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Compiling ship and airborne measurements for the Antarctic's second-generation magnetic anomaly map

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In 2001, the Antarctic Digital Magnetic Anomaly Project produced the ADMAP-1 compilation that included the first magnetic anomaly map of the region south of 60°S. To help fill ADMAP-1's regional coverage gaps, the international geomagnetic community from 2001 through 2014 acquired an additional 2.0+ million line-km of airborne and marine magnetic anomaly data. These new data together with surveys that were not previously in the public domain significantly upgraded the ADMAP compilation for Antarctic crustal studies. The merger of the additional data with ADMAP-1's roughly 1.5 million line-km of survey data produced the second-generation ADMAP-2 compilation. The present study comprehensively reviews the problems and progress in merging the airborne and ship magnetic measurements obtained in the harsh Antarctic environment since the first International Geophysical Year (IGY 1957–58) by international campaigns with disparate survey parameters. For ADMAP-2, the newly acquired data were corrected for the diurnal and International Geomagnetic Reference Field effects, edited for high-frequency errors, and levelled to minimize line-correlated noise. ADMAP-2 provides important new constraints on the enigmatic geology of the Gamburtsev Subglacial Mountains, Prince Charles Mountains, Dronning Maud Land, and other poorly explored Antarctic areas. It links widely separated outcrops to help unify disparate geologic and geophysical studies for new insights on the global tectonic processes and crustal properties of the Antarctic. It also supports studies of the Antarctic ice sheet's geological controls, the crustal transitions between Antarctica and adjacent oceans, and the geodynamic evolution of the Antarctic crust in the assembly and break-up of the Gondwana and Rodinia supercontinents.

Keywords: Antarctic Digital Magnetic Anomaly Project, Airborne and shipborne magnetic surveys, Data processing, Map compilation, Crustal studies of the Antarctic.

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1 Introduction

Geologic studies of the Antarctic region south of 60°S are greatly aided by magnetic surveying because of the crust's nearly ubiquitous cover of ice, snow, and seawater. Since the 1957–1958 International Geophysical Year (IGY 1957–58), multinational efforts had collected a substantial amount of magnetic data over the continent and offshore areas despite the formidable field logistics of surveying in the harsh and remote Antarctic environment. Over the subsequent decades, the lack of international coordination made it increasingly difficult to keep track of the mapped regions. This also limited understanding the regional geological implications of the surveys and the planning of new surveys. Resolutions addressing these issues from the Scientific Committee on Antarctic Research (SCAR) and the International Association of Geomagnetism and Aeronomy resulted in establishing the Antarctic Digital Magnetic Anomaly Project (ADMAP) in 1995 [*Johnson et al.*, 1997; *Chiappini et al.*, 1998; *Chiappini and von Frese*, 1999]. ADMAP accordingly facilitates coordinating the survey activities of the international Antarctic geomagnetic community and conserving the magnetic data for geological studies of the Antarctic.

In 2001, ADMAP released its first magnetic anomaly compilation that included the ADMAP-1 grid (Figure 1) which incorporated more than 1.5 million line-km of ship and airborne magnetic data collected from the IGY 1957–58 through 1999 together with some 5.6 million line-kms of

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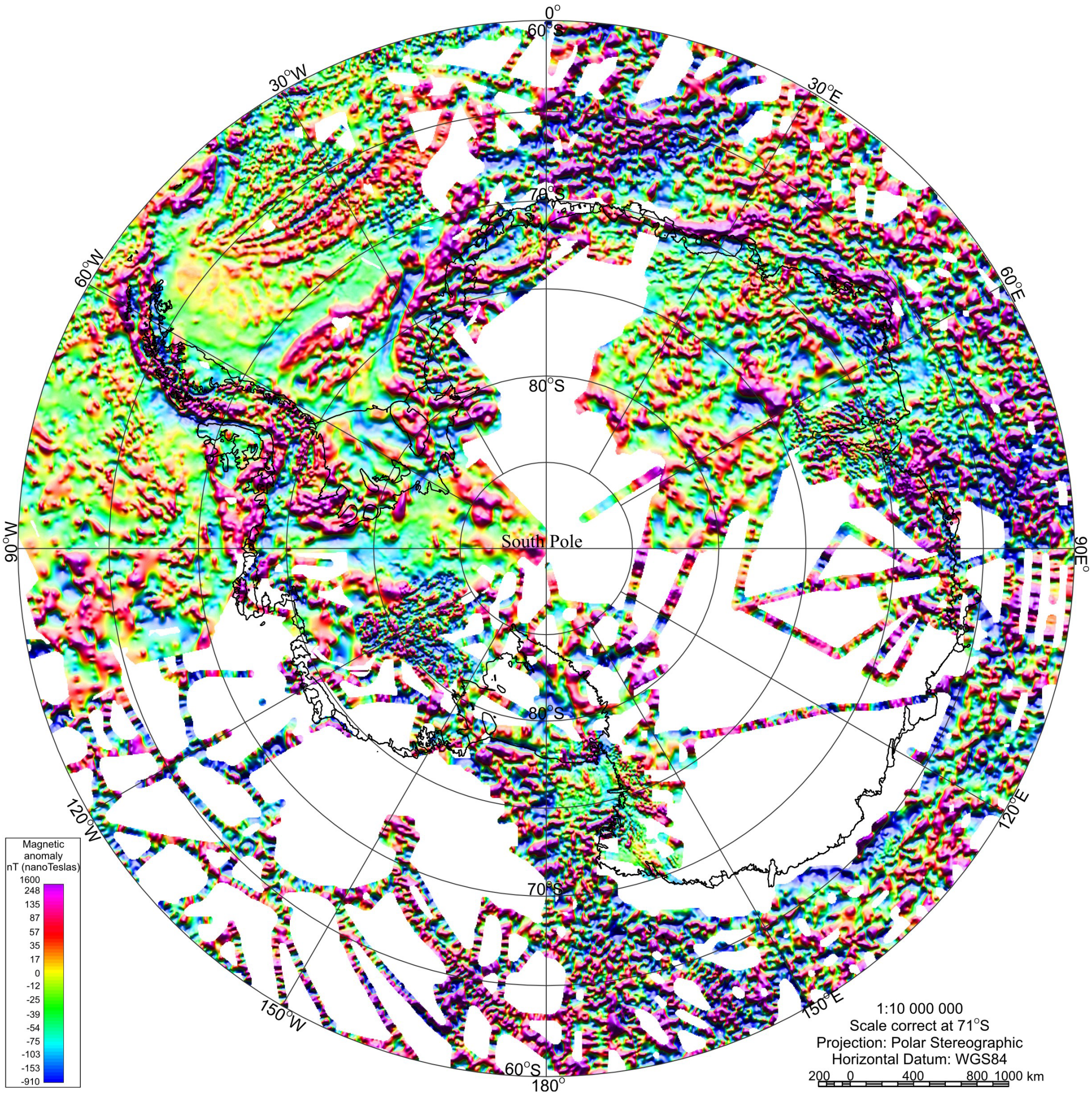

Figure 1: ADMAP-1 compilation of near-surface scalar total field magnetic anomalies in polar stereographic projection with central meridian = 0°E longitude and standard parallel = 71°S latitude [*Golynsky et al.*, 2001]. Generated from roughly 1.5 million line-km of airborne and ship magnetic observations, the 5-km grid of data at the variable altitudes of the composite surveys (Figure 6A) was low-pass filtered for about 10+ km wavelengths.

satellite magnetic observations from the Magsat mission [*Golynsky et al.*, 2001; *von Frese et al.*, 2007]. The large coverage gaps between the near-surface surveys were filled with anomaly estimates jointly constrained by the satellite and surrounding near-surface magnetic observations. Follow-on efforts improved the gap estimates using the more accurate and comprehensive magnetic observations from the post-Magsat era Ørsted and Champ satellite missions [*Kim et al.*, 2007]. In 2008, NOAA's National Centers for Environmental Information (`https://www.ngdc.noaa.gov`) archived the grids and supplemental near-surface survey data for public distribution and incorporated the ADMAP-1 grid into the first World Digital Magnetic Anomaly Map [*Maus et al.*, 2009].

However, the World Digital Magnetic Anomaly Map (WDMAM) only used the shorter wavelength components of the ADMAP-1 grid under the dubious objective of enhancing the long-wavelength compatibility between the near-surface and satellite datasets [*Maus et al.*, 2009]. Specifically, WDMAM replaced anomalies with wavelengths longer than about 400 km in the ADMAP-1 grid with downward continued satellite anomaly estimates. This substitution, however, corrupted ADMAP-1's contributions to WDMAM's south polar predictions because measurement and data processing errors substantially limit the near-surface sensitivity of satellite anomaly observations [*von Frese et al.*, 2013].

Figure 2 gives an overview of the geologically diverse crustal region covered by the ADMAP-1 magnetic anomaly compilation, whereas Figure 3

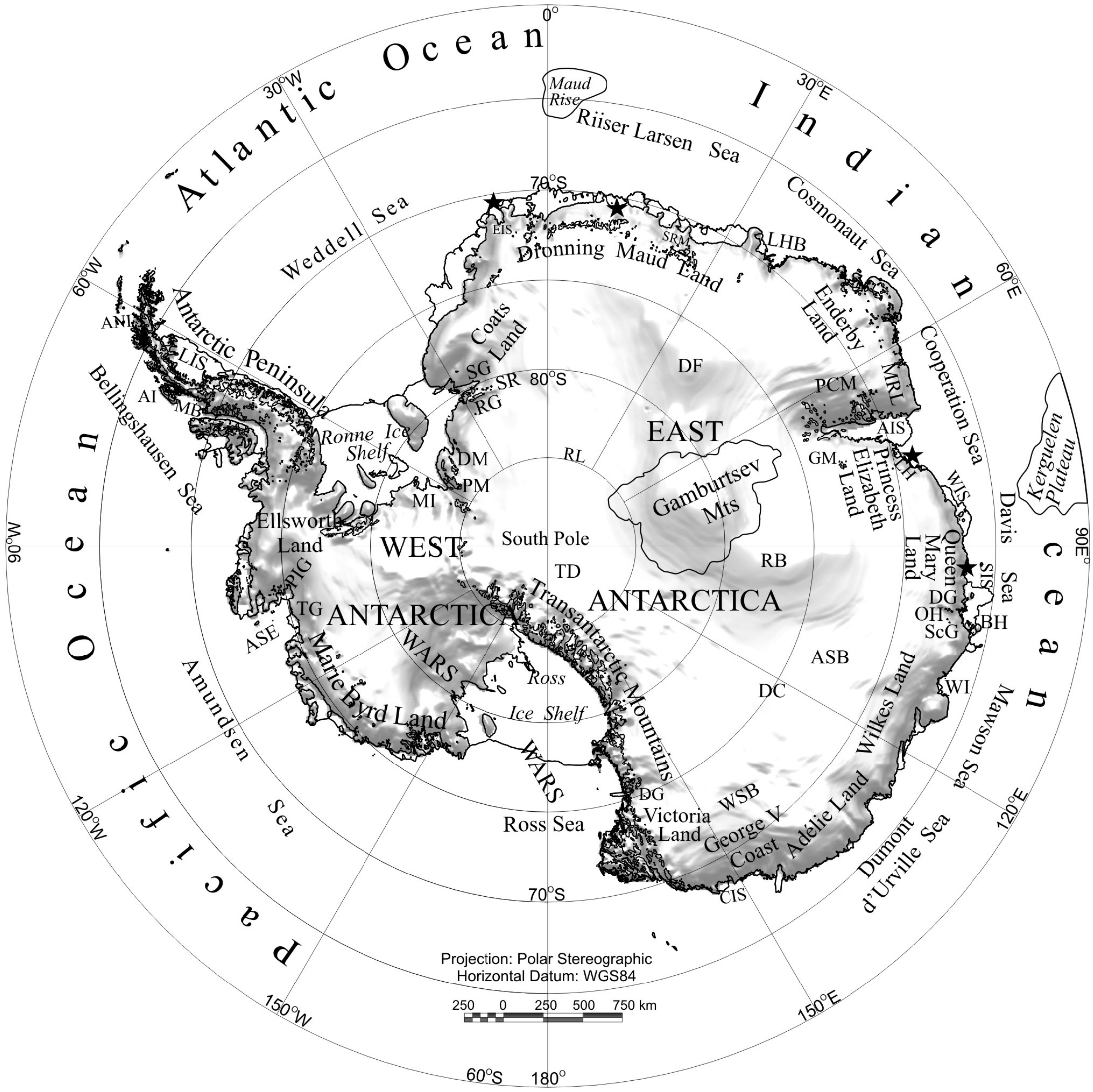

Figure 2: Shaded relief map of Antarctica's surface topography showing the distribution of selected geographical and geological features described in this study. Geographic name abbreviations include: AI – Adelaide Island; AIS – Amery Ice Shelf; ANI – Anvers Island; ASB – Aurora Subglacial Basin; ASE – Amundsen Sea Embayment; BH – Bunger Hills; CIS – Cook Ice Shelf; DC – Dome C; DF – Dome F; DG – Denman Glacier; DM – Dufek Massif; EIS – Ekström Ice Shelf; GM – Grove Mountains; LHB – Lützow-Holm Bay; LIS – Larsen Ice Shelf; LH – Larsemann Hills; MI – Möller & Institute Ice Streams; MRL – MacRobertson Land; OH – Obruchev Hills; PCM – Prince Charles Mountains; PIG – Pine Island Glacier; RB – Ridge B; RG – Recovery Glacier; RL – Recovery Lakes; ScG – Scott Glacier; SG – Slessor Glacier; SIS – Shackleton Ice Shelf; SR – Shackleton Range; SRM – Sør Rondane Mountains; TD – Titan Dome; TG – Thwaites Glacier; WARS – West Antarctic Rift system; WI – Windmill Islands; WIS – West Ice Shelf; WSB – Wilkes Subglacial Basin. Solid black stars locate the Mirny (93.0097°E, 66.5531°S), Neumayer III (8.25°W, 70.65°S), Novolazarevskaya (11.8666°E, 70.7666°S), and Progress (76.3833°E, 69.3833°S) stations cited in the text.

shows the affiliated marine and airborne magnetic survey line coverages and sponsors. The coverage gaps were particularly extensive between the mountainous regions of Dronning Maud Land and the South Pole, and through Wilkes Land and Adélie Land. Sparse late-1950's vintage data also covered other areas including Queen Mary Land and adjacent regions. The relatively more accessible coasts were covered by a discontinuous patchwork of local surveys, such as those over the Bunger and Obruchev Hills, and the Windmill Islands [*Golynsky et al.*, 2001].

Coverage of the Ross Ice Shelf area was limited to profiles collected in the early 1960's [*Behrendt and Wold*, 1963; *Behrendt*, 1964]. Better magnetic survey coverage of this region would greatly improve understanding the extent of the seismically mapped West Antarctic Rift System across the

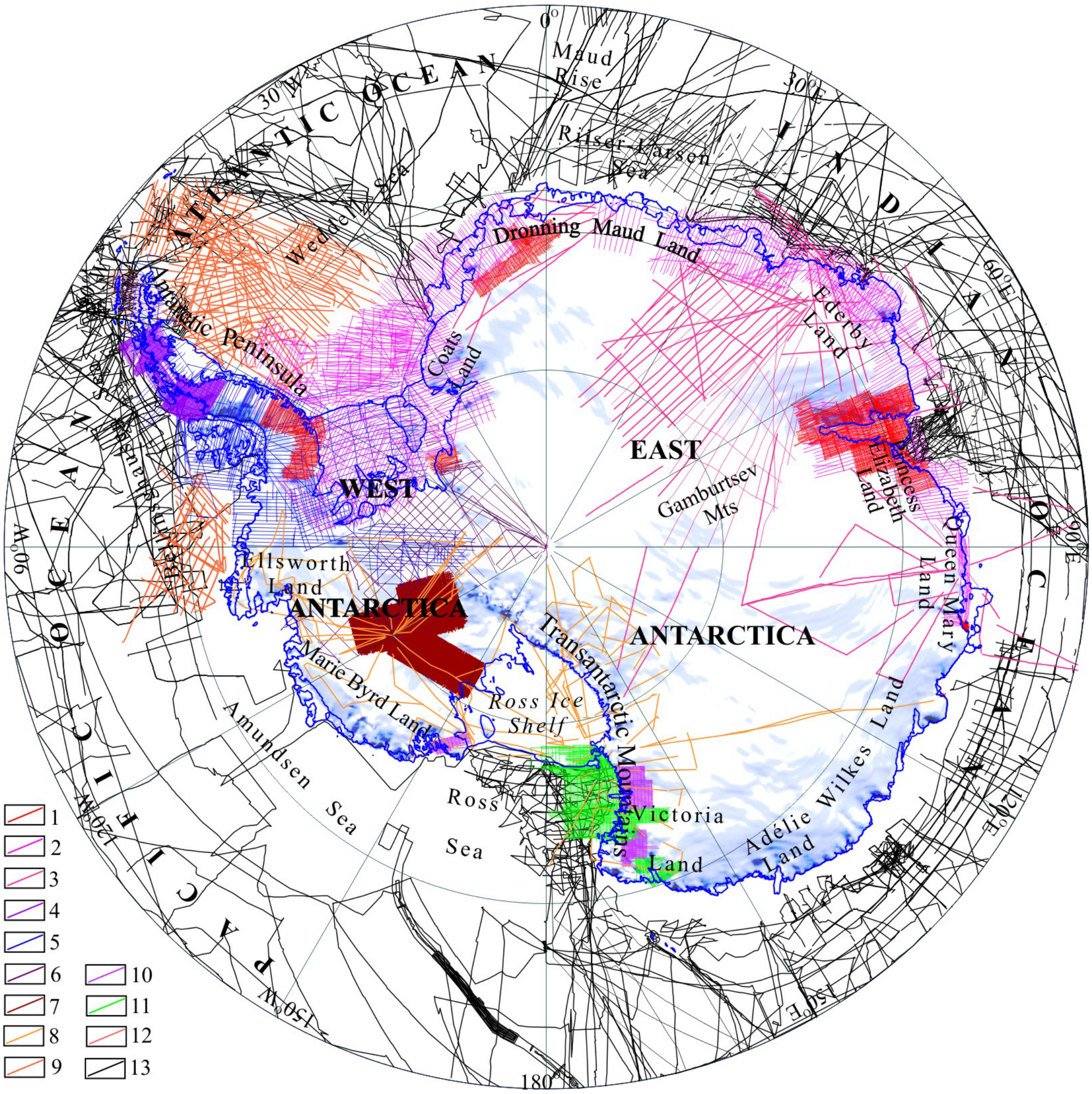

Figure 3: Previous line coverage from the ADMAP-1 near-surface magnetic surveys [*Golynsky et al.*, 2001]. Numerical identifiers for the depicted surveys are keyed to sponsors as follows: 1–3 – Soviet Antarctic Expedition (SAE); 4–5 – British Antarctic Survey (BAS); 6 – Scott Polar Research Institute (SPRI); 7 – Corridor Aerogeophysics of the Southeastern Ross Transect Zone (CASERTZ) program; 8 – USA reconnaissance flights; 9 – the US-Argentine-Chile (USAC) program; 10 – German-Italian Aeromagnetic Research in Antarctica (GITARA) program; 11 – the German Antarctic North Victoria Land Expedition (GANOVEX) program; 12 – Chilean surveys; and 13 – marine surveys of the USA, UK, Russia, Australia, and Japan.

Ross Ice Shelf and Sea [*Behrendt et al.*, 1991; *Cooper and Davey*, 1987; *Hinz and Block*, 1984; *Hinz and Kristoffersen*, 1987].

The most poorly mapped offshore sectors in ADMAP-1 were in the Amundsen Sea and eastern Ross Sea that only a handful of randomly oriented ship tracks sampled [*Golynsky*, 2007; *Gohl et al.*, 2013]. It also was evident that additional surveys of the eastern Weddell Sea and western Riiser-Larsen Sea were needed to better constrain the break-up of Antarctica and Africa and the spatial extent of Maud Rise's submarine igneous province [*König and Jokat*, 2006; *Kovacs et al.*, 2002].

2 New magnetic surveys

Accordingly, more than 2 million line-km of new airborne and ship magnetic data were collected in the post-ADMAP-1 period (Figure 4), which more than doubled ADMAP's database. In particular, the IGY 2008–09 saw efforts redoubled to generate new magnetic anomaly data alongside airborne laser altimetry, radio echo sounding, and gravity surveying in Antarctica. These data have been modelled for local and regional studies of the east and west Antarctic ice sheets and their subglacial landscapes and hydrology, as well as for the geological history and structure of the underlying

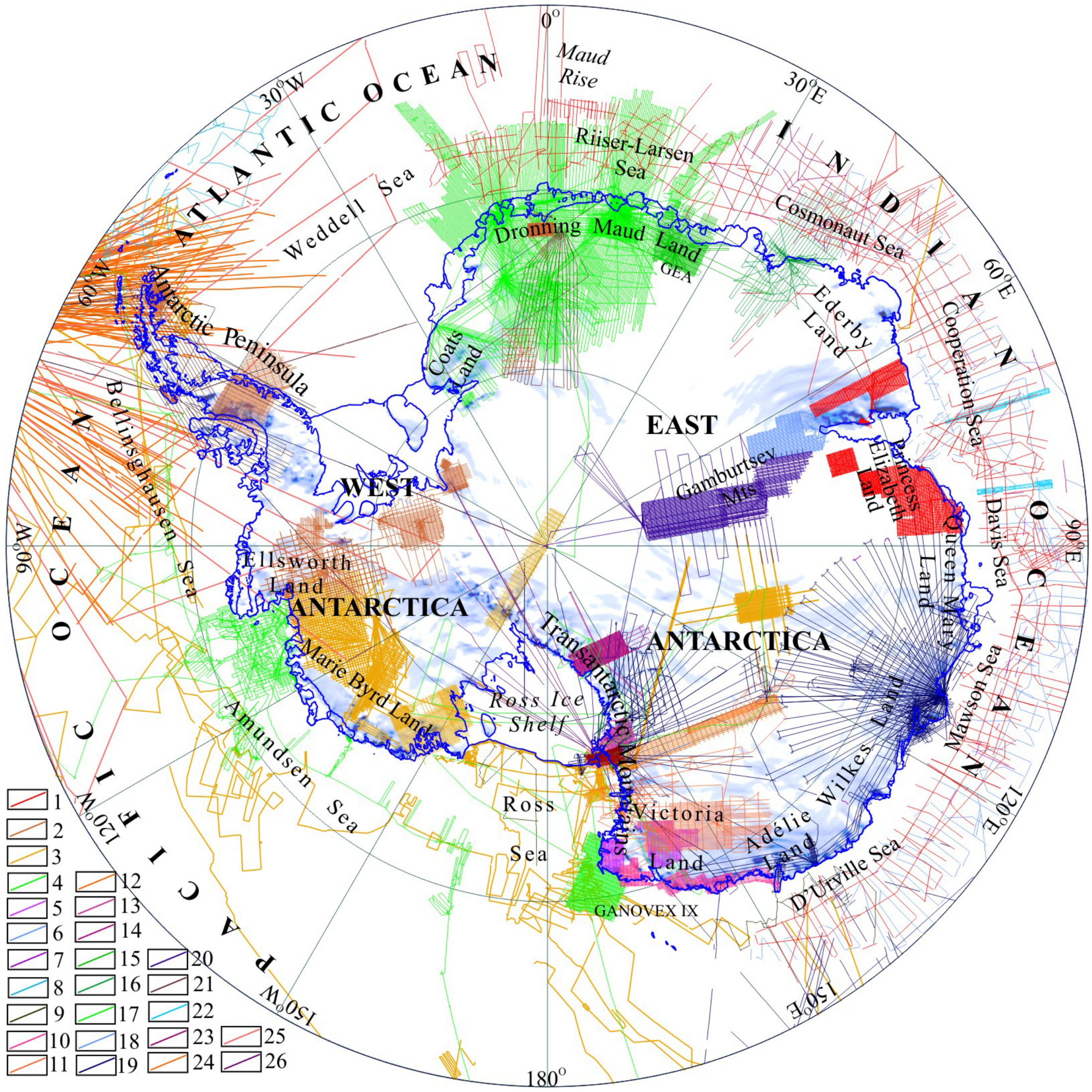

Figure 4: Added line coverage from the new near-surface magnetic surveys in the ADMAP-2 compilation: 1 – Russian Antarctic Expedition (RAE); 2 – British Antarctic Survey (BAS, UK); 3 – USA; 4 –Alfred Wegener Institute (AWI, Germany); 5 – Italy; 6 – Australia; 7 – Japan; 8 – Spain; 9 – France; 10 – GITARA VI; 11 – Icehouse Earth: Stability Or DYNamism? and Wilkes Basin/Transantarctic Mountains System Exploration (ISODYN/WISE); 12 – Aerogeophysical investigations across the Transantarctic Mountains and the Wilkes Subglacial Basin (AEROTAM); 13 – Transantarctic Mountains Aerogeophysical Research Activities (TAMARA); 14 – Central Transantarctic Mountains (CTAM); 15 – Geodynamic Evolution of East Antarctica (GEA) and AWI/BGR flights; 16 – AWI/National Institute of Polar Research (NIPR, Japan); 17 – GANOVEX IX; 18 – Prince Charles Mountains Expedition of Germany-Australia (PCMEGA); 19 – International Collaborative Exploration of the Cryosphere through Airborne Profiling (ICECAP/IceBridge); 20 – Antarctica's Gamburtsev Province (AGAP); 21 – ICEGRAV; 22 – AWI/BGR/RAE; 23 – Norwegian Petroleum Directorate (NPD)/RAE; 24 – USAC; 25 – Project Magnet; 26 – SPRI.

crust. Landmark surveys tackled the Gamburtsev Subglacial Mountains [*Ferraccioli et al.*, 2011], Wilkes Land [*Aitken et al.*, 2014; *von Frese et al.*, 2009, 2013], the Wilkes Subglacial Basin [*Ferraccioli et al.*, 2009a], Dronning Maud Land [*Mieth and Jokat*, 2014], and other geologically enigmatic frontier regions [*Damaske and McLean*, 2005; *Damaske et al.*, 2003; *Ferraccioli et al.*, 2002, 2005a,b, 2006; *Golynsky et al.*, 2006b; *Jokat et al.*, 2003; *Leinweber and Jokat*, 2012; *Shepherd et al.*, 2006; *Stagg et al.*, 2004; *Studinger et al.*, 2004, 2006].

As Figure 4 shows, major new aeromagnetic data contributions came from Germany's Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung (AWI) and the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), the University of Texas (UTEXAS), the Lamont-Doherty Earth Observatory (LDEO), the

British Antarctic Survey (BAS), and Russia's Polar Marine Geosurvey Expedition (PMGE) [*Damaske*, 1999; *Riedel et al.*, 2013; *Luyendyk et al.*, 2003; *Studinger et al.*, 2003; *Ferraccioli et al.*, 2003; *Ferris et al.*, 2003; *Golynsky et al.*, 2006a, 2013a]. Additionally, significant data contributions became available from several projects operated by cooperating institutions and agencies (e.g., [*Anderson et al.*, 2006; *Aitken et al.*, 2014; *Damaske and McLean*, 2005; *Ferraccioli et al.*, 2011; *Forsberg et al.*, 2017]).

Offshore, post-ADMAP-1 data from about 430,000 line-km of new airborne and marine surveys became available [*Golynsky et al.*, 2013b]. These data considerably improved the magnetic field coverage of the East Antarctic's continental margin via the marine surveys acquired largely by Russia, the USA, Australia, Japan, and Germany [*Granot et al.*, 2007; *Stagg et al.*, 2004; *Nogi et al.*, 2004; *Wobbe et al.*, 2012]. Cooperative Russian and Norwegian projects in the Riiser-Larsen Sea [*Leitchenkov et al.*, 2008], and the joint German and Japanese surveys of Lützow-Holm Bay [*Jokat et al.*, 2010] provided further significant magnetic data contributions.

3 Project logistics

The Korea Polar Research Institute (KOPRI) hosted a meeting of the ADMAP steering committee in August 2013 at Incheon, Republic of Korea, to initiate a workplan on the production of the second-generation magnetic anomaly map and digital database, ADMAP-2, for the Antarctic south of 60°S. KOPRI funded this effort for the period February 2014 to December 2015 at the All-Russian Scientific Research Institute for Geology and Mineral Resources of the World Ocean (VNIIOkeangeologia) in Saint Petersburg, Russia. Compilation efforts continued up until the end of 2016 to accommodate some late-arriving survey datasets.

Figure 5 shows the 1.5-km grid produced from the ADMAP-2 compilation. In contrast to the ADMAP-1 grid that was produced from only publicly available line data, the ADMAP-2 grid included proprietary data. These data largely came from the AGASEA (Airborne Geophysical Survey of the Amundsen Embayment) and GIMBLE (Geophysical Investigations of Marie Byrd Land Lithospheric Evolution) surveys flown respectively over the Amundsen Sea Embayment and Marie Byrd Land by the University of Texas (Young et al., 2017), the BBAS (Basin Balance Assessment and Synthesis) survey completed over the Thwaites and Pine Island Glacier catchments by BAS, and several RAE surveys over Princess Elizabeth Land.

The compilation excluded some surveys that were incompatible with neighboring surveys or replaced by more detailed surveying. The excluded data were mostly from the mid-1970's SAE-17-19 surveys over MacRobertson and Princess Elizabeth Lands, and the SAE-6 flights that were reflown in more comprehensive detail over the Novolazarevskaya Station (70°46′S, 11°52′E) and the Windmill Islands (SAE-1). New overflights also supplanted some US profiles over the Pensacola and Transantarctic Mountains and Marie Byrd Land [*Behrendt and Bentley*, 1968].

The rest of the aeromagnetic surveys in the ADMAP-2 compilation have been mostly published [*Aitken et al.*, 2014; *Ferraccioli et al.*, 2011; *Damaske and McLean*, 2005; *Golynsky et al.*, 2007; *Jordan et al.*, 2013b; *Mieth and Jokat*, 2014]. In making them internally consistent for publication, these data had been corrected for secular variations of the IGRF and diurnal effects, edited for high-frequency errors, and leveled to minimize line-correlated noise.

Further assembly of these datasets into a coherent map involved correcting for residual quality issues in the data collected and archived over the 60-year period since the IGY 1957–58. Here, the navigation errors ranged from a few kilometers in the early surveys to just a few meters or less in the recent surveys. However, the reference altitudes and continuations for some of the aeromagnetic surveys were difficult to establish. Information about the acquisition, processing, reduction, correction, and filtering of the data was frequently absent or incomplete. Characterizing the regional background field in the surveys was also problematic because the International Geomagnetic Reference Field (IGRF) poorly constrains historical epochs in the Antarctic region. The marine data, on the other hand, contained diurnal effects that were difficult and sometimes impossible to recognize and resolve. Whilst all survey data were received in digital form, some of them had been digitized from analogue records using a variety of techniques with variable accuracies and sampling rates [*Golynsky et al.*, 2000]. Some datasets also came with decimated observations, or as upward continued estimates to altitudes of 4 km or higher with suppressed higher frequency components.

Owing to these accuracy issues, pairs of overlapping or conterminous datasets usually exhibited systematic offsets, tilts, and other biases. Thus, the only effective means of merging the available anomaly grids was to reprocess and relevel the survey lines. The starting point for this varied from survey to survey, as some were delivered at an advanced stage of processing whilst others were delivered in raw form. After this reprocessing and relevelling, residual uncertainties in ADMAP-2's more than 61.5 million airborne and ship observa-

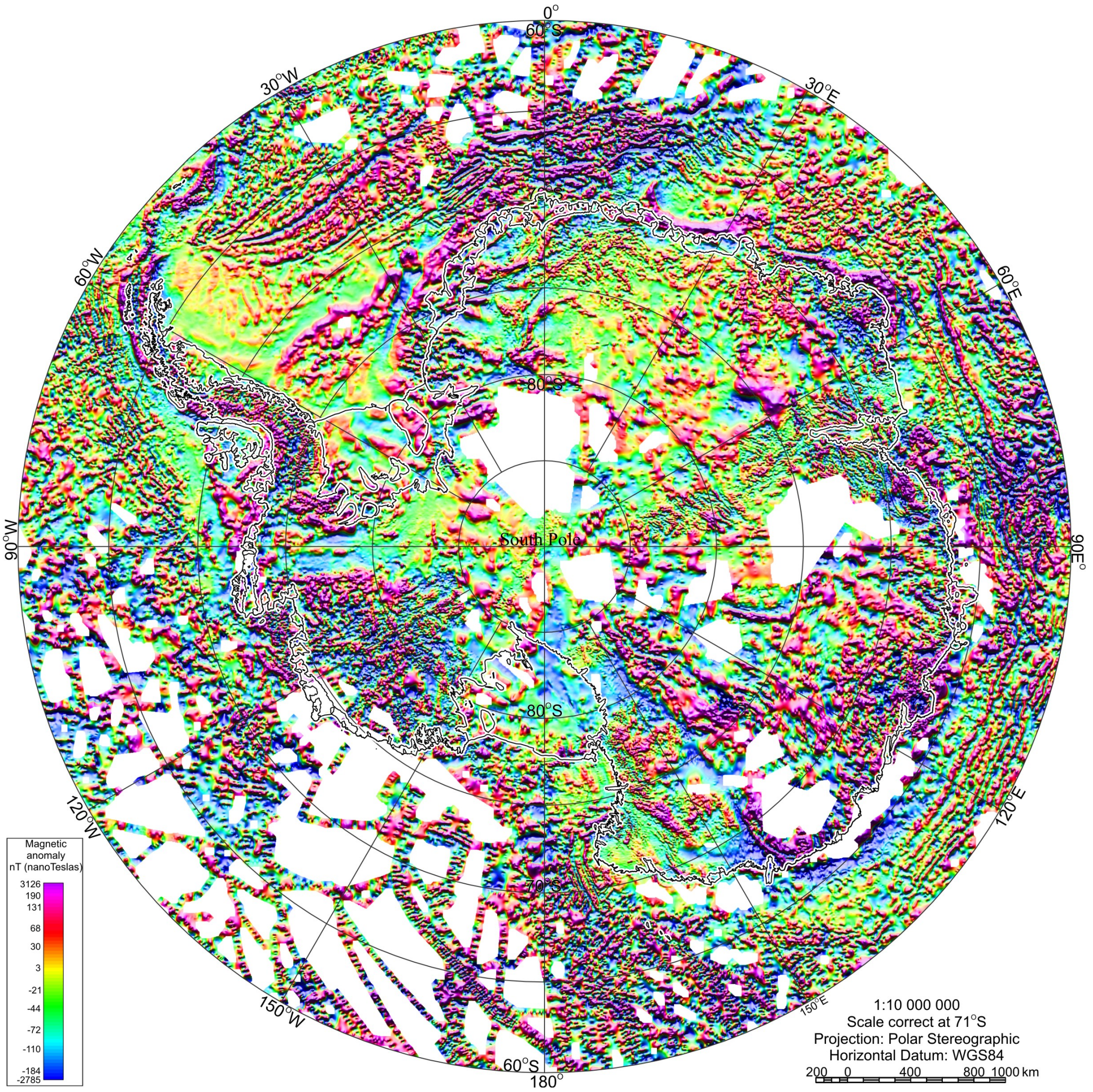

Figure 5: ADMAP-2 compilation of near-surface scalar total field magnetic anomalies in shaded-relief on a polar stereographic projection with central meridian = 0°E longitude and standard parallel = 71°S latitude [*Golynsky et al.*, 2017, 2018]. Generated from more than 3.5 million line-km of airborne and ship magnetic observations, the 1.5-km grid of data at the variable altitudes of the composite surveys (Figure 6A) was low-pass filtered for about 7+ km wavelengths.

tions limited the accuracy of the gridded magnetic anomaly estimates (Figure 5) to roughly 5–15 nT over continental terrain and perhaps twice this amount in the marine areas.

In addition to this estimate of reliability, the 1.5-km grid of scalar magnetic anomalies in Figure 5 involve rather heterogeneous data distributions with variable line spacings. The next section details the data handling procedures used to extract the anomaly grid from the heterogeneously distributed survey data.

3.1 Map compilation procedures

To combine the new magnetic survey data with the ADMAP-1 data, all survey lines were processed into regional grids that, in turn, were merged into the final continental-scale ADMAP-2 compilation. The survey lines were visually inspected to identify and limit the effects of data gaps, spikes, tares, and residual diurnal variations [*Damaske*, 1989]. This analysis also found several problematic profiles with irregular sampling or major levelling problems that were eliminated from the database for regions with adequate supplemental observations.

Based on inspection of the gridded and profiled data, Butterworth filters were designed to suppress high-frequency along-track noise [*Oasis*, 2014]. A specially developed interactive program eliminated so-called "tip-tank errors" in several of the recently acquired datasets. Artificial loops in the navigation data were also suppressed.

The new aeromagnetic data were then levelled within the following ten regional clusters: (i) the Antarctic Peninsula and surrounding marine areas, (ii) Dronning Maud Land, (iii) Enderby Land, (iv) Prince Charles and Gamburtsev mountains, (v) Wilkes Land, (vi) Victoria Land, (vii) Marie Byrd Land, (viii) the east and west Antarctic interiors, (ix) the East Antarctic continental margins, and (x) the West Antarctic continental margins [*Golynsky et al.*, 2017]. These data clusters, in turn, were stitched together to produce the ADMAP-2 magnetic anomaly grid of Figure 5 via the procedures outlined in section 4-below. Sub-subsection 3.1.1-below details the data processing of the Antarctic Peninsula survey cluster to exemplify the level of data processing that all 10 of the data clusters underwent. Sub-subsection 3.1.2-below on the other hand, considers the modifications of this workflow example to fully process the disparate survey parameters of the other 9 regional data clusters.

3.1.1 Detailed data processing example for the Antarctic Peninsula survey cluster

Over the Antarctic Peninsula and adjacent oceanic areas, the aeromagnetic survey data with about 20-km flight-line spacing [*Renner et al.*, 1985; *Dalziel and Pankhurst*, 1987; *Garrett et al.*, 1987; *Maslanyj et al.*, 1991; *Johnson and Smith*, 1992; *Johnson and Ferris*, 1997; *Golynsky et al.*, 2000]. were levelled and combined with available reconnaissance flight data [*Behrendt and Bentley*, 1968; *Hittelman et al.*, 1996; *LaBrecque et al.*, 1986; *Forsberg et al.*, 2017]. Some of the more detailed surveys with 3- to 5-km flight-line spacing were processed using standard levelling procedures [*Johnson*, 1999; *Ghidella et al.*, 2013; *Golynsky and Masolov*, 1999; *Ferraccioli et al.*, 2006; *Ferris et al.*, 2002], whereas the more detailed surveys such as over Adelaide Island [*Jordan et al.*, 2014] required no reprocessing.

After initial gridding, many of these surveys displayed corrugation effects of alternating maxima and minima on a few or more neighboring survey lines. As a rule, the corrugations stemmed from a lack of intersecting lines for internal levelling. However the line-levelling in some cases increased corrugation noise, which was suppressed by repeated levelling with appropriately adjusted corrections.

The new surveys flown with ~20-km flight-line spacing were used to test the consistency between regional BAS and Russian (Soviet) datasets that had been integrated side-by-side into the ADMAP-1 grid [*Golynsky et al.*, 2002b]. The test showed that the Russian dataset was offset by some 34 nT below the mean BAS anomaly amplitude. Accordingly, the Russian data were adjusted to the mean BAS amplitude, where the improved correspondence between the datasets was confirmed by cross-over analysis. Profiles that required additional levelling used constant DC-shift corrections, trend removal by low-order polynomials, and other standard adjustment procedures. Splined corrections also helped to suppress anomaly gradient discrepancies.

This improved dataset was leveled with the 2010–2011 BAS survey flown over the Möller and Institute (MI) Ice Stream catchments, and reconnaissance flights over the Antarctic Peninsula's Larsen Ice Shelf and Ellsworth Land [*Jordan et al.*, 2013b]. The main MI-survey grid was flown at a 7.5-km line spacing with 25-km tie lines. Exploratory lines with 50-km spacing provided cross-points with lines in surveys over the Dufek Intrusion [*Ferris et al.*, 2003] and the West Antarctic Rift System (WARS) and adjacent regions [*Behrendt et al.*, 1994; *Studinger et al.*, 2002; *Vaughan et al.*, 2006]. The amplitude differences of the MI data relative to the combined BAS/Russian datasets did not exceed 27.5 nT, and thus this value was added to all MI-survey lines. Applying adjustments based exclusively on traditional levelling of the combined BAS/Russian datasets left the more detailed and reliable MI-survey data unchanged.

The ICEGRAV data that international surveying had mapped over both sides of the Antarctic Peninsula [*Forsberg et al.*, 2018] were processed next. These data significantly improved coverage over regions of the Antarctic Peninsula and its margins that the older BAS data sampled only poorly. Delivered in completely raw form, the survey lines were filtered to remove noise spikes and other artefacts before levelling. As most of the data were unedited, numerous corrections were implemented that included splitting flights into line segments, filtering out instrument noise and other non-geologic data irregularities, and correcting numerous tip-tank errors. Preliminary visual inspections of the line data also removed spikes in all channels.

ICEGRAV's aeromagnetic profiles vary in altitude from 2500 to 4500 m across the Antarctic Peninsula, and so were downward continued using Geosoft's algorithms [*Pilkington and Thurston*, 2001]. The profiles overlapping the offshore USAC data were downward continued to the mean survey altitude of 500 m, whereas over the Antarctic Peninsula, they were downward continued to the mean BAS survey flight altitude of 2500 m. The downward continuation is limited by the amplification of residual noise and the non-uniqueness of the process. However, the effects of these limitations were minimized by applying spine-based corrections calculated from intersections with profiles of lower-altitude surveys. Additional adjustments to the ICEGRAV survey data included constant

DC-shift corrections, low-order polynomial trend removal, and other standard methods. Splined corrections also helped to suppress anomaly gradient discrepancies.

Project Magnet data flown at altitudes of 6000–9000 m were similarly downward continued and integrated with the USAC survey data collected over 5000–10000 m altitude flights from South America to the Weddell and Bellingshausen Seas, and the ICEGRAV data obtained by 5000–8000 m altitude flights over the Bellingshausen Sea. For example, Project Magnet profiles crossing the Antarctic Peninsula and surrounding oceanic areas were split into shorter fragments, and downward continued to the mean 500-m altitude of the USAC surveys over the Weddell and the Bellingshausen Seas, and to 2500-m altitude over the Antarctic Peninsula. The processing also suppressed non-geological high-frequency noise effects on each profile.

Cross-over analysis levelled the Project Magnet data relative to the USAC surveys in the Weddell and Bellingshausen Seas and the BAS profiles over the Antarctic Peninsula. This step highlighted the presence of an unrealistic negative trend in the regional ~20-km spaced BAS profiles over the northern part of the Antarctic Peninsula. To eliminate it, the BAS data were adjusted to intersect the ICEGRAV profiles. Additional tensioned spline adjustments helped mitigate line intersection discrepancies where necessary.

The elimination of this negative trend facilitated using the higher altitude data to estimate effective crustal anomaly values in the coverage gaps of lower altitude surveys. The northern Bellingshausen Sea shows a clear example where the positive and negative linear anomalies that presumably constrain seafloor spreading processes [*Eagles*, 2004; *Eagles et al.*, 2009] are significantly enhanced relative to their muted signatures in the smoothed background of the higher altitude ADMAP-1 data [*Golynsky et al.*, 2001]

The SPRI survey data for the Weddell Sea sector [*Drewry*, 1983] were previously adjusted to minimize their root-mean-square cross-over error, and gridded for the ADMAP-1 compilation [*Golynsky et al.*, 2002b]. These data, however, were not included with the publicly available ADMAP-1 DVD because the magnetic profiles contained a huge number of spikes induced by the simultaneous operation of the ice-penetrating radar. Unfortunately, this problem also contaminated the magnetic measurements obtained over the flights into the interior of Antarctica. For ADMAP-2, a newly developed interactive procedure replaced the spikes with values interpolated from the surrounding anomaly values using Akima's algorithm [*Akima*, 1970]. However, even this procedure was unable to salvage numerous SPRI data profile fragments for the ADMAP-2 compilation.

After cleaning out undesired spikes and other noise, the SPRI profiles were levelled and merged with the neighboring BAS and Russian survey profiles. They also were merged with the more detailed survey lines from the catchments of the Institute and Möller ice streams [*Jordan et al.*, 2013b], the South Pole transect data [*Studinger et al.*, 2006], and various CASERTZ survey profiles [*Blankenship et al.*, 1993; *Behrendt et al.*, 1994]. These datasets provided a static framework into which the SPRI profiles were adjusted using cross-over and DC-shift corrections, as well as low-order polynomial trend removals and other corrections. These procedures facilitated incorporating most of the SPRI data into the ADMAP-2 compilation.

Geosoft's Oasis montaj (OM) package processed the four new BAS aeromagnetic datasets collected over the central Antarctic Peninsula [*Johnson*, 1999; *Ferraccioli et al.*, 2006] into a coherent database. The profiles over the Marguerite Bay region were flown at ~1250-m altitude, and upward continued to 2500 m to emphasize the broader effects of the deeper crustal sources. However, this transformation also unified the dataset for the survey area at a constant 2500-m altitude.

Over the central Antarctic Peninsula, low-pass filtering suppressed high-frequency errors in the flight-line data. Also removed were erroneous loops or returns along the profiles, and any repeated observation coordinates were linearly re-interpolated between neighboring points. This preprocessing substantially improved the perceptibility of magnetic variations and reduced artificial anomaly roughness and offsets along the profiles.

The data quality assessed from the cross-over errors showed that the central Antarctic Peninsula datasets required minimal flight- and tie-line levelling. Thus, only a limited number of profiles were re-adjusted using OM's statistical levelling option with the least-squares removal of order "0" to "1" components. Flight-line striping artefacts or corrugations were particularly noticeable in the levelled gridded data for several areas with limited tie-lines. The most prominent example occurred in the southwestern corner of the surveyed area where several Anvers Island profiles showed minor low-amplitude artefacts. They appeared to be of non-geological origin, and thus were manually eliminated using OM's statistical levelling option. This procedure was repeated several times until the corrugation effects disappeared in the gridded data in shaded relief with the sun angle perpendicular to the profile's strike.

Additional processing of the central Antarctic Peninsula data considered their level offsets to overlapping surveys. The levelling differences were taken relative to the centrally located survey [Johnson, 1999]. This central survey extensively overlapped the other four surveys revealing discrepancies that ranged from -68 nT for the SPARC survey [Ferraccioli et al., 2006] to 43 nT for the LEX-indexed survey [Johnson, 1999]. The determined offsets were added or subtracted to each survey profile as appropriate.

For estimating and eliminating discrepancies between profiles in overlapping areas, the flight altitude differences and errors in measuring diurnal variations proved most useful. Substantial errors at intersections between neighboring survey profiles were analyzed individually to identify which of the profiles should be corrected. The analysis took into consideration the observed anomaly gradients, intensities, and trends of the intersecting points along the line, as well as the spectral characteristics, altitude differences, and other features of the profiles. For eliminating these errors, tensioned cubic splines fit to the intersection's discrepancies estimated the corrections.

The reprocessed central Antarctic Peninsula magnetic anomaly data were combined with the regional BAS profiles flown at ~20-km flight line spacing. This allowed us to establish the possible base level differences between the two datasets by examining cross-point errors in low-gradient segments of the longest tie-lines in the detailed dataset and the reconnaissance profiles. The determined systematic bias (DC-shift) between the two datasets did not exceed 68 nT, which also is roughly the amount by which the detailed dataset's average exceeded the regional dataset's average. Subtracting this value, accordingly, from all detailed profiles maintained the initial level of the SPARC survey [Ferraccioli et al., 2006].

The newly integrated database allowed the effective re-levelling of a number of regional profiles based on the detailed profiles in the Antarctic Peninsula regions lacking sufficient tie-line networks. The detailed profiles allowed checking for possible inconsistencies between the two datasets using cross-over analysis and the other above approaches. In general, the analysis left the detailed data unaffected relative to the reconnaissance data that DC-shifts and other adjustments corrected.

3.1.2 Processing the other ADMAP-2 compilation clusters

The remaining nine ADMAP-2 survey clusters were processed by workflows much like that used for the Antarctic Peninsula data. However, survey parameter variations within these clusters warranted considering additional processing issues. For example, frequency domain microlevelling was performed locally to reduce residual flight-line corrugation noise arising mostly from correcting airborne magnetic observations for unsmoothed base station-measured diurnal variations (e.g., [Luyendyk et al., 2003; Jokat et al., 2010]). The cross-over analysis also identified many aeromagnetic profiles with 500–600 nT regional base station-measured diurnal variations that were adjusted using splines and other low-order polynomials.

The use of all profiles within overlapping survey areas recovered the maximum possible magnetic anomaly detail. Initially, these profiles revealed possible level misfits or systematic biases between adjoining surveys. However, variance (dispersion) analysis established profile adjustments that essentially nullified the dispersion of the regional datasets. After applying all corrections, cross-over analysis of the adjusted profiles levelled them with the overlapping surveys. The corrections were mostly applicable to the older, poorer quality survey profiles except across the continental-oceanic margins where systematic differences in survey altitude between marine and airborne data occur. In merging surveys across the coastlines, preference was given to the typically better-quality, and more uniformly distributed aeromagnetic data over the shipborne measurements.

Over the shelf regions of Antarctica, marine data coverage commonly was sparse and only occasionally overlapped aeromagnetic surveys. For example, the continental margin-crossing aeromagnetic flights over Enderby and MacRobertson Lands were unchanged when merged and gridded with the marine data [Golynsky et al., 2002a]. Merging the Lützow-Holm Bay [Jokat et al., 2010] and Amundsen Sea [Gohl et al., 2013] survey lines flown at ~150-m altitude with marine profiles also yielded minimal downward continuation error. However, in other regions such as the eastern Weddell Sea [Jokat et al., 2003] and Riiser-Larsen Sea [Leinweber and Jokat, 2012], the merger of overlapping airborne and marine datasets required more extensive profile-specific downward continuation and levelling efforts.

4 Final grid production

To compile the ADMAP-2 grid in Figure 5, the regional grids of levelled and adjusted profiles were stitched to the more detailed grids based on aeromagnetic surveys with relatively tight flight-line spacings that varied from 0.5 to 5 km [Golynsky et al., 2017]. The more irregular networks of regional profiles were merged first to provide a framework for stitching together the more recently acquired, strongly weighted detailed anomaly grids. Masking each grid before stitching excluded extrapolated values along the

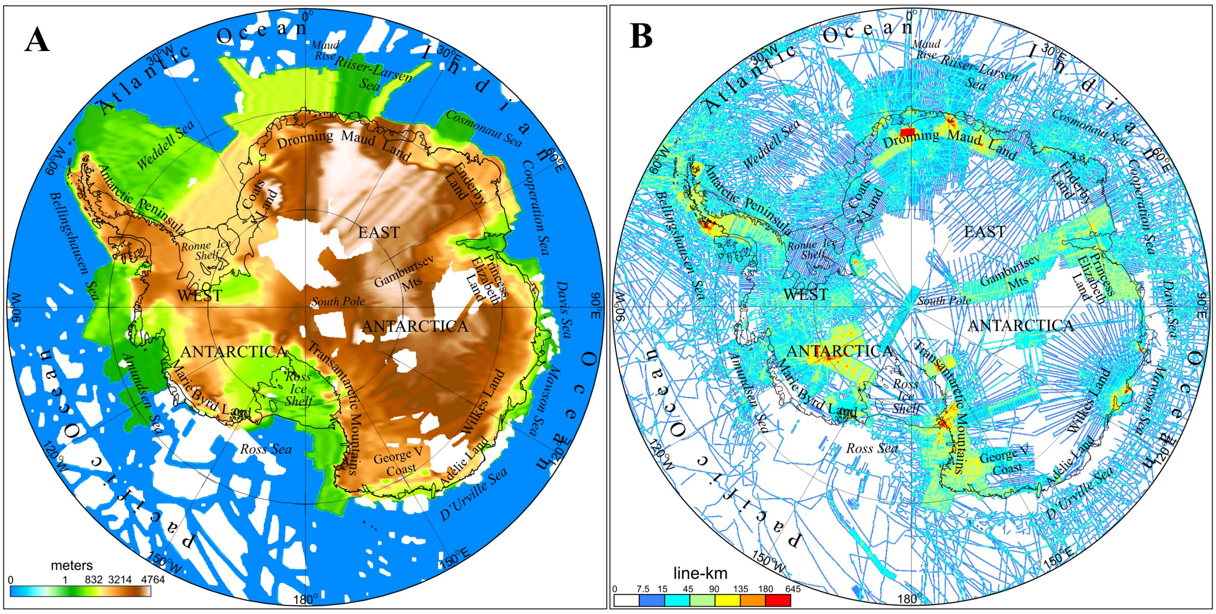

Figure 6: Altitude and density characteristics of magnetic surveys included into the ADMAP-2 compilation. **Map A** shows the flight elevation variations associated with the gridded magnetic anomaly values in Figure 5. The data density **Map B** shows the line-km length of survey data within the window radius of 7.5 km about each gridded anomaly estimate in Figure 5.

boundaries. The gridding employed the standard tensionless minimum curvature technique [*Briggs*, 1974].

Applications of OM's GridKnit™ suturing tool [*Oasis*, 2014] effectively merged the detailed and reconnaissance grids. In particular, the GridKnit™ suturing tool selected the grid values along the suture line from each grid, and then calculated the differences between the values. The Fast Fourier Transform of the differences yielded differential wavenumber-by-wavenumber corrections that were integrated into a correction weighting scheme to smoothly join the grid edges.

The variable spacing of the aeromagnetic survey lines resulted in different grid intervals for applying OM's minimum curvature gridding algorithm, which generally was set to a third or a quarter of the applicable line spacing. For example, the aeromagnetic data collected with the line spacing of 1 km by BAS' MAMOG survey over Dronning Maud Land were gridded at the 250-m interval [*Ferraccioli et al.*, 2005b]. However, the regional surveys over oceanic areas and in Antarctica's interior, like those flown by the Russian fixed-winged Il-18 aircraft and the ICECAP/IceBridge project, were gridded at the 5 km interval [*Aitken et al.*, 2014; *Golynsky et al.*, 2002a].

For the ADMAP-2 grid of Figure 5, all the aeromagnetic and marine grids were merged at the 1.5-km interval and filtered to pass anomaly wavelengths of about 7 km and greater. To retain the resolution of the individual grids as much as possible, no continuations to a common level were implemented. Thus, Figure 6A shows the elevation variations for the gridded magnetic anomaly values, and for quality control purposes, Figure 6B gives the data density map with the line-km length of survey profiles within the 7.5-km radius cap centered on each gridded anomaly estimate. Geologic interpretation of the compilation, therefore, should account for the spectral effects of the differing flight-line spacings and survey altitudes. In general, the anomaly patterns are most consistent with the magnetic effects of the underlying geology for the areas of detailed, good quality survey coverage, and less so in the other areas.

5 Discussion

This section reviews opportunities for expanding the ADMAP-2 compilation and broadly considers the geological issues that the new data may address. The ADMAP-2 compilation merged the near-surface magnetic survey data collected mainly between the IGY 1957–58 and 2013, although two surveys completed by the PMGE over Princess Elizabeth Land during 2014–2015 and the GIMBLE survey obtained by the University of Texas in 2013–2014 over Marie Byrd Land [*Young et al.*, 2017a] were also included. It provided new insights into the structure and evolution of Antarctica, including some of its Proterozoic-Archean cratons and Proterozoic-Paleozoic orogens, Paleozoic-Cenozoic magmatic arcs, continental rift systems and rifted margins, large igneous provinces, and the surrounding oceanic gateways (e.g., [*Golynsky et al.*, 2006a; *Ferraccioli et al.*, 2009b, 2011; *Mieth and Jokat*, 2014; *Kim et al.*, 2022].)

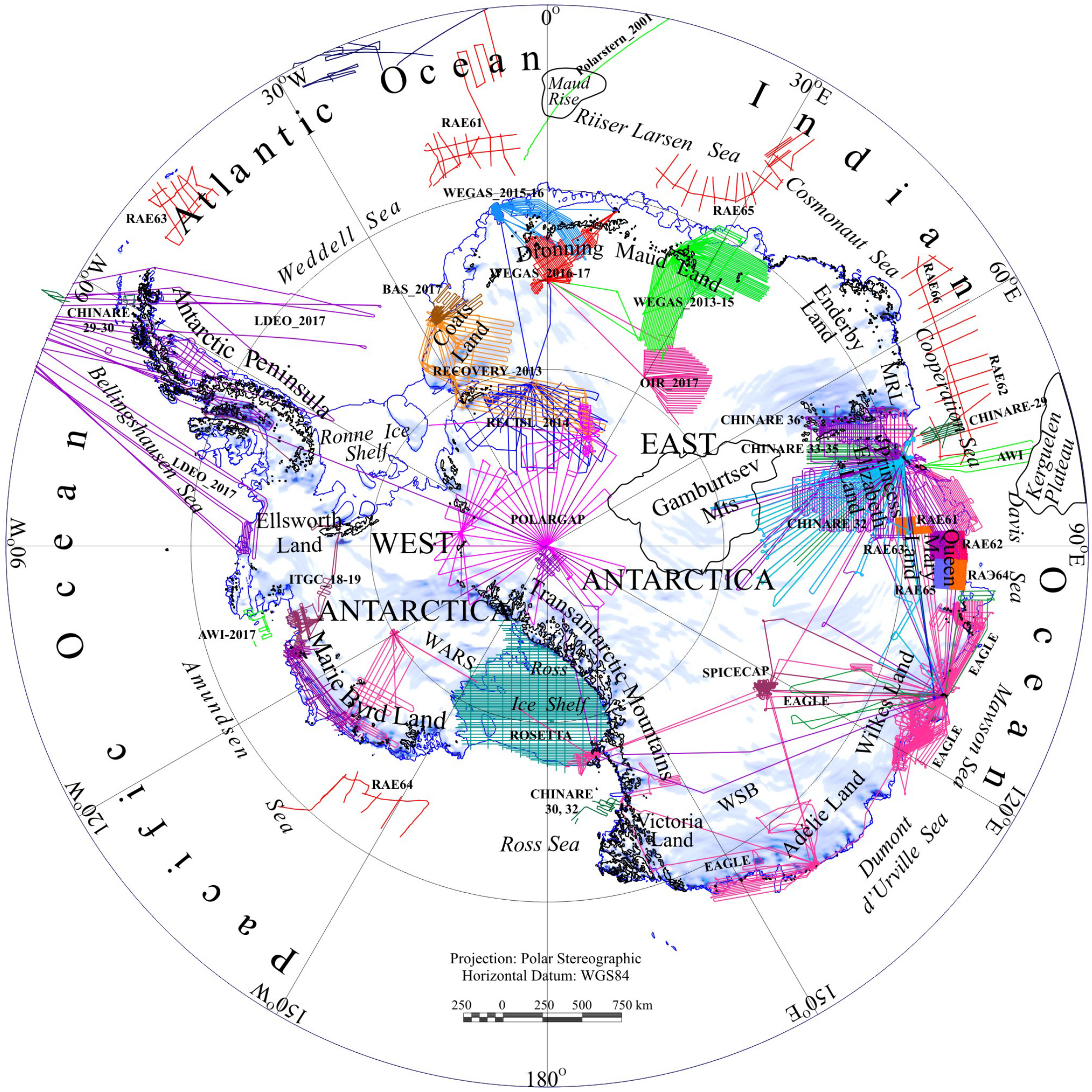

Figure 7: Line coverage of the post-ADMAP-2 near-surface magnetic surveys superimposed on a shaded relief map of the surface topography of Antarctica.

However, China, Denmark, Germany, Russia, and the UK and USA, as well as other international programs continue to expand geophysical mapping of tectonic and geologic structures of Antarctica's interior and continental margins. For example, Figure 7 shows that these campaigns obtained more than 660,000 line-km of new airborne and ship magnetic anomaly data since 2013 when data submissions for the ADMAP-2 compilation were effectively terminated [*Golynsky et al.*, 2017].

More specifically, with the 2013–2014 season, the Alfred Wegener Institute (AWI) in collaboration with the BGR collected about 114,700 km of aeromagnetic data in and around Dronning Maud Land. In the same season and the next, a large campaign of nearly 30 survey flights was carried out over the Sør Rondane Mountains and neighboring regions. This survey's results help to constrain the amalgamation of Gondwana from multiple volcanic island arc collisions between the ancient continental cores that today constitute continental elements of Antarctica, Africa and Arabia [*Ruppel et al.*, 2018].

In the 2015–2016 and 2016–2017 seasons, AWI completed two surveys over the Forster Magnetic Anomaly [*Mieth and Jokat*, 2014]. The survey data were combined with previous survey profiles to reduce the effective line spacing of the profile coverage from 10 km to 5 km. Interpretation of these data will offer new insights on the amalgamation of Gondwana. In the 2015–2016 field season, two high-resolution survey flights collected magnetic data over the Ekström Ice Shelf for significantly enhanced insight on the geophysical setting occupied by the Neumayer III station (70.645°S, 8.264°W). In the 2013–2014 and 2016–2017 seasons, AWI also collected gravity, magnetic and ice-probing radar data over the poorly known Recovery Lakes and Dome F regions, respectively.

Over the five austral seasons of the 2015–2020 period, Chinese scientists surveyed with moderately high spatial resolution one of the largest gaps in data coverage located in Princess Elizabeth Land (PEL). Geophysical surveying during the first season by the Snow Eagle 601 airborne platform flew mostly on lines radiating from the Russian Progress Station (69.37°S, 76.37°E) in the Larsemann Hills [*Cui et al.*, 2020; *Li et al.*, 2021]. The aerial survey maintained flight altitude at 600 m above the ice surface and covered the Grove Mountains, Amery Ice Shelf, Shackleton Ice Shelf, South Prince Charles Mountains, Ridge B, Titan Dome, West Ice Shelf, George V Coast, David Glacier Catchment, and other critical areas of East Antarctica. The Chinese National Antarctic Research Expeditions (CHINAREs) collected more than 121,000 line-km of aeromagnetic data in these regions.

Both the ICECAP/EAGLE (East Antarctic Grounding Lines Experiments) and ICECAP/PEL campaigns maintain active airborne surveys in these East Antarctic regions through international collaborations of scientists from Australia, China, France, Italy, South Korea, the UK, and USA. These programs mainly emphasize coastal areas like the George V Coast, which is poorly surveyed, but critically important for understanding the evolution of the Earth's largest ice sheet. CHINARE's comprehensive aerogeophysical mapping of PEL provides the first look at the gross lithology and large-scale structural geology of the central Antarctic Plate, which is the keystone for tectonic reconstructions, the debate over the extent of Indian-affiliated lithosphere in Antarctica, and other geologic issues [*Boger et al.*, 2001; *Aitken et al.*, 2014; *Daczko et al.*, 2018; *Mulder et al.*, 2019].

The East Antarctic Grounding Line Experiment (EAGLE) consists of large international programs focused on understanding the impact of coastal ocean circulation and subglacial freshwater discharge on Antarctic ice shelf cavities and the inner continental shelves of major glacier outlets [*Roberts et al.*, 2018]. In the 2015–2016 and 2016–2017 field seasons, EAGLE was implemented as part of the ICECAP collaboration to collect aerogeophysical data mainly over the East Antarctic critical grounding zone sections of the Totten Glacier, Denman Glacier, and Cook Ice Shelf. These data were merged with data from reconnaissance flights over the three regions and the high-resolution survey for old ice near Dome C (East Antarctica) that the ICECAP project surveyed in 2016 [*Young et al.*, 2017b]. The reconnaissance flight data densified the ICECAP/Icebridge project's network to better constrain the complex crustal geology beneath the ice sheet, and decode the possible effects of the sediments and heat flow on ice sheet stability. The combined data also provide crucial new inputs for ice sheet and climate modeling, and key site survey support to ice and bedrock drilling efforts. Since 2017, these collaborative efforts have collected more than 136,000 line-km of airborne magnetic data.

The Coats Land crust includes key piercing points for reconstructing linkages between East Antarctica and the Laurentian Mid-Continent Rift System within Rodinia [*Gose et al.*, 1997]. It also holds the inferred remnants of the major suture zone active during Gondwana's amalgamation in Pan-African times. It was largely unexplored until the ICEGRAV 2012–2013 field season, when the Recovery Frontier aerogeophysical survey of the region's major ice stream was flown in a Danish-Norwegian-UK-Argentine collaboration that collected some 24,215 line-km of laser altimetry, ice-probing radar, gravity and magnetic data [*Ferraccioli et al.*, 2018; *Forsberg et al.*, 2018]. The flight lines of opportunity were selected to fill major gaps in the Antarctic gravity coverage over the largely ice-covered Recovery and Slessor glacier catchments [*Scheinert et al.*, 2016].

The new data help to map the extent of major subglacial faults and thereby delineate the tectonic boundaries of the Coats Land, Shackleton Range, and Dronning Maud Land (DML) crustal provinces. They also facilitate studying the inferred Pan-African suture zone in the Shackleton Range and its tectonic relationships with the older Mawson Craton and Grenvillian terranes of DML and East Antarctica [*Ferraccioli et al.*, 2020].

The primary focus of the European Space Agency's (ESA) Antarctic airborne PolarGap survey during the 2015–2016 campaign was to obtain high-quality airborne gravity data for the polar cap south of 83.5°S to help augment the lack of satellite gravity coverage by ESA's near-polar orbiting GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) mission [*Forsberg et al.*, 2017]. Some 35,400 line-km of aeromagnetic and ice-penetrating radar data were also collected to help augment the south polar gap in ESA's near-polar orbiting geomagnetic field mapping SWARM mission, and the continental-scale topographic BEDMAP-2 [*Fretwell et al.*, 2013] and magnetic anomaly ADMAP-2 compilations. The PolarGap airborne survey covered the so called 'pole of ignorance' with reconnaissance airborne geophysical data that included medium-resolution magnetic and gravity anomaly estimates.

Analyses of the ADMAP-2 compilation augmented by the new datasets over the Recovery Lakes and South Pole frontiers may reveal further insights on the complex mosaic of Precambrian crustal provinces beneath East Antarctica [*Ferraccioli et al.*, 2020]. New geophysical constraints can critically test different hypotheses on East-West Gondwana amalgamation along the Shackleton and other candidate suture zones. In general, these data may provide a unique window on several distinct Precambrian terranes at the inferred leading edge of the composite Mawson Continent, and the unique occurrences of Pan-African rocks of ophiolitic affinity [*Talarico et al.*, 1999].

The Ross Ice Shelf (RIS) is one of the largest regions of ignorance because very little aeromagnetic surveying has been acquired here since the pioneering aerogeophysical surveys of the 1960's and 1970's [*Behrendt and Bentley*, 1968]. These early surveys were mainly flown as transits to, from, and between the main survey areas (e.g., [*Drewry*, 1983]. The RIS was crossed by only two profiles flown in 2013 by the NASA's Operation IceBridge aerogeophysical campaign [*Cochran et al.*, 2014]. The situation changed dramatically in 2015–2017 when the ROSETTA project conducted three surveying seasons using the LC-130 aircraft to map gravity, magnetic, ice-penetrating radar, and laser altimetry data [*Tinto et al.*, 2019]. ROSETTA's main survey lines were spaced at 10 km and oriented E–W, with N–S tie lines spaced at 55 km intervals. Flight elevation was on average 750 m above ground level at the flight speed of 180 knots. The survey was designed to increase the resolution of seafloor bathymetry to enhance ocean and ice sheet models for new insights into the evolution of ice flow and the tectonic development of the Ross Embayment.

The RAE 60–65 airborne surveys over Princess Elizabeth Land (PEL) in 2015–2020 were completed by the Russian Polar Marine Geosurvey Expedition (PMGE) using the standard profile spacing of 5 km with tie-line intervals of 15–25 km. The aerogeophysical surveys collected more than 35,000 line-km of magnetic and ice-probing radar data over the largely ice-covered PEL. These surveys provided new constraints on the suture between Indo-Antarctica and Australo-Antarctica (IAAS) that trends south-southeast from the Scott Glacier inland for some 1500 km [*Aitken et al.*, 2014]. More recently, it's been argued that the India-Australia paleo-plate boundary may pass through Antarctica close to the Mirny Station (93.01°E, 66.55°S) because it appears to correspond to an unnamed subglacial fault identified by *Aitken et al.* [2014] which intersects the coast near ~94°E. However, new detailed Russian bedrock topography and magnetic anomaly data mapped to the Mirny Station's east clearly fail to observe *Daczko et al.* [2018]'s dubbed Mirny Fault [*Golynsky et al.*, in-preparation] so that the location of the IAAS remains enigmatic.

Since the publication of the ADMAP-2 compilation, the PMGE programs mapped more than 23,000 line-km of integrated seismic, gravity and magnetic data along the continental margin of Antarctica. Conducted in the Amundsen, Cooperation, and Riiser Larsen seas, as well as in the western and eastern Weddell Sea, the data provide important new constraints on the petrological and tectonic attributes of the crust, as well as the continent-to-ocean boundary, sea-floor spreading, and Gondwana breakup [*Leychenkov et al.*, 2016]. The CHINARE expeditions collected similar geophysical data in the Cooperation and Ross Seas and around the Antarctic Peninsula [*Gao et al.*, 2017].

6 Conclusions

The ADMAP-2 compilation Figure 5 is the most wide-ranging and self-consistent map made to date of the Antarctic's crustal magnetic field. Its magnetic anomalies reflect a detailed tapestry of crustal terranes defined by diverse lithologies, ages, and thermal and metamorphic conditions [*Golynsky*, 2007; *McLean et al.*, 2009; *Ferraccioli et al.*, 2011; *Aitken et al.*, 2014; *Mieth and Jokat*, 2014].

Offshore, ADMAP-2's 430,000 line-km of new airborne and marine survey data significantly transform our view of the East Antarctic continental margins. Inland, the compilation delineates the diversity of Proterozoic-Archaean cratons, Proterozoic-Palaeozoic mobile belts, Palaeozoic-Cenozoic magmatic arc systems, and the rift basins between East and West Antarctica [*Jokat et al.*, 2010; *Ferraccioli et al.*, 2011; *Gohl et al.*, 2013; *Jordan et al.*, 2013a; *Aitken et al.*, 2014]. ADMAP-2 also resolves basement terranes and their intervening suture zones, intra-continental and continental margin rift basins, and regional plutonic and volcanic features like the Ferrar dolerites and Kirkpatrick basalts [*Ferraccioli and Bozzo*, 2003; *Ferraccioli et al.*, 2005a; *Golynsky et al.*, 2006b; *Goodge and Finn*, 2010; *Ferraccioli et al.*, 2011; *Mieth et al.*, 2014]. In combination with ice-probing radar, gravity, and other geophysical and geological data, the ADMAP-2 compilation provides transformative insights into continental rifting, intraplate orogenesis and basin subsidence, subduction and terrane accretion, seafloor spreading, and other fundamental global geological processes that affect the Antarctic. However, the still-patchy distribution of ADMAP-2's input data means that interpreting the grids requires care. Data coverage remains an important limiting factor in using ADMAP-2 for geological understanding of some areas offshore of West Antarctica and in the interior of East Antarctica.

Combining Swarm satellite magnetic observations with the near-surface ADMAP-2 grid using localized spherical coordinate equivalent point source (EPS) models (e.g., [*Kim et al.*, 2022]) or spherical harmonic Slepian basis functions [*Kim and von Frese*, 2017] can yield further insights on the crustal anomaly components in both datasets. By honoring the data sets in the least-squares sense, the EPS and Slepian coefficients improve modelling the crustal magnetic field at intervening altitudes where the standard downward or upward continuation of each input dataset is much less reliable. The Slepian coefficients also contribute updated global spherical harmonic coefficients, and thus can substantially enhance the Antarctic predictions of the World Digital Magnetic Anomaly Map.

The synthesis of the individual magnetic surveys into the ADMAP-2 compilation greatly enhances their utility for geological studies of the Antarctic. The acquisition of more than 616,000 line-km of new airborne and shipborne data by the international geomagnetic community is a significant contribution to the ADMAP database and the production of the next generation magnetic anomaly map for the Antarctic region south of 60°S. However, at present many of the new aeromagnetic surveys are not in public domain and cannot be combined with previous datasets. When integrated into the ADMAP compilation, these data may provide further insights on the complex mosaic of Precambrian crustal provinces that define the large-scale crustal architecture of East Antarctica and its linkages with the supercontinents Rodinia and Gondwana.

The ADMAP-2 grid of scalar total magnetic field anomaly values at an interval of 1.5 km may be freely downloaded from ADMAP websites maintained by the Alfred Wegener Institute (`https://www.pangaea.de/`), the British Antarctic Survey (`https//www.bas.ac.uk`), and the Korea Polar Research Institute (`http://admap.kopri.re.kr`). These websites also provide complete access to the survey data as supplied and reprocessed for the ADMAP-2 compilation, as well as ADMAP's reports to SCAR on its activities and the status of magnetic surveying in the Antarctic. Efforts also are underway to submit the ADMAP-2 grid and supplemental survey data to NOAA's National Centers for Environmental Information (NCEI) for public dissemination.

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