Emergence of Antarctic mineral resources in a warming world

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Abstract

The extent of ice-free land across Antarctica will increase in a warming world, driven by Antarctic Ice Sheet retreat and sea level change. Here we project a 170-560% increase in the extent of Antarctic ice-free land over the next three centuries using a state-of-the-art sea level model combined with moderate and high ice sheet melt scenarios. New ice-free land is projected to emerge in all regions with existing territorial claims – made by Argentina, Australia, Chile, France, New Zealand, Norway, and the United Kingdom – as well as in an unclaimed sector of West Antarctica. The geologic setting and distribution of known mineral occurrences indicate that ice-free land emergence is likely to expose new mineral deposits in these regions. Although the *Protocol on Environmental Protection to the Antarctic Treaty* prohibits mineral resource development in Antarctica (Antarctic Treaty Secretariat, 1991), its long-term durability remains uncertain. With the anticipated rise in the economic viability of Antarctic mineral resources over the coming centuries, the environmental impacts of mineral resource development will need to be weighed against the pressure of exploiting materials essential for sustainable development.

Main

The Antarctic Treaty was signed in 1959, during the Cold War, by three categories of states: those with territorial claims in Antarctica (i.e., Argentina, Australia, Chile, France, New Zealand, Norway, and the United Kingdom); non-claimant states (i.e., Belgium, Japan, and South Africa); and the two superpowers of the time – the United States and the Soviet Union (now Russia) (Antarctic Treaty Secretariat, 1959). Although seven states maintain territorial claims in Antarctica, the United States, Russia, and most other countries do not recognize such claims (Antarctic Treaty Secretariat, 1959; Thorp, 2012; Central Intelligence Agency, 2025). Of particular importance, Article IV of the Antarctic Treaty asserts that nothing in the treaty renunciates a state's previously asserted rights or territorial claims in Antarctica or prejudices a state's "recognition or non-recognition of any other state's right of or claim to territorial sovereignty in Antarctica." As such, Article IV "froze" all territorial claims in geopolitical time (Grob, 2007; Thorp, 2012), including the overlapping claims of Argentina, Chile, and the United Kingdom in the Antarctic Peninsula and Weddell Sea sectors (Dodds, 2012; Haward & Jackson, 2023) (Fig. 1). Only one sector of West Antarctica remains unclaimed (Fig. 1). Furthermore, the

Antarctic Treaty established that Antarctica, defined as the areas south of latitude 60°S including all ice shelves, be exclusively used for scientific research and peaceful purposes (Antarctic Treaty Secretariat, 1959).

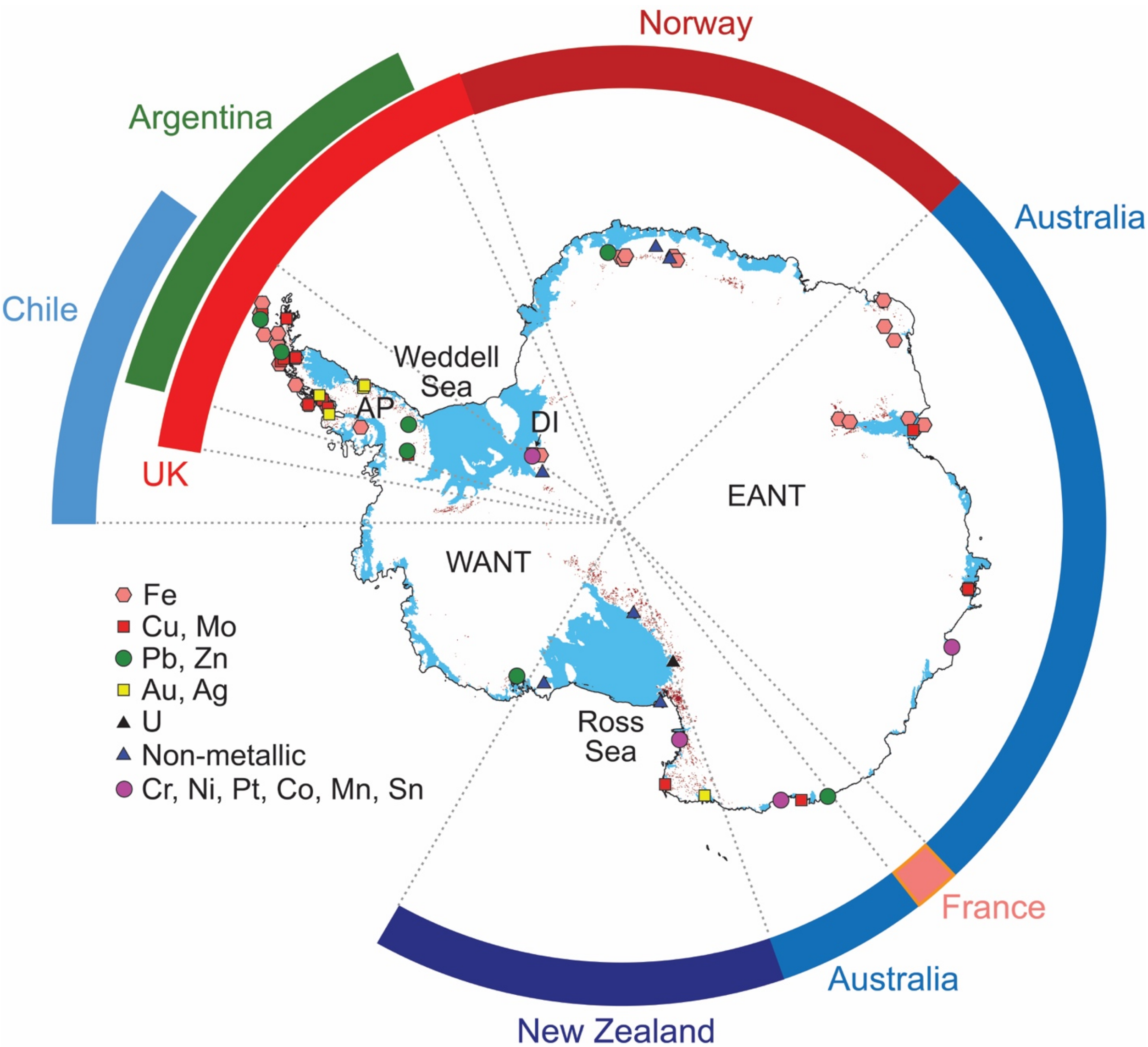

Fig. 1 | Territorial claims in Antarctica and known mineral occurrences (Guild et al., 1998). Grounded ice and ice shelves are shown in white and blue, respectively (Mouginot et al., 2017). Rock outcrops are plotted in dark red (Burton-Johnson et al., 2016). West Antarctica (WANT), East Antarctica (EANT), the Antarctic Peninsula (AP), and the Dufek Intrusion (DI) are labeled.

Symbols, with legend at bottom left, indicate known mineral occurrences. Dotted lines demark sectors discussed in the context of Fig. 5.

While territorial claims “froze” in 1959, the Antarctic physical environment has not remained frozen in time. At present, less than 0.5% (~21,745 km^2) of the Antarctic continent is free of ice cover (Burton-Johnson et al., 2016), with ice-free areas including coastal environments, mountain ranges, nunataks, valleys, islands, and cliffs (Fig. 1). The overriding Antarctic Ice Sheet has undergone rapid thinning and grounding-line retreat over the past few decades (Rignot et al., 2019; Shepherd et al., 2019), and ice sheet retreat is expected to continue over the coming centuries (Seroussi et al., 2024). This anthropogenically-driven process has led – and will continue to lead – to the emergence of ice-free land (henceforth “land”) due to both the direct effect of ice margin retreat and the Earth system response to changes in ice loading, i.e., glacial isostatic adjustment (GIA). Regarding the latter, at the margin of a rapidly melting ice sheet, sea level will generally fall due to the combined impact of post-glacial uplift and the loss of gravitational attraction between the ice and the surrounding oceans (e.g., Farrell & Clark, 1976).

The emergence of land in Antarctica over the coming centuries will have wide-ranging environmental impacts and implications for mineral resource development prospects, both of which will play a key role in shaping Antarctic geopolitics. Antarctica’s terrestrial biodiversity is largely concentrated in ice-free areas (Chown & Convey, 2007; Lee et al., 2017; Tóth et al., 2025), and these regions are also of particular importance for geologic, fossil, and soil sampling (O’Neill et al., 2017; Cox et al., 2023). Furthermore, scientific research stations and associated infrastructure – including wharfs, roads, and airfields (CONMAP, 2017) – are commonly built on land: 81% of buildings in Antarctica are located on ice-free land, with 76% concentrated in ice-free areas within just 5 km of the coast (Brooks et al., 2019). Research stations are known to substantially impact their surrounding environment through contamination, habitat damage, and the introduction of non-native species (e.g., Tin et al., 2009; Aronson et al., 2011; Brooks et al., 2018). Finally, with the growing global demand for mineral resources (e.g., National Research

Council, 2008; Watari et al., 2020; Vidal et al., 2022), interest in mineral resource development of ice-free areas in Antarctica is likely to intensify (Foster, 2012; Rintoul et al., 2018).

Although the *Convention on the Regulation of Antarctic Mineral Resource Activity* was adopted by the Antarctic Treaty Parties in 1988, this agreement never came into force (Antarctic Treaty Secretariat, 1988; Jackson, 2021; Press & Jackson, 2024; Stephens, 2024). Subsequently, the *Protocol on Environmental Protection to the Antarctic Treaty* (also known as the Madrid Protocol), was adopted in 1991 and came into force in 1998. The Madrid Protocol – part of what has been called the Antarctic Treaty System – provides the current framework for comprehensive environmental protection in Antarctica (Antarctic Treaty Secretariat, 1991). This protocol had two main objectives: to establish an environmental protection regime and prohibit all activities related to mineral resource development in Antarctica indefinitely. The Madrid Protocol does, however, allow for activities related to mineral resources, as long as they are for scientific purposes (Article 7; Antarctic Treaty Secretariat, 1991).

Starting in 2048, any of the Antarctic Treaty Consultative Parties will be permitted to call for an Article 25 review conference of the Madrid Protocol (Antarctic Treaty Secretariat, 1991). Ratification of proposed modification(s) or amendment(s) to the Madrid Protocol requires the support of a majority of the Antarctic Treaty's Consultative Parties and support from three-quarters of the 26 Antarctic Treaty Consultative Parties that originally adopted the protocol (Article 25; Antarctic Treaty Secretariat, 1991). In order for modification(s) or amendment(s) to enter into force, all 26 Parties that originally adopted the Madrid Protocol must agree unanimously (Article 25; Antarctic Treaty Secretariat, 1991). Furthermore, any change to the restriction on mineral resource activities in Article 7 will not go into effect unless a new binding legal regime has already been ratified and entered into force (Article 25; Antarctic Treaty Secretariat, 1991).

Speculation on the prospect of mineral resource development in Antarctica will likely increase in the years preceding a possible review conference in mid-century, 2048. Growing interest in the mineral resource potential of Antarctica may spur calls to modify the Madrid Protocol to allow mineral resource development or, alternatively, motivate state or non-state actors to disregard the

Protocol altogether. An Article 25 review conference would also make it possible to review the Antarctic Treaty itself under Article XII (Antarctic Treaty Secretariat, 1959), which would likely be destabilizing to the entire Antarctic Treaty System (Press & Jackson, 2024). To anticipate the nature of these issues, it is important to explore projections of the spatio-temporal pattern of land emergence and the mineral resource potential of Antarctica. To this end, we present the first such projections over the next three centuries. We focus on emergent land with potential mineral deposits and the connection of these regions to the territorial claims of Argentina, Australia, Chile, France, New Zealand, Norway, and the United Kingdom.

Mineral resource potential of Antarctica

The current understanding of Antarctica's mineral resources remains limited, partly due to the Madrid Protocol's restriction of mineral-related activities to scientific purposes. However, mineral occurrences identified in select ice-free regions across the continent have established the presence of potentially valuable deposits, including copper, iron, gold, silver, platinum, and cobalt (Fig. 1; Guild et al., 1998; Crispini et al., 2011; Yaxley et al., 2013). Insight into potential mineral deposits in Antarctica can be gained by considering both the tectonic history of the continent and structure of the continental lithosphere, which we consider, in turn, below.

Antarctica had a central position in the Gondwanan sector of the Pangea supercontinent (e.g., Behrendt, 1983; Craddock, 1990; Wilsher & de Wit, 1990; Boger, 2011), and all continents that bordered Antarctica during this period are host to large mineral deposits, including Australia, Africa, South America, and Asia (Craddock, 1990). Since these continents share a similar geologic architecture, it is reasonable to assume that large mineral deposits also exist in Antarctica (Wilsher & de Wit, 1990). The spatial distribution of mineral deposits is generally governed by a combination of geological factors, including tectonic setting, structural controls, and lithology (e.g., Robb, 2020). Individual mineral deposits are commonly part of larger mineral belts, which align with major structure features, such as orogenic fold belts, or are associated with specific lithological units, such as greenstone belts (Goldfarb et al., 2001; Groves et al., 2005; Robb, 2020). Several Phanerozoic fold belts in Africa, Australia, India, and South America extend into Antarctica (Boger, 2011), and mineral belts associated with these structures are also likely to continue into Antarctica (e.g., Behrendt, 1983; Craddock, 1990, Wilsher & de

Wit, 1990). An example of such a continuation is found in the Transantarctic Mountains of northern Victoria Land. Antarctica was located on the active paleo-Pacific margin of Gondwana, and northern Victoria Land was, more specifically, located adjacent to southeastern Australia and New Zealand during the Paleozoic (e.g., Boger, 2011; Crispini et al., 2011). Mountain-building (orogenesis) and hydrothermal events along the active paleo-Pacific margin of Gondwana led to the formation of gold deposits (e.g., Goldfarb et al., 2001; Bierlein et al., 2004). The Dorn Gold Deposit located in northern Victoria Land has been linked to the same tectonic and geological processes that produced gold provinces in Australia, New Zealand, and Tasmania (Crispini et al., 2011).

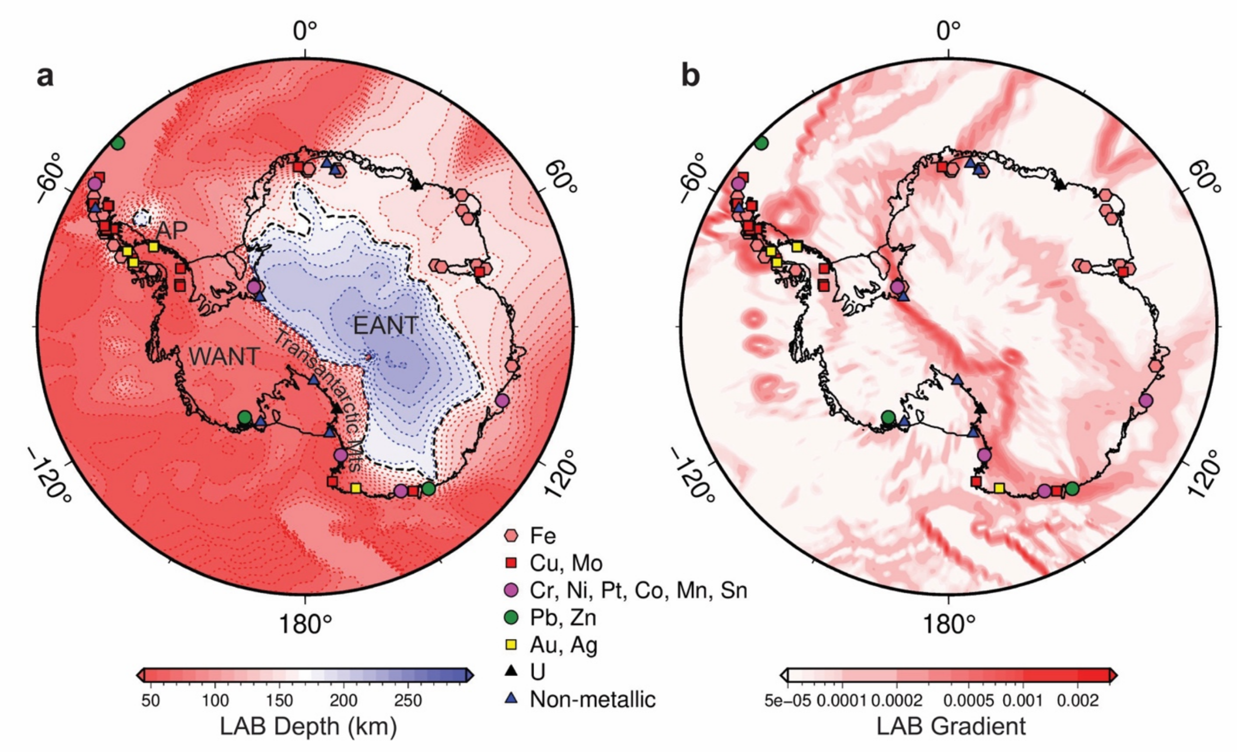

Fig. 2 | Lithospheric structure of Antarctica. a, Map of lithosphere-asthenosphere boundary (LAB) depth for Antarctica (An et al., 2015). Black dashed line contours 170-km LAB depth contour thickness. **b**, LAB gradient map based on **a**. Symbols, with legend at bottom center, indicate known mineral occurrences.

Potential mineral resources in Antarctica can also be inferred from existing constraints on solid Earth structure in Antarctica. Base metal deposits (copper, lead, zinc, nickel and associated byproducts) are broadly classified as being either sediment-hosted or magmatic-hosted, depending on whether their formation is primarily associated with sedimentary processes or magmatic activity. Globally, it has been shown that 85% of sediment-hosted base metal deposits (all containing at least 10 megatons of metal) are located within 200 km of the transition between thick and thin lithosphere (Hoggard et al., 2020). Likewise magmatic processes have also been invoked as a means to concentrate metals at the margins of thick lithosphere (Begg et al., 2010; Griffin et al., 2013; Chen et al., 2025) In Antarctica, significant base metal deposits are therefore most likely to be located adjacent to the Transantarctic Mountain front, in select sectors of East Antarctica, and offshore of the Antarctic Peninsula, all regions where transitions from thicker to thinner lithosphere occur (Fig. 2).

Although no proven oil or gas reserves have been identified in Antarctica, substantial resources are likely to exist in thick sedimentary basins offshore of the continent, including in the Ross Sea, Weddell Sea, and the East Antarctic margin (e.g., Behrendt, 1983; Kingston et al., 1991; Galushkin et al., 2018).

Land exposure due to Antarctic Ice Sheet retreat and sea level change

Over the next three centuries, land exposure will depend on the spatio-temporal pattern of ice sheet retreat and associated sea level changes. To estimate land exposure over the coming centuries, we compute sea level change for moderate and high Antarctic ice melt projections using a high-resolution global GIA model that incorporates realistic, 3-D variations in solid Earth viscoelastic structure (Latychev et al., 2005) (Methods; Extended Data Fig. 1). The GIA model solves for gravitationally self-consistent sea level changes for a specified space-time geometry of ice cover and solid Earth viscoelastic structure model, accounting for both migrating shorelines and Earth rotational effects (Kendall et al., 2005; Mitrovica et al., 2005; Mitrovica & Milne, 2003).

The moderate and high ice melt scenarios used in this study are from ice sheet simulations that applied ISMIP6 forcings from 2015 to 2100 (Seroussi et al., 2020; Nowicki et al., 2020) and were extended to 2300 using the MIROC4m climate model (Greve et al., 2023; Bakker et al., 2016) (Methods). We select two simulations from the ensemble of Greve et al. (2023) that represent moderate and high ice melt scenarios under the 21st century unabated warming pathway RCP 8.5 (CMIP5) / SSP5-8.5 (CMIP6). These two ice melt scenarios correspond to global mean sea level contributions of ~1.5 m (moderate ice melt) and ~3.3 m (high ice melt) by 2300. Ice sheet changes predicted by the Greve et al. (2023) simulations are characterized by significant retreat in West Antarctica and modest retreat elsewhere, consistent with other ISMIP6 ice sheet projections (Seroussi et al., 2024). Predicted sea level changes at 2100, 2200, and 2300, based on the 3-D Earth model and the two climate scenarios, reflect this geometry (Extended Data Fig. 2).

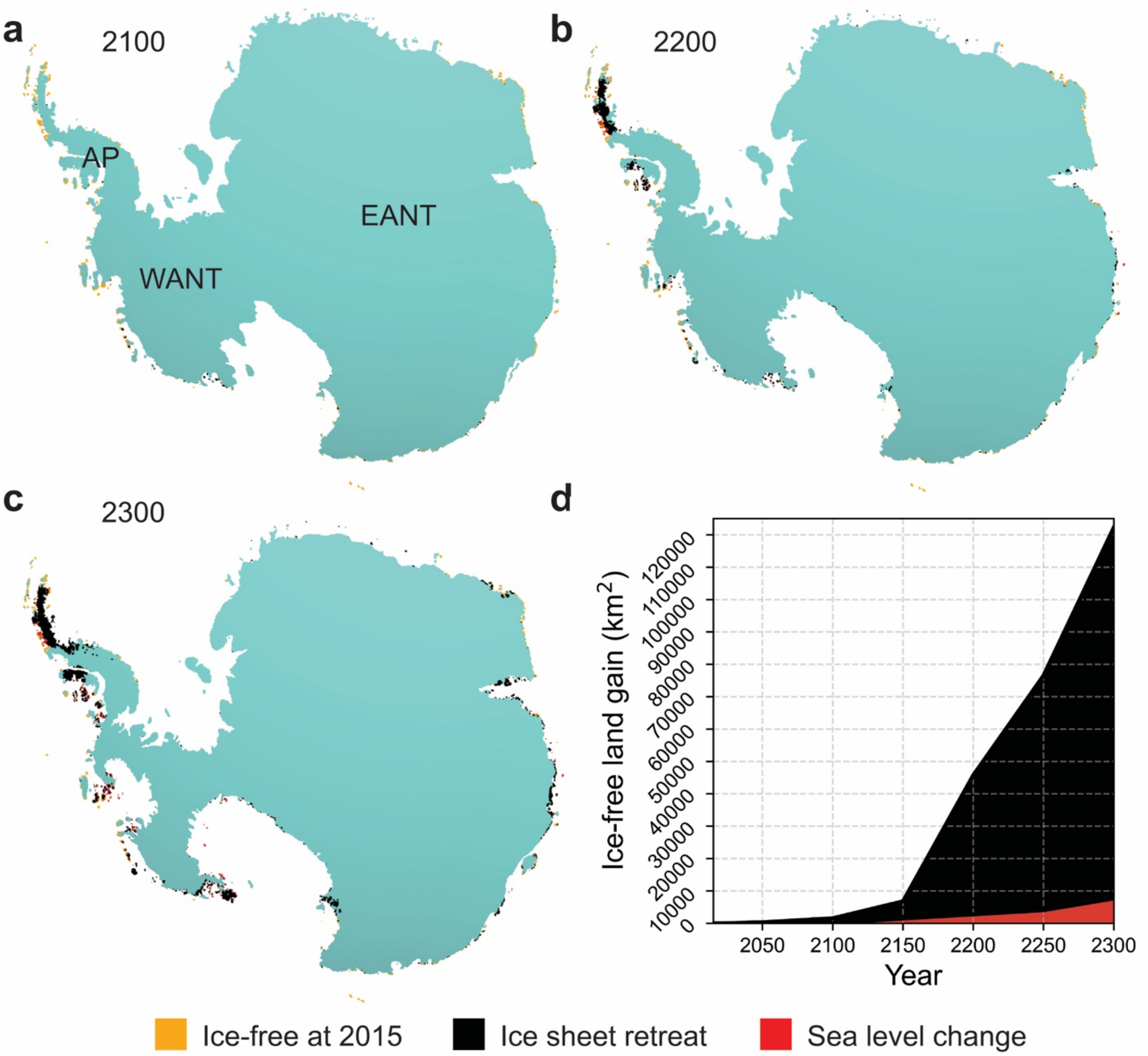

Fig. 3 | Land emergence for the high ice melt scenario. a-c, Projections of land emergence due to ice sheet retreat and sea level change for 2100, 2200, and 2300. The extent of grounded ice is shown in blue. Land area in 2015, calculated from the initial ice sheet extent of the adopted ice sheet model and high-resolution bedrock topography, is plotted in yellow ("Ice-free at 2015"). Note that we do not plot ice-free land observed at present as shown in Fig. 1; we only plot the change in ice-free land exposure due to ice sheet retreat and associated sea level change. **d**, Total land gains from 2015 through 2300. The contributions from ice sheet retreat and sea level change are plotted in black and red, respectively. Fig. 4 provides higher resolution plots in select regions for 2300. Extended Data Fig. 3 provides an analogous plot for the moderate ice melt scenario.

We predict that 36,812 km^2 and 121,844 km^2 of new land will emerge in Antarctica by 2300 due to the combined effects of ice retreat and sea level change for the moderate and high ice melt scenarios, respectively (Fig. 3; Extended Data Fig. 3; Extended Data Table 1). The upper bound represents a ~560% increase in land relative to the estimate of present-day ice-free land (21,745 km^2) reported by Burton-Johnson et al. (2016). A 210% increase in land area is projected under the same scenario for 2200, and a 6% increase is projected for 2100. Land emergence varies regionally over the next three centuries (Fig. 3; Extended Data Fig. 3). It is largest in West Antarctica over the remainder of this century, a region that is projected to gain 1,007 km^2 of land by 2100 in the high ice melt scenario. By 2200, land gains in the Antarctic Peninsula (37,911 km^2) far surpass those in West Antarctica (3,821 km^2) for the high ice melt scenario, and by 2300, land emergence reaches 76,097 km^2 in the Peninsula (Fig. 4b). Widespread land gains also occur in coastal East Antarctica in this case, particularly between Enerby Land and Queen Mary Land (Fig. 4c), reaching 17,469 km^2 by 2300.

Including the effects of sea level change in land gain estimates consistently results in larger projections of ice-free areas than estimates based on ice sheet retreat alone (Fig. 3; Extended Data Fig. 3; Methods). For the high ice melt scenario, 22% of the land exposed by 2150 results from sea level change (Fig. 3d). Under the moderate ice melt scenario, the relative contribution of sea level change to land exposure peaks in 2200, accounting for 24% of the land gain (Extended Data Fig. 3b, d). Despite the overall expansion in ice-free area, some regions experience localized land loss due to ice sheet advance or sea level rise. Up to 342 km^2 of land loss in such regions is predicted to occur by 2300. At the local scale, accounting for sea level change in projections of land emergence can cause smaller ice-free areas to coalesce into larger ones, often resulting in the formation of larger islands or peninsulas (Fig. 4b), as has been shown in other marine areas of the world (Tsuji et al, 2009).

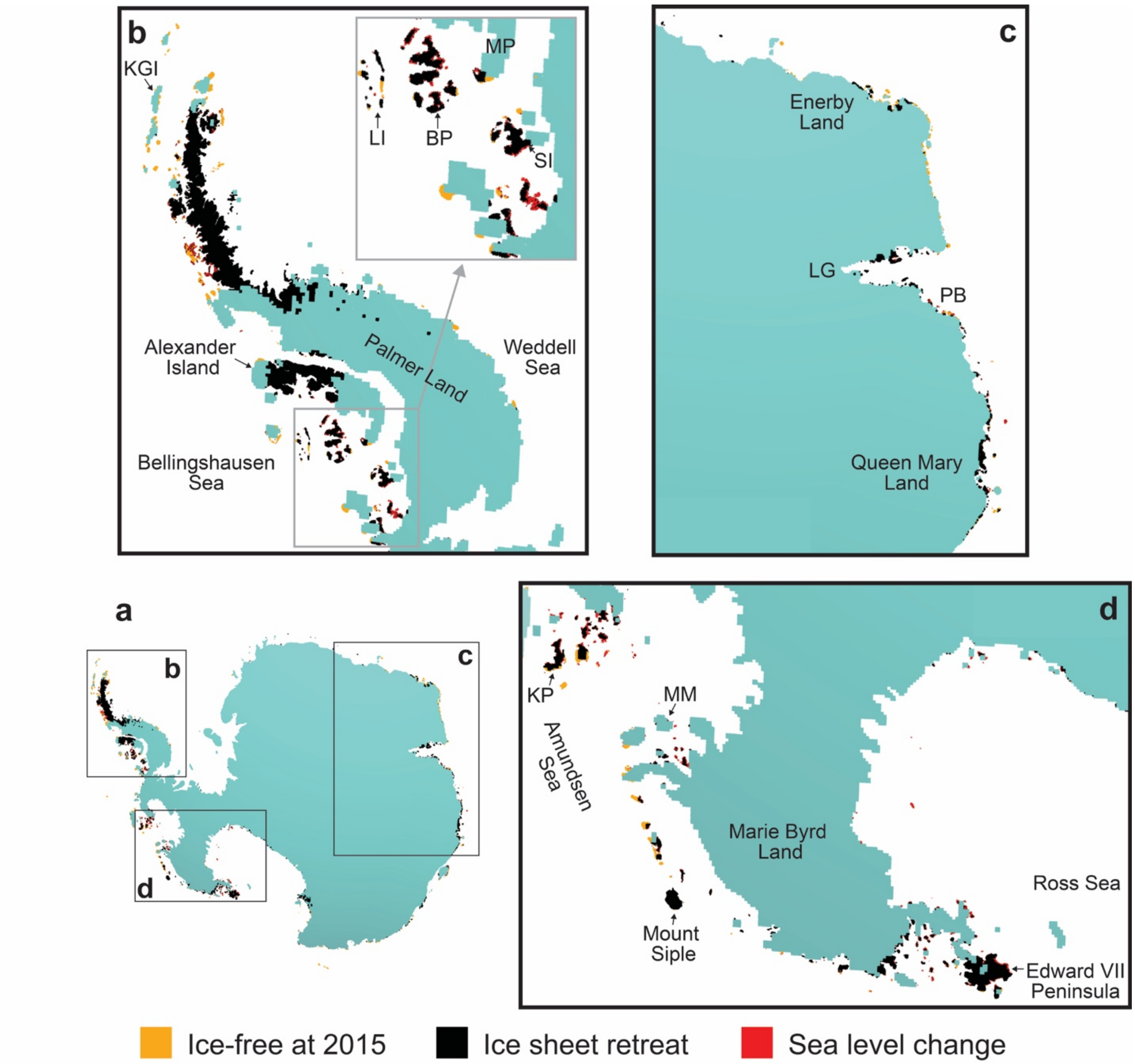

Fig. 4 | Regional-scale view of land emergence in 2300 for the high ice melt scenario. a, Map delineating regions shown in **b-d**. **b**, Land emergence in the Antarctica Peninsula at 2300. Labeled geographic features include King George Island (KGI), Beethoven Peninsula (BP), Monteverdi Peninsula (MP), Latady Island (LI), and Spaatz Island (SI). (c) Land emergence in a coastal sector of East Antarctica, with the Lambert Graben (LG) and Prydz Bay (PB) labeled. (d) Land emergence in the Ross Sea, Marie Byrd Land, and Amundsen Sea sectors of West Antarctica. Labeled geographic features include Mount Murphy (MM) and King Peninsula (KP). Extended Data Fig. 4 provides an analogous plot for the moderate ice melt scenario.

Land emergence in claimed territories

As the Antarctic Ice Sheet retreats over the coming centuries, the emergence of land may influence the willingness of Antarctic Treaty states, including those with and without territorial claims to advocate for mineral resource development in Antarctica. We contextualize projected land emergence within the framework of existing territorial claims in Figure 5, Extended Data Fig. 5, and Extended Data Table 2.

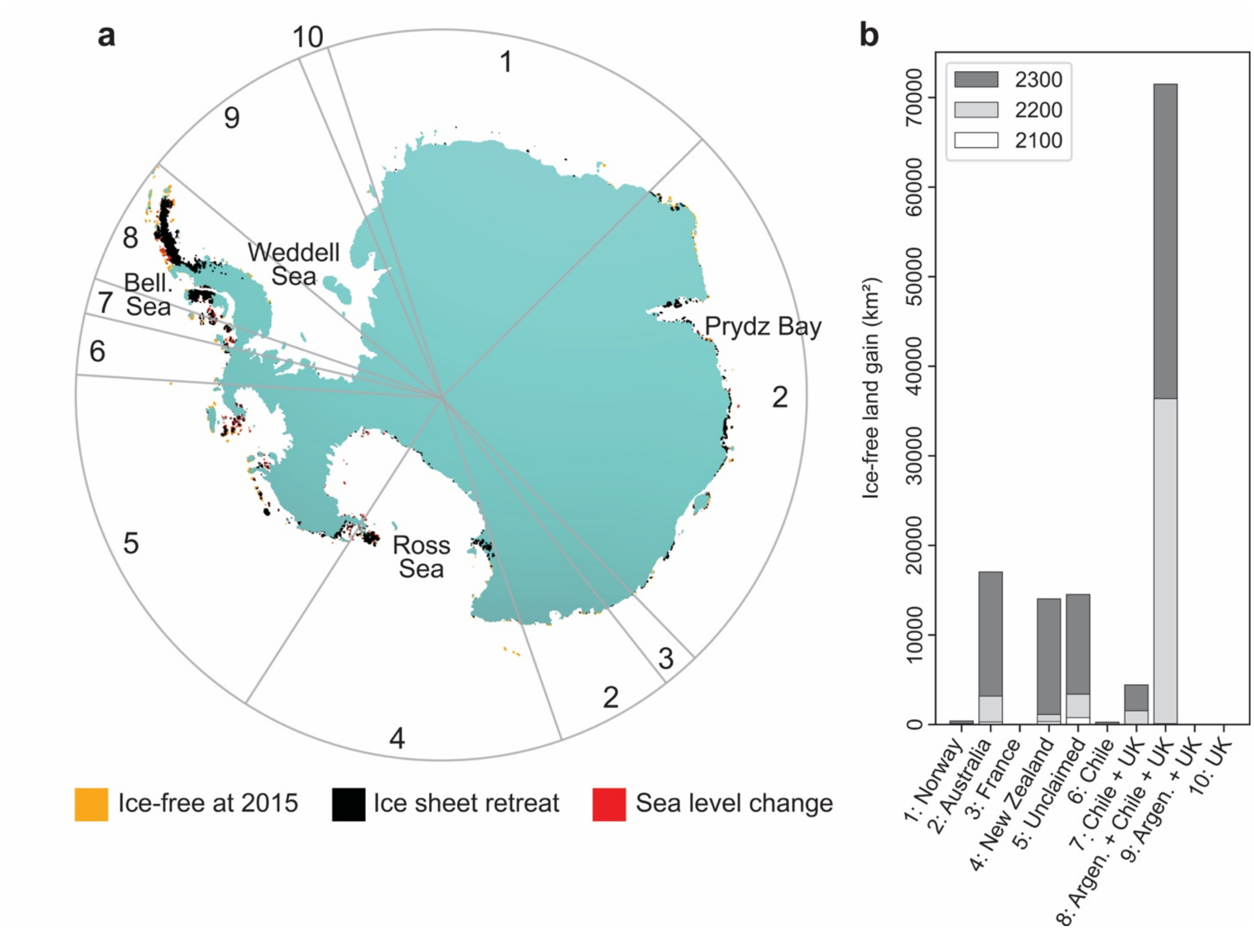

Fig. 5 | Land emergence in claimed territories for the high ice melt scenario. a, Land exposed in 2300 for the high ice melt scenario. Gray lines delineate sectors with territorial claims; numbers 1 through 10 correspond to countries or groups of countries labeled in the bar chart in **b**. Bellingshausen is abbreviated as "Bell.". **b**, Land emergence by claimed sector for 2100, 2200, and 2300. Extended Data Fig. 5 shows an analogous plot for the moderate ice melt scenario.

The largest land emergence across the continent is projected to occur in the sector of the Antarctic Peninsula that is claimed by Argentina, Chile, and the United Kingdom, with 36,330 km^2 of land gain by 2200 and 71,428 km^2 by 2300 for the high ice melt scenario (sector 8 in Fig. 5). Analogous figures for the moderate ice melt scenario are 3,076 km^2 and 33,832 km^2 (Extended Data Fig. 5). This sector hosts a broad range of mineral occurrences (Fig. 1), including copper, gold, silver, and iron, and together with its geological similarities to southern South America (Boger, 2011), suggests that land emergence within the sector will almost certainly expose additional deposits. We note that transitions from thinner to thicker lithosphere also occur in this sector (Hoggard et al., 2020; Figs. 1 and 2), further supporting this conclusion.

The Dufek Intrusion, a large layered mafic intrusion similar in structure to the Stillwater Complex (United States) and the Bushveld Complex (South Africa) (Ford, 1976; Jordan & Riley, 2024), is also situated in the territory claimed by Argentina, Chile, and the United Kingdom (Fig. 1). Layered mafic intrusions such as the Dufek Intrusion are of global interest for their potential to host platinum group elements (Begg et al., 2010); for example, ~70% of the world's platinum is currently mined from the Bushveld Complex (USGS, 2024). While our projections show limited land emergence in the Dufek Intrusion region by 2300, the projected retreat of the Filchner-Ronne Ice Shelf (Seroussi et al., 2024) and widespread land emergence on the nearby Antarctic Peninsula may enhance the logistical feasibility of mineral resource development in the region (Fig. 5).

Beyond the Antarctic Peninsula, notable land emergence is projected in territories claimed by Australia (16,972 km^2 gain in 2300) and New Zealand (13,890 km^2 gain in 2300) for the high ice melt scenario (Fig. 5; Extended Data Table 2). Copper and iron are the primary minerals that have been identified in Australia's claimed territory (Fig. 1). Continued land emergence may also expose new, potentially valuable mineral resources in the region. For example, New Zealand's claimed territory is situated near the strong transition in lithospheric thickness found along the Transantarctic Mountains front, making it possible that new mineral deposits will be exposed in the region by 2300 (Hoggard et al., 2020; Fig. 2). Finally, the Dorn Gold Deposit is located within the territory claimed by New Zealand (Crispini et al., 2011; Fig. 1, 5), yet new land emergence is not projected to occur near the location of the deposit.

Up to 14,518 km^2 of land is projected to emerge in the unclaimed territory of West Antarctica by 2300 in the high ice melt scenario (Fig. 5). Ice sheet retreat and associated sea level change will lead to widespread land emergence throughout the region, including the development of many new small islands in the Amundsen Sea and Ross Sea sectors (Fig. 4d). Given the region's prolonged magmatic history from early Jurassic through present (Jordan et al., 2020; Wilch et al., 2021; Lucas et al., in review), magmatic deposits likely exist in the unclaimed territory.

In addition to their effect on potential mineral resource activities, projected land emergence, ice shelf retreat, and changes in sea ice cover will likely ease challenges to hydrocarbon exploration and exploitation in Antarctica's thick sedimentary basins. These include prospective hydrocarbon deposits in the Weddell Sea, Ross Sea, Bellingshausen Sea, and near Prydz Bay (e.g., Behrendt, 1983; Kingston et al., 1991; Galushkin et al., 2018) – all areas of the continent that fall within territories claimed by Argentina, Australia, Chile, New Zealand, and the United Kingdom (Fig. 5).

Conclusions

With the accelerating global demand for critical mineral resources (Rowan, 2025), land emergence in Antarctica over the next three centuries may spark increased interest in mineral resource development on the continent. Newly exposed land will almost certainly reveal previously unidentified mineral deposits. Moreover, by increasing areas suitable for constructing infrastructure, land emergence will also reduce logistical barriers that currently limit the economic viability of mineral resource development in Antarctica. A given state's interest in advocating for mineral resource development in Antarctica may be linked to whether it holds a territorial claim, the economic value of mineral resources within that claimed territory, and the extent of land emergence. However, this interest may also come from states without territorial claims – such as, world superpowers, the United States, Russia, and China – or even non-state actors. In addition, geopolitical tensions are likely to rise, particularly concerning areas such as the Antarctic Peninsula and Weddell Sea sector, where territorial claims by Argentina, Chile, and the United Kingdom overlap.

Since 1998, the Madrid Protocol has prohibited all activities related to mineral resource development in Antarctica. However, looking ahead – especially to 2048, when any of the Consultative Parties to the Antarctic Treaty will be permitted to call for a review of the Madrid Protocol – the question of mineral resource development in Antarctica is likely to energetically resurface. Antarctica remains the only continent on which mineral resource development has not occurred. Whether this continues to be the case, and whether the spirit and intent of the Madrid Protocol remain intact, will be a complex issue. In a progressively warming world, where emergent mineral resources in Antarctica may become economically viable, the substantial environmental impacts of mineral exploitation will need to be measured against the necessity of developing mineral deposits important for sustainable development and the clean energy transition.

Online Methods

1. 3-D earth model and ice models adopted in GIA simulations

The GIA model used in this study requires two key inputs: a viscoelastic Earth model and a model of spatio-temporal variations in ice cover (i.e., ice model). The Earth model includes an elastic lithosphere with variable thickness and a mantle with laterally varying viscosity (Extended Data Fig. 1). Variations in lithospheric thickness are based on the model of An et al. (2015) in Antarctica and the model of Conrad & Lithgow-Bertelloni (2006) globally (Extended Data Fig. 1). Following Hay et al. (2017), lithospheric thickness is scaled to have an average value of 96 km in Antarctica, with a minimum thickness of 40 km. As described in detail by Lucas et al. (2025), mantle viscosity variations are based on the ANT-20 shear-wave seismic model (Lloyd et al., 2020) for the upper mantle beneath Antarctica and the GLAD-M25 shear wave model (Lei et al., 2020) across the rest of the globe (Extended Data Fig. 1). Mantle viscosity variations are superimposed on a 1-D reference viscosity profile, which has viscosities of 5×10^{20} Pa s and 5×10^{21} Pa s in the upper and lower mantle, respectively. The elastic and density structure of the Earth model varies radially and is based on the STW105 seismic tomography model (Kustowski et al., 2008). GIA simulations are performed on a global tetrahedral grid with a surface resolution of ~7 km over the Antarctic continent and ~12-15 km globally using Seakon software (Latychev et al., 2005).

We compute relative sea level changes for moderate and high Antarctic ice melt scenarios from simulations with the SICOPOLIS ice sheet model (Greve et al., 2023). SICOPOLIS adopts shallow-ice-'shelfy'-stream dynamics for grounded ice and shallow-shelf dynamics for floating ice (SICOPOLIS Authors, 2021). Horizontal resolution in the SICOPOLIS ice sheet simulations is 8 km, which is sufficient to capture grounding line migration dynamics (Gladstone et al., 2017; Chambers et al., 2022).

Our estimates of land exposure do not account for sea level changes resulting from ice loading changes following the Last Glacial Maximum (LGM). Estimates of relative sea level change and vertical crustal motion associated with ice loading changes since the LGM differ widely in the literature (e.g., Argus et al., 2014; van der Wal et al., 2015; Whitehouse et al., 2012; Ivins et al., 2013; Peltier et al., 2015; Gomez et al., 2018), and there remains significant uncertainty in ice loading changes in Antarctica throughout the Late Pleistocene and Holocene (e.g., Siegert et al., 2013; Bradley et al., 2015; Johnson et al., 2022; Balco et al., 2023). Present-day vertical motion rates associated with ice loading changes since the LGM generally range from -3 mm/year to 11 mm/year (e.g., Argus et al., 2014; van der Wal et al., 2015; Whitehouse et al., 2012; Ivins et al., 2013; Peltier et al., 2015; Gomez et al., 2018). Over the ~300-year period considered in this study, these vertical crustal motion rates correspond to maximum of ~3 m of crustal deformation due to GIA from post-LGM ice loading changes. These sea level changes are small relative to the projections in Extended Data Fig. 2 and would thus have a minor impact on our estimates of land exposure.

2. Computing ice-free land exposure

We determine ice-free land exposure by adding modeled topography changes (negative sea level changes) at selected times of interest to initial bedrock topography and checking that the area is both above sea level and free of grounded ice. The initial bedrock topography at the start of simulations is based on the 30 arc-sec resolution ETOPO2022, which adopts BedMachine bedrock topography in Antarctica (MacFerrin et al., 2024; Morlighem et al., 2020). The initial bedrock topography, along with the grounded ice extent (8 km resolution) and modeled sea-level changes (~7 km resolution) at selected times of interest, are all interpolated onto a common, near-uniform ~1 km spherical triangular grid covering the Antarctic domain prior to the computation of ice-free land area.

Further, it will be helpful to define a mask operator on that grid acting on a field *F:*

$$M(F) = 1 \; if \; F > 0,$$
$$M(F) = 0 \; if \; F \leq 0.$$

At some time, *t*, the ice-free land mask can be expressed as

$$L(t) = M[T(t)] * \left[1 - M\big(IAF(t)\big)\right],$$

where *T* and *IAF* are topography and ice above floatation, respectively. The spatial extent of ice-free land changes, *dL(t)*, with respect to the reference time, t_{ref}, at time, *t,* is then simply:

$$dL(t) = L(t) - L\big(t_{ref}\big).$$

Note that *dL*>0 corresponds to a land gain resulting from either ice retreat or sea level fall, while *dL*<0 corresponds to a land loss resulting from either ice advance or sea level rise. To single out the contribution of sea level change alone to the above expression at time t, set *IAF=IAF(t)* and obtain:

$$dD(t) = \left[M[T(t)] - M\big(t_{ref}\big)\right] * \left[1 - M[IAF(t)]\right].$$

We show positive *dD(t)* in red in Figs. 3-5 and Extended Data Figs. 3-5. The difference $dL - dD$ is the contribution to ice-free land change due to ice retreat, shown in black in Figs. 3-5 and Extended Data Figs. 3-5.

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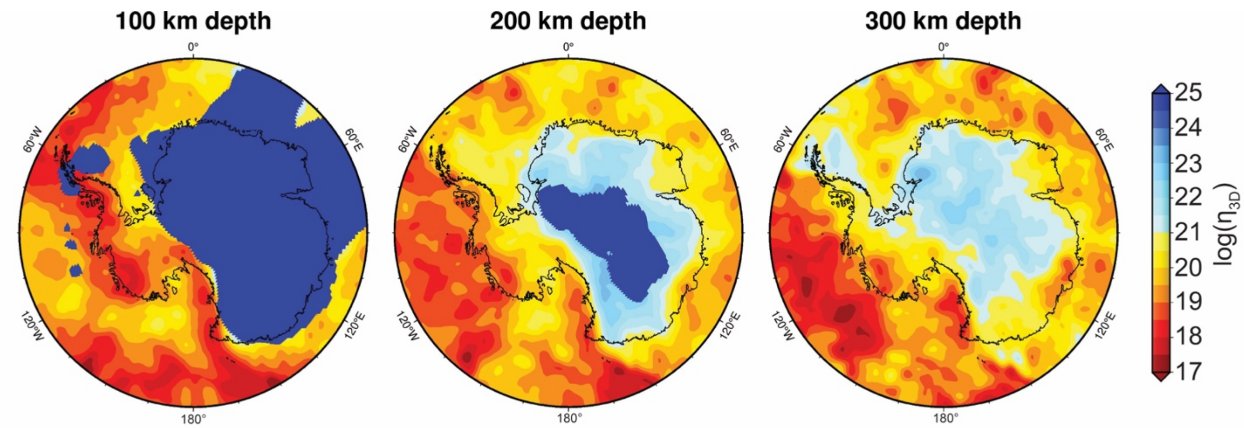
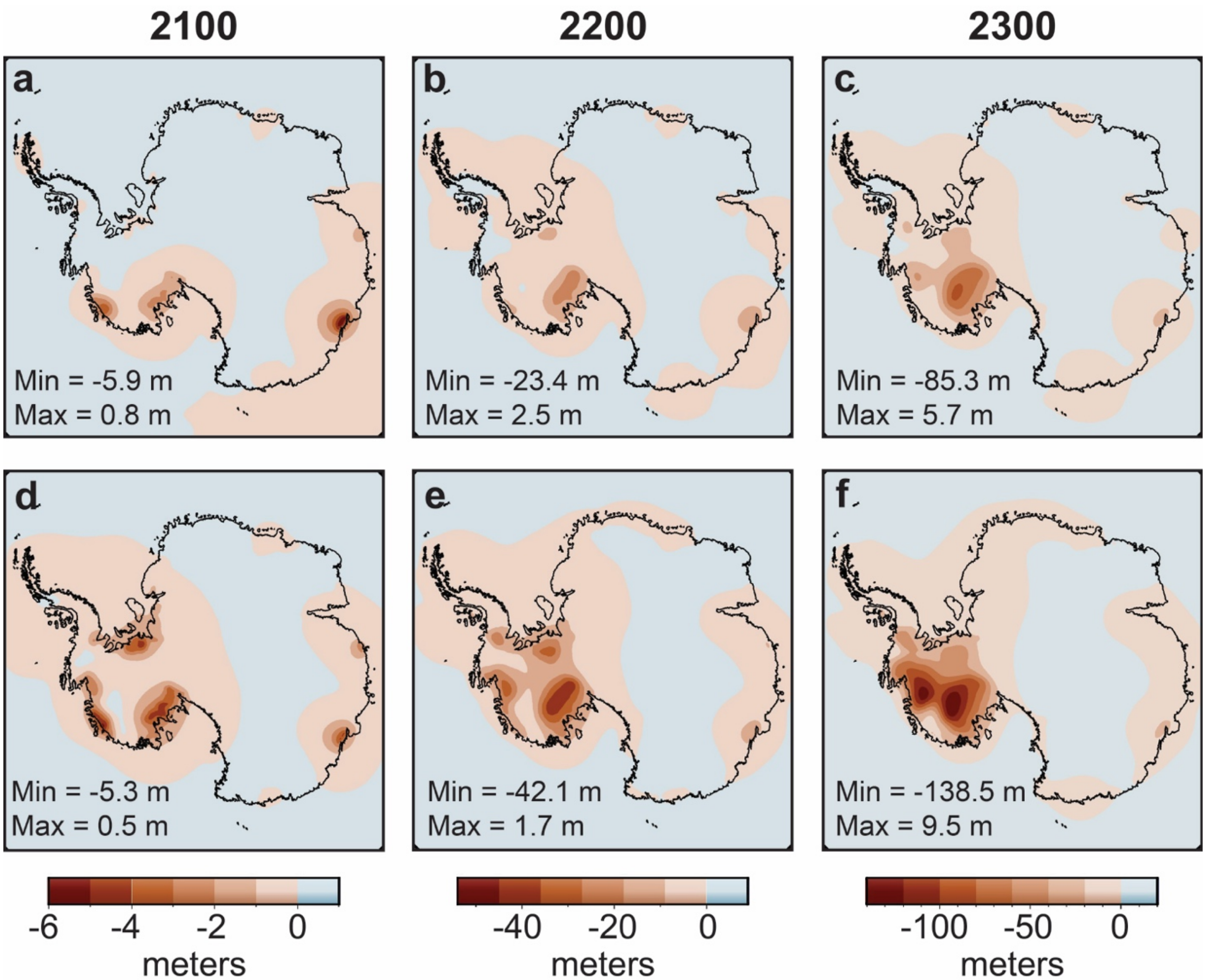
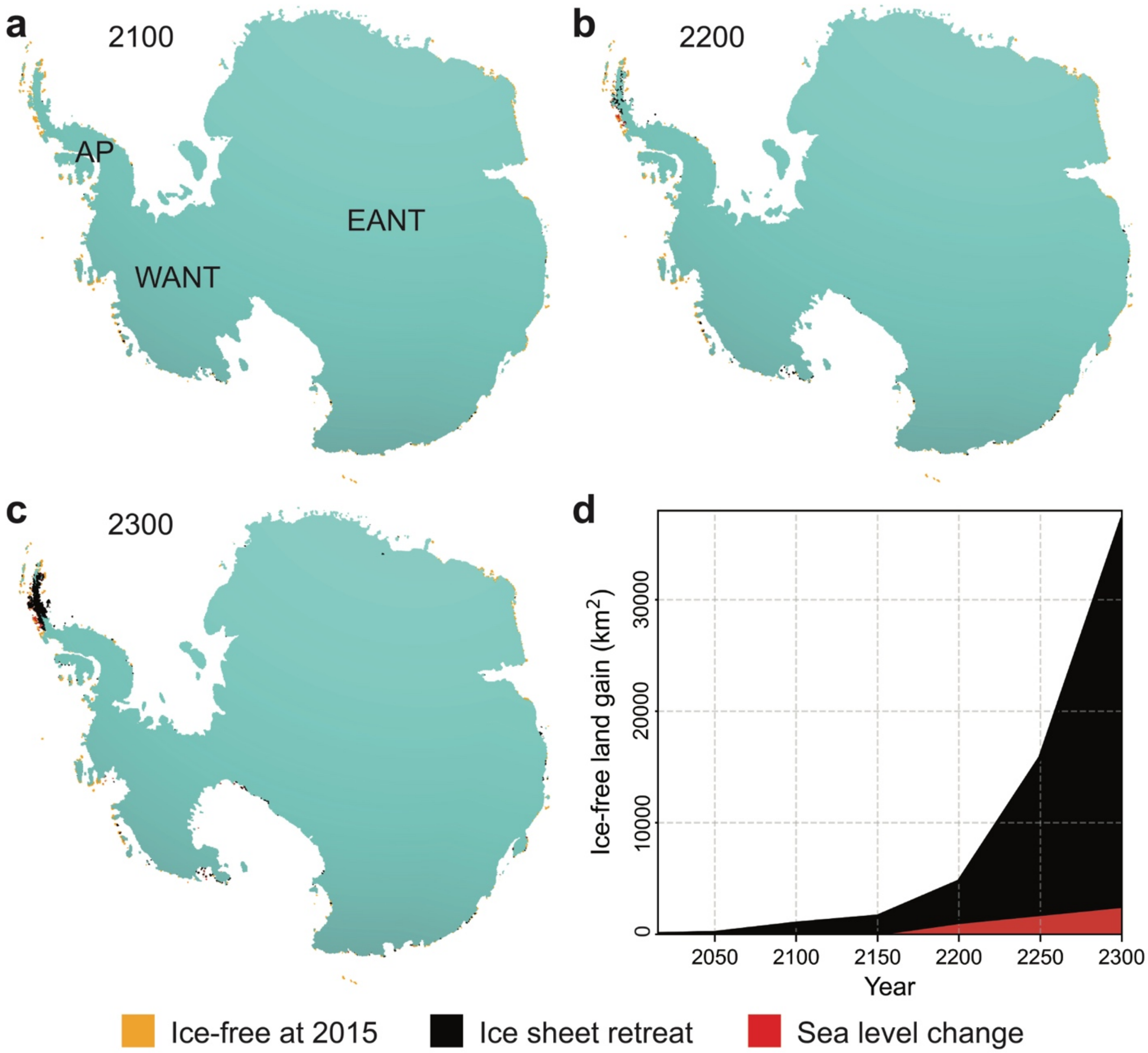
Extended Data Figures



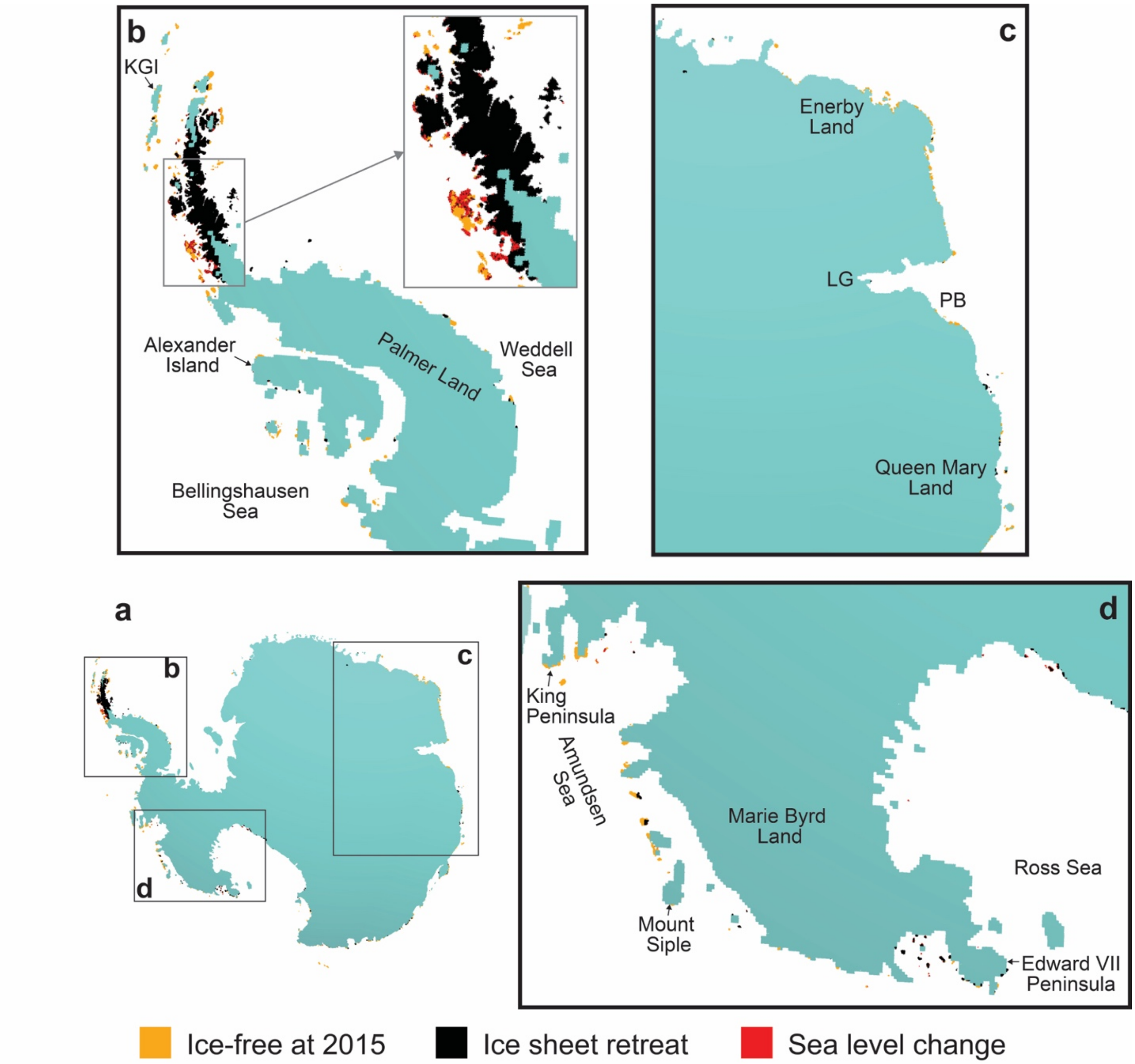
Extended Data Fig. 1 | 3-D Earth model used for GIA simulations. Mantle viscosity at 100 km, 200 km, and 300 km depth. The lithosphere, based on the model of An et al. (2015), extending to 100 km and 200 km depth is shown in saturated dark blue.



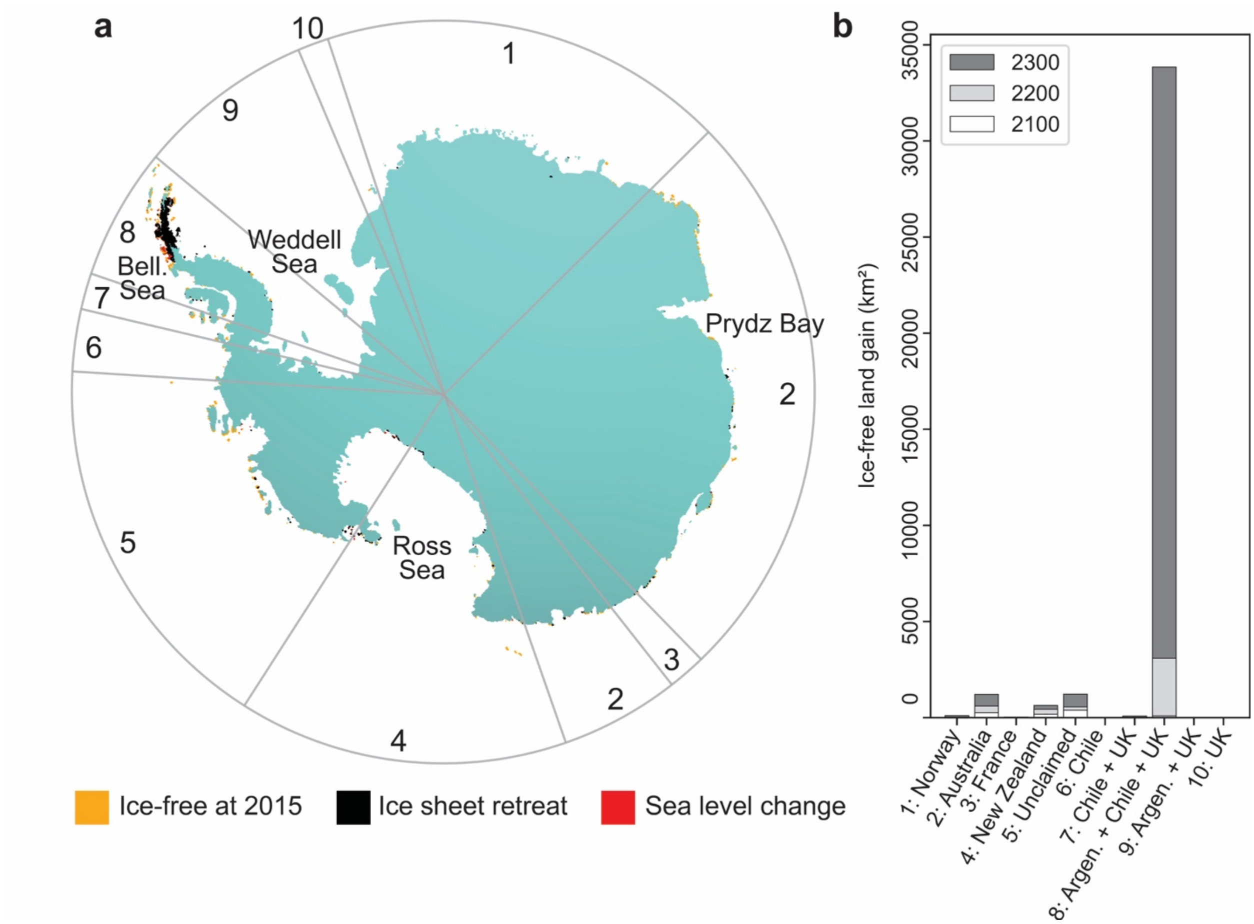
Extended Data Fig. 2 | Relative sea level change from 2015 for the **a-c** moderate ice melt and **d-f** high ice melt scenarios.



Extended Data Fig. 3 | Land emergence for the moderate ice melt scenario. **a-c**, Projections of land emergence due to ice sheet retreat and sea level change for 2100, 2200, and 2300. The extent of the grounded ice is shown in light blue. Land area in 2015, calculated from the initial ice sheet extent of the adopted ice sheet model and high-resolution bedrock topography, is also plotted. **d**, Total ice-free area gains from 2015 through 2300. The contributions from ice sheet retreat and sea level change are plotted in black and red, respectively. Extended Data Fig. 4 provides higher resolution plots in select regions for 2300.



Extended Data Fig. 4 | Regional-scale view of land emergence by 2300 for the moderate ice melt scenario. **a**, Map delineating regions shown in **b-d**. **b**, Ice-free land in the Antarctica Peninsula at 2300. King George Island (KGI) is labeled. **c**, Land emergence in a coastal sector of East Antarctica, with the Lambert Graben (LG) and Prydz Bay (PB) labeled. **d**, Land emergence in the Ross Sea, Amundsen Sea, and Marie Byrd sectors of West Antarctica.



Extended Data Fig. 5 | Land emergence in claimed territories for the moderate ice melt scenario. **a**, Land exposed at 2300 for the moderate ice melt scenario. Gray lines delineate sectors with territorial claims; numbers 1 through 10 correspond to countries or groups of countries labeled in the bar chart in **b**. **b**, Land emergence by claimed region for the years 2100, 2200, and 2300.

Extended Data Table 1 | Land emergence for the high and moderate ice melt scenarios.

	High ice melt		**Moderate ice melt**	
Year	Total ice-free area gain (km^2)	Ice-free area gain from sea level change (km^2)	Total ice-free area gain (km^2)	Ice-free area gain from sea level change (km^2)
2050	158	0	70	0
2100	1,364	38	915	-6
2200	45,597	2,733	4,586	1,080
2300	121,844	7,481	36,812	2,487

Extended Data Table 2 | Land emergence by sectors with territorial claims for the high and moderate ice melt scenarios. The number following each country or group of countries in the first column corresponds to the numbering used in Fig. 5 and Extended Data Fig. 5.

	High ice melt			**Moderate ice melt**		
Country	**2100**	**2200**	**2300**	**2100**	**2200**	**2300**
Norway (1)	0	100	390	0	1	107
Australia (2)	276	3,151	16,972	233	573	1,011
France (3)	19	19	48	19	19	30
New Zealand (4)	320	1,114	13,890	178	437	636
Unclaimed (5)	769	3,385	14,518	390	469	1,103
Chile (6)	2	2	263	1	2	9
Chile + UK (7)	-66	1512	4,403	13	13	84
Argentina + Chile + UK (8)	46	36,330	71,428	82	3,076	33,832
Argentina + UK (9)	0	3	8	0	0	4
UK (10)	0	0	-54	0	0	0