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SESSION 15

ICE SHEET-SOLID EARTH INTERACTIONS: GIA, LANDSCAPE EVOLUTION AND GEOTHERMAL HEAT FLUX

INTERNATIONAL SCIENCE COUNCIL SCAR SCIENTIFIC COMMITTEE ON ANTARCTIC RESEARCH

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Geothermal heat flow in Antarctica: current and future directions

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This presentation introduces the different methods applied to derive Antarctic geothermal heat flow (GHF), their advantages and limitations, and recommendations for future directions.

Antarctic GHF affects the temperature of the ice sheet, determining its ability to slide and internally deform, as well as the behaviour of the continental crust. However, GHF remains poorly constrained, with few and sparse local, borehole-derived estimates, and large discrepancies in the magnitude and distribution of existing continent-scale estimates from geophysical models. We review the methods to extract GHF, present a compilation of borehole and probe-derived estimates from measured temperature profiles, and recommend the following future directions: 1) Obtain more borehole-derived estimates from the subglacial bedrock and englacial temperature profiles. 2) Estimate GHF beneath the interior of the East Antarctic Ice Sheet (the region most sensitive to GHF variation) via long-wavelength microwave emissivity. 3) Estimate GHF from inverse glaciological modelling, constrained by evidence for basal melting. 4) Revise geophysically-derived GHF estimates using a combination of Curie depth, seismic, and thermal isostasy models. 5) Integrate in these geophysical approaches a more accurate model of the structure and distribution of heat production elements within the crust, and considering heterogeneities in the underlying mantle. And 6) continue international interdisciplinary communication and data access.

Associated Paper:

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Re-evaluating the elastic response to ice mass change in Antarctica

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Present-day mass loss across Antarctica evokes an instantaneous, elastic deformational response of the solid Earth. In regions such as the northern Antarctic Peninsula and the Amundsen Sea Embayment, elastic uplift rates at GNSS sites reach up to 7-10 mm/yr, or up to~30-45% of the observed uplift rate. In glacial isostatic adjustment (GIA) studies, this elastic response is often modeled and removed from the observed deformation, and the viscous component, inferred to be the residual deformation, is used for constraining mantle viscosity. Because the inferred viscous deformation depends on the accurate modelling of the elastic component, biases and uncertainties in the latter directly impact conclusions on the mantle's rheology. Often elastic deformation is modeled using a 1D Earth with parameters defined by a seismic velocity model, typically a globally averaged reference such as PREM or STW05. Regional differences from the global reference and 3D departures from the 1D profile result in biases and uncertainties in the modeled deformation that remain poorly understood. Additionally, coarse ice-load grids often used for modelling Antarctic-wide elastic deformation may not resolve changes of some rapidly changing glaciers and ice streams, potentially resulting in under predictions of elastic deformation rates. We quantify these uncertainties and their impact on GIA studies using an ensemble of 1D elastic structures sampled from density and seismic velocity models of Antarctica's crust and upper mantle with a combination of 10km resolution continent-wide ice mass balance estimates and new, high resolution ice mass balance estimates of the Amundsen Sea region.

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Magnetic and gravity views reveal intra-crustal heterogeneity in the Wilkes Subglacial Basin of East Antarctica

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The Wilkes Subglacial Basin (WSB) is a major intraplate tectonic feature in East Antarctica. Recent modelling of its subice topography lends support to a long-standing hypothesis predicting that the wide basin is linked to flexure of Precambrian cratonic lithosphere induced by the Cenozoic uplift of the adjacent Trasantarctic Mountains. However, potential field and radar exploration suggest that its narrower structurally controlled sub-basins may have formed in response to more localised Mesozoic to Cenozoic extension and transtension and superimposed Cenozoic glacial erosion.

Here we exploit new enhanced aerogeophysical and satellite gravity gradient imaging to reveal the 4D heterogeneity in the crust beneath the WSB. By stripping out the effects of crustal and lithosphere thickness variations we obtain residual intra-crustal gravity anomalies that are compared with enhanced aeromagnetic anomaly images. Depth to magnetic and gravity source estimates help constrain the first combined 2D magnetic and gravity models for the WSB.

Our first model reveals the lithospheric scale boundary along the eastern margin of the northern WSB that separates the Cambro-Ordovician Ross Orogen from an inferred Precambrian Wilkes Terrane. Further south the Precambrian basement appears to be both shallower and more felsic.

We conclude that these first order differences in basement depth, bulk composition and thickness of metasediment/sediment cover are likely to also affect geothermal heat flux variability beneath different sectors of the WSB, with potential cascading effects on subglacial hydrology and East Antarctic Ice Sheet flow.

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4D Antarctica: a new effort aims to help bridge the gap between Antarctic crust and lithosphere structure and geothermal heat flux

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Seismology, satellite-magnetic and aeromagnetic data, and sparse MT provide the only available geophysical proxies for large parts of Antarctica's Geothermal Heat Flux (GHF) due to the sparseness of direct measurements. However, these geophysical methods have yielded significantly different GHF estimates. This restricts our knowledge of Antarctica's contrasting tectono-thermal provinces and their influence on subglacial hydrology and ice sheet dynamics.
For example, some models derived from aeromagnetic data predict remarkably high GHF in the interior of the West Antarctic Rift System (WARS), while other satellite magnetic and seismological models favour instead a significantly colder rift interior but higher GHF stretching from the Marie Byrd Land dome towards the Antarctic Peninsula, and beneath parts of the Transantarctic Mountains. Reconciling these differences in West Antarctica is imperative to better comprehend the degree to which the WARS influences the West Antarctic Ice Sheet, including thermal influences on GIA. Equally important, is quantifying geothermal heat flux variability in the generally colder but composite East Antarctic craton, especially beneath its giant marine-based basins.
Here we present a new ESA project- 4D Antarctica that aims to better connect international Antarctic crust and lithosphere studies with GHF, and assess its influence on subglacial hydrology by analysing and modelling recent satellite and airborne geophysical datasets. The state of the art, hypotheses to test, and methodological approaches for five key study areas, including the Amundsen Sea Embayment, the Wilkes Subglacial Basin and the Totten catchment, the Recovery and Pensacola-Pole Basins and the Gamburtsev Sublgacial Mountains/East Antarctic Rift System are highlighted.

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Temporal and environmental constraints on the eruption history of Gaussberg Volcano

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Subglacial volcanic eruptions can have significant impact on ice sheet behavior and/or volume via short-term melting of ice and longer time-scale effects on regional geothermal heat flow, surface uplift and subsidence through time. Gaussberg volcano, located on the coast of East Antarctica at 89°19'E is an ice-free, glacially eroded, pillow-dominated, cone-shaped edifice that rises 370 m absl. Gaussberg volcano is the only confirmed volcano within this sector. Gaussberg volcano is suspected to have erupted entirely beneath ice.

Past research has focused on determining magma source and genesis. The timescale of volcanism is uncertain as a broad range of ages for the lavas (~56 ka, 9 Ma and 20 Ma) have been produced by K/Ar isotopic techniques. It is also unclear if Gaussberg is one edifice or an edifice that has been constructed within the remnants of earlier eruptive phases.

In this study we aim to constrain the age and environment of eruption of Gaussberg volcano using legacy samples originally collected by Sheraton and Ellis (ANARE 1977). The samples are ultrapotassic (11.7-12.1 K2O%) olivine-bearing lamproite lavas mainly comprising leucite, clinopyroxene and glass. We provide a new chronology of eruption using 40Ar/39Ar technique applied to leucite (20.5-21.7 wt% K2O). The volatile contents (H2O) of volcanic glass measured with Fourier-transform infrared spectroscopy will constrain the quench pressures of lavas and hence the thickness of overlying ice at time of eruption. We expect these new constraints on phases of volcano growth and paleoenvironment can inform Antarctic heat flow and ice sheet models.

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Absolute gravity measurements at Jang Bogo station and Mario Zucchelli station in Antarctica

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Using the FG5#210, we have conducted absolute gravity measurements at Jang Bogo station and Mario Zucchelli station in Terra Nova Bay. Jang Bogo station is a South Korean Antarctic research station which has been operated since 2014. There is a gravity point named JBSAG1 and we conducted the measurements at JBSAG1 from 17 to 24 November 2019. Since the JBSAG1 is located at the bottom of the narrow maintenance bay with the depth of about 1 meter, the vertical gravity gradient at the point is not linear w.r.t the height. This may cause additional errors for the comparison of the gravity values obtained by different types of gravimeters. We thus established another gravity point named JBSAG2 on the flat floor near JBSAG1 and conducted the measurements from 25 to 27 November. The precisions of these measurements were better than 0.4 micro gals.
In Mario Zucchelli station, there are two gravity points named TNB AB and IAGS where absolute gravity measurements have been repeatedly conducted thus far. We conducted the measurements at TNB AB from 30 November to 2 December, and from 3 to 5 December at IAGS. The measurements at both points were conducted with the measurement precision of less than 0.4 micro gals.
In this presentation, we report the outline of the measurements and the preliminary results.
This study was partially supported by JSPS KAKENHI Grant No. 17H06321.

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Antarctic Ice Sheet stability and its sensitivity to evolving bedrock topography and climate forcing

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Reproducing the large-scale oscillations in Antarctic ice volume that have been interpreted from ocean sediment cores has long proved challenging for ice sheet modelling studies. This is due to strong stabilising climate feedbacks following the growth of a continental sized ice sheet. Recent work to resolve this model-data disagreement has focused on the marine-based sectors of the ice sheet, which are vulnerable to marine ice sheet instabilities and potentially the recently proposed marine ice cliff instability. However, the larger scale changes in the Oligocene and Miocene (with some estimates of oscillations equivalent to 85–110% of the modern-day ice volume), requires substantial loss of terrestrially-based Antarctic ice. Additionally, recent reconstructions of the Antarctic bedrock topography suggest that the marine-sectors of Antarctica were less extensive in the past. This also supports a greater role for retreat of the terrestrially-based Antarctic Ice Sheet in the past. Here we explore how changes in bedrock topography affect ice sheet stability. We also explore how recent climate model simulations that have a greater polar amplification than earlier models affect the ability to simulate Antarctic Ice Sheet change consistent with the geological records.

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Thermal structure and heat flux of the Antarctic lithosphere

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Geothermal heat flux strongly influences ice temperature, viscosity and water content, as well as basal melting, which in turn determines the deformation response of ice under stresses applied by the overlying ice column. Therefore, high quality maps of geothermal heat flux are crucial when monitoring ice dynamics, shape and mass balance of the Antarctic Ice Sheet. Since direct measurements are sparse because of the large ice thicknesses, other solid earth models are necessary to estimate the heat flux. We determine the geothermal heat flux over the Antarctic continent based on a 3D thermal model of the lithosphere, obtained from seismic tomography using a mineral physics approach, and corrected for compositional changes through a joint inversion with gravity data in an iterative scheme. Since this model only provides reliable relative temperature variations but is somewhat biased in the absolute values, we calibrate it using standard geotherms for well-studied cratons for each depth layer, taking into account the non-linear relationship between velocity and temperature. The resulting model provides accurate temperature variations as well as consistent absolute temperatures within each layer. The lower boundary of the thermal lithosphere, defined here as the 1300°C isotherm, is found to lie around 100km in West Antarctica while extending down to almost 300km in East Antarctica. The resulting lithospheric heat flow also shows a clear distinction between East and West Antarctica with locally elevated fluxes in the Antarctic Peninsula and beneath the Ross Ice Shelf.

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Introducing "PetroChron Antarctica": A new geological database for interdisciplinary use

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It is increasingly clear that the Antarctic lithosphere has complex interactions with the oceans and cryosphere. A deeper understanding of these interactions depends on the ability to integrate large multidisciplinary datasets. However, global geological datasets are commonly discipline-specific, and Antarctic datasets are poorly represented.

We introduce a new relational database “PetroChron Antarctica” housing both geochemical and geochronology datasets from geological samples across Antarctica (south of 60°). Data are sourced from various existing databases (e.g. GEOROC, DateView, Petlab) and more than 350 individual publications. Also included are a range of geochemical indices, naming schema, and physical property estimates. Information is compiled in a standardised format for reliability and comparability. To increase filtering capability, this database has a relational structure containing numerous sub-tables adapted from the recently released global geochemical database (Gard, M., Hasterok, D., Halpin, J.A., 2019. Global whole-rock geochemical database compilation. Earth Syst. Sci. Data 11, 1553-1566.).

PetroChron Antarctica is an open-access public database. Data can be displayed and explored using the ESRI Online Web Feature Service, and can be readily integrated with other Antarctic geological and geophysical datasets (e.g. GeoMAP). Datasets will be available for download in a .csv format, but exist in a structure format acceptable for database management systems (e.g. SQL).

We hope that PetroChron Antarctica will lead to new understandings in the Antarctic geosciences (e.g., tectonic evolution, heat flow, landscape evolution) and have application across other scientific fields (e.g., ice sheet history, soil chemistry, biodiversity). We encourage contributions and feedback from the Antarctic community.

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Geothermal Heat Flux estimates from Thermal Isostasy

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Geothermal heat flux (GHF) is a necessary boundary condition for developing accurate dynamic glacial models, but GHF is poorly constrained. GHF estimates from seismic and magnetic-based methods show poor correlation to each other and to GHF constraints provided by observations on conjugate margins. This poor performance is likely due to the large uncertainties in thermophysical properties of the crust, particularly radiogenic heat production. The thermal buoyancy responds to the integrated thermal state of the lithosphere, expressing variations through differences in elevation, thereby providing an independent estimate of GHF. To obtain GHF from thermal isostatic calculations, we use Monte Carlo methods to fit elevation, seismic velocity estimates of mantle temperature and magnetic-based Curie depth estimates. This method requires input estimates of crustal thermophysical properties, which we predict using new empirical correlations to seismic velocity and density. These empirical models are developed from global and regional analyses of whole rock geochemistry and laboratory measurements and/or thermodynamic calculations of physical properties. Geochemical data from exposures of Antarctic terranes and conjugate margins are used to calibrate a priori heat production distributions and are key to producing more accurate models of lithospheric temperatures and GHF.

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Effects of Local Snowpack on geodetic observation at Syowa Station with UAV survey

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Syowa Station, located in East Ongul Island, East Antarctica, has three different space geodetic observation facilities (GNSS, DORIS, and VLBI) and a superconducting gravimeter. These geodetic observations are expected to capture the glacial isostatic adjustment (GIA) effect caused by the melting of the Antarctic ice sheet since the last glacial maximum. However, it is necessary to remove the effects of local snowpack close to the observation sites for detecting the GIA signal precisely from these geodetic observations.
In this study, we derived the detailed snowpack distribution in Syowa Station from unmanned aerial vehicle (UAV) photographic survey, and evaluated the effects of snow mass on those geodetic solutions: elastic deformation, and gravitational attraction.
We conducted the aerial photographs taken by UAV, “senseFly eBee Plus” and “DJI Inspire 2”, around once a month during the 59th Japanese Antarctic Research Expedition (JARE59) activity (2017-2019).
The digital elevation models (DEM) and the orthomosaic images were generated from the aerial photographs with the SfM software “Pix4Dmapper.” Then, the time-series of snowpack distribution in the survey area was extracted from changes in DEMs. In this presentation, we show the details of observed changes in the snowpack depth distributions, and discuss the comparison between the estimated elastic deformation and gravity effect of local snow accumulation and the geodetic solution derived from each geodetic facility.

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Instantaneous Slow Cooling of the Transantarctic Mountains

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Thermochronologic data collected along the Byrd Glacier Outlet of the Transantarctic Mountains (TAM) reveals a prolonged and punctuated denudational history.

Samples collected along two vertical transects, each with over 1000 m of vertical relief, separated by ~30 km, all have apatite fission track (AFT) cooling ages of ~80 Ma. The >1 km of relief with nearly identical cooling ages indicates rapid denudation associated with significant topography. The spatial extent of this rapid cooling indicates that this topography was of regional importance. These thick sections of crust with similar AFT ages suggest rapid cooling at ~80 Ma as up to 1.5 km of crust cooled below ~120° C.

In contrast, evaluation of the track lengths to estimate the thermal histories of the samples indicates long-term, slow cooling, of the crust, with all samples spending an extended period of time (10s of millions of years) within the partial annealing zone (PAZ: 120°C to 60°C). This instantaneous, but slow, cooling cannot be explained by regional erosion (vertical conduction).

However, this instantaneous slow cooling can be explained by incision of a deep gorge adjacent to the samples (dominated by horizontal conduction). Numerical simulations indicate that rapid incision of a gorge followed by slow regional erosion can result in >1 km of crust rapidly passing through the AFT closure temperature (~120°C), and then remaining in the PAZ for an extended time (10s of millions of years). This scenario of deep incision results in simultaneous, but relatively slow, cooling of the crust by horizontal conduction.

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Quantification of the Uncertainty in Retrieving Antarctic Mantle Rheology: Toward Systematic Intercomparison

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Modeling mantle viscous response to past ice sheet change is crucial to correcting space-based data (gravity and altimetry) to determine Antarctic ice mass balance. Terrestrial GPS stations, operating for more than a decade, do provide some GIA information about viscous response. While this information is spatially sparse, the station data has none-the-less helped to determine that West Antarctic mantle viscosity and lithospheric structure significantly deviate from those of Canada and Fennoscandia, places where mantle viscosity is fairly rigorously constrained. New seismic mapping by Lloyd et al [2020] using adjoint waveform inversion (ANT-20), reveal great heterogeneity in the Voigt averaged S-wave velocity down to 1000 km depth. Here we connect S-wave mapping to 3 different scaling relationships to mantle viscosity. We assume both S-wave velocity and mantle strength are related to local temperature, $T0(r) + \delta T (r, \theta, \phi)$, where $T0(r)$ is the spherically averaged value at radius, r, and $\delta T (r, \theta, \phi)$ is the local deviation from the spherical average. Resultant viscosity maps from the different scaling relations may then be intercompared. There is uncertainty in each scaling relationship. Each of the relations must correct for a temperature-dependent anelastic slowing of the S-waves that is not directly related to the wave slowing effects of thermal expansion [Karato 2008]. Assessment of this intercomparison is presented here and we discuss our progress in quantifying the uncertainty in bounding, the effective mantle viscosity down to 1000 km beneath the Antarctic continent.

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Investigating Eocene-Oligocene alpine glacier flow and erosion over the Gamburtsev Subglacial Mountains, East Antarctica using a numerical ice flow model.

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The Gamburtsev Subglacial Mountains (GSM) represent one of the nucleation sites of the East Antarctic Ice Sheet at the Eocene-Oligocene Transition (EOT). The mountains have an alpine morphology representing erosion under valley-constrained glaciers or a regional ice cap, the survival of which reflects long-term protection under cold-based, non-erosive. In the landscape are cirques and hanging valleys positioned above glacially overdeepened trunk valleys that radiate out from the mountain range. The overdeepenings and the elevations of the cirque floors are proposed to be co-located with the palaeo-ELA of these glaciers. Although it has been assumed that this ice reflected the climate at the EOT, there may have been glaciers on Antarctica at various stages since the Late Cretaceous. This brings into question the age of the glacial signal recorded in the GSM. Here I use a numerical glacier model (PISM) run at high-resolution and under a climate that cools gradually to understand the likely ice flow patterns and basal thermal regime of small-scale glaciation and the early icecap on the GSM. We also suggest potential erosion patterns, determined using a range of velocity to erosion rate relationships, that may have been experienced over the mountain range. In doing so we thereby hypothesise the length of time over which erosive glacial conditions persisted in order to overdeepen the GSM. Finally, I discuss the climate conditions under which these glaciers grew and consider whether the glacial landscape of the GSM was carved at the EOT or under earlier, warmer, conditions.

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Subglacial character of the Aurora Basin, East Antarctica, from novel seismic waveform modelling

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Rising sea levels present a serious and increasing threat to a large percentage of the global population. Whilst scientific focus has concentrated on the rapidly retreating West Antarctic ice sheet, East Antarctic ice sheets have the capability to dominate future contributions to sea level rise and there is evidence for a history of partial collapse. The character of the ice sheet – bedrock interface of the Wilkes and Aurora Basins, which underlie a significant proportion of the East Antarctic ice sheet, may have a substantial impact on ice sheet instability. Seismological methods are well established in their ability to infer detail in subsurface layers, and novel passive methods offer the potential to highlight hidden changes in the ice-rock structure through the variation of ambient signals passing through the basal layers. This research focuses on utilising these seismic techniques to generate a comprehensive basis of the Aurora Basin, with particular interest in the nature and thickness of sediment in the ice sheet – bedrock interface zone and whether this layer is saturated or frozen, with the long-term aim of providing early warning of ice sheet degradation. We apply newly developed computational tools in seismic waveform simulation, and a detailed compilation and analysis of existing geophysical data to determine the present framework of knowledge regarding the Aurora Basin and Totten Glacier. This study will also incorporate regional modelling of ice-atmosphere and ice-ocean interactions and consideration of surface and subglacial hydrology in order to provide a more complete understanding of present basal conditions.

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New geodetic constraints on GIA and elastic deformation in East Antarctica

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Geodetic observations of East Antarctic bedrock deformation are sparse, with sometimes more than 1000 km between GPS sites. We present initial results from a new network of six continuous GPS sites in the region 80-120° east (from Davis Station to beyond Totten Glacier). We also substantially extend the existing record at Bunger Hills. Forward and inverse models of present-day bedrock deformation due to GIA disagree substantially in this region. We compare the GPS-derived site velocities, including both horizontal and vertical velocities, with a range of forward and inverse GIA models and discuss potential elastic effects and the implication for the accuracy of GIA models in this region.

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Improved GPS bedrock time series in Antarctica considering observation-level signal-to-noise ratio data

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Many GPS bedrock coordinate time series from Antarctica are badly affected by large, transient artefacts that are especially evident in the horizontal coordinate components, but in some cases show impact on the vertical coordinates. It has been suggested that these are a result of build up of snow and ice within "choke ring" antennas that form the majority of sites within Antarctica. Treatment of these transient data has thus far focused on removing them via manual and hence subjective data editing. We investigate the observation-level signal-to-noise ratio (SNR) data recorded by modern GPS receivers, and first explore their usefulness for robust data editing. We show that the standard deviation of SNR time series in elevation bands shows substantial variation which correlates with the transient coordinate signals and that SNR-based editing is a robust and repeatable data editing approach that is useful in the analysis of Antarctic time series. We then attempt to improve the coordinate time series themselves by applying SNR-based observation weighting in the original GPS data analysis. We illustrate these methods on velocities estimated from time series from long-running sites within the ANET network of West Antarctica.

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A New Geothermal Heat Flux Model of Antarctica with Machine Learning

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Understanding the geothermal heat flux in Antarctica is crucial for ice sheet modelling and glacial isostatic adjustment. It affects the ice rheology and can lead to basal melting, thereby promoting ice flow. Direct estimates are sparse and models inferred from e.g. magnetic or seismological data differ immensely. While these different approaches are generally justified, they go along with strong simplifications and great uncertainties.
To overcome such shortcomings and assuming that heat flux is substantially related to its geodynamic setting, we adopt a machine learning approach. More specifically, we establish a Gradient Boosted Regression Tree model, in order to find an optimal predictor for locations with sparse direct heat flux estimates. With this technique, a complex relationship between geothermal heat flux and relevant geophysical features (e.g. gravity field, magnetic anomaly, crustal and lithospheric thickness) is generated. Thereupon, we can produce a map of predicted heat flux beneath the Antarctic ice sheet.
However, this approach largely relies on global data sets, which are notoriously unreliable in Antarctica. Therefore, validity and quality of the data sets is reviewed and discussed. Using regional and more detailed data sets of Antarctica's tectonic neighbors improves the predictions. The performance of the machine learning algorithm is explored by comparing the predictions to the existing estimates. Finally, we present a new geothermal heat flux model and discuss differences to previous predictions.

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Uppermost mantle structure beneath the Amundsen Sea Embayment, West Antarctica

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Knowledge of the uppermost mantle seismic velocity structure beneath the Amundsen Sea Embayment (ASE), West Antarctica is important for understanding the structure and tectonic evolution of the region, as well as for constraining the interactions between the solid Earth and the cryosphere. In this study, we investigate the uppermost mantle seismic structure beneath Thwaites Glacier and Pine Island Glacier using travel times from ~100 small ($0.6 < ML < 3.2$) seismic events (most likely glacial in origin) occurring from 2015-2017. Using seismic data collected by the Polar Earth Observing Network (POLENET/A-NET) and the UK Antarctic Network (UKANET), our tomographic inversion constrains uppermost mantle P-wave velocities (VPn). The results show variable uppermost mantle structure beneath Thwaites Glacier and Pine Island Glacier, with Pn velocities varying from ~8.15 km/s to ~8.35 km/s. We image lower Pn velocities beneath Pine Island Glacier, consistent with previous evidence suggestive of rifting. Beneath Thwaites Glacier, we image higher velocities. With variations in uppermost mantle seismic velocities being dependent on physical properties, such as temperature, composition, and grain size, it is evident that the ASE lithosphere should be considered laterally variable. Current glacial isostatic adjustment (GIA) models of the ASE assume a spatially homogeneous, elastic lithosphere (Barletta et al., 2018); however, in order to accurately capture short wavelength GIA signals, incorporating a laterally variable lithosphere may prove essential (Nield et al., 2018).

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Mantle xenoliths help constrain a 3-dimensional viscosity mantle map of Antarctica for better glacial isostatic adjustment (GIA) and heat flow modelling

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Several estimates for the Antarctic ice sheet contribution to sea level rise rely on modelling basal heatflow and the solid Earth response to changes in ice and water loading, known as glacial isostatic adjustment. Predicting this adjustment utilises ice sheet history and Earth models, which are exceptionally difficult to constrain for a continent under ice and require a multi-disclipinary approach. Mantle petrology and geochemistry studies can help and are an underutilised discipline for constraining Earth rheology in Antarctica. It studies, amongst other things, 'mantle xenoliths' which are fragments of lithospheric mantle rock brought to the surface by volcanic eruption. Mantle xenoliths can be studied to quantify properties including water content, grain size, chemistry (CFMAS), temperature and pressure. Over 100 years of mantle xenolith research has shown there is significant lateral variation in mantle properties between East and West Antarctica, and within West Antarctica. For example, between northern Victoria Land, southern Victoria Land and Marie Byrd Land there are differences in geothermobarometry, lithospheric geotherms and mantle water contents. Lithospheric mantle temperatures can be calculated from mantle xenoliths, including Cenozoic changes to heatflow in the Victoria Land portion of the West Antarctic rift system. Synthesis of the properties of the mantle from the study of mantle xenoliths can be reconciled with mantle properties determined by geophysical and remotely sensed methods to map in much finer, and geologically constrained, detail lateral and vertical variations in mantle properties to obtain better accuracy for glacial isostatic adjustment models and for basal heatflow models.

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Subglacial hydrology in the Ellsworth Subglacial Highlands and its evolution over the last 150 kyrs

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Subglacial water located at the onset of the ice streams has the potential to enhance ice flow downstream by lubricating the ice-bed interface. There are more than 400 subglacial lakes across Antarctica, of which 20% are in West Antarctica and the connections between these subglacial lakes is fundamental to understanding past and present ice sheet flow. We have recently demonstrated the presence of more than 30 subglacial lakes located in the Ellsworth Subglacial Highlands (ESH) near the Pine Island/Rutford/Institute ice divide and we aim to understand the connections between these under a range of ice sheet configurations. We characterize the present configuration of the drainage system and the connection of the subglacial lakes based on a new bed DEM of the region. We then use existing ice sheet model output that reconstructs the geometry of the ice sheet over the last 150 ka to understand the evolution of the subglacial hydrological system and find that >20 subglacial lakes have remained underneath the ice since the Last Interglacial. We show that a number of lakes are sensitive to small changes in the position of the ice divide between the Amundsen and Weddell Sea regions, and thus that these may have switched drainage direction under more restricted ice sheet configurations. Additionally, some lakes are connected in chains, and remain-so as the ice sheet evolves. The pathways of drainage from these lakes is linked to the hydrological network of the main WAIS ice streams, with particular concentrations of flow towards the Thwaites Glacier.

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Geodetic Measurements of GIA at Aboa, Vestfjella mountains, Western Dronning Maud Land

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Repeated absolute gravity measurements when used together with vertical rates from, e.g., GPS bring multiple benefits to geodynamical research. Gravity rates can be used to control observed vertical rates and predictions from GIA models. Plotting gravity rates versus vertical rates at a number of stations provides a slope that gives information on the mechanism behind the vertical rates (e.g., GIA) and an intercept that can be used to control the reference frame of the vertical rates. Absolute -gravity stations are an important part of the geodetic infrastructure of the Antarctic.

The Finnish Geospatial Research Institute (FGI) has occupied the absolute gravity station at the Finnish Antarctic Research Station Aboa (Western Dronning Maud Land) seven times since 1993. The permanent GPS station at Aboa was established in 2003 and has been in constant operation since.

Here we present latest results from geodetic measurements at the Aboa Station. The time series of absolute gravity is corrected for changes insnow and ice masses in the immediate proximity of the gravity station. The gravity time series is then compared with regional gravity change from the GRACE satellite: both indicate an increasing trend in gravity since around 2005. We have also performed a detailed PPP calculation of the Aboa GPS time series. It shows a moderate land uplift, in apparent contradiction with the gravity increase. The explanation appears to be that the direct attraction of the increasing regional snow mass, not the vertical motion, is the dominant effect in the absolute-gravity time series.

632

Constraining upper mantle viscosity from post-seismic deformation in the Northern Antarctic Peninsula following the 2013 magnitude 7.7 Scotia Sea earthquake

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Large earthquakes in the vicinity of Antarctica have the potential to cause post-seismic viscoelastic deformation on the continent, affecting measurements of displacement that are used to constrain models of glacial isostatic adjustment (GIA). In November 2013 a magnitude 7.7 strike-slip earthquake occurred in the Scotia Sea around 650 km from the northern tip of the Antarctic Peninsula. GPS coordinate time series from the Peninsula region show a change in rate after this event indicating a far-field post-seismic viscoelastic deformation signal is present. We use a global spherical finite element model to investigate the extent of post-seismic viscoelastic deformation in the northern Antarctic Peninsula. We investigate possible 1D earth models that can fit the GPS data and consider the effect of including a simple 3D earth structure in the region. These results can provide independent constraints on likely earth structure which is useful for studies of GIA and consideration of solid-earth feedbacks on ice-sheet evolution.

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Can a GIA model with lateral variations in Earth structure explain GPS displacement rates in the Southern Antarctic Peninsula?

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The one-dimensional, radially varying Earth structure adopted in many glacial isostatic adjustment (GIA) models leads to bias in model-predicted uplift rates in locations where rheological parameters differ significantly from the globally averaged 1D structure used. To overcome this problem, regional studies of GIA often make use of a 1D Earth structure that is representative of local parameters, for example to capture the low viscosity upper mantle in West Antarctica, although it remains unclear over what spatial scale the 1D Earth structure may be relevant. In the Southern Antarctic Peninsula GPS uplift rates reveal significant variability over short spatial scales, with differences of up to 5.8 mm/yr observed over a distance of only 500 km, which cannot be replicated using a GIA model that adopts a 1D regional Earth structure. Here we use a finite element GIA model that includes 3D Earth structure derived from a high resolution seismic velocity model to investigate whether lateral variations in lithospheric thickness and upper mantle viscosity can explain this small scale variability in uplift rates. Combining the 3D GIA model with an ice history that includes Late Holocene changes improves the fit to GPS observations in the Southern Antarctic Peninsula.

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GIA modeling of geodetic signals in East Antarctica for constraining the recent mass balance and the last deglaciation history

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Time series of gravity changes by GRACE, which launched in 2002, described in detail the movement and change of mass in Antarctica. However, the observation of gravity fields such as GRACE includes not only the change of ice mass but also the change of mass caused by the deformation of the solid Earth called Glacial Isostatic Adjustment (GIA). For this reason, an accurate estimate of the solid Earth deformation is required to prescribe the recent ice mass balance by gravity observations.
Furthermore, the current deformation rate of the solid Earth also includes the component induced by the melting of the Antarctic Ice Sheet (AIS) since the Last Glacial Maximum. Therefore, the estimates of the deglaciation history of the AIS on a time scale over 10,000 years derived from geomorphic and geological observations are also required. At present, several scenarios of the AIS deglaciation history based on geomorphic and geological data have been proposed and are still being debated.
In this study, we discuss the GIA-derived gravity change and crustal deformation in the East Antarctic region using the previously published AIS deglaciation models and the GIA modeling code currently under development. GIA is highly dependent on the viscosity structure of the Earth’s mantle as well as on the changes in surface loads. Therefore, we will conduct the numerical experiments with the extensive GIA model parameters and show the effects of the GIA-induced geodetic signals on the inferences of current and past ice mass fluctuations quantitatively.

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Quantifying the contributions of erosion and tectonics towards the lowering of subglacial topography beneath the Antarctic and Greenland Ice Sheets

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The Antarctic and Greenland Ice Sheets contain a combined volume of ice equivalent to ~65 metres of global mean sea level rise. Both ice sheets are likely to diminish in volume and thus contribute to global sea level rise over the coming centuries. Many outlet glaciers in Antarctica and Greenland are underlain by deep subglacial troughs; these glacial catchments have been identified as particularly vulnerable to sustained and potentially irreversible future ice mass loss. However, the origin of these subglacial landscapes remains unclear, as do the relative contributions of tectonic processes and fluvial/glacial erosion towards trough development.

Here we combine geomorphological analysis with gravity and magnetic modelling to constrain the processes responsible for the development of subglacial trough systems in northern Greenland and East Antarctica. We find that the landscapes in northern Greenland retain a stronger fluvial signature than in East Antarctica and have been less heavily modified by glacial erosion, which may reflect differences in the duration of glaciation and/or landscape erodibility.

Moreover, the morphology of several subglacial troughs in both Antarctica and Greenland is inconsistent with the modern ice flow regime. In some cases, we propose that these features formed via fault-induced subsidence prior to glacial inception, whereas other troughs were at least partially overdeepened by glacial erosion beneath an earlier ice sheet with a more restricted configuration than the present-day. This in turn yields insights into Antarctic and Greenland ice sheet behaviour and extent during past warmer climate intervals potentially analogous to future climate scenarios.

1233

An ensemble of glacial isostatic adjustment models for Antarctica derived from an ensemble of ice history models

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Understanding the response of the solid earth to past ice sheet change is an ongoing challenge for the estimation of present-day mass change from satellite gravimetry. The magnitude of the correction that must be made to account for ongoing solid earth deformation is similar to the change in the mass of the ice sheet itself, making estimates of change sensitive to this correction. We use a Maxwell-rheology sea level solver in combination with an ensemble of earth and deglacial history models to generate 2000 unique glacial isostatic adjustment (GIA) models. We compare each GIA ensemble member to a new GPS-derived surface velocity field. The GIA models are scored for the number of data points which they match within the uplift error, the number of points which show the correct sign of change and the overall root-mean-square error between the modelled and observed data. We assess the performance of the models over four key Antarctic regions, with a particular focus on investigating the likelihood of a Holocene readvance within the Weddell Sea region.

1415

Heat flow in southern Australia and connections with East Antarctica

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Viscosity and melt generation at the base of ice sheets are critically dependent upon heat flow. Yet subglacial heat flow is poorly constrained due to the logistical challenges of obtaining boreholes that intersect bedrock beneath thick ice cover. Currently, continental estimates of Antarctic heat flow are derived from geophysical methods that provide ambiguous constraints of crustal heat sources, despite their demonstrated importance for accurate predictions of future ice sheet behaviour. This study pursues an alternative approach by using heat flow measurements from the Coompana Province of southern Australia, which represents the geological counterpart of Wilkes Land, East Antarctica. We present nine new surface heat flow estimates from this previously uncharacterised region, ranging from 40–70 mW/m2 with an average of 57 ± 3 mW/m2. These values compare favourably to recent geophysically-derived estimates of 50–75 mW/m2 for the Totten Glacier catchment, and to the single in situ measurement of 75 mW/m2 from Law Dome. However, they are appreciably lower than the range of 56–120 mW/m2 (83 ± 13 mW/m2 average) for the abnormally enriched Proterozoic terranes of the Central Australian Heat Flow Province. This study provides the first regional heat flow map of geological provinces formerly contiguous with East Antarctica through the application of continent-scale heat flow datasets tied to a Jurassic plate tectonic reconstruction for Gondwana. Our approach reveals several discrepancies with current heat flow models derived from geophysical methods and provides a more robust analysis of subglacial heat flow using this plate tectonic synthesis as a proxy for East Antarctica.

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Heterogeneity in the deep Earth beneath East Antarctica in the 60-160 degree E sector.

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Interactions between the solid Earth and cryosphere, in modelling glacial isostatic adjustment, for example, have previously assumed a 1D Earth structure. More recent studies, however, have shown the merit of approaches that make use of a 3D Earth structure. While West Antarctica and parts of central Antarctica have much improved constraints on the heterogeneity of the deep Earth through recent geophysical studies, the 60-160 degree E sector of East Antarctica is less-well constrained.
This contribution makes use of newly recorded seismic signals in the region between Casey and Davis stations, geophysical data compilations, and plate reconstructions to construct the likely variation of physical properties in the lithosphere and asthenosphere in this region. We make use of newly written software for data synthesis in 3D, and volumetric visualisations in our analyses.
We present the results of this survey of, observed and probable, heterogeneity in the deep Earth across this sector. An important component of the synthesis are the associated uncertainties and identification of the most poorly constrained regions. It is likely that the region is more variable than previously thought with changes in physical properties being identified around the coast, and being probable in the region between the coast and the pole. We aim to make our results available to the interdisciplinary community, including ice sheet modellers, in the near future.

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Bedrock uplift in response to recent ice-mass change on northern Marguerite Bay, Antarctic Peninsula

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Rapid regional climate warming in the Antarctic Peninsula has led to several major ice shelves retreating, and eventually collapsing, since the 1970s. In response, feeding glaciers have exhibited rapid acceleration and thinning, and this dynamic ice unloading induces a solid Earth response which can be measured by geodetic observations. We investigate ice-mass change and bedrock deformation in the northern Marguerite Bay (NMB) region of the Antarctic Peninsula from ~2002 to 2018 in order to provide new constraints on Earth rheology. The mass balance estimation over this region suggests that the ice mass loss reduced around the Rothera research station since ~2012 and the Muller Ice Shelf since ~2009 compared to 2004-2012 and 2002-2009, respectively. GPS measurements of bedrock uplift in NMB show time-varying rates of uplift varying between ~2.2 and 7.0 mm/year over 2002-2018. A comparison between GPS and modeled viscoelastic deformation up to 2015 suggests an upper mantle viscosity of ~0.1-80×10^{18} Pa s but allows a wide range of effective elastic lithosphere thickness for NMB. This viscosity estimate is consistent with a north-south gradient in viscosity suggested by previous studies focused on specific regions within the Antarctic Peninsula and adds further evidence of low viscosity upper mantle in the northern Antarctic Peninsula.

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Recent ice-mass change and its effect on viscoelastic deformation rates around the northern Antarctic Peninsula

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The rapid viscoelastic uplift measured around the northern Antarctic Peninsula due to ice mass loss since ~2002, solid Earth modeling suggesting the upper mantle viscosities of ~6×10^{17} - 2×10^{18} Pa s and a wide range of lithosphere thicknesses. This finding was based on only one GPS station bedrock uplift. We extend the continuous GPS time series to include 5 additional years and the additional consideration of the horizontal components of deformation. GPS observations show strong uplift from 2002 to 2011 followed by reduced uplift rates to 2018. The observed horizontal displacements are directed towards the south-west, in accord with the known and ongoing ice-mass loss in the eastern Peninsula. The modeling of the east coordinate component confirms the viscosity range suggested by the uplift rates alone and providing important, largely independent, confirmation of that result. We also expand on the limited spatial coverage of the GPS data using Sentinel-1A C-band InSAR data from 2014.9-2017.8. In the Larsen-B region, large relative line-of-sight displacements are observed at outlet glaciers of low elevation where ice unloading is high. InSAR also indicates that mass loss around the southern part of the Larsen-A region is higher relative to the northern part. Comparing these InSAR data to updated viscoelastic modeling for the Larsen-B region refines the understanding of lithospheric thickness, demonstrating a poor fit to models with a thin lithosphere. InSAR shows a good agreement for lithospheric thicknesses in the range of ~85-160 km with the upper-mantle viscosities preferred from comparison with the GPS time series.

1224

Consistently Re-processed Geodetic GNSS Data in Antarctica as a Basis for Geodynamic Applications: the GIANT-REGAIN Project

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In-situ GNSS measurements taken at bedrock markers provide information and constraints on a variety of phenomena. Among these, glacial-isostatic adjustment (GIA) is of utmost interest because it links ice-mass change, solid Earth response and sea-level change. However, in Antarctica ice mass balance studies based on satellite gravimetry suffer most from the large uncertainty of GIA predictions. Therefore, we aim to strive for a comprehensive analysis of all geodetic GNSS data available in Antarctica to improve GIA models.
For this purpose, the "Geodynamics in Antarctica based on Reprocessing GNSS Data Initiative" (GIANT-REGAIN) was launched under the umbrella of the Scientific Committee on Antarctic Research, Expert Group on Geodetic Infrastructure in Antarctica (EG GIANT).
We compiled a data set comprising recordings from more than 250 permanent and episodic GNSS sites. The period of observations starts with the beginning of geodetic GNSS measurements in Antarctica in the mid-1990s and is limited to the end of 2017. The process of data and metadata acquisition will be reported, which entailed major efforts. The data set is being re-processed at three analysis centres (TUD, UTAS and OSU). Thus, effects arising from the application of different processing strategies and algorithms ("software noise") are investigated, and the reliability of inferred results will be cross-checked. As a core product we aim for one consistent set of vertical and horizontal deformation rates together with uncertainties that can be used for further analyses in Antarctic geodynamics, especially to improve our understanding of GIA.

1241

How to combine satellite gravimetry, satellite altimetry, and firn model products to resolve GIA over ice sheets?

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Solid-earth deformation through glacial-isostatic adjustment (GIA) is a major component in gravimetric mass balance studies in polar regions. In addition to GIA forward modeling products, the present-day GIA signal over ice sheets can be separated from ice mass changes, e.g. by combining satellite gravimetry, satellite altimetry and firn model products.

We present results of a sensitivity study where we investigated an inverse GIA estimation approach over Antarctica regarding the choice of degree-1 and C_{20} coefficients, different altimetry missions, time epochs, and the uncertainty of firn processes. The latter are characterized empirically using differences between two regional climate model products. Further, we tested a similar signal separation approach over the Greenland ice sheet. Our results demonstrate the limitations when combining observations of both geodetic sensors and firn model products, e.g. through the reconcilement of spatial resolution of data sets, uncertainties of low-degree harmonics, and firn/ice density assumptions for regional applications.

Moreover, we treat the signal separation over ice sheets as a parameter estimation problem in a global consistent framework. On the basis of these findings we will implement the estimation of the GIA signal from satellite observations in a global fingerprint inversion where it will be co-estimated with all parts of the global sea-level budget.

1508

How can geophysical imaging help constrain mantle viscosity to improve glacial isostatic adjustment models?

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Glacial Isostatic Adjustment (GIA) represents the viscous deformation associated with Earth's re-estabilishment of isostatic equilibrium after a significant ice sheet mass change. GIA occurs over thousands of years, depending on mantle viscosity, and thus Greenland and Antarctica are still responding to melting that occurred over the last 10,000 years or more. Because this GIA response overprints instantaneous uplift resulting from present-day melting, our models for GIA directly affect current estimates of ice loss and predictions of future sea level rise. Despite this, GIA analysis is beset with uncertainties regarding ice sheet history and Earth structure and many GIA models do not reproduce current observations of surface uplift.

We present an analysis for how geophysical data – specifically the combination of magnetotelluric (MT) and seismic data – can improve estimates of mantle viscosity and therefore help to constrain GIA models. We show that seismic and MT data together give the best possible constraints on upper mantle temperature, which is the primary control on viscosity, as well as providing important constraints on surface heat flow. In addition, MT data can be used to constrain the hydrogen content of mantle minerals, which is another major control on their viscosity. We show results from polar regions such as Svalbard, where the geophysical data significantly improved constraints on mantle viscosity compared to those that can be inferred from GIA data alone, and current research on the Greenland Ice Sheet, where we are collecting the first ever MT data to model lateral variations in mantle viscosity.

1356

A new geothermal heat flux map of Antarctica determined by seismology

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The seismic structure of the lithosphere is directly related to the thermal structure of the interior of the Earth. Thus, providing information about geothermal heat flux (GHF), which is an important boundary condition for modeling the dynamic Antarctic ice-sheet. We combine two latest Antarctic seismic models and make a comparison to the seismic structure of the continental US, whose GHF is well sampled and accurately measured. Local GHF estimates in Antarctica are then derived based on the hypothesis that similar mantle structures lead to similar GHFs. Based on this method, we show that the new GHF map has improved resolution and lower uncertainties compared to earlier seismologically derived maps, owing to the greatly improved tomographic images. Furthermore, the result is consistent with most of the independent local measurements. Overall, we find that the new map presents a West-East Antarctica dichotomy which has been shown in previous maps. One striking result is that we do not observe pervasive high GHF in the central region of West Antarctica. Instead, the new map reveals relatively low GHF in the central West Antarctic Rift system near the Siple Coast, coherent with a local measurement made at Siple Dome. Particularly, we find that high GHF estimates (> 80 mW/m2) emerge in the Thwaites Glacier region that is consistent with earlier radar-derived result and high GHF (>75 mW/m2) throughout the southern Transantarctic Mountains (sTAM) in the vicinity of the Titan Dome and Hercules Dome, co-located with the sub-ice lakes.

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Towards a reconciled heat flow map for Antarctica: Aq1

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Subglacial heat flow is used as a boundary condition for ice sheet models and in understanding the tectonic development and properties of the lithosphere. Existing Antarctic heat flow estimates at continental scale are based on univariate modelling of a geothermal gradient and do not agree. Disparities arise from assumptions regarding lithospheric properties such as crustal heat production, upper mantle composition and dynamic neotectonics.

We employ a 'similarity approach' that compares Antarctic observables with observables linked to existing high-quality heat flow measurements from global compilations. Previous studies that use similarity to interpolate heat flow values elsewhere, utilise datasets that do not extend to the Antarctic interior with sufficient reliability. Here, we optimise the similarity approach for existing Antarctic geophysical and geological datasets by applying a careful sensitivity analysis and introduce weighting of observables. Observables used include topography, distance to volcanoes, geophysical data sets, and derived products such as depth to Curie temperature isotherm, seismic wave speed and curvature of gravity field. We also include geological observations. In total, 15 observables are used.

The new heat flow map, Aq1, is presented together with uncertainty and measures of information entropy in widely used formats. We also provide the complete workflow as open source Python code relying on the agrid package. The complete computational framework allows for testing of alternative inputs and updates as new data becomes available.

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Separation of tectonic and glacial isostatic adjustment signals in East Antarctica from GPS horizontal velocities

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Observations of deformation due to glacial isostatic adjustment (GIA) provide a crucial constraint on the Earth's response to ice unloading, giving insight to the contribution of ice-covered regions to global sea level rise. However, accurate measurement of local geodetic motion presents a challenge due to tectonic plate rotation. The horizontal velocity component measured at GPS stations in East Antarctica has a plate rotation signal over an order of magnitude greater than the expected GIA motion. Incomplete separation of these components thus introduces significant bias into measured GIA velocities.

We present a study applying signal separation techniques to sets of synthetic data that replicate a combination of plate rotation and GIA-like horizontal velocities at 36 GPS stations across East Antarctica. We compare two approaches for removing the plate rotation component, where either: 1) the stations are unweighted; or 2) each station is weighted based on the spatial density of neighbouring stations. The synthetic tests show the spatial weighting of stations has a very significant effect on our ability to recover synthetic GIA signals.

We apply this second approach to observed horizontal velocities from 36 GPS stations across East Antarctica, and estimate the systematic uncertainty based on our study using synthetic data. We measure statistically significant (2σ level) GIA horizontal velocities at 25 of the 36 stations. Our techniques and open source software provide a toolbox not only to measure the GIA signal using current GPS installations but also to optimise the siting of stations in future campaigns.

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Feedback between ice dynamics and bedrock deformation for the LGM ice sheet in Antarctica

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Over glacial-interglacial cycles, the evolution of an ice sheet is influenced by Glacial isostatic adjustment (GIA) via two negative feedback loops. Firstly, vertical bedrock deformation due to a changing ice load alters ice-sheet surface elevation. Secondly, bedrock deformation will change the location of the grounding line of the ice sheet. GIA is mainly determined by the viscosity of the interior of the solid Earth which is radially and laterally varying. Underneath the Antarctic ice sheet, there are relatively low viscosities in West Antarctica and higher viscosities in East Antarctica, which affect the response time of the above mentioned feedbacks. However, most ice-dynamic models do not consider the lateral variations of the viscosity in the GIA feedback loops when simulating the evolution of the Antarctic ice sheet. We present a method to couple ANICE, a 3-D ice-sheet model, to a 3-D GIA finite element model. In this method the model computations alternate between the ice-sheet and GIA model until convergence of the ice thickness occurs at each timestep. We simulate the evolution of the Antarctic ice sheet from 120 000 years ago to the present, considering 1D and non-linear 3D rheologies. The results of the coupled simulation will be discussed and compared to results of the uncoupled ice-sheet model.

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Understanding the controls on Glacial Isostatic Adjustment across West Antarctica

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Solid Earth deformation across Antarctica, triggered by past ice-mass change, contaminates measurements of present-day ice-mass change and has the potential to influence future ice-sheet dynamics. In order to model this process, known as glacial isostatic adjustment (GIA), it is necessary to determine what periods of past ice-mass change dominate the contemporary GIA signal. It is often assumed that the spatial pattern of GIA reflects ice extent change since the Last Glacial Maximum (LGM), and this will hold true in regions where the mantle relaxes slowly, i.e. in high viscosity regions. However, recent observational and modelling studies suggest that upper mantle viscosities beneath parts of West Antarctica may be much lower than the global average. In such regions mantle relaxation will take place more quickly and the response to recent ice-mass change will dominate the deformation signal. Here, we use a GIA model that considers 3D variations in Earth rheology to quantify spatially variable relaxation times and identify which periods of past West Antarctic ice-mass change have the greatest influence on the current GIA signal.

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Upper mantle viscosity structure and lithospheric thickness of Antarctica estimated from recent seismic models

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Upper mantle viscosity structure and lithospheric thickness vary significantly across Antarctica, leading to strong differences in glacial isostatic adjustment (GIA). We produce new maps of these parameters using two new seismic models. Shen et al. [2018] use receiver functions and Rayleigh wave velocities to develop a higher resolution model for the upper 200 km beneath Central and West Antarctica. Lloyd et al [2019] use adjoint tomography to invert three-component earthquake waveforms for structure down to 800 km beneath Antarctica and adjacent oceanic regions. We estimate the mantle viscosity from the seismic structure assuming laboratory-derived relationships between seismic velocity, temperature, and rheology. Choice of parameters for the conversion is guided by recent estimates of mantle viscosity from geodetic measurements. We also compare several different methods of estimating lithospheric thickness. The mantle viscosity estimates indicate several orders of magnitude variation, with low viscosity ($< 10^{19}$ Pa s) beneath the Amundsen Sea Embayment (ASE) and the Antarctic Peninsula, suggesting a characteristic GIA time scale on the order of a hundred years. Lithospheric thickness is also highly variable, ranging from around 60 km in parts of West Antarctica to greater than 200 km beneath East Antarctica. Thin lithosphere and low viscosity between ASE and the Antarctic Peninsula likely result from the thermal effects of a slab window as the Phoenix-Antarctic plate boundary migrated northward. Low viscosity regions beneath the ASE and Marie Byrd Land coast connect to an offshore anomaly at depths of ~ 250 km, suggesting the involvement of larger-scale geodynamic processes.

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Error Budgets for GNSS-derived Crustal Motion Velocities in Antarctica: Implications for Constraining GIA Models

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Crustal displacement rates and patterns derived from GNSS measurements are a dominant constraint on GIA models for Antarctica, because other types of data constraints are sparse. Measurements accurate at the 1 mm/yr level or less would be optimal to test for the 'best' GIA model parameters through comparison of model-predicted and measured crustal motions. There are several confounding issues to achieving this level. Implementing common reference frames for model-predicted and measured motions is essential. Computing and removing the component of crustal displacement due to the elastic response to contemporary ice mass change is crucial in Antarctica, but acquisition of requisite mass balance data across our network extent is challenging and the methodology to best estimate elastic response is not yet robust. Like most high-latitude GNSS networks, ANET sites have utilized chokering antennas covered with SCIGN radomes. It is well known that snow and ice on antenna and radome exteriors causes data scatter and errors in positioning. Here we investigate an environmental effect, largely unique to Antarctica, that degrades the accuracy of velocity estimates – excursions in the daily position time series arising from intrusion of spindrift snow and subsequent accumulation of ice and meltwater inside the antenna chokerings, beneath the covering radome. We characterize the position time series and velocity estimates before and after mitigation of antenna icing and from data cleaning approaches. We find regional differences in icing-related errors, pointing to a need for a weighting scheme accounting for this when GNSS-derived velocities are compared with GIA model predictions.

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Spatial Scale of Crustal Deformation Patterns across West Antarctica

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The geodetic component of the Antarctic Polar Earth Observing Network (ANET-POLENET) provides high-precision bedrock crustal velocities across most of West Antarctica. Observed vertical and horizontal crustal displacements show complex patterns and vary strongly from the Transantarctic Mountains to the West Antarctic coastal region. Crustal deformation patterns derived from 1D glacial isostatic adjustment models vary spatially between maximum uplift to subsidence on scales between 750 and 1250 km, the response from two dominant LGM ice load centers in the Weddell and Ross embayment regions. For 3D GIA models, the spatial distance between predicted uplift and subsidence maxima reduces to 500 km in sectors of West Antarctica where earth rheology is weak and ice load changes continue to the Late Holocene. Crustal displacements measured from ANET continuous GNSS time series document spatial changes from uplift to subsidence over significantly shorter distances, on the order of 300-500 km. The measured spatial patterns in crustal deformation are of similar scale to lateral variations in seismic velocities and derived earth structure as resolved by recent seismic studies, highlighting the need for 3D earth models to understand GIA in Antarctica. Improved resolution of the deformation pattern associated with an uplift center and subsiding moat around it in the Amundsen Embayment region is provided by initial velocity solutions from newly deployed GNSS sites that have densified our measurement network. Our new results have important implications for patterns and rates of ice sheet – solid earth feedbacks.

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Active subglacial volcanism in West Antarctica as assessed by airborne geophysics: Distribution and context

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A combination of aerogeophysics, seismic observations and direct observation from ice cores and subglacial sampling has revealed at least 21 sites under the West Antarctic Ice sheet consistent with active volcanism (where active is defined as volcanism that has interacted with the current manifestation of the West Antarctic Ice Sheet). Coverage of these datasets is heterogenous, potentially biasing the apparent distribution of these features. Also, the products of volcanic activity under thinner ice characterized by relatively fast flow are more prone to erosion and removal by the ice sheet, and therefore potentially underrepresented. Unsurprisingly, the sites of active subglacial volcanism we have identified often overlap with areas of relatively thick ice and slow ice surface flow, both of which are critical conditions for the preservation of volcanic records. Overall, we find the majority of active subglacial volcanic sites in West Antarctica concentrate strongly along the crustal thickness gradients bounding the central West Antarctic Rift System, complemented by intra-rift sites associated with the Amundsen Sea to Siple Coast lithospheric transition.

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