Neogene environmental history deduced from glacigenic sediments on James Ross Island, northern Antarctic Peninsula

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Summary The stability, configuration and volume of the Cenozoic Antarctic Ice Sheet (AIS) are poorly known and contentious. Our investigation of late Neogene glacial and interglacial sediments from James Ross Island, northern Antarctic Peninsula, will inform this debate by providing critical new data from a part of the AIS that is particularly sensitive to climatic variability. James Ross Island contains the greatest number of Neogene sedimentary outcrops in Antarctica. Understanding the genetic history of these sediments will reveal critical information on the past behaviour and parameters of the Antarctic Peninsula Ice Sheet (APIS). The sedimentary lithofacies on James Ross Island include massive and bedded diamict and conglomerate, and laminated mudstone with dropstones. Our sedimentological analyses, including individual clast characteristics and fabrics, reveal a combination of basal tills, remobilised debris flow deposits, and glaciomarine sequences. Till micromorphology shows a high percentage of subglacial sediment deformation structures suggesting significant ice-bed coupling by the APIS. Whereas some glacigenic deposits contain only locally-derived clasts, others contain a high percentage of Antarctic Peninsula-derived detritus, indicating the influence of two scales of ice masses: a regional-scale APIS and a local ice cap similar to the glacial cover on James Ross Island today. The contact relationships between the glacial sediment and overlying volcanic rocks indicate that glaciation and volcanism were essentially contemporaneous, and the volcanic units have provided an excellent chronology for the glaciations, which is absent from Neogene sedimentary sequences elsewhere in Antarctica. A polythermal glacial regime is suggested for the Neogene glacial cover on James Ross Island, with conditions similar to the high Arctic today.

Citation: Nelson, A. E., J. L. Smellie, M. J. Hambrey, M. Williams, U. Salzmann, and M. J. Vautravers (2007), Neogene environmental history deduced from glacigenic sediments on James Ross Island, northern Antarctic Peninsula, in Antarctica: A Keystone in a Changing World - Online Proceedings of the 10th ISAES X, edited by A.K. Cooper and C.R. Raymond et al., USGS Open-File Report 2007-1047, Extended Abstract 058, 4 p.

Introduction

This study focuses on the late Neogene period between 2 and 10 Ma, when CO_2 emissions and temperatures reached the unprecedented magnitudes that are expected to recur this century. This paper and the results of a companion study of associated volcanic lithofacies (Smellie et al., 2007) aim to define the palaeoenvironmental history during the Neogene period in the northern Antarctic Peninsula region, particularly ice sheet parameters. They are intended to provide ground-truth as input to evaluate forward-looking, coupled atmosphere-ocean-biosphere-ice sheet climate models. The principal objective of this work is to better understand Neogene environmental conditions by examining glacial and interglacial sediments on James Ross Island. Goals are to determine the sediment provenance and thereby identify the likely scale of any ice sheet present (e.g. a regional-scale Antarctic Peninsula Ice Sheet or local ice cap); define the depositional setting (e.g. as debris flows or basal till); identify ice transport paths (e.g. subglacial, englacial supraglacial); establish the timing of geological events (glaciation and volcanism); and deduce critical parameters of the glacial cover (e.g. its overall configuration and glaciological class for multiple time slices).

The fieldwork for this project was completed between 2005 and 2007, in the James Ross Island region of northern Antarctic Peninsula (between 63.5° and 64.5° S; Fig. 1). James Ross Island is the largest island on the eastern side of the Peninsula. It is ice-capped but with extensive ice-free areas, and outcrops are dominated by volcanic rock as a result of 6 million years of eruptions from the Mount Haddington stratovolcano (Fig. 1). There are many reasons for conducting this study on James Ross Island: although mainly ice-capped, there are extensive ice-free areas of rock outcrop especially in the west, north and southeast; volcanic rocks are abundant and interbedded and can be used to constrain the chronology by Ar-isotope dating (Smellie et al., 2006); the area is particularly sensitive to climate change (Cook et al., 2005); and the area is easily accessible by ship.

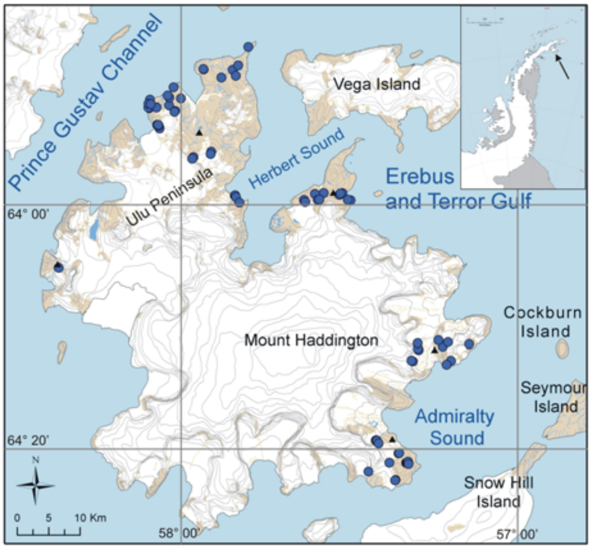

Figure 1 Map of James Ross Island, with localities of Neogene glacial sediments visited during the 2005-2007 field seasons noted.

The geology of James Ross Island has been extensively mapped by British Antarctic Survey (BAS) scientists throughout the last half-century during multiple geological field campaigns. Those workers noted the unsorted sediments dotted around the island in two distinct stratigraphic positions: unconformably overlying Cretaceous sediment at the base of thick Neogene volcanic rock sequences; and interbedded with the Neogene volcanic rocks themselves. Extensive isotopic dating of the associated lavas (by $^{40}Ar/^{39}Ar$) and shelly fossils within the sediments (by $^{87}Sr/^{86}Sr$) has resulted in a strong chronological framework (Smellie et al., 2006). There have been at least 50 eruptions in the last 6 m.y. (Smellie et al., 2007) most of which occurred during periods of ice cover, but which included at least three warm periods: 6.5-5.9, 5.03-4.22, and <0.88 Ma (with large errors, typically > 0.3 Ma; Smellie et al., 2006).

Using environmentally diagnostic glaciovolcanic characteristics of the James Ross Island lavas, it has proved possible to estimate palaeo-ice thicknesses based on features of lava-fed deltas on the island (Smellie et al., 2007). These indicate that the former ice cover was predominantly thin (200-350 m) but rarely increased to 600-750 m, and ice thicknesses increased toward the present day. The presence of fresh, unmodified surfaces above 600 m elevation indicate that there was never a “giant” ice sheet in the region at any time since latest Miocene time.

Until now, there has been only limited work on the Neogene glacial sediments on James Ross Island. Pirrie et al. (1997) formally defined the lithostratigraphy in terms of a Hobbs Glacier Formation (HGF), comprising two members: a lower diamictite and upper tuffaceous beds. Hambrey and Smellie (2006) investigated a few widely-distributed localities and proposed debris flow and basal till genetic interpretations of the different lithofacies. This study expands the previous work and incorporates new information from about 40 of the 60 outcrops recently discovered on the island. Our intention is to substantially improve our knowledge of the configuration, dynamics and ice—bed coupling characteristics of the Neogene APIS by a focused sedimentological study in the James Ross Island region.

By contrast, Neogene interglacial sediments are known to crop out on Cockburn Island, a small island 6 km east of James Ross Island (Jonkers, 1998; Jonkers and Kelley, 1998). Again, a formal lithostratigraphy has been defined, renaming the previously-known ‘pecten conglomerate’ found on Cockburn Island as the Cockburn Island Formation (CIF), Although initially dated at about 3 Ma (Jonkers, 1998), more recent $^{87}Sr/^{86}Sr$ dating suggests that it may be significantly older (c. 4.8 Ma; McArthur et al., 2006). Within the glacigenic sediment around James Ross Island are found fossil shell material scraped up from marine sediments that formed during late Neogene interglacials. In those warmer periods, abundant shallow marine organisms (e.g. molluscs, colonial bryozoans, foraminifers) flourished. By studying the fossils within glacial and interglacial sediment, we can further understand the marine environment around James Ross Island during the interglacials.

The fieldwork methodology involved a sedimentological approach based on lithofacies identification and analysis, stratigraphic logging, contact relationships (particularly relationships between glaciation and volcanism), clast characteristics (roundness, shape and fabric) in relation to ice transport paths (subglacial versus englacial), and sampling. Till micromorphology was determined from larger-than-normal (11 cm x 7.5 cm) thin-sections of impregnated samples, as it is sediment structure rather than mineralogy that is being observed.

Discussion

In the two field seasons thus far, over sixty localities of Neogene glacial sediments have been visited (Fig. 1). The lithofacies observed include massive diamict and conglomerate, weakly- and well-bedded diamict, and laminated mudstone with dropstones (Fig. 2a-b), which were formed as basal till and glaciomarine sediment, as well as remobilised versions of the same. Thin-section analysis of glacigenic sediment revealed pervasive shear-like fabrics in some units, such as rotational structures, grain fractures and linear structures. These formed by subglacial sediment deformation during glacier overriding, and indicate strong coupling at the ice-bed interface (Menzies, 2000; van der Meer et al., 2003).

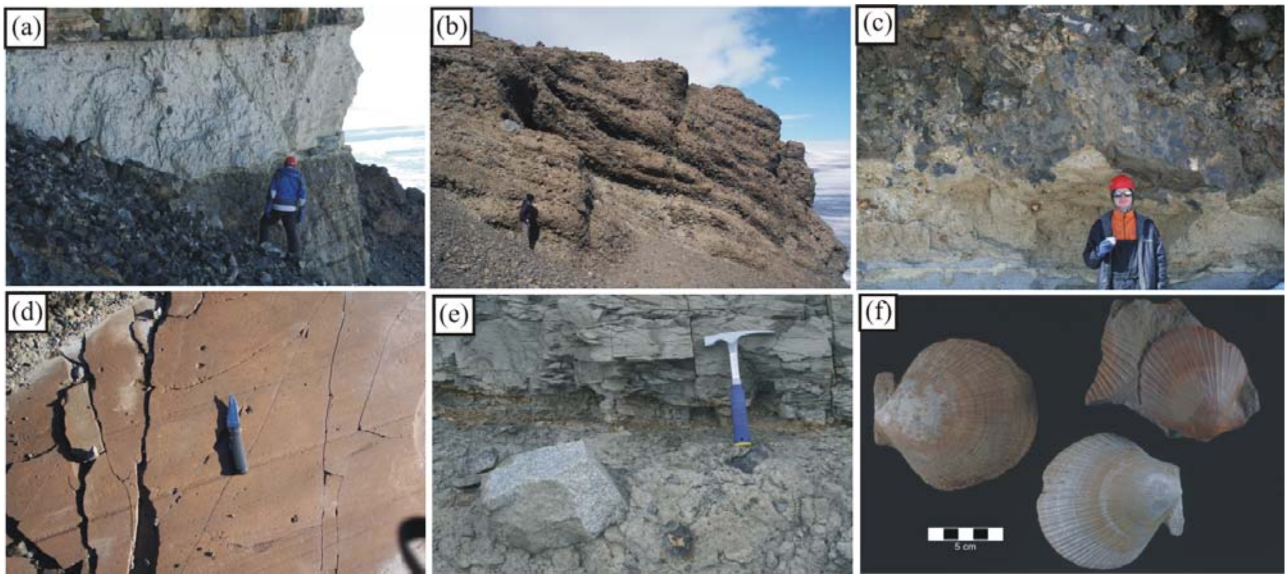

Figure 2. Photographs of Neogene-age glacigenic sediment on James Ross Island. (a) Massive, matrix-supported diamictite. (b) Bedded conglomerate and diamictite. (c) Mixing at contact between glacigenic sediment and volcanic breccias. (d) Glacial striae on Cretaceous bedrock. (e) Hobbs Glacier Formation (HGF), with lower diamict and upper tuffaceous members. Note boulder erratic in lower member. (f) Intact fossil pectens from the Cockburn Island Formation (CIF).

Timing of geological events

The nature of the contacts between the glacial sediment and the overlying volcanic units is key to understanding the timing of glaciation and volcanism. Three different contact relationships were observed. In cases where laminated tuffaceous sandstone/mudstone (i.e. HGF upper member) intervenes, contemporaneity between volcanism and glacial deposition is not clear. Conversely, intimate intermingling between diamict and hyaloclastite unambiguously indicates contemporaneous deposition. The dense lavas loaded rapidly onto saturated unconsolidated glacigenic facies, which, in their over-pressurized and less dense state, were squeezed upwards (Fig. 2c). Lastly, the presence of far-travelled sheets of lava intruding diamict also clearly indicates volcanism contemporaneous with glacial deposition.

Scale of glaciation

A large percentage of the facies associations so far investigated on James Ross Island indicate the presence of a local ice cap, similar to that centred on Mount Haddington today. Possible basal till is preserved at several localities, based on the stratigraphic context, fabric data from the lithofacies, local (James Ross Island) provenance of clasts, and bedrock surfaces with striations orientated approximately radial to Mount Haddington (Fig. 2d). Many sites contain glacigenic sediments with striated and abraded clasts that also have the characteristics of remobilised glacigenic sediment or subaqueous gravity-flow deposits. Resedimentation of subglacially-deposited debris is a feature common in glacial environments but volcano-related effects, such as generation of large quantities of meltwater during overriding by lava-fed deltas, is likely to enhance instability in the subglacial sedimentary environment. As a result, it is possible that few of the primary glacial deposits (basal tills) remain undisturbed. The locally-transported sediment lacks evidence for overriding by the APIS, which may therefore have been deflected where it became confluent with the local ice cap at its western margin (cf. Hambrey and Smellie, 2006). This simple history of ice sheet- to ice cap-dominated deposition is supported by ice striations on glacially modified surfaces on the Ulu Peninsula, which indicate tangential ice transport (i.e. APIS-related), but which are radial to Mount Haddington elsewhere.

Unambiguous evidence for an expanded APIS is preserved at many localities, principally by the ubiquitous presence of numerous geographically widely-distributed Antarctic Peninsula-derived erratics in the HGF (Fig. 2e). The presence of lonestones within diamicts on southestern James Ross Island suggest that transport from the Antarctic Peninsula was mainly by icebergs. The diamictite there, which forms the lower HGF, is rarely more than a few metres thick, stratified, occasionally coarse-tail graded, contains large rafts of Cretaceous sediments, and carries clasts with encrusting bryozoans. Although the diamictite is typically two orders of magnitude thinner than many glaciomarine sequences (cf. Hambrey, 1994), the sedimentological characteristics suggest sediment that was subglacially-transported, deposited as proximal glaciomarine sediment, and finally reworked by subaqueous mass-flow processes.

The scale of glaciation in the James Ross Island area varied through time. Before the growth of volcanic edifices on James Ross and Vega islands, the Antarctic Peninsula Ice Sheet expanded across the region from the west. As the volcanoes became established, they developed their own ice caps, and it was in this context that most of the subglacial eruptive activity took place.

Fossil record

Fossils were recovered from three different sediment types in the lower James Ross Island Volcanic Group (JRIVG). They occur in sediments that accumulated during interglacial warm periods in shallow marine seas, typified by the CIF in its type area but also at Cape Gage (Jonkers et al., 2002); in glacigenic sediments (HGF) at the base of and interbedded with the lava-fed deltas; and, more rarely, in waterlain volcanic tuffs (Williams et al., 2006). The richest fossil assemblages from the interglacial marine sediments contain abundant intact pecten molluscs (Fig. 2f), bryozoans, barnacles, palynomorphs and foraminifers. Conversely, although the glacigenic sediments contain similar fossil assemblages to those of the marine interglacial sediments, they are dominated volumetrically by molluscs and are highly fragmented. $^{87}Sr/^{86}Sr$ isotopic dating of the latter has demonstrated a wide range of ages for these fossils, even in the same datums, consistent with glacial reworking (Smellie et al., 2006).

Thermal regime

The James Ross Island glacigenic facies are dominated by silty diamicton/diamictite and conglomerate, with clasts bearing the imprint of subglacial transport. Combined with the presence of striated surfaces, the glaciers that produced these attributes must have been wet-based. However, although there is evidence for considerable remobilization of sediment by gravity-flow processes (consistent with rapid but short-duration melting related to overriding lava-fed deltas), few substantial meltwater deposits have been observed. Overall, the amount of debris being transported was limited, and there are few supraglacial characteristics. Furthermore, apart from rare glacially-abraded pavements, no distinct glacial landforms are preserved. Taken together, these observations suggest that the glaciers were polythermal in character, at least when they were transporting and depositing sediment. The most likely palaeoclimate was one resembling the high-Arctic of today (e.g. mean annual temperature of around -5°C, as in Svalbard), in other words, marginally warmer than the present-day climate in the Antarctic Peninsula region.

Acknowledgements. This work contributes to a British Antarctic Survey investigation called Ice-House Earth: Stability or Dynamism (ISODYN). It also contributes to the SCAR initiative Antarctic Climate Evolution (ACE). We wish to thank the officers and crew of the HMS *Endurance* who supported this work during the 2005-2007 field seasons, and to Tim Burton, Tom Spreyer, and Mark Laidlaw for their field assistance during the two seasons. We also acknowledge the editorial assistance of Alan Vaughan.

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