

Extensional Lithospheric Architecture Controls Mantle Carbon Dioxide Transfer into the Crust and Focuses Conductive Pathways to Iron Oxide Copper-Gold Mineral Systems

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Extensional Lithospheric Architecture Controls Mantle Carbon

Dioxide Transfer into the Crust and Focuses Conductive Pathways to

Iron Oxide Copper-Gold Mineral Systems

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Abstract

Iron oxide-copper-gold (IOCG) systems are typically associated with large-scale hydrothermal circulation along long-lived structural pathways, however, the three-dimensional lithospheric architecture connecting deep fluid sources to upper-crustal mineralisation remains poorly understood. Here, we present 3D magnetotelluric (MT) imaging from over 1,300 broadband sites across the eastern Gawler Craton and Olympic Domain in South Australia. The model images a series of conductive lower-crustal zones and vertically extensive pathways, which are interpreted as the preserved electrical footprint of deep fluid flow. In the northern Olympic Domain, including IOCG deposits at Olympic Dam, Acropolis, and Vulcan, these conductors form a strong linkage from the lower to upper crust, spatially associated with major IOCG systems, gravity highs, and displaced magnetic anomalies. We interpret this architecture as evidence for focused CO₂-rich supercritical fluid ascent, graphite precipitation and repeated structural reactivation linked to Hiltaba Suite-Gawler Range Volcanics

magmatism. In the southern Olympic Domain, including IOCG deposits at Oak Dam, Carrapateena, Emmie Bluff and Mount Gunson, deep conductors are present but do not exhibit the same clear connection to the upper-crust. These results suggest that IOCG prospectivity beneath cover is imaged not only by the presence of deep conductors but also by the continuity, geometry, and preservation of conductive fluid pathways between lower-crustal roots and upper-crustal mineral systems.

(206 Words)

Keywords: Iron oxide-copper-gold systems; Magnetotellurics; Olympic Domain; Gawler Craton; Crustal-scale fluid pathways; Deep crustal conductivity.

Introduction

Iron oxide-copper-gold deposits are among the most geologically complex hydrothermal mineral systems, integrating deep heat sources, multiple fluid reservoirs and structurally focused fluid flow across crustal-scales¹⁻⁵. Formation processes are often explained by models involving magmatic-hydrothermal, metamorphic and basinal fluid contributions⁴⁻⁸. A primary challenge in exploration is identifying how fluids and metals were transported through the crust. Consequently, the geometry of fluid pathways and crustal structures can be considered as significant as the ore bodies themselves^{1,2,9}.

Magnetotelluric imaging is an effective tool for investigating this issue because electrical resistivity is sensitive to interconnected conductive phases and pathways^{10,11}. Factors that influence the resistivity include the presence of graphite, sulphides, saline fluids, hydrothermal alteration products¹⁰⁻¹². At regional to crustal scales, resistivity reflects

broader mineral-system architecture, such as graphite-bearing lower-crustal roots, reactivated fluid pathways and preserved products of ancient fluid-rock interaction^{4,10,11,13}. Therefore, the strongest contribution of MT is not necessarily identifying where copper was deposited but imaging the architecture of deep fluid pathways that may have focused mineralising systems.

The Olympic Cu-Au Province in the eastern Gawler Craton (Figure 1) is one of the most important IOCG provinces globally. It hosts the supergiant Olympic Dam Cu-U-Au-Ag deposit and several other major deposits and prospects, including Acropolis (AC), Wirrda Well (WW), Oak Dam (OD), Carrapateena (CP), Emmie Bluff (EB), Mount Gunson (MG), Titan (TI) and Vulcan (VU)^{2,3,7}. These systems are largely concealed beneath post-mineral sedimentary cover, necessitating the reconstruction of their crustal architecture through integrated geological and geophysical datasets, such as gravity, magnetics, MT, seismic imaging, and drilling constraints^{2,14-18}. The broader eastern Gawler Craton records a long-lived crustal evolution from the Archean to the Mesoproterozoic, involving the Archean-Palaeoproterozoic basement, Mulgathing Complex, Donington Suite, Wallaroo Group, and Mesoproterozoic Hiltaba Suite-Gawler Range Volcanics magmatism^{2,19}. This inherited architecture established major crustal weaknesses that were reactivated during IOCG mineralisation around 1.6 Ga^{8,17,19}. The late Palaeoproterozoic-early Mesoproterozoic tectonic setting of the eastern Gawler Craton remains debated, but regional models invoke subduction-related modification of the lithosphere before ca. 1.6 Ga IOCG mineralisation. Betts et al. (2009)²⁰ proposed plume-modified orogenesis involving flat subduction, slab delamination and a subsequent switch to extension, whereas Skirrow et al. (2018)⁸ linked convergence and accretion to refertilisation and metasomatism of the lithospheric mantle,

71 followed by gravitational foundering. Although they differ in the inferred geodynamic driver,
72 both models provide a mechanism for exposing previously modified mantle to
73 asthenospheric heat, promoting mantle-derived magmatism, and lower-crustal melting.

74
75 The crustal framework of the eastern Gawler Craton is fundamental for interpreting regional
76 scale MT models. Deep seismic reflection data indicate that Olympic Dam is located near a
77 boundary between distinct crustal domains, and that the crust beneath the deposit is
78 characterised by a complex thrust-related architecture rather than a simple extensional
79 geometry²¹. The Roxby Downs Granite, which hosts Olympic Dam, is positioned above a
80 lower-crustal reduced-impedance "bland zone" interpreted as a potential source region for
81 high-temperature (~ 1000 °C) Hiltaba Suite magmatism²¹. Regional analyses of basement
82 structures further demonstrate that Mesoproterozoic metallogenic provinces in the Gawler
83 Craton are spatially associated with gravity, magnetic, and resistivity gradients, many of
84 which lack a clear surface expression¹⁷.

85
86 Geochemical and geochronological constraints at the deposit scale supports a model of
87 episodically reactivated pathways. For example, Olympic Dam records a long-lived,
88 multistage hydrothermal history from ca. 1.59 Ga to ca. 0.5 Ga, with Mesoproterozoic IOCG
89 mineralisation, interaction with sedimentary or basinal materials, and later uranium addition
90 during Neoproterozoic to Cambrian reactivation²²⁻²⁴. The Acropolis prospect, approximately
91 20 km southwest of Olympic Dam, is a magnetite ± apatite ± haematite system in which Cu
92 mineralisation is offset from early Fe-rich veins, implying overprinting by later Cu-bearing
93 fluids²⁵. Apatite chemistry at Acropolis and Wirrda Well records evolving fluid conditions and
94 supports a broader district-scale hydrothermal evolution²⁶. In the southern Olympic Domain,

Carrapateena records major IOCG mineralisation at ca. 1585 Ma and later hydrothermal or uranium-related events at ca. 600-500 Ma²⁷, whereas Oak Dam East is a breccia-hosted Fe oxide Cu-U-Au system formed through multiple high-temperature, hypersaline and Fe oxide alteration stages²⁸.

A geological and geophysical framework of the Olympic Domain is shown in Figure 1. The simplified geology distinguishes between a northern IOCG domain, comprising Titan, Vulcan, Olympic Dam, Acropolis and Wirrda Well, and a southern domain, which includes Oak Dam, Carrapateena, Emmie Bluff and Mount Gunson^{2,8}. The Bouguer gravity map in Figure 1 illustrates a consistent belt of positive anomalies across the northern Olympic Domain. Olympic Dam, Acropolis and Wirrda Well are located within or adjacent to this gravity-high corridor, which is consistent with dense source rocks and alteration products such as iron oxide-rich breccias, magnetite- or haematite-bearing alteration zones, and mafic to intermediate basement components^{2,8}. In contrast, the southern domain exhibits localised gravity highs near specific systems, but these anomalies appear more fragmented and do not form a continuous regional belt.

The TMI RTP magnetic response in Figure 1 is more heterogeneous than the Bouguer gravity map. Anomalies have shorter wavelengths, reflecting variations in magnetite abundance and structural boundaries^{2,17}. In the northern domain, magnetic anomalies are large and locally displaced relative to the gravity highs and deposit centres. This displacement is important because it suggests that magnetite-rich alteration, magnetic basement units and deposit-scale density anomalies are related, but not spatially identical. In the southern domain, magnetic anomalies are weaker and fragmented. The sedimentary-cover map confirms that

both domains are buried under significant post-mineral cover, with thickness increasing in parts of the northeastern Olympic Domain.

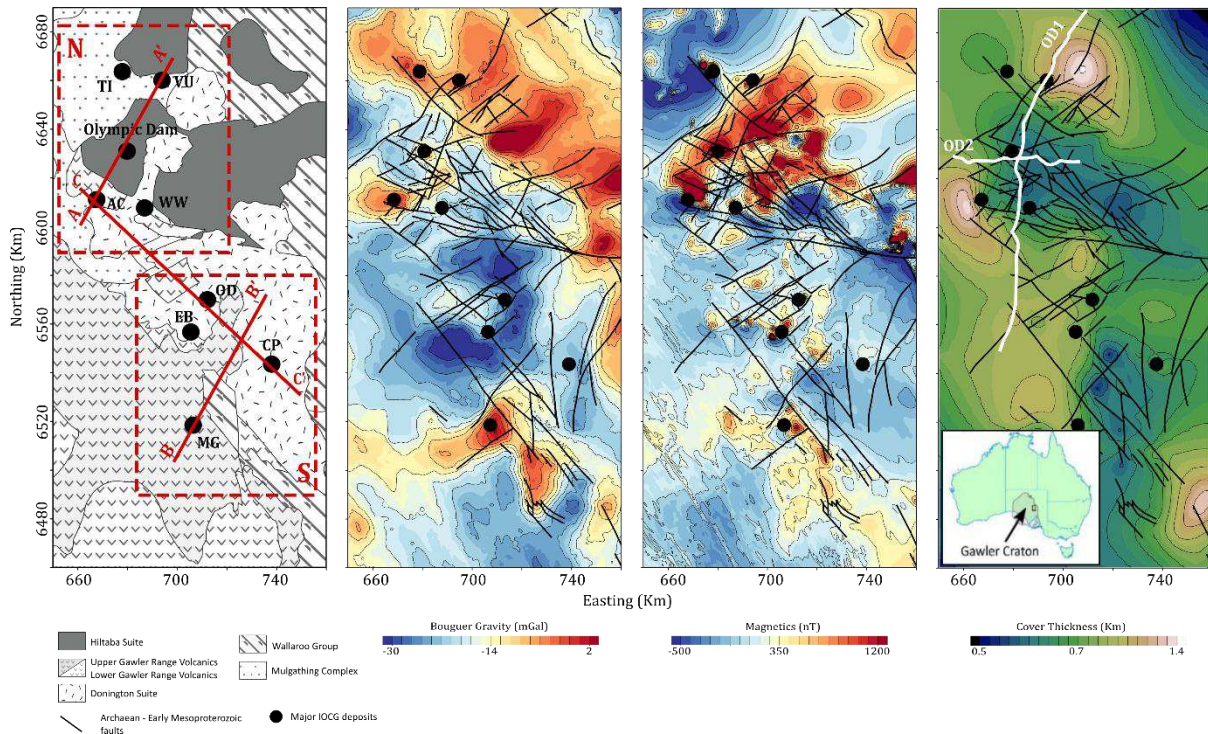


Figure 1: Regional geological and geophysical framework of the Olympic Domain, eastern Gawler Craton. Panels show simplified basement geology, Bouguer gravity, total magnetic intensity (RTP) and sedimentary cover thickness. Black circles mark major IOCG deposits and prospects, including Titan (TI), Vulcan (VU), Olympic Dam, Acropolis (AC), Wirrda Well (WW), Oak Dam (OD), Emmie Bluff (EB), Carrapateena (CP) and Mount Gunson (MG). Red dashed boxes outline the northern and southern Olympic Domain subregions. Red lines (A-A', B-B', and C-C') indicate the main cross-sections used for structural and resistivity comparison. White lines on the sedimentary cover map show seismic traverses OD1 and OD2. Magnetics and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDs) (<https://portal.ga.gov.au/persona/gadds>) and are released under the Creative Commons Attribution 4.0 (CC BY 4.0) licence (<https://www.ga.gov.au/copyright>).

134 Elevation of Proterozoic basement were sourced from Geognostics OZ SEEBASE 2021
135 (<https://www.geognostics.com/oz-seebase-2021>), also distributed under a CC BY 4.0 licence.
136 Background geology, sedimentary cover, faults and mineral deposit's locations were
137 obtained from Department for Energy and Mining SA (<https://map.sarig.sa.gov.au/>). All
138 figures were produced using Viridien Geotools v.4.0.6.12598
139 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) and Inkscape
140 v1.2.1 (<https://inkscape.org>).

141

142 Previous MT studies have established that Olympic Dam is underlain by a lower crustal
143 electrically conductive system, with narrow conductive zones connecting lower-crustal
144 conductors with upper-crustal IOCG systems^{11,12}. Broader AusLAMP and Gawler Craton MT
145 research outputs have extended this framework to lithospheric-scale resistivity structures,
146 including mantle anomalies, metasomatism, electrical anisotropy and craton-scale structural
147 architecture^{13,29-33}. Deposit-scale geophysical investigations beneath thick cover around the
148 Vulcan deposit, incorporating MT, natural-source induced polarisation and ambient noise
149 tomography demonstrate that covered IOCG systems can be characterised more robustly
150 when multiple geophysical methods are integrated^{14-16,18}.

151

152 In this study, 3D MT imaging is used to evaluate whether northern and southern IOCG
153 systems in the Olympic Domain are connected to lower-crustal conductive zones in a
154 consistent manner. The primary objective is to examine whether the MT model reveals deep
155 conductive pathways that span crustal depths. Such pathways may represent the preserved
156 signatures of CO₂-rich supercritical fluid flow leading to graphite precipitation, and sustained
157 permeability along inherited structures.

Results

Phase-invariant maps for periods of 0.02, 0.2, 2, 20, and 200 s are shown in Figure 2 as a means of summarising the electrical response and aperture for the measured bandwidth and provide an assessment of the MT dataset's spatial coherence. In general, red colours indicate that the Earth is more conductive with depth, blue regions are more resistive, and phases around 45 degrees suggest a reasonably uniform resistive structure with depth. Although the phase changes with period, all plots have the same dynamic colour range spanning 30 degrees. For the periods of 0.02 – 0.2 s, the phase responses closely reflect shallow sedimentary cover and near-surface heterogeneity, as shown in Figure 1d.

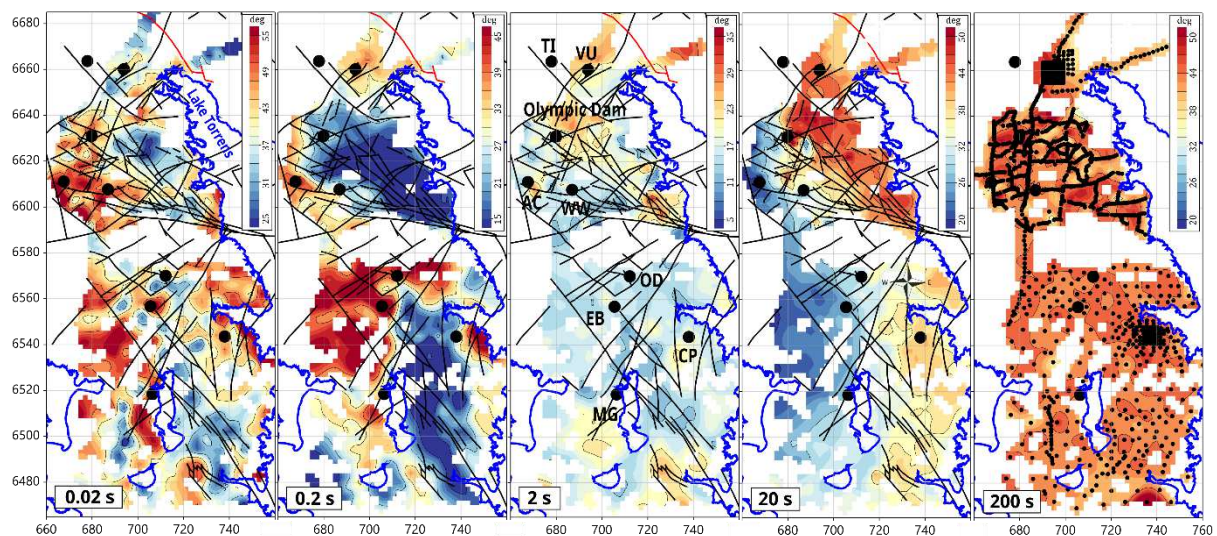


Figure 2: Maps show phase-invariant responses at 0.02 s, 0.2 s, 2 s, 20 s and 200 s across the Olympic Domain. Large black circles mark major IOCG deposits and prospects identified in Figure 1. Black lines denote Archean to Mesoproterozoic faults; and blue outlines indicate salt lakes. In the 200 s panel, small black dots indicate MT station locations. Areas are shown in UTM 53S projection. Faults and mineral deposit's locations were obtained from Department for Energy and Mining SA (<https://map.sarig.sa.gov.au/>). All figures were

175 produced using Viridien Geotools v.4.0.6.12598
176 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) and Inkscape
177 v1.2.1 (<https://inkscape.org>).
178

179 At a period of 2 s, the response begins to image upper-crustal structure, although this period
180 lies close to the MT dead band and therefore contains more scatter and local noise than the
181 neighbouring periods. However, small regions of higher phase (red colours) are notable
182 around Olympic Dam, Acropolis and Vulcan IOCG deposits. At 20 seconds, the response
183 shows significant sensitivity to deeper crustal structures, revealing a strong boundary
184 between the resistive (blue colours) southwestern domain and the more conductive
185 northeastern margin (red colours) of the Olympic Domain. At 200 seconds, the phase
186 response remains remarkably stable across most of the survey area (~45 degrees), with
187 variations generally limited to a few degrees, indicates a relative uniform regional scale
188 resistivity at sub-crustal depths. Consequently, Figure 2 supports a depth-dependent
189 interpretation where the north-south electrical contrast evolves from shallow cover and
190 upper-crustal heterogeneity into a broader, crustal-scale resistivity pattern.

191

192 The northern Olympic Domain is characterised by a prominent Bouguer gravity anomaly and
193 a strong TMI RTP magnetic response that is locally offset from the gravity high and known
194 deposit positions, as shown in Figure 3. This offset suggests that the dense and magnetic
195 source regions are not identical, reflecting differences between the depth-dependent redox
196 state of iron oxides^{2,8}. The potential-field patterns are also segmented by strong boundaries
197 that separate domains with contrasting gravity, magnetic and resistivity character. These
198 relationships demonstrate that the northern IOCG systems are situated within a structurally

complex basement architecture, as opposed to a simple, laterally uniform anomaly. At depths of 1-2 km in the resistivity slices, low-resistivity anomalies occur near IOCG deposits at Acropolois, Olympic Dam and the broader Vulcan region, though these features are laterally discontinuous and locally offset from deposit centres. There are no publically available MT data around the Titan deposit, and thus there is little constraint on the resistivity mode; this region has thus been shaded out. Shallow conductors frequently appear near major structures and along the margins of gravity and magnetic anomalies, suggesting that upper-crustal resistivity is likely influenced by lithological contrasts, Fe-oxide alteration and structurally focused fluid pathways rather than a single homogeneous conductive layer^{25,26}.

At depths of 5-10 km, conductive anomalies become broader and laterally extensive. These zones align with regional structural trends. This transition suggests that the shallow conductive responses near known deposits are not isolated upper-crustal anomalies but likely connect to deeper conductive corridors. At 20 km depth, the northern conductors merge into larger lower-crustal conductive trends. The northern domain contains a clear lower- to upper-crustal conductive linkage, with shallow IOCG systems located above or beside conductive corridors that connect downward into a broader lower-crustal conductor. This is consistent with the previous MT interpretations of Olympic Dam as overlying a deep crustal mineral-system conductor^{11,12}, but the present 3D model extends that concept across the northern Olympic Domain.

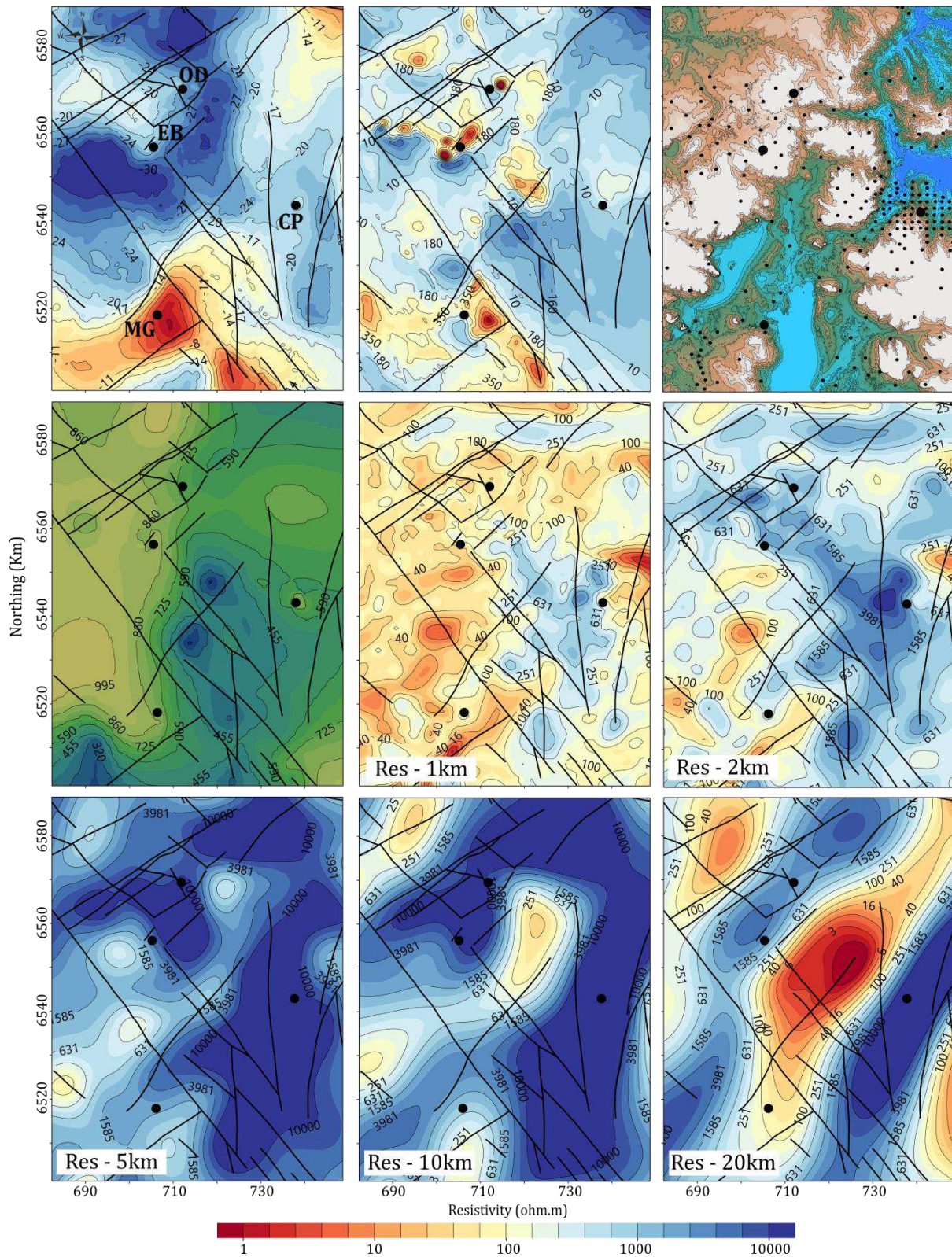
Domain. Small black dots on the elevation map indicate MT sites. Black lines represent Archean to early Mesoproterozoic faults. The area to the northwest has no MT sites and hence has been shaded to indicate there is less model constraint. Areas are shown in UTM 53S projection. Magnetism and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDS) (<https://portal.ga.gov.au/persona/gadds>) and are released under the Creative Commons Attribution 4.0 (CC BY 4.0) licence (<https://www.ga.gov.au/copyright>). Elevation of Proterozoic basement were sourced from Geognostics OZ SEEBASE 2021 (<https://www.geognostics.com/oz-seebase-2021>), also distributed under a CC BY 4.0 licence. Background geology, sedimentary cover, faults and mineral deposit's locations were obtained from Department for Energy and Mining SA (<https://map.sarig.sa.gov.au/>). 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 provides the equivalent comparison for the southern Olympic Domain, showing the maps of Bouguer gravity, TMI RTP, elevation, sedimentary cover, and MT resistivity depth slices. In contrast to the northern domain, the southern domain does not show the same coherent gravity and magnetic architecture. Local gravity and magnetic highs are present, and several coincide with major structural boundaries, but the potential-field response is more fragmented and cannot be assigned simply to each individual deposit. This is consistent with the more heterogeneous geology of the southern domain, where deposits such as Carrapateena and Oak Dam are significant IOCG systems but are hosted in different structural and lithological settings^{27,28}.

249 The southern resistivity maps fundamentally differ from the northern domain. The shallow
250 resistivity slices at 1-2 km show that much of the southern upper crust is resistive.
251 Conductive features are present locally, but they are more isolated and less clearly linked to
252 the deposits than in the northern domain. At 5-10 km depth, the southern domain is
253 dominated by broader resistive ($>1000 \Omega.m$) regions, and the conductive features are more
254 laterally offset or difficult to trace through the middle crust. Several northeast-southeast-
255 trending resistivity boundaries are visible; these appear to be truncated or disrupted toward
256 the southern domain, but their relationship to the upper-crustal deposits is less apparent
257 than in the northern domain. At 20 km depth, conductive structures appear more clearly in
258 the southern domain, forming broad northeast-southwest trending belts that are locally
259 truncated or segmented by larger structural boundaries. Thus, the southern domain does
260 image deep conductors, but they do not show the same vertically continuous connection to
261 upper-crustal deposits. This suggests that the southern IOCG systems may have been fed by
262 smaller, cooler, less carbon-rich or less well-preserved fluid pathways, or that the relevant
263 pathways are below the resolution of the regional MT model.

264

265



266

267

Figure 4: Maps are arranged from top left to bottom right and show Bouguer gravity,

268

magnetic intensity, elevation, sedimentary-cover thickness, and MT resistivity depth slices at

269

1, 2, 5, 10 and 20 km. Large black circles mark major IOCG deposits and prospects in the

southern Olympic Domain. Small black dots on the elevation map indicate MT sites. Black lines represent Archean to early Mesoproterozoic faults. Areas are shown in UTM 53S projection. Magnetism and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDs) (<https://portal.ga.gov.au/persona/gadds>) and are released under the Creative Commons Attribution 4.0 (CC BY 4.0) licence (<https://www.ga.gov.au/copyright>). Elevation of Proterozoic basement were sourced from Geognostics OZ SEEBASE 2021 (<https://www.geognostics.com/oz-seebase-2021>), also distributed under a CC BY 4.0 licence. Background geology, sedimentary cover, faults and mineral deposit's locations were obtained from Department for Energy and Mining SA (<https://map.sarig.sa.gov.au/>). 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 focuses on Olympic Dam and provides the deposit-scale example of the northern system. The upper panels demonstrate that Olympic Dam is associated with a prominent Bouguer gravity anomaly and a strong TMI anomaly, though the magnetic maximum is spatially offset from the primary gravity response and the known position of the deposit. This offset suggests that the dense haematite and magnetite source regions are distinct, which aligns with the complex nature of the deposit-scale system. This system comprises haematite-rich breccias, magnetite-bearing alteration or lithologies, mafic to ultramafic intrusions, altered Roxby Downs Granite and structurally juxtaposed volcanic-sedimentary units^{2,24,34-36}. The gravity and magnetic anomalies therefore should not be interpreted as direct images of ore alone, but as the integrated response of Fe oxide alteration, brecciation, intrusive components and basement architecture^{12,17,21}.

294

295 The plan-view geology and NW-SE geological section of D-D' line emphasise that Olympic
296 Dam is not a simple vertical pipe, but a structurally complex and multistage breccia-hosted
297 IOCG-U-Au-Ag system^{22-24,36}. Major structures, including the Oreskes, Conor, Jubilee and
298 Woodall fault systems, dissect and reorganise the breccia complex and control the present
299 geometry of lithological contacts, alteration zones and mineralisation^{22,24,36}. The
300 incorporation of quartz-rich sandstone and bedded clastic facies within the breccia complex
301 indicates interaction with basin materials and post-mineral structural reworking, rather than
302 a purely magmatic pipe-like system^{22,24}. In addition, U-Pb and trace-element data from
303 uraninite show that a significant part of the present uranium endowment, including high-
304 grade U zones, was added or upgraded during later hydrothermal events at ca. 0.7-0.5 Ga,
305 long after the initial Mesoproterozoic IOCG mineralisation²³.

306

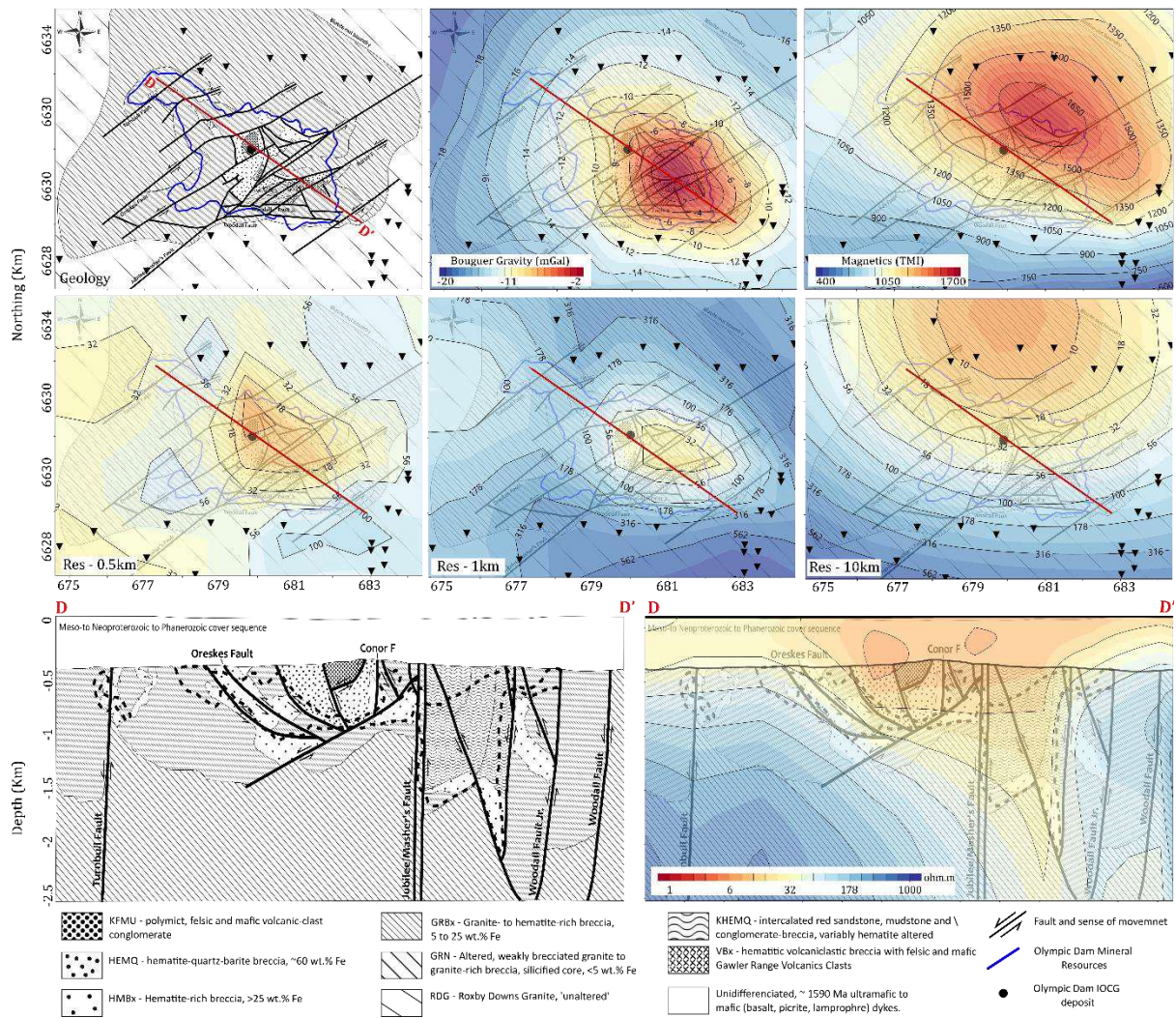


Figure 5: Deposit-scale geological and geophysical framework of Olympic Dam. Upper panels show, from left to right, simplified geology²³, Bouguer gravity, TMI, and MT resistivity slices at 0.5, 1 and 10 km depth. Black triangles indicate MT station locations, and the red line, D-D', marks the position of the geological cross-section through the Olympic Dam Breccia Complex. Areas are shown in UTM 53S projection. Magnetics and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDs) (<https://portal.ga.gov.au/persona/gadds>) and are released under the Creative Commons Attribution 4.0 (CC BY 4.0) licence (<https://www.ga.gov.au/copyright>). Faults and geology are from Ehrig et al., (2021). All figures were produced using Viridien Geotools

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and Inkscape v1.2.1 (<https://inkscape.org>).

The resistivity maps show shallow to upper-crustal conductive responses around Olympic Dam at 0.5-1 km depth, coincident with the breccia complex. At 10 km depth, the conductive anomaly is broader, indicating that the Olympic Dam conductive expression is embedded within a larger crustal-scale electrical architecture rather than being restricted to the deposit envelope. This interpretation is consistent with previous MT and seismic studies that imaged a deep conductive system beneath Olympic Dam and narrow conductive pathways linking lower-crustal conductors to upper-crustal IOCG systems^{11,12,21}, and similarly with the Vulcan deposit 40 km to the northeast¹⁵. Therefore, Figure 5 supports the interpretation that Olympic Dam represents a structurally modified upper-crustal trap developed above or adjacent to deeper conductive corridors, rather than the surface expression of a single simple vertical conductor^{2,8,11,12,17}. In the D–D' resistivity cross-section, the shallow conductive zone is not centred symmetrically beneath the deposit, but appears slightly asymmetric towards the east and is broadly aligned with the Jubilee and Woodall fault corridor. This geometry suggests that the Olympic Dam conductive response is structurally controlled, with the faults likely acting as upper-crustal pathways or boundaries for hydrothermal alteration.

Figure 6 presents a comparison of Bouguer gravity, magnetic intensity, and MT resistivity depth slices for the Acropolis and Vulcan IOCG deposits in the northern Olympic Domain. The potential field responses at Acropolis are larger, but similar in style to those over Olympic Dam, with the Bouguer gravity anomaly being of smaller wavelength centred over

the deposit, and a larger wavelength TMI anomaly towards the northeast. This discrepancy indicates that the dense and magnetic source regions are distinct, which is consistent with the Olympic Dam deposit. In such systems, magnetite-rich alteration, haematite overprints, mafic to intermediate lithologies, and brecciation contribute variably to the gravity and magnetic signatures^{25,26}. At a depth of 2 km, the resistivity map shows localised conductive zones slightly east of Acropolis, and by 10 km depth the resistivity pattern appears broader and more structurally defined, suggesting that the shallow Acropolis features are part of a larger crustal-scale conductive framework.

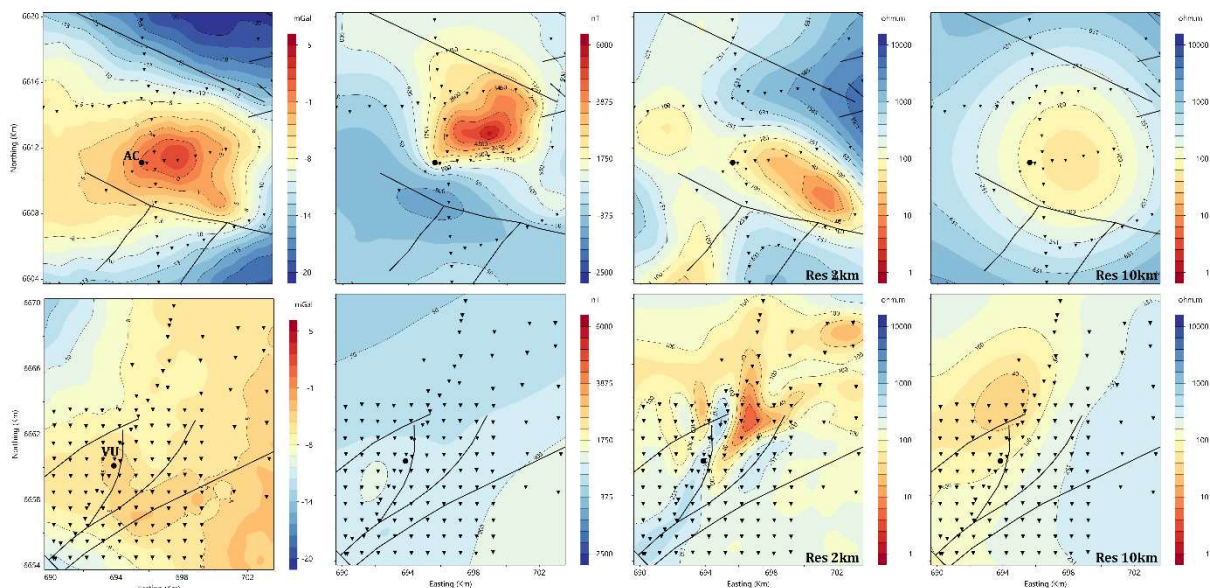


Figure 6: Deposit-scale geophysical and resistivity comparison for Acropolis (AC) and Vulcan (VU). Upper panels show Bouguer gravity, TMI, and the 3D MT model resistivity slices at 2 and 10 km depth for the AC prospect, and similarly in the lower panels for VU. Large black dots mark the main prospect locations, black triangles indicate MT station locations, and black lines represent Archean to early Mesoproterozoic faults. Areas are shown in UTM 53S projection. Magnetics and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDs) (<https://portal.ga.gov.au/persona/gadds>)

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Vulcan also exhibits a distinct geophysical signature but the Bouguer gravity and TMI anomalies are relatively subdued compared to Olympic Dam and Acropolis. The resistivity, at 2 km shows a narrow conductive zone located to the northeast of Vulcan, while at 10 km the response is broader but still identifiable against background. This geometry is consistent with previous deposit-scale geophysical studies indicating that Vulcan, despite being under significant cover of 750 m or more^{14-16,18}. The similarity of resistivity model for Acropolis, Olympic Dam and Vulcan supports the interpretation that the northern Olympic Domain was repeatedly focused by deep fluid flow.

Figure 7 depicts Bouguer gravity, TMI and MT resistivity depth slices for Oak Dam (upper panels) and Carrapateena (lower panels). At Oak Dam and Carrapateena, the Bouguer gravity map identifies a local anomaly near the deposit, though it is spatially restricted and lacks the continuity of gravity belts found in the northern Olympic Domain. The TMI anomalies for Oak Dam displays a compact, high-amplitude anomaly near the deposit, however the significant sedimentary cover (650 m or more) suggests this short-wavelength feature may not represent a genuine basement source, and consequently, it is not treated as primary geological evidence and maybe an artifact. For Carrapateena, the TMI anomaly is

present to the northeast of the deposit, but is of much smaller amplitude compared to the deposits in Figure 6.

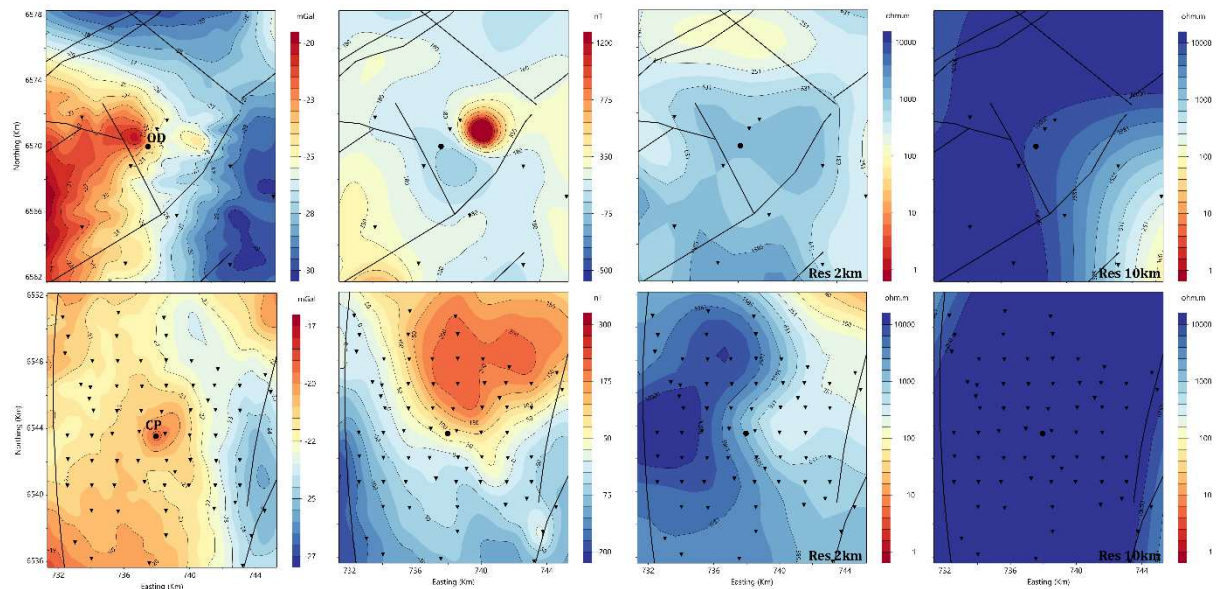


Figure 7: Deposit-scale geophysical and resistivity comparison for OD and CP. Upper panels show Bouguer gravity, magnetic intensity, and MT resistivity slices at 2 and 10 km depth for the OD prospect. Lower panels show the equivalent Bouguer gravity, magnetic intensity, and MT resistivity slices at 2 and 10 km depth for the CP prospect. Large black dots mark the main prospect locations, black triangles indicate MT station locations, and black lines represent Archean to early Mesoproterozoic faults. Areas are shown in UTM 53S projection. Magnetics and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDS) (<https://portal.ga.gov.au/persona/gadds>) and are released under the Creative Commons Attribution 4.0 (CC BY 4.0) licence (<https://www.ga.gov.au/copyright>). faults and mineral deposit's locations were obtained from Department for Energy and Mining SA (<https://map.sarig.sa.gov.au/>). All figures were produced using Viridien Geotools v.4.0.6.12598

398 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) and Inkscape
399 v1.2.1 (<https://inkscape.org>).
400

401 The 2 km resistivity map at Oak Dam reveals a relatively resistive to weakly conductive
402 upper-crustal response surrounding the deposit, while the 10 km slice is dominated by high
403 resistivity. Consequently, despite the local gravity expression and known iron oxide alteration
404 system, Oak Dam does not exhibit the same vertically continuous conductive architecture
405 found in the northern Olympic Dam-AC-VU system. This does not suggest that Oak Dam is
406 less fertile; rather, it indicates that its preserved electrical architecture is distinct, with
407 weaker or less direct connectivity between the upper and middle crust.
408

409 Carrapateena displays a different southern domain expression. Bouguer gravity map show a
410 small, local anomaly near the deposit, while the magnetic response is broader and more
411 diffuse than the compact magnetic feature observed near Oak Dam. Carrapateena is a
412 significant haematite-dominated IOCG system primarily hosted within Donington Suite
413 granite. It records a complex temporal evolution, including major Mesoproterozoic IOCG
414 mineralisation at approximately 1585 Ma and subsequent hydrothermal and uranium-
415 related events at approximately 600–500 Ma²⁷. The 2 km resistivity map around
416 Carrapateena is predominantly resistive, with no clear conductive pipe imaged beneath the
417 deposit. At a depth of 10 km, the area remains dominated by high resistivity, suggesting that
418 the upper- to mid-crustal electrical architecture beneath Carrapateena is less conductive and
419 shows less vertical connectivity than the structures identified beneath the northern Olympic
420 Domain.
421

Oak Dam and Carrapateena demonstrate that the southern Olympic Domain hosts significant IOCG mineralisation, but its geophysical and resistivity characteristics differ from those of the northern domain. Local gravity anomalies and broad magnetic gradients indicate dense or magnetic source bodies and iron oxide alteration, yet MT resistivity data show limited evidence of laterally continuous conductive corridors between the upper and middle crust. This contrast supports the interpretation that southern IOCG systems may be controlled by more localised structural and lithological traps, or that deeper conductive pathways are less preserved, less conductive, or laterally offset from the deposit locations.

Discussion

The most plausible explanation for strong lower-crustal conductivity is the presence of carbon, specifically graphite precipitated from CO₂-rich supercritical fluids¹⁰. These fluids exist under high pressure and temperature, exhibiting liquid-like density and gas-like viscosity, which makes them buoyant and highly mobile. Within deep magmatic-hydrothermal systems, CO₂-rich and H₂O-rich fluids can separate instead of mixing, potentially forming distinct pathways for carbon-rich fluids and hypersaline brines⁴.

This mechanism is consistent with the broader tectonomagmatic setting of the Olympic Domain. The Hiltaba Suite granites, Gawler Range Volcanics and associated IOCG mineralisation have been interpreted to have formed during an extensional to transtensional event, with extension broadly oriented NW-SE^{4,8}. Such an environment would have elevated thermal gradients, thinned the lithosphere and promoted ascent of mantle-derived or lower-crustal melts and volatiles. The yellow markers in Figure 8 show lithosphere-asthenosphere boundary (LAB) depths of 40, 60 and 100 km, illustrating how a shallower

LAB and higher heat flow would shift the crust-mantle system towards conditions favourable for melt and volatile ascent. In addition, CO₂-bearing mantle lithologies have markedly depressed solidi and can generate carbonatitic to carbonated silicate melts at temperatures below those required for volatile-free peridotite melting; these melts and exsolved CO₂-rich fluids provide a plausible mechanism for transferring mantle carbon into the lower crust^{37,38}. Within this framework, a mantle source does not require the carbon to be exclusively primordial. Carbon carried by subducted oceanic crust and sediments is variably returned by arc fluids and magmas or transported into deeper mantle reservoirs³⁹⁻⁴¹. The continental lithosphere can store carbon introduced by carbonate-rich melts and fluids over long timescales and later release it during rifting, lithospheric thinning, heating and decompression^{42,43}. A recent global analysis of carbonatite occurrences supports a two-stage “fertilisation–trigger” architecture, in which ancient subduction modifies the lithospheric mantle and a younger, tectonically distinct event initiates melting⁴⁴. This provides a general mechanism by which recycled mantle carbon may be transferred into the lower crust during later magmatism.

461

Figure 8 provides a pressure-temperature framework for this process. The pressure range of 0-2 GPa corresponds approximately to depths of 0-60 km, whereas the relevant crustal window for the Olympic Domain is approximately 0-50 km. An empirical advective geotherm is used here as a first-order approximation of how hot melts or fluids may cool during ascent^{10,45}. The exact behaviour of melt in the lower crust is uncertain, and we do not assume that melt remains mobile throughout the crust. However, the empirical curve provides a useful conceptual path for advective cooling of hot material rising from the lower crust. During this ascent, CO₂-rich fluids may separate from silicate melt and H₂O-rich or

hypersaline fluids, allowing carbon-rich and brine-rich fluid phases to evolve along partly independent pathways^{4,10}.

The semi-dashed curves in Figure 8 show the proportion of carbon remaining in the fluid, calculated from the GeoFluids model of Zhang and Duan (2010)⁴⁶, following the approach of Murphy et al. (2022)¹⁰. These curves are shown for near-FMQ oxygen fugacity conditions⁴⁷, under which ascending CO₂-rich fluids progressively lose carbon as graphite. The position of the curves is on oxygen fugacity, fluid composition and wall-rock buffering, none of which are independently constrained. Nevertheless, under plausible Olympic Domain thermal conditions, the model predicts that most carbon is exsolved from the fluid at ~ 15 km depth. This depth range matches the observed upper boundary of the deeper conductive zones in the 3D resistivity cross-sections (Figures 3 and 4). Under lower thermal flux, as inferred for parts of the southern Olympic Domain due to the absence of a-type melts, graphite precipitation would be expected to occur somewhat deeper.

It is important to distinguish this deeper graphite-precipitation mechanism from shallower reactions involving Fe-Ti-bearing rocks. In the lower crust, graphite precipitation can occur primarily through cooling and saturation of a CO₂-rich fluid, without requiring a specific wall-rock mineralogy¹⁰. At shallower crustal levels, however, CO₂-rich fluids moving through titanomagnetite-bearing rocks may also precipitate graphite through the oxyexsolution reaction^{10,47}: $6\text{Fe}_2\text{TiO}_4 + \text{CO}_2 = 2\text{Fe}_3\text{O}_4 + 6\text{FeTiO}_3 + \text{C}$. This reaction links CO₂-rich fluids, titanomagnetite-bearing rocks, magnetite, ilmenite and graphite precipitation. It provides one possible explanation for why some conductive pathways in the northern Olympic Domain show a spatial relationship with magnetic anomalies and magnetite-bearing IOCG

alteration. However, the relationship is not expected everywhere, as graphite can precipitate without magnetite production, particularly at deeper crustal levels where the conductivity mechanism is controlled mainly by carbon saturation in the ascending fluid.

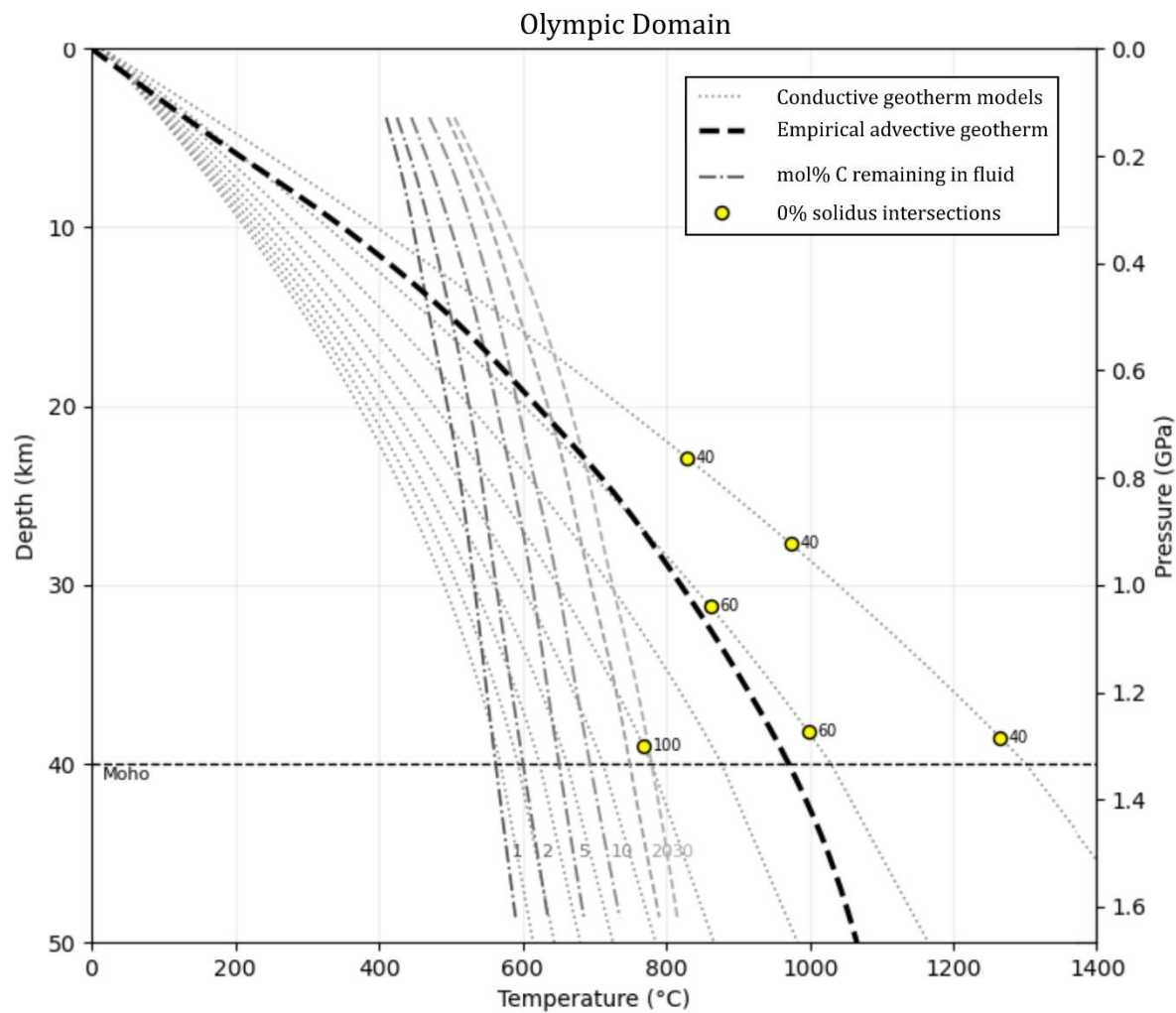


Figure 8: Pressure-temperature framework for CO₂-rich fluid flow and graphite precipitation in the Olympic Domain. Conductive geotherm models⁴⁸ and an empirical advective geotherm are compared with mol% C remaining in fluid curves calculated using the GeoFluids model of Zhang and Duan (2010)⁴⁶, following the approach of Murphy et al. (2022). Yellow markers indicate lithosphere-asthenosphere boundary depths of 40, 60 and

100 km, illustrating elevated thermal gradients expected during extension and Hiltaba-Gawler Range magmatism.

The northern Olympic Domain is interpreted as the region where lower-crustal melting forming Hiltaba Suite magmatism, and CO₂-rich fluid flux were most closely linked to upper-crustal IOCG systems. The presence of Hiltaba Suite rocks and Gawler Range Volcanics indicates that the lower crust reached high temperatures (~1000 C) during the ca. 1.6 Ga magmatic event, sufficient to generate felsic melts and associated volatile fluxes^{2,4,8,21}. These conditions provided a natural source for CO₂-H₂O supercritical fluids.

The A-A' section in Figure 9 images a lower-crustal conductor below 20 km, which is consistent with the model of graphite precipitation¹⁰. This lower-crustal conductor is also spatially coincident with the seismically transparent or weakly reflective lower-crustal zone imaged on the 03GA-OD1 seismic reflection line (Figure 1) beneath Olympic Dam²¹. We argue that the conductor is most likely derived from mantle-sourced CO₂ rich fluids, potentially from a significantly upwelling of carbonatitic melt around the Gawler Craton, potentially from subducted oceanic lithosphere⁴. In the tectonic model proposed here, carbon could have been introduced into the subcontinental lithospheric mantle during earlier subduction-related metasomatism and subsequently remobilised during ca. 1.6 Ga lithospheric destabilisation, mantle melting and Hiltaba Suite–Gawler Range Volcanics magmatism^{8,20,43}. However, MT resistivity constrains the presence and geometry of conductive material rather than its carbon provenance; a mantle contribution is therefore a plausible tectonomagmatic interpretation rather than a unique geophysical solution.

The narrower conductors that span the crust and link the lower crustal region may represent focused CO₂ rich fluids that are evolved from the very hot lower crust. These fluids are being generated at the same time as crustal melts that ascend to form Hiltaba granites. As the model is smooth, the actual pathways may be narrower and more conductive than depicted. Their vertical continuity suggests sustained fluid flow over an extended period rather than a single hydrothermal pulse, consistent with the multistage history of Olympic Dam, including Mesoproterozoic IOCG mineralisation, sedimentary or basinal interaction, and subsequent uranium reactivation²²⁻²⁴.

Acropolis preserves early Fe-rich magnetite ± apatite alteration followed by later Cu-bearing overprinting²⁵, while apatite chemistry at Acropolis and Wirrda Well records evolving fluid conditions²⁶. These deposit-scale observations are compatible with a crustal-scale system in which CO₂-rich deep fluids, hypersaline brines and evolving hydrothermal fluids repeatedly used the same structural architecture.

The northern domain also appears to be structurally bounded. Map and cross-sectional views show that conductive corridors align with major lineaments and structures that may correspond to long-lived faults such as the Elizabeth or Jubilee fault systems. These faults likely functioned as deep permeability zones separating the older Archean basement, the Paleoproterozoic Uyy Wallaroo Group, and Hiltaba-related magmatic domains. The conductors are therefore interpreted as structural fluid pathways controlled by the inherited crustal architecture.

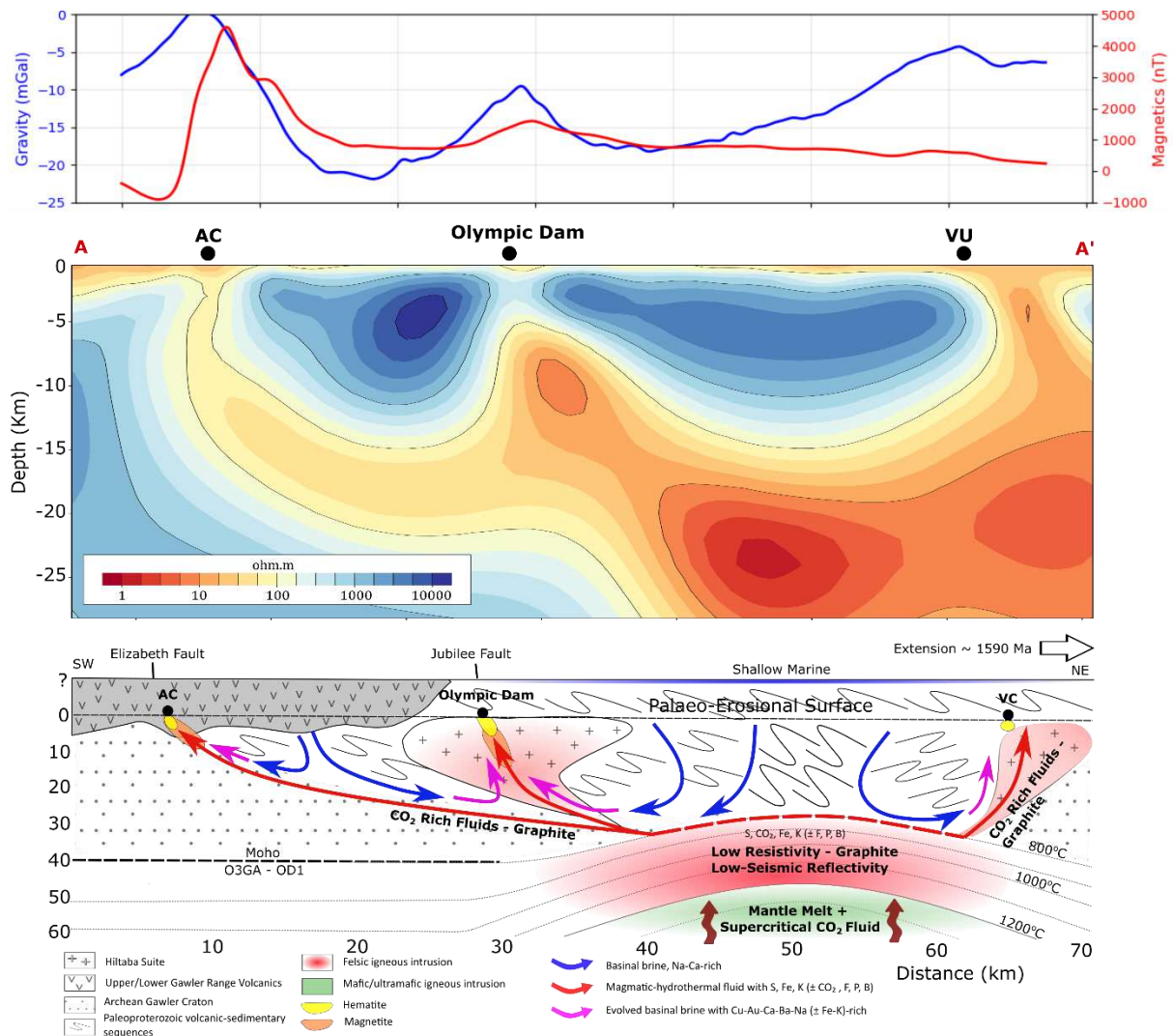


Figure 9: Northern Olympic Domain synthesis section A-A'. The section integrates gravity, magnetic profiles and 3D resistivity cross-section with a geological interpretation through the Olympic Dam-AC-VU corridor. Magnetics and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDS) (<https://portal.ga.gov.au/persona/gadds>) and are released under the Creative Commons Attribution 4.0 (CC BY 4.0) licence (<https://www.ga.gov.au/copyright>). 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>).

The southern Olympic Domain contains deep conductors, but these do not connect to the upper crust in the same way as in the north. The B-B' section in Figure 10 shows a red conductive region in the lower crust, but it does not clearly extend to the surface. This suggests that hot fluids or conductive reaction products were present at depth, but the carbon-rich pathway signature is weaker, smaller, laterally offset or unresolved.

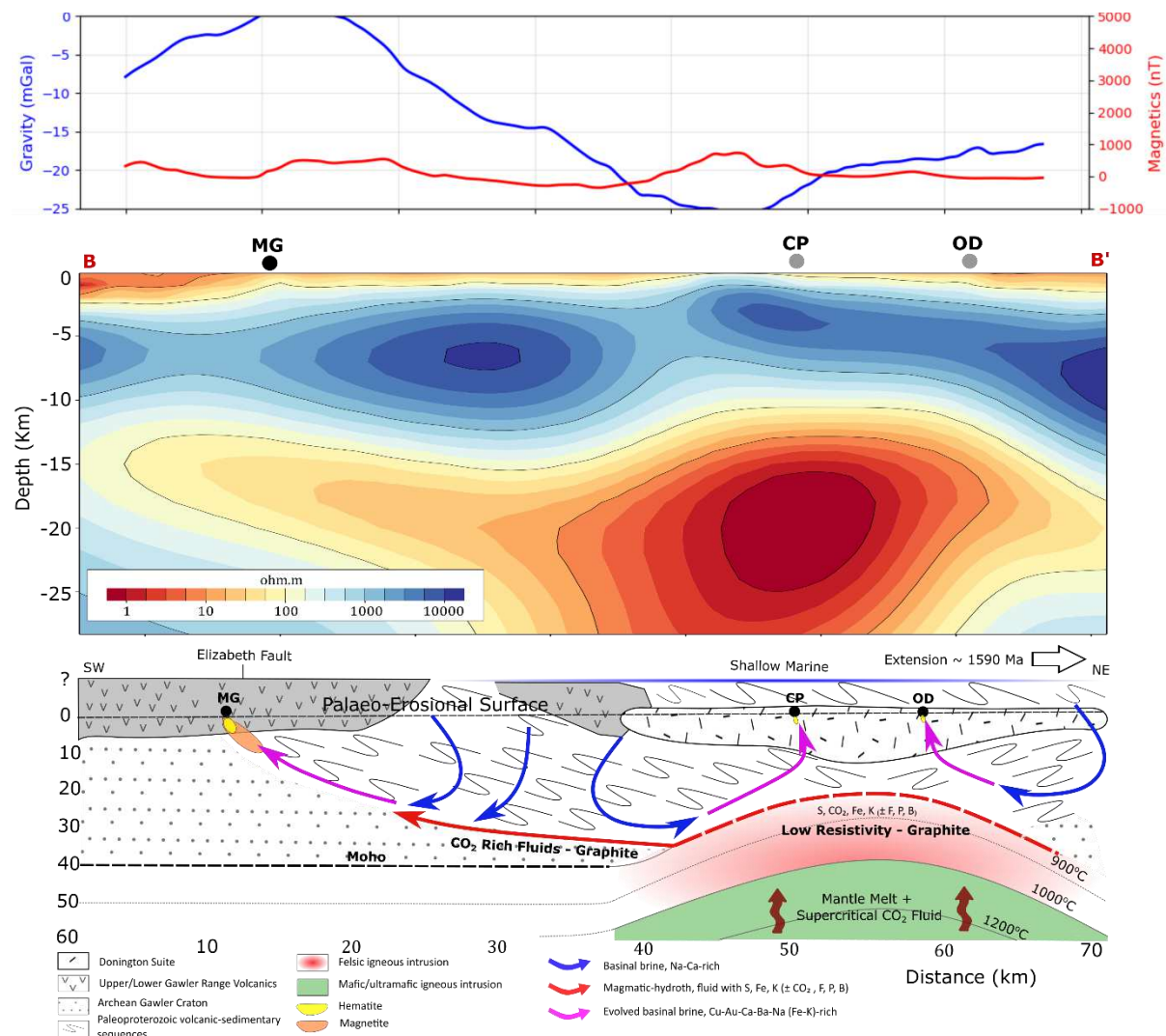


Figure 10: Southern Olympic Domain synthesis section B-B'. The section integrates gravity, magnetic profiles and 3D resistivity cross-section with a geological interpretation through the MG, CP and OD. Magnetics and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDS) (<https://portal.ga.gov.au/persona/gadds>) and are released under the Creative Commons

573 Attribution 4.0 (CC BY 4.0) licence (<https://www.ga.gov.au/copyright>). All figures were
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575 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>) and Inkscape
576 v1.2.1 (<https://inkscape.org>).

577

578 This difference with the northern Olympic Domain may reflect lower crustal temperature,
579 and thus melt volume lower or weaker CO₂ flux. In the south, the geology is dominated by
580 older 1850 Ma Donington Suite rocks in several areas, predating the Hiltaba-Gawler Range
581 Volcanics event by approximately 250 million years^{2,19}. The southern crust may, therefore,
582 have been heated and infiltrated by fluids, but at lower temperatures the same that do not
583 lead to crustal melting. If less melt was generated, then less CO₂-rich supercritical fluid may
584 have been released, producing a weaker carbon/graphite conductivity signature¹⁰.

585

586 Carrapateena and Oak Dam remain significant IOCG systems, but their MT expression differs
587 from Olympic Dam. Carrapateena records major IOCG mineralisation at ca. 1585 Ma and
588 later reactivation at ca. 600-500 Ma²⁷, while Oak Dam East records a complex high-
589 temperature, hypersaline, breccia-hosted Fe oxide Cu-U system²⁸. These deposits show that
590 southern mineralisation was substantial. However, the MT model suggests that the
591 preserved deep-to-shallow carbon-fluid pathway architecture is weaker or more cryptic than
592 in the northern domain.

593

594 A profile orthogonal to the cross sections in Figures 9 and 10 suggests repeated lower-crustal
595 conductors, spaced at ~ 40 km intervals (Figure 11). These conductors are not obvious in
596 gravity or magnetic data, which suggests that they are not simply dense or magnetic bodies.

Instead, they may represent repeated conductive pathways developed along crustal-scale structures. One possible interpretation is that these conductors follow a succession of rifted basins, detachment faults or half-graben margins. In such a setting, extension and heating would generate long-lived crustal permeability pathways, allowing CO₂-rich fluids to rise along deep crustal faults. This interpretation is broadly consistent with models in which Hiltaba Suite and Gawler Range Volcanics magmatism were associated with hot lower crust, extension and large-scale fluid flux^{4,8}. Conductors may therefore represent the electrical expression of repeated deep faults that focused carbon-rich fluids during and after magmatism. This pattern is comparable to the Missouri High-Conductivity Belt in the Midcontinent of North America⁴⁹.

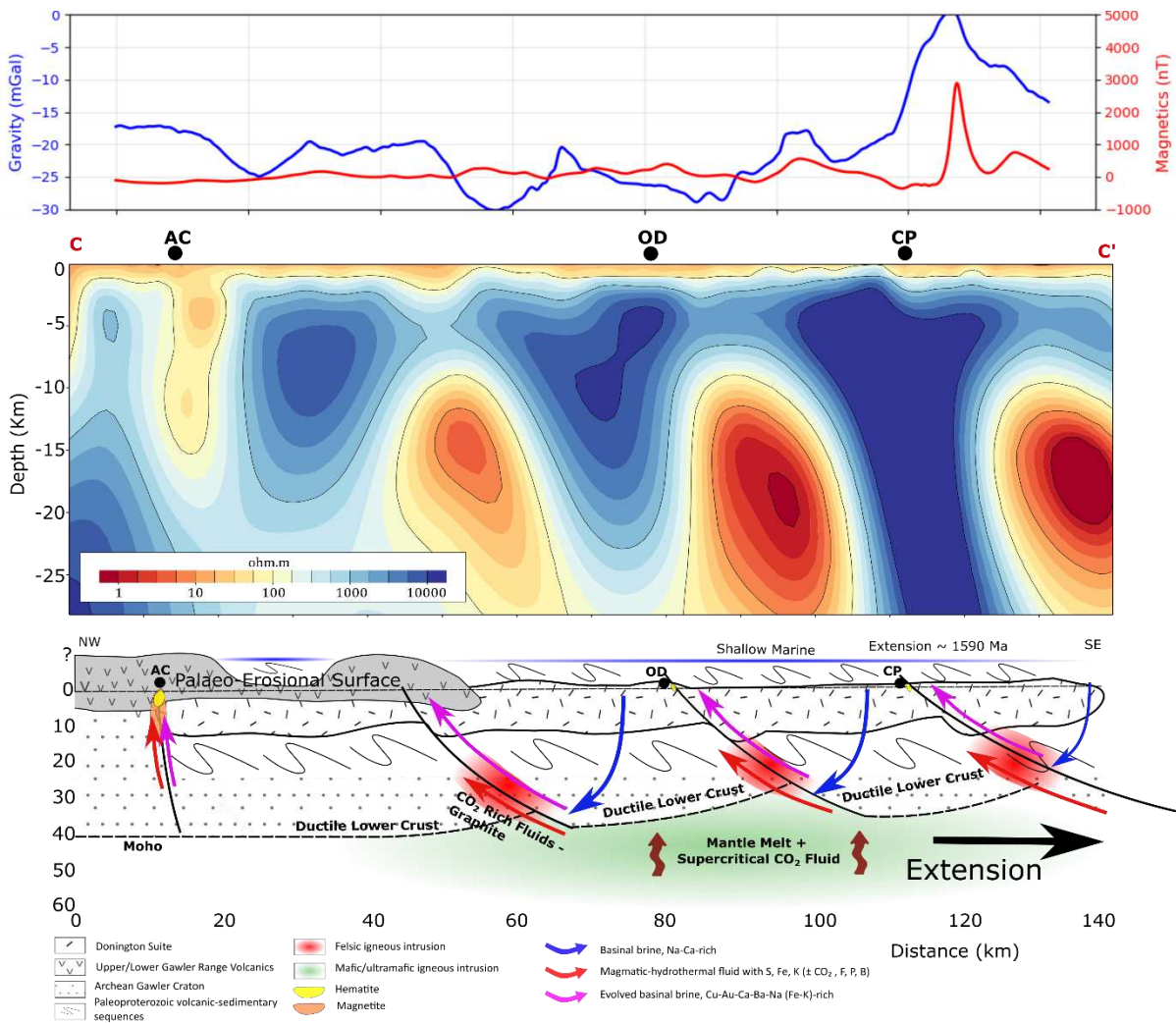


Figure 11: Domain-scale synthesis section C-C'. The section integrates gravity, magnetic profiles and 3D resistivity cross-section with a geological interpretation through the AC, OD, and CARRAPATEENA. Magnetism and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDS) (<https://portal.ga.gov.au/persona/gadds>) and are released under the Creative Commons Attribution 4.0 (CC BY 4.0) licence (<https://www.ga.gov.au/copyright>). 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>).

The MT results support a mineral-system model in which the key exploration criterion is not simply the presence of a lower-crustal conductor, but the geometry of its connection to the upper crust. Deep conductors (> 15 km) may mark carbon-rich roots or reduced reaction zones, but they are only strongly prospective where they connect to upper-crustal structures, with favourable host rocks, Fe oxide alteration systems and fluid-mixing sites. For the northern Olympic Domain, the combination of lower-crustal conductors, vertically extensive conductive pathways, gravity highs, displaced magnetic highs and multistage deposit histories indicates a well-connected mineral-system architecture with high heat flux causing extensive lower crustal melting to form Hiltaba Suite granites. For the southern domain, deep conductors are present but upper-crustal connections are weaker or more cryptic due to lower heat flux.

Conclusion

631 Three-dimensional MT imaging reveals a crustal-scale conductive architecture beneath the
632 Olympic Domain that is segmented between the northern and southern IOCG systems. In
633 the northern domain, lower-crustal conductors extend upward towards Olympic Dam,
634 Acropolis and Vulcan, forming comparatively continuous deep-to-shallow pathways. Their
635 geometry is consistent with focused migration of CO₂-rich supercritical fluids through
636 inherited crustal structures, possible carbon precipitation as graphite, and repeated
637 structural reactivation during mineral-system development. In contrast, although deep
638 conductors are also present in the southern domain, their connections with the upper crust
639 are weaker or more discontinuous. This difference may indicate a smaller or less efficiently
640 connected fluid system, greater modification after mineralisation, or poorer preservation of
641 its original carbon–fluid architecture.

642

643 These findings suggest that the fertility and preservation of IOCG systems beneath cover
644 depend not only on the presence of lower-crustal conductors, but also on their geometry,
645 continuity and structural connection to upper-crustal mineralising environments. MT cannot
646 directly detect copper mineralisation or uniquely determine the composition of a conductor.
647 Nevertheless, it can constrain where deep fluids may have migrated, where carbon may have
648 precipitated as conductive graphite, and where inherited structures repeatedly connected
649 lower-crustal fluid sources with upper-crustal mineral systems. Thus, MT provides a valuable
650 method for mapping the concealed carbon–fluid architecture of IOCG systems. When
651 integrated with gravity, magnetic, geological and seismic constraints, these observations can
652 help distinguish crustal pathways that were favourable for fluid focusing and IOCG formation
653 from conductors with limited upper-crustal connectivity, thereby improving exploration
654 targeting across covered terranes.

655

656 **Methods**

657 A database of over 1,300 broadband sites across the eastern Gawler Craton and Olympic
658 Domain in South Australia was used in this paper as shown in Figure 2, including BHP
659 Olympic Domain survey, a Geological Survey of South Australia/Olympic Domain survey,
660 Adelaide University Olympic Dam profile data¹², Adelaide University Olympic Dam extension
661 data¹¹, and Adelaide University Cariewerloo Basin data. frequency coverage, locally
662 extending from approximately 10^4 Hz to 10^{-4} Hz, although the usable bandwidth varies
663 between surveys and individual sites. The Vulcan broadband MT data were acquired using
664 AuScope and Geological Survey of South Australia LEMI-423 recorders with LEMI-120
665 induction coils, Ag-AgCl electrodes and two orthogonal 50 m electric dipoles, with four
666 components recorded for approximately 48 h at each station and a dedicated remote
667 reference located approximately 8 km north of the survey area. Other Olympic Domain data
668 were collected under contract using Phoenix MTU-5C systems with 50-100 m electric
669 dipoles.

670

671 Three dimensional inversions were carried out using Viridien Geotools software based on
672 the finite-difference forward modelling and a nonlinear conjugate gradient inversion
673 algorithm^{50,51}. The cell size of 1 km $\times$ 1 km, with padding cells that extended 50 km beyond
674 the inner grid in each horizontal direction, with a growth factor of 1.2 between adjacent
675 padding cells. The mesh was not rotated relative to the coordinate system. The model
676 surface was set at 250 m above sea level with no topography, and meshed in 10 m intervals
677 to sea level to accommodate low-resistivity sedimentary sequences. Below sea level the
678 cells sized increased at a rate of 10% to a maximum depth of 100 km. The final mesh

contained 133 cells in the west-east direction, 255 cells in the north-south direction, and 93 cells vertically, giving a total of ~3.15 million cells.

The inversion used 19 periods, spaced evenly at 5 per decade from 0.01 s to 316 s., and error floors were set at 5% on each of the four impedance components. 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 optimal model has $\tau_H = 1$ and $\tau_V = 1$. The final model achieved a root-mean-square (RMS) misfit of 1.342. Near-surface smoothing to a depth of 100 m was included to ensure that modelled resistivities near the surface were reasonably uniform across the mesh, based on the premise that near-surface sedimentary layers are laterally extensive and continuous between sites.

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Author contributions

H. Bizhani undertook modelling, data analysis and wrote the paper. G Heinson compiled the data sets, undertook modelling, wrote the paper and provided project supervision.

Data availability statement

The datasets analysed during the current study are publicly available from the repositories and data portals specified below. Broadband MT data, regional solid geology and faults are available through the South Australian Resources Information Gateway (<https://map.sarig.sa.gov.au/>). Elevation, magnetic and gravity 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>). Sedimentary basin data were sourced from the Geoscience Australia Portal (<https://portal.ga.gov.au/>) and are copyright Commonwealth of Australia (Geoscience Australia) 2018, released under the Creative Commons Attribution 4.0 International License (CC BY 4.0). Figures were generated using Viridien Geotools v.4.0.6.12598; Python v3.12.7 (<https://www.python.org/>), QGIS v3.34.3-Prizren (<https://qgis.org>), and Inkscape V1.2.1 (<https://inkscape.org/cs>).

Code availability statement

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

Additional Information (including a Competing Interests Statement)

The author(s) declare no competing interests.

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Figure legends

Figure 1: Regional geological and geophysical framework of the Olympic Domain, eastern Gawler Craton. Panels show simplified basement geology, Bouguer gravity, total magnetic intensity and sedimentary cover thickness. Black circles mark major IOCG deposits and prospects, including Titan (TI), Vulcan (VU), Olympic Dam, Acropolis (AC), Wirrda Well (WW), Oak Dam (OD), Emmie Bluff (EB), Carrapateena (CP) and Mount Gunson (MG). Red dashed boxes outline the northern and southern Olympic Domain subregions. Red lines (A-A', B-B', and C-C') indicate the main cross-sections used for structural and resistivity comparison. White lines on the sedimentary cover map show seismic traverses OD1 and OD2. Magnetism and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDs) (<https://portal.ga.gov.au/persona/gadds>) and are released under the Creative Commons Attribution 4.0 (CC BY 4.0) licence (<https://www.ga.gov.au/copyright>). Elevation of Proterozoic basement were sourced from Geognostics OZ SEEBASE 2021 (<https://www.geognostics.com/oz-seebase-2021>), also distributed under a CC BY 4.0 licence. Background geology, sedimentary cover, faults and mineral deposit's locations were obtained from Department for Energy and Mining SA (<https://map.sarig.sa.gov.au/>). 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>).

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913 Figure 2: Maps show phase-invariant responses at 0.02 s, 0.2 s, 2 s, 20 s and 200 s across the
914 Olympic Domain. Large black circles mark major IOCG deposits and prospects identified in
915 Figure 1. Black lines denote Archean to early Mesoproterozoic faults; green lines denote
916 Mesoproterozoic faults and blue outlines indicate salt lakes. In the 200 s panel, small black
917 dots indicate MT station locations. Areas are shown in UTM 53S projection. Faults and
918 mineral deposit's locations were obtained from Department for Energy and Mining SA
919 (<https://map.sarig.sa.gov.au/>). All figures were produced using Viridien Geotools
920 v.4.0.6.12598 (<https://www.viridiengroup.com/expertise/multiphysics-imaging/geotools>)
921 and Inkscape v1.2.1 (<https://inkscape.org>).

922 Figure 3: Maps are arranged from top left to bottom right and show Bouguer gravity,
923 magnetic intensity, elevation, sedimentary-cover thickness, and MT resistivity depth slices at
924 1, 2, 5, 10 and 20 km. Large black circles mark major IOCG deposits and prospects in the
925 northern Olympic Domain. Small black dots on the elevation map indicate MT sites. Black
926 lines represent Archean to early Mesoproterozoic faults. Areas are shown in UTM 53S
927 projection. Magnetics and gravity datasets were obtained from Geoscience Australia's
928 Geophysical Archive Data Delivery System (GADDs) (<https://portal.ga.gov.au/persona/gadds>)
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Figure 4: Maps are arranged from top left to bottom right and show Bouguer gravity, magnetic intensity, elevation, sedimentary-cover thickness, and MT resistivity depth slices at 1, 2, 5, 10 and 20 km. Large black circles mark major IOCG deposits and prospects in the southern Olympic Domain. Small black dots on the elevation map indicate MT sites. Black lines represent Archean to early Mesoproterozoic faults. Areas are shown in UTM 53S projection. Magnetics and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDs) (<https://portal.ga.gov.au/persona/gadds>) and are released under the Creative Commons Attribution 4.0 (CC BY 4.0) licence (<https://www.ga.gov.au/copyright>). Elevation of Proterozoic basement were sourced from Geognostics OZ SEEBASE 2021 (<https://www.geognostics.com/oz-seebase-2021>), also distributed under a CC BY 4.0 licence. Background geology, sedimentary cover, faults and mineral deposit's locations were obtained from Department for Energy and Mining SA (<https://map.sarig.sa.gov.au/>). 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: Deposit-scale geological and geophysical framework of Olympic Dam. Upper panels show, from left to right, simplified geology (after Ehrig et al., 2021), Bouguer gravity, magnetic intensity, and MT resistivity slices at 0.5, 1 and 10 km depth. Black triangles indicate MT station locations, and the red line, D-D', marks the position of the geological cross-section through the Olympic Dam Breccia Complex. Areas are shown in UTM 53S

projection. Magnetism and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDS) (<https://portal.ga.gov.au/persona/gadds>) and are released under the Creative Commons Attribution 4.0 (CC BY 4.0) licence (<https://www.ga.gov.au/copyright>). Faults and geology are from Ehrig et al., (2021). 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: Deposit-scale geophysical and resistivity comparison for AC and VU. Upper panels show Bouguer gravity, magnetic intensity, and MT resistivity slices at 2 and 10 km depth for the AC prospect. Lower panels show the equivalent Bouguer gravity, magnetic intensity, and MT resistivity slices at 2 and 10 km depth for the VU prospect. Large black dots mark the main prospect locations, black triangles indicate MT station locations, and black lines represent Archean to early Mesoproterozoic faults. Areas are shown in UTM 53S projection. Magnetism and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDS) (<https://portal.ga.gov.au/persona/gadds>) and are released under the Creative Commons Attribution 4.0 (CC BY 4.0) licence (<https://www.ga.gov.au/copyright>). Faults and mineral deposit's locations were obtained from Department for Energy and Mining SA (<https://map.sarig.sa.gov.au/>). 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: Deposit-scale geophysical and resistivity comparison for Oak Dam and Carrapateena. Upper panels show Bouguer gravity, magnetic intensity, and MT resistivity slices at 2 and 10 km depth for the Oak Dam prospect. Lower panels show the equivalent Bouguer gravity, magnetic intensity, and MT resistivity slices at 2 and 10 km depth for the CP prospect. Large black dots mark the main prospect locations, black triangles indicate MT station locations, and black lines represent Archean to early Mesoproterozoic faults. Areas are shown in UTM 53S projection. Magnetism and gravity datasets were obtained from Geoscience Australia's Geophysical Archive Data Delivery System (GADDS) (<https://portal.ga.gov.au/persona/gadds>) and are released under the Creative Commons Attribution 4.0 (CC BY 4.0) licence (<https://www.ga.gov.au/copyright>). Faults and mineral deposit's locations were obtained from Department for Energy and Mining SA (<https://map.sarig.sa.gov.au/>). 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 8: Pressure-temperature framework for CO₂-rich fluid flow and graphite precipitation in the Olympic Domain. Conductive geotherm models⁴⁸ and an empirical advective geotherm are compared with mol% C remaining in fluid curves calculated using the GeoFluids model of Zhang and Duan (2010)⁴⁶, following the approach of Murphy et al. (2022). Yellow markers indicate lithosphere-asthenosphere boundary depths of 40, 60 and 100 km, illustrating elevated thermal gradients expected during extension and Hiltaba-Gawler Range magmatism.

1005 Figure 9: Northern Olympic Domain synthesis section A-A'. The section integrates gravity,
1006 magnetic profiles and 3D resistivity cross-section with a geological interpretation through
1007 the Olympic Dam-AC-VU corridor. Magnetism and gravity datasets were obtained from
1008 Geoscience Australia's Geophysical Archive Data Delivery System (GADDS)
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1013 v1.2.1 (<https://inkscape.org>).

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1015 Figure 10: Southern Olympic Domain synthesis section B-B'. The section integrates gravity,
1016 magnetic profiles and 3D resistivity cross-section with a geological interpretation through
1017 the MG, CP and OD. Magnetism and gravity datasets were obtained from Geoscience
1018 Australia's Geophysical Archive Data Delivery System (GADDS)
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1023 v1.2.1 (<https://inkscape.org>).

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1025 Figure 11: Domain-scale synthesis section C-C'. The section integrates gravity, magnetic
1026 profiles and 3D resistivity cross-section with a geological interpretation through the AC, OD,
1027 and CP. Magnetism and gravity datasets were obtained from Geoscience Australia's
1028 Geophysical Archive Data Delivery System (GADDS) (<https://portal.ga.gov.au/persona/gadds>)

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