Six million years of environmental (glacial - interglacial) conditions preserved in volcanic lithofacies of the James Ross Island Volcanic Group, northern Antarctic Peninsula

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Summary The Neogene geological record in the James Ross Island region (northern Antarctic Peninsula) is dominated by the products of at least 50 mainly effusive basaltic volcanic eruptions that are preserved predominantly as lava-fed deltas and a smaller number of tuff cones. The volcanism was persistent over more than 6 million years resulting in construction of an extensive volcanic field and one of the largest and longest-lived stratovolcanoes in Antarctica. Most of the eruptions took place during glacial periods, and interpretation of the deltas has enabled critical parameters of the palaeo-ice cover to be deduced for the first time, for multiple time slices. However, the resolution of $^{40}Ar/^{39}Ar$ dating of young basaltic lavas is relatively poor compared with the duration of glacial—interglacial periods and precludes any Milankovitch-scale cyclicity being identified - a problem that is now becoming acute in palaeoenvironmental investigations of this type. The period was characterised by a relatively thin glacier cover in this area, typically just 200-350 m, interspersed with fewer periods of thicker ice c. 600-750 m in thickness. The glacier cover increased in thickness toward the present. Significantly, no evidence was found for the "giant" ice sheets predicted by some studies, at any time during the last 6 m.y. The glacier cover was formed predominantly of ice (*sensu stricto*) that was wet-based, erosive and probably sub-polar (polythermal). If it reached the continental shelf edge, it must have had a low profile dominated for most of the period by a local ice cap that draped James Ross Island and was presumably confluent with the Antarctic Peninsula Ice Sheet along its western margin. These results are the first evidence for the morphology, thickness and thermal regime of the glacier cover in the northern Antarctic Peninsula region for the late Neogene period.

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Introduction

When volcanoes erupt beneath a glacier or ice sheet, the resulting sequences can retain information about that interaction preserved in the lithofacies and sequence architecture (e.g. Smellie, 2000, 2001; Tuffen et al., 2002; Schopka et al., 2006). That information can be used to deduce critical parameters of the coeval glacier cover and, thereby, to reconstruct the characteristics, morphology and dynamics of former ice sheets (Smellie and Skilling, 1994; Smellie, 2000, 2006; Smellie et al., 2006a). However, the use of glaciovolcanic sequences to interpret past ice sheets is a relatively young technique. In particular, currently very few environmental investigations of long-lived (> 700 ka) glaciovolcanic terrains have been published (e.g. Helgason and Duncan, 2001; Loughlin, 2002) and none discuss the coeval ice sheet configurations. The James Ross Island Volcanic Group (JRIVG) is a large (c. 6000 km^2), long-lived (> 6 m.y.) basaltic volcanic field situated in northern Antarctic Peninsula and dominated by the Mount Haddington stratovolcano. It is in a pivotal position (northerly latitude, low elevation) to record the dynamics of the adjacent Antarctic Peninsula Ice Sheet (APIS). The APIS is climatically highly sensitive and currently under environmental stress, as shown dramatically by collapsing ice shelves, retreating glaciers and accelerated glacier flow (e.g. Cook et al., 2005).

Although it is generally assumed that melting of the APIS is unimportant compared to the possible global impact of volume variations in the much larger East and West Antarctic ice sheets, the APIS may have contributed disproportionately to global sea levels in the past, and recent assessments suggest that at present it could be making a significant contribution compared to other sub-polar alpine systems (e.g. Alaska). Furthermore, the small APIS would have been sensitive to sea level changes imposed by changes in Northern Hemisphere and East Antarctic Ice Sheet grounded ice volumes, and so acted to magnify global changes throughout the Quaternary. Prior to c. 3 Ma, the history of the APIS would have been driven mainly by changes in the glacial state of the rest of Antarctica. However, quantitative ice sheet data for the Antarctic Peninsula region are virtually absent, and are remarkably few even for the Last Glacial Maximum (LGM), for which we have the greatest knowledge; only the ice sheet margins are relatively well defined at LGM (Heroy and Anderson, 2005). Finally, given the marginal position of the Antarctic Peninsula relative to the West Antarctic Ice Sheet, and its more northerly latitude than any other part of Antarctica, greater variability in the APIS might be expected. Therefore, we are motivated by the need for considerably better APIS information, particularly that deduced from terrestrial ice-proximal deposits. Virtually all the published information on the APIS is derived from oxygen-isotope and other comparatively distal proxy records in marine sediment cores and much of the published information only goes back to about 3 Ma (e.g. Barker and Camerlenghi, 2002, and citations therein). They give no information on local ice sheet parameters, such as thickness, surface elevation or thermal regime. Ice sheet volumes are thus only poorly constrained.

The aims of this and a companion study (Nelson et al., 2007) are to evaluate the volcanic and sedimentary processes and the environmental implications that affected James Ross Island and adjacent areas of the Antarctic Peninsula during late Neogene time, when multiple transitions occurred between subglacial to subaerial volcanic eruptions and glacial sedimentation. Exceptional rock exposure provides a unique opportunity to examine the relationships between volcanogenic and glacigenic strata, and to deduce a far more detailed understanding of the palaeoenvironmental history than has previously been possible. The volcanic investigation is relatively advanced compared with the sedimentary study, but both investigations are complimentary and together provide a much more holistic view. In this abstract, we report the results of a multidisciplinary investigation of the history of palaeoenvironments preserved in the late Neogene (< c. 6 Ma) volcanic sequences in the James Ross Island region. Our study shows that the environmental history preserved in the JRIVG is dominated by evidence for glacial conditions and we are able, for the first time, to define several of the critical parameters of the APIS, its overall configuration and its glaciological class for multiple time slices throughout the period. The quantitative data derived from our study will help to substantially improve the accuracy of predictive ice sheet models for the Antarctic Peninsula for the eruptive period.

James Ross Island – topography, climate and geology

James Ross Island is situated on the east flank of northernmost Antarctic Peninsula (Figure 1). The island measures 60 km in a SW—NE direction, 70 km NW to SE, and reaches almost 1.5 km at its summit (Mt Haddington). It has a gently dipping shield-like morphology flanked by spectacular vertical rock cliffs a few hundred metres high (Figure 1). The island is situated in the eastern precipitation shadow of the Antarctic Peninsula, with estimated mean annual net precipitation typically < 1 m (water equivalent). An ice cap mainly 100-300 m thick covers most of Mount Haddington and gives rise to several small polythermal outlet glaciers, many of which terminate as tidewater glaciers. Ice-free areas that resemble the Dry Valleys of East Antarctica are particularly extensive in the west and northwest of the island. The geology is dominated by the JRIVG, a 1.5 km-thick volcanic province composed of basaltic lavas, hyaloclastite breccias and tuffs that form a large long-lived stratovolcano and multiple smaller satellite centres (Smellie et al., 2006b). The volcanic sequences unconformably overlie 6 km of Late Cretaceous marine clastic sedimentary rocks that were deposited in the James Ross back-arc basin.

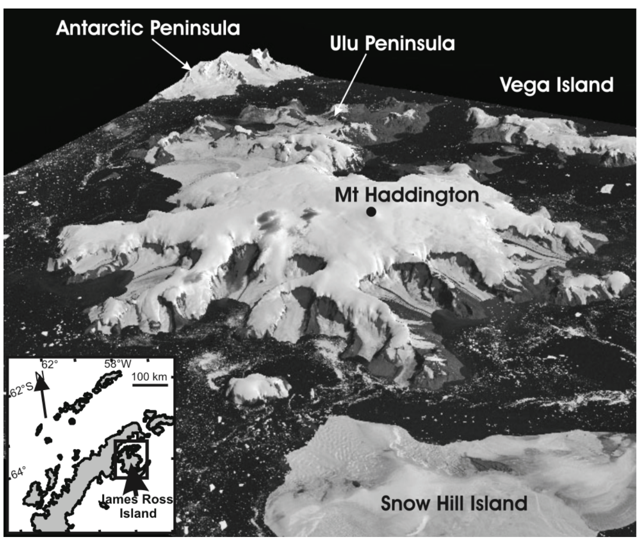

Figure 1. Perspective view of James Ross Island, looking northwest. Approximately three times vertical exaggeration.

Age of the James Ross Island Volcanic Group

Sixty nine new $^{40}Ar/^{39}Ar$ isotopic age determinations were completed on samples of *in situ* volcanic units from the JRIVG during our study, making Mt Haddington the most intensively isotopically dated stratovolcano in Antarctica. Specimens were selected mainly from the coarse-grained subaerial caprocks of lava-fed deltas; samples obtained from fine-grained lavas, especially pillow lavas, frequently yielded poor-quality ages for reasons unknown. The ages range between 6.16 Ma and < 80 ka, and Jonkers et al. (2002) obtained a $^{40}Ar/^{39}Ar$ age of 9.2 Ma on a fresh basalt lava clast in diamict. In addition, two essentially pristine Strombolian pyroclastic cones crop out on the Mt Haddington ice cap, and another occurs on Paulet Island, consistent with an age no more than several ka. We therefore suggest that the JRIVG may be dormant instead of extinct. Thus, eruptions in the JRIVG extended between 9.2 Ma and present, although all but one dated so far are younger than c. 6.2 Ma. They include at least 30 eruptions of lava-fed delta type and more than a dozen pyroclastic cones. In addition, work on Tabarin Peninsula and centres in Antarctic Sound identified at least 3 further lava-fed delta eruptions associated with satellite centres. That makes at least 50 temporally distinct eruptions identified in the region. Excluding the 9.2 Ma age, the eruption frequency over the past 6.2 m.y. is about 1 eruption every 120 ka. This is a very low eruption frequency compared with other well-documented volcanic regions (commonly years to centuries between eruptions). Although almost all of the exposed volcanic units on James Ross Island have been dated, the core of Mount Haddington is unexposed and therefore wholly unknown. Initial aerogeophysical modelling suggests that a substantial but undetermined thickness of volcanics with a wide age range may be present and subsided in the Cretaceous "basement" and may explain the oldest (9.2 Ma) published age (Jordan et al., 2007).

Discussion

The surface of the underlying Cretaceous sediments has a vertical relief of up to 200 m. Both it and the surfaces between the volcanic units are sharp and undulate on a horizontal scale of tens to hundreds of metres, with a surface "roughness" of decimetres to a few metres. Polishing and striations are well preserved on fine-grained lava and Cretaceous concretions, and an origin for the surfaces by glacial erosion seems undeniable. This is supported by the ubiquitous presence of patches and sheets of diamict, interpreted as basal glacial sediment (Nelson et al., 2007). The evidence for a glacial setting is unequivocal for most of the deltas, i.e. by advancement through an ice sheet or ice cap. They show some combination of the following diagnostic characteristics: rising passage zones, some with over-thickened subaerial lava units; caprocks with beds of massive hyaloclastite breccia; delta front overlap structures; and falling passage zones (cf. Smellie, 2006). This is confirmed for at least six deltas, which have authigenic zeolite compositions indicative of a freshwater (i.e. glacial) setting (Johnson and Smellie, 2007). Delta-front overlap structures (signifying basal water escape; Smellie, 2006) in several of the deltas indicate the presence of wet-based ice up to c. 2 Ma, at least, and significant erosion of the delta at Cape Purvis, Dundee Island, is interpreted as a possible indication of wet-based ice at < 132 ka. Together with information from associated glacial sediments (Nelson et al., 2007), either a temperate or sub-polar thermal regime is inferred. Delta thickness is the best proxy available for ice sheet thickness at the time of eruption, although theoretical considerations indicate that the measured values are probably up to c. 100 m lower than the true ice thicknesses. Our data consistently indicate typical measured delta thicknesses of c. 100-250 m, ranging to a maximum of 650 m (Figure 2). Two groups are shown by the data. One, informally designated "normal", has "corrected" thicknesses varying mainly between c. 200 and 350 m (about 90 % of the data set). A second, much smaller group and here termed "exceptional", indicates "corrected" thicknesses varying between c. 600 and 750 m thick. Both sets of corrected thicknesses are likely to be maximum values. When plotted against time, the data also show trends of ice thickness increasing towards present.

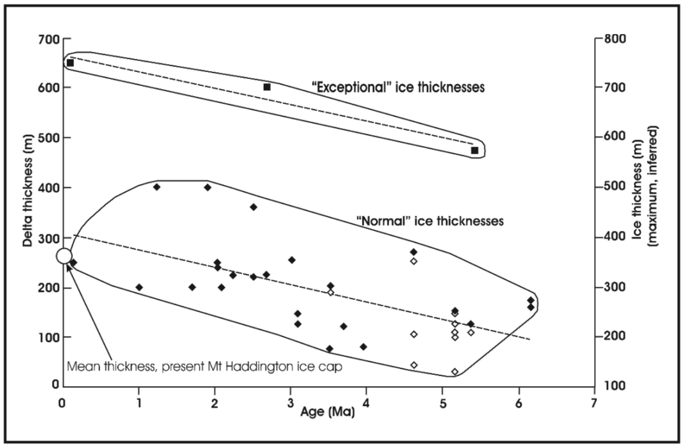

Figure 2. Diagram showing delta thickness and inferred palaeo ice sheet thickness versus age for the James Ross Island Volcanic Group. Open symbols are minimum-thickness data obtained at multiple localities for single deltas; the maximum measures thickness in each delta is regarded as the best estimate for minimum coeval ice thickness. The measured values are probably too low possibly by up to 100 m and are 'corrected' on the right axis

Determining a glacial setting for tuff cones is more difficult and none have been identified in the JRIVG. Conversely, many of the tuff cones were probably erupted under marine (i.e. interglacial) conditions (Smellie et al., 2006b). This is likely from the presence of very laterally extensive tephra beds traceable up to 5 km from their source and indicative of an unconfined setting, and Asterozoan fossil impressions in at least one example. Evidence for periods of marine conditions is also preserved indirectly in many of the sedimentary interbeds, which are locally rich in fragmented fossils. The fossils were reworked into glacial diamicts during subsequent glacial readvances (Smellie et al., 2006b; Nelson et al., 2007). $^{87}Sr/^{86}Sr$ isotopic dating of the shelly fossils demonstrates that at least three broad generally warmer periods are represented: 6.5-5.9, 5.03-4.22 and < 0.88 Ma, and another warm period may have occurred at around 2.54 (+0.86/-0.36) Ma (Smellie et al., 2006b). Of these, the early Pliocene is particularly well represented, although $^{87}Sr/^{86}Sr$ ages have very poor resolution during the late Miocene—early Pliocene.

With such thin ice present, it undoubtedly had a low profile corresponding to a local James Ross Island ice cap once the volcano was established (Hambrey and Smellie, 2006). Additional, more detailed information on ice sheet provenance and surface profiles is contained in the associated interbedded glacial sediments (Nelson et al., 2007). Our lava-fed delta data suggest that the maximum ice sheet thickness appears to have been ≤ 750 m. We also determined that the highest exposed lava surfaces, at c. 620 m a.s.l., display only frost shattering and are otherwise essentially unmodified by erosion. Those surfaces formed as a lava-fed delta emplaced at 4.61 Ma. Younger and older lavas at lower elevations show unequivocal evidence for erosion by wet-based ice. Thus, the high surfaces were not overridden by ice since their formation, consistent with the maximum ice sheet thickness deduced directly from the lava-fed deltas. This suggestion conflicts with the results of some modelling studies that have inferred maximum palaeo-ice thicknesses in northern Antarctic Peninsula at LGM exceeding 1.5 km but is consistent with more recent modelling that suggests thicknesses less than 1 km (cf. Denton et al., 1991; Denton and Hughes, 2002).

The precision on the $^{40}Ar/^{39}Ar$ ages is good for young basalt lavas with comparatively low potassium contents, and averages ± 100 ka (2-sigma) for the majority (67 %) of our dated samples. For our most accurate and precise dated samples, the precision averages ± 60 ka (42% of samples). However, this resolution is still too poor to distinguish Milankovitch cyclicity, a problem that is becoming increasingly acute in palaeoenvironmental studies of young basaltic sequences (cf. Smellie et al., 2006a,b). This is an important issue. In present context, about 90 % of the volcanic units in the James Ross Island region were emplaced under glacial conditions. This figure is probably implausibly high and we suggest that it is more realistic to expect that eruptions occurred during both glacial and interglacial periods. If so, it suggests that a glacial cover persisted even during the warmer interglacials. They should thus be regarded as ice-poor rather than ice-free periods and the region may have broadly resembled that of today, with an ice cap persisting on James Ross Island (cf. Figure 1).

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