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Middle Jurassic air fall tuff in the sedimentary Latady Formation, eastern Ellsworth Land

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Abstract: Rhyolitic volcanism along the proto-Pacific margin of Gondwana occurred at intervals throughout the Jurassic. Silicic melt generation has been interpreted as a result of interaction between mantle plumes and subduction modified lower crust. The rhyolitic Mount Poster Formation of the southern Antarctic Peninsula is *c.* 184 Ma in age (V1), whereas silicic volcanism of the northern Antarctic Peninsula is *c.* 168 Ma (V2). A thin, (13.5 cm) reworked air fall tuff, interbedded with sandstone and mudstone of the Latady Formation in the southern Antarctic Peninsula has a REE pattern similar to V2 volcanic material but is isotopically similar to the extracaldera, low-Ti rhyolites of the V1 Mount Poster Formation. The tuff is interbedded with lithofacies that have been assigned a Callovian age (164–159 Ma) in the west of the area. Simple mixing between a MASH source and reworked Early Jurassic (184 Ma) V1 volcanic material during V2 volcanism in the area explains the apparent discrepancy between the faunal age and the isotopic characteristics of the ash fall. This supports a Middle Jurassic (168 Ma) age that also corresponds to a 167 ± 3 Ma age from Mt Rex on the periphery of the Mount Poster Formation, which was previously thought to be anomalous.

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Key words: Antarctic Peninsula, Gondwana, Mount Poster Formation, rhyolite, volcanic

Introduction

Early to Late Jurassic rhyolitic and intermediate volcanism in the Antarctic Peninsula has been related to the interaction between the Discovery–Shona–Bouvet group of plumes and subduction prior to break-up along the proto-Pacific margin of Gondwana (Pankhurst *et al.* 2000, Riley *et al.* 2001). This period of magmatic activity lasted over 30 million years but can be broken down into three discreet volcanic episodes differentiated by chemistry, geochronology and geographical distribution. Aerial units associated with these volcanic rocks are rare but can provide essential marker horizons in the sedimentary units with which they are associated. This paper describes the petrology and whole rock geochemistry of an air fall deposit from Witte Nunataks in eastern Ellsworth Land, in the southern Antarctic Peninsula, (Fig. 1) and discusses its relationship to Jurassic volcanic rocks of the Antarctic Peninsula. The volcanic unit is interbedded with the Jurassic, sedimentary, Latady Formation and is the first to be described and characterized from the area.

Geological setting

Jurassic silicic volcanic rocks of the Antarctic Peninsula

The spatial, temporal and geochemical distributions of the three episodes of volcanic activity during the Jurassic reflect changes in the relative proportions of magma–crustal interaction, fusibility of the lower crust and relative proximity to the mantle plume centres. The volcanic rocks of the Antarctic Peninsula show an age progression from south to north (old to young) reflecting migration away from the mantle plumes (Pankhurst *et al.* 2000). The geochemistry shows an evolution from a dominantly upper crustal signature in the first episode (V1; Mount Poster Formation) to lower crustal partial melts in a MASH zone for the second (V2; Mapple Formation) (Riley *et al.* 2001). The first phase of volcanism (V1) is essentially coincident with Karoo–Ferrar magmatism in southern Africa and Antarctica (*c.* 183 Ma, Riley & Knight 2001). It crops out as the Mount Poster Formation in eastern Ellsworth Land and the Brennecke Formation in eastern Palmer Land (Fig. 1). Precise U–Pb dating of zircons from the Mount Poster Formation have yielded ages of 188 ± 3 Ma, and 189 ± 3 Ma from Mount Peterson and the Sweeney Mountains (Fig. 1) respectively (Fanning & Laudon 1999). However, a magmatic age of 167 ± 3 Ma has been derived from a porphyritic rhyolite at Mount Rex (Fig. 1), which also contains inherited zircons of *c.* 185 Ma age (Fanning & Laudon 1999). U–Pb (zircon) ages of 184.2 ± 2.5 and 183.9 ± 1.7 Ma have been reported by Pankhurst *et al.* (2000) on rhyolitic ignimbrites from the Brennecke Formation.

Isotopically uniform, intermediate melts were generated by anatexis of hydrous, readily fusible lower crust (created in a continental margin setting) in response to mafic underplating associated with the Discovery–Shona–Bouvet group of plumes. These partial melts would have mixed with fractionated components of the mafic underplate, followed by subsequent storage and homogenization

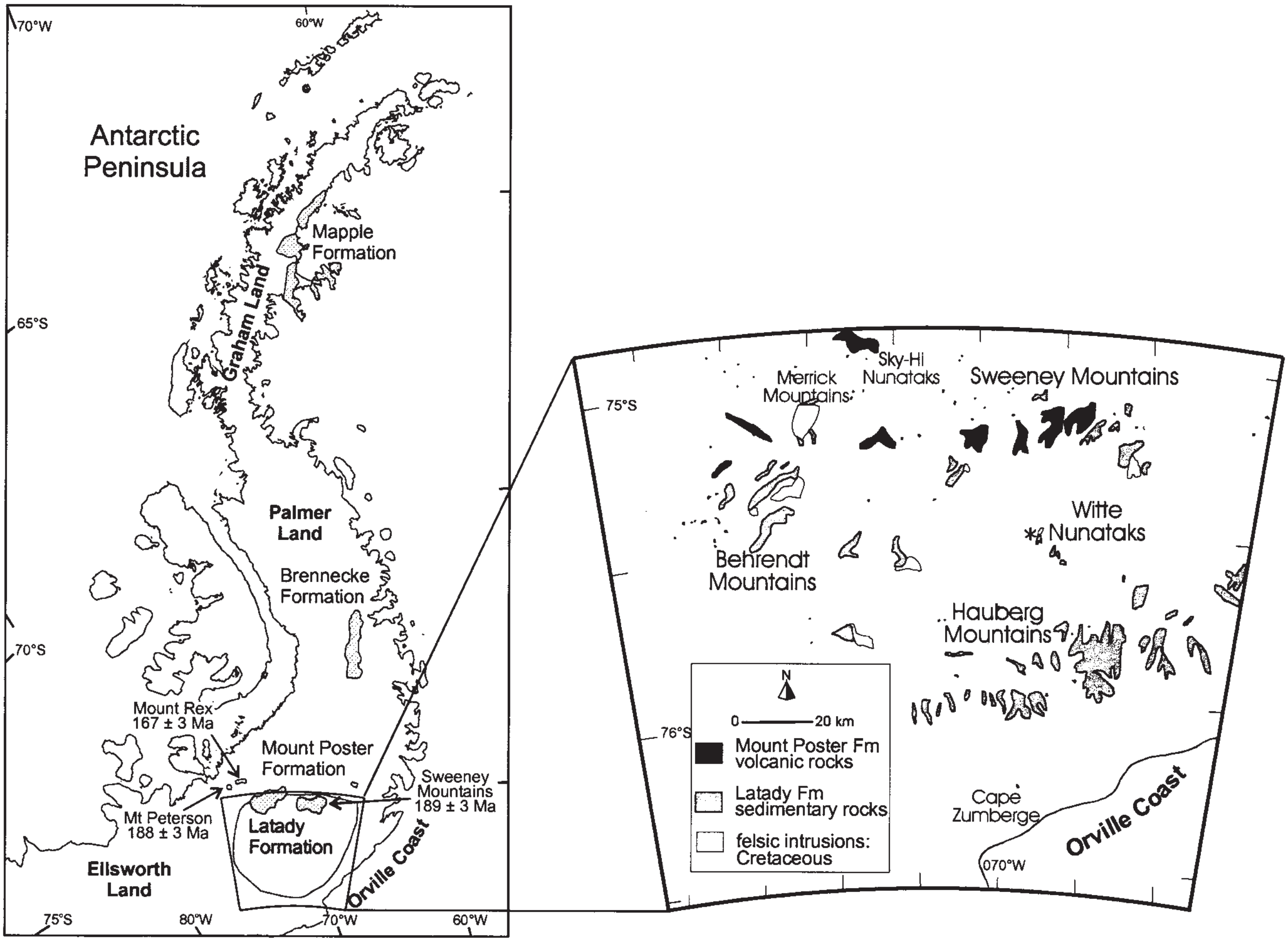

Fig. 1. Map of the Antarctic Peninsula showing the main outcrop areas of Jurassic volcanic rocks. Dates for the Mount Poster Formation are from Fanning & Laudon (1999). Inset shows the outcrop distribution of Latady and Mount Poster formations in eastern Ellsworth Land. Position of the air fall horizon is marked by a star.

(MASH magma). This magma then rose to upper crustal magma chambers. The geochemistry of the earliest volcanic rocks (V1) has been interpreted as primarily upper crustal melts (paragneiss) mixed with a minor component of this MASH magma (Riley *et al.* 2001). The Mount Poster Formation is predominantly intracaldera dacitic to rhyodacitic pyroclasitc rocks and lava flows with minor extracaldera rocks interbedded with sedimentary rocks (Riley & Leat 1999).

The second episode (V2, *c.* 168 Ma) is widespread in eastern Graham Land (Fig. 1) where it crops out as the Mapple Formation (Riley & Leat 1999). The geochemistry and information from inherited zircons are consistent with V2 magmas generated by modification of the MASH domain magma by fractional crystallization, coupled with assimilation of upper crust with very similar isotopic properties to that of the MASH magma (Pankhurst *et al.* 2000, Riley *et al.* 2001). The Mapple Formation crops out as thick rhyolitic ignimbrite flows with minor air fall units and lava flows (Riley & Leat 1999). They overlie and are locally interbedded with the Early to Middle Jurassic Botany Bay Group (Farquharson 1984), which consists of essentially terrestrial or lacustrine sedimentary facies.

The final episode (V3, *c.* 155 Ma) shows a significant westward shift and crops out in southern Patagonia (Pankhurst *et al.* 2000). The province is dominated by locally produced rhyolitic ignimbrites and the geochemistry suggests a source with subduction characteristics and a less marked crustal signature. As this episode is not significant in the Antarctic Peninsula it is not considered further.

The Latady Formation

The Latady Formation of the Orville Coast, eastern Ellsworth Land (Fig. 1) is dominated by shallow marine and minor terrestrial sedimentary rocks (Laudon *et al.* 1983). The formation can be divided into five separate lithofacies deposited during initial rifting prior to Gondwana break-up. Because of the timing of subsidence in this area, a good understanding of the basin history will aid in distinguishing

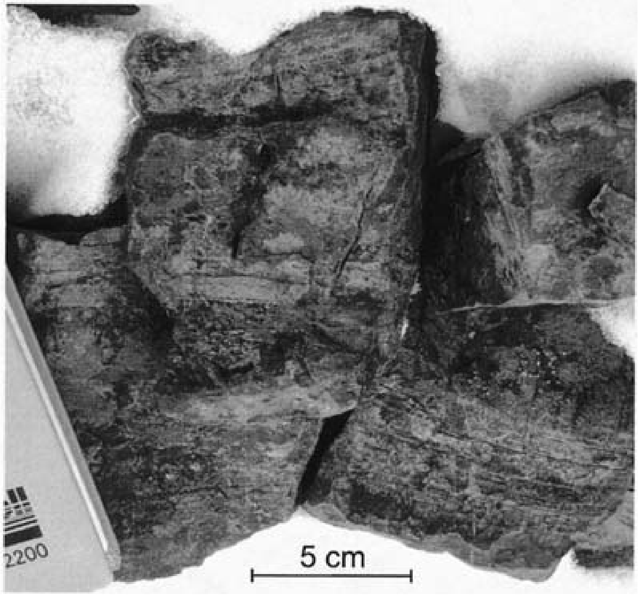

Fig. 2. Photo of the air fall tuff in the field showing sub mm bedding.

the relative effects of mantle plume impact and passive subduction forces during rifting. However, the depositional age of the basin is not well constrained. In the northern part of the area (Sweeney Mountains; Fig. 1), the sedimentary rocks are interbedded with silicic volcanic rocks of the Mount Poster Formation currently understood to be *c.* 188 Ma or early Toarcian. The Behrendt Mountains on the west contain Middle Jurassic Bajocian and Callovian assemblages (Quilty 1983), whilst the Hauberg Mountains in the south contain a diverse Upper Jurassic, Kimmeridgian to Tithonian fauna (Thomson 1983). In other words, large-scale regional younging occurs to the south and east. However, detailed fieldwork indicates that chevron folding, localized faulting and regional-scale open folding have disturbed this generalized stratigraphy at the local scale. Therefore, it is important to try and gather independent and absolute reference points on specific lithofacies in order to interpret the basin history, for example, using interbedded volcanic horizons. Previous authors (e.g. Rowley *et al.* 1983) have mentioned rare tuffaceous horizons interbedded with the sedimentary facies, but none have been described or assigned an age.

Air fall volcanic horizon from Witte Nunataks

Geological setting and petrology

Witte Nunataks are located in the central part of eastern Ellsworth Land (Fig. 1) and consist of two main nunataks with scattered outlying exposures. The northerly nunatak is underlain by a granitoid that has locally baked the sedimentary units. Away from the intrusion, the outcrop is dominated by sandstone and mudstone containing a low energy marine fauna deposited under quiet, anoxic conditions. On the basis of the faunal assemblage and lithofacies correlation with material in the Behrendt Mountains (Quilty 1983), the sedimentary rocks at Witte Nunataks are assumed to be Callovian in age, but direct evidence is lacking.

The air fall tuff is 13.5 cm thick and interbedded with sandstone and fine-grained mudstone in a small exposure lying approximately 1.5 km east of the northerly nunatak (Fig. 1). The rock is very fine-grained and is characterized

Table I. Major, trace element and isotope geochemistry for sample R7820.2. Majors analysed by XRF, traces by ICP-MS, isotopes by TIMS. Epidote removal calculation based on all iron being in epidote.

Major elements			Minor and trace elements		REE		Isotopic data	
		No epidote						
SiO_2	46.60	*54.56*	Sc	15.7	La	51.82	$^{87}Sr/^{86}Sr_{(m)}$	0.713875
TiO_2	0.82	*0.92*	V	119.23	Ce	104.93	$^{87}Sr/^{86}Sr_{(168)}$	0.713871
Al_2O_3	19.60	*17.64*	Cr	130.64	Pr	13.24	$^{143}Nd/^{144}Nd_{(m)}$	0.512317
Fe_2O_3T	8.78	*0.00*	Co	8.6	Nd	52.87	$\varepsilon Nd_{(168)}$	-5.2
MnO	0.34	*0.43*	Ni	40.6	Sm	12.25		
MgO	2.63	*3.31*	Cu	3.4	Eu	3.29		
CaO	21.15	*22.77*	Zn	192.6	Gd	12.91		
Na_2O	0.08	*0.10*	Ga	31.1	Tb	1.95		
K_2O	0.00	*0.00*	Rb	0.82	Dy	11.06		
P_2O_5	0.22	*0.28*	Sr	1324	Ho	2.26		
LOI	-0.18		Y	67.4	Er	6.11		
Total	99.95		Zr	182.2	Tm	1.010		
			Nb	23.78	Yb	6.02		
			Cs	0.21	Lu	0.91		
			Ba	17.20				
			Hf	5.84				
			Ta	1.47				
			Pb	0.98				
			Th	24.81				
			U	6.98				

by a pale, grey yellow colour in contrast to other fine-grained horizons in the Latady Formation, which are dominantly black or grey mudstone. Post depositional epidote veining associated with introduction of epidote to the groundmass, common in the silicic volcanic rocks of Ellsworth Land, has destroyed a large part of the original petrological features, but extremely fine bedding (mm scale) (Fig. 2) and grading in the slightly coarser units can still be identified. The lower contact is obscured but there is nothing to indicate grading of the sedimentary units into the volcanic horizon. In contrast, the upper contact, although distinct, shows some evidence of grading into the overlying mudstone. The upper part of the volcanic horizon (*c.* 4 cm) shows ripple cross lamination consistent with subaqueous reworking. Quartz and calcic plagioclase remain from the original mineralogy but the secondary epidote represents up to 20% of the whole rock mineralogy. The effect of the additional epidote on the chemical characteristics of the rock can be removed by a simple calculation and the major element chemistry is then consistent with an intermediate composition (Table I).

Geochemistry

Analytical techniques

Sr and Nd isotope compositions were determined using static multicollection on a Finnegan Triton mass-spectrometer to an internal precision of better than 5 ppm (1 s.e.m.). During the period of analysis, ten analyses of the Sr isotope standard NBS987 gave a value of 0.710269 ± 0.000008 (2σ errors); reported $^{87}Sr/^{86}Sr$ values are normalized to a value of 0.710250 for this standard. Sixteen analyses of the internal J&M Nd isotope standard gave a value of 0.511113 ± 0.000004 (2σ errors); reported $^{143}Nd/^{144}Nd$ values were normalized to a value of 0.511130 for this standard, equivalent to 0.511864 for La Jolla.

Major and selected trace element analysis was by standard XRF techniques at the Department of Geology, University of Keele, with methods fully detailed in Floyd (1985).

Rare earth element (REE) abundances were determined by ICP-MS at the University of Durham. To ensure complete dissolution fused glass beads rather than powdered samples were used. The glass beads were prepared using a Li-borate flux, crushed and dissolved by standard acid (HF-HNO_3) digestion. The analytical methods, precision, and detection limits are comparable to those detailed in Pearce *et al.* (1995).

Results

Given the altered nature of the ash horizon and introduction of 20% post depositional epidote, the major element chemistry will not be considered and only REE and isotope chemistry will be discussed here.

Much of the following discussion is based on the assumed immobility of REE under the conditions required to generate this rock. The regional metamorphic grade in the Latady Formation is very low, only locally reaching temperatures high enough to generate andalusite in contact aureoles around granitoid bodies. As the REE are predominantly hosted by heavy minerals, which are composed of high field strength elements such as Zr, Hf, Ti, the effect of this low-grade metamorphism on the REE pattern is minimal. Typical concentrations of epidote in felsic rocks contribute less than 1% of each REE to the whole rock (Gromet & Silver 1983). Despite the introduction of 20% post depositional epidote, the low concentration of REE in epidote means the effect on the overall REE pattern will still be minimal.

The REE abundances are shown in Table I and plotted in Fig. 3. The REE patterns of the Witte Nunataks sample is compared with silicic volcanic rocks of the Mount Poster and Mapple formations (Riley *et al.* 2001) and is most

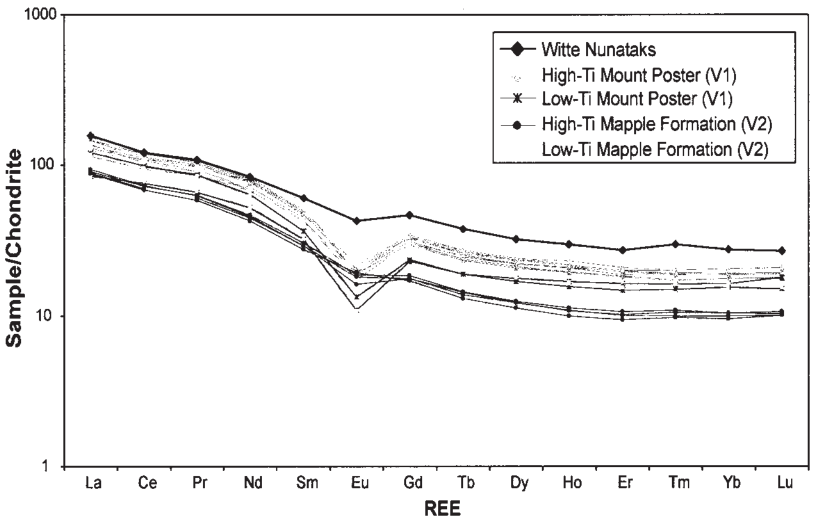

Fig. 3. Chondrite normalised (Nakamura 1974) REE diagram for Witte Nunataks and examples from the Mount Poster and Mapple formations (Riley *et al.* 2001). The Witte Nunataks sample is most readily correlated to the high-Ti Mapple Formation which has been highlighted.

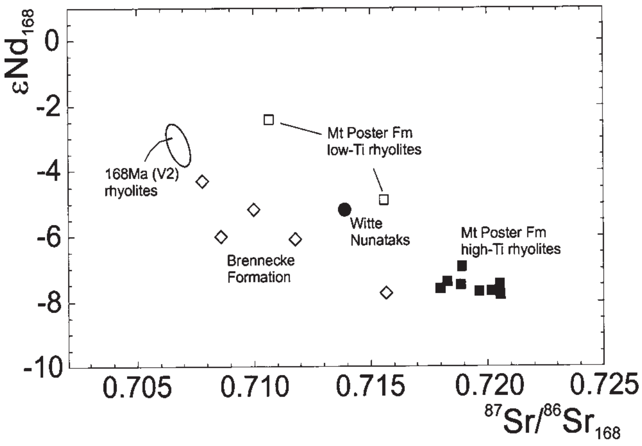

Fig.4. eNd_i vs. $^{87}Sr/^{86}Sr_i$ plot comparing the Witte Nunataks tuff with the fields for volcanic rocks from the Mount Poster (Riley *et al.* 2001), Brennecke (Wever & Storey, 1992; I.L. Millar, unpublished data) and Mapple (Riley *et al.* 2001) formations.

readily comparable with the high-Ti Mapple Formation suite defined by Riley *et al.* (2001). The trace of the pattern from Ce to Sm is straight rather than curved, and the europium anomaly only slightly negative (Eu/Eu* = 0.80 cf. an average of 0.77 for the high-Ti Mapple Formation and an average of 0.55 for the other suites).

Sr and Nd isotopes differentiate well between the Mount Poster, Brennecke and Mapple formations (Riley *et al.* 2001). Sr and Nd isotope ratios from the Witte Nunataks tuff (Table I) have been corrected to an initial value using an eruption age of 168 Ma. The $^{87}Sr/^{86}Sr$ ratios are considerably more radiogenic than the voluminous rhyolites of the northern Antarctic Peninsula (V2, Mapple Formation), but less so than the intracaldera (high-Ti) rhyolites of the Mount Poster Formation (Riley *et al.* 2001) (Fig. 4). The $^{87}Sr/^{86}Sr$ initial ratio (0.7139) is more akin to the $^{87}Sr/^{86}Sr$ values of the low-Ti (extracaldera) rhyolites of the Mount Poster Formation (0.7106–0.7156). The εNd value of -5.2 falls between the ranges of the Mount Poster Formation low-Ti (-2.4 to -4.9) and high-Ti (-6.9 to -7.8) groups. The tuff is plotted in Fig. 4 relative to the fields for the Mapple, Mount Poster and Brennecke formations.

Discussion

An Early Jurassic (V1) age for the Witte Nunataks tuff is implied given its isotopic similarity to the proximal extracaldera Mount Poster Formation. However, the tuff is interbedded with marine sedimentary rocks which are believed to be Callovian in age (comparison with similar fauna from the Behrendt Mountains) and the REE patterns are similar to the 168 Ma Mapple Formation. In addition, intermediate volcanics are thought to be absent in the older V1 Mount Poster Formation, which is dominantly silicic (SiO_2 > 70%), but are more widespread in the younger V2 Mapple Formation.

A key factor in resolving this conflict could be the U–Pb SHRIMP age from Mount Rex in the west of the region, where Fanning & Laudon (1999) report an age of 167 ± 3 Ma for a porphyritic rhyolite. More significant is the presence of inherited zircons with an age of *c.* 185 Ma, overlapping with the U–Pb ages of 189 ± 3 and 188 ± 3 Ma from the Sweeney Mountains and Mount Peterson respectively (Fig. 1). Inherited zircons with Early Jurassic ages are reported from elsewhere in the Peninsula (Pankhurst *et al.* 2000) and point to a widespread lower crustal melting event at this age. However, the 167 ± 3 Ma age from Mount Rex, plus the association of the Witte Nunataks tuff with likely Callovian age sedimentary rocks places doubt on a V1 (184 Ma) age for the ash fall. If this is the case, then the ash fall horizon at Witte Nunataks could form the co-ignimbrite ash component of a local pyroclastic flow erupted around 168 Ma in the north of the area.

The interpretation that there was active volcanism in eastern Ellsworth Land at *c.* 168 Ma is consistent with the geochemical evidence presented in Riley *et al.* (2001). Generation of V1 volcanic rocks in the Mount Poster Formation requires the existence of a MASH type magma, which is also a key component of V2 volcanic rocks in the northern Antarctic Peninsula (Riley *et al.* 2001). Therefore, the existence of V2 type magmas in eastern Ellsworth Land would also be anticipated, being generated from the same MASH parent magma and undergoing fractional crystallization and assimilation. The marked effect of V1 on the chemistry of the Witte Nunataks ash fall is not surprising when the previous volcanic history is considered. Unlike the Mapple Formation, which represents the first cycle of volcanism in that part of Graham Land, V2 is the second cycle in eastern Ellsworth Land. Recycling and assimilation of material within the upper crustal magma chambers of the caldera has resulted in a mix between fresh V2 type magma and older reworked V1 material (Fig. 4). The inherited zircon age of 185 Ma reported from Mount Rex confirms the presence of older magma generated during V1.

The quiet, low energy anoxic sedimentary lithofacies at Witte Nunataks are very similar to the Middle Jurassic facies identified in the Behrendt Mountains (Quilty 1983). A V2 (Middle Jurassic) age for the Witte Nunataks tuff is consistent with low energy deposition across the basin. The implication that the low energy anoxic lithofacies were deposited contemporaneously suggests that it might be reasonable to use the lithofacies as time equivalents. In the absence of a well-defined stratigraphy for the Latady Formation, it has not been possible previously to suggest a viable basin evolution model. However, dating of the other lithofacies using fossil flora and fauna, and combining this with independent marker horizons such as the Witte Nunataks tuff, make it possible to build up a stratigraphy. The different lithofacies in the Latady Formation can be used as time slices and from there, to define and interpret the Latady Basin history for the first time.

Conclusions

The air fall volcanic tuff from Witte Nunataks in eastern Ellsworth Land has isotopic characteristics similar to the V1, low-Ti, extracaldera Mount Poster Formation. As the extracaldera samples were erupted contemporaneously with the Mount Poster Formation ignimbrites, then the isotopic evidence suggests an Early Jurassic age for the surrounding sedimentary lithofacies at Witte Nunataks. However, this is not compatible with the predicted Callovian age based on faunal similarities with well studied outcrops in the west of the region (cf. Quilty 1983) or the chemical similarities with the *c.* 168 Ma Mapple Formation. The occurrence of 167 Ma (V2) volcanic rocks in the area (Mount Rex) indicates the presence of Middle Jurassic rhyolites in eastern Ellsworth Land and the identification of inherited zircons at 185 Ma (Fanning & Laudon 1999) in the same sample confirm reworking of crustal material generated during V1 in the production of V2 volcanics.

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