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.
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 understood1,2. The Archean and Paleoproterozoic history of the Mawson Continent3,4 (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 Craton2,3,5. 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 Gondwana2,5–8. In contrast the paleo-Pacific (Transantarctic Mountains) side of the Mawson Continent was flanked by a late Neoproterozoic rifted margin, formed during Rodinia breakup9,10. 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 Ma11–13. In our study area a distinct Queen Maud Terrane (QMT) with more abundant volcanic rocks14,15 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 Antarctica11,15.

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.
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 CTAM\(^{20}\) 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 rocks\(^{20}\). 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. 1a), which includes the previously defined highly magnetic South Pole Province and Nimrod igneous province towards the CTAM. 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). The underlying lithosphere also has the most elevated seismic velocities in the study area, at depths of 75–150 km (Supplementary Fig. 2a, c).

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 includes a 1–3 km-thick fault-bounded sedimentary basin. 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). Seismic models indicate elevated lithospheric velocities generally occur at depths of 50–75 km in the PolarGAP Province (Supplementary Fig. 2b, c).

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 CTAM 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. Bouger 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). 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).

**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). The high amplitude aeromagnetic anomalies have previously been attributed to a largely unreworked Paleo to Mesoproterozoic igneous province. Subglacially derived samples of ~1850 Ma igneous rocks with high measured magnetic susceptibility from the CTAM are consistent with this interpretation. The craton-like mantle suggested by magnetotelluric models and relatively thick seismically fast lithospheric mantle 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 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. Similar curvilinear anomalies surround the cryptic Valkyrie Craton. 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 region. 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.
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 margin. 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 arc, and granitic clasts in tills downstream and flanking the glacier flowing over anomaly M2 are dated to 510 Ma. In the QMT area of the Pensacola Embayment magnetic anomalies with similar amplitude and wavelength to anomalies M2–M4 overlie exposed Ross-age granites (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 Craton 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 embayments. 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 CTAM (Fig. 1b) and further east in Australia. 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 sediments. 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) and an embayment in the cratonic margin of Australia, concealed beneath the Thomson Orogen (Fig. 4c, d). Both these embayments exhibit abrupt truncation of highly magnetic Precambrian basement provinces, similar to that observed over the Pensacola Embayment. 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.
In this case anomaly M1 could be a displaced fragment of the inferred CTAM Nimrod igneous province. 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 suggested. However, a dextral strike-slip fault by itself is not kinematically possible given the overall sinistral sense of motion between East and West Gondwana. 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 Adélie. Formation of the Pensacola Embayment entirely through dextral offset during the EAAO therefore appears unlikely.

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 areas. 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 rocks, young mantle extraction ages, 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

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**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 deformation. **b** Ouachita Embayment (dashed line) over aeromagnetic data, with additional structural lineations picked from magnetic data (black lines). **c** Sketch of late Neoproterozoic rifted margin of Western Australia with continental rift interpreted to underlie Thomson Orogen. **d** Australian aeromagnetic map. Note embayment in the geophysically defined Tasman Line.
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 corrections 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 Ossian 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-8ffoo3e – Polar–Gap]. “Filling the GOCO polar gap in Antarctica and AVHRR light 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 publicly available sources are shown in Supplementary Note S2.

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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 aerogravity 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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