1: Introduction

1.1 WHAT IS GLACIAL GEOLOGY AND WHY IS IT IMPORTANT?

Glacial geology is the study of the landforms and sediments created by ice sheets and glaciers, both past and present. Within Earth history, ice sheets and glaciers have grown and decayed many times, making them a key part of the Earth's environmental system (Box 1.1). The present landscape in many mid-latitude areas is a function of the ice sheets and glaciers that grew and decayed during the Cenozoic Ice Age. During the Cenozoic – the past 65 million years – the Earth's climate has changed dramatically. The Antarctic Ice Sheet developed, followed by ice sheets in Greenland and elsewhere in the Arctic north. Later, large mid-latitude ice sheets developed in North America, Scandinavia, Europe, New Zealand and

BOX 1.1: HISTORY OF ICE ON EARTH

Ice has been part of the Earth's environmental system at several points throughout its 4.6 billion year history, and the passage of ancient ice sheets is recorded predominantly by glaciomarine sediments deposited and preserved in a variety of geological basins (Eyles, 2008). Much of this record can be interpreted by using our present understanding of glacial processes and products to interpret the past. In essence this is the application of the fundamental geological principle of uniformitarianism – the present is the key to the past. However, the Earth's Neoproterozoic glacial record challenges this idea. During the late 1990s the 'Snowball Earth' concept emerged (Hoffman and Schrag, 2002). The 'Snowball Earth' hypothesis envisages a series of cataclysmic global glaciations in which glacial ice reached tropical latitudes and the

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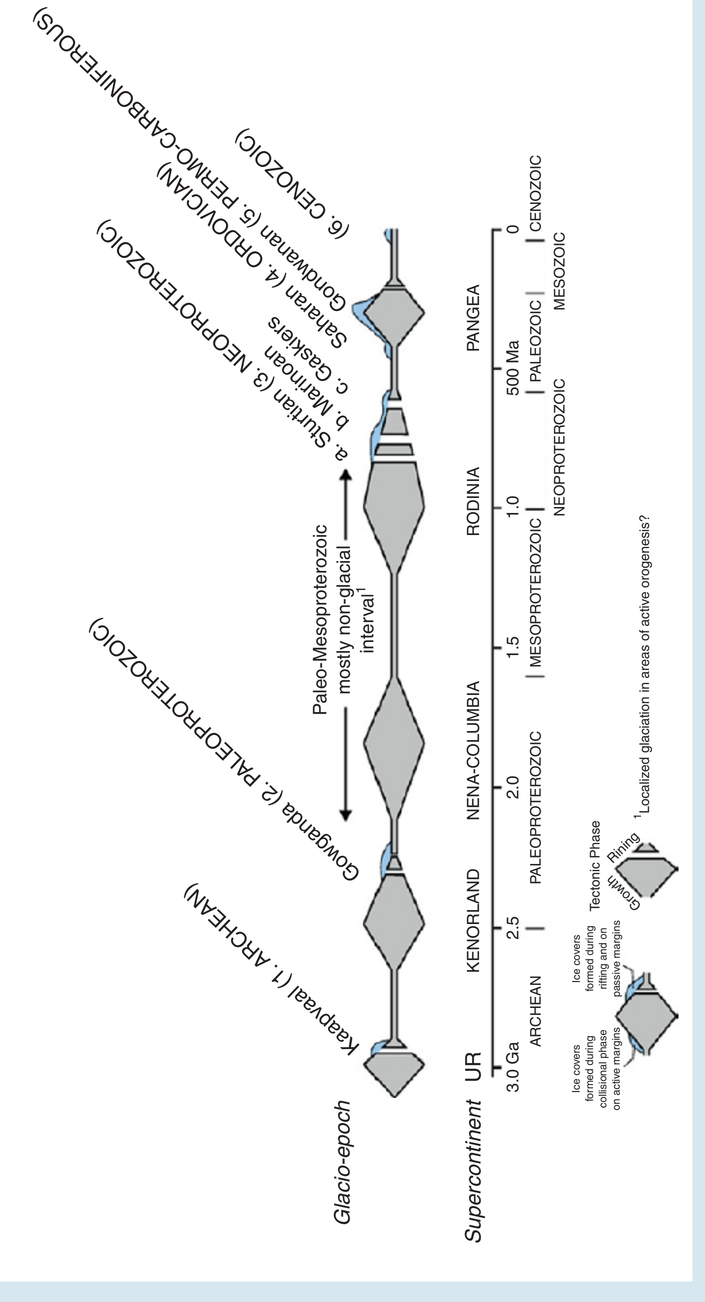

Glacio-epoch
Supercontinent
Kaapvaal (1. ARCHEAN)
Gowganda (2. PALEOPROTEROZOIC)
Paleo-Mesoproterozoic
mostly non-glacial
interval[1]
a. Sturtian (3. NEOPROTEROZOIC)
b. Marinoan
c. Gaskiers
Saharan (4. ORDOVICIAN)
Gondwanan (5. PERMO-CARBONIFEROUS)
(6. CENOZOIC)
UR
KENORLAND
NENA-COLUMBIA
RODINIA
PANGEA
3.0 Ga
2.5
2.0
1.5
1.0
500 Ma
0
ARCHEAN
PALEOPROTEROZOIC
MESOPROTEROZOIC
NEOPROTEROZOIC
PALEOZOIC
MESOZOIC
CENOZOIC
Ice covers formed during collisional phase on active margins
Ice covers formed during rifting and on passive margins
Tectonic Phase
Growth
Rining
[1]Localized glaciation in areas of active orogenesis?

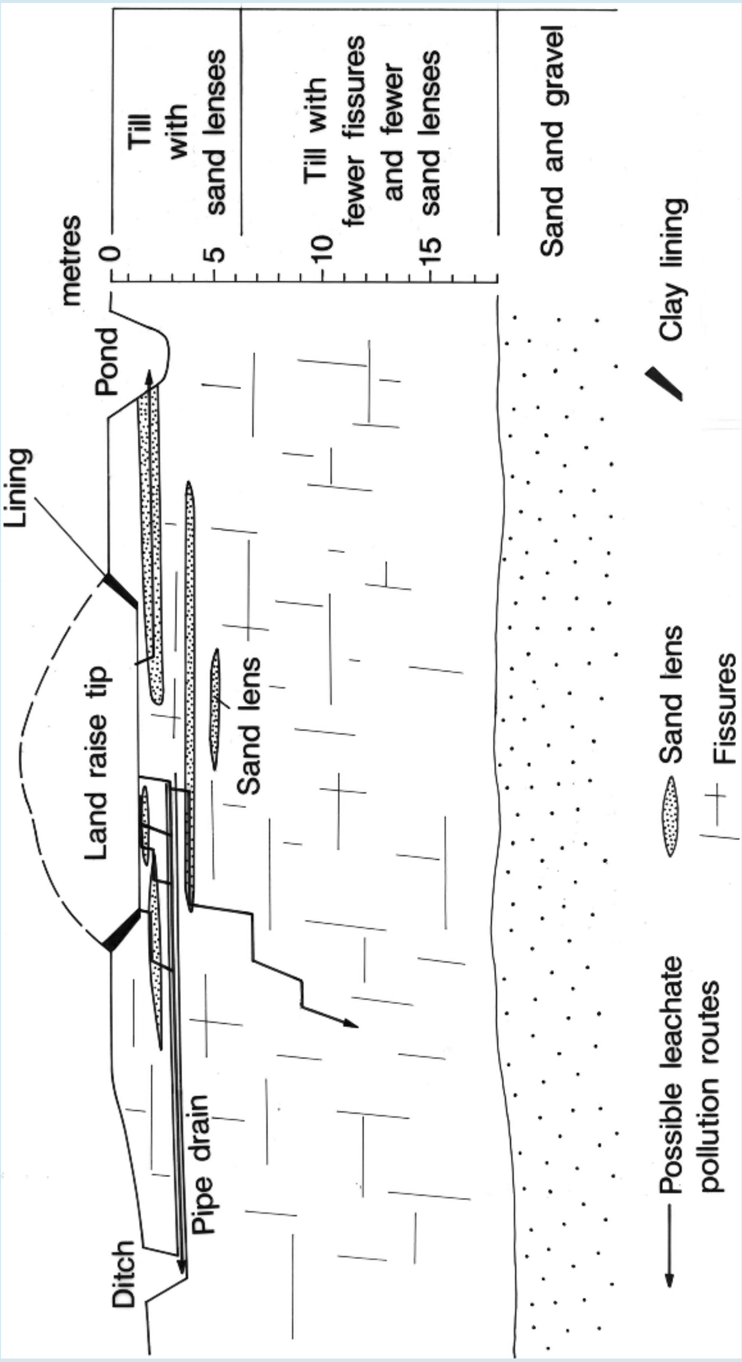
Earth's hydrological system almost completely shut down. The glacial processes involved in this global freeze would have been very different from those of the Cenozoic Ice Age. This hypothesis has become the source of considerable controversy over recent years and a number of alternative ideas have been advanced to explain the presence of glacial sediments at low latitudes at this time. One of these hypotheses, the Zipper Rift model, is based on the idea of adiabatic or uplift-driven glaciation associated with the progressive rifting of the Rodinia supercontinent. The debate surrounding 'Snowball Earth' continues to generate controversy as geologists attempt to decipher the record contained within the glacial rocks of the Neoproterozoic. The key to these debates lies in our ability to read the clues within these ancient glacial records and, in particular, in a rigorous understanding of contemporary glacial processes and products.

Sources: Eyles, N. (2008) Glacio-epochs and the supercontinental cycle after 3.0 Ga: tectonic boundary conditions for glaciation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **258**, 89–129. Hoffman, P.F. and Schrag., D.P. (2002) The Snowball Earth hypothesis: testing the limits of global change. *Terra Nova*, **14**, 129–55. Reproduced with permission from: Eyles, N. (2008) *Palaeogeography, Palaeoclimatology, Palaeoecology*, **258**, figure 1, p. 9].

BOX 1.2: CENOZOIC GLACIAL SEDIMENTS: AN ENGINEERING LEGACY

During the Cenozoic Ice Age approximately 30% of the Earth's land surface was glaciated and as a consequence over 10% of our land is now covered by glacial sediments – tills, silts, sands and gravels. In a country such as Britain this proportion is even higher. Any form of construction on or in these sediments must consider their engineering properties. At what angle will the sediment stand if excavated? How will they respond when loaded? How variable are they? How permeable are they? These questions can be answered only by a detailed knowledge of the sediments and of the processes that deposited them: the contribution of the glacial geologist.

A good example is provided by a proposed development at Hardwick Air Field in Norfolk. In 1991 Norfolk County Council applied for planning permission to build a waste hill (land raise) 10 m high to dispose of 1.5 million m^3 of domestic waste over 20 years. Crucial to their proposal was the assertion that the area was underlain by glacial till, rich in clay, which would act as a natural impermeable barrier to the poisonous fluids (leachate) generated within the decomposing waste. Normally an expensive containment


Ditch
Pipe drain
Land raise tip
Lining
Pond
Sand lens
metres
0
5
10
15
Till with sand lenses
Till with fewer fissures and fewer sand lenses
Sand and gravel
Possible leachate pollution routes
Sand lens
Fissures
Clay lining

liner is required to prevent contamination of the ground water by the leachate. This proposal became the subject of local debate and as a consequence the planning application was called to public planning enquiry in 1993. At this enquiry the objectors used a detailed knowledge of glacial till to argue that it was inadequate as an impermeable barrier in its natural state. Till contains fissures and pockets of sand through which the leachate may pass. The proposal was rejected, partly on the basis of this evidence. This example illustrates how knowledge of glacial sediments is vital to making engineering decisions within glaciated terrains.

Source: Gray, J.M. (1993) Quaternary geology and waste disposal in South Norfolk, England. *Quaternary Science Reviews*, **12**, 899–912. [Modified from: Gray, J.M. (1993) *Quaternary Science Reviews*, **12**, figure 9, p. 905].

Patagonia. These ice sheets dramatically changed the landscape beneath them and have left a record of their presence in the form of glacial landforms and sediments. This record shows that these ice sheets are not only a consequence of oscillations in global climate, which has driven their growth and decay with amazing regularity during the past two million years, but that they have also helped to drive climate change by modifying and interacting with the atmosphere. Understanding these ice sheets and glaciers is vital if we are to understand the mechanisms of global climate change.

In many parts of the world a distinct landscape composed of many different landforms and sediments was created by the glaciers of the Cenozoic Ice Age. This glacial landscape still survives today. It determines the distribution of valuable resources such as aggregates, and the way in which we build roads, railways, factories and houses (Box 1.2). The aesthetic appeal of this glacial landscape, to be found in many upland areas of North America and Europe, for example, is also the product of these glaciers. The spectacular mountain scenery is the result of glacial erosion, whereas glacial deposition often produces a gently rolling landscape. If we are to understand the form and texture of this glacial landscape we must understand the glaciers that produced it.

The landforms and sediments left by these glaciers are the clues from which they can be reconstructed and their behaviour studied. This subject, palaeoglaciology, is of increasing importance as we seek to understand how the glacial system interacts with other parts of the Earth's global system. By studying glacial landscapes and reconstructing the glaciers that created them we can examine the way in which glaciers grow, decay and interact with climate. From such research we can begin to predict what will happen when the mid-latitude ice sheets next return because, although the present is optimistically termed the Postglacial, there is no reason to suppose that large glaciers or ice sheets will not return to the mid-latitudes in the future.

1.2 THE AIM AND STRUCTURE OF THIS BOOK

Glaciers are the scribes of the Cenozoic Ice Age and they have etched its story upon the landscape. It is a story that has been written repeatedly upon the same page with the successive growth and decay of each glacier. Each glacier has destroyed, remoulded or buried the evidence of earlier phases of glaciation. Deciphering the story of this complex geological record is therefore difficult and requires careful detective work. The landforms and sediments left by former glaciers provide the clues from which to reconstruct their form, mechanics and history. This book shows you how to interpret these clues.

We start first by looking at contemporary glacial environments around the world in order to illustrate the diversity of the glacial systems that exist today. This is followed by two chapters that introduce the basic mechanics of the glacial system to provide an understanding of how glaciers work. We explain how ice sheets and glaciers grow, flow and decay. In Chapters 5 and 6 we explore the processes of glacial erosion and consider the landforms that they create; landforms which can be seen in the landscape today and which provide information about the dynamics of the glaciers that created them. In Chapters 7–11 we tackle the processes of glacial sedimentation and landform development, all of which provide important evidence of glacier activity. The final chapter examines how we can use the clues in the landscape to reconstruct ancient glacial systems – the study of palaeoglaciology. Important terms in the text are highlighted in *italics* either when they are first used or when they are particularly pertinent to the subject being considered. Some terms therefore will appear in *italics* more than once.