Chapter 1

Introduction

1.1 Motivation

Improving projections of the rate of global sea level rise in response to a warming world is vital for effectively mitigating future environment and socio-economic impacts (Durand et al., 2022). A large portion of the uncertainties in sea level rise projections is related to the contribution from the Antarctic Ice Sheet. The Antarctic Ice Sheet contains a total volume of ice equivalent to 57.2 m of sea level rise (Fretwell et al., 2013). Satellite altimetry observations show that Antarctica contributed ~ 5 mm to mean sea level over the last ~ 20 years (2003-2019) (Smith et al., 2020), and of the various components of sea level rise, the contribution from Antarctica is accelerating the fastest (Nerem et al., 2018). By the end of the century, Antarctica is projected to contribute between 0.03 and 0.28 m to mean sea level (RCP 8.5, Intergovernmental Panel on Climate Change (IPCC), 2022). Optimal strategies for preparing coastal communities to best mitigate the impacts of rising sea level depends on where in this range of uncertainties the true sea level rise will be. Some of the uncertainty in how the Antarctic Ice Sheet will respond to a warming world stems from a lack of understanding of the complex interactions between the ice and the underlying earth.

1.2 Solid-earth influences on ice dynamics

The solid-earth influences ice sheets through several mechanisms, which we group as those resulting from bedrock topography, geologic structures, and bedrock physical properties.

1.2.1 Bedrock topography

Onshore bed topography and offshore bathymetry exert fundamental controls on how the Antarctic Ice Sheet behaves. Offshore, where the ice is floating, the influence of the bathymetry is limited to the guiding of ocean circulations. Bathymetric ridges have been shown to block, or re-direct, the inflow of melt-inducing waters to the ocean cavity beneath floating ice shelves (De Rydt et al., 2014; Zhao et al., 2019; Goldberg et al., 2020). Approximately 75% of Antarctica's coastline is composed of these floating ice shelves, and 83% of total ice discharged into the Southern Ocean from Antarctica is through these shelves, highlighting their significance to Antarctica's ice budget (Rignot et al., 2013). Of the 83% of total ice loss from Antarctica through ice shelves, basal melt is responsible for 55% (Rignot et al., 2013). Some of this melt occurs from surface waters, where bathymetry has little effect, but for many of the largest ice shelves, the majority of basal melt occurs along the deep grounding zone (Adusumilli et al., 2020). Here, the melt-inducing water bodies are dense and flow into the ice shelf cavities along the seafloor (Holland, 2008; Tinto et al., 2015). Therefore, bathymetric features act to guide or block these circulations from reaching the grounding zone where they can melt the ice base. In addition to steering ocean currents, bed topography, in regions of grounded ice, acts to steer the ice flow.

As revealed by extensive seismic and swath bathymetry data in Antarctica's Ross Sea (Figure 1.1a), the dynamics of an advancing or retreating ice sheet are predominantly controlled by the physiography of the bed (Halberstadt et al., 2016; Anderson et al., 2019). If large troughs and banks exist, advancing ice is initially confined by these features, while the banks remain ice-free (Anderson et al., 2014). Eventually, after the ice has covered the entire region, the retreat is initially confined to these narrow troughs, while the banks retain grounded ice for much longer (Halberstadt et al., 2016; Anderson et al., 2019). As the ice thins or retreats into regions of deeper bed topography, these banks remain grounded, while the rest of the ice sheet decouples from the bed, begins floating and forms an ice shelf (Shipp et al., 1999). This remaining grounded ice on bathymetric highs forms pinning points.

Pinning points are regions of locally grounded ice within a floating ice shelf (Matsuoka et al., 2015). The friction between the bed and ice base at these points impart a critical resisting force to the discharge of upstream ice; an effect known as buttressing (Thomas, 1979; Dupont & Alley, 2005). Since the base of ice shelves is flat relative to the underlying bathymetry, the morphology of the seafloor is the dominant controls the location and geometry of these pinning points. The bedrock topography has been thought to be relatively constant over a millennial timescale, meaning that pinning points geometries vary mostly by temporal changes in the ice thickness. However, recent studies of glacial isostatic adjustment, the vertical rebound of the Earth following deglaciation, throughout West Antarctica have demonstrated high spatial variability and short (multi-centennial-to-millennial) timescales for these vertical land movements (Coulon et al., 2021; Barletta et al., 2018; Kachuck et al., 2020). As the bedrock beneath portions of West Antarctica continues to rebounds, the number and extent of these pinning points will likely increase, possibly providing a stabilizing effect to the ice sheet.

All of these above controls on ice dynamics imparted by the physiography of the bed rely on accurate knowledge of bed topography and bathymetry. Due to the inherently challenging nature of Antarctic fieldwork, and the logistical challenge of measuring bed elevations beneath thick ice, 50% of the Antarctic Ice Sheet is more than 5 km from the nearest measurement of bed elevation (Figure 1.1a, Morlighem et al., 2020). This value increases greatly if the floating ice shelves are included. For grounded ice, the dominant techniques for direct measurements of bed elevation data are airborne radio-echo sounding, over-snow radar, and seismic surveying (Figure 1.1b, Fretwell et al., 2013). In the open ocean, bathymetry data is typically collected with ship-borne multibeam echo sounding, seismic surveying (Figure 1.1b), or from satellite-altimetry. Acquiring bathymetry data beneath floating ice shelves presents

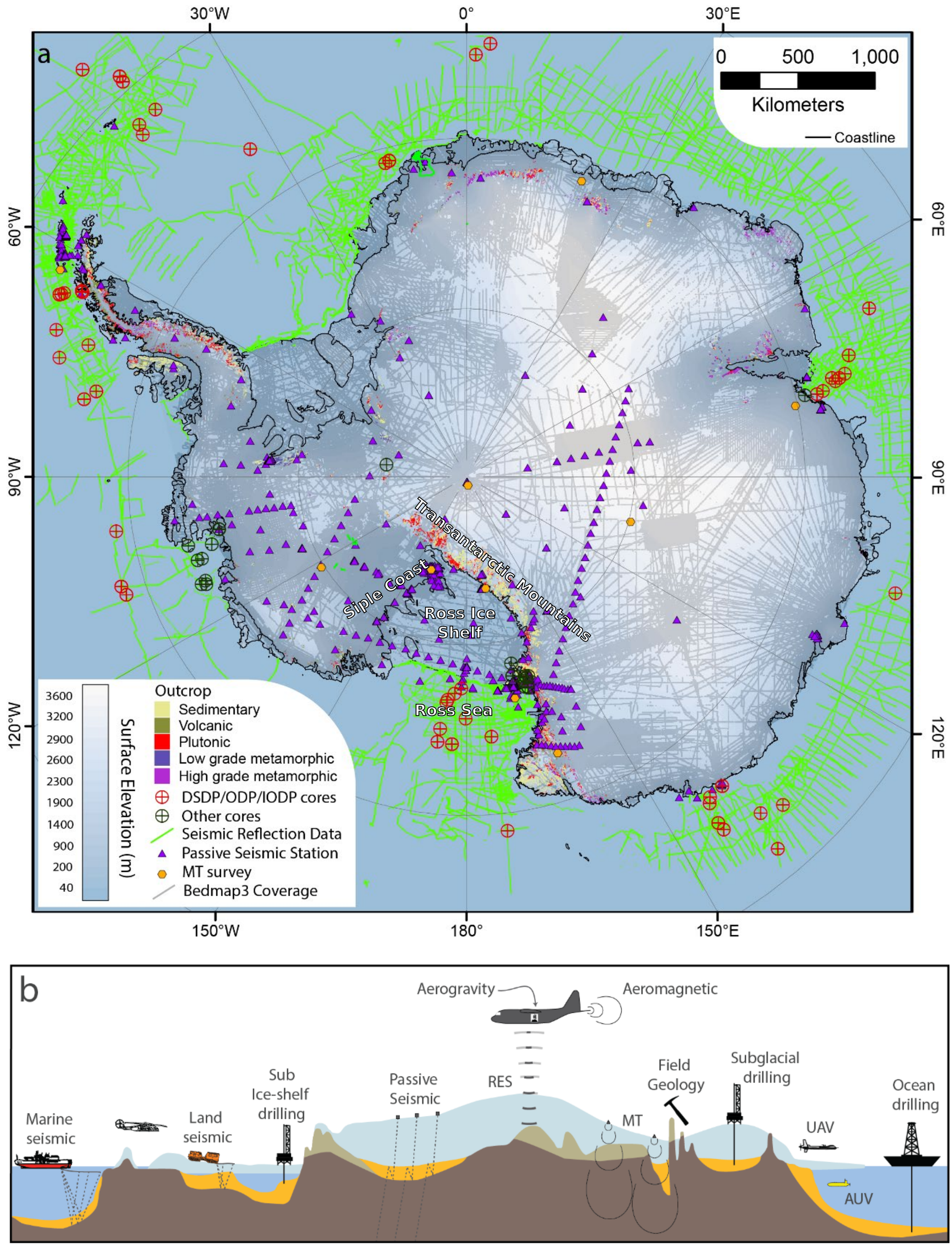

Figure 1.1: Summary of existing geologic and geophysical data for Antarctica. **a)** Map of data coverage in Antarctica indicating outcropping regions, drill core sites, seismic and magnetotelluric surveys, and bed elevation data points of Bedmap3, mostly from airborne radio-echo sounding (Frémand et al., 2022). **b)** Various methods of acquiring information sub-surface geology. Figure adapted from Aitken et al. (2023a).

a particular challenge. The efficient shipborne methods are unavailable since the ice shelves are persistent year-round, unlike the sea ice in the open ocean. Radio-echo sounding, either ground-based or airborne, cannot image through the water column. Direct observations through drilling are possible and exist, but typically require drilling through 100's to 1000's of meters of ice (Figure 1.1, Clough & Hansen, 1979;

Patterson et al., 2022). Autonomous underwater vehicles (Figure 1.1b) present another option, but are expensive and have limited range (Dowdeswell et al., 2008; Nicholls et al., 2006). The only feasible method of direct observations of sub-ice shelf bathymetry is over-snow seismic surveying (Figure 1.1b). However, for the vast area of many ice shelves, even sparse coverage ($\sim$ 50 km spacing) of seismic points across the ice shelf takes several field seasons of data acquisition (Bentley, 1984).

1.2.2 Geologic structures

Additional solid-earth influences on the overriding ice include the delivery of geothermal heat and subglacial water to the ice base and the vertical deformation of the bedrock in response to changing ice loads. Geothermal heat influences ice dynamics through several mechanisms; 1) increasing the temperature of the ice which lowers its viscosity, leading to enhanced flow via internal deformation (Llubes et al., 2006), 2) meltwater lubrication of the bed reduces friction, enhancing flow (Pollard et al., 2005), and 3) increasing the ability of the bed to deform via increased pore-fluid pressure, which increases ice flow (Tulaczyk et al., 2000). The latter two effects, while enhanced by geothermal heat through the melting of ice, also occur with simply the presence of liquid water at the ice-bed interface. As briefly mentioned in the above section, glacial isostatic adjustments of the bedrock following changes in ice load can influence the ice by altering the geometry and locations of grounded ice.

Each of these effects; geothermal heat flow, subglacial water availability, and glacial isostatic adjustment, are in turn influenced by geologic structures within the upper crust. A portion of subglacial water comes from either transport along the ice-bed interface, or from the melting of the ice base. However, an often overlooked component of the subglacial hydrologic system is groundwater stored in deep sedimentary aquifers. For example, hydrologic modelling of the ice streams of the Siple Coast (Figure 1.1a) estimated the components of the hydrologic budget to be 8% from local basal melting, 47% from inflow from the ice sheet interior, and 45% from groundwater reservoirs (Christoffersen et al., 2014). These modelling observations of extensive groundwater have been recently verified beneath the Whillans Ice Stream by a magnetotelluric survey. This survey imaged an extensive groundwater aquifer within a sedimentary basin, containing at least an order of magnitude more water than the shallow hydrologic system (Gustafson et al., 2022). The vertical flow of this basinal groundwater is controlled by the pressure of the overriding ice sheet. As this overburden pressure decreases with thinning ice, groundwater is discharged to the ice base (Gooch et al., 2016; Li et al., 2022). This discharge is likely concentrated along pre-existing weaknesses or impermeable surfaces, such as fault damage zones, or the margins of crystalline basement (Jolie et al., 2021). During this ice-induced hydraulic unloading, regional geothermal heat is advected along the fluid pathways, leading to potentially highly elevated heat flow delivered to the ice base (Li et al., 2022; Ravier & Buoncristiani, 2018). In addition to concentrating both subglacial water and geothermal heat, these faults, or more generically, regions of the crust which have experienced recent faulting, will respond differently to stresses induced by glacial isostatic adjustment. To a first order, the isostatic response of the solid-earth to changing ice load is controlled by the rheology of the mantle (Whitehouse et al., 2019). However, on a more local scale, pre-existing faults are shown to accommodate glacial isostatic rebound-induced stresses (Peltier et al., 2022; Steffen et al., 2021).

To be able to understand the above influence of the solid-earth on the ice, we must have some fundamental knowledge of the geologic structures beneath the ice. This includes knowing where sedimentary basins, and possible aquifers within, are located, where faults likely intersect the ice base, and the geometry of the crystalline basement. Each of these components is difficult to image directly. Drilling, seismic surveys, or geologic analysis of rock outcrops all provide valuable information but are not feasible to cover wide regions (Figure 1.1). Indirect methods are therefore needed. These include techniques such as gravity, magnetic, or electromagnetic methods. Each of these techniques records measurements of the spatial variation of a potential field, such as the Earth's gravity, magnetic, or electromagnetic fields. These fields are all partially dependant on a physical Earth property, such as rock density, magnetic susceptibility, or resistivity. From these relationships, sub-surface geologic information can be learned.

1.2.3 Basal roughness

The last major influence on the ice from the solid-earth we present is the roughness of the bed which the ice sheet flows over. This bed roughness is important on both a micro and macro scale. At a micro-scale, roughness is determined by the material which the bed is composed of. A bed of erosion-resistance crystalline basement, for example, can greatly hinder the flow of ice. This material results in high friction with the ice base, slowing the sliding of ice (Bell et al., 1998). Conversely, beds composed of fine-grained tills allow fast ice flow. This fast flow is predominantly due to deformation within the till as the ice flows (Alley et al., 1986). In between the end members of crystalline basement and fine grain till are lithified sedimentary rocks, for example. This type of bed may initially lead to high friction with the ice, but due to their high erodability, sedimentary rock will quickly generate till (Anandakrishnan et al., 1998). A macro-scale view of basal roughness is also important for ice dynamics. As observed at the Siple Coast (Figure 1.1a) ice streams, there is a strong inverse relation between bed roughness, from scales of 5 km to >40km, and ice stream velocities (Siegert et al., 2004). The composition of the bed also plays an important role in the total effective resistance imparted on ice flow from pinning points (Still et al., 2019).

To best quantify the effect of basal roughness on ice dynamics, information on the material properties of the bed is needed. While sediment samples beneath the ice yield valuable information, they may only represent the bed at the specific location where they were sampled. The most fundamental information needed is the generic rock type of the bed, namely, is the bed loose, unconsolidated sediment, lithified sedimentary rock, or crystalline rock? Aitken et al. (2023a) provide a detailed review of Antarctica's sedimentary basins, and the methods employed to determine both the presence of sediment and the sediment thickness. These methods, as well as the methods described in the above sections, are shown in Figure 1.1, as reproduced from Aitken et al. (2023a).

With the dominant solid-earth influences on ice dynamics laid out, we will now introduce the study area of this thesis, Antarctica's Ross Ice Shelf.

1.3 Ross Ice Shelf

The Ross Ice Shelf is Antarctica's largest ice shelf ($\sim 480,000\ \mathrm{km}^2$), Figure 1.1). It is situated between the Transantarctic Mountains and Marie Byrd Land. It buttresses a catchment of ice that flows from both the East and West Antarctic Ice Sheets. This catchment contains 11.6 m of global sea level equivalent (Tinto et al., 2019; Fretwell et al., 2013; Rignot et al., 2011). Compared to many other ice shelves, the Ross Ice Shelf is currently relatively stable (Rignot et al., 2013; Moholdt et al., 2014). However, geologic evidence from throughout the Ross Sea and the Siple Coast shows that in the past ~7,000 years the shelf has experienced rapid destabilization, disintegration, and large-scale grounding line retreat (e.g., Venturelli et al., 2020; Naish et al., 2009). This major Holocene retreat is thought to have been primarily caused by ocean forcings (Lowry et al., 2019), as bathymetric troughs guided in the inflow of melt-inducing ocean circulations (Tinto et al., 2019). Once destabilized, the grounding line retreat from the outer continental shelf to the present-day location was controlled primarily by the physiography and geology of the bed (Halberstadt et al., 2016; Anderson et al., 2019). This shows the importance of the solid-earth's influence on the dynamics of the Ross Ice Shelf.

1.3.1 Past investigations

By examining solid-earth influence on ice dynamics, we identified some key data needed to understand these influences. This data included onshore bed topography, offshore bathymetry, the distribution of sediment, and upper crustal structures such as faults and the topography of the basement. Here, we summarize the history of data collection in the Ross Ice Shelf region specific to these geologic and physiographic features. Geological and geophysical exploration has occurred in the Ross Embayment for over a century. The earliest of these include the 1901-1904 *Discovery* expedition, the 1907-1909 *Nimrod* expedition, and the 1910-1913 *Terra Nova* expedition. These expeditions laid the groundwork of interest in the Ross Embayment from a scientific perspective. The first major survey of the Ross Ice Shelf was part of the 1957-1959 International Geophysics Year traverses. The three over-snow traverses all included a portion of the ice shelf and collected radar, gravity, and seismic data to determine ice thickness, surface elevation, and bed elevation (Crary, 1959). These surveys produced early evidence of the extensive below-sea-level bed, thin crust, and distinct geologic provinces throughout West Antarctica (Bentley et al., 1960). In the 1970s the Ross Ice Shelf Geophysical and Glaciological Survey (RIGGS, Bentley, 1984) consisted of a systematic grid of seismic surveys over the entire ice shelf with an average spacing between survey points of 55 km. After the RIGGS survey, there were a total of ~ 223 point-source seismic surveys across the ice shelf, all yielding sub-ice shelf bathymetry depths. Of these, eight reported sediment thicknesses beneath. Several faults were hypothesized, based on 2D gravity profiles conducted at many of the stations (Greischar et al., 1992). Since the 1970s, there have been many additional local surveys on the ice shelf, but these have been focused along the grounding zones (e.g., Patterson et al., 2022; Horgan et al., 2017; Muto et al., 2013a; Stern et al., 1994; ten Brink et al., 1993; Wannamaker et al., 2017). The next, and most recent major data-collection campaign on the Ross Ice Shelf was the ROSETTA-ice project.

The Ross Ocean and ice Shelf Environment, and Tectonic setting Through Aerogeophysical surveys and modelling project (ROSETTA-ice, Tinto et al., 2019), was a 3-season (2015-2017) airborne geophysical survey of the Ross Ice Shelf. It flew a regular grid of flight lines, with nominal N-S and E-W line spacings of 10 and 55 km, respectively. During each flight, various geophysical data was collected, including ice-penetrating radar, gravity, magnetics and laser altimetry. So far, these ROSETTA-ice data have been used to begin characterizing the geologic nature of the crust (Tinto et al., 2019), to model the depths to the sea floor (Tinto et al., 2019), and to quantify basal melt (Das et al., 2020).

Following 60 years of surveying and exploration of the Ross Ice Shelf, our fundamental understanding of the subglacial geology and physiography is still lacking. For an area almost twice the size of New Zealand, we have approximately 8 locations of reported sediment thickness, several hypothesized locations of faults, gaps of over 100 km without bathymetric depths, and limited understanding of our uncertainty in the bathymetry where it has been modelled/interpolated. With this, we propose several research questions which we aim to answer in this thesis.

1.4 Research questions

The aim of this thesis is to improve our geologic knowledge beneath the Ross Ice Shelf in order to better understand the past, present, and future interactions between the ice, ocean, and solid-earth. We aim to accomplish this by answering the following questions:

1. What is the geologic structure of the upper crust beneath the Ross Ice Shelf? If there are sediments, what is their thickness and distribution? Where are the major faults likely located?

2. How can bathymetry beneath an ice shelf best be modelled? Are there further improvements that can be made to the gravity-inversion process? What are the predominant sources of uncertainty, and how can these be limited?

3. How deep is the bathymetry beneath the Ross Ice Shelf and where are we most and least certain about it?

4. What are the geologic controls on the Ross Ice Shelf's stability?

1.5 Outline

This thesis is comprised of five chapters.

This chapter, Chapter 1, establishes the context behind the research, introduces the study region, proposes a series of research questions, and contains an outline of this thesis.

Chapter 2 is adapted from a journal paper submitted to Geophysical Research Letters (Tankersley et al., 2022), reformatted to be included in this thesis. It presents a model of the basement topography, and overlying sediment distribution, beneath the Ross Ice Shelf. We used airborne magnetic data from the ROSETTA-ice project, and a depth-to-magnetic source technique to model the sediment-basement contact. This revealed large-scale, fault-controlled extensional basins throughout the sub-Ross Ice Shelf crust. From this, we were able to draw a wide range of inferences on the likely influence of this basement topography on the past, present, and future ice sheet, as well as some tectonic implications. These results provided the first holistic view of the upper crust beneath the Ross Ice Shelf.

Chapter 3 detailed our development of a method to model the depth to the sea floor beneath a floating ice shelf. This method is a gravity inversion, where observations of changes in Earth's gravitational field are used to model bathymetry beneath an ice shelf. We developed open-source Python code with the aim for other researchers to utilize the inversion. We tested the inversion against a suite of synthetic and semi-realistic data. This confirmed the feasibility of using gravity data to attain bathymetry depths in an Antarctic setting. Additionally, these synthetic tests revealed the relative importance of various aspects of a gravity inversion. These included the importance of *a priori* constraints on the bathymetry, the large errors which can be introduced during the removal of the regional component of gravity, and several suggestions for optimal survey design to minimize error in the resulting bathymetry model. Our use of Monte Carlo simulation provides both a spatially variable estimation of uncertainty in the resulting bathymetry and an estimate of the various sources of this uncertainty.

Chapter 4 used the inversion algorithm developed in Chapter 3 to create a new bathymetry model and associated uncertainties beneath the Ross Ice Shelf. Our model shows some major differences with past bathymetry models, highlighting areas of the ice shelf that should be carefully considered in future surveys. These include a deeper bathymetric trench along the Transantarctic Mountains, a thicker ocean cavity along a portion of the ice front which may allow the incursion of warm ocean waters and a deeper ground line along the Siple Coast. Our uncertainty analysis shows the region of highest uncertainties is along the Transantarctic Mountain Front. Within this chapter, we perform a comprehensive review of past bathymetry-gravity inversions, for all Antarctic studies, and several Greenland studies. This highlighted some key differences, which we believe we have improved on.

Chapter 5 presents a synthesis of the 3 research chapters, and provides a discussion of the research questions. Various future works are suggested and the main conclusions of this thesis are presented. The research chapters in this thesis were written with the intent to publish, including Chapter 2 which is already published. Therefore, I have chosen to keep the style of writing consistent throughout the thesis, with the use of plural possessive pronouns ("we") instead of singular ("I").