An introduction to the geochemistry and geophysics of the Antarctic mantle

Martin, Adam P.; van der Wal, Wouter; de Boer, Bas

DOI
10.1144/M56-2022-21

Publication date
2023

Document Version
Final published version

Published in
Geological Society Memoir

Citation (APA)
Martin, A. P., van der Wal, W., & de Boer, B. (2023). An introduction to the geochemistry and geophysics of the Antarctic mantle. *Geological Society Memoir*, *56*(1), 1-16. https://doi.org/10.1144/M56-2022-21

An introduction to the geochemistry and geophysics of the Antarctic mantle

Adam P. Martin[1]*, Wouter van der Wal[2] and Bas de Boer[3]
[1]GNS Science, Private Bag 1930, Dunedin, New Zealand
[2]Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands
[3]Earth and Climate Cluster, Faculty of Science, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands
APM, 0000-0002-4676-8344
*Correspondence: a.martin@gns.cri.nz

Abstract: The Antarctic mantle, bounded between the core and the Mohorovičić discontinuity, is one of the most difficult targets of study on Earth because of ice cover and rare outcrops. A multidisciplinary approach is adopted in this volume, using petrology, geochemistry, remote-sensed data and geodesy to characterize the Antarctic mantle. This characterization has application to rates of glacial isostatic adjustment, heat flow, sea-level rise and tectonics. It places the Antarctic mantle domain in a global framework on a scale not attempted before. In this chapter we review the historical development of mantle studies in Antarctica, outline current research directions, introduce the volume chapters and provide a summary and outlook.

Preamble

The Antarctic mantle plays a key role in understanding the driving forces of global plate tectonics (Turcotte and Oxburgh 1967). Mantle attached to plates generates pull forces that account for around 50% of the driving force on plate tectonics (Conrad Clinton and Lithgow-Bertelloni 2002; Bercovici 2003). The Antarctic Plate borders several major plates, and traces of all the past supercontinents are contained in the Antarctic subsurface (Harley *et al.* 2013). The mantle controls large-scale uplift and subsidence of the surface topography and the lithospheric heat flow of Antarctica, thereby influencing the evolution of the Antarctic Ice Sheet via change in surface elevation and melting (e.g. Shapiro and Ritzwoller 2004; Whitehouse *et al.* 2012). Thus, the Antarctica mantle plays a central role in questions of large scientific and societal relevance; however, our understanding of it remains poor due to the inaccessibility of the Antarctic continent. A better understanding of the Antarctic mantle requires novel integration of multiple research fields.

This Memoir is the first dedicated to understanding the mantle properties of the whole Antarctic continent. It combines petrographical, geochemical, remote-sensed and geophysical techniques. The first eight chapters of this volume cover studies from mantle xenoliths and igneous rocks, this is followed by eight chapters covering geophysical studies and the final chapter is a summary. The volume aims to characterize the Antarctic mantle and to discuss its role in the dynamics that shape the Antarctic surface and ice sheets. The field of Earth sciences requires multidisciplinary efforts, and the difficulties of remoteness, weather and ice cover make this especially true when addressing the most important scientific questions in Antarctica. This volume has adopted a multidisciplinary approach in combining chapters from different fields of Earth sciences, namely geochemistry and geophysics, and it is hoped that this perspective will highlight how combining different measurement types allows better characterization of the Antarctic mantle and its role in geodynamic processes.

The top of the mantle is defined by a pronounced change in P-wave velocities from 6.7–7.2 km s^{-1} in the lower crust to 7.6–8.6 km s^{-1} in the mantle, this is known as the Mohorovičić discontinuity (Moho: e.g. Meissner 1986; Grad *et al.* 2009) (Fig. 1). In Antarctica, the onshore Moho depth varies between approximately 20 and 60 km (Pappa *et al.* 2019*a*). The Moho can also be associated with a chemical, thermal, mineralogical and density change from material rich in silica and magnesia (simatic) in the lower crust to peridotitic and pyroxenitic material in the upper mantle (Herzberg *et al.* 1983; Griffin and O'Reilly 1987). The mantle is bounded by the Moho and the core (Fig. 1). It occurs in several layers marked by boundaries, including the lithosphere–asthenosphere boundary, which is a rheological, thermal or seismic boundary separating a relatively rigid (lithospheric) layer and a weak asthenosphere (Karato *et al.* 2008; Eaton *et al.* 2009; Fischer *et al.* 2010). The depth of the lithosphere–asthenosphere transition is influenced by temperature, water content, chemical composition, extent of partial melt and grain size (Kawakatsu *et al.* 2009; Green *et al.* 2010; O'Reilly and Griffin 2010). Deeper boundaries in the mantle have clearer seismic expressions. Seismically defined discontinuities occur at depths of 410 and 660 km in the mantle (Adams 1971; Revenaugh and Jordan 1991; Shearer and Flanagan 1999), and are associated with phase changes of olivine to wadsleyite (Katsura and Ito 1989) and of ringwoodite to perovskite and magnesiowustite (Ito and Takahashi 1989), respectively. The 660 km discontinuity marks the boundary between the upper and lower mantle (e.g. Kaufmann and Lambeck 2000; Paulson *et al.* 2007; Čížková *et al.* 2012).

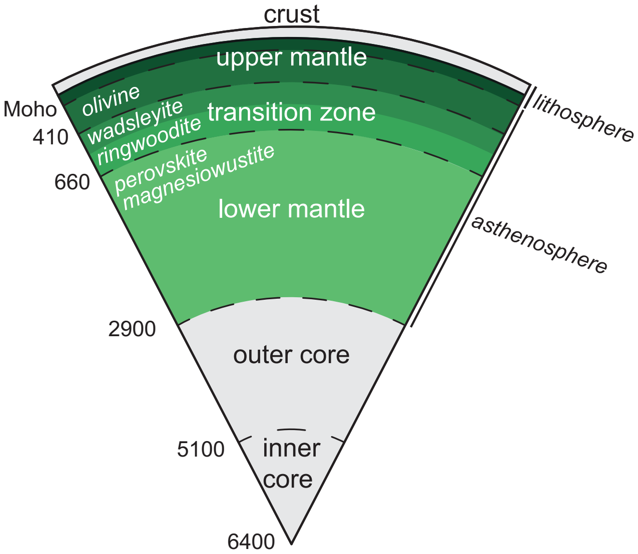

Fig. 1. Schematic cross-section through the Earth showing the crust, mantle and core, and highlighting significant boundaries and phase changes within the mantle (depth in km).

From: Martin, A. P. and van der Wal, W. (eds) 2023. *The Geochemistry and Geophysics of the Antarctic Mantle*.
Geological Society, London, Memoirs, **56**, 1–16,
First published online 14 November 2022, https://doi.org/10.1144/M56-2022-21

This volume brings together studies on mantle xenoliths included in igneous rocks, studies on primitive igneous rocks that can inform us about mantle properties, studies that interpret geophysical measurements and studies on geodynamic processes. Mantle xenoliths record information about the lithospheric mantle, whilst primitive igneous rocks include information about the asthenospheric upper mantle. Geophysical techniques include seismology, gravity and magnetic measurements. Together, they can provide information on structure from the uppermost mantle down to the core–mantle boundary. The depth sensitivity of each measurement type varies. Geodynamic processes include mantle convection, tectonics, glacial isostatic adjustment (GIA) and post-seismic deformation that are controlled by rock properties recorded in geochemical studies and with geophysical measurements. Finally, surface changes driven by underlying mantle convection, tectonics and GIA can be detected by geodetic techniques.

This chapter provides a brief historical perspective of Antarctic mantle research. We present a review of the most important Earth sciences questions that drive the study of the Antarctica mantle. An overview of the chapters in this volume is provided here, along with a summary and outlook.

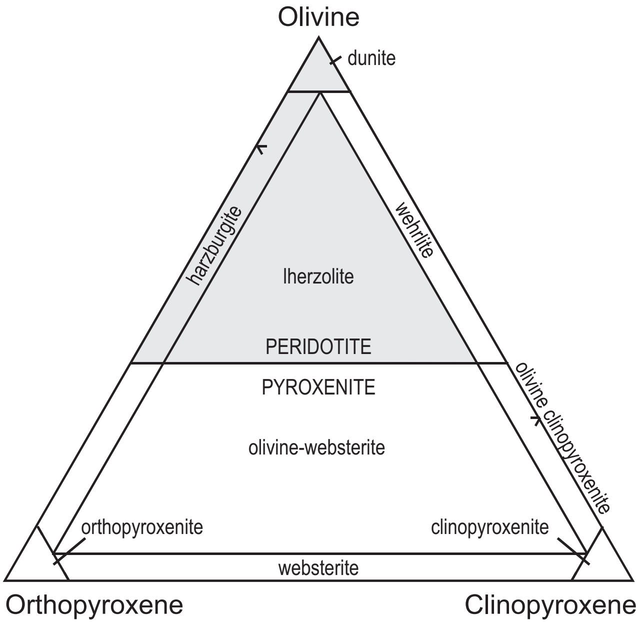

Fig. 2. Olivine–pyroxene ternary diagram. Source: Le Maitre *et al.* (2002).

Background

Mantle geochemistry

Peridotite and pyroxenite xenoliths are fragments of the mantle entrained during volcanic eruptions. They are often an important component in the primitive alkalic rocks commonly found in Antarctica (Smellie *et al.* 2021). It is important to study mantle xenoliths as some information is only determined from physical samples of the mantle such as the mineralogy, the variety of rock types and the interrelationships between rock types (Nixon 1987*a*; Shervais 1988). Mantle xenoliths are critical in understanding the mantle as often they are the only direct sample of mantle available for many areas (Pearson *et al.* 2003). Because of the speed at which mantle xenoliths are brought to the surface they freeze in the mineralogical and chemical signatures of their depth of origin, in contrast to tectonically emplaced slices of the mantle that typically equilibrate extensively during emplacement (Pearson *et al.* 2003). Information on the pressure and temperature of the lithospheric mantle can be derived via thermobarometry studies. Thermobarometry is the experimental study of coexisting minerals that can be utilized to refine the pressure and temperature that mantle xenoliths last crystallized (e.g. Wood and Banno 1973; Macgregor 1974). The results may define a ‘palaeogeotherm’, which is a pressure–temperature curve through the lithosphere (Howells and O’Hara 1978; Berg *et al.* 1989). These curves are similar in shape to modern-day geotherm curves, providing confidence in their interpretation (Condie 2022). Mantle xenoliths can also be studied for the lattice-preferred orientation (LPO) of olivine and pyroxene. These LPO studies can provide evidence of past deformation events, estimates of the propagation speed of seismic waves in the lithospheric mantle and the degree of mantle anisotropy (Mainprice and Silver 1993; Tommasi *et al.* 1999; Kovács *et al.* 2018). Thus, the study of mantle xenoliths shows the composition of the Earth’s lithosphere, how the lithosphere varies from place to place and how the lithosphere evolved (Nixon 1987*a*). The study of mantle xenoliths is vital in building accurate geochemical and physical models of the Earth’s lithosphere (Kovács *et al.* 2018).

Peridotite and pyroxenite xenoliths can be defined based on their modal proportion of olivine, clinopyroxene and orthopyroxene (Fig. 2). Common rock names for peridotite are lherzolite (olivine + clinopyroxene + orthopyroxene), harzburgite (olivine + orthopyroxene) and dunite (olivine). Common rock names for pyroxenite are wehrlite (olivine + clinopyroxene), clinopyroxenite (clinopyroxene), websterite (clinopyroxene + orthopyroxene) and orthopyroxenite (orthopyroxene). An idealized upper-mantle assemblage (Fig. 3) can be drawn from high-pressure experimental data, mantle xenolith compositions and seismic velocity measurements. Idealized geotherms for a continental shield, ocean plate and upwelling mantle beneath an ocean ridge are also shown (Fig. 3). The aluminosilicate assemblage of the lherzolite rock type (olivine + clinopyroxene + orthopyroxene) changes with depth and temperature (Fig. 3) from garnet (deepest) to spinel to plagioclase (shallowest). All three aluminosilicate lherzolite phases are recorded in Antarctica. Spinel lherzolite is the most common. Garnet–spinel lherzolite is reported from East Antarctica and plagioclase-bearing spinel lherzolite is reported from the West Antarctic Rift System and elsewhere (Fig. 4).

Peridotite xenoliths were collected from Antarctica and described during the very earliest Antarctic scientific expeditions (Prior 1902, 1907; Thomson 1916). Around this time, workers on Indian and African specimens first began hypothesizing that peridotite xenoliths were associated with a layer beneath the crust: i.e. the mantle (Fermor 1913; Wagner 1914). This concept was not applied to Antarctic peridotite xenoliths until the mid-twentieth century. For example, Talbot *et al.* (1963) found that their study of peridotite and dunite xenoliths from Kerguelen Island was inadequate to distinguish between a cognate or mantle origin but Forbes (1963), using strain indicators and preferred indicatrix orientations, preferred a non-cognate, mantle origin for the peridotite and dunite xenolith samples they studied from south Victoria Land. This interpretation has since been universally adopted.

Since the 1960s, the chemistry, isotopes and physical properties of Antarctic mantle xenoliths have been characterized to understand the petrogenesis, uplift and thermal regime of the mantle and suprajacent igneous rocks (e.g. Gamble *et al.* 1988; Zipfel and Wörner 1992; Warner and Wasilewski 1995; Wörner and Zipfel 1996; Handler *et al.* 2003; Coltorti *et al.* 2004; Foley *et al.* 2006; Perinelli *et al.* 2012; Bonadiman *et al.* 2014; Martin *et al.* 2015; Day *et al.* 2019). Other notable

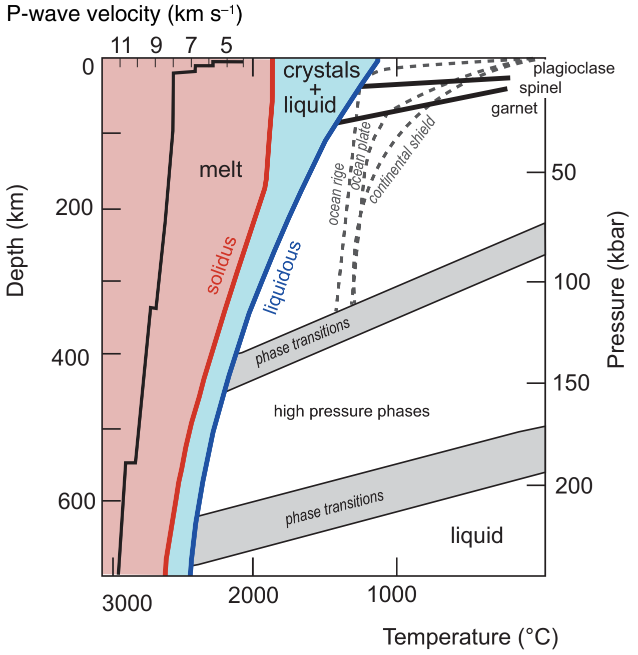

Fig. 3. Schematic phase diagram for the upper mantle with typical geotherms plotted for comparison, after Wyllie (1981). Average P-wave velocities are also shown for reference (Dziewonski and Anderson 1981; Kennett *et al.* 1995).

developments in understanding the Antarctic mantle include proposing a mantle plume beneath Marie Byrd Land (Kyle *et al.* 1994; Weaver *et al.* 1994; LeMasurier and Landis 1996; Storey *et al.* 1999; Lloyd *et al.* 2015) based on crustal doming and the distribution of volcanic rocks and thermal anomalies. The existence of a mantle plume beneath south Victoria Land (Kyle *et al.* 1992; Phillips *et al.* 2018) is much less certain (see **Martin *et al.* 2021*a***, *b* for a discussion).

Studies of primitive igneous rocks in Antarctica have also been used to interpret chemical and isotopic heterogeneity in the Antarctic mantle (Sun and Hanson 1975; Hart *et al.* 1995, 1997; Wörner 1999; Panter *et al.* 2006; Sims and Hart 2006; Cooper *et al.* 2007; Nardini *et al.* 2009; Martin *et al.* 2013), and mantle metasomatism (Sheraton and Black 1982; Futa and Le Masurier 1983; Sheraton 1983). Isotopes of Pb, Sr and Nd were measured in primitive igneous rocks on the Antarctic Peninsula to show similarities in their Sr- and Nd-isotope composition to a HIMU (high μ: enriched in ^{206}Pb and ^{208}Pb) mantle source, and similarities in their Pb-isotope values and some incompatible trace element ratios to a mid-ocean ridge basalt (MORB) mantle source (Hole *et al.* 1993). Volcanic rocks in north Victoria Land (Hart and Kyle 1993) and Marie Byrd Land (Hart *et al.* 1997) showed Sr–Nd–Pb compositions consistent with a HIMU component being involved. Early studies from north Victoria Land and Marie Byrd Land have also proposed an EMII (Enriched Mantle II: low $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}$, high $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$, and high $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ and $^{208}\mathrm{Pb}/^{204}\mathrm{Pb}$ at a given value of $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$) or subduction-impregnated subcontinental lithosphere component in the mantle source (Hart and Kyle 1993; Hart *et al.* 1995). These regional variabilities in mantle source have also been measured in Sr–Nd–Pb isotopes and trace element ratios of mantle xenoliths (Wysoczanski 1993; Martin *et al.* 2015), and Martin *et al.* (2015) proposed an EMI (Enriched Mantle I: low $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}$, low $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$, and high $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ and $^{208}\mathrm{Pb}/^{204}\mathrm{Pb}$ at a given value of $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}$) component in the south Victoria Land mantle. A carbonate-like fluid or melt has also been proposed in the mantle source of volcanic rocks and mantle xenoliths in Antarctica (Foley *et al.* 2006; Kogarko *et al.* 2007; Aviado *et al.* 2015; Martin *et al.* 2015). This brief summary demonstrates that a chemical and isotopic heterogeneity of the Antarctic mantle has been suggested for several decades.

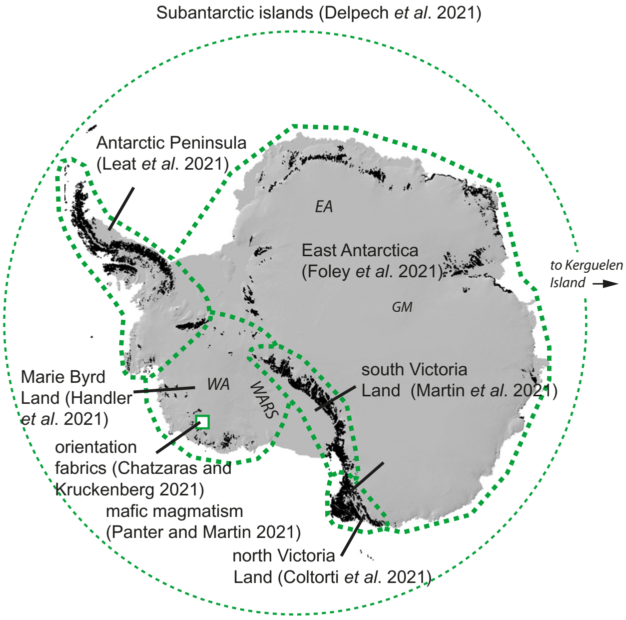

Fig. 4. Diagram showing the location in Antarctica of geochemistry chapters and locations discussed in the text. EA, East Antarctica; GM, Gamburtsev Mountains; WA, West Antarctica; WARS, West Antarctic Rift System. Black polygons indicate exposed bedrock.

Despite numerous publications on mantle xenoliths from specific localities, to date, there has been no continent-wide review of Antarctic mantle xenoliths, leading to Antarctica being a missing key piece of global compilations of mantle xenolith data (e.g. Ross *et al.* 1954; Jagoutz *et al.* 1979; Nixon 1987*a*; Meisel *et al.* 2001; Pearson *et al.* 2003, who included two Antarctic samples of plagioclase-bearing peridotite in their compilation). The most comprehensive work so far has been the inclusion of some Antarctic regions in a major reference work on mantle xenoliths (Nixon 1987*a*). In this, Nixon (1987*b*) provided the mineral chemistry of one East Antarctic xenolith and the whole-rock chemistry of four other East Antarctic xenoliths; and in Kyle *et al.* (1987), a thorough review of mantle xenolith occurrences in Victoria Land was provided.

Mantle geophysics

Systematic surveying of Antarctica began with the International Geophysical Year (1957–58). Seismic transects (around 13 000 km worth) across East Antarctica and West Antarctica led to the realization that Antarctica formed a single continent (Evison *et al.* 1959; Siegert *et al.* 2018), with thicker crust in East Antarctica compared to West Antarctica (Evison *et al.* 1960). Since that time, the suite of seismic measurements has been expanding, with active seismic measurements first being collected during US and Soviet expeditions (Kaminuma 1979).

In these early geophysical expeditions, a signal from the mantle remained elusive in the seismic measurements. At first, the absence of reflections from mantle depths was thought to illustrate that the Antarctic mantle was fairly homogeneous (Adams 1968). Later, this was shown to be a result of limited earthquake travel paths. The addition of waves from nuclear explosions showed that there was, in fact, considerable inhomogeneity (Adams 1971). The second problem for observing Antarctic Earth structure was what was at the time believed to be an absence of large Antarctic earthquakes compared to other continents (Evison 1967). At this time, seismic measurements remained restricted to a few permanent stations at mainly coastal regions, and models tailored to Antarctica could only be developed from global seismic datasets using occasional earthquake signals that travelled through the Antarctic mantle (Ritzwoller *et al.* 2001). Large improvements in understanding occurred with the initiation of projects from 2000 onwards, and a large array of seismographs deployed across the interior of the continent as part of the Fourth International Polar Year (2007–08) demonstrated for the first time that intraplate earthquakes occur in Antarctica with the same frequency as for other continents (Lough *et al.* 2018).

Gravity measurements started at the end of the 1950s (Harada *et al.* 1958; Bull 1960). However, only when simultaneous ice-thickness measurements were included with the measurements could there be inferences made on the lithospheric structure. A robust feature found from gravity data is a large and sudden increase in lithospheric thickness from West to East Antarctica, at the location of the Transantarctic Mountains (Behrendt *et al.* 1966). It was also hypothesized that asthenospheric mantle effects could be seen in gravity data, notably post-glacial rebound in the Ross Sea (Bennett 1964) and a negative, long-wavelength signal thought to be caused by mantle convection (Kaula 1972).

When using seismic and gravity data to reveal the Earth structure in polar regions, it should be noted that both sets of data need to be corrected to remove the effect caused by the thickness of ice. Therefore, a crucial advance in Antarctic seismic and gravity studies was the airborne campaign undertaken to measure the thickness of, and structure within, ice using radar echo sounding (Drewry 1982). Radar techniques are still to be applied continent-wide in Antarctica and in recent digital elevation maps radar data gaps were filled with gravity data (Fretwell *et al.* 2013).

Interpretations made from seismic and gravity measurements in terms of mantle structure can also be supported by tectonic evolution studies. Early on, the role of the Antarctic Plate in the global picture of tectonics was recognized: for example, from the Ferrar Large Igneous Province signalling the Mesozoic break-up of Gondwana (Dietz and Holden 1970; Elliot 1992). Understanding Antarctica's place in the plate tectonics puzzle also helps when studying parallels between Antarctica and other regions such as Australia and India, and seismic studies showed that the East Antarctic mantle was similar to other, adjacent Precambrian shields (Knopoff and Vane 1978).

The signal of mantle dynamics such as GIA can be recorded in palaeosea-level data. In Antarctic, initially only a handful of palaeosea-level curves were available, which could be interpreted as rebound following the partial demise of the Antarctic Ice Sheet (Clark and Lingle 1979). Quantifying the interpretation requires estimates for the thickness of the Antarctic Ice Sheet through time and numerical models for GIA and sea-level change, which became available in the 1970s. For a long time, the volume of the past Antarctic Ice Sheet could only be derived by subtracting the known contributions from other, non-Antarctic land masses from the global mean sea-level change since the last glacial maximum (LGM: e.g. Lambeck *et al.* 2000). A gradual increase in the number of ice-extent and sea-level data, and the collection of geodetic data of elevation change, improved this situation.

The 1990s saw the first geodetic measurements collected and compiled under the coordination of the Scientific Committee on Antarctic Research (SCAR: Manning 2001). Initially, measurements by GPS receivers placed on bedrock had to be repeated in separate campaigns. At the turn of the century, however, permanent global navigation satellite system (GNSS) stations could be established. This greatly increased the spatial coverage of measurements of elevation change and showed for the first time ongoing changes across the continent that could not be solely explained by ice melt combined with GIA since the LGM (e.g. Thomas *et al.* 2011).

Studies of mantle convection and associated tectonics in Antarctica via geophysical studies is yet to receive as much as attention as GIA studies (although see Austermann *et al.* 2015 and Faccenna *et al.* 2008 for recent exceptions). This is mainly because topography and the geoid have a less direct relationship than that found between GPS measurement of uplift rate and GIA. Despite this, Antarctica has an important part to play in global studies (e.g. Steinberger *et al.* 2012).

A consequence of mantle convection and plate tectonics is post-seismic deformation: the slow readjustment of the mantle after an earthquake. The stress release cannot be predicted from convection or plate tectonic models alone, therefore post-seismic deformation is a separate topic. For studying post-seismic deformation, data at the right location and at the right time have only been available recently, and the study of post-seismic deformation in Antarctica is in its infancy (King and Santamaría-Gómez 2016).

The cost of logistics and extensive ice cover means that satellite missions play an outsized role in the polar regions relative to other areas globally. Measurement conditions for satellite are favourable for high latitudes because of the geometry of satellite orbits. As the satellite moves through its orbit the Earth rotates with smaller ground velocity near the poles, resulting in smaller ground-track spacing and higher resolutions. One limitation is a data gap near the Antarctic pole. Examples of missions that contribute to solid Earth studies now follow.

The satellite gravity missions GRACE (Gravity Recovery and Climate Experiment) and GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) provided increased resolution of the gravity field, to below 100 km, and contributed to the understanding of the Antarctic lithospheric structure (e.g. Pappa *et al.* 2019*b*). The remarkable accuracy of the satellite data means that measurement accuracy hardly plays a role in gravity interpretations. It is so sensitive that mass change of the Antarctic Ice Sheet could be observed in GRACE data (Velicogna and Wahr 2006), which is for a large part due to GIA (King *et al.* 2012). In the absence of direct measurements, forward models are the only method to quantify GIA. This spurred new and updated GIA models for Antarctica (Whitehouse *et al.* 2012; Ivins *et al.* 2013; Argus *et al.* 2014). There has been a concerted effort to fill the satellite polar gap and other regions of importance with airborne gravity data (Forsberg *et al.* 2011, 2018).

The SWARM satellite delivered measurements of the magnetic field that could link lithospheric structures from Antarctica to other continents (e.g. Ebbing *et al.* 2021). To study the mantle, several corrections to the SWARM-derived magnetic measurements are necessary such as for the core and crustal magnetic field and ionospheric effects (see Civet *et al.* 2015 for details). Recently, the compilation of magnetic data from marine and airborne data (ADMAP) was augmented by 2.0 million line-kilometres of new airborne and marine magnetic anomaly data to create ADMAP2 (Golynsky *et al.* 2018). The SWARM satellite data have been used to extend the ADMAP2 dataset, filling residual data gaps (Kim *et al.* 2022).

Radar remote sensing from satellite does not observe the solid Earth directly but is complementary to the interpretation of other geophysical data. The technique transmits microwave pulses and detects the backscattered echo from the surface. Satellite radar measurements were initially designed for

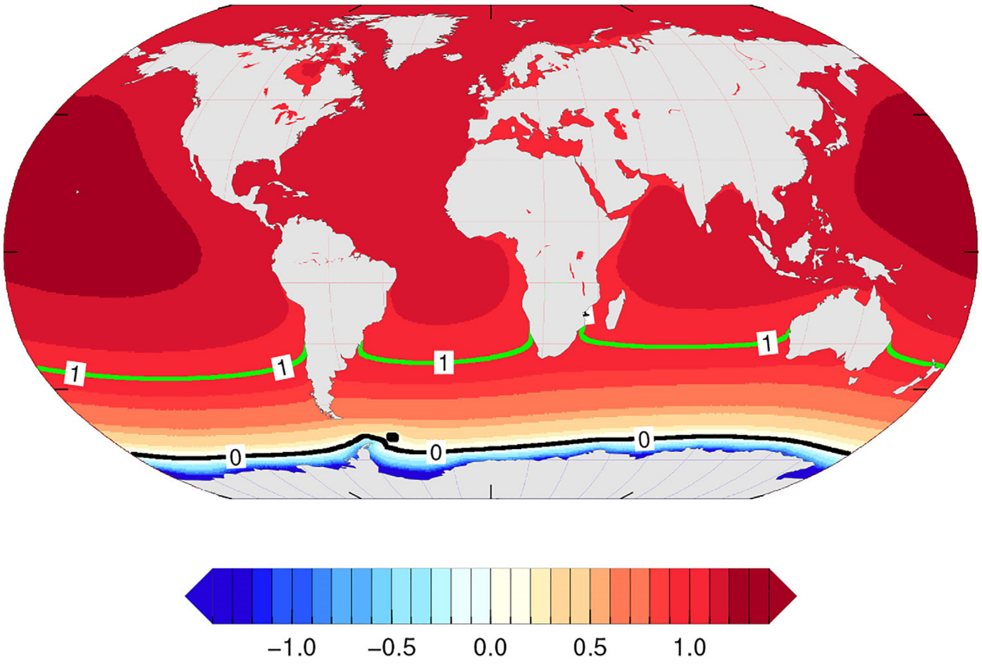

Fig. 5. Sea-level fingerprint of the melting of the Antarctic Ice Sheet normalized relative to 1 mm of global mean sea-level equivalent contribution. Blue is sea level lowering, the black line is no change, red is sea-level rising and the green line (at *c.* 45° S) is the exact global mean. The melt is applied uniformly over the ice sheet, with an elastic Earth, assuming that melting occurs over a short period of time. Calculated using SELEN4 (Spada and Melini 2019), including harmonic degrees 0–128 and rotational effects.

measurements over the sea. Errors over ice are large relative to the open ocean because of the slope of the ice surface (Rémy *et al.* 1989). Despite these challenges, satellite radar accuracy was sufficient to obtain measurements of the average elevation of the ice surface, which, combined with airborne and terrestrial radar measurements of ice thickness, helps in the interpretation of seismic and gravity data. Over time, the errors associated with radar techniques were decreased through improved data-processing approaches such as waveform retracking, which derives more parameters from the returned pulse (Rémy and Parouty 2009). The increased accuracy of ice-elevation observations allowed the detection of changes in elevation of the Antarctic Ice Sheet itself (Davis and Ferguson 2004).

Overview of the impact of the Antarctic mantle on ice sheets and sea level

Ice-sheet melting leads to inhomogeneous sea-level rise globally because of changes in the Earth's gravity field resulting from the ice-sheet melt (Fig. 5). As a result, a large part of the northern hemisphere will experience sea-level increases higher than the mean due to the melting of the Antarctic Ice Sheet (i.e. north of the green line on Fig. 5). The role Antarctica will play in sea-level rise, however, is not well known partly because of uncertainty in characterizing the Antarctic mantle necessary for GIA modelling, which plays a key role in monitoring and predicting the loss in mass of the Antarctica Ice Sheet. The reason for the importance of GIA in monitoring ice loss is that GIA model predictions are required to correct gravity measurements as discussed above, which is vital for measuring current ice-mass loss. Two reasons for the importance of GIA in predicting ice loss are outlined below.

The effect of the mantle on ice loss is through GIA-induced bedrock uplift and accompanying grounding-line migration (e.g. Gomez *et al.* 2010). The West Antarctic Ice Sheet (WAIS) is a marine ice sheet, with the underlying bed in large parts below current sea level by 1000 m or more (Fig. 6), with the bed often deepening upstream. These factors make the WAIS vulnerable to warming ocean temperatures through a process called marine ice sheet instability (MISI: e.g. Pattyn 2018). The ice discharge across the grounding line increases with increasing ice thickness. Therefore, when the ice sheet retreats, this can lead to increased dynamic thinning of the ice sheet. A retreat moves the grounding line into areas that may have the bedrock surface at a lower elevation and covered by a greater thickness of ice relative to the original grounding line, which again leads to increased ice discharge in a process that can become self-repeating (Fig. 7). A retreating grounding line slowed down by GIA-induced bedrock uplift (Gomez *et al.* 2010) can also affect sea level by pushing out seawater during uplift (Gomez *et al.* 2010).

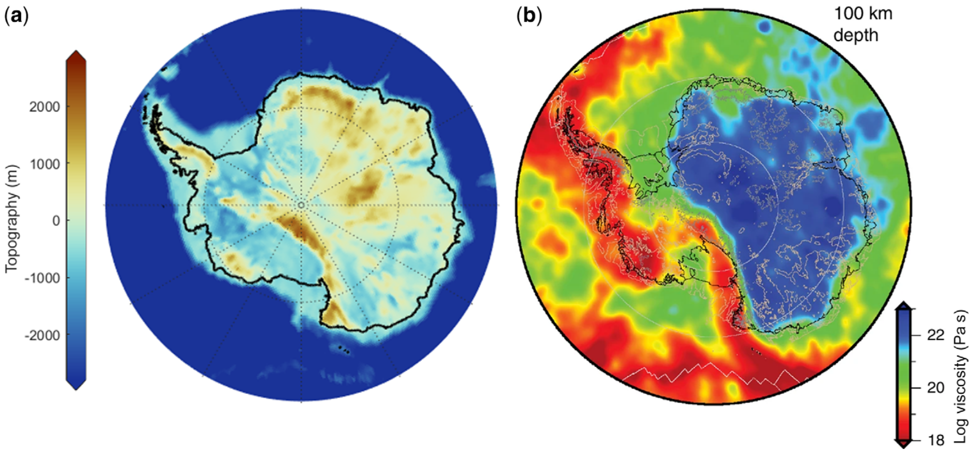

Fig. 6. Topography and viscosity diagrams of Antarctica. (**a**) Bedrock elevation relative to the present sea level of Antarctica (Bedmap2: Fretwell *et al.* 2013). (**b**) Spatial variations in the estimated upper-mantle viscosity underneath Antarctica at a depth of 100 km (fig. 4a from Whitehouse *et al.* 2019). Copyright for both figures: http://creativecommons.org/licenses/by/4.0/

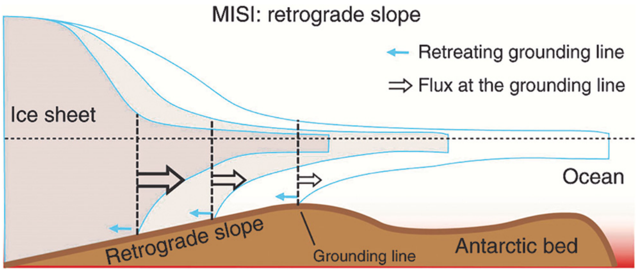

Fig. 7. Schematic representation of marine ice-sheet instability (MISI). Generally, ice discharge increases with increasing ice thickness at the grounding line. The grounding line is the transition from grounded to floating ice. When the bedrock is sloping back towards the interior, this may lead to the unstable retreat of the ice sheet because ice flux increases as the grounding line retreats (MISI). Source: Pattyn (2018, fig. 1a). Copyright: http://creativecommons.org/licenses/by/4.0/

Secondly, heat from the mantle largely controls large-scale variations in geothermal heat flow, which exerts a strong influence on ice-sheet changes (e.g. Sutter *et al.* 2019). Bedrock heating underneath the Antarctic Ice Sheet is important for feeding basal hydrology through the basal melting of ice. Basal sliding of the ice is likely to be enhanced when the ice sheet is temperate at the bottom, leading to a more rapid response in a retreating phase of the ice sheet. It is therefore an important factor to consider in future ice-sheet stability studies. Several geothermal heat-flow models exist (e.g. Shapiro and Ritzwoller 2004; Fox Maule *et al.* 2005; An *et al.* 2015; Martos *et al.* 2017) that show differences between West and East Antarctica related to the crustal structure, tectonic history and heat from the mantle (Fig. 8). However, current uncertainties and differences between models are large (Burton-Johnson *et al.* 2020*a*, *b*; Lösing *et al.* 2020).

Antarctic mantle: open questions

Accurately and precisely characterizing the Antarctic mantle is vital in understanding how the solid Earth will respond to climate-change effects and plate-tectonic forcing. This has been recognized as a key area of research for Antarctica (e.g. Kennicutt *et al.* 2015) as it affects ice-sheet change, sea-level contribution, tectonics and mantle dynamics. Here we establish current research directions and open questions that can be informed by mantle studies. This volume should go part way to addressing several of these questions.

Topography, composition and mantle structure

Antarctica hosts extreme topography: the Gamburtsev Subglacial Mountains are the world's largest intraplate mountain range, and are likely to have been the focal point for the initiation of the East Antarctic Ice Sheet (Paxman *et al.* 2016). Along the western shoulder of the West Antarctic Rift System, the Transantarctic Mountains are the world's largest example of rift-flank uplift (ten Brink and Stern 1992). **What supports Antarctica's largest mountain ranges?**

The thickness of the lithosphere plays a role in explaining current topography because it determines how much topography can be supported isostatically. Estimates of the thickness of the lithosphere in the West Antarctic Rift System suggest that it is abnormally low and similar estimates of East Antarctica show it is abnormally high. **What mantle parameters make the West Antarctic Rift System abnormally depressed and East Antarctica abnormally elevated?** For computational expediency, traditional models of GIA in Antarctica have used a radially varying 1D approximation of the Earth, leading to errors in the estimates of the present-day GIA signal through failure to capture known variations in the Earth structure across Antarctica (Nield *et al.* 2018). **How does lithospheric thickness vary across Antarctica?**

Seismic velocity maps show clear differences between East and West Antarctica. To a first order, seismic velocity anomalies can be interpreted as thermal anomalies (Cammarano *et al.* 2003), which is consistent with the geological history. However, the boundary between the two domains it not well imaged. **How are high-velocity East Antarctica and low-velocity West Antarctica connected?** A mantle plume beneath Marie Byrd Land has long been postulated to explain the regional doming, patterns of volcanism and elevated heat flow (e.g. Kyle *et al.* 1994; Seroussi *et al.* 2017). A mantle plume could be consistent with seismic models but other interpretations of seismic data are possible because of the limited resolution at depth of this method (Hansen *et al.* 2014).

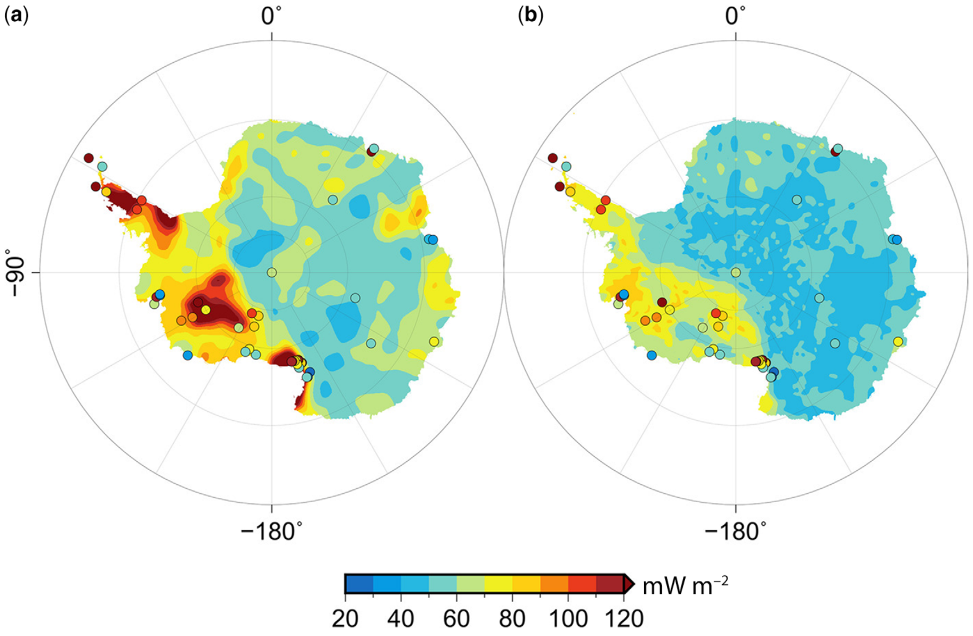

Fig. 8. Geothermal heat flow from (**a**) Martos *et al.* (2017) and (**b**) Shen *et al.* (2020). Heat-flow measurements are represented by circles. Source: Lösing and Ebbing (2021, fig. 8). Copyright: http://creativecommons.org/licenses/by/4.0/

Therefore, other lines of geochemical and geophysical evidence have to be used to arrive at a conclusion on the presence of a plume. **Is a plume beneath Marie Byrd Land required by observations? Are there other plumes beneath Antarctica?**

Geochemistry and geophysical studies have long recognized inhomogeneity in the Antarctic mantle: for example, between East and West Antarctica, and also within regions at the scale of kilometres to thousands of kilometres (Hart *et al.* 1995; Martin *et al.* 2014). The recent inclusion of 3D variability in Earth models has improved GIA signal estimations (van der Wal *et al.* 2015), however more work remains. **How many distinct mantle domains are there in Antarctica? At what scale do mantle domains need to be defined to be useful in modelling?**

A number of mantle reservoirs (HIMU, EMI and EMII) have been identified in Antarctica. **What mantle reservoirs (chemical and isotopic) exist in the Antarctic mantle? Do they vary at a continental-scale? Is there a HIMU-reservoir *sensu stricto*?** This leads onto another question once the Antarctic mantle is defined: **How does the Antarctic mantle domain compare with adjacent mantle domains (e.g. South America, Australia, Zealandia and Africa) at a global scale?**

Change in topography and mantle structure

Models for elastic rebound and Antarctica GIA models do not match well with the estimated velocities made from extensive GPS campaigns (Bevis *et al.* 2009; Thomas *et al.* 2011; Groh *et al.* 2012). In part, this is because ice thickness varies on century- or decadal-long timescales not currently considered in GIA models (Nield *et al.* 2014; Barletta *et al.* 2018). Horizontal GPS velocities are dominated by plate rotation, but neotectonic deformation and GIA also play a role (King *et al.* 2015; Vardić *et al.* 2022). Even though the GIA contribution is small relative to other parameters, its sensitivity is such that even the sign is dependent on the mantle viscosity (Hermans *et al.* 2018). In some regions, post-seismic deformation can be detected (King and Santamaría-Gómez 2016) but the following over-arching question remains: **What mantle processes contribute to observed present-day vertical and horizontal motion, and at which temporal and spatial scales?**

Convection, GIA and post-seismic deformation are a function of mantle viscosity. Some modelling includes 3D viscosity variations (Kaufmann *et al.* 2005; King and Santamaría-Gómez 2016; Gomez *et al.* 2018; Whitehouse 2018). In most cases, spatial variations in viscosity are scaled from seismic velocity anomalies but this is a highly uncertain procedure (e.g. Barnhoorn *et al.* 2011; O'Donnell *et al.* 2017). This raises the question: **How well can viscosity be derived from seismic models and geochemical data, and how can the viscosity information from geochemistry be incorporated into modelling?**

Viscosity is a macroscopic parameter that aggregates material properties such as water content, grain size, temperature, pressure and composition (e.g. Hansen *et al.* 2016). Water content can be detected in xenoliths and with magnetotelluric measurements, and also indirectly in seismic evidence (Emry *et al.* 2015). Xenoliths provide grain size, water content and pressure–temperature variations. Xenoliths and magnetotelluric measurements represent information that is currently underused in geodynamics models and should be incorporated where present. To aim for better viscosity models we need to know: **How do mantle material properties vary laterally across Antarctica and with depth?**

Another important cross-disciplinary consideration is at what scale do continental-sized geophysical, remote-sensed or modelling studies intersect with regional- to local-sized petrological or geochemical studies? This is a fundamental problem of scales, from the macroscopic to the continent. **Do we need to make geophysical studies finer grained or petrological studies coarser grained?**

Integration across multiple temporal scales is also important. Mantle processes operate on a timescale from decades to millions of years. New models allow integration of GIA and post-seismic models (Nield *et al.* 2022). However, mantle-deformation experiments and geodynamic models demonstrate that both short- and long-term viscosity determines post-seismic deformation (e.g. Pollitz and Thatcher 2010), and viscosity changes due to stress that changes through time (e.g. van der Wal *et al.* 2013). In general, viscosity can be seen as dependent on the frequency of loading (Lau *et al.* 2021). **What viscosity is representative for which mantle process in Antarctica and how can they be integrated?**

Influence on ice

The strong feedback between solid Earth and ice through surface heat flow enhances basal sliding, leading to a more rapid response in a retreating phase of the ice sheet. Surface heat flow reflects crustal composition but is also driven by the subadjacent mantle. The effects of geothermal heat flow on ice dynamics has been a long-standing issue for ice-sheet models and estimates vary greatly (e.g. Burton-Johnson *et al.* 2020*a*, *b*). **What is the contribution of the mantle to surface heat flow and, hence, ice-sheet basal melting?** A second feedback between solid Earth and ice affects the grounding line. **What is the effect of GIA on the position of the ice-sheet grounding line in Antarctica?**

The Antarctic mantle also plays a significant role in estimates of the mass balance of the ice sheet as observations need to be corrected for GIA. The GIA signal must first be subtracted from the GRACE data before calculating the true spatial distribution and magnitude of current ice-mass change in Antarctica (e.g. Velicogna and Wahr 2006; Thomas *et al.* 2011). The GIA models do not always agree with each other or with empirical estimates (Martín-Español *et al.* 2016). In addition, new regional (Barletta *et al.* 2018) and 3D GIA models are being developed (Powell *et al.* 2020; Blank *et al.* 2021). Improved constraints on the Antarctica mantle can help to answer the question: **What is the contribution of GIA to the observed mass change and corresponding sea-level change?**

Volume overview

The chapters by **Coltorti *et al.* (2021)**, **Delpech *et al.* (2021)**, **Foley *et al.* (2021)**, **Handler *et al.* (2021)**, **Leat *et al.* (2021)** and **Martin *et al.* (2021*a*)** on mantle xenoliths in volcanic rocks review occurrences from select geographical areas that together cover all of Antarctica (Fig. 4). Important locations covered by **Chatzaras and Kruckenberg (2021)** and **Panter and Martin (2021)** focused on specific topics are also marked in Figure 4. The chapters by **Bredow *et al.* (2021)**, **Ivins *et al.* (2021)**, **Pappa and Ebbing (2021)**, **Paxman (2021)**, **Scheinert *et al.* (2021)**, **van der Wal *et al.* (2022)**, **Wannamaker *et al.* (2021)** and **Wiens *et al.* (2021)** on geophysics, and the overview chapter by **Martin (2021)**, are more continental scale in nature.

Mantle xenoliths of East Antarctica and the mantle properties inferred from igneous rocks of East Antarctica are reviewed by **Foley *et al.* (2021)**. These volcanic rocks have been erupted through rifts and associated cratons of East Antarctica in a setting unique to that of West Antarctica. Mantle xenoliths are only known from three locations and all come from Indo-Antarctica-affiliated lithosphere. The xenoliths are spinel bearing or spinel–garnet bearing, and contain geochemical and mineralogical evidence for multiple enrichment events that can often be linked to activity along major translithospheric structures. The authors note that local modification of the mantle by melt infiltration may influence large-scale images derived from geophysical data.

South Victoria Land as the first locality of mantle xenolith study in Antarctica has more than a 100 year record of scientific data, which **Martin *et al.* (2021*a*)** collate and interpret into a new petrogenetic model. The region has Paleoproterozoic stabilization ages with some evidence for younger regions of mantle. The mantle has been affected by fluids related to oceanic crust subduction at *c.* 0.5 Ga and older events, as well as a thermal and chemical disturbance associated with Cenozoic volcanism. A unique feature is the iron enrichment beneath Ross Island observed in the whole-rock chemistry of primitive magmas, peridotite and pyroxenite xenoliths, and the chemistry of mantle olivine. This iron enrichment is potentially related to iron-rich crust or the exchange of iron across the core–mantle boundary. The peridotite mantle of the entire region has been cross-cut by multiple episodes of pyroxenite veining.

North Victoria Land contains numerous active, dormant and extinct Cenozoic volcanoes with abundant mantle xenolith cargoes. **Coltorti *et al.* (2021)** synthesize the abundant published and unpublished data to provide a petrogenetic overview of the mantle from this region. A palaeogeotherm is calculated, oxygen fugacity of the lithospheric mantle is reported relative to the fayalite–magnetite–quartz buffer and the water content of nominally anhydrous minerals is reported. A long history from old depletion to recent refertilization and metasomatism is discussed, including a refertilization episode related to the Jurassic Ferrar Large Igneous Province emplacement and metasomatism related to Cenozoic magmatism.

Marie Byrd Land has numerous Cenozoic volcanoes with entrained mantle xenoliths, the occurrences and petrogenetic implications of which are reviewed by **Handler *et al.* (2021)**. They show mantle compositions that have experienced 10–25% melt depletion and which have been variably metasomatized and refertilized. The timing of events show a Proterozoic lithospheric mantle and evidence for Ordovician events related to the complex tectonic history of the region, consistent with a protracted history of Paleozoic convergence and subduction.

In the Antarctic Peninsula, there are multiple generations of mantle xenolith-bearing igneous rocks erupted under differing tectonic settings. **Leat *et al.* (2021)** review the mantle xenolith occurrences and contextualize them according to their tectonic setting and age. Xenoliths are restricted to post-subduction volcanic rocks emplaced in forearc or back-arc positions. The xenoliths are spinel bearing, and may be residues from a mid-ocean ridge setting from the upper mantle, and were subsequently accreted to form harzburgitic, oceanic lithosphere.

Studies of mantle xenoliths on the subantarctic islands have greatly informed our understanding of the mantle but are included too infrequently in discussions on the Antarctic mantle. **Delpech *et al.* (2021)** review the information from mantle xenoliths afforded by these island windows into the mantle, as well as discussing serpentinized peridotite dredged from fracture zones and suprasubduction zone peridotite from the Sandwich Plate. They show that the subcontinental and oceanic lithospheric mantle contains ancient fragments that underwent depletion significantly earlier than the formation of the overlying crust, and there are frequent signs of subsequent metasomatic enrichment.

Other focused chapters have been invited. **Panter and Martin (2021)** provide an overview of the West Antarctic mantle deduced from mafic magmatism, and show that mantle composition varies by tectonic setting and time. The mantle-source changes coincide with changes in crustal structure and composition that are also visible in tomographic models and seismic data. Marie Byrd Land magmatism results from plume activity, with chemical and isotopic evidence for a component of subduction-modified mantle that is distinct from the mantle in Victoria Land. Relative to Victoria Land, Marie Byrd Land mantle has a weaker focal zone (FOZO) component and more of the high-μ (HIMU) component.

Chatzaras and Kruckenberg (2021) review crystallographic preferred orientation studies on Antarctic mantle xenoliths to inform seismic anisotropy studies. They report the petrology, microstructure and seismic properties of the mantle beneath Marie Byrd Land. There is evidence for diachronous reactive melt percolation and refertilization, which is likely to have modified seismic velocities and anisotropy. They show that seismic properties are mainly controlled by the strength of the olivine crystallographic texture, and suggest that variations in the mantle structure are related to 3D deformation during the region's prolonged tectonic history.

The chapters in the geophysics section of the volume focus on remote measurements and their interpretation, as well as on geodynamic processes. Measurement campaigns and surveys are described as appropriate to acknowledge the effort required to obtain the data, to highlight which parts of Antarctica remain understudied and to draw awareness to uncertainties stemming from the practical limitations of working in the testing Antarctic environment.

Magnetotelluric measurements are collected along select profiles in Antarctica to study lithosphere and mantle temperature, water content, and to make compositional inferences. **Wannamaker *et al.* (2021)** reanalyse measurements from three campaigns. Near the South Pole, their study shows low resistivity at Moho depths consistent with elevated thermal data. The Ellsworth–Whitmore block study shows near-cratonic geothermal conditions, as well as lithological variability. Moderate mantle hydration incompatible with extensive melting is indicated in the Ross Sea study.

Wiens *et al.* (2021) describe the seismic models that have been developed for parts, or the entirety, of Antarctica. The chapter reviews different sources (distant earthquakes, active seismic and ambient noise), different waves (S-waves and P-waves) and different techniques (receiver functions, tomography and full-waveform tomography), and their sensitivity to mantle structure and Moho depth. Large contrasts in seismic wave speed are seen across Antarctica, with slow velocities below large parts of West Antarctica and thick lithosphere below East Antarctica.

Pappa and Ebbing (2021) review gravity and magnetic field measurements, as well as surface heat flow in Antarctica. This chapter discusses integration with petrology to derive upper-mantle temperature and to reduce ambiguity due to unknown lithospheric structure. First-order results agree with seismic models and provide extra compositional information. Magnetic anomalies reflect different crustal terranes but can also be inverted for the Curie depth, from which surface heat flow can be derived. Uncertainties in surface heat-flow estimates are reviewed.

Paxman (2021) explains the importance of palaeotopography as a boundary condition for ice-sheet modelling. Paxman reviews how structural inheritance played a role in shaping early Antarctic ice sheets, and the role of the lithosphere and the mantle in shaping the topography. Lithospheric cooling contributed to subsidence, which made the WAIS increasingly sensitive to MISI, and dynamic topography provides support to palaeotopography in Antarctica (e.g. the support of the Transantarctic Mountains) together with other processes.

On relatively long timescales, viscosity controls mantle convection and plumes. **Bredow *et al.* (2021)** review simulations of mantle convection. They discuss simulations that give the directions of Antarctic mantle flow and the locations of possible mantle plumes. These simulations show that the elevated heat flow supports a mantle plume in Marie Byrd Land. Simulations of dynamic topography show it to be negative in East Antarctica, contrary to what is expected from the high topography.

Mantle rheology is utilized to model dynamic processes. Mantle rheology is the science that describes the deformation and flow of Earth materials. **Ivins *et al.* (2021)** describe how seismic tomography, material parameters and empirical constants can be combined to obtain viscosity maps. They use an S-wave velocity model (Lloyd *et al.* 2020) to estimate viscosity at different depths in the upper mantle using three approaches, and discuss the resulting differences.

Geodetic measurements can detect the response to past ice-sheet-thickness changes in terms of crustal motion or gravity change. **Scheinert *et al.* (2021)** explain the processing procedure and the importance of correcting for the effect of current ice-sheet changes. They review regional studies in the Amundsen Sea sector and the Antarctic Peninsula, where fast relaxation is detected. This chapter discusses measurements of ice-height and ice-mass changes, and discusses how they can be combined to improve estimates of ice melt and GIA.

Viscosity maps as input for GIA modelling are reviewed in **van der Wal *et al.* (2022)**. The history of GIA research, GIA observations, modelling techniques, and interactions between GIA and the solid Earth are discussed. An important development is the realization that low viscosity in West Antarctica results in faster response times of the mantle, and higher sensitivity to recent ice-thickness changes. This also implies a key role for GIA in modelling ice-thickness changes of marine-terminating glaciers that are sensitive to elevation change. In addition, this chapter discusses the post-seismic deformation detected in GNSS observations, which also require low viscosity in the upper mantle.

Martin (2021) collates a review of the composition and chemistry of mantle xenoliths from Antarctica using the continent-wide dataset made possible by this Memoir and places this into a global context. The Antarctic mantle is heterogeneous at all scales, which opens up a number of research questions and has implications for geophysical models of the lithospheric mantle.

Summary and outlook

Both the historical overview and the chapters in this volume show how concerted efforts such as the International Polar Year have increased our knowledge of the Antarctic mantle. Technological developments are also an important driver for Antarctic Earth science, from lower detection limits in geochemical studies (**Handler *et al.* 2021**), novel isotopic studies (**Martin 2021**) and micro-fabric studies (**Chatzaras and Kruckenberg 2021**), and better stand-alone GNSS instruments (**Scheinert *et al.* 2021**) to more precise magnetotelluric measurements (**Wannamaker *et al.* 2021**) and satellite measurements (**Pappa and Ebbing 2021**). This in turn drove the developments of numerical models for mantle composition (**Wiens *et al.* 2021**), rheology (**Ivins *et al.* 2021**) or mantle-dynamics studies that can integrate those measurements (**van der Wal *et al.* 2022**). With measurements still limited in most of Antarctica, studying the Antarctic mantle is a truly multidisciplinary effort.

In this Memoir, several open questions are tackled, such as how does the mantle support mountain ranges (**Paxman 2021**) and are there multiple Antarctic mantle plumes (**Bredow *et al.* (2021)**; **Martin *et al.* 2021*a***, *b*)? Definitively answering questions like these will require a combination of several models (lithosphere model, convection and composition).

Large contrasts between West Antarctica and East Antarctica signal changes in temperature and, to a lesser extent, changes in composition that are seen in mantle xenolith studies and in seismic wave speed. Quantifying mantle parameters is necessary for their use in geodynamic models but is subject to considerable uncertainty (**Martin 2021**; **Wiens *et al.* 2021**). The uncertainty in viscosity derived from a single seismic velocity model is discussed in **Ivins *et al.* (2021)**. Other uncertainties that could be usefully refined include uncertainty from seismic models and uncertainties in mantle flow laws that relate deformation to applied stress. Currently, the exact mantle properties everywhere in Antarctica are imprecisely known because of poor mantle xenolith coverage and the coarseness of geophysical observations in some regions. However, it is encouraging that forward modelling of viscosity can recover the low viscosities derived from geodetic measurements in the Amundsen region and the Antarctic Peninsula (**Ivins *et al.* 2021**). Combinations of mantle chemistry from rocks and xenoliths, seismic data and gravity based on petrophysics will also be useful in refining Antarctic mantle properties for more accurate modelling of, for example, GIA and bedrock heat flow (e.g. Fullea *et al.* 2021). The suggested improvements listed in this paragraph, once undertaken, will also improve estimates of flexural rigidity that are crucial for palaeotopography studies (e.g. Paxman *et al.* 2019).

Viscosity is timescale dependent and varies by orders of magnitude from post-seismic deformation to GIA to mantle convection. It is still an open question as to whether stress-dependent viscosity and transient viscosity need to be included in geodynamic models (**Ivins *et al.* 2021**). In the latter case, is considering short-term and long-term viscosity sufficient or does viscosity need to be considered as a function of loading frequency (Lau *et al.* 2021)? A consistent description of viscosity must consider deformation at the microscopic scale from observations on mantle xenoliths (**Chatzaras and Kruckenberg 2021**) and laboratory experiments (e.g. Hansen *et al.* 2016). Further improvements should focus on integrating information from mantle xenoliths (**Martin 2021**) and information from depths where wadsleyite and ringwoodite dominate the mantle composition (Fig. 1) and where the scaling is especially unconstrained.

GIA and post-seismic deformation can be simulated with one numerical model such as that of Nield *et al.* (2022), which means that the same viscosity structure can be tested against observations of post-seismic deformation and GIA in areas where both occur. Even if multiple models are used, at least using the same viscosity description derived from geochemistry and geochemical studies would be beneficial so that observational constraints from different regions and processes are available for the same unknown rheological parameters. Horizontal velocities are underused for GIA, and are sensitive to tectonics, convection and post-seismic deformation. An improved palaeosea-level database would be another very beneficial constraint to the GIA models as such data best capture the relaxation through time.

The best approach for predicting mantle heat flow is an open question actively being considered (e.g. Burton-Johnson *et al.* 2020*a*, *b*). Different approaches yield estimates of different magnitudes at different spatial resolution. Better estimates can be produced by integration of data from boreholes, rock outcrops and mantle xenoliths with geophysical data including seismic, gravity and magnetic (Burton-Johnson *et al.* 2020*a*). Using new techniques such as machine learning can help this integration and assist in quantify uncertainties (e.g. Lösing and Ebbing 2021).

Geodynamic models have been developed for simulating surface elevation at timescales from hours to millions of years due to, for example, tectonics, GIA, sediment erosion or loading, thermal subsidence and mantle-dynamics topography (**Bredow *et al.* 2021**; **Paxman 2021**). An example of subsidence and uplift due to GIA can be seen in Figure 9. Although Figure 9 shows relative sea-level changes, these largely correspond to solid Earth deformation rates as the changes in the equipotential surface that determines the sea level are typically an order of magnitude smaller.

The bedrock topography determines how ice can flow towards the ocean (e.g. Paxman *et al.* 2019); topography changes affect the position on the grounding line. **van der Wal *et al.* (2022)** focused on feedbacks in the last glacial cycle; this influence can be quantified in similar processes across timescales.

Dynamic topography calculated with numerical models of mantle convection (**Bredow *et al.* 2021**) are more frequently being used when interpreting past observations of relative sea level such as during the last interglacial (Austermann *et al.* 2017) and the Pliocene, which is a period that is studied extensively as an analogue to future warming. These dynamic topography studies can also be used in coupled ice–landscape evolution models. This would open up the possibility of better connecting Antarctic ice evolution and palaeotopography to measured sediment deposits located outside Antarctica (cf. Pollard and DeConto 2020).

Under future projections of climate warming, the Antarctic Ice Sheet is likely to contribute several metres of sea-level rise by 2300 (DeConto *et al.* 2021). Therefore, precise estimates of Antarctic ice loss are necessary. Over the next centuries, the Antarctic Ice Sheet will interact with the ocean and the atmosphere but also with the solid Earth. Recent studies have already shown that the fast response of the Earth underneath the WAIS is important to determine its precise response to future warming (Gomez *et al.* 2015; Konrad *et al.* 2015; Larour *et al.* 2019; Kachuck *et al.* 2020; Powell *et al.* 2021) but models with realistic mantle properties and better-constrained viscosity are necessary to quantify the effect.

This volume represents the current state of knowledge on the Antarctic mantle. It should be useful to new students entering the field, as well as to active researchers in Antarctic and global mantle studies.

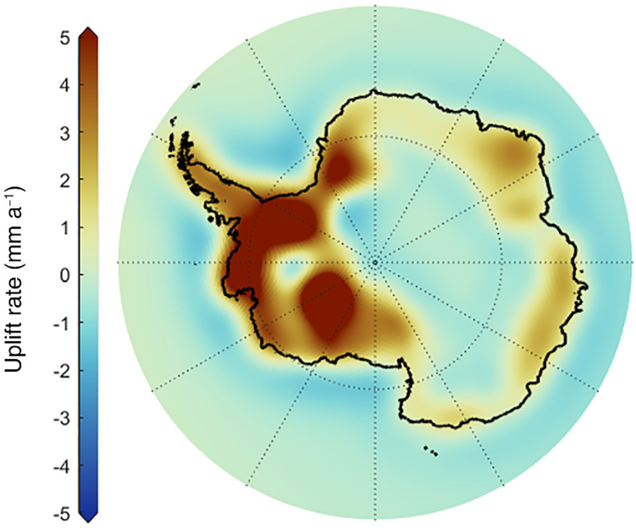

Fig. 9. The uplift rate (in mm a^{-1}) from glacial isostatic adjustment due to the past melting of ice sheets over Antarctica. Past ice-sheet input is the ICE-6G D global model (Peltier *et al.* 2018) and viscosity profile is the radially varying 1D viscosity model VM5a. Source: data were obtained from https://www.atmosp.physics.utoronto.ca/~peltier/data.php

Acknowledgements Thanks go to Pippa Whitehouse and Tom A. Jordan who reviewed this chapter, and to Phillip T. Leat for editorial handling.

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions **APM**: conceptualization (equal), data curation (equal), investigation (equal), writing – original draft (equal); **WVDW**: conceptualization (equal), investigation (equal), writing – original draft (equal), writing – review & editing (equal); **BDB**: visualization (supporting), writing – original draft (supporting).

Funding This contribution was in part supported by contract ANT1801.

Data availability Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

References

Adams, R.D. 1968. Early reflections of P′ P′ as an indication of upper mantle structure. *Bulletin of the Seismological Society of America*, **58**, 1933–1947.

Adams, R.D. 1971. Reflections from discontinuities beneath antarctica. *Bulletin of the Seismological Society of America*, **61**, 1441–1451, https://doi.org/10.1785/BSSA0610051441

An, M., Wiens, D.A. *et al*. 2015. Temperature, lithosphere–asthenosphere boundary, and heat flux beneath the Antarctic plate inferred from seismic velocities. *Journal of Geophysical Research: Solid Earth*, **120**, 8720–8742, https://doi.org/10.1002/2015JB011917

Argus, D.F., Peltier, W., Drummond, R. and Moore, A.W. 2014. The Antarctica component of postglacial rebound model ICE-6G_C (VM5a) based on GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories. *Geophysical Journal International*, **198**, 537–563, https://doi.org/10.1093/gji/ggu140

Austermann, J., Pollard, D. *et al*. 2015. The impact of dynamic topography change on Antarctic ice sheet stability during the mid-Pliocene warm period. *Geology*, **43**, 927–930, https://doi.org/10.1130/G36988.1

Austermann, J., Mitrovica, J.X., Huybers, P. and Rovere, A. 2017. Detection of a dynamic topography signal in last interglacial sea-level records. *Science Advances*, **3**, e1700457, https://doi.org/10.1126/sciadv.1700457

Aviado, K.B., Rilling-Hall, S., Bryce, J.G. and Mukasa, S.B. 2015. Submarine and subaerial lavas in the West Antarctic Rift System: Temporal record of shifting magma source components from the lithosphere and asthenosphere. *Geochemistry, Geophysics, Geosystems*, **16**, 4344–4361, https://doi.org/10.1002/2015GC006076

Barletta, V.R., Bevis, M. *et al*. 2018. Observed rapid bedrock uplift in Amundsen Sea Embayment promotes ice-sheet stability. *Science*, **360**, 1335–1339, https://doi.org/10.1126/science.aao1447

Barnhoorn, A., van der Wal, W., Vermeersen, B.L. and Drury, M.R. 2011. Lateral, radial, and temporal variations in upper mantle viscosity and rheology under Scandinavia. *Geochemistry, Geophysics, Geosystems*, **12**, Q01007, https://doi.org/10.1029/2010GC003290

Behrendt, J.C., Meister, L. and Henderson, J.R. 1966. Airborne geophysical study in the Pensacola Mountains of Antarctica.

Science, **153**, 1373–1376, https://doi.org/10.1126/science.153.3742.1373

Bennett, H.F. 1964. *A Gravity and Magnetic Survey of the Ross Ice Shelf Area, Antarctica*. Research Report 64-3. University of Wisconsin, Madison, WI.

Bercovici, D. 2003. The generation of plate tectonics from mantle convection. *Earth and Planetary Science Letters*, **205**, 107–121, https://doi.org/10.1016/S0012-821X(02)01009-9

Berg, J.H., Moscati, R.J. and Herz, D.L. 1989. A petrologic geotherm from a continental rift in Antarctica. *Earth and Planetary Science Letters*, **93**, 98–108, https://doi.org/10.1016/0012-821X(89)90187-8

Bevis, M., Kendrick, E. *et al*. 2009. Geodetic measurements of vertical crustal velocity in West Antarctica and the implications for ice mass balance. *Geochemistry, Geophysics, Geosystems*, **10**, Q10005, https://doi.org/10.1029/2009GC002642

Blank, B., Barletta, V., Hu, H., Pappa, F. and van der Wal, W. 2021. Effect of lateral and stress-dependent viscosity variations on GIA induced uplift rates in the Amundsen Sea Embayment. *Geochemistry, Geophysics, Geosystems*, **22**, e2021GC009807, https://doi.org/10.1029/2021GC009807

Bonadiman, C., Nazzareni, S., Coltorti, M., Comodi, P., Giuli, G. and Faccini, B. 2014. Crystal chemistry of amphiboles: implications for oxygen fugacity and water activity in lithospheric mantle beneath Victoria Land, Antarctica. *Contributions to Mineralogy and Petrology*, **167**, 1–17, https://doi.org/10.1007/s00410-014-0984-8

Bredow, E., Steinberger, B., Gassmöller, R. and Dannberg, J. 2021. Mantle convection and possible mantle plumes beneath Antarctica – insights from geodynamic models and implications for topography. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2020-2

Bull, C. 1960. Gravity observations in the Wright Valley Area, Victoria Land, Antarctica. *New Zealand Journal of Geology and Geophysics*, **3**, 543–552, https://doi.org/10.1080/00288306.1960.10420142

Burton-Johnson, A., Dziadek, R. and Martin, C. 2020*a*. Geothermal heat flow in Antarctica: current and future directions. *The Cryosphere*, **14**, 3843–3873, https://doi.org/10.5194/tc-14-3843-2020

Burton-Johnson, A., Dziadek, R. *et al*. 2020*b*. *Antarctic Geothermal Heat Flow: Future Research Directions*. SCAR-SERCE White Paper. Scientific Committee on Antarctic Research (SCAR), Cambridge, UK, https://scar.org/scar-library/search/science-4/research-programmes/serce/5454-scar-serce-white-paper-on-antarctic-geothermal-heat-flow/

Cammarano, F., Goes, S., Vacher, P. and Giardini, D. 2003. Inferring upper-mantle temperatures from seismic velocities. *Physics of the Earth and Planetary Interiors*, **138**, 197–222, https://doi.org/10.1016/S0031-9201(03)00156-0

Chatzaras, V. and Kruckenberg, S.C. 2021. Effects of melt-percolation, refertilization and deformation on upper mantle seismic anisotropy: constraints from peridotite xenoliths, Marie Byrd Land, West Antarctica. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2020-16

Civet, F., Thébault, E., Verhoeven, O., Langlais, B. and Saturnino, D. 2015. Electrical conductivity of the Earth's mantle from the first Swarm magnetic field measurements. *Geophysical Research Letters*, **42**, 3338–3346, https://doi.org/10.1002/2015GL063397

Čížková, H., van den Berg, A.P., Spakman, W. and Matyska, C. 2012. The viscosity of Earth's lower mantle inferred from sinking speed of subducted lithosphere. *Physics of the Earth and Planetary Interiors*, **200–201**, 56–62, https://doi.org/10.1016/j.pepi.2012.02.010

Clark, J.A. and Lingle, C.S. 1979. Predicted relative sea-level changes (18,000 years BP to present) caused by late-glacial retreat of the Antarctic ice sheet. *Quaternary Research*, **11**, 279–298, https://doi.org/10.1016/0033-5894(79)90076-0

Coltorti, M., Beccaluva, L. *et al*. 2004. Amphibole genesis via metasomatic reaction with clinopyroxene in mantle xenoliths from Victoria Land, Antarctica. *Lithos*, **75**, 115–139, https://doi.org/10.1016/j.lithos.2003.12.021

Coltorti, M., Bonadiman, C., Casetta, F., Faccini, B., Giacomoni, P.P., Pelorosso, B. and Perinelli, C. 2021. Nature and evolution of the northern Victoria Land lithospheric mantle (Antarctica) as revealed by ultramafic xenoliths. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2020-11

Condie, K.C. 2022. The mantle. *In*: Condie, K.C. (ed.) *Earth as an Evolving Planetary System*. 4th edn. Academic Press, London, 81–125.

Conrad Clinton, P. and Lithgow-Bertelloni, C. 2002. How mantle slabs drive plate tectonics. *Science*, **298**, 207–209, https://doi.org/10.1126/science.1074161

Cooper, A.F., Adam, L.J., Coulter, R.F., Eby, G.N. and McIntosh, W.C. 2007. Geology, geochronology and geochemistry of a basanitic volcano, White Island, Ross Sea, Antarctica. *Journal of Volcanology and Geothermal Research*, **165**, 189–216, https://doi.org/10.1016/j.jvolgeores.2007.06.003

Davis, C. and Ferguson, A. 2004. Elevation change of the Antarctic ice sheet, 1995–2000, from ERS-2 satellite radar altimetry. *IEEE Transactions on Geoscience and Remote Sensing*, **42**, 2437–2445, https://doi.org/10.1109/TGRS.2004.836789

Day, J.M.D., Harvey, R.P. and Hilton, D.R. 2019. Melt-modified lithosphere beneath Ross Island and its role in the tectonomagmatic evolution of the West Antarctic Rift System. *Chemical Geology*, **518**, 45–54, https://doi.org/10.1016/j.chemgeo.2019.04.012

DeConto, R.M., Pollard, D. *et al*. 2021. The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature*, **593**, 83–89, https://doi.org/10.1038/s41586-021-03427-0

Delpech, G., Scott, J.M. *et al*. 2021. The subantarctic lithospheric mantle. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2020-13

Dietz, R.S. and Holden, J.C. 1970. Reconstruction of Pangaea: Breakup and dispersion of continents, Permian to Present. *Journal of Geophysical Research*, **75**, 4939–4956, https://doi.org/10.1029/JB075i026p04939

Drewry, D. 1982. Ice flow, bedrock, and geothermal studies from radio-echo sounding inland of McMurdo Sound, Antarctica. *Antarctic Geoscience*, **1**, 977–983.

Dziewonski, A.M. and Anderson, D.L. 1981. Preliminary reference Earth model. *Physics of the Earth and Planetary Interiors*, **25**, 297–356, https://doi.org/10.1016/0031-9201(81)90046-7

Eaton, D.W., Darbyshire, F., Evans, R.L., Gruetter, H., Jones, A.G. and Yuan, X. 2009. The elusive lithosphere–asthenosphere boundary (LAB) beneath cratons. *Lithos*, **109**, 1–22, https://doi.org/10.1016/j.lithos.2008.05.009

Ebbing, J., Dilixiati, Y., Haas, P., Ferraccioli, F. and Scheiber-Enslin, S. 2021. East Antarctica magnetically linked to its ancient neighbours in Gondwana. *Scientific Reports*, **11**, 5513, https://doi.org/10.1038/s41598-021-84834-1

Elliot, D.H. 1992. Jurassic magmatism and tectonism associated with Gondwanaland break-up: an Antarctic perspective. *Geological Society, London, Special Publications*, **68**, 165–184, https://doi.org/10.1144/GSL.SP.1992.068.01.11

Emry, E., Nyblade, A.A. *et al*. 2015. The mantle transition zone beneath West Antarctica: Seismic evidence for hydration and thermal upwellings. *Geochemistry, Geophysics, Geosystems*, **16**, 40–58, https://doi.org/10.1002/2014GC005588

Evison, F.E. 1967. Note on the aseismicity of Antarctica. *New Zealand Journal of Geology and Geophysics*, **10**, 479–483, https://doi.org/10.1080/00288306.1967.10426752

Evison, F.F., Ingham, C.E. and Orr, R.H. 1959. Thickness of the Earth's crust in Antarctica. *Nature*, **183**, 306–308, https://doi.org/10.1038/183306a0

Evison, F.F., Ingham, C.E., Orr, R.H. and Le Fort, J.H. 1960. Thickness of the Earth's crust in Antarctica and the surrounding oceans. *Geophysical Journal International*, **3**, 289–306, https://doi.org/10.1111/j.1365-246X.1960.tb01704.x

Faccenna, C., Rossetti, F., Becker, T.W., Danesi, S. and Morelli, A. 2008. Recent extension driven by mantle upwelling beneath the Admiralty Mountains (East Antarctica). *Tectonics*, **27**, TC4015, https://doi.org/10.1029/2007TC002197

Fermor, L.L. 1913. Preliminary note on garnet as a geological barometer and on an infra-plutonic zone in the Earth's crust. *Geological Survey of India Records*, **43**, 41–47.

Fischer, K.M., Ford, H.A., Abt, D.L. and Rychert, C.A. 2010. The lithosphere–asthenosphere boundary. *Annual Review of Earth and Planetary Sciences*, **38**, 551–575, https://doi.org/10.1146/annurev-earth-040809-152438

Foley, S.F., Andronikov, A.V., Jacob, D.E. and Melzer, S. 2006. Evidence from Antarctic mantle peridotite xenoliths for changes in mineralogy, geochemistry and geothermal gradients beneath a developing rift. *Geochimica et Cosmochimica Acta*, **70**, 3096–3120, https://doi.org/10.1016/j.gca.2006.03.010

Foley, S.F., Andronikov, A.V., Halpin, J.A., Daczko, N.R. and Jacob, D.E. 2021. Mantle rocks in East Antarctica. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2020-8

Forbes, R.B. 1963. Ultrabasic inclusion from the basalts of the Hut Point area, Ross Island, Antarctica. *Bulletin Volcanologique*, **26**, 13–21, https://doi.org/10.1007/BF02597270

Forsberg, R., Olesen, A.V., Yildiz, H. and Tscherning, C.C. 2011. Polar gravity fields from GOCE and airborne gravity. *In*: Ouwehand, L. (ed.) *Proceedings of the 4th International GOCE User Workshop*, *Munich, Germany*, *31 March – 1 April 2011 (ESA SP-696, July 2011)*. European Space Agency, Noordwijk, The Netherlands, https://earth.esa.int/eogateway/documents/20142/37627/Polar_Gravity_Fields_GOCE_Airborne_Gravity_R.Forsberg.pdf

Forsberg, R., Oleson, A.V. *et al*. 2018. Exploring the Recovery Lakes region and interior Dronning Maud Land, East Antarctica, with airborne gravity, magnetic and radar measurements. *Geological Society, London, Special Publications*, **461**, 23–34, https://doi.org/10.1144/SP461.17

Fox Maule, C., Purucker, M.E., Olsen, N. and Mosegaard, K. 2005. Heat flux anomalies in Antarctica revealed by satellite magnetic data. *Science*, **309**, 464–467, https://doi.org/10.1126/science.1106888

Fretwell, P. *et al*. 2013. Bedmap2: improved ice bed, surface and thickness datasets for Antarctica. *The Cryosphere*, **7**, 375–393, https://doi.org/10.5194/tc-7-375-2013

Fullea, J., Lebedev, S., Martinec, Z. and Celli, N.L. 2021. WINTERC-G: mapping the upper mantle thermochemical heterogeneity from coupled geophysical–petrological inversion of seismic waveforms, heat flow, surface elevation and gravity satellite data. *Geophysical Journal International*, **226**, 146–191, https://doi.org/10.1093/gji/ggab094

Futa, K. and Le Masurier, W.E. 1983. Nd and Sr isotopic studies on Cenozoic mafic lavas from West Antarctica: Another source for continental alkali basalts. *Contributions to Mineralogy and Petrology*, **83**, 38–44, https://doi.org/10.1007/BF00373077

Gamble, J.A., McGibbon, F., Kyle, P.R., Menzies, M. and Kirsch, I. 1988. Metasomatised xenoliths from Foster Crater, Antarctica: Implications for lithospheric structure and process beneath the Transantarctic Mountain front. *Journal of Petrology*, Special Volume, **1**, 109–138, https://doi.org/10.1093/petrology/Special_Volume.1.109

Golynsky, A.V., Ferraccioli, F. *et al*. 2018. New Magnetic Anomaly Map of the Antarctic. *Geophysical Research Letters*, **45**, 6437–6449, https://doi.org/10.1029/2018GL078153

Gomez, N., Mitrovica, J.X., Huybers, P. and Clark, P.U. 2010. Sea level as a stabilizing factor for marine-ice-sheet grounding lines. *Nature Geoscience*, **3**, 850–853, https://doi.org/10.1038/ngeo1012

Gomez, N., Pollard, D. and Holland, D. 2015. Sea-level feedback lowers projections of future Antarctic Ice-Sheet mass loss. *Nature Communications*, **6**, 8798, https://doi.org/10.1038/ncomms9798

Gomez, N., Latychev, K. and Pollard, D. 2018. A coupled ice sheet–sea level model incorporating 3D Earth structure: variations in Antarctica during the last deglacial retreat. *Journal of Climate*, **31**, 4041–4054, https://doi.org/10.1175/JCLI-D-17-0352.1

Grad, M., Tiira, T. and Group, E.W. 2009. The Moho depth map of the European Plate. *Geophysical Journal International*, **176**, 279–292, https://doi.org/10.1111/j.1365-246X.2008.03919.x

Green, D.H., Hibberson, W.O., Kovács, I. and Rosenthal, A. 2010. Water and its influence on the lithosphere–asthenosphere boundary. *Nature*, **467**, 448–451, https://doi.org/10.1038/nature09369

Griffin, W.L. and O'Reilly, S.Y. 1987. The composition of the lower crust and the nature of the continental Moho-xenolith evidence. *In*: Nixon, P.H. (ed.) *Mantle Xenoliths*. Wiley- Interscience, New York, 413–430.

Groh, A., Ewert, H. *et al*. 2012. An investigation of glacial isostatic adjustment over the Amundsen Sea sector, West Antarctica. *Global and Planetary Change*, **98**, 45–53, https://doi.org/10.1016/j.gloplacha.2012.08.001

Handler, M.R., Wysoczanski, R.J. and Gamble, J.A. 2003. Proterozoic lithosphere in Marie Byrd Land, West Antarctica: Re–Os systematics of spinel peridotite xenoliths. *Chemical Geology*, **196**, 131–145, https://doi.org/10.1016/S0009-2541(02)00410-2

Handler, M.R., Wysoczanski, R.J. and Gamble, J.A. 2021. Marie Byrd Land lithospheric mantle: a review of the xenolith record. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2020-17

Hansen, L.N., Warren, J.M., Zimmerman, M.E. and Kohlstedt, D.L. 2016. Viscous anisotropy of textured olivine aggregates, Part 1: Measurement of the magnitude and evolution of anisotropy. *Earth and Planetary Science Letters*, **445**, 92–103, https://doi.org/10.1016/j.epsl.2016.04.008

Hansen, S.E., Graw, J.H. *et al*. 2014. Imaging the Antarctic mantle using adaptively parameterized P-wave tomography: Evidence for heterogeneous structure beneath West Antarctica. *Earth and Planetary Science Letters*, **408**, 66–78, https://doi.org/10.1016/j.epsl.2014.09.043

Harada, Y., Suzuki, H. and Ohashi, S. 1958. Determination of the differences in gravity values at Chiba (Japan), Singapore, Cape Town and Antarctica. *Journal of the Geodetic Society of Japan*, **5**, 53–60.

Harley, S.L., Fitzsimons, I.C. and Zhao, Y. 2013. Antarctica and supercontinent evolution: historical perspectives, recent advances and unresolved issues. *Geological Society, London, Special Publications*, **383**, 1–34, https://doi.org/10.1144/SP383.9

Hart, S.R. and Kyle, P.R. 1993. Geochemistry of McMurdo Volcanics Group rocks. *Antarctic Journal of the United States*, **28**, 14–16.

Hart, S.R., Blusztajn, J. and Craddock, C. 1995. Cenozoic volcanism in Antarctica: Jones Mountains and Peter I Island. *Geochimica et Cosmochimica Acta*, **59**, 3379–3388, https://doi.org/10.1016/0016-7037(95)00212-I

Hart, S.R., Blusztajn, J., LeMasurier, W.E. and Rex, D.C. 1997. Hobbs Coast Cenozoic volcanism: implications for the West Antarctic rift system. *Chemical Geology*, **139**, 223–248, https://doi.org/10.1016/S0009-2541(97)00037-5

Hermans, T., van der Wal, W. and Broerse, T. 2018. Reversal of the direction of horizontal velocities induced by GIA as a function of mantle viscosity. *Geophysical Research Letters*, **45**, 9597–9604, https://doi.org/10.1029/2018GL078533

Herzberg, C.T., Fyfe, W.S. and Carr, M.J. 1983. Density constraints on the formation of the continental Moho and crust. *Contributions to Mineralogy and Petrology*, **84**, 1–5, https://doi.org/10.1007/BF01132324

Hole, M.J., Kempton, P.D. and Millar, I.L. 1993. Trace-element and isotopic characteristics of small-degree melts of the asthenosphere: Evidence from the alkalic basalts of the Antarctic Peninsula. *Chemical Geology*, **109**, 51–68, https://doi.org/10.1016/0009-2541(93)90061-M

Howells, S. and O'Hara, M.J. 1978. Low solubility of alumina in enstatite and uncertainties in estimated palaeogeotherms. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **288**, 471–486, https://doi.org/10.1098/rsta.1978.0029

Ito, E. and Takahashi, E. 1989. Postspinel transformations in the system Mg_2SiO_4–Fe_2SiO_4 and some geophysical implications. *Journal of Geophysical Research: Solid Earth*, **94**, 10 637–10 646, https://doi.org/10.1029/JB094iB08p10637

Ivins, E.R., James, T.S., Wahr, J.O., Schrama, E.J., Landerer, F.W. and Simon, K.M. 2013. Antarctic contribution to sea level rise observed by GRACE with improved GIA correction. *Journal of Geophysical Research: Solid Earth*, **118**, 3126–3141, https://doi.org/10.1002/jgrb.50208

Ivins, E.R., van der Wal, W., Wiens, D.A., Lloyd, A.J. and Caron, L. 2021. Antarctic upper mantle rheology. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2020-19

Jagoutz, E., Palme, H. *et al*. 1979. The abundances of major, minor and trace elements in the Earth's mantle as derived from primitive ultramafic nodules. *In*: *Proceedings of the Tenth Lunar and Planetary Science Conference*, *Houston, Texas*, *March 19–23, 1979*. Pergamon Press, Oxford, UK, 2031–2050.

Kachuck, S.B., Martin, D.F., Bassis, J.N. and Price, S.F. 2020. Rapid viscoelastic deformation slows marine ice sheet instability at Pine Island Glacier. *Geophysical Research Letters*, **47**, e2019GL086446, https://doi.org/10.1029/2019GL086446

Kaminuma, K. 1979. Seismological bulletin of Syowa Station, Antarctica, 1977. JARE data reports. *Seismology*, **12**, 1–39.

Karato, S.-I., Jung, H., Katayama, I. and Skemer, P. 2008. Geodynamic significance of seismic anisotropy of the upper mantle: New insights from laboratory studies. *Annual Review of Earth and Planetary Sciences*, **36**, 59–95, https://doi.org/10.1146/annurev.earth.36.031207.124120

Katsura, T. and Ito, E. 1989. The system Mg_2SiO_4–Fe_2SiO_4 at high pressures and temperatures: Precise determination of stabilities of olivine, modified spinel, and spinel. *Journal of Geophysical Research: Solid Earth*, **94**, 15 663–15 670, https://doi.org/10.1029/JB094iB11p15663

Kaufmann, G. and Lambeck, K. 2000. Mantle dynamics, postglacial rebound and the radial viscosity profile. *Physics of the Earth and Planetary Interiors*, **121**, 301–324, https://doi.org/10.1016/S0031-9201(00)00174-6

Kaufmann, G., Wu, P. and Ivins, E.R. 2005. Lateral viscosity variations beneath Antarctica and their implications on regional rebound motions and seismotectonics. *Journal of Geodynamics*, **39**, 165–181, https://doi.org/10.1016/j.jog.2004.08.009

Kaula, W.M. 1972. Global gravity and tectonics. *In*: Robertson, E.C. (ed.) *The Nature of the Solid Earth*. McGraw-Hill, New York, 385–405.

Kawakatsu, H. *et al*. 2009. Seismic evidence for sharp lithosphere-asthenosphere boundaries of oceanic plates. *Science*, **324**, 499–502, https://doi.org/10.1126/science.1169499

Kennett, B.L.N., Engdahl, E.R. and Buland, R. 1995. Constraints on seismic velocities in the Earth from traveltimes. *Geophysical Journal International*, **122**, 108–124, https://doi.org/10.1111/j.1365-246X.1995.tb03540.x

Kennicutt, M.C.II, Chown, S.L. *et al*. 2015. A roadmap for Antarctic and Southern Ocean science for the next two decades and beyond. *Antarctic Science*, **27**, 3–18, https://doi.org/10.1017/S0954102014000674

Kim, H.R., Golynsky, A.V., Golynsky, D.A., Yu, H., von Frese, R.R.B. and Hong, J.K. 2022. New magnetic anomaly constraints on the Antarctic crust. *Journal of Geophysical Research: Solid Earth*, **127**, e2021JB023329, https://doi.org/10.1029/2021JB023329

King, M.A. and Santamaría-Gómez, A. 2016. Ongoing deformation of Antarctica following recent Great Earthquakes. *Geophysical Research Letters*, **43**, 1918–1927, https://doi.org/10.1002/2016GL067773

King, M.A., Bingham, R.J., Moore, P., Whitehouse, P.L., Bentley, M. and Milne, G.A. 2012. Lower satellite-gravimetry estimates of Antarctic sea-level contribution. *Nature*, **491**, 586–589, https://doi.org/10.1038/nature11621

King, M.A., Whitehouse, P.L. and van der Wal, W. 2015. Incomplete separability of Antarctic plate rotation from glacial isostatic adjustment deformation within geodetic observations. *Geophysical Journal International*, **204**, 324–330, https://doi.org/10.1093/gji/ggv461

Knopoff, L. and Vane, G. 1978. Age of East Antarctica from surface wave dispersion. *Pure and Applied Geophysics*, **117**, 806–815, https://doi.org/10.1007/BF00879981

Kogarko, L.N., Kurat, G. and Ntaflos, T. 2007. Henrymeyerite in the metasomatized upper mantle of Eastern Antarctica. *The Canadian Mineralogist*, **45**, 497–501, https://doi.org/10.2113/gscanmin.45.3.497

Konrad, H., Sasgen, I., Pollard, D. and Klemann, V. 2015. Potential of the solid-Earth response for limiting long-term West Antarctic Ice Sheet retreat in a warming climate. *Earth and Planetary Science Letters*, **432**, 254–264, https://doi.org/10.1016/j.epsl.2015.10.008

Kovács, I., Patkó, L., Falus, G., Aradi, L.E., Szanyi, G., Gráczer, Z. and Szabó, C. 2018. Upper mantle xenoliths as sources of geophysical information: the Perşani Mts. area as a case study. *Acta Geodaetica et Geophysica*, **53**, 415–438, https://doi.org/10.1007/s40328-018-0231-2

Kyle, P.R., Wright, A.C. and Kirsch, I. 1987. Ultramafic xenoliths in the late Cenozoic McMurdo Volcanic Group, western Ross Sea embayment, Antarctica. *In*: Nixon, P.H. (ed.) *Mantle Xenoliths*. Wiley- Interscience, New York, 287–293.

Kyle, P.R., Moore, J.A. and Thirlwall, M.F. 1992. Petrologic evolution of anorthoclase phonolite lavas at Mount Erebus, Ross Island, Antarctica. *Journal of Petrology*, **33**, 849–875, https://doi.org/10.1093/petrology/33.4.849

Kyle, P.R., Pankhurst, R., Mukasa, S., Panter, K., Smellie, J. and McIntosh, W. 1994. *Sr, Nd and Pb Isotopic Variations in the Marie Byrd Plume, West Antarctica*. US Geological Survey Circular, **1107**.

Lambeck, K., Yokoyama, Y., Johnston, P. and Purcell, A. 2000. Global ice volumes at the Last Glacial Maximum and early Lateglacial. *Earth and Planetary Science Letters*, **181**, 513–527, https://doi.org/10.1016/S0012-821X(00)00223-5

Larour, E., Seroussi, H., Adhikari, S., Ivins, E., Caron, L., Morlighem, M. and Schlegel, N. 2019. Slowdown in Antarctic mass loss from solid Earth and sea-level feedbacks. *Science*, **364**, eaav7908, https://doi.org/10.1126/science.aav7908

Lau, H.C.P., Austermann, J., Holtzman, B.K., Havlin, C., Lloyd, A.J., Book, C. and Hopper, E. 2021. Frequency dependent mantle viscoelasticity via the complex viscosity: Cases from Antarctica. *Journal of Geophysical Research: Solid Earth*, **126**, e2021JB022622, https://doi.org/10.1029/2021JB022622

Leat, P.T., Ross, A.J. and Gibson, S.A. 2021. Ultramafic mantle xenoliths in the Late Cenozoic volcanic rocks of the Antarctic Peninsula and Jones Mountains, West Antarctica. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2019-44

Le Maitre, R.W., Streckeisen, A., Zanettin, B., Le Bas, M., Bonin, B. and Bateman, P. (eds) 2002. *Igneous Rocks: A Classification and Glossary of Terms. Recommendations of the International Union of Geological Sciences Subcommission of the Systematics of Igneous Rocks*. 2nd edn. Cambridge University Press, Cambridge, UK.

LeMasurier, W.E. and Landis, C.A. 1996. Mantle-plume activity recorded by low-relief erosion surfaces in West Antarctica and New Zealand. *Geological Society of America Bulletin*, **108**, 1450–1466, https://doi.org/10.1130/0016-7606(1996)108<1450:MPARBL>2.3.CO;2

Lloyd, A.J., Wiens, D.A. *et al*. 2015. A seismic transect across West Antarctica: Evidence for mantle thermal anomalies beneath the Bentley Subglacial Trench and the Marie Byrd Land Dome. *Journal of Geophysical Research: Solid Earth*, **120**, 8439–8460, https://doi.org/10.1002/2015JB012455

Lloyd, A.J., Wiens, D.A. *et al*. 2020. Seismic structure of the Antarctic upper mantle imaged with adjoint tomography. *Journal of Geophysical Research: Solid Earth*, **125**, https://doi.org/10.1029/2019JB017823

Lösing, M. and Ebbing, J. 2021. Predicting geothermal heat flow in Antarctica with a machine learning approach. *Journal of Geophysical Research: Solid Earth*, **126**, e2020JB021499, https://doi.org/10.1029/2020JB021499

Lösing, M., Ebbing, J. and Szwillus, W. 2020. Geothermal heat flux in Antarctica: Assessing models and observations by Bayesian inversion. *Frontiers in Earth Science*, **8**, 105, https://doi.org/10.3389/feart.2020.00105

Lough, A.C., Wiens, D.A. and Nyblade, A. 2018. Reactivation of ancient Antarctic rift zones by intraplate seismicity. *Nature Geoscience*, **11**, 515–519, https://doi.org/10.1038/s41561-018-0140-6

Macgregor, I.D. 1974. The system MgO–Al_2O_3–SiO_2: Solubility of Al_2O_3 in enstatite for spinel and garnet peridotite compositions. *American Mineralogist*, **59**, 110–119.

Mainprice, D. and Silver, P.G. 1993. Interpretation of SKS-waves using samples from the subcontinental lithosphere. *Physics of the Earth and Planetary Interiors*, **78**, 257–280, https://doi.org/10.1016/0031-9201(93)90160-B

Manning, J. 2001. *The SCAR Geodetic Infrastructure of Antarctica*. Report from the Second SCAR Antarctic Geodesy Symposium, Warsaw, July 1999. SCAR Report Number 20. Scientific Committee on Antarctic Research (SCAR), Cambridge, UK, 22–30.

Martin, A.P. 2021. A review of the composition and chemistry of peridotite mantle xenoliths in volcanic rocks from Antarctica and their relevance to petrological and geophysical models for the lithospheric mantle. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2021-26

Martin, A.P., Cooper, A.F. and Price, R.C. 2013. Petrogenesis of Cenozoic, alkalic volcanic lineages at Mount Morning, West Antarctica and their entrained lithospheric mantle xenoliths: Lithospheric v. asthenospheric mantle sources. *Geochimica et Cosmochimica Acta*, **122**, 127–152, https://doi.org/10.1016/j.gca.2013.08.025

Martin, A.P., Price, R.C. and Cooper, A.F. 2014. Constraints on the composition, source and petrogenesis of plagioclase-bearing mantle peridotite. *Earth-Science Reviews*, **138**, 89–101, https://doi.org/10.1016/j.earscirev.2014.08.006

Martin, A.P., Price, R.C., Cooper, A.F. and McCammon, C.A. 2015. Petrogenesis of the rifted southern Victoria Land lithospheric mantle, Antarctica, Inferred from petrography, geochemistry, thermobarometry and oxybarometry of peridotite and pyroxenite xenoliths from the Mount Morning eruptive centre. *Journal of Petrology*, **56**, 193–226, https://doi.org/10.1093/petrology/egu075

Martin, A.P., Cooper, A.F., Price, R.C., Doherty, C.L. and Gamble, J.A. 2021*a*. A review of mantle xenoliths in volcanic rocks from southern Victoria Land, Antarctica. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2019-42

Martin, A.P., Cooper, A.F., Price, R.C., Kyle, P.R. and Gamble, J.A. 2021*b*. Erebus Volcanic Province: petrology. *Geological Society, London, Memoirs*, **55**, 447–489, https://doi.org/10.1144/M55-2018-80

Martín-Español, A., King, M.A., Zammit-Mangion, A., Andrews, S.B., Moore, P. and Bamber, J.L. 2016. An assessment of forward and inverse GIA solutions for Antarctica. *Journal of Geophysical Research: Solid Earth*, **121**, 6947–6965, https://doi.org/10.1002/2016JB013154

Martos, Y.M., Catalán, M., Jordan, T.A., Golynsky, A., Golynsky, D., Eagles, G. and Vaughan, D.G. 2017. Heat flux distribution of Antarctica unveiled. *Geophysical Research Letters*, **44**, 11,417–11,426, https://doi.org/10.1002/2017GL075609

Meisel, T., Walker, R.J., Irving, A.J. and Lorand, J.-P. 2001. Osmium isotopic compositions of mantle xenoliths: a global perspective. *Geochimica et Cosmochimica Acta*, **65**, 1311–1323, https://doi.org/10.1016/S0016-7037(00)00566-4

Meissner, R. 1986. *The Continental Crust: A Geophysical Approach*. International Geophysics Series, **34**. Academic Press, Orlando, FL.

Nardini, I., Armienti, P., Rocchi, S., Dallai, L. and Harrison, D. 2009. Sr–Nd–Pb–He–O isotope and geochemical constraints on the genesis of Cenozoic magmas from the West Antarctic Rift. *Journal of Petrology*, **50**, 1359–1375, https://doi.org/10.1093/petrology/egn082

Nield, G.A., Barletta, V.R. *et al*. 2014. Rapid bedrock uplift in the Antarctic Peninsula explained by viscoelastic response to recent ice unloading. *Earth and Planetary Science Letters*, **397**, 32–41, https://doi.org/10.1016/j.epsl.2014.04.019

Nield, G.A., Whitehouse, P.L., van der Wal, W., Blank, B., O'Donnell, J.P. and Stuart, G.W. 2018. The impact of lateral variations in lithospheric thickness on glacial isostatic adjustment in West Antarctica. *Geophysical Journal International*, **214**, 811–824, https://doi.org/10.1093/gji/ggy158

Nield, G.A., King, M.A., Steffen, R. and Blank, B. 2022. A global, spherical finite-element model for post-seismic deformation using Abaqus. *Geoscientific Model Development*, **15**, 2489–2503, https://doi.org/10.5194/gmd-15-2489-2022

Nixon, P.H. 1987*a*. *Mantle Xenoliths*. Wiley-Interscience, New York.

Nixon, P.H. 1987*b*. Indian–Australian and Antartic plates – Introduction. *In*: Nixon, P.H. (ed.) *Mantle Xenoliths*. Wiley- Interscience, New York, 241–248.

O'Donnell, J.P., Selway, K. *et al*. 2017. The uppermost mantle seismic velocity and viscosity structure of central West Antarctica. *Earth and Planetary Science Letters*, **472**, 38–49, https://doi.org/10.1016/j.epsl.2017.05.016

O'Reilly, S.Y. and Griffin, W.L. 2010. The continental lithosphere–asthenosphere boundary: Can we sample it? *Lithos*, **120**, 1–13, https://doi.org/10.1016/j.lithos.2010.03.016

Panter, K.S. and Martin, A.P. 2021. West Antarctic mantle deduced from mafic magmatism. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2021-10

Panter, K.S., Blusztajn, J., Hart, S.R., Kyle, P.R., Esser, R. and McIntosh, W.C. 2006. The origin of HIMU in the SW Pacific: Evidence from intraplate volcanism in southern New Zealand and subantarctic islands. *Journal of Petrology*, **47**, 1673–1704, https://doi.org/10.1093/petrology/egl024

Pappa, F. and Ebbing, J. 2021. Gravity, magnetics and geothermal heat flow of the Antarctic lithospheric crust and mantle. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2020-5

Pappa, F., Ebbing, J. and Ferraccioli, F. 2019*a*. Moho depths of Antarctica: Comparison of seismic, gravity, and isostatic results. *Geochemistry, Geophysics, Geosystems*, **20**, 1629–1645, https://doi.org/10.1029/2018GC008111

Pappa, F., Ebbing, J., Ferraccioli, F. and van der Wal, W. 2019*b*. Modeling satellite gravity gradient data to derive density, temperature, and viscosity structure of the Antarctic lithosphere. *Journal of Geophysical Research: Solid Earth*, **124**, 12 053–12 076, https://doi.org/10.1029/2019JB017997

Pattyn, F. 2018. The paradigm shift in Antarctic ice sheet modelling. *Nature Communications*, **9**, 2728, https://doi.org/10.1038/s41467-018-05003-z

Paulson, A., Zhong, S. and Wahr, J. 2007. Limitations on the inversion for mantle viscosity from postglacial rebound. *Geophysical Journal International*, **168**, 1195–1209, https://doi.org/10.1111/j.1365-246X.2006.03222.x

Paxman, G.J.G. 2021. Antarctic palaeotopography. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2020-7

Paxman, G.J.G., Watts, A.B., Ferraccioli, F., Jordan, T.A., Bell, R.E., Jamieson, S.S.R. and Finn, C.A. 2016. Erosion-driven uplift in the Gamburtsev Subglacial Mountains of East Antarctica. *Earth and Planetary Science Letters*, **452**, 1–14, https://doi.org/10.1016/j.epsl.2016.07.040

Paxman, G.J.G., Jamieson, S.S.R., Hochmuth, K., Gohl, K., Bentley, M.J., Leitchenkov, G. and Ferraccioli, F. 2019. Reconstructions of Antarctic topography since the Eocene–Oligocene boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **535**, 109346, https://doi.org/10.1016/j.palaeo.2019.109346

Pearson, D., Canil, D. and Shirey, S. 2003. Mantle samples included in volcanic rocks: xenoliths and diamonds. *In*: Carlson, R.W. (ed.) *The Mantle and Core*. Treatise on Geochemistry, **2**, 171–275, https://doi.org/10.1016/B0-08-043751-6/02005-3

Peltier, W.R., Argus, D.F. and Drummond, R. 2018. Comment on 'An assessment of the *ICE-6G_C (VM5a)* glacial isostatic adjustment model' by Purcell *et al*. *Journal of Geophysical Research. Solid Earth*, **123**, 2019–2018, https://doi.org/10.1002/2016JB013844

Perinelli, C., Andreozzi, G., Conte, A., Oberti, R. and Armienti, P. 2012. Redox state of subcontinental lithospheric mantle and relationships with metasomatism: insights from spinel peridotites from northern Victoria Land (Antarctica). *Contributions to Mineralogy and Petrology*, **164**, 1053–1067, https://doi.org/10.1007/s00410-012-0788-7

Phillips, E.H. , Sims, K.W.W. *et al*. 2018. The nature and evolution of mantle upwelling at Ross Island, Antarctica, with implications for the source of HIMU lavas. *Earth and Planetary Science Letters*, **498**, 38–53, https://doi.org/10.1016/j.epsl.2018.05.049

Pollard, D. and DeConto, R.M. 2020. Continuous simulations over the last 40 million years with a coupled Antarctic ice sheet–sediment model. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **537**, 109374, https://doi.org/10.1016/j.palaeo.2019.109374

Pollitz, F.F. and Thatcher, W. 2010. On the resolution of shallow mantle viscosity structure using postearthquake relaxation data: Application to the 1999 Hector Mine, California, earthquake. *Journal of Geophysical Research: Solid Earth*, **115**, B10412, https://doi.org/10.1029/2010JB007405

Powell, E., Gomez, N., Hay, C., Latychev, K. and Mitrovica, J. 2020. Viscous effects in the solid Earth response to modern Antarctic ice mass flux: Implications for geodetic studies of WAIS stability in a warming world. *Journal of Climate*, **33**, 443–459, https://doi.org/10.1175/JCLI-D-19-0479.1

Powell, E.M., Pan, L., Hoggard, M.J., Latychev, K., Gomez, N., Austermann, J. and Mitrovica, J.X. 2021. The impact of 3-D Earth structure on far-field sea level following interglacial West Antarctic Ice Sheet collapse. *Quaternary Science Reviews*, **273**, 107256, https://doi.org/10.1016/j.quascirev.2021.107256

Prior, G.T. 1902. Report on the rock specimens collected by the Southern Cross Antarctic Expedition. *In*: *Report on Southern Cross Expedition*. British Museum, London, 321–332.

Prior, G.T. 1907. Report on the rock specimens collected during the 'Discovery' Antarctic Expedition, 1901–1904. *Natural History*, **1**, 101–160.

Rémy, F. and Parouty, S. 2009. Antarctic ice sheet and radar altimetry: A review. *Remote Sensing*, **1**, 1212–1239, https://doi.org/10.3390/rs1041212

Rémy, F., Mazzega, P., Houry, S., Brossier, C. and Minster, J. 1989. Mapping of the topography of continental ice by inversion of satellite-altimeter data. *Journal of Glaciology*, **35**, 98–107, https://doi.org/10.3189/002214389793701419

Revenaugh, J. and Jordan, T.H. 1991. Mantle layering from ScS reverberations: 2. The transition zone. *Journal of Geophysical Research: Solid Earth*, **96**, 19 763–19 780, https://doi.org/10.1029/91JB01486

Ritzwoller, M.H., Shapiro, N.M., Levshin, A.L. and Leahy, G.M. 2001. Crustal and upper mantle structure beneath Antarctica and surrounding oceans. *Journal of Geophysical Research*, **106**, 30 645–30 670, https://doi.org/10.1029/2001JB000179

Ross, C.S., Foster, M.D. and Myers, A.T. 1954. Origin of dunites and of olivine-rich inclusions in basaltic rocks1. *American Mineralogist*, **39**, 693–737.

Scheinert, M., Engels, O., Schrama, E.J.O., van der Wal, W. and Horwath, M. 2021. Geodetic observations for constraining mantle processes in Antarctica. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2021-22

Seroussi, H., Ivins, E.R., Wiens, D.A. and Bondzio, J. 2017. Influence of a West Antarctic mantle plume on ice sheet basal conditions. *Journal of Geophysical Research: Solid Earth*, **122**, 7127–7155, https://doi.org/10.1002/2017JB014423

Shapiro, N.M. and Ritzwoller, M.H. 2004. Inferring surface heat flux distributions guided by a global seismic model: particular application to Antarctica. *Earth and Planetary Science Letters*, **223**, 213–224, https://doi.org/10.1016/j.epsl.2004.04.011

Shearer, P.M. and Flanagan, M.P. 1999. Seismic velocity and density jumps across the 410- and 660-kilometer discontinuities. *Science*, **285**, 1545–1548, https://doi.org/10.1126/science.285.5433.1545

Shen, W., Wiens, D.A., Lloyd, A.J. and Nyblade, A.A. 2020. A geothermal heat flux map of Antarctica empirically constrained by seismic structure. *Geophysical Research Letters*, **47**, e2020GL086955, https://doi.org/10.1029/2020GL086955

Sheraton, J.W. 1983. Geochemistry of mafic igneous rocks of the northern Prince Charles Mountains, Antarctica. *Journal of the Geological Society of Australia*, **30**, 295–304, https://doi.org/10.1080/00167618308729257

Sheraton, J.W. and Black, L.P. 1982. Geochemistry and geochronology of Proterozoic tholeiite dykes of East Antarctica: evidence for mantle metasomatism. *Contributions to Mineralogy and Petrology*, **78**, 305–317, https://doi.org/10.1007/BF00398925

Shervais, J.W. 1988. A review of Volcanic Rocks: *Mantle Xenoliths*. Peter H. Nixon, Ed. Wiley- Interscience, New York, 1987. xviii, 844 pp. *Science*, **241**, 366–367, https://doi.org/10.1126/science.241.4863.366

Siegert, M.J., Jamieson, S.S.R. and White, D. 2018. Exploration of subsurface Antarctica: uncovering past changes and modern processes. *Geological Society, London, Special Publications*, **461**, 1–6, https://doi.org/10.1144/SP461.15

Sims, K.W.W. and Hart, S.R. 2006. Comparison of Th, Sr, Nd and Pb isotopes in oceanic basalts: Implications for mantle heterogeneity and magma genesis. *Earth and Planetary Science Letters*, **245**, 743–761, https://doi.org/10.1016/j.epsl.2006.02.030

Smellie, J.L., Panter, K.S. and Geyer, A. (eds) 2021. *Volcanism in Antarctica: 200 Million Years of Subduction, Rifting and Continental Break-up*. Geological Society, London, Memoirs, **55**, https://doi.org/10.1144/M55

Spada, G. and Melini, D. 2019. SELEN4 (SELEN version 4.0): a Fortran program for solving the gravitationally and topographically self-consistent sea-level equation in glacial isostatic adjustment modeling. *Geoscientific Model Development*, **12**, 5055–5075, https://doi.org/10.5194/gmd-12-5055-2019

Steinberger, B., Torsvik, T.H. and Becker, T.W. 2012. Subduction to the lower mantle – a comparison between geodynamic and tomographic models. *Solid Earth*, **3**, 415–432, https://doi.org/10.5194/se-3-415-2012

Storey, B.C., Leat, P.T., Weaver, S.D., Pankhurst, R.J., Bradshaw, J.D. and Kelley, S. 1999. Mantle plumes and Antarctica–New Zealand rifting: evidence from mid-Cretaceous mafic dykes. *Journal of the Geological Society, London*, **156**, 659–671, https://doi.org/10.1144/gsjgs.156.4.0659

Sun, S.S. and Hanson, G.N. 1975. Origin of Ross Island basanitoids and limitations upon the heterogeneity of mantle sources for alkali basalts and nephelinites. *Contributions to Mineralogy and Petrology*, **52**, 77–106, https://doi.org/10.1007/BF00395006

Sutter, J., Fischer, H., Grosfeld, K., Karlsson, N.B., Kleiner, T., Van Liefferinge, B. and Eisen, O. 2019. Modelling the Antarctic Ice Sheet across the mid-Pleistocene transition–implications for Oldest Ice. *The Cryosphere*, **13**, 2023–2041, https://doi.org/10.5194/tc-13-2023-2019

Talbot, J.L., Hobbs, B.E., Wilshire, H.G. and Sweatman, T.R. 1963. Xenoliths and xenocrysts from lavas of the Kerguelen Archipelago. *American Mineralogist*, **48**, 159–179.

ten Brink, U. and Stern, T. 1992. Rift flank uplifts and Hinterland Basins: Comparison of the Transantarctic Mountains with the Great Escarpment of southern Africa. *Journal of Geophysical Research: Solid Earth*, **97**, 569–585, https://doi.org/10.1029/91JB02231

Thomas, I.D., King, M.A. *et al*. 2011. Widespread low rates of Antarctic glacial isostatic adjustment revealed by GPS observations. *Geophysical Research Letters*, **38**, L22302, https://doi.org/10.1029/2011GL049277

Thomson, J.A. 1916. *Report on the Inclusions of the Volcanic Rocks of the Ross Archipelago (with Appendix by F. Cohen)*. Report of the British Antarctic Expedition, 1907–1909.

Tommasi, A., Tikoff, B. and Vauchez, A. 1999. Upper mantle tectonics: three-dimensional deformation, olivine crystallographic fabrics and seismic properties. *Earth and Planetary Science Letters*, **168**, 173–186, https://doi.org/10.1016/S0012-821X(99)00046-1

Turcotte, D.L. and Oxburgh, E.R. 1967. Finite amplitude convective cells and continental drift. *Journal of Fluid Mechanics*, **28**, 29–42, https://doi.org/10.1017/S0022112067001880 van der Wal, W., Barnhoorn, A., Stocchi, P., Gradmann, S., Wu, P., Drury, M. and Vermeersen, B. 2013. Glacial isostatic adjustment model with composite 3-D Earth rheology for Fennoscandia. *Geophysical Journal International*, **194**, 61–77, https://doi.org/10.1093/gji/ggt099

van der Wal, W., Whitehouse, P.L. and Schrama, E.J.O. 2015. Effect of GIA models with 3D composite mantle viscosity on GRACE mass balance estimates for Antarctica. *Earth and Planetary Science Letters*, **414**, 134–143, https://doi.org/10.1016/j.epsl.2015.01.001

van der Wal, W., Barletta, V., Nield, G. and van Calcar, C. 2022. Glacial isostatic adjustment and post-seismic deformation in Antarctica. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2022-13

Vardić, K., Clarke, P.J. and Whitehouse, P.L. 2022. A GNSS velocity field for crustal deformation studies: The influence of glacial isostatic adjustment on plate motion models. *Geophysical Journal International*, **231**, 426–458, https://doi.org/10.1093/gji/ggac047

Velicogna, I. and Wahr, J. 2006. Measurements of time-variable gravity show mass loss in Antarctica. *Science*, **311**, 1754, https://doi.org/10.1126/science.1123785

Wagner, P.A. 1914. *The Diamond Fields of Southern Africa*. Transvaal Leader, Johannesburg, South Africa.

Wannamaker, P.E., Stodt, J.A., Hill, G.J., Maris, V. and Kordy, M.A. 2021. Thermal regime and state of hydration of the Antarctic upper mantle from regional-scale electrical properties. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2020-4

Warner, R.D. and Wasilewski, P.J. 1995. Magnetic petrology of lower crust and upper mantle xenoliths from McMurdo Sound, Antarctica. *Tectonophysics*, **249**, 69–92, https://doi.org/10.1016/0040-1951(95)00014-E

Weaver, S.D., Storey, B.C., Pankhurst, R.J., Mukasa, S.B., DiVenere, V.J. and Bradshaw, J.D. 1994. Antarctica–New Zealand rifting and Marie Byrd Land lithospheric magmatism linked to ridge subduction and mantle plume activity. *Geology*, **22**, 811–814, https://doi.org/10.1130/0091-7613(1994)022<0811:ANZRAM>2.3.CO;2

Whitehouse, P.L. 2018. Glacial isostatic adjustment modelling: historical perspectives, recent advances, and future directions. *Earth Surface Dynamics*, **6**, 401–429, https://doi.org/10.5194/esurf-6-401-2018

Whitehouse, P.L., Bentley, M.J., Milne, G.A., King, M.A. and Thomas, I.D. 2012. A new glacial isostatic adjustment model for Antarctica: calibrated and tested using observations of relative sea-level change and present-day uplift rates. *Geophysical Journal International*, **190**, 1464–1482, https://doi.org/10.1111/j.1365-246X.2012.05557.x

Whitehouse, P.L., Gomez, N., King, M.A. and Wiens, D.A. 2019. Solid Earth change and the evolution of the Antarctic Ice Sheet. *Nature Communications*, **10**, 503, https://doi.org/10.1038/s41467-018-08068-y

Wiens, D.A., Shen, W. and Lloyd, A.J. 2021. The seismic structure of the Antarctic upper mantle. *Geological Society, London, Memoirs*, **56**, https://doi.org/10.1144/M56-2020-18

Wood, B.J. and Banno, S. 1973. Garnet–orthopyroxene and orthopyroxene–clinopyroxene relationships in simple and complex systems. *Contributions to Mineralogy and Petrology*, **42**, 109–124, https://doi.org/10.1007/BF00371501

Wörner, G. 1999. Lithospheric dynamics and mantle sources of alkaline magmatism of the Cenozoic West Antarctic Rift System. *Global and Planetary Change*, **23**, 61–77, https://doi.org/10.1016/S0921-8181(99)00051-X

Wörner, G. and Zipfel, J. 1996. A mantle P–T path for the Ross Sea Rift margin (Antarctica) derived from Ca-in-olivine zonation patterns in peridotites xenoliths of the Plio-Pleistocene Mt. Melbourne Volcanic Field. *Geologisches Jahrbuch B*, **89**, 157–167.

Wyllie, P.J. 1981. Plate tectonics and magma genesis. *Geologische Rundschau*, **70**, 128–153, https://doi.org/10.1007/BF0176 4318

Wysoczanski, R.J. 1993. *Lithospheric xenoliths from the Marie Byrd Land volcanic province, West Antarctica*. PhD thesis, Victoria University of Wellington, Wellington, New Zealand.

Zipfel, J. and Wörner, G. 1992. Four- and five-phase peridotites from a continental rift system: Evidence for upper mantle uplift and cooling at the Ross Sea margin (Antarctica). *Contributions to Mineralogy and Petrology*, **111**, 24–36, https://doi.org/10.1007/BF00296575