 75-125 kms depth (Fig. 3f and Fig. 3g) is comparatively
161 homogeneous, with only moderate variations in resistivity, predominantly between
162 approximately 100 and 1,000 Ohm.m. Some of this subdued spatial variability probably
163 reflects the smooth-model regularisation imposed during inversion rather than resolvable
164 lithospheric structure.

165 A major change in electrical structure occurs at approximately 175 km depth (Fig. 3h), near
166 the inferred base of the lithosphere, where a pronounced conductive anomaly is imaged
167 beneath the Archean core of the Gawler Craton. The anomaly is ~ 10 Ohm.m, representing a
168 decrease of two to three orders of magnitude relative to the overlying lithospheric mantle,
169 and has been noted from previous models and inversions^{31,32}, although the depth from
170 smaller arrays of MT sites could only be constrained to be >130 km. A similar low resistivity
171 region has been imaged beneath the Superior Craton in Canada⁶⁴ and the Rio de la Plata
172 Craton in Brazil⁶⁵. This conductive structure is less evident at 225 km depth (Fig. 3i), where
173 the model returns to a more spatially homogeneous resistivity distribution. The vertical
174 confinement of this anomaly therefore indicates a discrete conductive layer or region near
175 the lithosphere–asthenosphere boundary beneath the Gawler Craton, rather than a
176 conductor extending continuously into the deeper mantle.

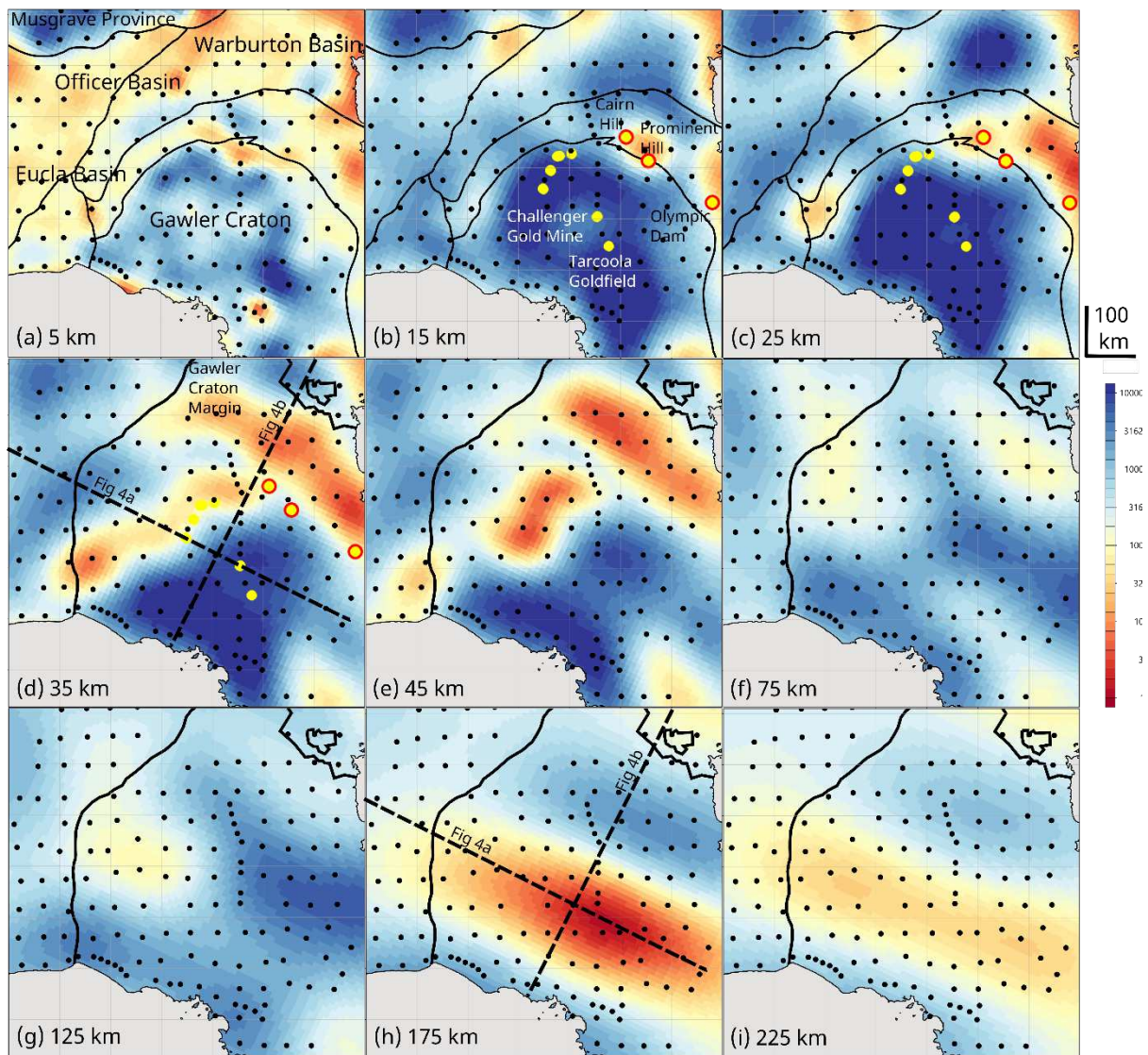


Figure 3. Three-dimensional isotropic resistivity model slices for depths ranging from 5-225 km. At upper crustal depth (5-25 km) major crustal boundaries are shown by thick black lines⁶¹. All figures were produced using Viridien Geotools v.4.0.6.12598 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) and Inkscape v1.2.1 (<https://inkscape.org>).

Two resistivity cross-sections extracted from the 3D model are shown along the profiles located in Fig. 3d and Fig. 3h. The first profile (Fig. 4a) extends approximately 800 km from northwest to southeast, crossing from the margin into the central part of the Gawler Craton.

187 The section is displayed with a vertical exaggeration of two. Superimposed on the resistivity
188 model are contours of shear-wave velocity anomalies⁵⁴, expressed in m s^{-1} . Within the crust,
189 velocity anomalies are calculated relative to the CRUST2.0 reference model⁶⁶, whereas
190 below 40 km depth they are referenced to the mantle velocity model⁶⁷. Regions of
191 anomalously high and low shear-wave velocity anomalies are denoted by H and L,
192 respectively.

193 The most prominent mantle conductor has a resistivity of approximately 10 Ohm.m and
194 occurs directly beneath the region of highest shear-wave velocity. Importantly, the
195 conductor is concentrated near the lower boundary of this high-velocity region, where the
196 vertical shear-wave velocity gradient is greatest. A secondary conductive structure is evident
197 near the base of the crust at approximately 40 km depth. This conductor spatially coincides
198 with a pronounced low-velocity anomaly, where shear-wave velocities are reduced by
199 approximately 250 m s^{-1} relative to the reference model. Figure 4b shows an approximately
200 orthogonal, 600-km-long transect, also displayed with a vertical exaggeration of two. A
201 similar relationship between electrical resistivity and seismic velocity is observed. The
202 principal mantle conductor occurs beneath the high-velocity lithospheric anomaly and is
203 again concentrated near the region of greatest velocity gradient towards its lower boundary.
204 The conductivity decreases with increasing depth below this feature. A separate low-
205 resistivity structure is evident within the crust and coincides with a shear-wave velocity
206 reduction of approximately 250 m s^{-1} .

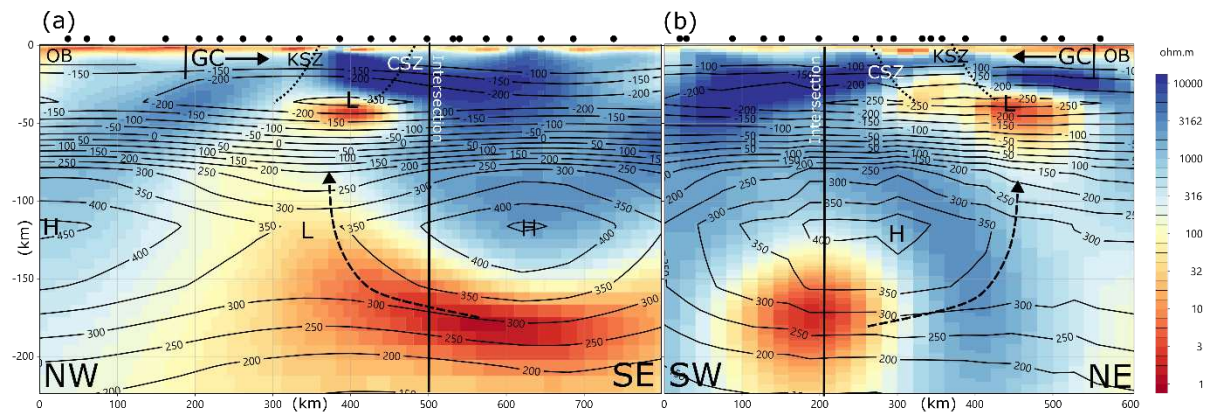


Figure 4. Cross-sections of resistivity models in Figs 3d and 3h, along with shear-wave velocity anomalies⁵⁴ as contours. Projected dip of major shear zones interpreted from seismic data⁶⁸, including the Karari Shear Zone (KSZ) and Coorabie Shear Zones (CSZ)⁶⁹⁻⁷¹, are superimposed on the section. The mapped margin of the Gawler Craton (GC) lies outside the principal conductive structure, indicating that the deep electrical boundary does not correspond directly with the mapped crustal boundary. Dashed lines indicate possible melt migration pathways from sub-lithosphere to underplating at Moho depths. All figures were produced using Viridien Geotools v.4.0.6.12598 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) and Inkscape v1.2.1 (<https://inkscape.org>).

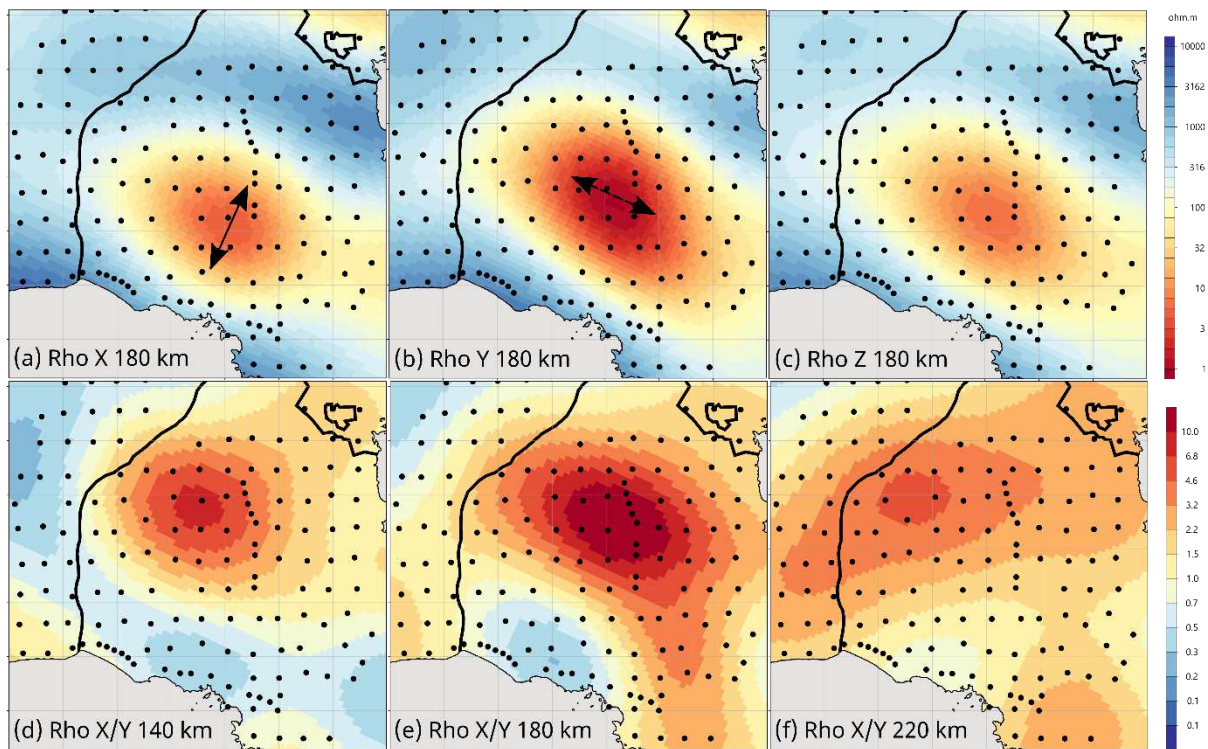
Previous studies of lower-lithosphere resistivity anomalies beneath the Slave Craton and Gawler Craton suggested that structures causing low resistivity are anisotropic in nature^{32,64} due to channelized flow from metasomatizing fluids and melts from the asthenosphere. We have undertaken a new anisotropic 3D inversion of the MT responses in Fig. 2; details of methodology and parameterisation are provided in the Methods section. The inversion solves for three orthogonal resistivity components within each model cell. The vertical resistivity (ρ_z) provides the reference component, while the two horizontal components (ρ_x

and ρ_y) are permitted to differ from ρ_z by up to a factor of 10. This limit is an imposed regularisation constraint rather than a physically determined bound and was selected to prevent the anisotropic solution from departing excessively from the corresponding isotropic model. The anisotropic inversion retained the orientation of the original model grid, 25° clockwise from geographic north. Consequently, the x direction is oriented southwest–northeast (25° clockwise from geographic north) and the y direction northwest–southeast (115° clockwise). It is not computationally feasible to define an arbitrary angle of anisotropy, so the choice of coordinate frame was based on previous forward modelling³² and the geometry of the conductor in Fig. 3h.

The anisotropic inversion was initiated using the final isotropic resistivity model, such that the resulting model represents a perturbation of the preferred isotropic solution rather than an independently derived anisotropic resistivity structure. The anisotropic inversion converged to an RMS data misfit of 1.45, compared with approximately 1.82 for the isotropic model, indicating an improved fit to the observed MT responses of 20%.

Figures 5a–c show the three resistivity components at 180 km depth. The southwest–northeast component (ρ_x ; Fig. 5a) and vertical component (ρ_z ; Fig. 5c) exhibit similar spatial distributions, with minimum resistivities of ~10 Ohm.m beneath the central Gawler Craton. In contrast, the northwest–southeast component (ρ_y ; Fig. 5b) exhibits resistivities of 1 Ohm.m within the same region. Thus, the principal lower-lithospheric conductor identified in the isotropic inversion is strongly anisotropic, with electrical resistivity in the northwest–southeast direction approximately one order of magnitude lower than in the orthogonal horizontal direction.

248 The depth dependence of this anisotropy is illustrated by the ratio of the two horizontal
 249 resistivity components (ρ_x/ρ_y) at 140, 180 and 220 km depth (Fig. 5d–f). At 140 km depth,
 250 the magnitude of horizontal resistivity anisotropy is approximately a factor of three. The
 251 contrast increases substantially with depth, reaching a factor of ~ 10 at 180 km, before
 252 decreasing to less than a factor of three at 220 km depth. The strongest anisotropic
 253 response is therefore concentrated near 180 km depth and coincides spatially with the
 254 lower-lithospheric conductor identified in the isotropic model. The smooth regularisation
 255 applied during inversion will inevitably distribute anisotropic structure over a finite vertical
 256 interval, limiting the precision with which its upper and lower boundaries can be
 257 determined. The Supplementary section shows additional cross-sections (Fig. S3) and planar
 258 sections (Fig. S4) of the anisotropic resistivity model.



260 **Figure 5.** (a-c) Anisotropic resistivity at a depth of 180 km for three axes of orientation of
 261 resistivity; (d-f) Ratio of horizontal resistivity components at depths of 140, 180 and 220 km.

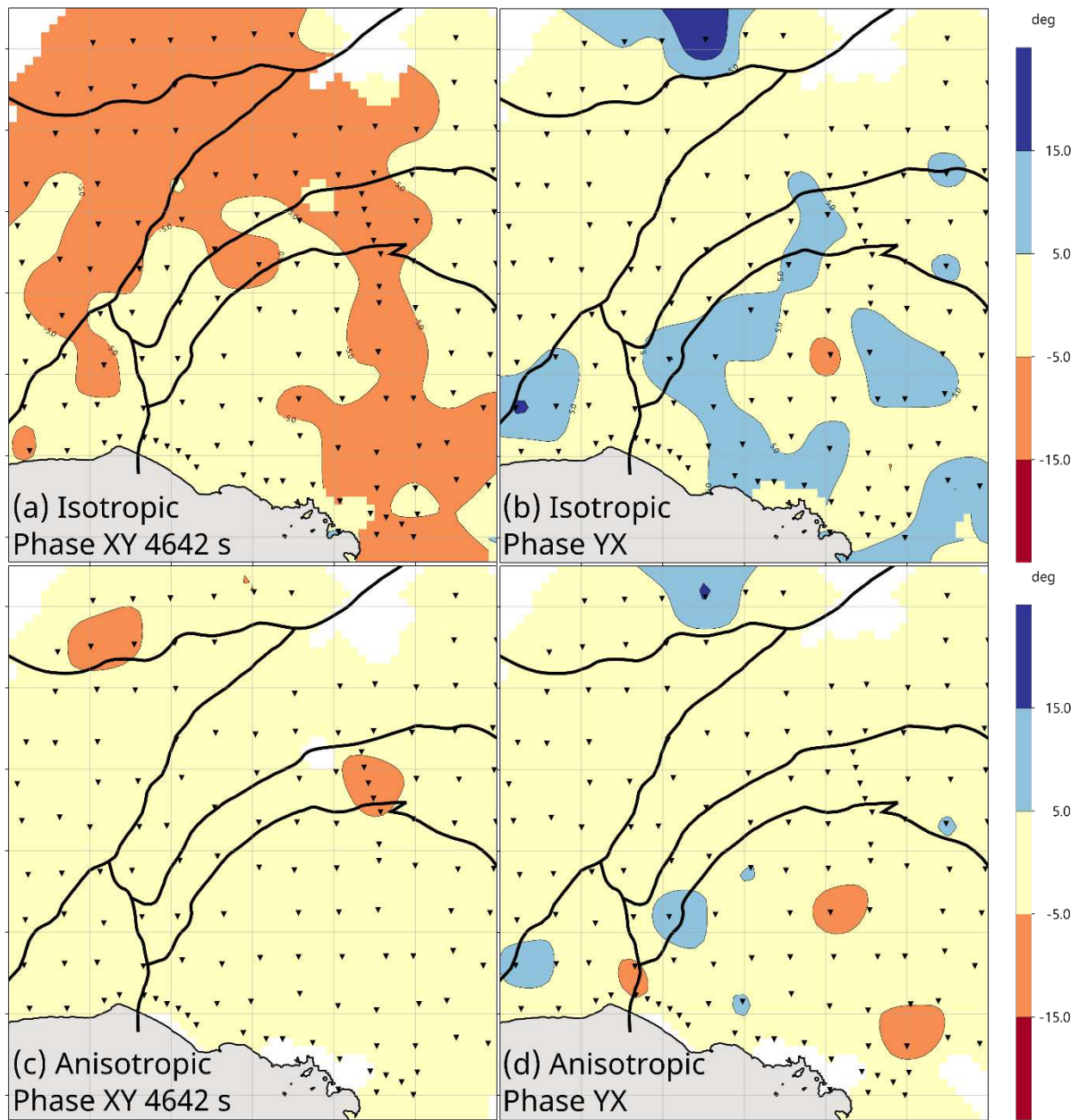
262 All figures were produced using Viridien Geotools v.4.0.6.12598
263 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) and Inkscape
264 v1.2.1 (<https://inkscape.org>).
265

266 A reduction in RMS misfit by 20% for the anisotropic inversion does not, by itself,
267 demonstrate that anisotropy is required by the data. To assess whether the improvement is
268 systematic and associated specifically with the long-period responses that constrain the
269 lower lithosphere, we compare the phase residuals (observed – model) for the off-diagonal
270 impedance components (XY and YX) predicted by both isotropic and anisotropic models.
271 Figure 6 shows the phase residuals at a period of 4,642 s, where the MT responses have
272 substantial sensitivity to the deep lithospheric and sub-lithospheric electrical structure;
273 additional phase residual plots at shorter periods are shown in the Supplementary section
274 Fig. S5. Residuals within $\pm 5^\circ$ are shown in yellow, whereas increasingly positive and negative
275 residuals outside this interval are represented by blue and orange–red colours, respectively.
276 For the isotropic model at 4,642 s, the XY and YX phase components display systematic
277 residuals between the observed and modelled responses. Although there is spatial
278 variability across the survey area, the residuals exhibit a coherent and opposing pattern
279 between the two off-diagonal components, with XY phase residuals are commonly less than
280 -5° , whereas YX phase residuals commonly exceed $+5^\circ$. The complementary nature of these
281 residual patterns indicates that the isotropic model is unable to simultaneously reproduce
282 both horizontal components of the long-period MT response.
283 In contrast, the anisotropic model produces substantially smaller phase residuals for both
284 the XY and YX components at 4,642 s. Across most of the study region, residuals fall within

285 $\pm 5^\circ$, and the systematic opposing residual pattern observed for the isotropic model is

286 substantially reduced. The improvement is therefore not simply reflected in a lower global

287 RMS misfit but occurs coherently in off-diagonal impedance components at long periods.



288

289 **Figure 6.** Phase residuals (observed – model) for the XY and YX components of the isotropic

290 model (a, b) and the anisotropic model (c, d). All figures were produced using Viridien

291 Geotools v.4.0.6.12598 ([https://www.viridiengroup.com/expertise/multiphysics-](https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools)

292 [imaging/geotools](https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools)) and Inkscape v1.2.1 (<https://inkscape.org>).

293

294 Figure 7 compares depth profiles extracted from the 3D anisotropic resistivity model with
295 predicted mantle resistivity profiles for the Gawler Craton and shear-wave velocity
296 anomalies. The first profile in Fig. 7a is extracted from the central Gawler Craton, directly
297 above the lower-lithospheric conductor. The three coloured curves represent the orthogonal
298 components of the anisotropic resistivity model with ρ_y – blue, ρ_x -red and ρ_z - green.
299 Predicted resistivity profiles are for a depleted lherzolitic mantle containing 0, 100 and 200
300 ppm H_2O ^{50,72}. Across much of the lithosphere above 150 km depth, the three resistivity
301 components are similar and broadly consistent with the predicted resistivities of lherzolitic
302 mantle containing 100–200 ppm H_2O . This correspondence is consistent with mantle
303 xenolith observations⁵⁰, which suggest fertilisation or metasomatism of the Gawler Craton
304 lithosphere associated with thermal and chemical flux from the underlying mantle. The
305 resistivity profiles therefore indicate that the lithospheric mantle is unlikely to be
306 represented by a completely dry lherzolitic composition, although resistivity alone cannot
307 uniquely constrain mantle water content.

308

309 A pronounced departure from the predicted mantle resistivity profiles occurs at
310 approximately 180 km depth. Here, the most conductive horizontal component ρ_y has a
311 minimum of 1 Ohm.m, compared with approximately 5–10 Ohm.m for the orthogonal
312 horizontal ρ_x and vertical ρ_z components. These values are substantially lower than
313 predicted for the hydrated lherzolite models, demonstrating that hydration of nominally
314 anhydrous mantle minerals alone is unlikely to account for the magnitude of the observed
315 conductivity. The coincidence of the minimum resistivity with the maximum anisotropic
316 contrast further indicates that the process responsible for the conductor has a strongly

317 directional electrical response. At shallower depths < 100 km the crust and mantle are
318 otherwise highly resistive, of the order of 1,000–10,000 Ohm.m. In these regions, the
319 magnitude of the resistivity is poorly constrained by MT data. Resistivity decreases rapidly
320 towards the surface as a consequence of conductive sedimentary cover.

321

322 The pronounced decrease in resistivity at approximately 180 km depth also occurs near a
323 reduction in shear-wave velocity. Although the seismic model does not resolve a discrete
324 low-velocity layer coincident with the conductor, the low-resistivity region lies immediately
325 beneath the highest shear-wave anomalous velocities, consistent with a relatively cold, thick
326 and compositionally depleted cratonic lithosphere⁵⁰. The electrical conductor is therefore
327 concentrated near the lower boundary of the high-velocity lithospheric keel, rather than
328 within its interior.

329

330 A second 1D profile extracted near the margin of the Gawler Craton in Fig. 7b shows a
331 different relationship between crustal and mantle structure. Below the Moho, the three
332 anisotropic resistivity components closely follow predicted resistivity profiles for hydrated
333 lherzolitic mantle. This correspondence suggests that hydration and/or metasomatic
334 modification may extend across a substantial region of the lithospheric mantle rather than
335 being restricted to the central craton. The most prominent feature of the marginal profile,
336 however, is a significant decrease in resistivity near the base of the crust at approximately 40
337 km depth. This conductor exhibits less electrical anisotropy than the lower-lithospheric
338 anomaly beneath the central craton and coincides with a modest reduction in shear-wave
339 velocity. The spatial correspondence between reduced resistivity and reduced seismic

velocity at the crust–mantle boundary provides independent evidence for modification of the lower crust and/or uppermost mantle along the margin of the Gawler Craton.

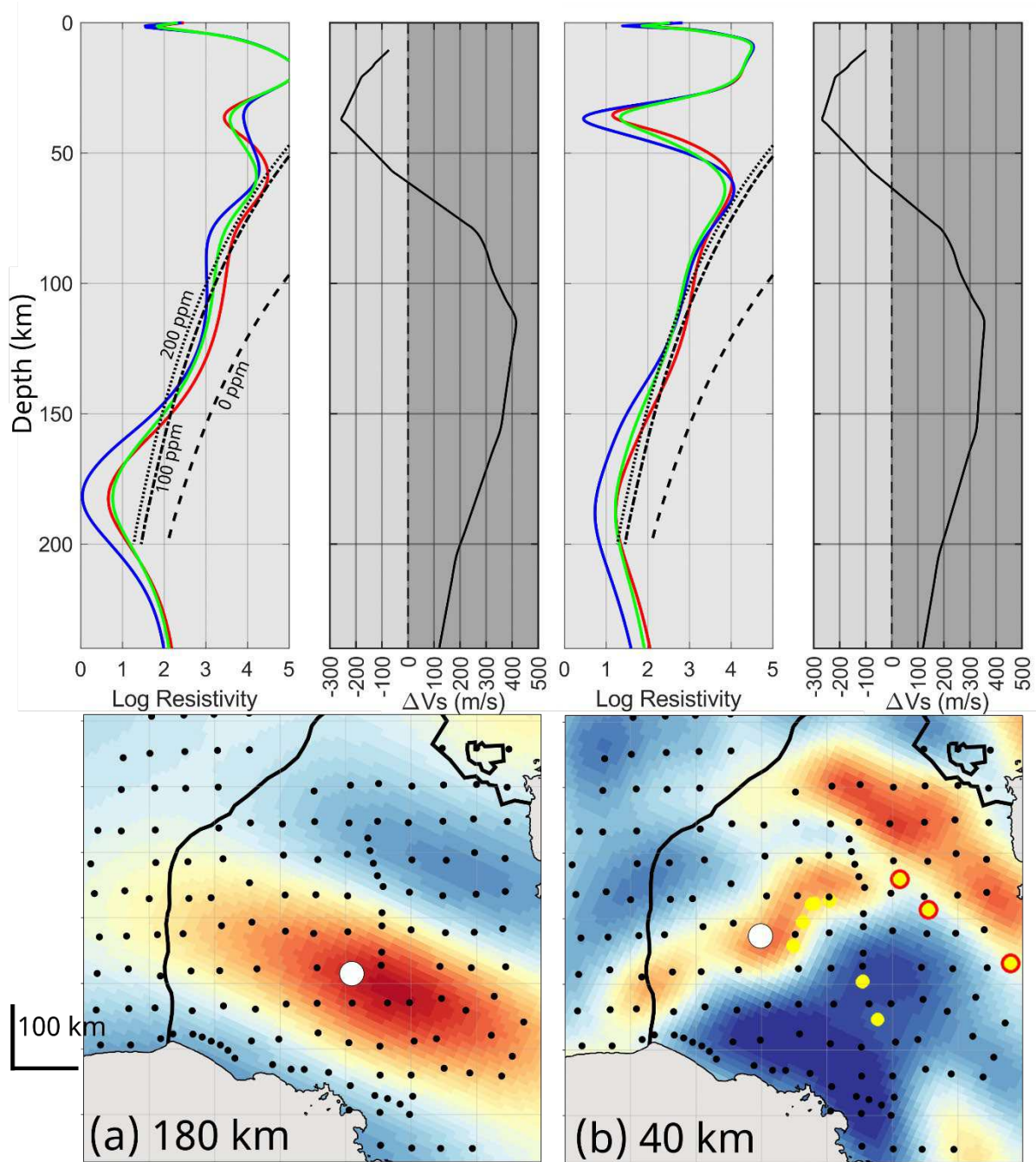


Figure 7. One-dimensional resistivity and shear-wave velocity models for sites (a) directly above the conductive lower-lithosphere, and (b) above the conductive crust-mantle at Moho depths along the margin of the Archean Gawler Craton. The three coloured curves

represent the orthogonal components of the anisotropic resistivity model with ρ_y – blue, ρ_x – red and ρ_z – green. Lherzolite mantle resistivity models for 0, 100 and 200 ppm H₂O are shown⁷². Anomalous shear-wave velocity models⁵⁴ are shown with fast anomalies > 0 m/s in the dark grey, and slow anomalies < 0 m/s in light grey. Figures were produced using Viridien Geotools v.4.0.6.12598 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>), Matlab (R2021a <https://matlab.mathworks.com/>) and Inkscape v1.2.1 (<https://inkscape.org>).

Discussion

The anisotropic inversion reveals a pronounced low-resistivity region immediately beneath the seismically defined lithospheric keel of the Gawler Craton. At approximately 180 km depth, resistivity decreases to 1–10 Ohm.m and exhibits horizontal anisotropy approaching a factor of ten. In contrast, within the overlying lithosphere the observed resistivity is broadly consistent with moderately hydrated mantle containing approximately 100–200 ppm H₂O. This interpretation agrees with mantle xenolith studies^{50,51}, which indicate metasomatic modification of the depleted Archean core of the Gawler Craton and increasing hydration below approximately 100 km depth. The electrical structure therefore suggests a transition from a highly resistive cratonic interior to hydrated and metasomatically modified mantle at greater depths.

Hydration of nominally anhydrous mantle minerals alone, however, is insufficient to explain the exceptionally low resistivities observed at 180 km depth. An olivine-dominated mantle⁷³ is expected to have a resistivity of approximately 350 Ohm.m under relevant lithospheric

370 conditions. Increasing water content substantially enhances proton conduction and reduces
371 mantle resistivity, but the predicted resistivities remain considerably higher than the
372 observed values⁷⁴. The minimum resistivity of 1 Ohm.m is more than an order of magnitude
373 below that predicted for the hydrated mantle models considered here. An additional
374 interconnected conductive phase is therefore required to explain the electrical observations.

375 One possible mechanism is the presence of hydrous minerals such as phlogopite^{58,59,75}.
376 Phlogopite is one of the few hydrous minerals stable in the upper mantle and may reduce
377 bulk resistivity to approximately 10 Ohm.m and has a stability to a depth approaching 200
378 km under appropriate pressure, temperature and compositional conditions^{30,76}. Fluorine
379 substitution in phlogopite has also been proposed to further reduce electrical resistivity^{58,59}
380 fluorine-rich phlogopite-bearing mantle therefore cannot be excluded as a possible
381 contributor to the observed conductor. However, relatively few laboratory measurements
382 constrain the electrical properties of fluorine-bearing phlogopite at the pressures and
383 temperatures appropriate to the base of cratonic lithosphere. Consequently, this mechanism
384 is presently difficult to assess quantitatively.

385 An alternative explanation is the presence of a small fraction of interconnected carbonatite
386 melt²⁶⁻²⁸. Carbonatite melts are exceptionally electrically conductive²⁶ and have substantially
387 lower solidus temperatures than silicate mantle melts. Critically, carbonatite melts have
388 favourable wetting properties in mantle mineral assemblages and can therefore form
389 interconnected networks at very small melt fractions. Consequently, very small quantities of
390 carbonatite melt can have a disproportionately large effect on bulk electrical resistivity.

391 Using SIGMELTS⁷⁷ for mantle resistivity parametrisation, we estimate that a carbonatite melt
392 fraction of approximately 0.05 vol.% is sufficient to reduce bulk mantle resistivity to 1

393 Ohm.m under conditions appropriate to the base of the Gawler Craton lithosphere. The
394 observed range of 1–10 Ohm.m can therefore be reproduced without requiring the large
395 melt fractions normally associated with extensive silicate partial melting. At such low
396 fractions, carbonatite melt may potentially persist within the mantle over long geological
397 timescales²⁷.

398 The strong electrical anisotropy provides an additional constraint on the geometry of the
399 conductive phase. The maximum anisotropy occurs at approximately the same depth as the
400 minimum resistivity, suggesting that the conductor is preferentially interconnected in one
401 horizontal direction. Metasomatism at the base of cratonic lithosphere may promote the
402 migration and localisation of melts along fractures or grain-scale pathways controlled by
403 lithospheric fabric and regional stress^{17,78}. A comparable relationship has been proposed
404 beneath the Superior Craton⁶⁴, with lower-lithospheric electrical anisotropy approaching an
405 order of magnitude. The Gawler Craton observations are therefore consistent with small-
406 volume conductive melt being preferentially interconnected along an anisotropic network
407 near the base of the lithosphere. A cartoon schematic of the geological framework is shown
408 in Figure 8, adapted from the cross-sections from Skirrow et al.⁴³

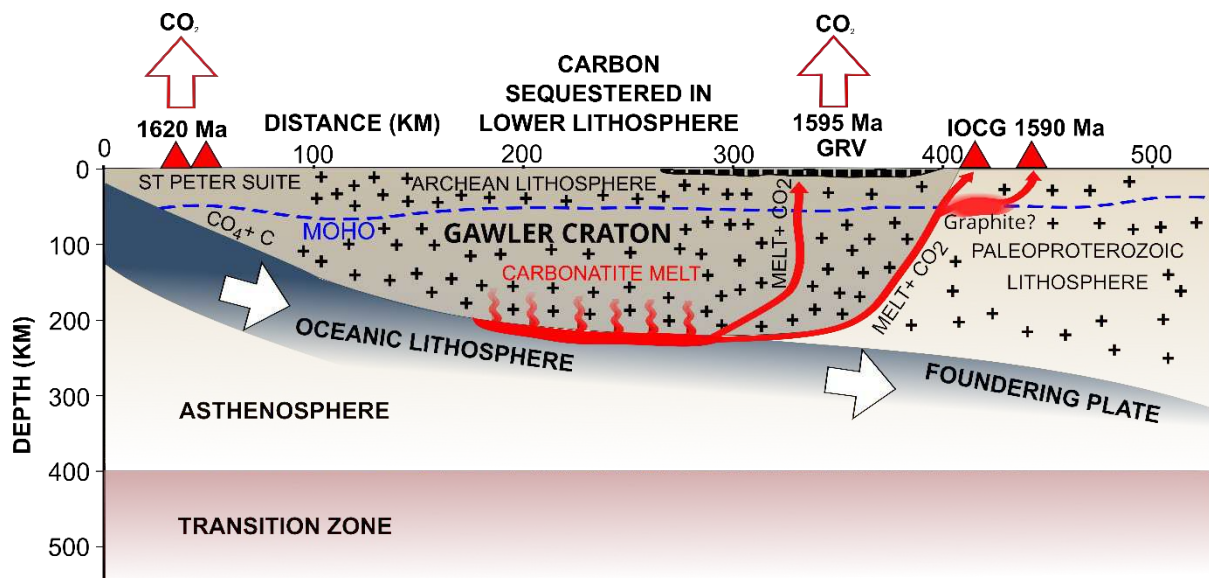


Figure 8. Schematic representation of a Paleoproterozoic subduction system beneath the Gawler Craton, from what is now southwest towards the northeast. Subduction is hypothesised to commence ~1620 Ma (forming arc magmatism in St Peter Suite), and at 1595-1590 Ma related to Gawler Range Volcanics (GRV) and IOCG mineralisation in the Olympic Domain. Carbonatite melt is present at the base of the Gawler Craton and potentially rises in channelised flow orthogonal to the plate subduction polarity. Figure adapted from⁴³.

The orientation of electrical anisotropy in the 3D inversion is defined by the coordinate system of the prescribed numerical model on the basis of previous forward-modelling studies³² and the elongated geometry of the conductor at the base of the lithosphere, rather than being a free parameter. Shear-wave splitting (SKS) studies^{53,56} identified a dominant seismic anisotropy beneath the South Australian Craton that is approximately orthogonal to the present-day direction of Australian plate motion, with a mean fast-axis orientation of the ~68° ± 19° relative to geographic north, and mean splitting is time of 0.95 ± 0.27 s. This

425 compares with the electrical anisotropy that has the higher resistivity at 25° relative to
426 geographic north.

427 Rather than requiring agreement between the two observations, we suggest that this
428 difference reflects distinct physical mechanisms operating at different depths within and
429 beneath the cratonic lithosphere. The seismic anisotropy is interpreted to predominantly
430 reflect deformation fabric frozen into the lithospheric mantle, whereas the strongest
431 electrical anisotropy in our model occurs at approximately 180 km depth, close to or
432 beneath the seismically defined base of the lithospheric keel. Electrical anisotropy may
433 therefore reflect the geometry and connectivity of the conductive phase at the lithosphere–
434 asthenosphere transition rather than the crystallographic fabric responsible for SKS splitting.

435 This distinction is consistent with the proposed presence of very small fractions of
436 interconnected carbonatite melt. Electrical resistivity is exceptionally sensitive to the
437 presence and connectivity of a highly conductive melt phase, such that melt fractions
438 substantially below 0.1 vol.% can produce large changes in bulk resistivity. If carbonatite
439 melt is preferentially distributed along aligned grain boundaries, fractures or other
440 permeable pathways, it could generate strong electrical anisotropy without requiring a
441 corresponding crystallographic fabric in the surrounding mantle. We suggest that seismic
442 anisotropy primarily records inherited deformation within the cratonic lithosphere, whereas
443 the deeper electrical anisotropy reflects preferential connectivity of a conductive phase,
444 potentially carbonatite melt, near the base of the lithosphere.

445 Carbonatite melt also provides a potential mechanism for transferring carbon and other
446 incompatible components from the asthenospheric mantle into the upper lithosphere^{13,79},
447 as shown in Fig. 8. We propose that the presently observed low melt fraction may represent

448 the residual expression of a system that previously contained larger volumes of carbon-rich
449 melt. At higher melt fractions, carbonatite would be highly mobile¹³ and could migrate
450 laterally along the base of the cratonic keel before being focused towards its margins.
451 Variations in lithospheric thickness, permeability and stress at craton margins could provide
452 pathways for carbonatite and associated silicate melts and fluids to migrate into the
453 overlying lithosphere.

454 The electrical structure surrounding the Archean Gawler Craton is consistent with such a
455 mechanism. Conductive lower-crustal and uppermost-mantle regions approximately follow
456 parts of the craton margin rather than the central Archean cratonic keel. These conductors
457 are spatially associated with modest reductions in seismic shear-wave velocity. Although the
458 seismic anomalies are comparatively weak, their spatial correspondence with the electrical
459 structures provides independent evidence for modification of the lower crust and
460 uppermost mantle around the craton margin.

461 Present-day aqueous or saline fluids are unlikely to provide a satisfactory explanation for
462 persistent resistivities of 1–10 Ohm.m within the lower crust of a tectonically stable craton.
463 Maintaining interconnected free fluids over geological timescales at depths of 35–45 km is
464 problematic because fluids are expected to migrate, react with the surrounding rocks, or
465 become incorporated into mineral phases. A more persistent conductive phase is therefore
466 required.

467 Graphite precipitated from carbon-rich fluids provides one such mechanism, as shown in Fig.
468 8. Graphite is highly conductive when sufficiently interconnected and can remain stable over
469 geological timescales and can precipitate from C–O–H fluids (comprising H₂O, CO₂ and CH₄ as
470 the most important fluid species) as pressure, temperature and oxygen fugacity evolve

471 during migration through the lower crust⁸⁰⁻⁸². Under conditions appropriate to the Gawler
472 Craton of low heat flow ($\sim 50 \text{ mW.m}^{-2}$)⁸³ and low-geothermal gradient⁵⁰, graphite
473 precipitation may be favoured at depths of approximately 35–45 km⁸¹. This depth range
474 corresponds closely to the prominent lower-crustal conductors imaged around parts of the
475 craton margin.

476 We therefore propose a linked mantle-to-crustal carbon system. Small fractions of
477 carbonatite melt presently retained near the base of the lithosphere can account for the
478 exceptionally low resistivity and strong anisotropy observed at approximately 180 km depth.
479 During earlier periods of enhanced melt production, larger volumes of carbonatite and
480 associated carbon-rich melts and fluids may have migrated laterally towards the margins of
481 the Archean cratonic keel and subsequently ascended into the lithosphere. Progressive
482 reaction and oxidation of these carbon-bearing fluids within the lower crust could have
483 resulted in graphite precipitation, producing the persistent crustal conductors observed
484 today. In this interpretation, the deep anisotropic conductor and the lower-crustal
485 conductors represent different expressions of a long-lived carbon-rich metasomatic system
486 extending from the base of the Gawler Craton lithosphere into its crustal margins.

487 **Conclusion**

488 We interpret the low resistivity at the base of the Gawler Craton as evidence for carbonatite
489 melt concentrated near the lithosphere–asthenosphere boundary. We propose that
490 Paleoproterozoic oceanic lithosphere was subducted beneath the craton from the
491 southwest, introducing carbon-rich material that metasomatized the base of the lithosphere
492 and generated anisotropic melt-filled structures. Along the craton margins, this carbonatite
493 melt was mobilized into the lower crust, producing mafic underplating and the precipitation

of graphite, thereby creating conductive lower crustal zones. The close spatial association between these conductive pathways and major IOCG deposits suggests that carbonatite melts played an important role in their formation. We further propose that a small fraction of carbonatite melt has remained trapped beneath the lithosphere since approximately 1.6 Ga, preserving the highly conductive mantle signature observed today.

Methods

A database of 200 long-period (10-10000 s) MT responses was established from a combination of new AuLAMP sites⁵⁵ and legacy data^{31,60} as shown in Fig. 2a-d, and in the Supplementary section Fig. S1 and S2. The sites cover an area of 800 km by 800 km, with a typical site spacing of 55 km.

Long-period MT sites were typically collected at 10 Hz for between 4-6 weeks, with either AuScope and Geoscience Australia LEMI 424 instruments with fluxgate sensors and two 50 to 100 m dipoles with Ag-AgCl electrodes, or with AuScope EarthData Loggers and Bartington Mag-03 fluxgate sensors, also with 50 m dipoles and Ag-AgCl or Pb-PbCl electrodes. Long-period MT response estimates in the frequency domain were obtained using the BIRRPS processing codes^{84,85}. Additional data processing and editing were carried out using MTPy⁸⁶ and Viridien Geotools V.4.0.3.12574 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>).

Three-dimensional inversions were carried out using Viridien Geotools v.4.0.6.12598 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) software based on the finite-difference forward modelling and a nonlinear conjugate gradient inversion

algorithm^{87,88}. A grid of 112 by 125 cells was orientated 25° clockwise from geographic north, with a 10 km inner grid covering all sites in Fig. 2. Padding extending 500 km in each direction with a 20% increase in grid size with adjacent padding cells from the inner grid. Given the relatively small topographic gradients, topography was not modelled, however, ocean bathymetry was included. Vertically, the top layer from sea level was 5 m thick, increasing by 5% per cell with depth to 410 km, and then at 20% per cell with depth to 800 km, for a total of 179 vertical cells steps, and a total of ~2.5 million cells. The start model was 100 Ohm.m to 410 km depth, 10 Ohm.m from 410 - 670 km, and 1 Ohm.m below 670 km. The deeper mantle resistivities were included based on robust global satellite-derived models⁸⁹ and have the additional benefit of satisfying boundary conditions of negligibly small induced fields that are uniform below the transition zone.

The inversion used 16 periods, spaced evenly at 5 per decade from 10 s to 10000 s. Error floors were set at 5% on each of the four impedance components, and a fixed error floor of 0.02 for the vertical field. The inversion included an estimate of site-by-site local distortion, but a high weighting was used to allow the inversion to include variability mostly as resistivity in the subsurface. Horizontal smoothing (τ_H) and vertical smoothing (τ_V) were varied between 0.01 and 1; our preferred model with no bias between horizontal and vertical smoothing with $\tau_H = \tau_V = 0.1$. Near-surface smoothing to a depth of 500 m was included to ensure that modelled resistivities near the surface were uniform across the mesh, based on the premise that near-surface sedimentary layers are laterally extensive and continuous between sites.

Overall, after 50 iterations from the start model, the isotropic misfit had an RMS of 1.82. Model fits for apparent resistivity invariant and phase invariant are shown in the Supplementary Section Figure for periods of 21 s, 215 s and 2154 s; fits of the tipper magnitudes are also shown in Figure for periods of 215 s and 2154 s. Layer conductance models are shown in Supplementary Section Figure S1 for smoothing parameters τ_H and τ_V ranging from 1 to 0.01.

Anisotropic inversion was carried out using Viridien Geotools v.4.0.6.12598 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) software. The anisotropic inversion minimises misfit with the vertical component of resistivity ρ_z and then allows ρ_x and ρ_y to vary by up to a factor of 10 from ρ_z . The start model was the isotropic model, on the assumption that anisotropy is a perturbation of the isotropic model, rather than starting from a half space. After 50 iterations, the RMS was 1.45. Data misfits for isotropic and anisotropic models are shown in Fig. 6 and Supplementary Fig. S5.

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Author contributions

G. Heinson compiled the data sets, undertook modelling, data analysis and wrote the paper. D. Baker undertook modelling.

Data availability statement

The AusLAMP long-period magnetotelluric time series and higher-level products are archived at the National Computational Infrastructure under the AusLAMP collection (<https://doi.org/10.25914/5eaa30cc934d0>). The South Australian time series, from packed raw archives through level 1 and level 2 products, are available at <https://doi.org/10.25914/bzd5-n780>. South Australian state delivery is via SARIG (<https://map.sarig.sa.gov.au/>). Processed magnetotelluric transfer functions for the surveys used in this study are available through AusMT (<http://AusLAMP%20South%20Australia><https://ausmt.auscope.org.au>), Australia's Magnetotelluric Data Portal, with provenance information and links to the original data sources provided for each survey. Elevation data were sourced from Geoscience Australia's Geophysical Archive Data Delivery System (<https://portal.ga.gov.au/persona/gadds>) released under a CC BY 4.0 license (<https://www.ga.gov.au/copyright>).

587 Figures were generated using Viridien Geotools, V.4.0.3.12574; Python v3.12.7
588 (<https://www.python.org/>), QGIS v3.34.3-Prizren (<https://qgis.org>), and Inkscape V1.2.1
589 (<https://inkscape.org/cs>).

590

591

592 **Code availability statement**

593 The custom scripts used in this study for data processing and visualization are available from
594 the corresponding author upon reasonable request. Magnetotelluric numerical modelling
595 was undertaken using using Viridien Geotools v.4.0.6.12598
596 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>).

597

598 **Additional Information** (including a Competing Interests Statement)

599 The author(s) declare no competing interests.

600

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604

605 **Figure legends** (these are limited to 350 words per figure)

606 **Figure 1.** Broad-scale geological map of the Gawler Craton and Musgrave Province. The
607 inner grid of the 3D model is shown by the dashed line, aligned 25° clockwise from
608 geographic north. The broader mesh extends 500 km beyond the inner grid as padding cells.
609 Figure adapted from⁴⁷, re-drawn using Inkscape v1.2.1 (<https://inkscape.org>).

Figure 2. Phase tensors across the study area, coloured by minimum phase, at periods of (a) 21 s, (b) 215 s, and (d) 2,154 s. Induction arrows in the Parkinson convention, are shown for a period of 1,000 s. Thicker black lines represent major crustal boundaries⁶¹. All figures were produced using Viridien Geotools v.4.0.6.12598 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) and Inkscape v1.2.1 (<https://inkscape.org>).

Figure 3. Three-dimensional isotropic resistivity model slices for depths ranging from 5-225 km. At upper crustal depth (5-25 km) major crustal boundaries are shown by thick black lines⁶¹. All figures were produced using Viridien Geotools v.4.0.6.12598 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) and Inkscape v1.2.1 (<https://inkscape.org>).

Figure 4. Cross-sections of resistivity models in Figs 3d and 3h, along with shear-wave velocity anomalies⁵⁴ as contours. Projected dip of major shear zones interpreted from seismic data⁶⁸, including the Karari Shear Zone (KSZ) and Coorabie Shear Zones (CSZ)⁶⁹⁻⁷¹, are superimposed on the section. The mapped margin of the Gawler Craton (GC) lies outside the principal conductive structure, indicating that the deep electrical boundary does not correspond directly with the mapped crustal boundary. Dashed lines indicate possible melt migration pathways from sub-lithosphere to underplating at Moho depths. All figures were produced using Viridien Geotools v.4.0.6.12598 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) and Inkscape v1.2.1 (<https://inkscape.org>).

Figure 5. (a-c) Anisotropic resistivity at a depth of 180 km for three axes of orientation of resistivity; (d-f) Ratio of horizontal resistivity components at depths of 140, 180 and 220 km. All figures were produced using Viridien Geotools v.4.0.6.12598

(<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) and Inkscape v1.2.1 (<https://inkscape.org>).

Figure 6. Phase residuals (observed – model) for the XY and YX components of the isotropic model (a, b) and the anisotropic model (c, d). All figures were produced using Viridien Geotools v.4.0.6.12598 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) and Inkscape v1.2.1 (<https://inkscape.org>).

Figure 7. One-dimensional resistivity and shear-wave velocity models for sites (a) directly above the conductive lower-lithosphere, and (b) above the conductive crust-mantle at Moho depths along the margin of the Archean Gawler Craton. The three coloured curves represent the orthogonal components of the anisotropic resistivity model with ρ_y – blue, ρ_x – red and ρ_z – green. Lherzolite mantle resistivity models for 0, 100 and 200 ppm H₂O are shown⁷². Anomalous shear-wave velocity models⁵⁴ are shown with fast anomalies > 0 m/s in the dark grey, and slow anomalies < 0 m/s in light grey. Figures were produced using Viridien Geotools v.4.0.6.12598 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>), Matlab (R2021a <https://matlab.mathworks.com/>) and Inkscape v1.2.1 (<https://inkscape.org>).

Figure 8. Schematic representation of a Paleoproterozoic subduction system beneath the Gawler Craton, from what is now southwest towards the northeast. Subduction is hypothesised to commence ~1620 Ma (forming arc magmatism in St Peter Suite), and at 1595-1590 Ma related to Gawler Range Volcanics (GRV) and IOCG mineralisation in the Olympic Domain. Carbonatite melt is present at the base of the Gawler Craton and potentially rises in channelised flow orthogonal to the plate subduction polarity. Figure adapted from⁴³.

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659 **References**

- 660 1 Hu, H., Zhang, L. F., Lan, C. Y. & Liu, Z. C. Petrological evidence for deep subduction of
661 organic carbon to subarc depths. *Communications Earth & Environment* **4**,
662 doi:10.1038/s43247-023-01085-w (2023).
- 663 2 Spandler, C., Merdith, A. S. & Griffin, A. Linking carbonatites, rare earth ores, and
664 subduction-fertilized mantle lithosphere. *Science Advances* **12**,
665 doi:10.1126/sciadv.aeb2942 (2026).
- 666 3 Ague, J. J. & Nicolescu, S. Carbon dioxide released from subduction zones by fluid-
667 mediated reactions. *Nature Geoscience* **7**, 355-360, doi:10.1038/ngeo2143 (2014).
- 668 4 Plank, T. & Manning, C. E. Subducting carbon. *Nature* **574**, 343-352,
669 doi:10.1038/s41586-019-1643-z (2019).
- 670 5 Kelemen, P. B. & Manning, C. E. Reevaluating carbon fluxes in subduction zones, what
671 goes down, mostly comes up. *Proceedings of the National Academy of Sciences* **112**,
672 E3997-E4006, doi:doi:10.1073/pnas.1507889112 (2015).
- 673 6 Humphreys-Williams, E. R. & Zahirovic, S. Carbonatites and global tectonics. *Elements*
674 **17**, 339-344, doi:10.2138/gselements.17.5.339 (2021).
- 675 7 Dasgupta, R. & Hirschmann, M. M. Melting in the Earth's deep upper mantle caused
676 by carbon dioxide. *Nature* **440**, 659-662, doi:10.1038/nature04612 (2006).
- 677 8 Chen, C. F. *et al.* Carbonated sediment recycling and its contribution to lithospheric
678 refertilization under the northern North China Craton. *Chemical Geology* **466**, 641-
679 653, doi:10.1016/j.chemgeo.2017.07.016 (2017).
- 680 9 Foley, S. F. Rejuvenation and erosion of the cratonic lithosphere. *Nature Geoscience*
681 **1**, 503–510, doi:10.1038/ngeo193 (2008).
- 682 10 Gao, M. D., Wang, Y., Foley, S. F. & Xu, Y. G. Variable mantle redox states driven by
683 deeply subducted carbon. *Science Advances* **11**, doi:10.1126/sciadv.adu4985 (2025).
- 684 11 Chowdhury, P. & Dasgupta, R. Sulfur extraction via carbonated melts from sulfide-
685 bearing mantle lithologies - Implications for deep sulfur cycle and mantle redox.
686 *Geochim Cosmochim Acta* **269**, 376-397, doi:10.1016/j.gca.2019.11.002 (2020).

- 687 12 Chen, C. *et al.* Sulfide-rich continental roots at cratonic margins formed by
688 carbonated melts. *Nature (London)* **637**, 615-621, doi:10.1038/s41586-024-08316-w
689 (2025).
- 690 13 Ezad, I. S. *et al.* Incipient carbonate melting drives metal and sulfur mobilization in
691 the mantle. *Science Advances* **10**, eadk5979, doi:10.1126/sciadv.adk5979 (2024).
- 692 14 Xue, S. & Li, Y. The partitioning of chalcophile and siderophile elements (CSEs)
693 between sulfide liquid and carbonated melt. *Geochim Cosmochim Acta* **388**, 94-113,
694 doi:10.1016/j.gca.2024.11.019 (2025).
- 695 15 Blanks, D. E. *et al.* Fluxing of mantle carbon as a physical agent for metallogenic
696 fertilization of the crust. *Nature Communications* **11**, 4342, doi:10.1038/s41467-020-
697 18157-6 (2020).
- 698 16 Hou, Z., Liu, Y., Tian, S., Yang, Z. & Xie, Y. Formation of carbonatite-related giant rare-
699 earth-element deposits by the recycling of marine sediments. *Scientific Reports* **5**,
700 10231, doi:10.1038/srep10231 (2015).
- 701 17 Foley, S. F. & Fischer, T. P. An essential role for continental rifts and lithosphere in the
702 deep carbon cycle. *Nature geoscience* **10**, 897-902, doi:10.1038/s41561-017-0002-7
703 (2017).
- 704 18 Mather, B. R., Müller, R. D., Dutkiewicz, A. & Zahirovic, S. Carbon emissions along
705 divergent plate boundaries modulate icehouse-greenhouse climates.
706 *Communications Earth & Environment* **7**, 48, doi:10.1038/s43247-025-03097-0
707 (2026).
- 708 19 Liu, D. Y. *et al.* Paleoproterozoic deep carbon cycle recorded in carbonatites.
709 *Precambrian Research* **417**, doi:10.1016/j.precamres.2024.107669 (2025).
- 710 20 Liu, Z. C. *et al.* The global deep carbon cycle started in the Paleoproterozoic Era.
711 *Lithos* **510**, doi:10.1016/j.lithos.2025.108113 (2025).
- 712 21 McCammon, C. *et al.* Deep Earth carbon reactions through time and space. *American*
713 *Mineralogist* **105**, 22-27, doi:10.2138/am-2020-6888CCBY (2020).
- 714 22 Pintér, Z. *et al.* Experimental investigation of the composition of incipient melts in
715 upper mantle peridotites in the presence of CO₂ and H₂O. *Lithos* **396**,
716 doi:10.1016/j.lithos.2021.106224 (2021).

- 717 23 Prelević, D. *et al.* Recent advances made by reaction experiments on melting of
718 heavily metasomatized hydrous mantle. *Earth-Science Reviews* **256**, 104881,
719 doi:<https://doi.org/10.1016/j.earscirev.2024.104881> (2024).
- 720 24 Walter, M. J. *et al.* Primary carbonatite melt from deeply subducted oceanic crust.
721 *Nature* **454**, 622-625 (2008).
- 722 25 Huang, Y. *et al.* Upper mantle low-velocity layer tied to volatile-charged carbonate
723 melts. *Science Advances* **12**, eaec1018, doi:doi:10.1126/sciadv.aec1018 (2026).
- 724 26 Gaillard, F., Malki, M., Iacono-Marziano, G., Pichavant, M. & Scaillet, B. Carbonatite
725 melts and electrical conductivity in the asthenosphere. *Science* **322**, 1363-1365,
726 doi:10.1126/science.1164446 (2008).
- 727 27 Yoshino, T., Laumonier, M., McIsaac, E. & Katsura, T. Electrical conductivity of basaltic
728 and carbonatite melt-bearing peridotites at high pressures: Implications for melt
729 distribution and melt fraction in the upper mantle. *Earth and Planetary Science*
730 *Letters* **295**, 593-602, doi:10.1016/j.epsl.2010.04.050 (2010).
- 731 28 Zhao, B., Zhu, J., Chen, Q. & Yoshino, T. Electrical conductivity of carbonatite melts to
732 20 GPa: Constraints on partial melting atop the 410-km discontinuity and in the
733 lower mantle transition zone. *Journal of Geophysical Research: Solid Earth* **131**,
734 e2025JB033390, doi:<https://doi.org/10.1029/2025JB033390> (2026).
- 735 29 Sun, J., Yang, Y., Ingrin, J., Wang, Z. & Xia, Q. Impact of fluorine on the thermal
736 stability of phlogopite. *American Mineralogist* **107**, 815-825, doi:10.2138/am-2022-
737 8051 (2022).
- 738 30 Shu, C. T., Foley, S. F., Ezad, I. S., Daczko, N. R. & Shcheka, S. S. Experimental melting
739 of phlogopite websterite in the upper mantle between 1.5 and 4.5 GPa. *J Petrol* **65**,
740 doi:10.1093/petrology/egae030 (2024).
- 741 31 Thiel, S. & Heinson, G. Electrical conductors in Archean mantle; result of plume
742 interaction? *Geophysical research letters* **40**, 2947-2952, doi:10.1002/grl.50486
743 (2013).
- 744 32 Tietze, K., Thiel, S., Brand, K. & Heinson, G. Comparative 3D inversion of
745 magnetotelluric phase tensors and impedances reveals electrically anisotropic base
746 of Gawler Craton, South Australia. *Exploration Geophysics* **55**, 575-601,
747 doi:10.1080/08123985.2023.2281615 (2024).

748 33 Hand, M., Reid, A. & Jagodzinski, E. Tectonic framework and evolution of the Gawler
749 Craton, Southern Australia. *Economic Geology* **102**, 1377–1395,
750 doi:10.2113/gsecongeo.102.8.1377 (2007).

751 34 Reid, A. J. & Daly, S. J. The Mulgathing and Sleaford Complexes of the Gawler Craton;
752 a historical perspective of the geology and mineral potential. *MESA journal* **52**, 4-12
753 (2009).

754 35 Dutch, R. A., Hand, M. & Kelsey, D. E. Unravelling the tectonothermal evolution of
755 reworked Archean granulite facies metapelites using in situ geochronology: an
756 example from the Gawler Craton, Australia. *Journal of Metamorphic Geology* **28**, 293-
757 316, doi:10.1111/j.1525-1314.2010.00867.x (2010).

758 36 Hoatson, D. M. *et al.* Late Archean Lake Harris Komatiite, central Gawler Craton,
759 South Australia; geologic setting and geochemistry. *Economic geology and the*
760 *bulletin of the Society of Economic Geologists* **100**, 349-374,
761 doi:10.2113/gsecongeo.100.2.349 (2005).

762 37 Armit, R. *et al.* Late Palaeoproterozoic evolution of the buried northern Gawler
763 Craton. *Precambrian Research* **291**, 178-201, doi:10.1016/j.precamres.2017.01.023
764 (2017).

765 38 Halpin, J. A. & Reid, A. J. Earliest Paleoproterozoic high-grade metamorphism and
766 orogenesis in the Gawler Craton, South Australia: The southern cousin in the Rae
767 family? *Precambrian Research* **276**, 123-144, doi:10.1016/j.precamres.2016.02.001
768 (2016).

769 39 Stewart, J. R., Betts, P. G., Collins, A. S. & Schaefer, B. F. Multi-scale analysis of
770 Proterozoic shear zones: An integrated structural and geophysical study. *J Struct Geol*
771 **31**, 1238-1254, doi:10.1016/j.jsg.2009.07.002 (2009).

772 40 Swain, G. M., Hand, M., Teasdale, J., Rutherford, L. & Clark, C. Age constraints on
773 terrane-scale shear zones in the Gawler Craton, southern Australia. *Precambrian*
774 *Research* **139**, 164-180, doi:10.1016/j.precamres.2005.06.007 (2005).

775 41 Reid, A. J. & Hand, M. Mesoarchean to Mesoproterozoic evolution of the southern
776 Gawler Craton, South Australia. *Episodes* **35**, 216-225, doi:DOI
777 10.18814/epiiugs/2012/v35i1/021 (2012).

778 42 Pankhurst, M. J., Schaefer, B. F., Betts, P. G., Phillips, N. & Hand, M. A
779 Mesoproterozoic continental flood rhyolite province, the Gawler Ranges, Australia:

780 the end member example of the Large Igneous Province clan. *Solid Earth* **2**, 25-33,
781 doi:10.5194/se-2-25-2011 (2011).

782 43 Skirrow, R. G., van der Wielen, S. E., Champion, D. C., Czarnota, K. & Thiel, S.
783 Lithospheric architecture and mantle metasomatism linked to iron oxide Cu-Au ore
784 formation: Multidisciplinary evidence from the Olympic Dam region, South Australia.
785 *Geochemistry Geophysics Geosystems* **19**, 2673-2705, doi:10.1029/2018gc007561
786 (2018).

787 44 Skirrow, R. G. Iron oxide copper-gold (IOCG) deposits - A review (part 1): Settings,
788 mineralogy, ore geochemistry and classification. *Ore Geology Reviews* **140**,
789 doi:10.1016/j.oregeorev.2021.104569 (2022).

790 45 Skirrow, R. G. Iron oxide copper-gold (IOCG) deposits - A review (part 2): fluid, metal
791 and sulfur sources and ore genesis. *Ore Geology Reviews* **189**,
792 doi:10.1016/j.oregeorev.2026.107120 (2026).

793 46 Flint, R. B., Rankin, L. R. & Fanning, C. M. Definition; the palaeoproterozoic St. Peter
794 suite of the western Gawler craton. *Geological Survey of South Australia Quarterly*
795 *Geological Notes* **114**, 2-8 (1990).

796 47 Reid, A. J. *et al.* Resolving tectonic settings of ancient magmatic suites using
797 structural, geochemical and isotopic constraints; the example of the St Peter Suite,
798 southern Australia. *Australian journal of earth sciences* **67**, 31-58,
799 doi:10.1080/08120099.2019.1632224 (2020).

800 48 Swain, G. *et al.* Petrogenesis of the St Peter Suite, southern Australia; arc magmatism
801 and Proterozoic crustal growth of the South Australian Craton. *Precambrian research*
802 **166**, 283-296, doi:10.1016/j.precamres.2007.07.028 (2008).

803 49 Betts, P. G. *et al.* Mesoproterozoic plume-modified orogenesis in eastern
804 Precambrian Australia. *Tectonics* **28**, doi:10.1029/2008tc002325 (2009).

805 50 Sudholz, Z. J. *et al.* Multi-stage evolution of the South Australian Craton; petrological
806 constraints on the architecture, lithology, and geochemistry of the lithospheric
807 mantle. *Geochemistry, geophysics, geosystems* **23**, n/a, doi:10.1029/2022GC010558
808 (2022).

809 51 Selway, K., Özaydın, S. & Payne, J. Metasomatism and depletion of the southern
810 Gawler Craton from combined mantle xenocryst and AusLAMP magnetotelluric data.

811 *Exploration geophysics (Melbourne)* **55**, 602-616,
812 doi:10.1080/08123985.2023.2282711 (2024).

813 52 Eakin, C. M. Lithospheric architecture and mantle flow revealed by quasi-Love wave
814 scattering beneath Australia. *Communications Earth & Environment* **2**, 276,
815 doi:10.1038/s43247-021-00276-7 (2021).

816 53 Eakin, C. M., Davies, D. R., Ghelichkhan, S., O'Donnell, J. P. & Agrawal, S. The
817 influence of lithospheric thickness variations beneath Australia on seismic anisotropy
818 and mantle flow. *Geochemistry, Geophysics, Geosystems* **24**,
819 doi:10.1029/2023gc011066 (2023).

820 54 de Laat, J. I. *et al.* Structure and evolution of the Australian plate and underlying
821 upper mantle from waveform tomography with massive data sets. *Geophysical*
822 *Journal International* **234**, 153-189, doi:10.1093/gji/ggad062 (2023).

823 55 Thiel, S., Reid, A., Heinson, G., Brand, K. & Li, L. Mantle-derived fluid flux controls
824 Olympic Dam-style Fe oxide-Cu-Au mineralisation. *Scientific Reports* **16**,
825 doi:10.1038/s41598-025-33477-7 (2026).

826 56 Ba, K., Gao, S. S., Song, J. & Liu, K. H. Seismic azimuthal anisotropy beneath a fast
827 moving ancient continent: Constraints from shear wave splitting analysis in Australia.
828 *Journal of Geophysical Research: Solid Earth* **128**, e2022JB025866,
829 doi:<https://doi.org/10.1029/2022JB025866> (2023).

830 57 Tietze, K., Thiel, S., Brand, K. & Heinson, G. Comparative 3D inversion of
831 magnetotelluric phase tensors and impedances reveals electrically anisotropic base
832 of Gawler Craton, South Australia. *Exploration Geophysics*,
833 doi:10.1080/08123985.2023.2281615 (2023).

834 58 Li, Y., Jiang, H. T. & Yang, X. Z. Fluorine follows water: Effect on electrical conductivity
835 of silicate minerals by experimental constraints from phlogopite. *Geochimica Et*
836 *Cosmochimica Acta* **217**, 16-27, doi:10.1016/j.gca.2017.08.020 (2017).

837 59 Li, Y., Yang, X. Z., Yu, J. H. & Cai, Y. F. Unusually high electrical conductivity of
838 phlogopite: the possible role of fluorine and geophysical implications. *Contrib*
839 *Mineral Petr* **171**, doi:10.1007/s00410-016-1252-x (2016).

840 60 Thiel, S. & Heinson, G. Crustal imaging of a mobile belt using magnetotellurics: An
841 example of the Fowler Domain in South Australia. *Journal of Geophysical Research:*
842 *Solid Earth* **115**, doi:10.1029/2009jb006698 (2010).

843 61 Korsch, R. J., Doublier, M. P., Hagemann, S. G., Lisitsin, V. & Huston, D. L. Major crustal
844 boundaries of Australia, and their significance in mineral systems targeting. *Ore*
845 *geology reviews* **76**, 211-228, doi:10.1016/j.oregeorev.2015.05.010 (2016).

846 62 Heinson, G., Didana, Y., Soeffky, P., Thiel, S. & Wise, T. The crustal geophysical
847 signature of a world-class magmatic mineral system. *Scientific reports* **8**, 10608-
848 10606, doi:10.1038/s41598-018-29016-2 (2018).

849 63 Kennett, B. L. N., Salmon, M., Saygin, E. & Group, A. W. AusMoho: the variation of
850 Moho depth in Australia. *Geophysical Journal International* **187**, 946-958,
851 doi:10.1111/j.1365-246X.2011.05194.x (2011).

852 64 Roots, E. A. *et al.* Channelized metasomatism in Archean cratonic roots as a
853 mechanism of lithospheric refertilization. *Nature Communications* **16**,
854 doi:10.1038/s41467-025-62912-6 (2025).

855 65 Bologna, M. S. *et al.* Electrical structure of the lithosphere from Rio de la Plata Craton
856 to Paraná Basin: Amalgamation of cratonic and refertilized lithospheres in SW
857 Gondwanaland. *Tectonics* **38**, 77-94, doi:<https://doi.org/10.1029/2018TC005148>
858 (2019).

859 66 Bassin, C. G. L., Laske, G. & Masters, G. The current limits of resolution for surface
860 wave tomography in North America. EOS Trans AGU 81:F897. *Eos* **81**, F897 (2000).

861 67 Lebedev, S. & Van Der Hilst, R. D. Global upper-mantle tomography with the
862 automated multimode inversion of surface and S-wave forms. *Geophysical Journal*
863 *International* **173**, 505-518, doi:10.1111/j.1365-246X.2008.03721.x (2008).

864 68 Wise, T., Pawley, M., Thiel, S., Dutch, R. & Anonymous. Geology, geophysics,
865 geochemistry of a hidden Palaeoproterozoic ocean-continent transition in the
866 northern Gawler Craton. *ASEG Extended Abstracts* **2018**, 1-5,
867 doi:10.1071/ASEG2018abM3_1G (2018).

868 69 Fraser, G., Reid, A. & Stern, R. Timing of deformation and exhumation across the
869 Karari Shear Zone, north-western Gawler Craton, South Australia. *Australian Journal*
870 *of Earth Sciences* **59**, 547-570, doi:10.1080/08120099.2012.678586 (2012).

871 70 Pollett, A., Thiel, S., Bendall, B., Raimondo, T. & Hand, M. Mapping the Gawler
872 Craton-Musgrave Province interface using integrated heat flow and magnetotellurics.
873 *Tectonophysics* **756**, 43-56, doi:10.1016/j.tecto.2019.02.017 (2019).

874 71 Thomas, R. J., Hand, M. & Reid, A. Tectonic evolution of the Karari Shear Zone,
875 northwestern Gawler Craton. *Precambrian Research* **166**, 123–138,
876 doi:10.1016/j.precamres.2008.01.010 (2008).

877 72 Özaydin, S. & Selway, K. MATE: An analysis tool for the interpretation of
878 magnetotelluric models of the mantle. *Geochemistry Geophysics Geosystems* **21**,
879 doi:10.1029/2020gc009126 (2020).

880 73 Constable, S. SEO3: A new model of olivine electrical conductivity. *Geophysical*
881 *Journal International* **166**, 435–437, doi:10.1111/j.1365-246X.2006.03041.x (2006).

882 74 Wang, D., Li, H., Yi, L. & Shi, B. The electrical conductivity of upper-mantle rocks:
883 water content in the upper mantle. *Physics and Chemistry of Minerals* **35**, 157–162,
884 doi:10.1007/s00269-007-0207-1 (2008).

885 75 Bettac, S. P., Unsworth, M. J., Pearson, D. G. & Craven, J. New constraints on the
886 structure and composition of the lithospheric mantle beneath the Slave craton, NW
887 Canada from 3-D magnetotelluric data-Origin of the Central Slave Mantle Conductor
888 and possible evidence for lithospheric scale fluid flow. *Tectonophysics* **851**,
889 doi:10.1016/j.tecto.2023.229760 (2023).

890 76 Steenstra, E. S. *et al.* Thermal Stability of F-Rich Phlogopite and K-Richterite During
891 Partial Melting of Metasomatized Mantle Peridotite With Implications for Deep Earth
892 Volatile Cycles. *Journal of Geophysical Research: Solid Earth* **129**, e2023JB028202,
893 doi:<https://doi.org/10.1029/2023JB028202> (2024).

894 77 Pommier, A. & Le-Trong, E. “SIGMELTS”: A web portal for electrical conductivity
895 calculations in geosciences. *Computers & Geosciences* **37**, 1450–1459,
896 doi:<https://doi.org/10.1016/j.cageo.2011.01.002> (2011).

897 78 Foley, S. F. Rejuvenation and erosion of the cratonic lithosphere. *Nature Geoscience*
898 **1**, 503–510, doi:10.1038/ngeo261 (2008).

899 79 Chen, C. F. *et al.* Sulfide-rich continental roots at cratonic margins formed by
900 carbonated melts. *Nature* **637**, doi:10.1038/s41586-024-08316-w (2025).

901 80 Huizenga, J.-M. Thermodynamic modelling of a cooling C–O–H fluid–graphite system:
902 implications for hydrothermal graphite precipitation. *Miner Deposita* **46**, 23–33,
903 doi:10.1007/s00126-010-0310-y (2011).

904 81 Murphy, B. S., Huizenga, J. M. & Bedrosian, P. A. Graphite as an electrically
905 conductive indicator of ancient crustal-scale fluid flow within mineral systems. *Earth*

- and Planetary Science Letters* **594**, 117700,
doi:<https://doi.org/10.1016/j.epsl.2022.117700> (2022).
- 82 Zhang, C. & Duan, Z. GFluid: An Excel spreadsheet for investigating C–O–H fluid
composition under high temperatures and pressures. *Computers & Geosciences* **36**,
569-572, doi:<https://doi.org/10.1016/j.cageo.2009.05.008> (2010).
- 83 Neumann, N., Sandiford, M. & Foden, J. Regional geochemistry and continental heat
flow: implications for the origin of the South Australian heat flow anomaly. *Earth and
Planetary Science Letters* **183**, 107-120, doi:[https://doi.org/10.1016/S0012-
821X\(00\)00268-5](https://doi.org/10.1016/S0012-821X(00)00268-5) (2000).
- 84 Chave, A. D. & Thomson, D. J. Bounded influence magnetotelluric response function
estimation. *Geophys J Int* **157**, 988-1006, doi:10.1111/j.1365-246X.2004.02203.x
(2004).
- 85 Chave, A. D. & Thomson, D. J. A bounded influence regression estimator based on the
statistics of the hat matrix. *J R Stat Soc C-Appl* **52**, 307-322, doi:Doi 10.1111/1467-
9876.00406 (2003).
- 86 Krieger, L. & Peacock, J. R. MTyp: A Python toolbox for magnetotellurics. *Computers
& geosciences* **72**, 167-175, doi:10.1016/j.cageo.2014.07.013 (2014).
- 87 Mackie, R. L. & Madden, T. R. 3-Dimensional Magnetotelluric Inversion Using
Conjugate Gradients. *Geophys J Int* **115**, 215-229, doi:DOI 10.1111/j.1365-
246X.1993.tb05600.x (1993).
- 88 Rodi, W. & Mackie, R. L. Nonlinear conjugate gradients algorithm for 2-D
magnetotelluric inversion. *Geophysics* **66**, 174-187, doi:Doi 10.1190/1.1444893
(2001).
- 89 Kuvshinov, A., Grayver, A., Tøffner-Clausen, L. & Olsen, N. Probing 3-D electrical
conductivity of the mantle using 6 years of Swarm, CryoSat-2 and observatory
magnetic data and exploiting matrix Q-responses approach. *Earth, Planets and Space*
73, 67, doi:10.1186/s40623-020-01341-9 (2021).

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