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Geophysics in Antarctica: Achievements, Current Capabilities, and Future Directions

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Abstract. The Antarctic Ice Sheet (AIS) plays a major role in the global climate, providing a natural laboratory to study the processes that interlink the cryosphere, solid Earth, atmosphere, and hydrosphere. Through its ongoing mass loss, the AIS currently contributes to global-mean sea-level rise at a rate of 0.4 mm/a. However, its impact on and feedback with climate and

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the details associated with sea-level changes are still poorly understood. To generate more reliable projections for the future, there is an urgent need to substantially improve our knowledge of the solid-Earth properties and subsequent response to ice-mass variations in space and time. This issue has been identified as a key question by the international community, strongly supported by the Scientific Committee on Antarctic Research (SCAR).

We review how state-of-the-art Global Navigation Satellite Systems (GNSS) and seismic networks in Antarctica, in combination with further ground-based, airborne and satellite-based geophysical measurements, have been used to significantly advance our understanding of solid-Earth processes and their impact on the cryosphere. Based on these recent achievements, a vision is articulated for science-driven, multidisciplinary geophysical observations and corresponding technological developments. Future research activities should be coordinated to answer the most urgent science questions. For example, how can we consistently test and model, respectively, a realistic mantle rheology, including lateral inhomogeneities and transient relaxation, together with AIS mass changes on all time scales since the last glacial maximum, including Holocene retreat and re-advance? What processes and boundary conditions should coupled ice-sheet / gravity-rotation-deformation models include in order to reflect realistically the complex interaction between the solid Earth, ice sheet and ocean? Long-term observations and improved modelling must be combined to develop precise and reliable projections for Antarctica's future mass change and associated contribution to sea-level change at both regional and global scales.

1 Introduction

Antarctica hosts the largest contiguous ice mass on Earth, with a maximum thickness of almost 4,800 m and a continental extent larger than Europe. Divided into East Antarctica, West Antarctica, and the Antarctic Peninsula, more than 99.6% of the continent is covered by glacial ice, comprising approximately 90% of all global ice coverage and approximately 70% of Earth's freshwater storage. The entire mass of the Antarctic Ice Sheet (AIS) holds the potential to increase global-mean sea level (GMSL) by 58 m (Pritchard et al., 2025). Antarctica plays a major role in the global climate and in the Earth system, and it provides a natural laboratory to study the feedback processes between the cryosphere, solid Earth, atmosphere, and hydrosphere (Fig. 1; (Whitehouse et al., 2019)). However, the evolving impact of the AIS on our changing climate and associated sea-level variations has high uncertainty. The IPCC (2023) reported that AIS contributions to the GMSL rate of rise was four times larger during 2010 to 2019 than during 1992 to 1999. From 2003 to 2016, the AIS contribution to GMSL rise was $0.3\ (\pm 0.1)$ mm/a (Horwath et al., 2022), and it has further increased to $0.4(\pm 0.1)$ mm/a (Ludwigsen et al., 2024) in recent years. This corresponds to 11% of the total GMSL change of $3.72\ (\pm 0.3)$ mm/a (ibidem).

However, the gravity effect caused by glacial isostatic adjustment (GIA) is not well known and, thus, induces a large uncertainty when correcting gravimetric mass-change estimates inferred from measurements by satellite gravimetry missions GRACE and GRACE-FO. The GIA uncertainty alone amounts to about one-third of the total mass change amplitude from 2002 to 2020 (Groh and Horwath, 2021). To improve projections of Antarctica's future contributions to GMSL rise, we must improve our understanding of the complex interactions between different components of the Earth system, such as those between the cryosphere, solid Earth, and ocean. These processes may either stabilize or destabilize the ice sheet, especially at

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its margin. For example, marine ice-sheet instability (MISI; Weertman (1974); Konrad et al. (2015); Gomez et al. (2024)), which describes the instability of the grounding line position, can promote ice-mass loss, but it is strongly dependent on the underlying bed and solid-Earth characteristics as well as on ocean feedback (cf. Sec. 2.5). Marine ice-cliff instability (MICI; Pollard et al., 2015; DeConto and Pollard, 2016; DeConto et al., 2021), rapid calving resulting from ice-shelf collapse, may also lead to increased mass loss. However, since these mechanisms are given low confidence, the IPCC (2023) did not account for these or other such processes in the 'likely range' of GMSL projections. Thus, the upper bound for Antarctica's contribution to projected GMSL at 2100 (relative to 1995–2014) is 0.34 m, but projections that include MICI and MISI increase to 0.56 m (IPCC, 2023). Ultimately, AIS contributions to GMSL rise are potentially the largest, but also the most uncertain, component in future projections.

To gain a better understanding of how the solid Earth may stabilize or destabilize the AIS demands improved knowledge of Earth's material properties, which govern the solid-Earth response to ice-ocean mass loading and unloading in space and time. This also holds true for improving GIA model predictions, which are crucially needed to reduce the large uncertainty when estimating the AIS mass balance from satellite gravimetry. Networks of ground-based observational stations employing Global Navigation Satellite Systems (GNSS) and seismics, and further geophysical techniques such as magnetotellurics, come into play as they provide measurements from which inferences of bedrock displacement and Earth's rheological properties can be made. Further, ground-based observations are needed to constrain key solid-Earth properties such as density, elastic and anelastic parameters, resistivity, electrical and magnetic properties, and geothermal heat flow. Since the AIS largely prevents direct sampling of the sub-ice geologic materials and structure, geophysical instruments are particularly important in studying Antarctica.

To focus on the key question of Antarctica's contribution to GMSL, the Scientific Committee on Antarctic Research (SCAR)[1] initiated its Scientific Research Program "Instabilities and Thresholds in Antarctica" (INSTANT). One focus of this program is to improve the temporal and spatial coverage of ground-based and in-situ observations, which are vital to advancing our understanding of how the solid Earth interacts with the ice, atmosphere, and ocean. Technique-specific capabilities have not been optimally applied either because the severe Antarctic environmental conditions and corresponding logistical difficulties have constrained fieldwork or because synergies spanning different techniques and data types are still in development. Therefore, INSTANT established the sub-committee "Probing the Solid Earth and its Interactions" (PSE), which aims to enhance the performance and effectiveness of geophysical networks by substantially improving cooperation between scientists from different disciplines who are collecting ground-based and in-situ measurements in Antarctica and by promoting collaboration between data collection and modeling efforts.

This review paper summarizes the achievements made by the scientific community over the last three decades in exploiting geodetic and geophysical observations to investigate Antarctic solid-Earth structure and its interactions with other Earth systems. Furthermore, it discusses the state-of-the-art geophysical observational networks that have been deployed as well as broad implications for multidisciplinary research. We articulate a vision for science-driven operations to advance ground-based geophysical observations and instrumentation in Antarctica in the future. In Section 2, we discuss the history of Antarctic geo-

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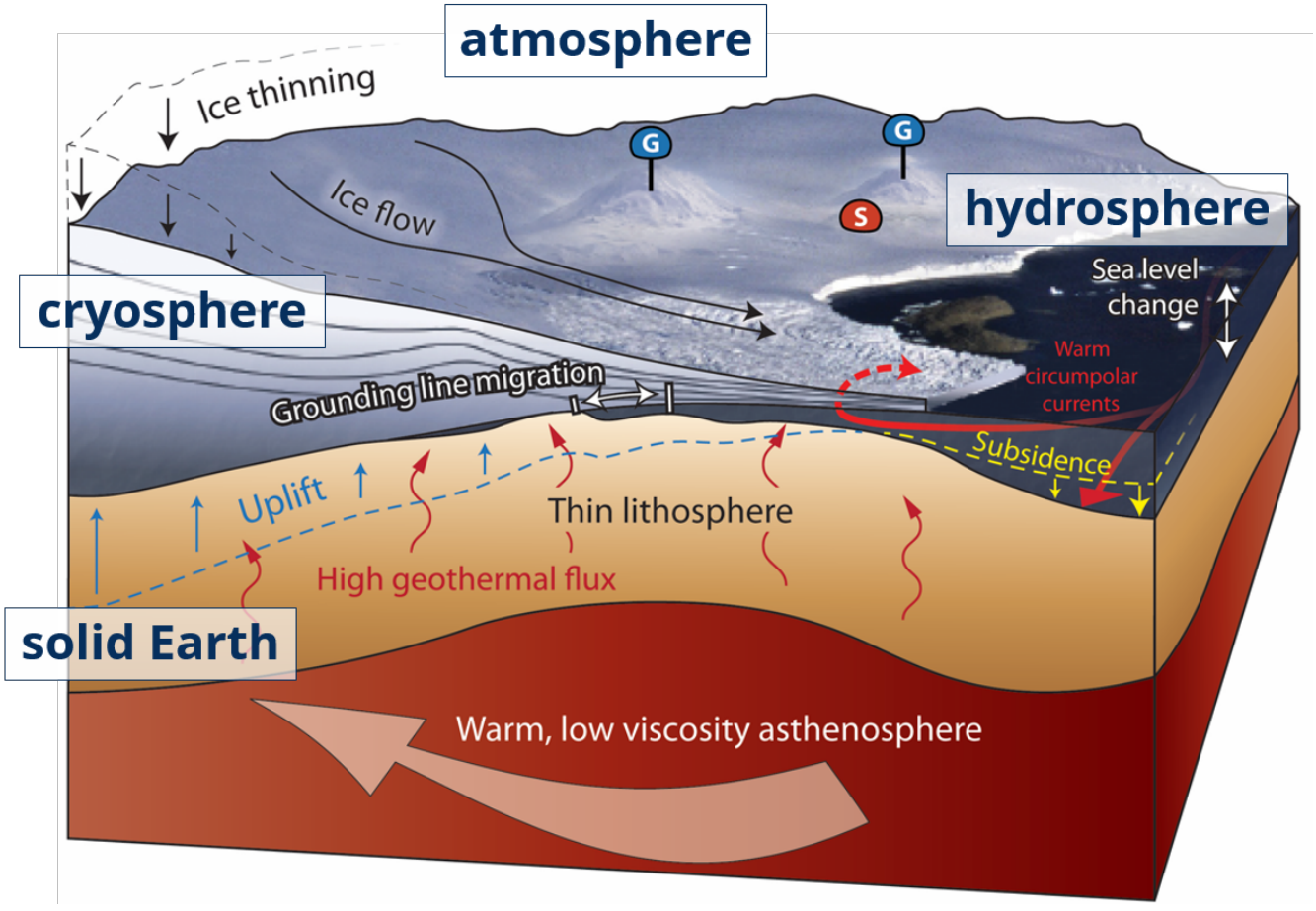


Figure 1. Sketch of the processes that interlink the different spheres of Antarctic Earth science. Adapted from © W. Blocher and the ANET-POLENET Team, 2017.

physical deployments (2.1), the major ground-based observational techniques, such as GNSS (2.2) and seismology (2.3), that have been employed, and ongoing or emerging multidisciplinary efforts (2.4). The following subsections elaborate on the impacts of these efforts on our understanding of GIA (2.5) and on space weather and atmospheric research (2.6). Section 3 then discusses the implications for contemporary and future Antarctic investigations by identifying key science priorities and by critically reviewing the current challenges for future progress and sustained operation. Section 4 provides an overall summary of our conclusions.

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2 Science

2.1 Geophysical Deployments Across Antarctica

Since the turn of the millennium, more than 200 seismic stations and more than 200 geodetic GNSS stations on bedrock have been operated across Antarctica, with a maximum number of daily GNSS observations (about 100) reached in 2016 (Buchta et al., 2025). Over half of these stations have been deployed in West Antarctica, the Antarctic Peninsula, and along the Transantarctic Mountains (Fig. 3). West Antarctica gained special attention since it yields evidence for a different geologic evolution compared to largely cratonic East Antarctica. Caused by the separation of East from West Antarctica between 43 to 26 Ma ago (Cande et al., 2000), the development of the West Antarctic Rift System was accompanied by volcanic activity (especially in Marie Byrd Land) (Zundel et al., 2024). Rifting may have formed deep troughs, possibly expressed now as the Bentley Subglacial Trench or the Mt. Murphy Rift (Spiegel et al., 2016; Zundel et al., 2024).

At present, the West Antarctic Ice Sheet (WAIS) is undergoing major ice-mass loss at a rate of approximately 140 Gt/a (The IMBIE Team, 2018; Shepherd et al., 2019), but confidence in this rate is undermined by uncertain solid-Earth processes, amongst others. GNSS sites used for geodynamic studies must be deployed on exposed bedrock. Such outcrops are more abundant within West Antarctica and the Transantarctic Mountains. On the contrary, seismic instrument deployments do not require placement on bedrock. In East Antarctica, these have focused on particular geologic features, such as the Gamburtsev Subglacial Mountains, which were the focus of a major, coordinated research target during the 4th International Polar Year 2007-2008 (IPY-4). GNSS receivers in East Antarctica are mostly distributed near the continental edge where bedrock exposure is available. The uneven distribution of geophysical networks has left substantial gaps across the continent, not just in East Antarctica but in notable areas of tectonic interest (e.g., the southern Transantarctic Mountains), compromising the ability to construct high-resolution data-informed models. Filling these observational gaps in a strategic way has focused discussion within the polar geoscience community, summarized in this paper.

Most of the geophysical networks across Antarctica arose from single- or multiple-PI, hypothesis-driven proposals. Some of these, such as the Polar Earth Observing Network (POLENET) / Antarctic Network (ANET) project (Wiens et al., 2007), have spanned larger geographical areas and have been maintained for longer periods of time (that is, longer than two years) compared to other typical field experiments. Such long-period deployments provide the necessary continuous observations needed for GNSS surface deformation studies and provide greater volumes of seismic event data, but they also impose a higher logistical burden, particularly if they require multiple field visits to retrieve data and for technical maintenance or snow accumulation removal (Aster and Simons, 2015). Balancing logistical requirements, cost, observational duration, and science productivity when designing network deployments is a critical issue for the polar geophysics community.

Recent technical advances have also improved the quality and completeness of seismic and GNSS data collection in Antarctica. Open data from project deployments allows additional science applications beyond the purposes of their original science objectives. Additionally, these data attract a larger pool of geoscientists into the polar research community. Over the past several years, a growing number of efforts have been aimed at synthesizing collected data, especially during the relatively "quiet era" of fieldwork during and following the COVID-19 pandemic (e.g., Shen et al., 2020; Peña Castro et al., 2024; Buchta

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et al., 2025). New results from such comprehensive data analyses have demonstrated additional scientific merit for the ongoing geophysical infrastructure in Antarctica.

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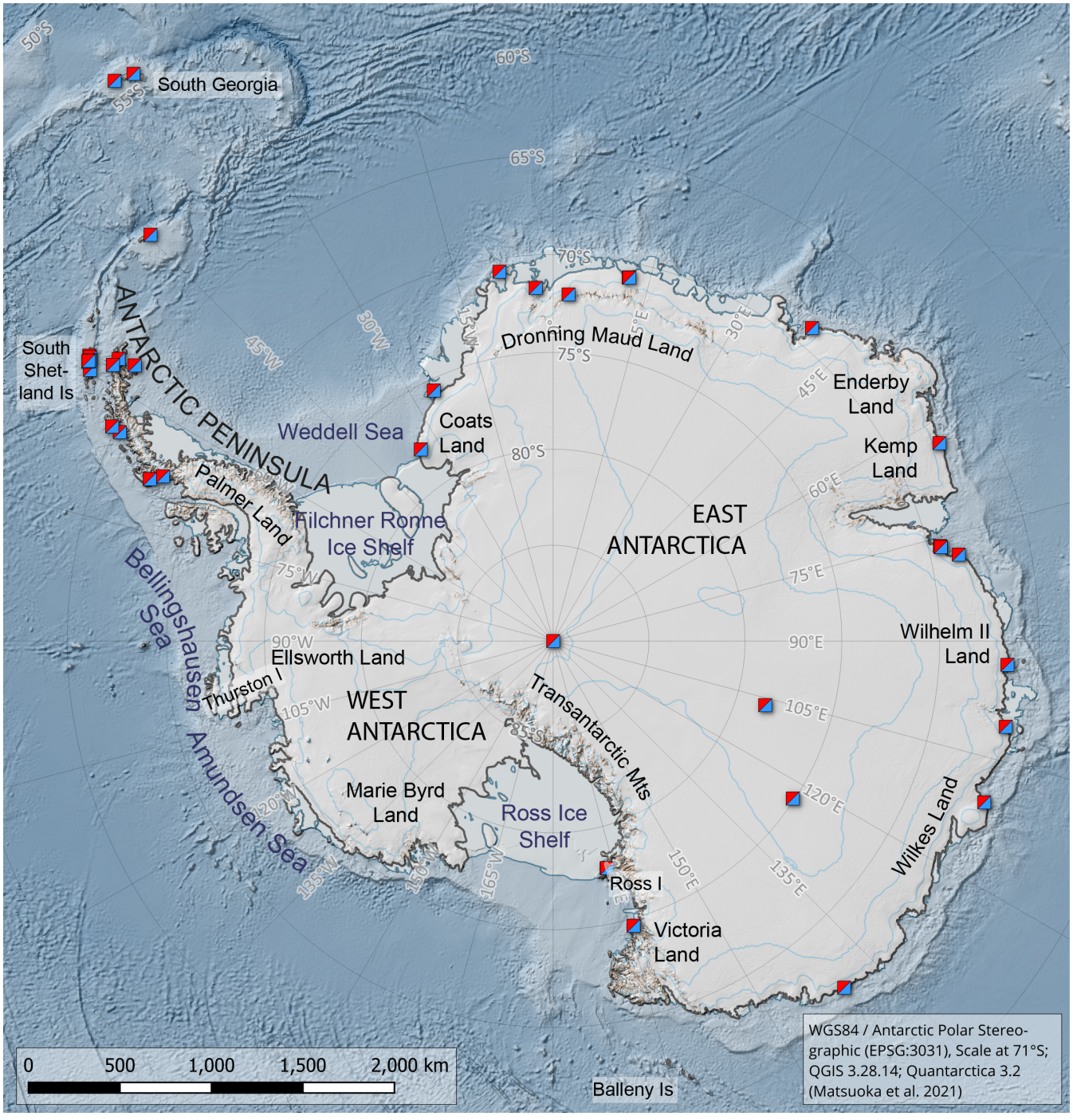


Figure 2. Overview map of Antarctica with geographic names mentioned in the text. Also shown are Antarctic overwintering stations (squares); data: Composite Gazetteer of Antarctica, https://data.aad.gov.au/aadc/gaz/scar/.

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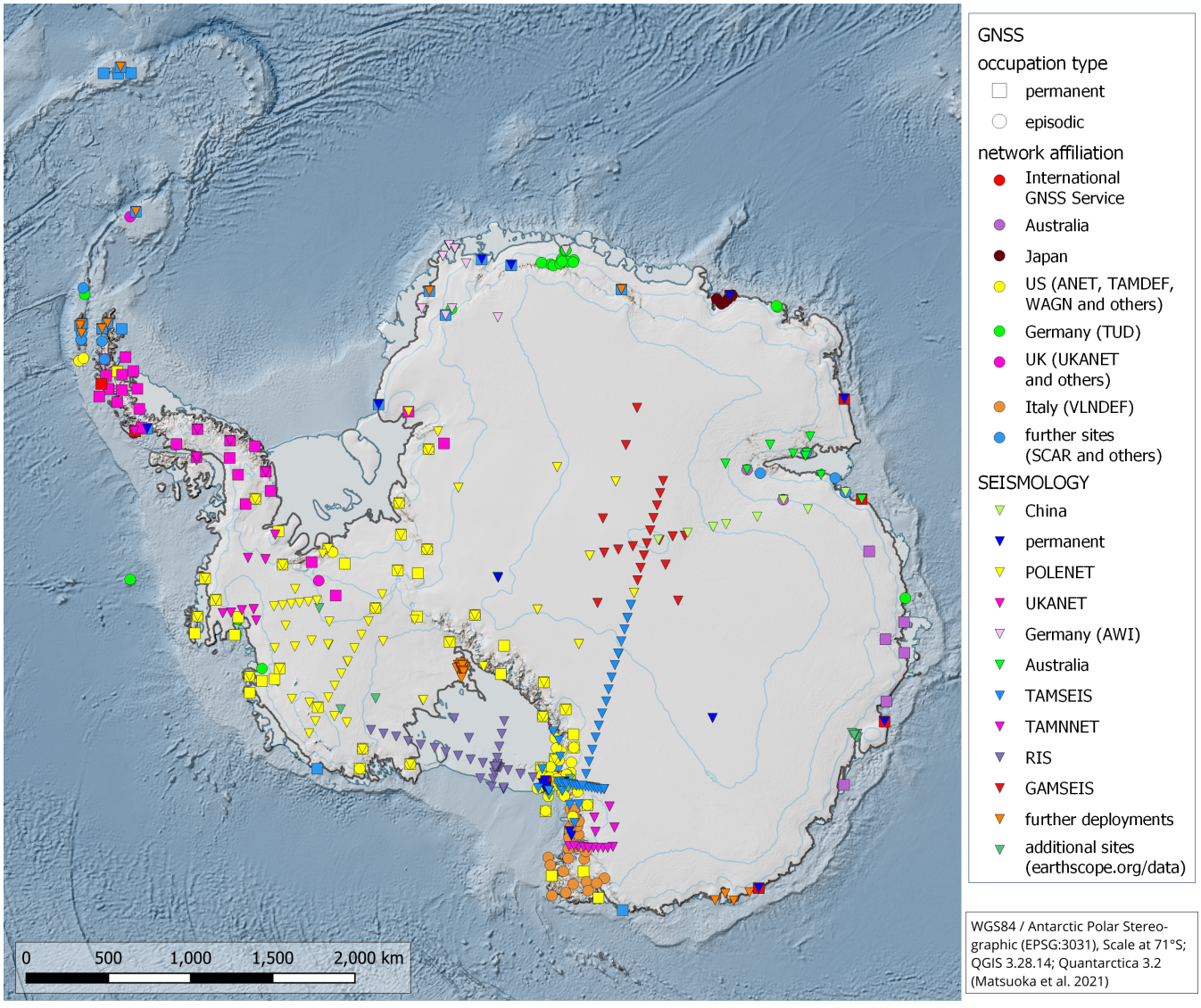


Figure 3. Map summarizing the deployment of GNSS and seismic stations across Antarctica over the past three decades. GNSS occupation type is given by square (permanent) and circle (episodic) symbols, respectively. Colors denote network affiliation, differently for GNSS and seismology (triangles). The uneven distribution of these networks leaves large gaps in parts of East Antarctica, including areas of significant tectonic, glaciological, geological, and climate interest. The deployment of plate- and intraplate-motion GNSS stations is constrained to bedrock exposures; therefore, a higher GNSS site density is found in exposed regions of the Antarctic Peninsula, in West Antarctica, and along the Transantarctic Mountains. Shown are stations where data is available at open-access repositories, such as the EarthScope Data Management Center (https://www.earthscope.org/data). The GNSS sites correspond to those used in the GIANT-REGAIN project (Buchta et al., 2025).

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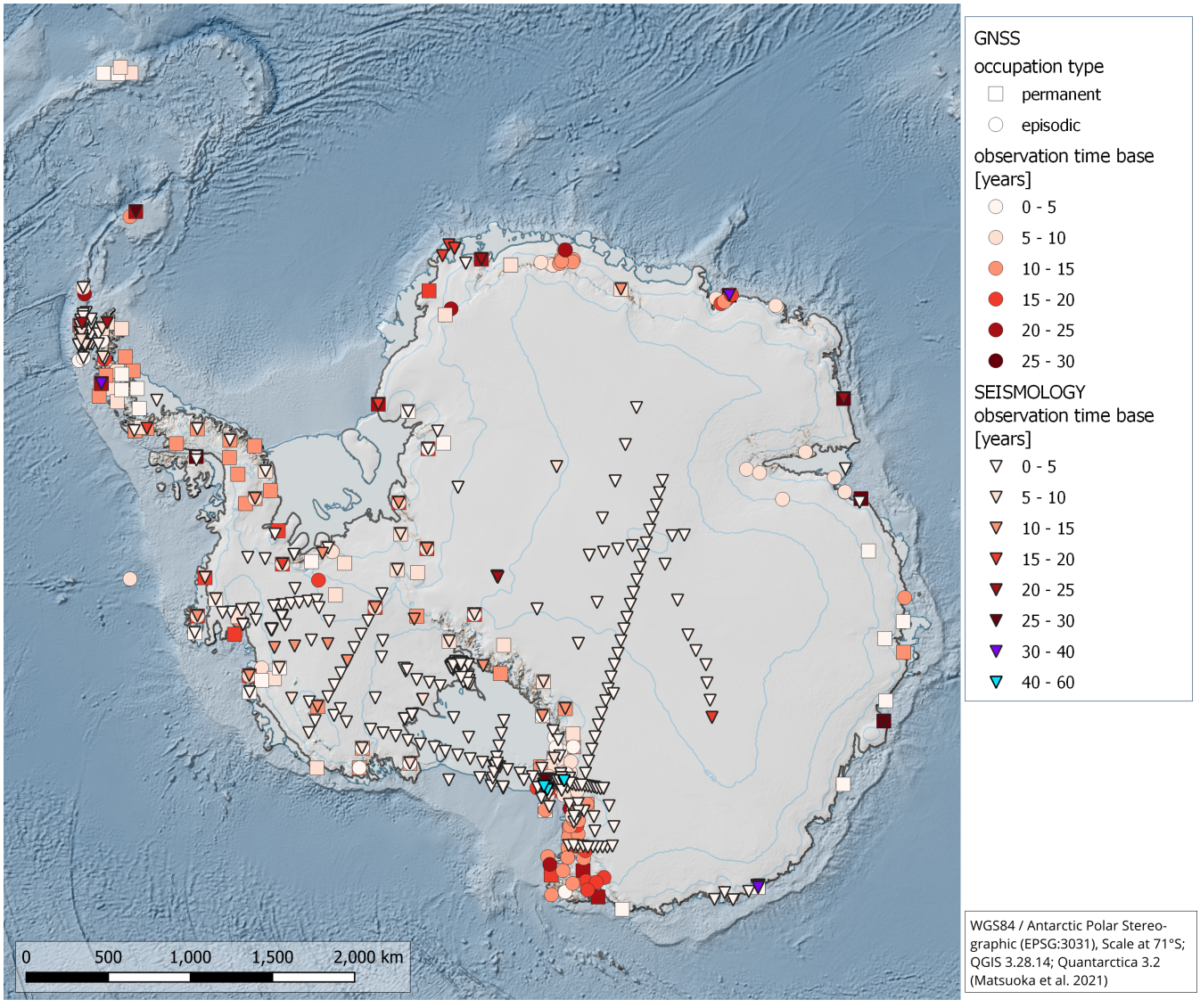


Figure 4. Occupation time base for GNSS and seismic stations across Antarctica as of end of 2021 (cf. Fig. 3 for network affiliation and data availability). Color scale for observation times of up to 30 years are the same for GNSS and seismology. GNSS occupation type is given by square (permanent) and circle (episodic), respectively. For seismology, only those stations are shown where a time duration of the deployment could be retrieved.

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2.2 GNSS – application of continuous and episodic measurement time series

The deployment of Global Positioning System (GPS) hardware, monumented on bedrock, in Antarctica has revolutionized our understanding of the continent's geodynamics. Before the 1990s, our understanding of Antarctic plate motion and GIA was based on models constrained by observations remote from present-day Antarctica in time and space. At that time, the (incorrect) view of the AIS was that it only slowly responded to changes in external forcing. Likewise, the Antarctic solid-Earth structure was viewed as responding only over millennia or longer timescales, driven by past glacial changes and mantle convection. The question of ongoing, internal deformation within Antarctica due to tectonic processes was an untested hypothesis, and the continent was thought to be largely unaffected by recent earthquakes.

Since the early 1990s, GPS observations have provided direct measurements of Antarctica's changing shape. These observational networks have now broadened to GNSS, which include GPS, GLONASS, Galileo and others, and Figure 5 provide examples of these systems deployed in the polar region. The data collected have turned previous assumptions on their head and provided fundamental new insights that show solid-Earth processes are as relevant to climate studies as they are to understanding the internal structure of our planet. In the following subsections, we summarize the lessons we have learned from almost three decades of using geodetic GNSS for geodynamic research in Antarctica. A more detailed treatment of this topic and corresponding applications to constrain mantle processes can be found in Scheinert et al. (2023).

2.2.1 Plate motion and tectonic processes

The first geodetic estimates of Antarctic plate motion were published in the mid 1990s, based on as few as two GPS sites (Larson et al., 1997) but quickly extending to about ten sites located around the coastal margin of the continent (Sillard et al., 1998). At the same time, GPS epoch measurements were exploited to geodetically determine Antarctic tectonics, especially within the Antarctic Peninsula (Dietrich, 1996). In subsequent years, additional continuous and numerous campaign sites were deployed, yielding estimates of plate rotation based on dozens of measurements (Dietrich et al., 2001; Donnellan and Luyendyk, 2004). These geodetic estimates suggested the absence of significant tectonic deformation within Antarctica but revealed substantial and important differences from geological estimates of plate rotation.

These analyses assumed any horizontal motion other than that due to tectonic processes was largely negligible for the Antarctic mainland. In recent years, it has been shown that relatively small horizontal deformations associated with GIA (Klemann et al., 2008; King et al., 2016; Vardić et al., 2022) or with post-seismic deformation (King and Santamaría-Gómez, 2016) may result in non-negligible biases to geodetic estimates of plate rotation (Turner et al., 2020). In the absence of highly accurate GIA models and the presence of post-seismic horizontal deformation, this issue remains somewhat unresolved.

Deformation within Antarctica has long been investigated. Geodetic evidence for a potential active rifting within West Antarctica could not be found. However, ongoing opening of the Bransfield Basin was identified using GPS measurements (e.g., Dietrich and Rülke, 2008; Taylor et al., 2008), showing the deformation of the offshore islands moving about 7 mm/a relative to the Antarctic Peninsula.

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Figure 5. Examples of GNSS deployments in Antarctica, showing power systems (comprising solar modules and, optionally, wind generators), radome-covered or compact antennas and various types of monuments. Upper left: Bunger Hills (Queen Mary Coast, East Antarctica); upper right: Hutton Mountains (Palmer Land, Antarctic Peninsula); lower left: Mt. Murphy (Amundsen Sea Embayment, West Antarctica); lower right: Gaussberg (Wilhelm II Coast, East Antarctica).

2.2.2 Co-seismic and post-seismic deformation

The Antarctic continent is located far from major plate boundaries; therefore, tectonic seismic activity is low. However, co-seismic and post-seismic deformation has been detected, and GPS has been used to estimate far-field co-seismic deformation and to constrain fault rupture models (Ye et al., 2014; King and Santamaría-Gómez, 2016). These observations are especially valuable given the often remote location of the earthquakes and the poor geometry of seismic observations. Using a combination of campaign and continuous GPS data from one remote site, King and Santamaría-Gómez (2016) showed that a part of East Antarctica experienced co-seismic displacement on the order of 10 mm after the M_w 8.2 Balleny Islands earthquake and then sustained post-seismic deformation over the following two decades. Using viscoelastic models, they suggested that the post-seismic deformation may be non-negligible over much of the continent today. On the other side of Antarctica, Nield et al.

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(2023) used GPS data and models to suggest that the northern Antarctic Peninsula experienced both co-seismic and ongoing viscoelastic post-seismic deformation following the large 2013 and 2003 Scotia Sea earthquakes.

2.2.3 Glacial isostatic adjustment

Results obtained from geodetic GNSS observations are of utmost scientific value for GIA research as they allow us to verify or falsify results from geophysical GIA modeling. Moreover, GNSS results allow for independent validation of GIA estimates inferred from other geodetic satellite methods, such as satellite gravimetry-altimetry combinations (Riva et al., 2009; Gunter et al., 2014; Sasgen et al., 2017; Engels et al., 2018; Willen et al., 2024). Further, GNSS measurements are used to constrain geophysical (e.g. Caron et al., 2018) and empirical GIA models (e.g. Martín-Español et al., 2016; Sasgen et al., 2017).

The first observations of vertical velocities ascribed to GIA began to emerge in the mid-to-late 2000s (Tregoning et al., 1999, 2000; Raymond et al., 2004; Dietrich and Rülke, 2008; Bevis et al., 2009). The number of sites for which vertical velocities were reported grew relatively quickly over the following years, especially in West Antarctica and in coastal regions (Argus et al., 2011; Thomas et al., 2011a). Compared with available GIA models at that time, the GPS velocities had a different spatial pattern, often with lower uplift rates (Thomas et al., 2011a). Subsequent site densification, especially in the Antarctic Peninsula and West Antarctica, has further supported this broad pattern (Fig. 6). For the Amundsen Sea Embayment, Willen et al. (2025) demonstrated that the information from GNSS measurements agrees well with a region-wide GIA model inferred from gravimetry-altimetry combination. Although more recent GIA models are in somewhat better agreement with the GPS velocities, disagreements of more than 10 mm/a are evident in some locations (Martín-Español et al., 2016; Liu et al., 2018). Further progress in understanding GIA, as well as other geodynamic processes in Antarctica, can be expected with the recently published coordinate time series consistently analyzed by the GIANT-REGAIN project for about 280 geodetic GNSS sites (Buchta et al., 2025).

GNSS uplift rates have been used to provide evidence for low viscosity upper mantle beneath regions of West Antarctica and the Antarctic Peninsula (Fig. 6). The first evidence for substantially reduced upper mantle viscosities than those generally modeled emerged in the region of the Amundsen Sea Embayment (Groh et al., 2012; Busch et al., 2017; Barletta et al., 2018), with geodetic uplift rates that were higher than could be explained through elastic deformation alone (see Sec. 2.2.4). This finding is consistent with uplift rates assessed by other geodetic observation methods (Willen et al., 2025). Strong evidence for upper mantle viscosities of the order of 10^{18} Pa·s was provided for the northern Antarctic Peninsula, where the onset of ice-mass loss following the collapse of the Larsen-B ice shelf changed uplift rates so dramatically that they could only be reproduced by modeling the uplift as a viscoelastic response to the ice loading changes (Nield et al., 2014). Subsequent studies have helped refine our understanding of upper mantle rheology in these regions (Zhao et al., 2017; Barletta et al., 2018; Samrat et al., 2020, 2021), including using a combination of satellite altimetry and tide gauge data (Rezvani et al., 2024).

These geodetic and seismic constraints, in turn, led to new understanding of the importance and magnitude of the solid-Earth rapid braking effect on ice-sheet retreat (cf. Sec. 2.5), especially in the Amundsen Sea Embayment (Gomez et al., 2010; Adhikari et al., 2014; Konrad et al., 2015; Barletta et al., 2018; Larour et al., 2019; Kachuck et al., 2020; Gomez et al., 2024; Lucas et al., 2025; van Calcar et al., 2025). Spatial patterns of GPS uplift rates, combined with models of GIA, have also

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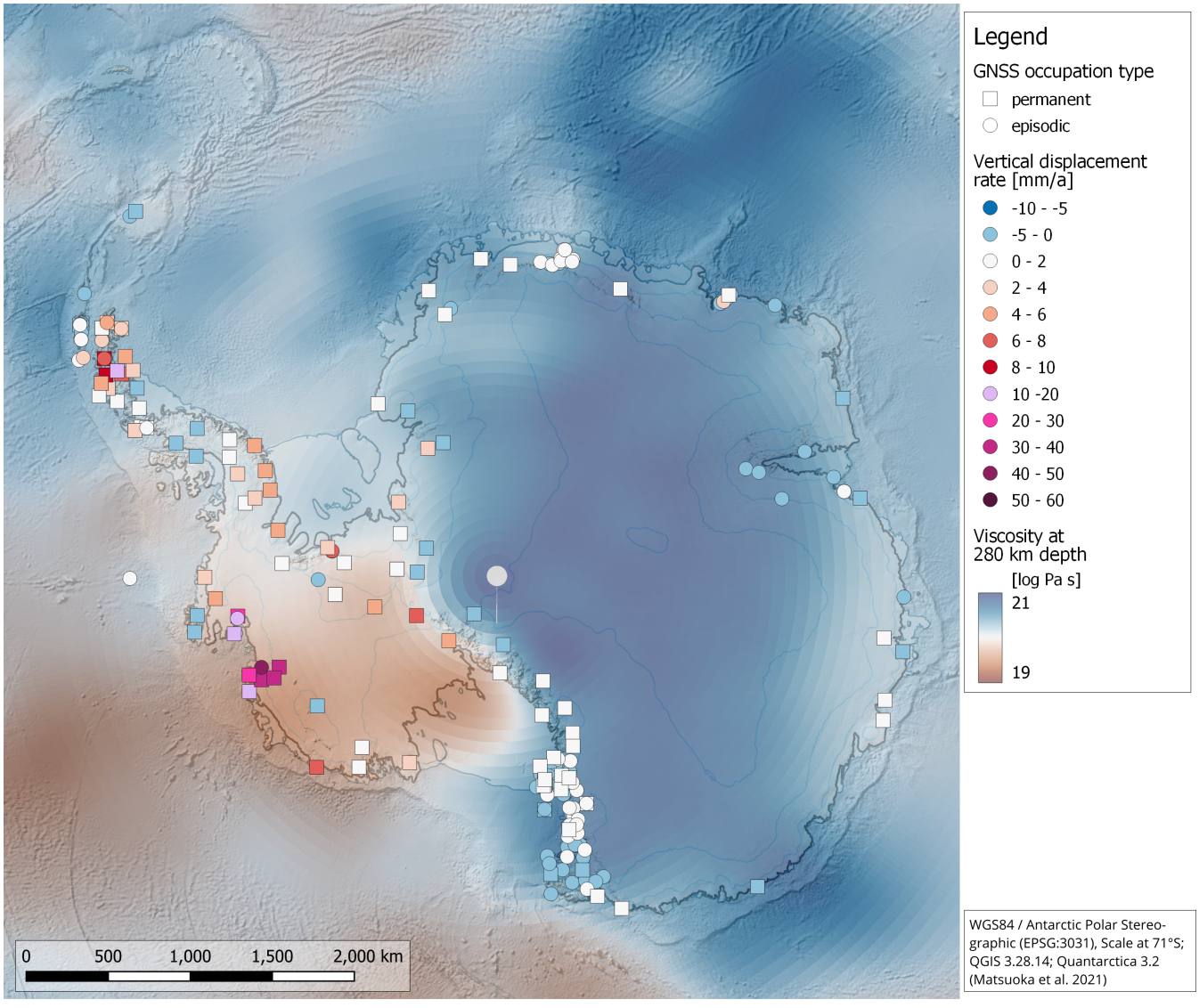


Figure 6. GNSS-derived vertical displacement rates at sites that are part of the GIANT-REGAIN project (Buchta et al., 2025). These rates originate from preliminary analysis that includes a reduction for the immediate elastic effect, thus referring to GIA-induced uplift or subsidence. In the background, the upper mantle viscosity at 280 km depth is shown, predicted from a model by Bagge et al. (2021), which is based on seismic tomography. This model indicates a lateral variability of two orders of magnitude, with low viscosities beneath West Antarctica and high viscosities beneath East Antarctica. Low and high viscosities lead to shorter and longer GIA response times, respectively.

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been used to infer unmodeled ice-sheet mass changes during the Late Holocene. These regions include the Weddell Sea sector (Bradley et al., 2015; Wolstencroft et al., 2015) and a portion of East Antarctica (King et al., 2022). Late Holocene retreat and re-advance of the ice sheet is now an emerging research topic in paleo ice-sheet and GIA studies (e.g., Kingslake et al., 2018) (see also Sec. 3.1 and 3.2).

2.2.4 Short-period loading deformations

While many of the GNSS applications to the study of Earth deformation have focused on the response of the solid Earth to past surface loading changes, it is now clear that elastic deformations due to contemporaneous loading changes are non-negligible. Notably, these include changes due to ice-flow dynamics and surface mass balance (SMB), such as those discovered by Tregoning et al. (2009) in Enderby Land, East Antarctica. Studies of viscous deformation using GNSS depend on calculating and removing elastic deformation due to contemporaneous loading changes from the total displacements measured by GNSS. These are largely due to ice dynamic variations, often from changes in ice-shelf buttressing, either in the Antarctic Peninsula or in the Amundsen Sea Embayment, but can also be governed by changes in SMB like in Dronning Maud Land. This is especially true for time series that span less than a few years, although large SMB variations also occur over longer periods (King and Watson, 2020). Koulali et al. (2022, 2025) and King et al. (2022) showed that variations in SMB, if not considered, would bias GNSS observations of vertical GIA by several millimeter per year. They showed that the misfit of a linear model is reduced when GNSS time series were corrected for SMB-driven deformation. Furthermore, in regions where the mantle viscosity is low, such as the Antarctic Peninsula, large variations in SMB can invoke not only an elastic solid-Earth response but a short-term viscous response as well (Nield et al., 2025). Correcting for this additional viscous response can increase the GNSS-derived uplift rates by up to $1-3$ mm/a but heavily depends upon the SMB model used. This highlights the importance of reducing the uncertainties of SMB models (Mottram et al., 2021) in computations of the elastic (and short-term viscoelastic) solid-Earth response. The role of extreme precipitation events, related to atmospheric rivers, may be particularly important in producing step-like changes in coordinate time series (Li et al., 2023).

2.2.5 Volcanic signals

GNSS has also been applied to detect volcanic signals in Antarctica (e.g., Grapenthin et al., 2022), leading to an improved understanding of active volcanic processes within the tectonic landscape. For example, GNSS stations that are part of the large Victoria Land Network for DEFormation control (VLNDEF) confirm activity at Mt. Melbourne volcano and identify active tectonics at two main lineaments (Zanutta et al., 2017, 2018) as well as a residual clockwise rotation of the Victoria Land block relative to East Antarctica (Zanutta et al., 2020). Poli et al. (2021) attributed a swarm of tens of thousands of earthquakes in the Bransfield Basin to a volcanic origin based on geodetic observations from nearby GNSS data acquisition stations. Long-term, uninterrupted GNSS data collection enables surface deformation assessment in Antarctic regions known to have high volcanic activity (Berrocoso et al., 2012). Denoising GNSS time series using independent component analysis (ICA) and spatiotemporal filtering offers the potential to detect subtle geophysical signals (Li et al., 2019). As the quantity of available data increases, the potential use of more powerful statistical methods can be realized. For example, machine learning

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approaches, including symbolic regression, convolutional neural networks, Gaussian processes, and transfer learning, may be applied to these time series. Recent work at Mt. Erebus volcano has used GNSS data from Ross Island, which was recorded, in part, by seven continuous sites that have operated since the 1990s. These data have allowed for a complete geodetic analysis of the open-vent volcanic system, suggesting that the long-wavelength subsidence at Mt. Erebus can be partly attributed to the growth and corresponding crustal loading of the volcano (Grapenthin et al., 2022).

2.2.6 Other physical and geophysical effects

In addition to solid-Earth deformation, GNSS sites on bedrock are sensitive to the ground surface and atmospheric conditions around the antenna; notably, multi-path signals reflected from the changing snow surface elevation, tropospheric water vapor, and ionospheric total electron content. Early work (e.g., Thomas et al., 2011b; Negusini et al., 2016) demonstrated the ability of long-running Antarctic GNSS observations to retrieve in-situ tropospheric water vapor without the need for manual radiosonde launches (cf. Section 2.6). A further challenge is that tropospheric conditions may lead to the seasonal build-up and melting of ice within the antenna radome if it is not sealed to prevent the ingress of wind-driven snow (Argus et al., 2014; Konfal et al., 2016). This, in turn, may introduce an apparent seasonal change of up to a few mm in measured vertical position, thus corrupting model inferences of solid-Earth load response (Koulali and Clarke, 2020). Identification and removal of such artifacts in the data rely on the existence of continuous or nearly-continuous observational time series spanning several years.

2.2.7 Ice-surface height and sea-level variations

As discussed in Sec. 2.2.3, GIA is closely interlinked to regional sea-level change as well as to SMB variations that may impact long-term bedrock displacement rates. However, in-situ data on regional sea-level change are sparse, as provided by tide gauge installations around Antarctica (e.g., Galassi and Spada, 2017). Here, GNSS interferometric reflectometry (GNSS-IR) offers a different technique that allows for the observation of regional sea level and of several other phenomena. GNSS-IR is a low-cost remote sensing technique that relies on signals of opportunity, and it only requires lightweight, low-power receiver-only systems. The technique can also be applied to data from existing continuous GNSS stations along coastlines. Depending on the application, the antenna can be mounted on bedrock or at the ice surface.

The concept of scattering, which forms the basis for GNSS-IR, was introduced by Hall and Cordey (1988) through the use of multi-static principles, thereby laying the groundwork for the development of the Passive Reflectometry and Interferometry System (PARIS) by Martín-Neira (1993). Based on the knowledge of scattering GNSS signals, GNSS-IR has become a promising complement to retrieve surface height variations (e.g. Larson and Williams, 2023), which are estimated from the signal-to-noise ratio of the data from a single GNSS receiver. In Antarctica, numerous GNSS-IR studies have been conducted over the last decade to monitor how sea- and ice-level variations over several years depend on climate system evolution (Peng et al., 2021; Nievinski and Larson, 2014a, b). The analysis and interpretation of scattered signals holds the potential to provide a variety of insights, including the detection of current sea level, retrieving information about the topmost and uppermost layers of the ice body due to the penetration depth of GNSS carrier waves, and to monitoring ocean wind and waves (Cartwright et al., 2019; Rius et al., 2017; Selbesoğlu, 2023; Simeonov et al., 2021; Tabibi et al., 2020).

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For sea-level monitoring, GNSS-IR offers significant advantages relative to tide gauges since the reflected and direct signals can be obtained with only one GNSS receiver which also measures the vertical land motion (Peng et al., 2021). Geremia-Nievinski et al. (2020) investigated the accuracy of GNSS-IR for sea-level monitoring using data from eight POLENET GNSS stations in Antarctica and demonstrated that the GNSS-IR approach could estimate sea level at a level compatible with a conventional tide gauge, with a correlation coefficient of 0.90. Further, Selbesoğlu (2023) examined one year of data from the Palmer Station GNSS site and found a correlation of 0.91 between GNSS-IR and conventional tide-gauge sea-level measurements. Consequently, GNSS-IR holds the promise of bridging the observational gap in sea-level monitoring within coastal zones in Antarctica over a broad swath near the coastline (up to 0.5 kilometers), thereby surpassing the capabilities of traditional tide gauges (Peng et al., 2021; Santamaría-Gómez et al., 2012). However, challenges remain in identifying and removing the effects of sea ice.

2.3 Seismology

Seismology was included in one of the first scientific expeditions to the continent (1901-1904; Milne (1905)); however, the collection of seismic data proceeded slowly through the 20th and early 21st century due to the harsh environmental and logistical conditions. Today, there are just a few continuously recording seismic stations on the continent that have operated for more than 20 years, mostly located at or in the vicinity of coastal science bases, with just two stations operating in the deep interior (at Amundsen-Scott Station, South Pole, and at Concordia Station, Dome C) (cf. Fig. 4). Integrated into global seismographic networks (e.g., Global Seismographic Network (GSN), GEOSCOPE, GEOFON), such long-running stations provide high-quality, near real-time data (e.g., Anthony et al., 2021; Ringler et al., 2022). Despite their limited numbers, these stations have proved critical to global-scale Earth tomography as well as to imaging Antarctic plate-scale geophysical structure. Data from long-operational stations, integrated with limited duration campaign seismic deployments, provide information on a wide range of seismic sources as well as robust observations of secular and seasonal changes in ice and ocean waves encoded within the seismic background signal (Anthony et al., 2015, 2017; Pratt et al., 2017; Aster et al., 2023).

Seismic studies in Antarctica's interior using portable digital stations started with six temporary broadband stations from the 1998–2001 ANUBIS project (Anandakrishnan et al., 2000), which, though limited to summer operation, spurred progress in improved power and data storage. The 2000–2003 TAMSEIS project expanded to 46 stations (e.g., Lawrence et al., 2006), and year-round operation was achieved through GAMSEIS and POLENET/ANET using low-power instruments, dual power systems, Iridium telemetry, and specially engineered enclosures (e.g., Hansen et al., 2009; Chaput et al., 2014). These innovations enabled deployments across the continent, providing records for a few years each, or in the case of POLENET, for over 15 years. Growing coverage eventually led to over 200 non-contemporaneous sites, which helped to produce models with tenfold improvements in crustal and mantle resolution, thereby clarifying tectonics, geodynamics, and Earth–cryosphere interactions (Fig. 7; Wiens et al., 2023). More recently, high-rate data from isolated stations (Chaput et al., 2018, 2022), nodal arrays (e.g., Zhang et al., 2024), and distributed acoustic sensors (DAS) (e.g., Yang et al., 2024; Fichtner et al., 2025) have extended cryoseismological studies to the firn and ice-column scale.

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Pioneering seismic investigations since the early 21st century revealed distinct features of Antarctica, including: 1) the dichotomy of the seismic structure between West and East Antarctica; (e.g., Ritzwoller et al., 2001; Danesi and Morelli, 2001; Sieminski et al., 2003); 2) an absence or reduced level of tectonic seismicity throughout the continent (Reading, 2006; Peña Castro et al., 2024), which is partially attributable to the sparsity of the observational networks; and 3) seismic signals related to cryospheric dynamics (Martin et al., 2010; Pirli et al., 2015; Guerin et al., 2021; Wiens et al., 2024) and Antarctica's environment (Aster et al., 2010; Grob et al., 2011; Anthony et al., 2017; Pratt et al., 2017). Both structural and source studies provide unique contributions to understanding the glacially obscured geologic and tectonic structure, the stress state of the continent, the interconnected processes between the solid Earth, the oceans, and the ice sheet, as well as the structure, dynamics, and evolution of the cryosphere. These and many other discoveries provide strong motivation for greater and sustained Antarctic seismic network coverage. In the following subsections, we summarize the results stemming from 21st century Antarctic seismic initiatives.

2.3.1 Advancements in Seismic Structure: Crust and Upper Mantle

Shallow structures, including sedimentary layers and the crystalline crust, provide rich information about the geological history of continents. Particularly, sedimentary rocks in Antarctica, their distribution beneath the AIS, in combination with the presence of liquid water, determine the frictional and rate-state sliding properties along the ice-sheet basal interface, thus critically influencing ice-flow dynamics (Berdahl et al., 2023). The properties of sediment (e.g., mechanical and thermal properties, pore volume) differ considerably from more consolidated strata and basement crystalline crust; therefore, knowledge of sediment spatial distribution and thickness is important to correctly determine future ice-sheet behavior. Due to the thick ice coverage, many of the sedimentary basins beneath the AIS are still not robustly delineated. In a recent review, Aitken et al. (2023) provided a comprehensive summary of measurement techniques (including passive and active source seismology and potential field methods) to determine the presence of sediments beneath the ice.

Crustal thickness across Antarctica reflects its tectonic evolution, marked by a sharp contrast between West and East Antarctica (Cande et al., 2000; Reading et al., 2022). Moho depth has been mapped using seismic tomography (An et al., 2015), receiver functions (Hansen et al., 2010; Chaput et al., 2014; Ramirez et al., 2016; Hansen et al., 2016), and joint inversions (Bayer et al., 2009; Shen et al., 2018; Baranov et al., 2021). West Antarctica, assembled along Gondwana's southern margin, includes contrasting provinces: relatively thicker crust beneath the Antarctic Peninsula (~ 34 km) and Marie Byrd Land (~ 28 km) and thinner crust under the Ronne Ice Shelf side of the Transantarcic Mountains (less than 20 km) (Jordan et al., 2020; Shen et al., 2018). In contrast, East Antarctica is underlain by ancient cratons, with crustal thickness ranging from more than 55 km beneath the Gamburtsev Subglacial Mountains to less than 20 km under the Lambert Rift. Intermediate crustal thickness values are found beneath Dronning Maud Land (~ 45 km) (Bayer et al., 2009), while beneath the Wilkes and Aurora Subglacial Basins, crustal thickness estimates are more varied, ranging from ~ 25 to ~ 40 km (Baranov and Morelli, 2013; Hansen et al., 2016; Shen et al., 2018; Li and Aitken, 2024).

Antarctic upper mantle structure has been traditionally inferred by regional studies, but since the mid-2010s, it has often been constrained using integrated datasets from these regional deployments. Various tomographic techniques have been used,

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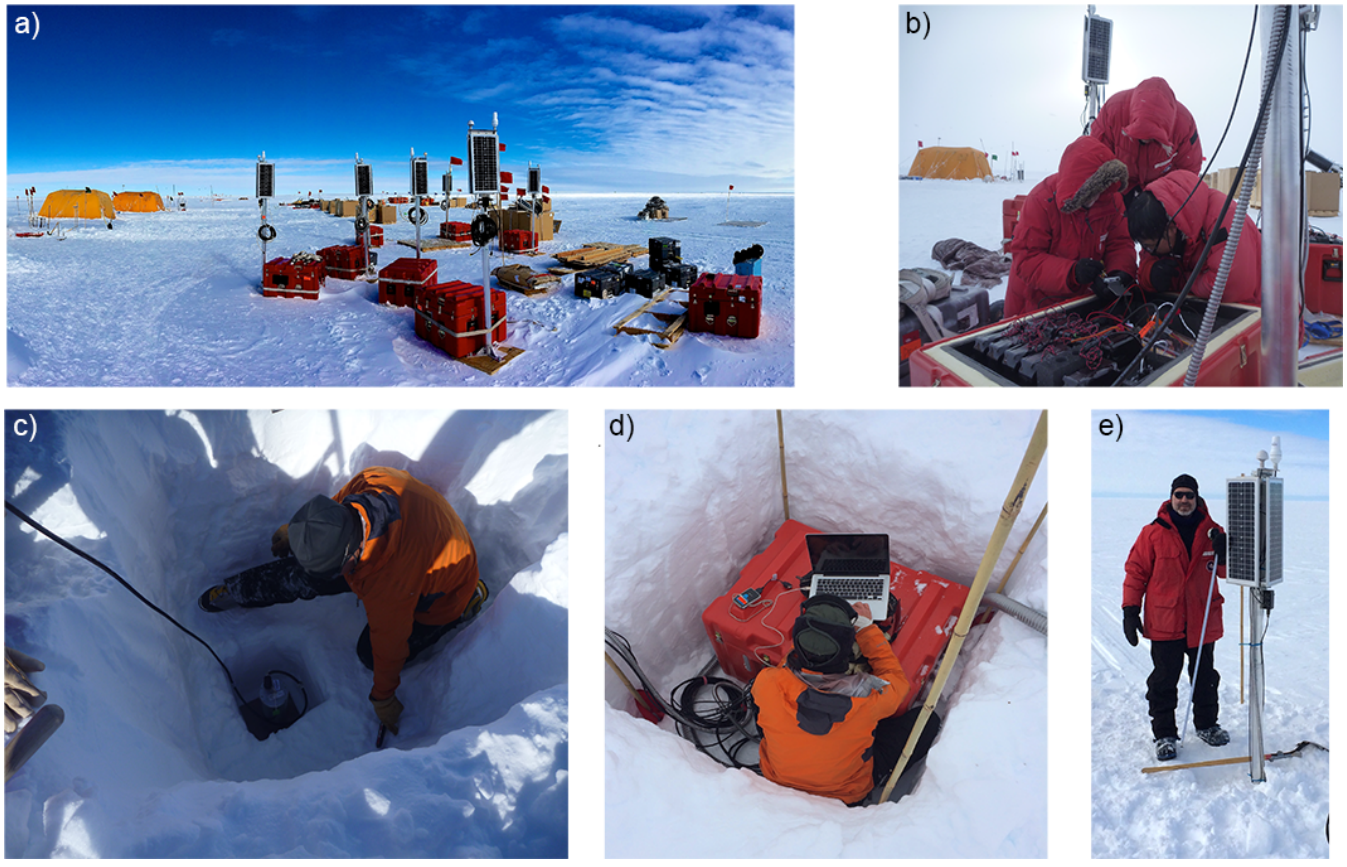


Figure 7. Example deployment of two-year continuously recording, autonomous broadband seismic stations on the Ross Ice Shelf during the RIS/DRIS experiment (Bromirski et al., 2015). a) Stations in transport configuration, showing solar/communications assemblies and data acquisition systems in ultra-insulated field cases. Up to three such stations in this configuration can be transported simultaneously by Twin Otter aircraft. b) Field installation of primary lithium-thionyl-chloride batteries for continuous winter (dark) operation. c) Firn installation and orientation of a Nanometrics Trillium 120 posthole broadband seismometer. d) Installation and field check of data acquisition system. e) Following installation, the solar/communications mast assembly of solar panels, GPS, and Iridium satellite state-of-health antennas is the sole component remaining above the snow surface.

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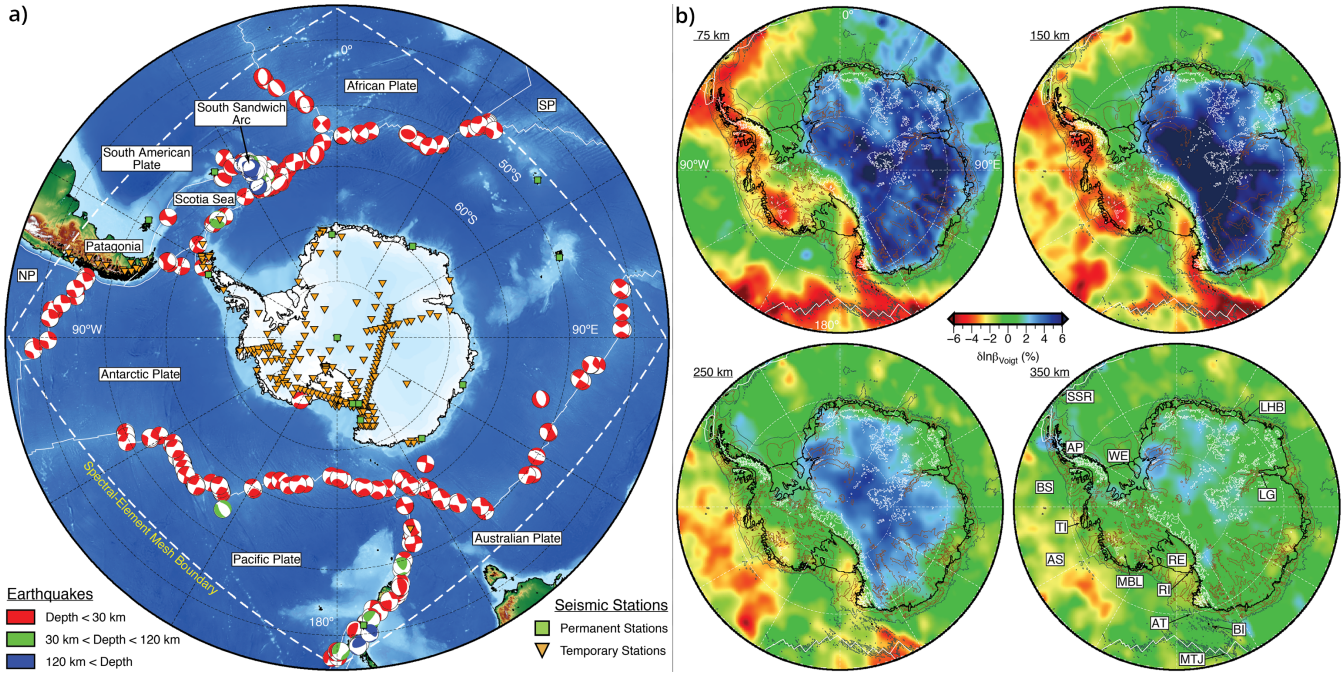


Figure 8. Full-waveform inversion model (ANT-20) for the Antarctic plate constrained by body and surface waves with periods from 15 to 150 s recorded by permanent and temporary seismic stations. a) Earthquake sources and stations. b) Voigt average shear-wave speed structure at 75, 150, 250, and 350 km depths. Abbreviations: AT—Adare Trough, AS—Amundsen Sea, AP—Antarctic Peninsula, BI—Balleny Islands, BS—Bellingshausen Sea, LG—Lambert Graben, LHB—Lützow-Holm Bay, MTJ—Macquarie Triple Junction, MBL—Marie Byrd Land, RE—Ross Embayment, RI—Ross Island, SSR—South Scotia Ridge, TI—Thurston Island, WE—Weddell Embayment. Adapted from Lloyd et al. (2020).

including Rayleigh wave inversions (from earthquakes and ambient noise; An et al., 2015; Shen et al., 2018), P-wave travel-time delays (Hansen et al., 2020), and full waveform inversion (FWI; Lloyd et al., 2020; Hansen and Emry, 2025). The resulting images reveal a highly heterogeneous upper mantle, reflecting diverse geodynamic processes. West Antarctica features include a possibly disrupted mantle plume beneath Marie Byrd Land, fragments of the subducted Phoenix plate and slab window, heterogeneity reflecting Cenozoic and recent extension (Lloyd et al., 2015), localized low-velocity zones beneath young volcanism, and processes along the Transantarctic Mountains, including lithospheric delamination (Heeszel et al., 2013; Shen et al., 2017; Seroussi et al., 2017) and thermal loading and flexure (Brenn et al., 2017). East Antarctica shows fast, thick Archean to Proterozoic lithosphere centrally, variable structure in Dronning Maud Land, and thinner lithosphere along the coast and beneath the Lambert Graben (Heeszel et al., 2013) as well as beneath the Wilkes and Aurora Subglacial Basins (Lloyd et al., 2020; Chua and Lebedev, 2025; Hansen and Emry, 2025). These advances reveal lithospheric structure and geodynamic processes that influence GIA, sea level, and the ice sheet (Gomez et al., 2024).

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2.3.2 Advancements in Seismic Structure, Mantle Transition Zone and Deeper Structures

The mantle transition zone (MTZ), marked by seismic discontinuities near 410 and 660 km depth, varies in thickness with temperature and pressure, making it a useful probe of mantle conditions (Bina and Helffrich, 1994). Since the 2000s, only limited studies have targeted the MTZ structure beneath Antarctica. Receiver function analyses, often used to map MTZ topography (Langston, 1979; Shearer, 1991), reveal a slow anomaly above the MTZ in East Antarctica (Vinnik and Farra, 2007), a deepened MTZ base ($\sim$ 720 km) beneath Mt. Erebus, consistent with anomalously high temperature mantle, and uniform MTZ thickness beneath Ross Island (Andrews and Deuss, 2008), suggesting that most anomalies are confined to the upper mantle (shallower than $\sim$ 660 km). Later work (Reusch et al., 2008; Emry et al., 2020) found MTZ thinning beneath the Transantarctic Mountains, possibly linked to a deep-seated plume, while the MTZ beneath West Antarctica generally shows average thickness with localized thinning near Marie Byrd Land and the Bentley Subglacial Trench, possibly due to hot lower-mantle upwelling (Emry et al., 2015).

Lower mantle and core structure beneath Antarctica remain poorly resolved, but Antarctic stations provide unique high-latitude ray paths into Earth's deep interior. Seismic data have revealed lower-mantle scatterers interpreted as ancient subducted slabs (e.g., (Ma et al., 2016)) and widespread slow anomalies along the core–mantle boundary (Hansen et al., 2020, 2023; Agboola et al., 2024). Core phases sampled near the rotation axis support the idea of inner-core super-rotation (Song and Li, 2000), providing additional insights about core structure, anisotropy, and dynamics (Tromp, 2001; Wang et al., 2024). Additionally, Antarctic data has shown increasing inner-core inhomogeneity with depth, offering clues to its growth history (Peng et al., 2021).

2.3.3 Advancements in Understanding Antarctic Seismic Sources

Antarctica was long thought to be mostly aseismic. The installation of GSN stations in the mid-1990s revealed intraplate earthquakes, including clusters in the Transantarctic Mountains and the continental interior (Reading, 2007). Regional networks, including the long-running Mt. Erebus networks, have detected widespread volcanic (Rowe et al., 1998, 2000; Zandomeneghi et al., 2013; Knox et al., 2018) and non-volcanic activity (Peña Castro et al., 2024), while smaller deployments have identified seismicity in the West Antarctic Rift System and events near Lützow-Holm Bay, some linked to deglaciation. Later arrays, including TAMSEIS, GAMSEIS, and POLENET/ANET, have greatly expanded geographic coverage, uncovering examples of tectonic activity (Winberry and Anandakrishnan, 2003). These findings include magmatic earthquake swarms in Marie Byrd Land (Lough et al., 2013), extensional events near the Gamburtsev Subglacial Mountains (Lough et al., 2018), the M_n 8.1 Balleny Islands earthquake (possibly GIA-related, (Himeno et al., 2011)), and a massive swarm of about 85,000 events in the Bransfield Strait tied to dike intrusion (Ivins et al., 2003; Cesca et al., 2022). Despite these advances, sparse station coverage still limits understanding of Antarctic intraplate stress, deformation, and cryosphere dynamics.

Antarctic seismic records contain abundant cryospheric signals and have helped drive advances in cryoseismology (Podolskiy and Walter, 2016; Aster and Winberry, 2017). Impulsive sources include regions of prolific ice fracture and basal stick-slip, while non-impulsive signals arise from oceanic and atmospheric forcing. Glacial seismicity near grounding lines is highly sen-

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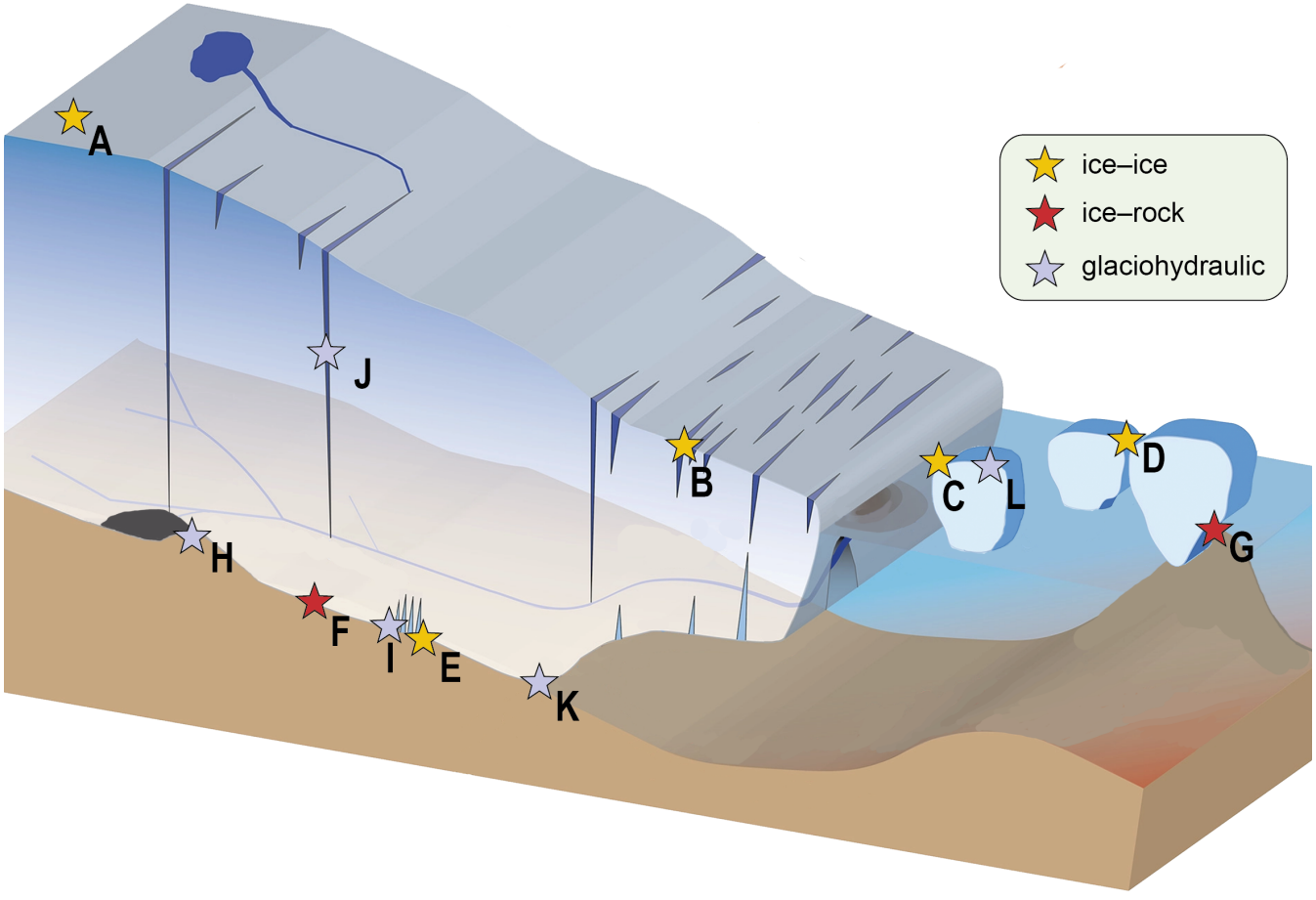


Figure 9. A summary of Antarctic cryoseismic source types (stars) with a high degree of vertical exaggeration. (A)–(E): Ice–ice dynamic processes; (A): Ice-sheet icequakes and firnquakes; (B): Surface crevasse opening or collapse; (C): Calving; (D): Iceberg–iceberg collision, rifting, and fracture; (E): Basal crevasse opening or collapse; (F): Glacial basal stick-slip; (G): Iceberg grounding stick-slip; (H)–(L): Ice-water interactions; (H): Subglacial lake drainage and water transport; (I): Basal crevasse water transport and resonance; (J): Moulin water transport and tremor; (K): Terminus discharge; (L): Iceberg/calving impact and water column sources. Modified from Aster and Winberry (2017) using a figure from Catania et al. (2020).

365 sitive to tides and swells, and the Whillans Ice Stream exhibits quasi-characteristic, tidally triggered stick-slip at ∼M7 scale (Wiens et al., 2008, 2024). Ice shelves also generate strong seismic signals from gravity-flexural waves and slip at grounding zones (Bromirski et al., 2015, 2017; Aster et al., 2021). Additional signals stem from calving, englacial fracturing, and interactions with ocean waves and tsunamis. Drifting and colliding icebergs produce seismic and seismoacoustic waves that propagate thousands of kilometers, shaping the Southern Ocean soundscape. Iceberg seismicity includes tremor lasting hours, generated
370 by ice-ice or ice-seafloor collisions (MacAyeal et al., 2008; Martin et al., 2010). The extensive Antarctic sub-glacial meltwater system further modulates bed friction and produces englacial and subglacial hydrologic signals.

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While much of the Antarctic glacial system exhibits velocity strengthening stick-slip behavior and thus slides without detectable seismicity, prolific basal seismicity is observed at specific glacial beds over rapid (Zoet et al., 2012; Danesi et al., 2007; Hudson et al., 2023) and slow (e.g., Lipovsky and Dunham, 2017; Barcheck et al., 2021) time-scales. This includes basal tremor, interpreted as a superposition of small stick-slip events (Winberry et al., 2017; Podolskiy et al., 2021; Barcheck et al., 2021). Understanding basal stick-slip and general basal rheology is fundamental to glacial dynamics and cryoseismology (e.g., Tsai et al., 2017; Zoet and Iverson, 2020; Gilbert et al., 2023).

Antarctic ambient seismic noise originates primarily from the atmosphere and oceans. Large-scale ocean noise intensity is controlled by gravity wave energy in the Southern Ocean and damping by seasonally varying sea ice (Grob et al., 2011; Anthony et al., 2015; Aster and Winberry, 2017; Pratt et al., 2017). Swell and infragravity waves propagating from storm centers (e.g., MacAyeal et al., 2006; Cathles et al., 2009) generate the large-scale microseism wavefield ($4--20$ s periods) (Anthony et al., 2015; Pratt et al., 2017) via two mechanisms: 1) Shallow direct ocean swell tractions on the seafloor as the primary mechanism; 2) Forces generated by standing wave components from interfering ocean waves as the secondary mechanism (e.g., Ardhuin et al., 2015). Ambient microseism noise is widely used, often jointly with earthquake data, for Earth imaging from the crust to the upper mantle (e.g., Shen et al., 2018) (cf. Sec. 2.3.1).

Finally, high-frequency ambient noise (> 10 Hz) originates from wind, short-period ocean waves, and anthropogenic sources. This wavefield is used to image firn, ice/water column thickness, and basal sediment (e.g., Zhan et al., 2013; Diez et al., 2016; Aster et al., 2021; Chaput et al., 2022). Characterizing wind noise is also key for assessing detectability of other signals (e.g., Anthony et al., 2015; Frankinet et al., 2021; Zhou et al., 2022). Temporal variations in ambient noise are effective for studying cryospheric, oceanic, and hydrological changes. For example, microseism intensity correlates with the southern annular mode and seasonal sea ice extent (e.g., Aster et al., 2008; Anthony et al., 2017; Pratt et al., 2017; Aster et al., 2023), while changes in cryospheric noise and icequake activity constrain dynamic processes like melt/refreezing (e.g., MacAyeal et al., 2018; Chaput et al., 2018, 2023), basal processes affecting ice-stream stability (e.g., Guerin et al., 2021), and permafrost thaw (e.g., James et al., 2019).

2.4 Multidisciplinary Studies

Multidisciplinary studies offer another means to address many scientific questions relating to the solid-Earth structure beneath Antarctica, and are defined as studies where two or more observables (such as magnetic anomalies and seismic velocities) or knowledge synthesis frameworks (such as plate tectonic reconstructions) are combined. In this section, we outline the combination of single variable data compilations, the importance of resolving the underlying physical properties or attributes, the data layers that comprise available inputs for multidisciplinary studies, and the on-ground electromagnetic methods that are making an increasing contribution to Antarctic geophysical investigations. We then provide an overview of the main multivariate approaches that reveal new insights about Antarctica's solid Earth, such as combined forward and inverse modeling, statistical approaches, and machine learning.

Satellite datasets offer wide-area coverage and consistent resolution (e.g., Lu et al., 2020; Ebbing et al., 2021), while airborne data potentially add crucial detail (e.g., Frémand et al., 2022). Single variable geophysical data compilations for Antarctica of-

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ten make use of satellite and airborne data in combination, with a small component of ground-based data. Notable compilations include a continent-wide gravity anomaly grid (Scheinert et al., 2016, 2024; Charrassin et al., 2025) and magnetic anomaly maps (Golynsky et al., 2018). Oceanic crust, ultramafic, mafic, intermediate igneous rocks, and sedimentary units that include these lithologies typically give rise to high-amplitude gravity anomalies and pronounced large magnetic anomalies. Density values for rock-forming minerals vary over a narrow range (Telford et al., 1990), within one order of magnitude (2.3 –4.0 g cm^{-3}), whereas magnetic susceptibility varies over many orders of magnitude (0 –19,000 $\times 10^{-3}$ SI). Magnetic minerals can be effectively absent or highly concentrated. This contrast in distribution characteristics and the range between gravity and magnetic observations illustrates that relevant underlying aspects of the attributes being represented must be managed carefully in subsequent multivariate analysis.

Data layers available for inclusion in multivariate studies include gravity anomalies, magnetic anomalies, seismic velocities and derived properties, such as lithosphere-asthenosphere boundary (LAB) depth and electromagnetic characteristics (Stål et al., 2020). Multiple types of geophysical data are acquired in a single airborne campaign (e.g., ICECAP data, as used by Aitken et al., 2014), typically in association with ice-sheet geophysical investigations that make primary use of airborne radar data (Schroeder et al., 2020). One of many uses of radar datasets is to constrain subglacial bed elevation and related products (Bedmap3; Pritchard et al., 2025; Frémand et al., 2023): mapped bed elevation is often used to provide a context for data analysis or data display for interpretation, and it is a critical data layer in many multivariate studies.

In addition to the GNSS and seismic techniques considered in the previous sections, the magnetotelluric (MT) technique is increasing in use for solid-Earth and ice-bedrock interface zone investigations in Antarctica (Hill, 2020). Using natural variations of the Earth's own magnetic and electrical fields, 3D maps of electrical resistivity can be inferred (Chave and Jones, 2012). Long-period MT data yields information about heterogeneities in the asthenosphere and deep lithosphere. Broadband MT data can be used to infer processes at shallower depths, such as saline incursions of sea water in the ice-bedrock interface zone.

The toolbox of multivariate techniques has rapidly expanded in recent years given improved dataset compilations, open-access data sharing (cf. Sec. 3.4), and computation capabilities. Multivariate analyses include physics-based approaches, such as combining forward modeling results and those using joint inversion; statistics-based approaches, such as likelihood mapping and similarity methods; and machine learning approaches, with many different algorithms now expanding the computational options across a wide range of multivariate studies.

2.4.1 The crust and lithosphere from multidisciplinary studies

Continent-wide constraints on tectonic structure have been derived using satellite data (Ebbing et al., 2021). For example, aeromagnetic anomalies shown in the context of a plate tectonic reconstruction can be tracked across continental margins of Australia, India, Africa, and into East Antarctica. The continuation of anomalies between former neighbours in Gondwana reinforces the evidence for a shared tectonic history. This is shown in Fig. 10, where aeromagnetic data were conformed to satellite data. Satellite data provide the long-wavelength foundation to improve the consistency of data that originates from different continents, and shorter wavelength features are captured by aeromagnetic surveys. Taking a contrasting approach,

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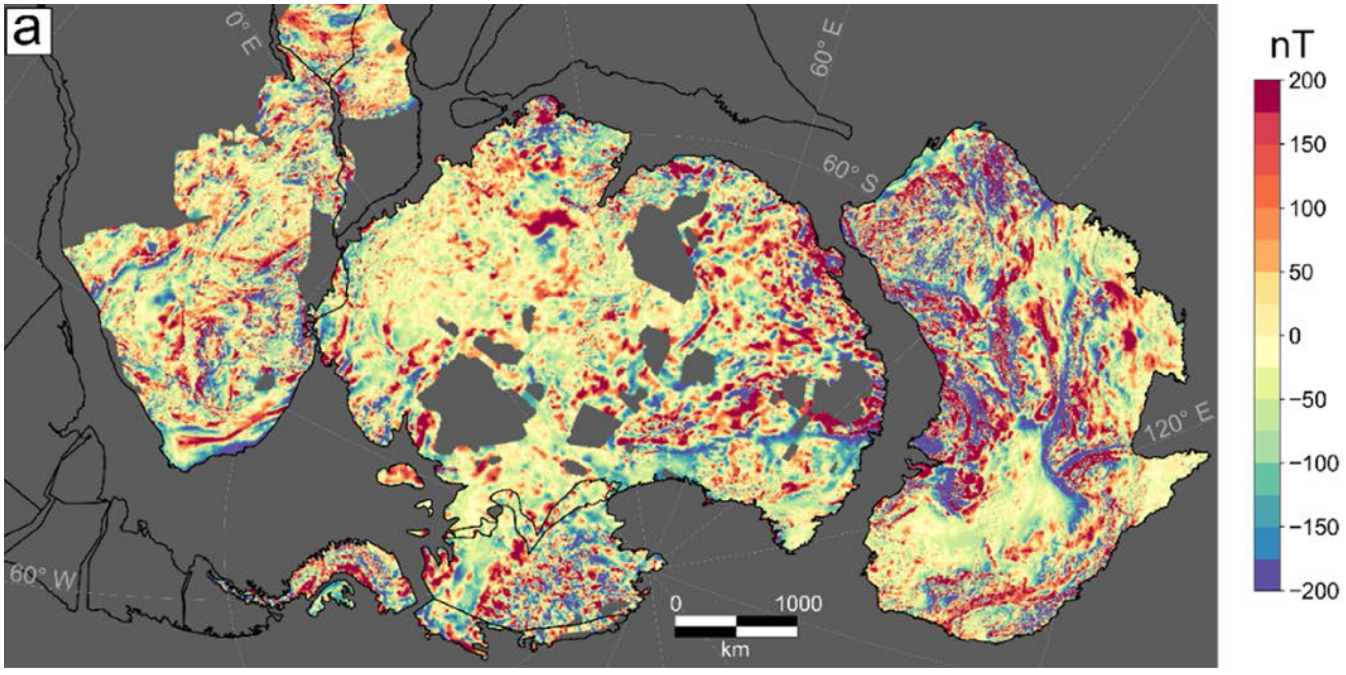


Figure 10. Magnetic data compilation, where airborne datasets (e.g., Golynsky et al., 2018) were conformed to a satellite model (LCS-1, Olsen et al., 2017) (LCS-1) using an equivalent layer approach and were superposed on a deformable Gondwana plate reconstruction. From Ebbing et al. (2021).

a density model of Antarctica has also been used to infer crustal heterogeneity in order to predict heat producing element contributions to geothermal heat flow (Li and Aitken, 2024).

On a regional scale, aeromagnetic constraints employed with multidisciplinary data have been used to map the structure across Dronning Maud Land (Ruppel et al., 2018). Interpretation of magnetic anomalies in this example study suggest a significant area of East Antarctic crust is composed of either accreted oceanic arc terranes or major shear zones of Pan-African origin. Aeromagnetic and gravity variations have also helped to constrain the sub-ice tectonic structure beneath Wilkes Land, Terre Adelié, and surrounding regions using variation of information joint inversions (Lösing et al., 2022; Lowe et al., 2024). This has revealed, for example, large batholiths and other intrusive structures in East Antarctica. Joint interpretation of gravity and magnetic anomalies has thus proven valuable as a means to discriminate between subsurface density and compositional variations.

Forward modelling of multidisciplinary data has advanced our understanding of the Antarctic lithosphere. For example, such studies have constrained the LAB to a depth greater than 200 km beneath East Antarctica (Haeger et al., 2019). Further refinement was achieved using combined airborne and satellite data, revealing LAB depths up to 230 km below the Gamburtsev Subglacial Mountains (Pappa et al., 2019; Pappa and Ebbing, 2023). The presence of deep lithospheric boundaries, based on multivariate data and a likelihood approach (Stål et al., 2019), supports locations of some East Antarctic interior boundaries,

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as inferred from forward modelling. The thermal structure of the Antarctic lithosphere is important both in terms of basal heat supply and rheological properties (Hazzard et al., 2023). In a continent-wide study drawing on both seismic and density results, compositional effects have been separated from temperature effects, suggesting a warmer East Antarctic mantle than previously inferred (Li et al., 2025). As structural variations with depth is further refined at regional scales, insights into crustal structure and geothermal heat flow can follow, as exemplified, for instance by progress in understanding the Wilkes Subglacial Basin (Lowe et al., 2023).

2.4.2 The ice-bedrock interface zone from multidisciplinary studies

The ice-bedrock interface zone (IBIZ) encompasses the many layers between pure ice and the largely impermeable crystalline bedrock. This can include ice with sediment inclusions, frozen and unfrozen unlithified sediments, lithified sediments, permeable basement rock, and a range of possible water contents, which are considered by subglacial hydrology and groundwater investigations (Siegert et al., 2018). Many of these components impact enthalpy change and energy balance throughout the IBIZ (Aschwanden et al., 2012; Burton-Johnson et al., 2020), and they also significantly influence the interplay between ice-sheet basal sliding and internal deformation (e.g., McArthur et al., 2023). Collectively, these factors have notable implications for the stability of the AIS. Studies of the IBIZ overlap with studies of the solid Earth for Antarctica and often make use of multivariate data, so a few examples are provided here.

The nature and extent of sub-ice sedimentary basins across Antarctica have been inferred using multivariate constraints (Aitken et al., 2023). The porosity of such sedimentary material is generally relatively high; therefore, water flow is likely routed through this layer at the base of the ice sheet and, consequently, has important implications for ice-sheet dynamics (Li et al., 2022). At a regional scale, channelized versus dendritic-like water flow beneath Totten Glacier has been investigated by Dow et al. (2020). This area is important since it drains ice from part of the Aurora Subglacial Basin, a region that may be susceptible to collapse in the future.

Constraints on bedrock topography have been improved by incorporating remotely sensed ice-flow velocities (BedMachine; Morlighem et al., 2019). Purely observational-based compilations (Bedmap2, Bedmap3; Fretwell et al., 2013; Pritchard et al., 2025) provide the starting model, and iterative improvements rely on updated Antarctic gravity anomalies and more advanced inversion schemes (Charrassin et al., 2025). Ice-bed roughness and other topographic features may also be informed by statistical means and incorporate surface observations (Graham et al., 2017; MacKie et al., 2020; Ockenden et al., 2023). Geothermal heat flow modeling has been substantially advanced by empirical, data-driven methods, as reviewed by Reading et al. (2022). Moreover, Stål et al. (2024) emphasized the importance of crustal components of lithospheric composition and ongoing tectonism in controlling Antarctic geothermal heat flow.

2.4.3 Insights from multivariate computation

Computational techniques provide relevant to knowledge regarding the Antarctic lithosphere. For example, inferences from global datasets can be employed, uncertainty quantification and its implications for interdisciplinary research can be implemented, unquantified uncertainty can be evaluated, and mapped results can be compared. In many cases, future field data

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collection in Antarctica will anticipate semi-automated data processing; hence, it is useful to look ahead to optimise data collection for both traditional and accelerated analyses.

Globally mapped results provide an appealing and viable means of inferring knowledge regarding sub-ice Antarctica since there are relationships between tectonic settings and geophysical observables (e.g., Lucazeau, 2019). This allows to use compiled, globally mapped results to infer characteristics within lesser-known regions (Stål et al., 2022). A related approach is to infer values for Antarctica based on a result for another continent that is closely related within a global reference dataset. This approach generally provides better resolution at the expense of looser control on underlying assumptions. Data-driven approaches, including statistical and machine learning techniques, significantly add to the deterministic physics-based toolboxes of other methods and often provide complementary information or useful comparisons (Stål et al., 2021; Lösing and Ebbing, 2021). It is also worth noting that some techniques, such as those using physics-informed neural networks, draw on both data-driven and physics-based foundations.

Data-driven approaches enable multiple metrics that can be used to quantify uncertainty, and using different metrics helps to convey both the (spatially variable) variance and robustness of the results (Stål et al., 2021). In this context, robustness is defined as a given value (or mapped set of values) having a very high probability of being correct within its stated uncertainty bounds (uncertainty can be understood as variance). The combination of a large uncertainty range and high robustness is appropriate for interdisciplinary research result use, such as ensemble-based ice-sheet modeling (Reading et al., 2022). Some approaches allow the user to select datasets to include or exclude, which introduces significant unquantified uncertainty (i.e., uncertainty not captured by any variance or other metrics), although it is worth noting that results from these approaches can be important in hypothesis generation (Reading et al., 2022, Supplement).

Statistical and machine learning approaches are excellent aggregators for multiple datasets. They provide a means of constraining an inference process irrespective of whether datasets have some physical relationship or whether they are largely independent, with the advantage that the majority of available data can contribute directly to the final result. Handling multiple datasets and related metadata used in multivariate analysis in a computationally efficient way is a non-trivial task, but it is enabled by software libraries that support efficient processing across array-type data structures (Stål and Reading, 2020). Some datasets perform better as aggregators than others, serving as anchor datasets, which typically have fairly high rank order in terms of predictive capability to allow for the inference of useful results. Proven anchor datasets include a number of seismic observables and the gravity shape index (Stål et al., 2021, Supplement).

Data sharing and collaborative usage of aggregated datasets can be fostered with digital twins, which is an enabling technical area of Antarctic research[2]. There is great value in expanding and maintaining updated databases for surface observations and change identification, as such actions will enhance the resolution of current and future satellite-based gravity and magnetic data (e.g. MAGIC[3]) to study the lithosphere and deeper Earth structure. In general, Antarctic continental and global multivariate geoscience data compilation and sharing initiatives have significant potential to extend the value of all ground-based instrument

[2]https://dte-antarctica.org, last access: 20 March 2025.
[3]Mass-Change and Geosciences International Constellation, https://www.eoportal.org/satellite-missions/magic, last access: 15 December 2025

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observations. In turn, mutual benefit will be provided by improved Antarctic ground-based station coverage (e.g., to seismic tomography results) to global compilations and ongoing data-driven geoscience research more widely.

2.5 Broad Implications: GIA, Ice-Sheet Evolution, and Contributions to Sea Level

The response of the AIS to climate change represents the largest uncertainty in sea-level rise projections. Its evolution is governed by interactions among the ice sheet, atmosphere, ocean, and the underlying solid Earth (Fig. 1). Interactions are especially critical at the grounding zone (the transition between grounded ice and floating ice shelves) where feedbacks involving bedrock motion, sea level, and ice dynamics strongly influence the timing and extent of ice retreat on centennial timescales (Larour et al., 2019; Yousefi et al., 2022; Gomez et al., 2024; Houriez et al., 2025). These feedbacks include negative responses associated with local bedrock and geoid changes as well as positive feedbacks linked to regional sea-level change. Their strength and timescale are sensitive to mantle rheology, which is particularly important in regions such as the Amundsen Sea Embayment and the Antarctic Peninsula, where mantle viscosity is inferred to be much lower than the global average.

To understand such interactions, focus has increasingly shifted to models that couple changes in Earth's gravity field and solid-Earth deformation (so-called gravity, rotation, and deformation - GRD - models) with ice dynamics. The fidelity of GRD models is, in turn, dependent on reliable representations of the solid-Earth structure. Recent studies have begun incorporating time-dependent and laterally varying viscosity in GRD models. Resulting projections show that solid-Earth responses, including bedrock uplift, can significantly influence both future sea-level rise and coastal impacts worldwide, informing assessments such as those presented in IPCC (2023). Recent studies indicate that rapid uplift beneath submarine portions of the AIS interior could push water out into the wider ocean, a process called water expulsion, which could further contribute to GMSL rise (Pan et al., 2021; Yousefi et al., 2022)

Beyond solid-Earth effects, a major contributor to AIS projection uncertainty is the variability in the spatial pattern of regional sea-level change. This pattern is highly sensitive to the geometry of Antarctic ice loss and varies substantially across current ice-sheet projections (Kopp et al., 2015; Larour et al., 2020; Roffman et al., 2023; Gomez et al., 2024). Accurate representation of individual ice-stream dynamics and boundary conditions is therefore essential for constraining future AIS contributions to sea-level change. In particular, improved knowledge of spatial variations in bedrock topography and mantle rheology beneath Antarctica, especially within vulnerable marine-based sectors of both West and East Antarctica, is required to produce robust projections.

The ongoing GIA signal from past ice loading and unloading contributes substantial uncertainty to satellite-gravimetry-derived ice-mass loss estimates (The IMBIE Team, 2018; Groh and Horwath, 2021), with an average GIA mass correction of 54 ± 18 Gt/a (compared to the estimated -109 ± 56 Gt/a for Antarctic ice-mass change between 1992-2017). Constraining the ice history and the rheological structure of the solid Earth is also key to reducing this uncertainty, particularly in East Antarctica, where large discrepancies have been found between GIA models (Martín-Español et al., 2016; The IMBIE Team, 2018; Whitehouse et al., 2019; Groh and Horwath, 2021).

Much of what we know about the solid-Earth structure and rheology beneath Antarctica has come from seismic and geodetic observations (cf. Sec. 2.2). The high vertical displacement rates (up to 63 mm/a; Fig. 6) in the Amundsen Sea Embayment and

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the Antarctic Peninsula cannot be explained by traditional GIA or elastic rebound models (Nield et al., 2014; Barletta et al., 2018; Samrat et al., 2021); rather, they can only be reproduced by models with low mantle viscosity, likely between 10^{17} and $4 \cdot 10^{19}$ Pa·s, or 10 to 300 times smaller than the global average. Recent work suggests that both lateral viscosity variations and transient rheology (Ivins et al., 2020; Hazzard et al., 2023, cf. Fig. 11) in the upper mantle could explain such large deviations from previously expected viscosity profiles. Both forward GIA modeling (constrained against RSL and GNSS data) and Bayesian calibration of mantle rheology (based on geothermal heat flux, laboratory constraints, and seismic tomography) reveal that effective regional mantle viscosities associated with the last deglaciation and with the loading history over the last century differ by a factor of 3 to 100 (Fig. 11). Consensus has yet to be established regarding the respective contribution of these two aspects of mantle rheology. The 3D viscosity structure of the Antarctic mantle can be estimated from seismic tomography (cf. Sec. 2.3) and mineral physics parameterization; however, large uncertainties, both systematic and heuristic, exist in such mapping efforts (Ivins et al., 2023a). In particular, we note an outstanding discrepancy between the coarse spatial resolution of viscosity anomalies (Lucas et al., 2020) compared to observations of the ice sheet, which presents an issue for effective coupling. In this regard, improvements are limited by the insufficient density and coverage of current seismic and geodetic networks.

The spatial resolution of regional vertical land motion can be aided by expanding the number of GNSS installations, especially in regions with low mantle viscosity and/or considerably heterogeneous viscosity structure (Lucas et al., 2025). The horizontal displacement pattern should be taken into consideration in such regions. This type of improved spatial characterization will also help us to determine if GIA-induced land motion is a driver for processes that stabilize or destabilize the grounding line. This feedback mechanism, termed MISI (cf. Sec. 1), was investigated, among others, by Schoof (2012), Gomez et al. (2024), and van Calcar et al. (2025). On one hand, the stability (or steady-state equilibrium) depends on the retreat or advance of the grounding line under the condition of net mass loss or gain. Stability can be reached only in locations "where bedrock slopes downwards sufficiently steeply" (Schoof, 2012). On the other hand, under a low climate forcing, bedrock uplift, together with a relative sea-level fall in the vicinity of the lost ice mass, may reduce the ice loss at the grounding zone and lead to a stabilization effect. That said, Gomez et al. (2024) argue that, under strong climate forcing and an underlying mantle with short relaxation times, ice-sheet retreat exceeds any counteracting uplift effect and sea-level feedback (Fig. 12). Thus, GNSS-inferred displacement data with improved spatial coverage would provide input conditions for the coupled ice-sheet/GRD models that are currently being used to generate projections for important collaborative efforts, such as ISMIP7 and the IPCC reports.

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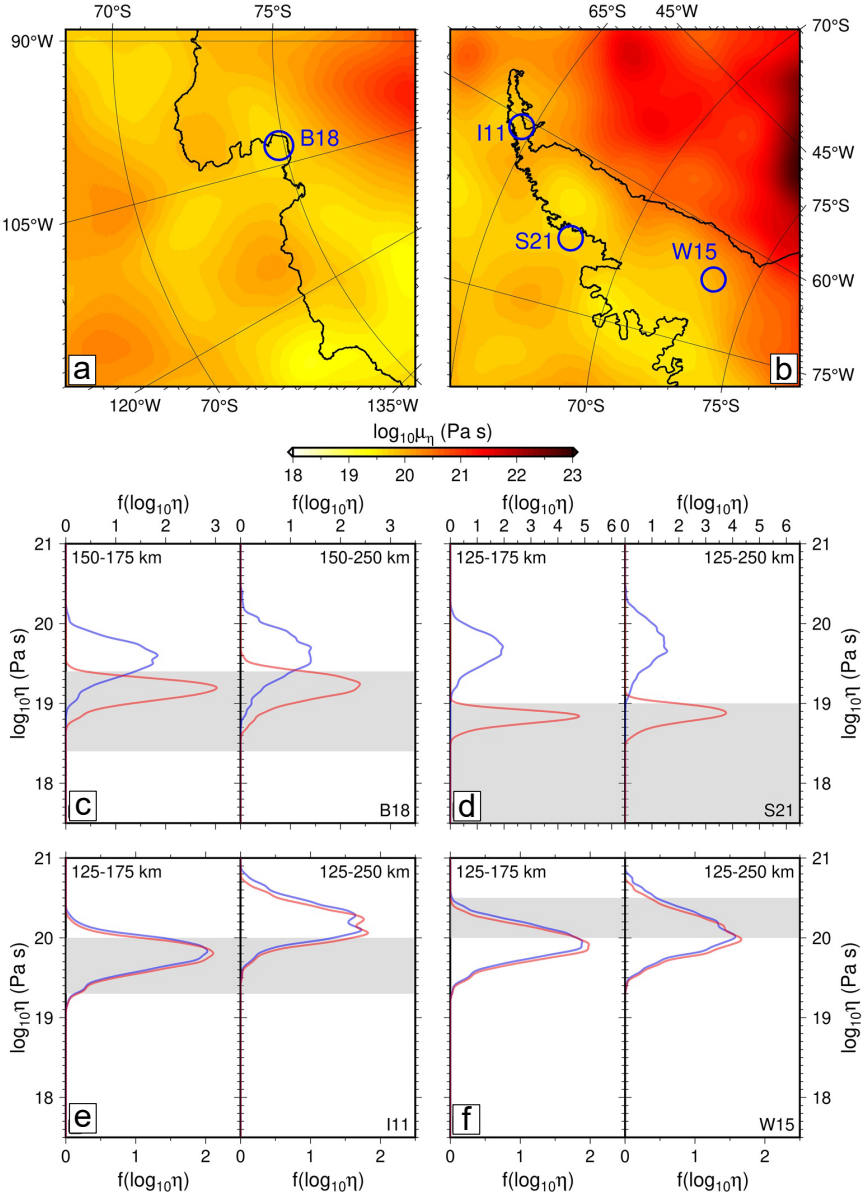


Figure 11. Comparison of upper mantle viscosity estimates based on GPS, laboratory experiment constraints, and seismic tomography. Panels (a) and (b) show the mean viscosity structure at 150 km depth beneath the Amundsen Sea Embayment and the Antarctic Peninsula, respectively, with lateral sampling regions overlain in blue. (c)-(f) Probability density distribution of inferred diffusion creep steady-state (blue) and time-dependent (red) viscosity compared to geodetic estimates (gray) from the sample regions indicated in the upper panels (B18, S21, I11, and W15 are shown in panels (c), (d), (e), and (f), respectively). From Hazzard et al. (2023, Fig. 13). B18: GPS observations 2002–2014, ice retreat from 1900 to 2014, viscosity estimate $\log_{10}\eta = 18.4 \ldots 19.4$ (Barletta et al., 2018); S21: GPS observations 1999–2020, ice retreat from 1999 to 2020, viscosity estimate $\log_{10}\eta = 17.5 \ldots 19.0$ (Samrat et al., 2021); I11: GPS observations 2003–2009, overall retreat from LGM to present, viscosity estimate $\log_{10}\eta = 19.3 \ldots 20.0$ (Ivins et al., 2011); W15: GPS observations 2009–2013, ice retreat from LGM to present, viscosity estimate $\log_{10}\eta = 20.0 \ldots 20.5$ (Wolstencroft et al., 2015).

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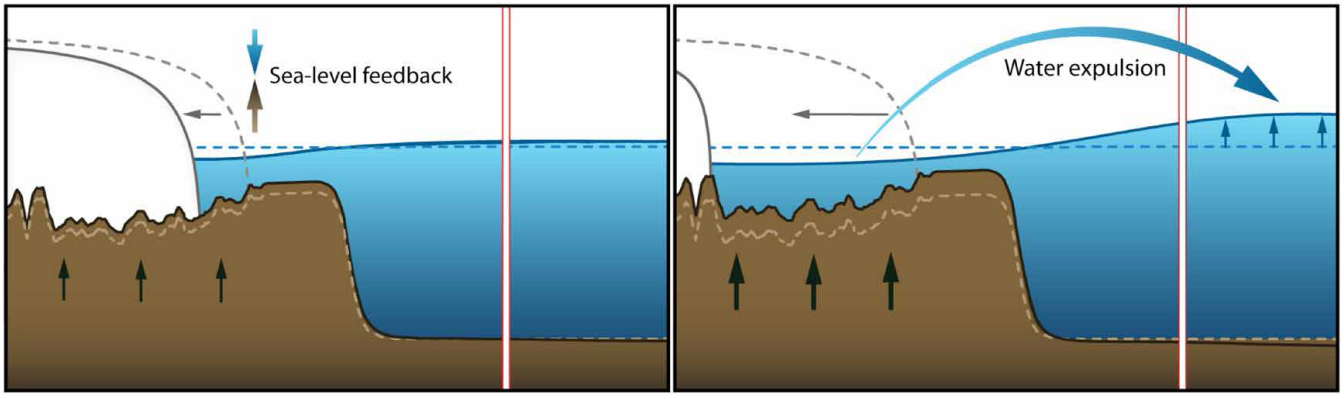


Figure 12. Sketch illustrating sea-level feedback and water expulsion mechanisms. Dashed lines denote original position and extent, respectively, of ice sheet, bedrock and ocean surface. Under low climate forcing, a sea-level feedback mechanism dominates where uplifting bedrock and lowering sea surface beneath marine sectors, underlain by low viscosity, reduce ice loss across the grounding line, leading to reduced far-field sea-level rise (left panel). Exposed ocean areas in Antarctica continue to rebound, expelling water and increasing far-field sea level more relative to the scenario with a rigid bed (right panel). Under low climate forcing, the sea-level feedback dominates and GIA reduces (marine) ice-sheet contribution to GMSL. Under strong climate forcing, the ice-sheet retreat is too fast, and bedrock uplift does not have a substantial feedback regardless of whether a rigid (non-deforming) or 3D viscoelastically deforming Earth model is adopted. Hence, sea-level feedback is weaker and water expulsion is the dominant effect amplifying ice-sheet contribution to GMSL. From Gomez et al. (2024).

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2.6 Broad implications: Space Weather Research and Atmospheric Parameters

Space weather refers to phenomena that occur in the upper atmosphere, mainly in the thermosphere and ionosphere. Today, space weather is considered a natural hazard that increasingly threatens both human life and technology, particularly as we move toward further reliance on infrastructure that is vulnerable to extremes in space weather phenomena.

There are several reasons why Antarctic measurements (Fig. 13) of the geomagnetic field as well as the ionosphere and thermosphere conditions are crucial to our understanding of and ability to forecast space weather. First, the space environment over the northern and southern polar regions is not symmetric, and the interplay between asymmetries, which vary on a range of temporal and spatial scales, has profound global impacts on a number of space weather phenomena. Thus, it is not possible to comprehensively understand or forecast such phenomena without simultaneous observational constraints in both the Antarctic and the Arctic. Second, certain processes at high geomagnetic latitudes can only be observed, or are best observed, in Antarctica since high magnetic latitudes in the Arctic are mostly in the ocean, where observations are challenging or impossible. Third, there are processes in the polar atmosphere/ionosphere that can only be studied in Antarctica as they occur more frequently and/or have different properties in that region when compared to the Arctic. For all of these reasons, the importance of Antarctic space weather measurements is emphasized by Kennicutt et al. (2014), and inspires the goals and science questions of the SCAR Antarctic Geospace and ATmosphere reseArch (AGATA) Scientific Research Programme[4] as well as those of other international and national space weather research organizations. An additional driver is that GNSS sites in the Antarctic Peninsula and parts of West Antarctica lie at magnetically conjugate latitudes to areas of North America where ionospheric observatories exist, thus allowing direct comparison of datasets during solar storms and other ionospheric phenomena (e.g., Meng et al., 2025).

There are many interconnections between geoscientific and terrestrial weather/atmospheric and space weather research, which have potential for intensified exploitation. Ground-based GNSS receivers are not only used by the geodetic research community but also provide a key diagnostic used for space weather research: total electron content along the line of sight between the ground-based receiver to a given GNSS satellite. This diagnostic is useful for both fundamental space weather research (e.g., Yue et al., 2016; Zou et al., 2023) and as an input to space weather nowcast and forecast models. It is particularly important in the high-latitude southern hemisphere as this region is sparsely sampled; yet, it plays an important role in determining global geospace dynamics. It is now standard practice for measurements from various repositories to be aggregated and processed to general global 2D maps of the ionosphere electron content (e.g., Rideout and Coster, 2006; Alfonsi et al., 2022). The need for expanded networks returning near real-time data is likely to increase in the next decade to feed space weather nowcasts/forecasts (e.g., several activities related to the implementation of the PROSWIFT legislation in the USA, SWIMMR initiative in the UK, PECASUS ICAO Consortium). Other examples of mutual-interest instrumentation include magnetometers, electrometers and magnetotelluric stations, weather packages (measurements of wind, temperature, etc.), and aerosol units (such as in the AERONET network).

[4]https://scar.org/science/research-programmes/agata, last access: 11 May 2025

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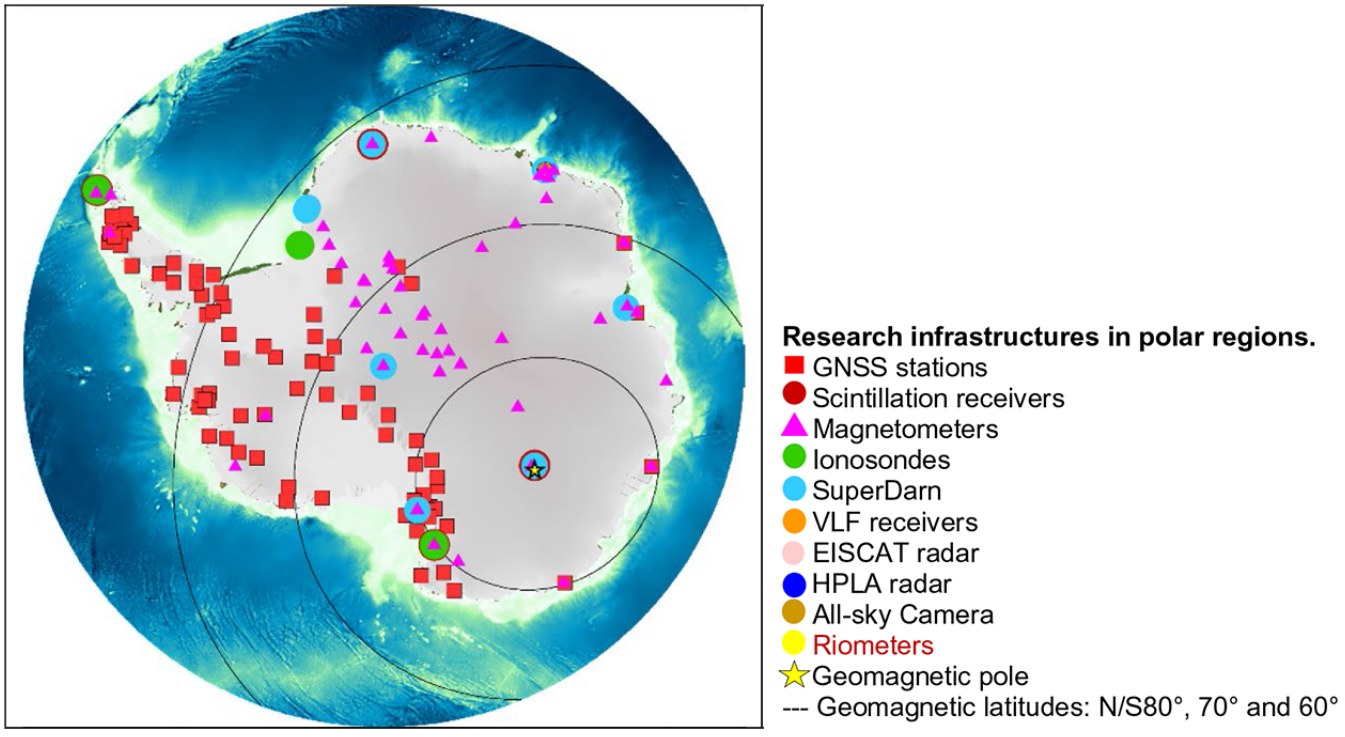


Figure 13. Shared deployments of scientific instrumentation infrastructure across Antarctica (selected established stations are shown to indicate the coverage of measurements). Notably, Antarctic GNSS stations and magnetometers are rarely co-located, limiting our progress in addressing topic research questions. Figure modified from Alfonsi et al. (2022, Fig. 1).

3 Implications for Contemporary and Future Investigations in Antarctica

Beyond the progress achieved so far in understanding the complex interactions between the AIS, solid Earth, atmosphere, and ocean, as reviewed in Section 2, a multitude of important science questions remain open. We present a list of these questions in Appendix A and will concisely discuss the most important aspects in Section 3.1. Section 3.2 presents special characteristics of key Antarctic areas that make them particularly suitable study areas for specific science questions.

3.1 Science priorities

Arguably, a primary science priority is the need to decisively improve our ability to produce accurate projections of Antarctica's contribution to GMSL rise. This includes better projections of how much and how fast the AIS will lose mass in response to a warming climate. To achieve this, more precise and reliable information on the ice sheet's dynamic response to Earth system feedbacks are required. In this respect, understanding GIA is a key to characterizing the coupled GRD response. Respective models need to be upgraded to integrate more complexity and capture spatio-temporal variations, amongst others to monitor and predict grounding line migration and corresponding ice-sheet instabilities (Whitehouse et al., 2019). Continued ground-based

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observations across the entire continent are indispensable to constrain model parameters and the resultant model predictions. Moreover, Antarctica provides a natural laboratory to study a range of processes and feedbacks within the Earth system which cannot be captured elsewhere.

3.1.1 **Sea-level change and ice-mass balance** (Questions 1 to 5)

Estimating current and future sea-level change on global and regional scales constitutes one of the most urgent global science questions today. Antarctica's current and future contribution to sea-level change cannot be captured without continuously monitoring the AIS mass balance (Horwath et al., 2022; Ludwigsen et al., 2024). For this, a consistent, accurate and reliable geodetic reference frame has to be provided and maintained over the long term. The International Terrestrial Reference Frame (ITRF) (Altamimi et al., 2023) forms a backbone to measure climate-related changes of the shape of the Earth, including elevation changes in the Earth, sea, and ice surfaces. In this respect, geodesy provides critical infrastructure to climate science[5]. Additional permanent GNSS installations can complement existing IGS GNSS sites in Antarctica to provide data for future ITRF realizations. Furthermore, it is of the utmost importance to extend the number of tide gauge installations since they provide independent in-situ observations of relative sea level. GNSS-IR at coastal installations provide an alternative to gain further in-situ sea-level measurements (cf. Sec. 2.2.7; Peng et al., 2021).

Our understanding of the interplay between AIS mass balance and GIA is critical, particularly where the mass and gravity effect has to be taken into account. As stated in Sections 1 and 2.5, the GIA mass correction still causes the largest uncertainty in mass balance estimates based on satellite gravimetry. This problem has to be urgently addressed, requiring GIA model capabilities to incorporate full coupling between ice sheet and gravity, rotation and deformation feedbacks. As these types of coupled models emerge, benchmarking and undertaking model intercomparison projects (MIP) in collaboration with other currently ongoing initiatives from the ice sheet, ocean dynamics, and climate science communities are essential.

3.1.2 **The benefit of expanding the temporal and spatial coverage of geodetic observations** (Questions 6 to 10)

To effectively address the questions of different time and spatial scales, both in the ice-load history and the response of the solid Earth, we have to consider and enhance the temporal and spatial resolution of bedrock displacement data provided by GNSS networks, together with the insights gained from seismological networks. Historically, the linear Maxwell model, which is the simplest model of Earth's viscoelastic rheology, has been used to predict GIA in Antarctica. This is partly due to the lack of ground-based and in-situ observational evidence to justify more complex rheological models. Evidence from outside of Antarctica, particularly from post-seismic and laboratory studies, strongly suggests that the asthenosphere and upper mantle are unlikely to behave according to a Maxwell model; instead, transient deformation phases likely exist, such as those described by an extended Burgers material (EBM) model (Lau and Holtzman, 2019; Ivins et al., 2022) or power-law rheology (van der Wal et al., 2015; Blank et al., 2021). Ivins et al. (2023b) showed that significant trade-offs exist between the amplitude of transient relaxation and its timescale when only linear trends are considered.

[5]https://ggim.un.org/UNGGCE/documents/Policy_Brief_Geodesy_is_critical_to_climate_science.pdf, last access: 15 July 2025

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Previous work that investigated post-seismic deformation using satellite gravimetry (Broerse et al., 2014) and GNSS records (Klein et al., 2016) has shown that continuous time series, spanning multiple years with weekly to monthly displacement rates, can be used to successfully isolate the rheological parameters that control transient relaxation time and amplitude. In their study of post-seismic deformation, Nield et al. (2023) suggested that additional rheological complexity somewhat improves model agreement with GNSS coordinate time series. Future large earthquakes present important opportunities to probe the mantle rheology beneath Antarctica, more so than past earthquakes in the Antarctic Peninsula, since the GNSS network is now more extensive and provides higher quality observations. Our ability to remove contaminating signals, such as SMB, has also greatly improved. The Scotia Arc, in particular, experiences regular $M_w > 7$ earthquakes that may deform the Antarctic Peninsula. Modeling these deformations is still in its infancy and, as with GIA, will require models that consider lateral solid-Earth variations as well as modern ice-loading changes (Nield et al., 2023). Observations of the changing uplift rate in regions with low mantle viscosity provide further opportunities to test competing rheological models and to couple them with ice-sheet evolution (Barletta et al., 2018; Gomez et al., 2024). The massive ice loss in the drainage basins of the Amundsen Sea Embayment provides a natural experiment to probe the viscoelastic properties of the Earth's interior, especially in terms of its heterogeneity (Lucas et al., 2025). Likewise, events such as the rapid onset of deformation in the Antarctic Peninsula following the 2002 Larson-B ice-shelf breakup provide a globally-unique natural experiment on shallow mantle rheology in the context of well-observed changes in surface loading.

Extended GNSS observations of Earth deformation, combined with increasingly sophisticated seismological and GIA models, are required to improve constraints on rheology. Displacement time series of at least decadal length are essential to characterize the transient and steady-state viscosity. Thus, maintaining and extending the current GNSS network, not only in regions with low viscosity but also throughout the continent, is essential to enable new breakthrough discoveries regarding mantle rheology. This is of great importance for regions where GIA model uncertainty is a dominant uncertainty, as especially in East Antarctica where there is not yet agreement as to the sign of mass change (The IMBIE Team, 2018; Otosaka et al., 2023). Further improvements in the rheological models will, in turn, require seismic (e.g., Ivins et al., 2023b), magnetotelluric (e.g., Lijun and Derrick, 2016), and geological observations.

Similarly, expanding the number of GNSS installations in regions with low mantle viscosity (like the Amundsen Sea Embayment) is extremely important to be able to improve the spatial resolution of local vertical land motion as well as to incorporate horizontal displacement patterns (Lucas et al., 2025). Processes that can either stabilize or destabilize ice-sheet retreat (e.g., Schoof, 2012; Gomez et al., 2024) could be tested using a denser network of GNSS measurement sites.

Holocene changes of the AIS (retreat and re-advance) remain poorly defined by geological, geomorphological, and ice dynamics studies. However, these are important for present-day deformation rates, with the exact time period of relevance depending on regional upper mantle viscosity and the magnitude of load change. In much of West Antarctica, load changes in the recent few hundred to a few thousand years are important (Bradley et al., 2015; Wolstencroft et al., 2015; Nield et al., 2012), whereas in East Antarctica, with a longer relaxation time, load changes over several millenia are likely most relevant (King et al., 2022; Johnson et al., 2022). This might be even more crucial in view of contemporary ice-mass gain in regions of East Antarctica, which may lead to subsidence, further hindering a correct separation of past and present-day effects.

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3.1.3 **Earth structure, rheology, and geodynamics** (Questions 11 to 16)

Determining the lithospheric structure and mantle rheology beneath Antarctica is not only essential to our understanding of Earth's response to changing loads on different temporal and spatial scales, but it also provides powerful insights into the tectonic processes shaping the continent. To address these topics, seismic studies in Antarctica are taking full advantage of evolving data processing capabilities (e.g., full waveform and adjoint tomography), which are fostering a range of scientific discoveries. Further, these seismic constraints can be converted to temperature and composition estimates (e.g., Faul and Jackson, 2005; Ivins et al., 2023b), which in turn, can be used to estimate lithospheric thickness and mantle rheology (e.g., Austermann et al., 2015; Ivins et al., 2023b). Both conversions rely on mineral physics constraints (e.g., Hirth and Kohlstedt, 2003; Wu et al., 2012). While inherent uncertainties and trade-offs between these parameters must be considered, geophysical proxies are still the most expedient avenue toward generating spatially extensive estimates of these important lithosphere-asthenosphere characteristics. Ensemble approaches (e.g., Mordret, 2018) can be employed to evaluate the range of plausible thermal and viscosity structures, thereby allowing for quantitative assessments of mantle flow variations and ice-sheet behavior. Plate motion and tectonic deformation can also be inferred from GNSS-inferred 3D coordinate time series, which provide information on temporal deformation patterns. That said, open questions remain with respect to the separability of horizontal displacement rates due to GIA and horizontal velocities due to plate motion (King et al., 2016; Turner et al., 2020; Vardić et al., 2022). Improved estimates of Antarctica's mantle rheology will help to improve GRD modeling.

3.1.4 **Structure of the deeper mantle and the Earth's core** (Questions 17 to 20)

Antarctic seismic investigations are critical in terms of addressing questions about deeper mantle structure and the Earth's core. While some of these topics do directly influence the continent itself, others are broader-scale questions that are relevant to the large-scale inner workings of our planet. For example, recent studies have highlighted anomalously slow features just above the core-mantle boundary (CMB) beneath Antarctica, which could be the remnants of subducted slabs (e.g., (Hansen et al., 2020, 2023; Agboola et al., 2024). These materials may be associated with an ubiquitous layer in the deep mantle, with variable characteristics. If present, this layer could have notable effects on core heat flux, the formation and dynamics of mantle plumes, and/or coupling mechanisms between the mantle and the core (e.g., Nakagawa and Tackley, 2010; Li and Zhong, 2017; Mound et al., 2019), but further CMB sampling is needed to evaluate this possibility. Seismic data collected in Antarctica have also made major contributions to our understanding of the structure, rotation, and rheology of Earth's core. For instance, seismic studies have shown differential rotation between the inner core and the mantle, with the inner core accelerating and decelerating in recent years, and this temporal variability may be associated with viscous deformation, meaning the inner core is not as solid as originally thought (e.g., Tkalčić et al., 2013; Vidale et al., 2025), but more data are needed to confirm these observations. Seismic stations in Antarctica provide a unique vantage point to record waves that sample these deep portions of our planet.

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3.1.5 **Cryospheric processes** (Questions 21 to 26)

Monitoring the AIS and predicting its future evolution requires improved understanding of individual processes, the interlinkage between them, and their feedbacks across boundary interfaces, including the subglacial bed, atmosphere and ocean. Geophysical networks provide important observables to advance cryospheric research.

Antarctic seismology also encompasses the study of force systems that excite seismic waves. From such investigations, we have learned much about the different geodynamic processes (e.g., tectonic, volcanic, cryospheric) that shape the continent. Cryospheric seismicity is extraordinarily prolific, but most events are small and seismic source studies in Antarctica are thus largely impeded by the lack of station coverage of sufficient density (see Sect. 2.3); additional broadband and/or DAS instruments are required to further identify, locate, and monitor seismic events with high resolution. Machine learning-based applications (e.g., Ross et al., 2018; Zhu and Beroza, 2018; Woollam et al., 2019; Mousavi et al., 2020), which provide reliable automatic detections of seismic events, can be applied to such datasets, and fuzzy logic algorithms can be employed to differentiate between glacial versus non-glacial sources (e.g., Gajek et al., 2017).

Cryospheric processes involve snow fall and compaction, and subsequently the surface mass balance plays an important role in understanding and correctly capturing present-day ice-mass change. In that respect, GNSS-IR (at stations installed on the ice) has the potential to provide valuable data on snow surface height as well as on the upper layers due to the depth-penetrating signal (Nievinski and Larson, 2014a, b).

3.1.6 **Seismic wavefields** (Question 27)

Seismic wavefields in Antarctica are strongly influenced by the presence or absence of sea ice. Investigations of the IBIZ, for example, should be preferentially carried out in late summer when the highest amplitudes of the ambient wavefield can potentially yield details on sub-ice sediments and the crust. This can likely be obtained even from relatively short-duration passive seismic deployments. Techniques that rely on earthquake signals require longer deployments (typically one to two years minimum), and these can also potentially provide information on any seasonal changes in the IBIZ.

3.1.7 **Improved general circulation models** (Question 28)

Antarctica is a critical environment for observing and assessing the impacts of global climate change. Monitoring changes in atmospheric structure, including water vapor, albedo, and aerosols, using various instruments and methodologies is of great importance. Long-term analyses of these and other parameters from distributed locations across Antarctica would make substantial contributions to climate and general circulation models and to future predictions relevant to atmospheric and cryospheric research. There are also connections with space weather via two-way coupling/forcing with the ionosphere and thermosphere as well as changes in atmospheric chemistry from cosmic rays. In short, there are many physical linkages between the ionosphere, atmosphere, cryosphere, ocean, and the solid Earth that are crucial to our understanding of dynamics in each of these regions. As such, there is great need for interdisciplinary collaborations and coordinated observational campaigns, data assim-

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ilation, and modeling efforts to improve our understanding of these connections and to enhance the accuracy and reliability of general circulation/climate models.

Many projects require access to similar regions of Antarctica and, as noted above, have a shared interest in the deployment of certain instruments. Unfortunately, due to limited coordination between past projects, instruments are often not co-located. For example, magnetometers tend to be deployed on the East Antarctic Plateau, whereas dense networks of GNSS receivers are often deployed in West Antarctica or in coastal regions (Fig. 13). Sharing field logistics and resources would benefit multiple research communities and would enable stronger arguments to be made to access particularly remote, difficult to reach portions of Antarctica.

3.2 Key Areas for Future Geodetic-Geophysical Observations

In the following subsections we highlight specific regions of Antarctica that are of greatest scientific interest either because continuous, long-time series in these regions are of the utmost importance and/or observational gaps need to be closed in order to answer the critical questions discussed in Section 3.1. We recommend future field locations are targeted in multiple ways: 1) conventional gap-guided targeting where current datasets are especially sparse, 2) model-guided targeting to identify key locations where new data would have high impact (McCormack et al., 2022), and 3) anchor-dataset guided targeting to improve the performance of statistical and machine learning approaches. Contemporary targeting strategies can provide a highly impactful addition to the gap-guided approach within the priority regions below.

3.2.1 West Antarctica and the Amundsen Sea Embayment

Glaciers in West Antarctica are undergoing rapid ice loss in response to changing atmospheric and oceanic conditions (Poinelli et al., 2025). In particular, rates of ice loss at Pine Island Glacier and Thwaites Glacier in the Amundsen Sea Embayment have increased fivefold over the past few decades (Shepherd et al., 2019). Glaciers in this region are already large contributors to sea-level rise (Rignot et al., 2019) but total collapse of the WAIS would raise sea level by over three meters (Bamber et al., 2009).

Due to the significant ice loss occurring in this region and the inferred low mantle viscosity (see Sec. 2.2.3), this is a primary region to probe Earth's rheology. The Amundsen Sea Embayment has the highest GNSS-derived vertical displacement rates of anywhere in Antarctica and even on the entire planet (6), and the fast response of the solid Earth to changes in present-day ice loss provides a natural experiment to constrain the rheologic structure, particularly transient behaviour, from long and continuous GNSS time series. Furthermore, seismic imaging has constrained small-scale (less than 100 km) spatial variability in upper mantle viscosity in this region (Lucas et al., 2025). Including localised lateral viscosity variations in GIA models can substantially affect model-predicted crustal deformation and relative sea-level changes (Lucas et al., 2025) and, therefore, can impact solid Earth-–ice sheet-–sea-level feedbacks that may act to stabilize retreat of the WAIS in the future.

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3.2.2 Antarctic Peninsula

The upper mantle viscosity beneath the Antarctic Peninsula has been inferred to be several orders of magnitude lower than the global average (see Sec. 2.2.3). Faster solid-Earth response times in the Amundsen Sea region indicate that present-day displacement is dominated by changes in the ice sheet occurring over decades to centuries instead of millennia.

The ice history in this region is complex, and over the past 2,000 years there have been periods of both ice loading and unloading as the climate has fluctuated (Nield et al., 2012; Wolstencroft et al., 2015). Ongoing GNSS measurements, in conjunction with GIA models, will enable us to unravel the relative contribution of past ice changes to present-day displacement.

On a decadal time scale, widespread retreat and collapse of ice shelves since the 1970s has led to an acceleration and thinning of tributary glaciers, resulting in increased ice-mass loss (Cook and Vaughan, 2010). The solid-Earth response to this ice loss has already been observed in GNSS time series (Nield et al., 2014; Samrat et al., 2020; Nield et al., 2025). In the future, continuous GNSS measurements offer the opportunity to observe the Earth's response to ice-mass changes as the system regains equilibrium and rates of ice loss diminish. Furthermore, the GNSS network in the Antarctic Peninsula is important to maintain in order to capture the Earth's response to possible future ice shelf collapses and subsequent rapid ice loss. This will enable us to place tighter constraints on the Earth's rheology, including identification of potential transient behaviours, but this is only possible with long, continuous time series.

3.2.3 Ellsworth and Coats Land and the Filchner-Ronne Ice Shelf

Our knowledge of AIS deglaciation around the Filchner-Ronne Ice Shelf remains a critical source of uncertainty in GIA models. There are large misfits between GIA model predictions and GNSS observed uplift rates in this region, particularly on the western side of the Ronne Ice Shelf (Wolstencroft et al., 2015) , with many GIA models significantly over-predicting uplift rates (Whitehouse et al., 2019). This suggests existing models of deglaciation are incorrect.

A possible explanation for the misfit is that the glaciation history is not sufficiently captured in the modeling. In this region, the ice sheet may have retreated behind the present-day grounding line during the Holocene and subsequently re-advanced (Bradley et al., 2015; Kingslake et al., 2018). This later loading associated with re-advance would damp the uplift predicted by GIA models and reduce the misfit to GNSS observed displacement, particularly at sites showing subsidence (Bradley et al., 2015). Here, GNSS networks provide important constraints on model output, particularly because the role of GIA in retreat and re-advance is currently being debated (Lowry et al., 2024).

Coats Land remains the region of Antarctica where GIA models show the biggest differences in uplift rates. Leading GIA models estimate uplift of approximately the same magnitude, but the opposite sign (Whitehouse et al., 2019). Continued measurements of bedrock displacement are imperative to improving GIA models in this area.

3.2.4 East Antarctica

East Antarctica exhibits regions of different characteristics. The Transantarctic Mountains mark the boundary between cratonic East Antarctica and rifted West Antarctica. The deep structure of this boundary, documented by seismic studies, shows a pro-

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found change in crustal thickness and inferred mantle viscosity. Understanding how these structure and rheological gradients modulate the Earth's response to changing ice-sheet mass needs to be advanced through targeted GNSS and seismic measurements. Recent geodetic evidence has suggested the Transantarctic Mountains may be uplifting much slower than previously suggested by geodetic estimates, in disagreement with some GIA model predictions (Koulali et al., 2025).

Northern Victoria Land is another key area of investigation. While MISI has been highlighted within marine basins in West Antarctica (e.g., Joughin et al., 2014; Rignot et al., 2014), improved ice thickness measurements in East Antarctica (e.g., Greenbaum et al., 2015) reveal the presence of several deep basins that may have been prone to the MISI in the past and may be again in the future (e.g., Stokes et al., 2022). For example, the Wilkes Subglacial Basin (at approximately 145°E, west of Victoria Land, cf. Fig. 3) may have significantly contributed to past sea-level change (e.g., Blackburn et al., 2020) and could contribute up to $3-4$ m of sea-level rise in the future (e.g., Mengel and Levermann, 2014; Stokes et al., 2022). As discussed recently by National Academies Press (2024), parts of East Antarctica are rapidly losing mass and may have even greater potential for sea-level contributions than West Antarctica. As such, Northern Victoria Land was highlighted as a priority target for focus on current and future sea-level rise.

The vast coastal zone of East Antarctica has been explored to different extents in terms of geophysical observables. GNSS recordings on bedrock are sparse, especially in eastern Dronning Maud Land (approximately 15° to 35°E), Enderby and Kemp Land (approximately 40° to 60°E), and from 75° to 155°E longitude. However, large marine basins within East Antarctica could substantially contribute to future sea-level rise, particularly on multi-century timescales and under high-end climate warming scenarios. For example, new evidence published by Hansen and Emry (2025) shows that the mantle beneath submarine portions of the Wilkes and Aurora Subglacial Basins may be underlain by low viscosity mantle. Modern ice-mass balance estimates for East Antarctica also disagree, not just in terms of magnitude but even in terms of sign (The IMBIE Team, 2018). Some of the regions, especially eastern Dronning Maud Land, Enderby, and Kemp Land, are thought to be associated with positive ice-mass balance in recent years. Glaciers in these areas are still grounded when they reach the ocean. Other parts of East Antarctica host glaciers that are marine-based, such as the Denman and Totten Glaciers. Jones et al. (2022) proposed significant and rapid thinning, with grounding line retreat beyond its current position, along the entire east AIS margin during the early to mid-Holocene. Subsequent ice-sheet re-advance has also been found in parts of East Antarctica, such as near Rauer Islands (e.g., Berg et al., 2010) and further east at Bunger Hills (e.g., Berg et al., 2020). King et al. (2022) advocated that re-advance is the reason for GIA-related subsidence (-0.5 to -2 mm/a) west of Denman Glacier, as inferred by GNSS data. Densified and continuous GNSS time series recordings are critical to help unravel Holocene ice-sheet retreat and re-advance. Co-located geophysical measurements, like seismology and magnetotellurics (Ramirez et al., 2022; Manassero et al., 2025), are needed to narrow down mantle rheology parameters. Thus, expanding observational networks in this region will provide foundational knowledge of ice-Earth interactions.

3.2.5 South Pole and the Deep Antarctic Interior

Across the vast expanse of Antarctica, the region surrounding the South Pole holds particular scientific importance. The South Pole lies within East Antarctica, near the southern end of the Transantarctic Mountains. Understanding the subsurface prop-

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erties in this region is not only essential for tectonic reconstructions of the East Antarctic craton but is also needed to assess how this region influences ice dynamics and global climate. The East Antarctic Ice Sheet, which overlies this area, exhibits significant topographic variations, indicative of complex mantle dynamics and geothermal anomalies, all of which impact past and ongoing ice-sheet evolution. Despite the scientific significance of the South Pole and its surroundings, this region remains poorly studied given sparse seismic coverage. Only one permanent seismic station (QSPA/SPA) is located at the South Pole (blue triangle in Fig.3) with its nearest broadband neighbor over 250 km away.

3.3 Enhancing Observational Capabilities

Technological advances are essential to answer the key scientific questions outlined in Sections 3.1 and 3.2. Both long-running (several years or longer than a decade) and short-term (months to years) geophysical observations are foundational to improving our understanding of the Antarctic continent. Improvements in instrumentation over the past decade(s) have included data loggers and sensors designed for the harsh climatic conditions and integration of satellite communications in sensors. That said, there is room for improvement, particularly in power consumption and communications. While most aspects of geophysical and geodetic deployment design are constantly evolving to improve both data quality and efficiency, we highlight several avenues that will provide the greatest benefits to the polar Earth science community in the following subsections.

3.3.1 Improved autonomous power solutions

Lowering the power consumption of geophysical instrumentation and GNSS equipment remains a high priority since power systems at remote locations remain a significant component of the logistical burden; their failure creates observational gaps. Recent collaborations between academically focused instrument facilities and industry partners have led to significant improvements, and even marginal gains in the future will have significant impacts on the scope of upcoming deployments. Thus, investment in reliable long-term power systems still has high priority.

Solar power is a viable option during the Antarctic summer, but to maintain power throughout the winter darkness, large banks of deep-cycle rechargeable batteries are required. Such batteries are logistically challenging and hazardous to transport to remote sites (cf., Fig. 5). A compromise is almost always made between a relatively low-cost, logistically expensive solution (i.e., lead-acid batteries) or a high-cost, logistically cheaper option (i.e., multiple types of lithium batteries). The lithium option typically has a limited life span; however, recently deployed rechargeable lithium battery systems are showing promising results. Wind turbines are vulnerable to mechanical failure in the extreme cold and at high wind conditions, their power output is high, and overcharging can damage batteries. Improved solutions for lower-weight, reliable long-term deployments are needed.

3.3.2 Reliable low-power data telemetry

A principal challenge for remote deployments is station telemetry to provide instrument state-of-health and to transfer data, thus reducing the frequency of site visits. Although successfully implemented with Iridium for GNSS data, telemetry remains an

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issue for the relatively large data-volumes recorded by seismic deployments. As a result, most seismic instruments in Antarctica (deployed away from permanent stations) require periodic service visits to recover the full dataset. Although taking advantage of newly-deployed, fast-developing, low-orbit satellite constellations seems to be an attractive solution, greater power will be required and these systems are often developed by private companies, which could pose additional reliability and cost risks compared with state-owned systems. Emerging enablers for both seismic and multivariate data analysis include high-volume data transfer optimized by data analysis on-location, followed by satellite transfer of a reduced volume of partly processed data (known as edge computing; Ji et al., 2024). For some field deployments, and in combination with semi-automated data processing, this will enable new observation approaches as well as streamlining data transfer for established techniques.

3.3.3 Joint approaches for key properties and observations

The concept of considering joint constraints on key properties offers the potential for step-change advances in inferring key properties of the Antarctic subsurface. An example of a promising combined technique is the joint consideration of seismic and magnetotelluric data, which provides better constraints on mantle viscosity (Ramirez et al., 2022; Manassero et al., 2025), an important input in GIA studies (cf. Sec. 2.5). Further, the use of high-precision radar sounding may provide a ground-breaking way of enabling GNSS time-series data to yield information about bedrock displacement in ice-covered locations (Schroeder et al., 2024).

3.3.4 Ease and Duration of Deployment

Traditionally, geophysical and geodetic instruments in remote areas have been deployed in two principal ways: (1) land-traverses by snowmobiles/tracked vehicles or (2) airborne support by fixed-wing aircraft or helicopters. Instruments are often deployed near remote camps, or their installation is coordinated within larger international collaborative programs that use both land-traverses and airborne support. Ski-equipped fixed-wing aircraft allow the community to reach some of the farthest, and otherwise most difficult, regions of Antarctica, and this has served as the backbone logistical foundation for field programs such as POLENET. However, long-distance flights limit ground time and deployment capacity. Long-distance land traverses, on the other hand, require extensive logistical preparations. Moreover, although well designed to survive the Antarctic winter and other environmental challenges, current polar instrumentation is still bulky and requires large logistical resources for its transportation and deployment.

Other options are being explored to reduce logistical burdens, including diverse means of transportation and new techniques that reduce logistic dependencies. For example, in some regions, wheeled vehicles (e.g., Arctic Trucks[6]) provide long-distance traverse capabilities with light-weight logistics support. Better-designed wind turbines and rechargeable, high-density lithium batteries can reduce the need for heavy non-rechargeable batteries to provide winter power. Lighter, smaller, and more powerful observational capabilities (e.g., combined instrument types), coupled with wheeled vehicles, leads to better deployment potential for large-scale observational networks at costs traditionally associated with small field campaigns. This is an important issue because the ground time needed for installation and maintenance is a decisive factor in logistical planning. This also

[6]https://arctictrucks.com/, last access: 16 Sept 2025

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relates to the topic of data retrieval. If full datasets can be telemetered, logistically expensive site visits can be dramatically reduced. That said, snow accumulation at long-term, autonomous site locations must also be considered, and new systems will need to be designed so that they are locatable and eventually retrievable under such conditions.

3.4 Advancing Antarctic Science Through International Cooperation: A Forward-Looking Strategy

Reaching the science goals detailed in this overview will depend on ambitious data collection campaigns, including, for example, rolling deployments of seismic and other geophysical instruments and acquisition of continuous, long-term GNSS time series. A key requirement is data acquisition at large spatial scales to answer questions across the Antarctic continent. Such large-scale and long-term instrument deployments pose special obstacles because logistical support for deep fieldwork at remote sites is challenging and expensive. As noted in a series of Antarctic science vision reports over the past decades (National Academies Press, 2012, 2015; SCAR, 2023), a crucial means to overcome logistical obstacles is by pooling resources from many nations. Our community discussions have led to suggestions to implement multi-national collaboration to reach our science goals.

3.4.1 Strengthening Geophysical and Geodetic Community Planning

National and multi-national long-term science plans are a proven means to achieve consensus on priorities and establish a plan for successive science goals, used, for example, by the ice coring and astrophysics polar communities (National Academies Press, 2023; National Science Foundation, 2025a, b). Establishing such plans for Antarctic geophysical deployments can send clear messages to national Antarctic research programs on future science priorities and logistical needs that require multi-national support. Multiple strategies to achieve this are suggested below.

Engage internationally through SCAR and COMNAP

SCAR provides a central forum for grass roots development of international science plans. Forming ‘Action Groups’ under the SCAR science groups can be used to engage scientists with parallel interests, achieve consensus on science priorities, and form strategies for acquiring the relevant data sets to achieve science goals. Biennial SCAR conferences provide regular opportunities to gather the international science community and advance planning. SCAR groups can engage with the Council of Managers of National Antarctic Programs (COMNAP)[7] to present their goals and strategies and discuss feasible approaches for coordinated field campaigns that can be implemented by multiple nations.

Information Platform and Open Data

Collaboration in both science and field campaigns could be advanced by implementing a platform to disseminate information on research projects and planned field programs. Excellent models of such systems are the ISAAFFIK Arctic Gateway (Denmark)[8], a user driven web platform supporting Arctic research and collaboration, and the Southern Ocean Observing System

[7]https://www.comnap.aq/, last access: 16 Sept 2025
[8]https://isaaffik.org/, last access: 16 Sept 2025

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(SOOS)[9], currently based in Australia, which aims to facilitate and enhance Southern Ocean observations. Polar instrument systems pose unique engineering challenges due to extreme environmental conditions and months without sunlight as well as logistical challenges, such as limited cargo capacity and ground time at remote sites. Information exchange on successful engineering solutions on a range of instrument system scales can greatly improve efficiency for field deployments and continuous data collection. An information platform with content on technology, together with community discussions, perhaps modeled after the U.S. Polar Technology workshops, could support information exchange and foster innovative development. In the U.S., EarthScope[10] represents a successful model for focused efforts, driving technological development, facilitating measurement campaigns, and archiving data to service the geophysical and geodetic communities.

The value of Antarctic geophysical observations can be greatly augmented by adopting open data protocols. One crucial step would be to establish an international network for scientific data transmission from Antarctica. Communication with remote instruments documents operational health and allows satellite transfer of data, both of which significantly reduce requirements for site visits and the overall logistical footprint. Data should be transferred to open access repositories, all interlinked internationally and adhering to the FAIR principle (findable, accessible, interoperable and reusable data) (Wilkinson et al., 2016).

Maintaining a healthy community

Deep-field polar fieldwork requires unique skills in planning for and operating in remote, extreme environments. Introducing students and early career researchers to fieldwork as members of field teams serves to open doors for them to become successful independent polar researchers. It is important for national Antarctic research programs to enhance opportunities for field participation for early-career scientists.

Enhancing individual skills in using geophysical data effectively, as well as facilitating the creation of innovative new approaches to data use, is essential to amplify the value of geophysical datasets acquired with great effort and expense. One proven model is implementation of multidisciplinary, international training schools (Sherman et al., 2025). Community workshops on new data analysis methods and applications are also keystone activities to promote advanced data use.

3.4.2 Establishing multi-national planning and funding mechanisms

It is universally agreed that international collaboration is crucial to meet Antarctic science objectives that cannot be achieved by a single nation; yet, substantial barriers to the implementation of international programs remain. Several models for multi-national research programs in Antarctica have been used successfully. One model, used for many programs during IPY-4, relies on research groups seeking funding for a collaborative science plan from their own national agencies and logistical support programs. A similar model also requires successful proposals from research teams in multiple nations, but logistical support is pooled, and the contribution from each national program is established by a 'memorandum of understanding.' These approaches have 'multiple jeopardy' in that each national program must approve both science funding and logistical support for the research plan to succeed. At present, there is no established mechanism for review/award for a single proposal from

[9]https://soos.aq/, last access: 16 Sept 2025
[10]https://www.earthscope.org/, last access: 16 Sept 2025

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a multi-nation research team. Developing multi-national funding mechanisms could provide the means to achieve instrument deployments at large spatial scales and over longer time frames.

Although past collaborative mechanisms have achieved greater science breadth and spatial scope for measurement campaigns, the challenge of support for long-term plans remains, either for sequential deployments planned in different regions or long-duration time series acquisitions. An international consortium model has the potential to support long-term science plans and alternative options for logistical support, while providing flexibility in the level of science funding and logistical commitments from national programs. In a mode similar to the former International Ocean Discovery Program (IODP)[11] or the current IceCube[12] program, nations with Antarctic research programs could contribute funding to a consortium to support deep-field logistic platforms capable of remote geophysical deployments. Nations could select their level of funding and logistic contributions, which could be modified through time. A consortium could also provide a pathway for non-governmental foundations or other organizations to contribute to science support. A multi-national science advisory structure would maintain an updated science plan and establish priorities for field campaigns. Maintaining a flexible funding pool would allow innovative approaches to field support, such as contracting air or land traverse support from non-governmental organizations. Such a pool could also support a data transfer collaboration. The science arm of the consortium could take on tasks such as creating an information platform and promoting innovative data analysis, as highlighted above.

3.4.3 Planning for the next International Polar Year

The 5th International Polar Year (IPY-5)[13], planned for 2032–2033, offers unique opportunities for multidisciplinary and multinational Antarctic research. The preceding IPY-4 (2007-2008) created a framework to initiate new collaborations and to elevate Antarctic geophysical networks to a new, unprecedented level. For example, the POLENET project (spanning both the Antarctic and Arctic) was one of the largest projects initiated during IPY-4 (Wilson et al., 2011), and it has yielded a wealth of new discoveries (see Section 2) as well as a crop of younger generation polar geophysicists, who are fueling current efforts. This review paper provides the framework for community efforts to advance Antarctic Earth science through geophysical measurements for IPY-5.

4 Summary

The AIS, comprising 70% of global freshwater, contributes substantially to GMSL, recently estimated at 0.4 mm/a. The high uncertainty in future projections stems significantly from a lack of well-founded knowledge regarding the properties of the solid Earth and its response to ice-mass variations, which can stabilize or destabilize the AIS. Specifically, GIA model uncertainty accounts for about one-third of the total AIS mass change amplitude estimated from satellite gravimetry. Addressing this problem requires improved measurements of bedrock displacement and of solid-Earth properties beneath Antarctica, especially regarding viscoelasticity.

[11] https://www.iodp.org/
[12] https://icecube.wisc.edu/
[13] https://ipy5.net/, last access: 15 December 2025

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GNSS have revolutionized our understanding of geodynamics in Antarctica, demonstrating that solid-Earth processes are relevant to climate studies and overturn previous assumptions of slow response. Starting in the 1990s with a focus on plate tectonics, geodetic GNSS observations now suggest a coherent Antarctic plate motion without large internal tectonic deformation. Since then, our knowledge of the response of the solid Earth has considerably expanded, supported by long GNSS time series and seismic networks. In addition, seismological recordings provide crucial, independent constraints on the Earth's internal structure, particularly mantle viscosity, which is a key parameter for GIA models, and sub-ice geology, which provides critical boundary conditions for ice dynamics.

Since 2000, more than 400 GNSS and seismic stations have been deployed across Antarctica. We note that deployments are unevenly distributed, concentrated along the Transantarctic Mountains, the Antarctic Peninsula, and in West Antarctica, reflecting the availability of exposed bedrock for GNSS monumentation. This uneven coverage leaves substantial gaps, especially in East Antarctica, which continues to limit our ability to correctly identify ice-load history and solid-Earth structure effects in GIA. Further, in order to discriminate deformation processes at shorter time scales (centuries to decades) and to investigate possible GIA-related processes that may stabilize or further destabilize the ice sheet, GNSS recordings at higher spatial resolution are needed in select regions. Notably, in order to constrain key properties of the Earth's internal structure, joint deployments of additional GNSS and seismic stations, along with other geophysical observations, provides a promising way for the future. For instance, the joint consideration of seismic and magnetotelluric data provides better constraints on mantle viscosity. Finally, we note that as future Antarctic deployments focus on key science questions, they will also generate new unexpected discoveries and knowledge.

Future efforts must decisively move beyond basic mapping to focus on coupled systems modeling. This requirement will already be taken into account in upcoming projects such as Antarctica InSync[14] and IPY-5. The two most critical needs are:

1. Consistently testing and modeling a realistic mantle rheology (including lateral inhomogeneities and transient relaxation) alongside AIS mass changes across all timescales.

2. Developing coupled ice-sheet / GRD models that fully integrate the complex nature of the sub-ice geology as well as the solid-Earth–ice-sheet–ocean interaction to yield accurate projections of GMSL change.

To achieve climate-relevant certainty in Antarctic mass loss and sea-level contributions, sustained and strategically placed geophysical observations (GNSS, seismic, and additional sensors) are essential to constrain Earth structure and improve GIA modeling. The solid-Earth community must prioritize filling observational gaps to inform comprehensive, predictive Earth system models.

Code and data availability. Code or data are not provided with this review paper. For data availability, see respective statements in the published papers referenced in the text.

[14] https://www.antarctica-insync.org/, last access 15 December 2025

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Appendix A: Science questions

Below, we present the list of science questions that are referred to in Section 3.1.

1. What ongoing GNSS observations in Antarctica best contribute to realizing a global geodetic reference frame that would allow for high-resolution measurements of climate, ice-mass and sea-level changes, and to resolve GIA-related deformation in polar regions?
2. How can a considerably extended number of in-situ sea-level recordings at the Antarctic coast, taken by tide gauges and/or by GNSS reflectometry, be used to improve observations of regional sea-level change?
3. How is the AIS mass balance currently changing, both in terms of regional surface mass changes and ice dynamical responses?
4. In which way(s) should our understanding of GIA corrections with respect to ice-mass balance and geoid change be revised?
5. What processes do coupled ice-sheet/GRD models need to include, and how can we assess their accuracy?
6. How can observed bedrock displacements be used to investigate Earth's short-time anelastic and viscoelastic responses to contemporary mass load changes?
7. To what extent can currently measured bedrock displacements help to discriminate long-term (millennial) and short-term (centuries to decades) solid-Earth response to AIS mass change, and be used to unravel Holocene ice-sheet retreat and re-advance?
8. What is the sensitivity of current and future GIA model predictions of bedrock displacement to present-day observational constraints?
9. How has ongoing deformation from mass loading that occurred before the instrumental record affected ice-sheet dynamics during the past, and how might this inform us about projections of the future evolution of the AIS, bedrock, and sea level?
10. What additional data are needed to independently constrain the ice sheet's history (e.g., from glacial geology)?
11. What is the composition, rheology, and geologic history of the crust and the lithosphere?
12. How do we consistently characterize (upper) mantle rheology, including both lateral viscosity variations and transient relaxation? How can we distinguish between their relative importance and contributions?
13. What are the connections between onshore and offshore structures and their geodynamic implications?

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14. What are the connections between earthquake-triggered (postseismic) and GIA-related deformation, and how can this be used to probe mantle rheology?
15. What is the absolute motion of the Antarctic plate, and is there active intraplate tectonic deformation within the continent?
16. Are there geodynamically active regions of Antarctica that have yet to be identified and, if so, what are their corresponding origins?
17. How does the structure of the mantle transition zone vary beneath Antarctica, and does it indicate regions affected by deeper mantle Earth processes?
18. What is the lowermost mantle structure beneath the southern hemisphere and how does this inform us about mantle convection processes and high temperature, high pressure mineral physics?
19. Are there anomalous structures along the core-mantle boundary, and if so, what are their origins?
20. What are the internal structures and boundary processes for the outer and inner cores?
21. What are the subglacial properties and processes relevant for past and future ice-sheet dynamics?
22. What role do geological controls, erosion, and sedimentation play in ice-sheet dynamics?
23. How do glaciological, geological, and geophysical records inform us about ice-sheet and landscape evolution, including submarine and subglacial morphologies?
24. How can seismic instrumentation help reveal the extent, formation, and healing of fractures that create rifts in ice shelves?
25. How can the spatial and temporal distribution of seismic events further inform us about glacial processes and their feedback with oceanic and atmospheric conditions?
26. What are the relationships between basal stick-slip events and sub-ice geologic conditions?
27. What is the content of the seismic wavefield?
28. How can we improve our understanding of climate, general atmospheric circulation and space weather in Antarctica?

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