

An embayment in the East Antarctic basement constrains the shape of the Rodinian continental margin

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East Antarctic provinces lay at the heart of both Rodinian and Gondwanan supercontinents, yet poor exposure and limited geophysical data provide few constraints on the region's tectonic evolution. The shape of the Mawson Continent, the stable nucleus of East Antarctica, is one of Antarctica's most important, but contested features, with implications for global plate reconstructions and local tectonic models. Here we show a major marginal embayment 500–700 km wide, cuts into the East Antarctic basement in the South Pole region. This embayment, defined by new aeromagnetic and other geophysical data, truncates the Mawson Continent, which is distinct from basement provinces flanking the Weddell Sea. We favour a late Neoproterozoic rifting model for embayment formation and discuss analogies with other continental margins. The embayment and associated basement provinces help define the East Antarctic nucleus for supercontinental reconstructions, while the inherited marginal geometry likely influenced evolution of the paleo-Pacific margin of Gondwana.

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East Antarctica remains the least known continent on Earth due to its remote location and extensive blanketing ice sheet. Its coastal rocks preserve critical but cryptic records of Earth's evolution from Archean times. While we know that parts of East Antarctica were involved in assembly and breakup of major supercontinents including Nuna, Rodinia and Gondwana, the details of East Antarctica's internal tectonic structure remain poorly understood^{1,2}.

The Archean and Paleoproterozoic history of the Mawson Continent^{3,4} (Fig. 1a) is best recorded in Terre Adélie and the Central Transantarctic Mountains (CTAM) of East Antarctica and in Australia. This continent developed around a >1700 Ma nucleus known as the Mawson Craton (Fig. 1a), which included the Australian Gawler Craton^{2,3,5}. Incorporation of the Australian Coompana Province and Albany-Fraser Orogen, and their Antarctic extensions, between 1500 and 1140 Ma formed the wider Mawson Continent. One margin of the Mawson Continent was subsequently affected by continental collision along the Australo-Antarctica/Indo-Antarctica suture and the East African Antarctic Orogen (EAAO) during the final assembly of Gondwana^{2,5–8}. In contrast the paleo-Pacific (Transantarctic Mountains) side of the Mawson Continent was flanked by a late Neoproterozoic rifted margin, formed during Rodinia breakup^{9,10}. This rifted margin

was overprinted by the Ross Orogen and associated magmatic arc, caused by subduction of paleo-Pacific oceanic lithosphere from ~580 to ~460 Ma^{11–13}. In our study area a distinct Queen Maud Terrane (QMT) with more abundant volcanic rocks^{14,15} and younger Sm/Nd mantle extraction ages (1100–1500 Ma) in Ross age granites¹⁶ compared to the CTAM has been noted (Fig. 1b). Geological and provenance studies show the QMT developed as part of the Ross Orogen on the margin of East Antarctica^{11,15}.

The first-order similarity in age between Archean and Paleoproterozoic rocks exposed in the CTAM¹⁷ and the Southern Terrane of the Shackleton Range¹⁸ (Fig. 1b) suggest that the Mawson Continent may extend through the South Pole study region. If true, a simple continuation of the linear craton margin imaged for ~2000 km from Terre Adélie to the CTAM by aeromagnetic and satellite magnetic compilations¹⁹ might be expected. In detail, aeromagnetic and provenance data in the CTAM region suggest the presence of an in-board highly magnetic but unexposed Paleo to Mesoproterozoic subglacial igneous province²⁰. This is flanked by exposed weakly magnetised Archean and Paleoproterozoic basement and rift margin sequences, both reworked by the Ross Orogen²⁰. Close to South Pole a prominent magnetic lineament was previously interpreted as the edge of the East Antarctic craton, or a younger structure,

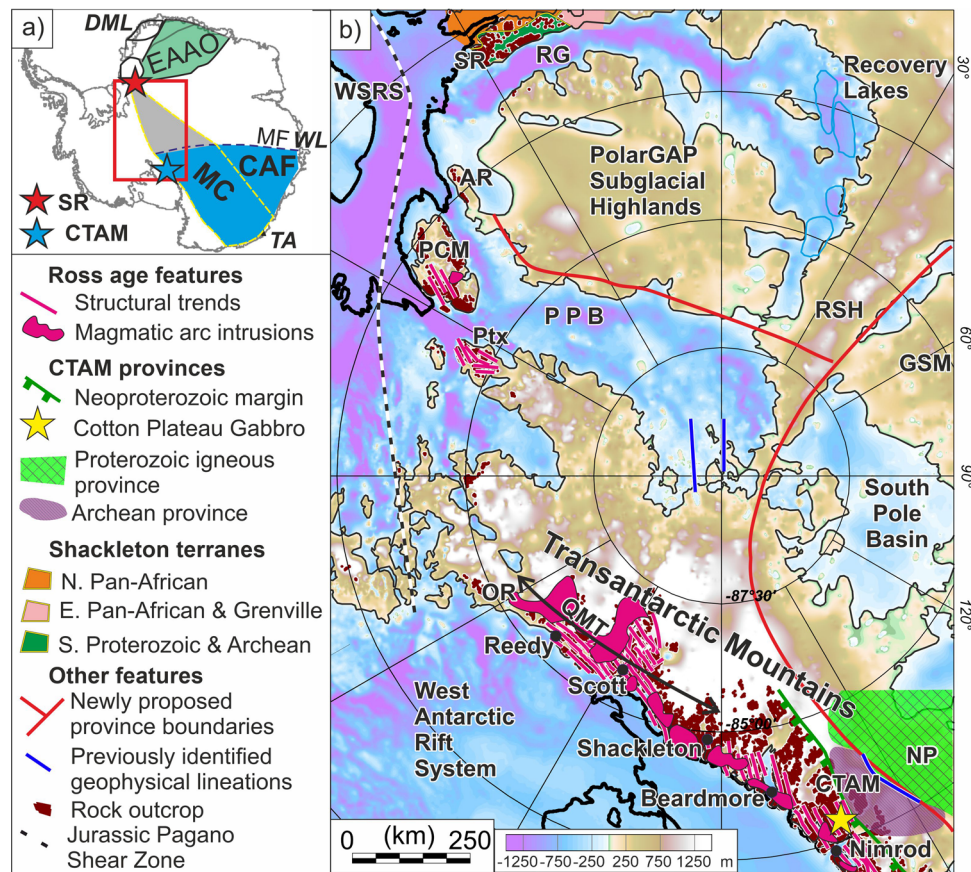


Fig. 1 Geological setting of the study area. **a** Study area (red box) in its Antarctic context. The Mawson Continent includes the >1700 Ma Mawson Craton (MC) and ~1500–1140 Ma continuations of the Australian Coompana Province and Albany-Fraser Orogen (CAF). Note alternative models for the Mawson Continent, either extending from Terre Adélie (TA) to the Shackleton Range (SR)² grey, or being truncated close to the Central Transantarctic Mountains (CTAM)^{5,7} blue. The edge of the Mawson Continent is identified in Wilkes Land (WL) and interpreted to follow the Mirny Fault (MF)⁷. The East African Antarctic Orogeny (EAAO) shown in green in Dronning Maud Land (DML) places an additional limit on the extent of the Mawson Continent⁸. **b** Study area with geology and subglacial topography⁴⁸. Note unexposed Nimrod Igneous Province (NP), and exposed but reworked Archean and Paleoproterozoic province in the CTAM^{20,25}. Key glaciers dissecting the Transantarctic Mountains are named. Ross-age structural trends from mapped exposures^{49–51}. Additional abbreviations from north to south are: Recovery Glacier (RG), Weddell Sea Rift System (WSRS), Argentina Range (AR), Pensacola Mountains (PCM), Recovery Subglacial Highlands (RSH), Pensacola-Pole Basin (PPB), Patuxent Mountains (Ptx), Gamburtsev Subglacial Mountains (GSM), Ohio Range (OR) and Queen Maud Terrane (QMT) (black arrow)^{15,16}.

such as an intracontinental transform exploiting this inherited boundary (Fig. 1b)²¹. However, the paucity of data coverage prevented linkage of this anomaly with exposures of the late Neoproterozoic rifted margin rocks in the CTAM²⁰ including the ~670 Ma Cotton Plateau gabbro (Fig. 1b)¹⁰.

Here we present new aerogeophysical imaging over the South Pole region (see Supplementary Notes S1, S2, Fig. 2, and Supplementary Fig. 1) filling a critical gap in geophysical data coverage in East Antarctica. Our geophysical interpretation helps constrain the extent of the margin of the Mawson Continent, and

leads us to hypothesise that a major embayment formed during late Neoproterozoic rifting along the craton margin. Our study has important implications for understanding of both Rodinia and Gondwana-related tectonic processes in this part of East Antarctica.

Results

Geophysical characterisation of subglacial provinces. Our interpretation is based on the identification of distinct

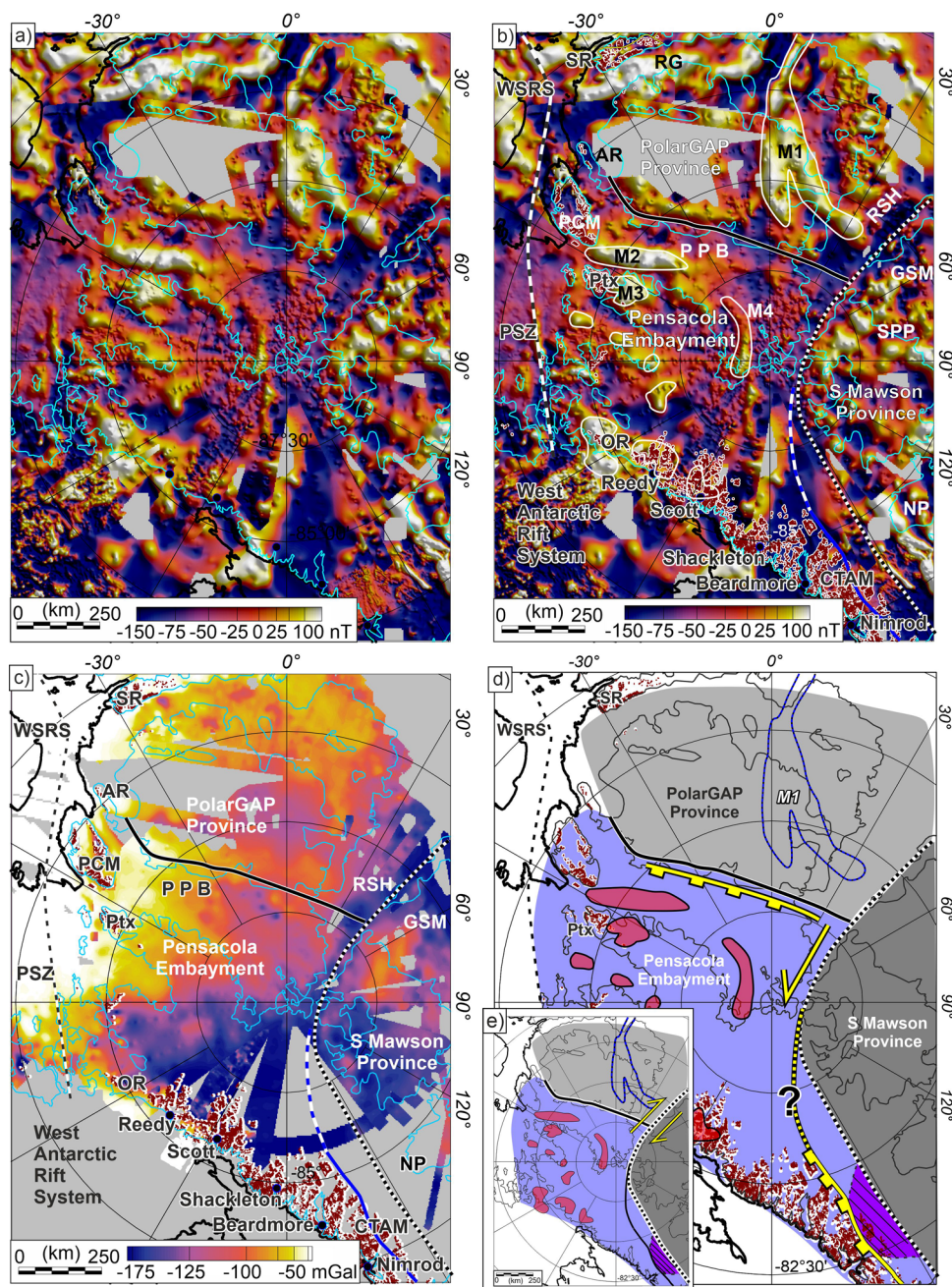


Fig. 2 Geophysical compilation and interpretation. **a** Magnetic anomaly map. Thin blue line is zero m elevation contour from Fig. 1b. **b** Annotated aeromagnetic anomaly map. Dotted black line marks edge of Southern Mawson Province. Solid black line separates Pensacola Embayment and PolarGAP Provinces. Blue line in CTAM marks exposed (solid) and inferred (dashed) edge of Archean rocks²⁰. White outlines mark anomalies discussed in the text. Other features as in Fig. 1b. **c** Bouguer gravity anomaly map. **d** Preferred interpretive sketch. Basement provinces in grey and Pensacola Embayment in purple. Red bodies interpreted Ross intrusions. Yellow lines and arrows indicate Neoproterozoic rift margin segments and linking transfer fault. Note geometry of junction between CTAM rifted margin and proposed transfer fault (?) is unconstrained. **e** Alternative dextral model for formation of the Pensacola Embayment.

geophysically defined crustal provinces (Figs. 1b and 2). Province boundaries are identified by coincident linear magnetic and topographic features, separating areas with generally internally consistent magnetic and topographic character. Linear topographic features likely reflect differential erosion of contrasting lithologies and/or uplift across geological boundaries. Magnetic anomalies sharing a trend with the topography, or being truncated at a topographic feature, support the inference that the topographic feature is a geological boundary, rather than a purely erosive feature. Crustal thickness and lithospheric mantle structure from gravity and seismic data provide additional information about the provinces.

The first province, we term the Southern Mawson Province, is bounded by the eastern edge of the ~650 km long Recovery Subglacial Highlands and an associated linear negative magnetic anomaly (Figs. 1b and 2). Internally this province is characterised by the low-lying South Pole Basin, but includes the foothills of the Gamburtsev Subglacial Mountains and Transantarctic Mountains (Fig. 1b). Magnetic anomalies with amplitudes of up to 400 nT and wavelengths of 30–50 km typify this region (Fig. 2a), which includes the previously defined highly magnetic South Pole Province²² and Nimrod igneous province towards the CTAM²⁰. Bouguer gravity anomalies show a broad low over this province (Fig. 2c), indicative of generally thicker crust. This is supported by seismic data which indicate the crust of the Southern Mawson Province is 41–48 km thick (Supplementary Fig. 2d)²³. The underlying lithosphere also has the most elevated seismic velocities in the study area, at depths of 75–150 km (Supplementary Fig. 2a, c)²³.

The second province we term the PolarGAP Province includes the PolarGAP Subglacial Highlands and parts of the Recovery Subglacial Highlands (Fig. 1b). This region includes a ~700 km long and ~200 nT amplitude bifurcating anomaly (M1) (Fig. 2a, b). The eastern branch of M1 traverses the Recovery Subglacial Highlands, before terminating against the Southern Mawson Province. The M1 western branch terminates at the margin of the Pensacola-Pole Basin. The PolarGAP Province is more sparsely covered by aerogeophysical data, but its southern boundary is marked by a linear positive magnetic anomaly flanking the Pensacola-Pole Basin, which contains a 1–3 km-thick fault-bounded sedimentary basin²⁴. The northern edge of the PolarGAP Province is marked by a ~50 km wide and 300 km long 300 nT magnetic anomaly beneath and south of the Recovery Glacier. Bouguer gravity anomalies show more positive values than in the Southern Mawson Province (Fig. 2c), suggesting either thinner crust, or more likely denser crust given that seismic models suggest crust of approximately equivalent thickness (SFig. 2d)²³. Seismic models indicate elevated lithospheric velocities generally occur at depths of 50–75 km in the PolarGAP Province (Supplementary Fig. 2b, c)²³.

The Pensacola Embayment, the final province we identify, extends approximately from South Pole to the West Antarctic margin (Figs. 1b and 2). The boundary with the Southern Mawson Province follows the eastern edge of the Recovery Subglacial Highlands and associated negative magnetic anomaly. The path of this boundary is not constrained towards the Transantarctic Mountains, but a connection with the boundary between the highly magnetic inferred Nimrod igneous province and reworked weakly magnetic margin observed in the CTAM²⁰ is likely. The boundary with the PolarGAP Province is noted above. The Pensacola Embayment is characterised by a regional magnetic low, and includes both the low-lying Pensacola-Pole Basin and uplifted QMT sector of the Transantarctic Mountains. The regional magnetic low is punctuated by 100–250 nT anomalies M2–M4 and by similar amplitude anomalies in the Scott and Reedy Glacier areas. Anomalies of up to 500 nT are

seen in the Ohio Range. Bouguer gravity anomalies of –50 to –200 mGal with wavelengths of >100 km are indicative of variation in crustal thickness on the order of 5 km across the embayment. Seismic models suggest the Pensacola Embayment includes the thinnest East Antarctic crust in our study area (~39 km), although crust up to 47 km is seen beneath the Transantarctic Mountains (SFig. 2d)²³. Seismic models show slower seismic velocities in the lithospheric mantle in this province compared to either the Southern Mawson or PolarGAP Provinces (Supplementary Fig. 2a, b)²³.

Interpretation of basement provinces. The geophysical characterisation outlined above defines province geometry, but not age, or magnetic anomaly sources. The most robust constraining information would be from associated basement outcrops, but these are lacking. Glacially transported sediments can provide evidence for subglacial basement age and type, but are less definitive, as transport distance, recycling and differential erosion of basement rocks make the interpretation less unique. The similarity, or contrast, of geophysical signatures can be used as circumstantial evidence for the age and origin of subglacial geology, either supporting other data, or as the foundation for new hypotheses.

Our interpretation of the Southern Mawson Province follows previous authors in suggesting that the Mawson Craton underlies this area (Figs. 1 and 2)^{2,5}. The high amplitude aeromagnetic anomalies have previously been attributed to a largely unworked Paleo to Mesoproterozoic igneous province²⁰. Subglacially derived samples of ~1850 Ma igneous rocks with high measured magnetic susceptibility from the CTAM are consistent with this interpretation²⁵. The craton-like mantle suggested by magnetotelluric models²⁶ and relatively thick seismically fast lithospheric mantle²³ are also consistent with a cratonic interpretation.

Our magnetic compilation shows the relatively uniform and unbroken magnetic signature of the Mawson Continent margin seen extending ~2000 km from Terre Adélie to the CTAM^{20,27} terminates at the Recovery Subglacial Highlands (Figs. 2a and 3). The PolarGAP province therefore lies outside the structurally continuous Mawson Continent and may represent either a displaced fragment of the Mawson Continent, or a distinct geological province. Within the PolarGAP Province the source of anomaly M1 is unknown, but it is similar in aspect and amplitude to elongate anomalies seen in the Antarctic and South African Namaqua-Natal Belt (Fig. 3), which formed by accretion of island arc terrains to the southern edge of the Grunahogna/Kalahari Craton^{28–30}. Similar curvilinear anomalies surround the cryptic Valkyrie Craton^{8,27} (Fig. 3). The similarity of anomalies lead us to hypothesise that the source for anomaly M1 is a magmatic arc which developed, or accreted against the edge of a local cratonic block, or the Mawson Continent. We do not know the age of the arc, but speculate that if it developed against the Mawson Continent and prior to the formation of the Pensacola Embayment (see below) it is Late Meso to Early Neoproterozoic in age. An alternative hypothesis is that anomaly M1 is a displaced ribbon of the highly magnetic basement seen the CTAM region²⁰. These alternative hypotheses could be tested by direct sampling and dating of the PolarGAP Province basement. Alternatively analysis of detrital zircons, for example from blue ice regions adjacent to the Recovery Glacier ~350 km downstream of anomaly M1, could help to constrain both the basement age and juvenile, or craton marginal setting of any arc derived rocks. This test would be most robust if a proximal source could be supported by identification and analysis of large basement clasts, rather than potentially recycled or far transported individual zircons.

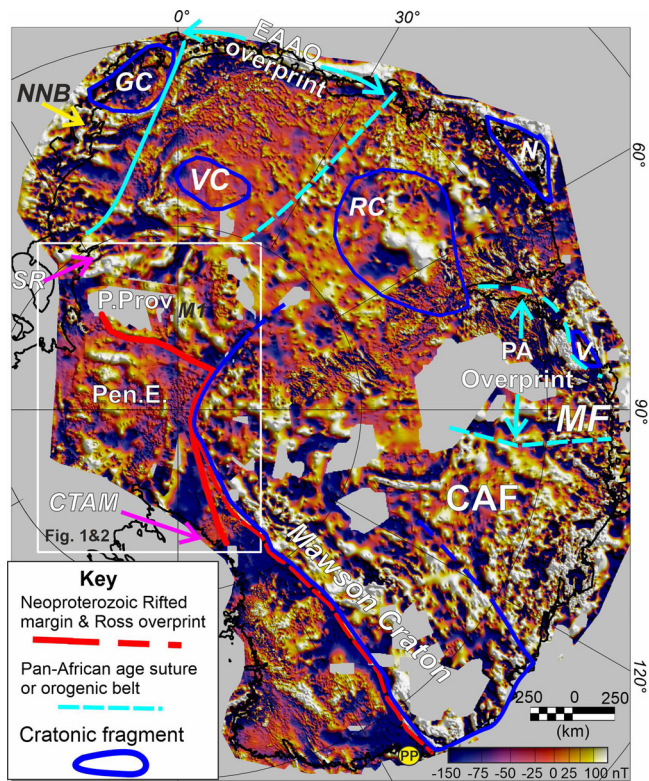


Fig. 3 Province boundaries in a wider East Antarctic context. Province boundaries overlain on East Antarctic aeromagnetic compilation from this study and ADMAP2²⁷. The Mawson Continent includes the Mawson Craton, and continuations of the Australian Coompana/Albany-Fraser provinces (CAF). It is bounded by the Mirny Fault (MF)⁷ and associated zone of Pan African age overprint (PA)^{52,53}, the PolarGAP Province (P. Prov), and the Pensacola Embayment (Pen. E). Other cratons⁵⁴ include; Grunehogna (GC), Rucker (RC), Napier Complex (N), Valkyrie (VC), and Vestfold Hills (V). Smaller Archean provinces are not shown. Note Namaqua Natal Belt (NNB) formed by accretion of island arc terrains against the Grunehogna Craton, prior to collision between African-Antarctic provinces with the wider East Antarctic continent along the broad East African Antarctic Orogeny (EAAO)⁸. Yellow circle (PP) marks Ross age granites exposed at Penguin Point defining the inboard extent of the >500 km wide Ross Orogen³⁶.

The Pensacola Embayment. The generally weakly magnetic background field in the Pensacola Embayment is interpreted as a ~700 km wide region where the Southern Mawson and PolarGAP Province magnetic basement is either missing, or extensively reworked. In the CTAM the Neoproterozoic rifted margin and a ~60 km wide zone of basement reworked by the Ross Orogen, show a similar quiet background magnetic field²⁰. On a regional scale, the boundary of the highly magnetic interior provinces is also taken to mark the craton margin (Fig. 3)^{20,31}. In the Pensacola Embayment thinner crust interpreted from seismic and gravity studies^{23,32}, generally slower seismic velocities in the lithospheric mantle (Supplementary Fig. 2)²³, and warmer mantle interpreted from magnetotelluric studies at South Pole³³ are all consistent with reworked or younger lithosphere in this region. Sm/Nd mantle extraction ages of ~1300 Ma from the Pensacola Mountains³⁴ and between 1100 and 1400 Ma in the QMT¹⁶, support the presence of a distinct region of younger lithosphere, rather than Ross-age reworking of the Mawson Continent, which produced Ross age granites with mantle extraction ages of >1500 Ma seen in the CTAM and further north¹⁶.

Although the Pensacola Embayment shows a weakly magnetic background field, it is punctuated by a number of distinct local magnetic anomalies with amplitudes >100 nT. The source for subglacial anomalies M2–M4 is unknown, although M4 was previously linked to the cratonic margin²¹. Our new compilation shows M4 lies outside the interpreted cratonic Southern Mawson Province, suggesting an alternative interpretation may be possible. In the Pensacola Mountains the tip of anomaly M2 is close to a Ross age caldera most likely associated with the inboard edge of a magmatic arc¹³, and granitic clasts in tills downstream and flanking the glacier flowing over anomaly M2 are dated to 510 Ma³⁵. In the QMT area of the Pensacola Embayment magnetic anomalies with similar amplitude and wavelength to anomalies M2–M4 overlie exposed Ross-age granites²¹ (Supplementary Fig. 3). Susceptibility data from the Ohio State Polar Rock Repository (Supplementary Fig. 4) show that these granites, and others in the QMT sector of the Transantarctic Mountains, often have susceptibilities an order of magnitude higher than seen in the adjacent CTAM. We therefore consider Ross age granites as a plausible source for the Pensacola Embayment magnetic anomalies. However, this cannot be considered definitive without direct sampling. Our interpretation implies the Ross Orogen impacted a region 500–700 km wide, similar to the width of the orogeny along the Terre Adélie coast where Ross age intrusions are exposed in close proximity to the Mawson Craton³⁶ and ~500 km inboard from the Transantarctic Mountains (Fig. 3).

Discussion

A Rodinian rifted margin model for Pensacola Embayment.

One mechanism for creating an embayment in the East Antarctic basement could be distributed extension associated with rifting, potentially leading to removal of a micro-continental block (Fig. 2d). Even without the removal of a crustal block, along strike changes in rift geometry from upper plate to lower plate across transfer faults during asymmetric rifting can lead to the formation of marginal embayments³⁷. The age of this proposed rifting event is unknown, but Neoproterozoic sequences associated with the paleo-Pacific rifted margin of Rodinia are exposed both in the CTAM¹⁰ (Fig. 1b) and further east in Australia³⁸. The regional magnetic low over the Pensacola Embayment could then represent the signature of a cryptic late Neoproterozoic rifted margin of Rodinia, buried beneath Ross-age and younger sediments²⁴. In this scenario, assuming rifting was orthogonal to the craton margin in the adjacent CTAM, the Pensacola Embayment/Southern Mawson Province boundary could have acted as a sinistral transfer fault linking two separate rift segments. It is likely that such a transfer fault would exploit any pre-existing tectonic discontinuity, which may be represented by the boundary between the PolarGAP and Southern Mawson provinces.

Embayments are an important feature of many rifted margins. Potential analogues to the Pensacola Embayment include the Ouachita Embayment in the margin of Laurentia (Fig. 4a, b)^{39,40} and an embayment in the cratonic margin of Australia, concealed beneath the Thomson Orogen (Fig. 4c, d)^{38,41}. Both these embayments exhibit abrupt truncation of highly magnetic Precambrian basement provinces, similar to that observed over the Pensacola Embayment^{41–44}. The shape and architecture of these better known embayments reflects a combination of crustal extension and strike-slip and/or transform motion (Fig. 4a, c). We suggest this geometry is analogous to that of the Pensacola Embayment (Fig. 2d).

A dextral model for Embayment formation. An alternative model for the Pensacola Embayment includes a dextral strike slip fault between the PolarGAP and Southern Mawson Province

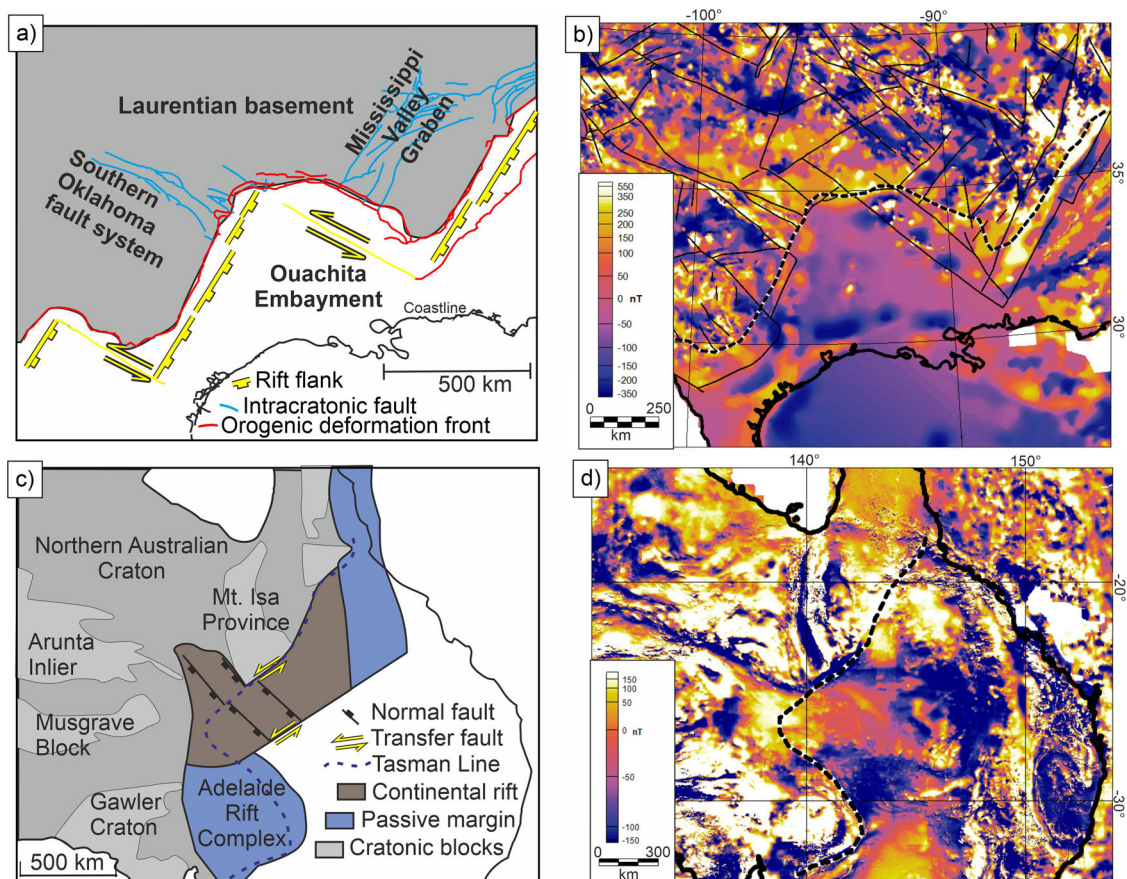


Fig. 4 Analogous embayments in magnetic cratonic basement created by rifting. **a** Sketch of late Neoproterozoic to early Cambrian Ouachita Embayment and extent of subsequent orogenic deformation³⁹. **b** Ouachita Embayment (dashed line) over aeromagnetic data⁴², with additional structural lineations picked from magnetic data (black lines)⁴⁴. **c** Sketch of late Neoproterozoic rifted margin of Western Australia with continental rift interpreted to underlie Thomson Orogen⁴¹. **d** Australian aeromagnetic map⁴³. Note embayment in the geophysically defined Tasman Line (black dashed line).

(Fig. 2e). In this case anomaly M1 could be a displaced fragment of the inferred CTAM Nimrod igneous province²⁰. The age of the required dextral movement is unknown, but strike slip faulting and escape of continental fragments from within the ~500 Ma EAAO has been suggested⁴⁵. However, a dextral strike-slip fault by itself is not kinematically possible given the overall sinistral sense of motion between East and West Gondwana⁴⁵. Dextral movement between the PolarGAP and Southern Mawson Province during the EAAO implies the Southern Mawson Province was a block escaping from within the EAAO, with a conjugate sinistral fault required further east within the Mawson Continent. The required sinistral displacement of the margin of the Mawson Continent would be several hundred kilometres, and this is not supported by recent aeromagnetic compilations which show a relatively unbroken continental margin extending from the CTAM to Terre Adélie²⁷ (Fig. 3). Formation of the Pensacola Embayment entirely through dextral offset during the EAAO therefore appears unlikely.

Impact of the Pensacola Embayment on subsequent processes.

Although a late Neoproterozoic rift origin for the Pensacola Embayment is preferred, we know this region was extensively overprinted by the Ross Orogeny^{10,12,13,15}. Analogue and field studies have suggested that variations in crustal strength, such as across a marginal embayment, can trigger development of arcuate features oblique to the compression direction in subsequent orogenic events, as seen for example in the Ouachita Orogen⁴⁶.

The interpreted Ross age intrusions M2 and M4, and structural trends in the Patuxent Range, are oblique to the main trend of the Ross Orogen. They may therefore reflect development of oblique compressional orogenic features due to interaction of the Ross Orogen with the pre-existing Pensacola Embayment. Juxtaposition of a local cratonic root and a subduction zone can also trigger complex distortion of the down-going slab and development of slab tears and windows in adjacent areas⁴⁷. Along strike variability in the orientation of the interpreted Ross intrusions M2 and M4 could therefore alternatively be explained by magmatic processes triggered by interaction between the down-going slab and the end of the Mawson Craton. Further geodynamic modelling using our new description of the continental basement margin is required to constrain the details of how the Pensacola Embayment may have influenced deformation and magmatism in the subsequent orogeny. However, we consider it likely that the distinct lithospheric character of the Pensacola Embayment helps explain the observed abundance of volcanic rocks¹⁴, young mantle extraction ages¹⁶, and high magnetic susceptibility of Ross age granites (Supplementary Fig. 4) in the QMT relative to the CTAM.

Although geophysical data alone cannot uniquely define the geological history of this sector of Rodinia it provides a framework for future geological interpretation to be considered when studying this enigmatic region. The presence of distinct basement provinces favours a more spatially restricted Mawson Continent to be used in Rodinian reconstructions. The embayment in the basement of East Antarctica we identify also likely

impacted the geodynamic evolution of the Ross Orogeny, causing contrasts in magmatism and deformation along the margin of Gondwana. The clear topographic boundaries which, in conjunction with aeromagnetic data, helped us define the provinces attest to the continuing impact of these ancient structures on the geological and geomorphic evolution of Antarctica.

Methods

This paper is based primarily on aeromagnetic data from the 2015/16 European Space Agency (ESA) PolarGAP survey (see Supplementary Note S1), integrated with aeromagnetic data from a number of previous surveys (see Supplementary Fig. 1 and Supplementary Note S2). Standard aeromagnetic processing corrections²⁷ were applied to the PolarGAP data (see Supplementary Table 1). The line aeromagnetic data was then integrated into a single database with data from the previous surveys (see Supplementary Fig. 1 and Supplementary Note S2). The integrated line magnetic data was levelled using utilities within the Sequent Oasis montaj Geosoft software suite to minimise the impact of line-to-line noise, most likely due to solar-induced geomagnetic events not adequately removed by prior processing. Data was then plotted using Geosoft software and interpreted in terms of geological and tectonic provinces and boundaries. Airborne gravity data from the PolarGAP survey, described in Supplementary Note S3 was also utilised, together with airborne gravity data from a number of previous surveys.

Reporting summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The key PolarGAP aeromagnetic and aerogravity datasets in Figs. 2 and 3 are available from the European Space Agency <https://doi.org/10.5270/esa-8f003e> – PolarGap: “Filling the GOCE polar gap in Antarctica and ASIRAS flight around South Pole” and from the NERC UK Polar Data Centre Polar Airborne Geophysics Data Portal <https://www.bas.ac.uk/project/nagdp/>. Other datasets and their publically available sources are shown in Supplementary Note S2.

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References

- Harley, S. L., Fitzsimons, I. C. W. & Zhao, Y. in *Antarctica and Supercontinent Evolution* 383 (eds Harley, S. L., Fitzsimons, I. C. W. & Zhao Y.) 1–34 (Geological Society of London Special Publication, 2013).
- Boger, S. D. Antarctica—before and after Gondwana. *Gondwana Res.* **19**, 335–371 (2011).
- Fanning, C. M., Moore, D. H., Bennett, V. C. & Daly, S. J. The ‘Mawson Continent’: Archaean to Proterozoic crust in the East Antarctic Shield and Gawler Craton, Australia. A cornerstone in Rodinia and Gondwana. *Geol. Soc. Aust. Abstr.* **41**, 135 (1996).
- Payne, J. L., Hand, M., Barovich, K. M., Reid, A. & Evans, D. A. D. Correlations and reconstruction models for the 2500–1500 Ma evolution of the Mawson Continent. *Geol. Soc. Lond., Special Publ.* **323**, 319 (2009).
- Fitzsimons, I. C. W. in *Proterozoic East Gondwana: Supercontinent Assembly and Breakup* 206 (eds Yoshida, M., Windley, B. F. & Dasgupta, S.) 93–130 (Geological Society of London, 2003).
- Aitken, A. R. A. et al. The subglacial geology of Wilkes Land, East Antarctica. *Geophys. Res. Lett.* **41**, 2390–2400 (2014).
- Mulder, J. A. et al. A multiproxy provenance approach to uncovering the assembly of East Gondwana in Antarctica. *Geology* **47**, 645–649 (2019).
- Jacobs, J. et al. Two distinct Late Mesoproterozoic/Early Neoproterozoic basement provinces in central/eastern Dronning Maud Land, East Antarctica: the missing link, 15–21°E. *Precamb. Res.* **265**, 249–272 (2015).
- Goode, J. W. Geological and tectonic evolution of the Transantarctic Mountains, from ancient craton to recent enigma. *Gondwana Res.* **80**, 50–122 (2020).
- Goode, J. W., Myrow, P. M., Williams, I. S. & Bowring, S. A. Age and Provenance of the Beardmore Group, Antarctica: constraints on Rodinia supercontinent breakup. *J. Geol.* **110**, 393–406 (2002).
- Goode, J. W., Williams, I. S. & Myrow, P. M. Provenance of Neoproterozoic and lower Paleozoic siliciclastic rocks of the central Ross orogen, Antarctica: Detrital record of rift-, passive-, and active-margin sedimentation. *Geol. Soc. Am. Bull.* **116**, 1253–1279 (2004).
- Curtis, M. L., Millar, I. L., Storey, B. C. & Fanning, M. Structural and geochronological constraints of early Ross orogenic deformation in the Pensacola Mountains, Antarctica. *Geol. Soc. Am. Bull.* **116**, 619–636 (2004).
- Storey, B. C., Macdonald, D. I. M., Dalziel, I. W. D., Isbell, J. L. & Millar, I. L. Early Paleozoic sedimentation, magmatism, and deformation in the Pensacola Mountains, Antarctica: the significance of the Ross orogeny. *Geol. Soc. Am. Bull.* **108**, 685–707 (1996).
- Rowell, A. J. & Rees, M. N. Early Palaeozoic history of the upper Beardmore Glacier area: implications for a major Antarctic structural boundary within the Transantarctic Mountains. *Antarct. Sci.* **1**, 249–260 (1989).
- Paulsen, T. S. et al. Detrital mineral ages from the Ross Supergroup, Antarctica: implications for the Queen Maud terrane and outboard sediment provenance on the Gondwana margin. *Gondwana Res.* **27**, 377–391 (2015).
- Borg, S. G. & DePaolo, D. J. Laurentia, Australia, and Antarctica as a Late Proterozoic supercontinent: constraints from isotopic mapping. *Geology* **307–310**, [https://doi.org/310.1130/0091-7613\(1994\)1022<0307:LAAAAA>1132.1133.CO;1](https://doi.org/310.1130/0091-7613(1994)1022<0307:LAAAAA>1132.1133.CO;1) (1994).
- Goode, J. W. & Fanning, C. M. Mesoarchean and Paleoproterozoic history of the Nimrod Complex, central Transantarctic Mountains, Antarctica: stratigraphic revisions and relation to the Mawson Continent in East Gondwana. *Precamb. Res.* **285**, 242–271 (2016).
- Will, T. M. et al. Palaeoproterozoic to Palaeozoic magmatic and metamorphic events in the Shackleton Range, East Antarctica: Constraints from zircon and monazite dating, and implications for the amalgamation of Gondwana. *Precamb. Res.* **172**, 25–45 (2009).
- Ebbing, J., Dilixiati, Y., Haas, P., Ferraccioli, F. & Scheiber-Enslin, S. East Antarctica magnetically linked to its ancient neighbours in Gondwana. *Sci. Rep.* **11**, 5513 (2021).
- Goode, J. W. & Finn, C. Glimpses of East Antarctica: aeromagnetic and satellite magnetic view from the central Transantarctic Mountains of East Antarctica. *J. Geophys. Res.* **115**, <https://doi.org/10.1029/2009JB006890> (2010).
- Studinger, M., Bell, R. E., Fitzgerald, P. G. & Buck, W. R. Crustal architecture of the Transantarctic Mountains between the Scott and Reedy Glacier region and South Pole from aerogeophysical data. *Earth Planet. Sci. Lett.* **250**, 182–199 (2006).
- Ferraccioli, F. et al. East Antarctic rifting triggers uplift of the Gamburtsev Mountains. *Nature* **479**, 388–392 (2011).
- Shen, W. et al. The crust and upper mantle structure of Central and West Antarctica from Bayesian Inversion of Rayleigh Wave and Receiver Functions. *J. Geophys. Res.: Solid Earth* **123**, 7824–7849 (2018).
- Paxman, G. J. G. et al. Subglacial geology and geomorphology of the Pensacola-Pole Basin, East Antarctica. *Geochem. Geophys. Geosyst.* **20**, 2786–2807 (2019).
- Goode, J. W., Fanning, C. M., Fisher, C. M. & Vervoort, J. D. Proterozoic crustal evolution of central East Antarctica: age and isotopic evidence from glacial igneous clasts, and links with Australia and Laurentia. *Precamb. Res.* **299**, 151–176 (2017).
- Wannamaker, P. et al. Uplift of the central transantarctic mountains. *Nat. Commun.* **8**, 1588 (2017).
- Golynsky, A. V. et al. New magnetic anomaly map of the Antarctic. *Geophys. Res. Lett.* **45**, 6437–6449 (2018).
- Golynsky, A. & Jacobs, J. Grenville-Age versus Pan-African magnetic anomaly imprints in western Dronning Maud Land, East Antarctica. *J. Geol.* **109**, 136–142 (2001).
- Wang, C.-C. et al. Grenville-age continental arc magmatism and crustal evolution in central Dronning Maud Land (East Antarctica): Zircon geochronological and Hf-O isotopic evidence. *Gondwana Res.* **82**, 108–127 (2020).
- Mieth, M. & Jokat, W. New aeromagnetic view of the geological fabric of southern Dronning Maud Land and Coats Land, East Antarctica. *Gondwana Res.* **25**, 358–367 (2014).
- Ferraccioli, F., Armadillo, A., Jordan, T. A., Bozzo, E. & Corr, H. Aeromagnetic exploration over the East Antarctic Ice Sheet: a new view of the Wilkes Subglacial Basin. *Tectonophysics* **478**, 62–77 (2009).
- Pappa, F., Ebbing, J. & Ferraccioli, F. Moho depths of Antarctica: comparison of seismic, gravity, and isostatic results. *Geochem. Geophys. Geosyst.* **20**, 1629–1645 (2019).
- Wannamaker, P. E., Stodt, J. A., Pellerin, L., Olsen, S. L. & Hall, D. B. Structure and thermal regime beneath the South Pole region, East Antarctica, from magnetotelluric measurements. *Geophys. J. Int.* **157**, 36–54 (2004).
- Storey, B. C. et al. Upper Proterozoic rift-related rocks in the Pensacola Mountains, Antarctica: precursors to supercontinent breakup? *Tectonics* **11**, 1392–1405 (1992).
- Agrios, L. M. et al. Detrital geochronology and lithologic signatures of Weddell Sea Embayment ice streams, Antarctica—implications for subglacial geology and ice sheet history. *GSA Bull.* <https://doi.org/10.1130/B36117.1> (2021).
- Di Vincenzo, G., Talarico, F. & Kleinschmidt, G. An ⁴⁰Ar–³⁹Ar investigation of the Mertz Glacier area (George V Land, Antarctica): implications for the Ross Orogen–East Antarctic Craton relationship and Gondwana reconstructions. *Precamb. Res.* **152**, 93–118 (2007).

37. Lister, G. S., Etheridge, M. A. & Symonds, P. A. Detachment faulting and the evolution of passive continental margins. *Geology* **14**, 246–250 (1986).
38. Greene, D. C. Neoproterozoic rifting in the southern Georgina Basin, central Australia: implications for reconstructing Australia in Rodinia. *Tectonics* **29**, <https://doi.org/10.1029/2009TC002543> (2010).
39. Thomas, W. A. The Iapetan rifted margin of southern Laurentia. *Geosphere* **7**, 97–120 (2011).
40. Thomas, W. A. & Astini, R. A. The Argentine Precordillera: a Traveler from the Ouachita Embayment of North American Laurentia. *Science*, 752–757, <https://doi.org/10.1126/science.1273.5276.1752> (1996).
41. Spampinato, G. P. T., Betts, P. G., Ailleres, L. & Armit, R. J. Early tectonic evolution of the Thomson Orogen in Queensland inferred from constrained magnetic and gravity data. *Tectonophysics* **651–652**, 99–120 (2015).
42. Bankey, V. et al. *Digital Data Grids for the Magnetic Anomaly Map of North America* (USGS, 2002).
43. Petkovic, P. & Milligan, P. *Magnetic Anomaly Grid of the Australian Region, 3.1* (Geoscience Australia, 2002).
44. Sims, P. K., Saltus, R. & Anderson, E. D. Preliminary Precambrian Basement Structure Map of the Continental United States—an Interpretation of Geologic and Aeromagnetic Data, Vol. 31 (USGS, 2005).
45. Jacobs, J. & Thomas, R. J. Himalayan-type indenter-escape tectonics model for the southern part of the late Neoproterozoic-early Paleozoic East African-Antarctic orogen. *Geology* **32**, 721–724 (2004).
46. Calignano, E. et al. Oblique contractional reactivation of inherited heterogeneities: cause for arcuate orogens. *Tectonics* **36**, 542–558 (2017).
47. Taramón, J. M., Rodríguez-González, J., Negro, A. M. & Billen, M. I. Influence of cratonic lithosphere on the formation and evolution of flat slabs: insights from 3-D time-dependent modeling. *Geochem. Geophys. Geosyst.* **16**, 2933–2948 (2015).
48. Jordan, T. A. et al. Anomalously high geothermal flux near the South Pole. *Sci. Rep.* **8**, 16785 (2018).
49. Davis, M. B. & Blankenship, D. *Geology of the Scott-Reedy Glaciers Area, Southern Transantarctic Mountains, Antarctica. GSA Map Series MCH093F* (The Geological Society of America, 2005).
50. Paulsen, T., Encarnación, J. & Grunow, A. M. Structure and timing of transpressional deformation in the Shackleton Glacier area, Ross orogen, Antarctica. *J. Geol. Soc. London* **161**, 1027–1038 (2004).
51. Storey, B. C., Vaughan, A. P. M. & Millar, I. L. in *Weddell Sea Tectonics and Gondwana Break-up*, (eds Storey, B. C., King, E. C. & Livermore, R. A.) Vol. 108 87–103 (Geological Society Special Publication, 1996).
52. Liu, X. et al. Late Pan-African granitoids from the Grove Mountains, East Antarctica: age, origin and tectonic implications. *Precamb. Res.* **145**, 131–154 (2006).
53. Mikhalsky, E. V. et al. The geological composition of the hidden Wilhelm II Land in East Antarctica: SHRIMP zircon, Nd isotopic and geochemical studies with implications for Proterozoic supercontinent reconstructions. *Precamb. Res.* **258**, 171–185 (2015).
54. Jacobs, J. et al. Cryptic sub-ice geology revealed by a U-Pb zircon study of glacial till in Dronning Maud Land, East Antarctica. *Precamb. Res.* **294**, 1–14 (2017).

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Author contributions

All authors contributed to the final preparation and presentation of the manuscript. Specifically T.A.J. created the aeromagnetic data compilation, wrote the initial text and prepared the figures. R.F. provided the aero gravity data and information on processing. F.F. provided additional insight into the geological background of the region. R.F. and F.F. devised and led the PolarGAP project together with Kenichi Matsuoka from the Norwegian Polar Institute (NPI).

Competing interests

The authors declare no competing interests.

Additional information

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