Contents

1

The Antarctic Ice Sheet Puzzle

1.1 Prelude

Today Planet Earth is in trouble. Several decades of scientific observations and studies have revealed the progressive and rapid deterioration in the health of our world's natural environment. Increasingly, alarms are being sounded regarding the dependence of humanity on the use of fossil fuels. The emissions from their combustion have dramatically increased the quantity of greenhouse gases in the atmosphere. The result is a world that continues to lurch towards disastrous warming, and despite warning calls to governments, there has been insufficient application of mitigation measures or preparedness to adapt to a new order. The fate of millions of individuals—their lives, livelihoods, and heritage—hangs on a thread as sea levels rise inexorably, storms and extreme weather events become more prevalent, and heat waves and wildfires increasingly threaten cities and the countryside.

The great ice sheets in Greenland and Antarctica, the latter the size of Europe, play a key role in the climate story and occupy a central stage in the long-term well-being of our world. On the one hand they reveal, through physical and chemical analysis of their layers of accumulated snow and ice, a remarkable and detailed record of changes in climate extending back 800,000 years. On the other hand, the destiny of the ice locked away in the ice sheets is crucial to future sea levels. The reduction in size of the ice sheets is already contributing to a steady rise in sea level—20 mm in the last two decades.[2] This shrinking is not purely a matter of melting around the periphery in response to atmospheric and ocean warming. These external forcings

[2] IPCC: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte, V; et al. (eds.), Cambridge: CUP.

are having complex effects on the flow and stability of immense ice drainage basins that have the potential to discharge substantial additional volumes of fresh water into the ocean. Furthermore, these current changes are committing our world to sea-level rise for many centuries to come.

To understand the response of the ice sheets to climate, sophisticated models have been developed and are continuously being refined. All require data on the glaciological characteristics of the ice sheets. Of fundamental importance are the shape, thickness, bed topography, basal conditions such as melting or freezing, the net gain or loss of mass in the form of snow and ice, and other internal indicators of past flow or changes of state. The technique of radio-echo sounding (RES) and the many surveys that were undertaken principally in Antarctica in the late 1960s and '70s that form the substance of this book yielded the first comprehensive database for many of these parameters. They are affording, in several instances, the baseline from which we can assess the changes in ice volume and behaviour that will continue to challenge the environmental conditions of our planet. Before embarking on the story of these explorations, however, it is salutary to look back to the early questions about Antarctica and the search for methods to probe its icy carapace.

1.2 Some History

As soon as humans spied and later set foot on the remote Antarctic continent in the second decade of the nineteenth century and became aware of its ice cover they quickly desired to know more of its extent, shape, thickness, and behaviour. Exploratory ventures of the early part of that century—for example, the expeditions of James Clark Ross, Charles Wilkes, and Dumont D'Urville—brought back tantalising reports to Europe and North America of this enormous frozen region (Figure 1.1[3]). Their findings and records fed the fecund minds of natural scientists and learned societies and gained prominence in contemporary texts about the natural world.

James Croll, Robert Ball, James Geikie, and others—seized by these accounts—speculated on their significance and interpreted their wider implications. Sir Robert Ball, Lowndean Professor of Astronomy and Geometry at the University of Cambridge, ventured his thoughts on the matter

[3] Captain Sir James Clark Ross (1847) *A Voyage of Discovery and Research in the Southern and Antarctic Regions, during the Years 1839–43*, in two vols, London: John Murray.

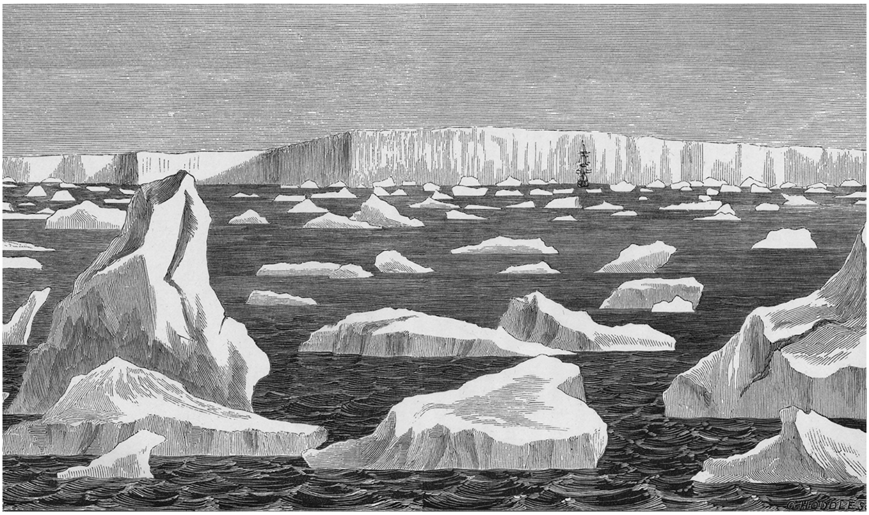

Figure 1.1. The Great Ice Barrier (now known as the Ross Ice Shelf). (From a drawing by Sir James Clark Ross; see footnote 3).

in a little book, *The Cause of an Ice Age*, published in 1892: 'It seems, however that in its [Antarctica's] vicinity lies an extensive tract which is crushed under an ice-sheet far transcending, both in area and thickness, the pall which lies over Greenland. From the dimensions of the Antarctic icebergs, it becomes possible to estimate the thickness of the layer of ice, from the fringe of which those icebergs have broken away. It is now generally believed that the layer of ice which submerges the Antarctic continent must have a thickness amounting to some miles'.[4] A few years earlier, James Croll had made calculations on the possible depth of the ice sheet. He based his estimate on rudimentary notions of the flow of an ice mass which gave a depth in the centre of the continent of 39 km![5] Croll did consider this value excessive and revised his numbers downwards, also referring to the known thickness of icebergs, and gave as his best guess a thickness of 4 mi (6 km). Both Ball and Croll were remarkably close to what we know today as the thickest ice, which is just a shade under 5 km deep.[6]

[4] Ball, R (1892) *The Cause of an Ice Age*, 2nd ed., London: Kegan Paul, Trench, Trübner, 180pp.

[5] Croll, J (1875) *Climate and Time in Their Geological Relation*, London: Stanford, 577pp.

[6] Robin, G de Q, quotes an 1879 article by Croll that gives the thickness as 3 mi (4.8 km). 'The thickest ice measured by the SPRI RES programme was 4776 m in the subglacial Astrolabe Basin of Wilkes Land (footnote 1). A new maximum from the same area was reported in 2013 of 4897 m by the

It was not until the advent of the twentieth century that the prospect materialised of being able to gain some more exact measure of these large ice masses. Notions of drilling through the ice were entertained but soon abandoned after the deepest holes extended only a few tens of metres. Eric von Drygalski during his 'Gauss' expedition (1901–1903) attempted to bore a hole and reached about 30 m; the technology was incapable of penetrating to any great depth.[7] However, by the 1920s, geophysicists had devised methods of sounding through rock strata using sound waves generated by near-surface explosions. Such seismic sounding was initially applied to the exploration for oil—by identifying suitable rock structures for later drilling—and it was not long before the technique's potential was appreciated for the depth sounding of glaciers. Initial early exploration in the European Alps confirmed that the albeit rudimentary technique held promise for the great ice sheets. The first to grasp both the significance and the opportunity was the legendary German meteorologist Alfred Wegener. Although noted for his exposition on continental drift, Wegener became fascinated in his later career by the polar regions and organised expeditions to explore the geophysical conditions in Greenland. Pioneering the seismic method with an early apparatus (Figure 1.2), Wegener's team was able to undertake the first dependable measurements of Greenland ice during his 1929–31 expedition, when the team achieved a reliable determination of 2000 m.[8]

Such experimental forays in Greenland were not pursued further until after World War II, when the French Expéditions Polaires Françaises commenced activities under the charismatic leadership of Paul Emile Victor.[9] Using more modern electronic equipment, Alain Joset and Jean-Jacques Holtzscherer made more than 400 spot soundings in the central regions of the ice cap and revealed depths of over 3000 m. These measurements demonstrated that within the interior of this large island the bedrock was below sea level.[10] Such expeditions provided clear expectations that similar

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Bedmap consortium (see Fretwell et al. (2013) (footnote 368). The average ice thickness of the whole continent by the SPRI analysis was 2160 m, and by the Bedmap consortium, 2126 m.

[7] Fogg, G E (1992) *A History of Antarctic Science*, Cambridge: CUP, 483pp.

[8] Sorge, E (1933) The scientific results of the Wegener expeditions to Greenland, *Geographical Journal* 81 (4): 333–44; Brockamp, B; Sorge, E; and Wölken, K (1933) Bd. II: *Seismik, Wissenschaftliche Ergebnisse der Deutschen Grönland-Expedition Alfred Wegener 1929 und 1930–31*, Leipzig: F A Brockhaus.

[9] I had the privilege of a most convivial meeting and lunch with Victor many years later when he was a tax exile from mainland France, living on a motu in the lagoon of Bora Bora in French Polynesia.

[10] Joset, M A; and Holtzscherer, J-J (1954) Détermination des épaisseurs de l'inlandsis de Groenland, *Annales de Géophysique* 10:351–81.

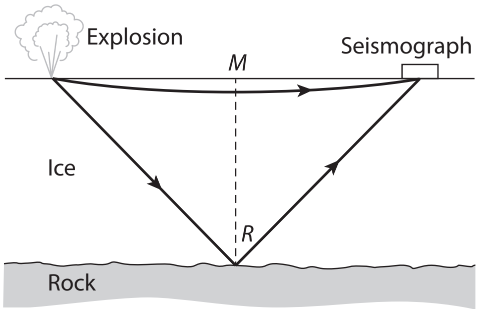

Figure 1.2. The seismic technique as used on the Wegener Expedition (R is the point of reflection at the bed, and M is the point vertically above it on the surface). (From Sorge (1933); see footnote 8).

thicknesses were to be encountered in Antarctica. But transferring the technology south was a much greater logistical and costly enterprise, so much so that Richard Foster Flint, writing in the first edition of his seminal textbook, *Glacial and Pleistocene Geology*, published in 1957, stated: 'The thickness of the ice sheet is virtually unknown except along a single seismic traverse, 600 km long, near the margin, where the maximum thickness is 2,400 m'. (p. 42). We shall return to these early seismic forays and the more extensive programmes of sounding conducted during and after the International Geophysical Year (IGY) (1957–58) in the next chapter, but we need to investigate further the 'single seismic traverse line' that Flint reported.

The Norwegian-British-Swedish Expedition (NBSE), which operated between 1949 and 1952, was a post–World War II collaborative operation that set the standards and logistic template for much of what was later undertaken in the IGY; it was also the first and one of the most successful examples of international scientific cooperation in Antarctica. The expedition was the brainchild of Hans W:son Ahlmann, professor of physical geography at the University of Stockholm, and one of an early and influential group of scientists with a keen interest in the study of the polar regions and glaciology. The expedition developed many of the techniques which would be adopted by all major scientific expeditions thereafter. Dr Albert 'Bert' Crary (chief scientist of the United States Antarctic Research Program in the 1960s) set the expedition in context some years later: 'The era of extensive exploration can be said to have had its beginning in the Norwegian-British-Swedish

Expedition.'[11] The story of the expedition was told in the official account by the leader, John Gaeiver, not long after its return[12] and latterly by Charles Swithinbank[13] in a very readable account from the perspective of one of the young scientists in the party. Several scientific reports were produced which are still of considerable value today.

A major objective of the expedition was to conduct seismic sounding of the ice thickness. This work was to be undertaken by tracked vehicles during an oversnow traverse across the floating ice shelf by the coast and thence onto the grounded ice sheet of the high polar plateau as far inland as the fuel supplies and terrain would allow. The person in charge of this programme was Gordon Robin, an Australian physicist who had previously worked as a meteorologist with the Falkland Islands Dependencies Survey (FIDS—the precursor to the British Antarctic Survey) on Signy Island in the South Orkney Islands.[14] Robin's painstaking and tireless efforts to achieve consistent and dependable seismic results were probably the crowning glory of the NBSE, and his pioneering techniques and experience were the model for later sounding campaigns. Robin's interest in probing the ice sheet and investigating its physical properties and behaviour did not diminish upon his return to Britain in 1953.

In 1955 Robin took the directorship of the SPRI at Cambridge University and continued to pursue his glaciological interests (Figure 1.3). With the appointment of Dr Stanley Evans to the Institute in 1959 Robin found another scientist with complementary experience in remote sounding (Figure 1.4). Evans had spent time at the British base of Halley Bay during the IGY, studying the ionosphere. It was his expertise in radio frequency research combined with Robin's glaciological background that spawned the development of a new and highly productive technique that revolutionised the study of glaciers and ice sheets—radio-echo sounding (RES). The RES method and its application engaged the author of this book as a young graduate student in the late 1960s and consequently dominated a significant part of his career. To tell the story fully of how this new technology evolved and became the standard for penetrating ice sheets and glaciers we

[11] Crary, A P (1962) The Antarctic, *Scientific American*, 207 (3): 60–73.
[12] Gaeiver, J (1954) *The White Desert*, London: Chatto and Windus, 304pp.
[13] Swithinbank, CWM (1999) *Foothold on Antarctica*, London: Longman, 260pp.
[14] Drewry, D J (2003) Children of the 'Golden Age': Gordon de Quetteville Robin, *Polar Record* 39 (208):61–78.

Figure 1.3. Dr Gordon de Quetteville Robin during his time as director of the SPRI at the University of Cambridge between 1955 and 1983. (Courtesy SPRI).

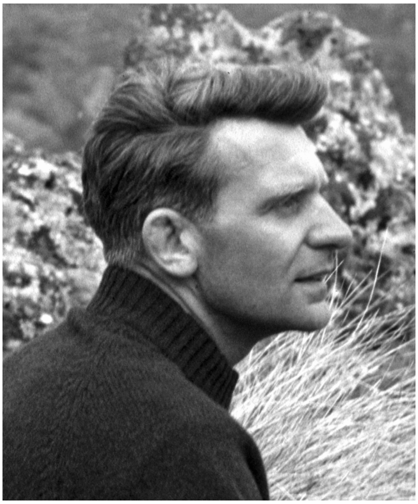

Figure 1.4. Dr Stanley Evans, in New Zealand, 1969.

must first travel back to the early days of seismic sounding and the work by many countries, but notably that of the United States and the then Soviet Union. Their efforts provided us with the first glimpse of the true dimension of the vast ice sheet of Antarctica and what lies beneath its icy shell, and that stimulated the development of alternative techniques.

Index

Page numbers in *italics* refer to figures and illustrations.