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Jurassic silicic volcanism in the Transantarctic Mountains: Was it related to plate margin processes or to Ferrar magmatism?

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Abstract Silicic volcanism in the Transantarctic Mountains, represented by rhyolitic tuff that mainly precedes emplacement of the Ferrar Large Igneous Province, is important in interpretation of the tectonic evolution of the Antarctic sector of Gondwana. Sr and Nd isotope data indicate that the tuffs are not directly related to Ferrar magmatism nor to melting of the underlying Ross orogen crust yet zircon gives a U-Pb age of 182.7±1.8 Ma, similar to the U/Pb age for the Ferrar. Distribution of the silicic tuffs along 1400 km of the Transantarctic Mountains suggests, alternatively, a relationship to the Gondwana plate margin. Although West Antarctica comprises Mesoproterozoic crustal terrains, few analyzed rocks are compatible isotopically with the Lower Jurassic tuffs. The source of the tuffs must lie in unexposed Early Jurassic magmatic centers in West Antarctica or an unexposed crustal terrain beneath the Transantarctic Mountains.

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Introduction

Silicic magmatism was an integral part of some large igneous provinces, such as the Parana-Etendeka (e.g. Peate, 1997). In that and other instances silicic extrusive rocks of anatectic origin are interbedded with voluminous tholeiitic lavas. In the Transantarctic Mountains (TAM) (Fig. 1; Elliot, 2000) silicic shards and volcaniclastic debris occur in stratigraphic sequences (Hanson Fm) underlying Lower Jurassic Ferrar extrusive rocks, as clasts enclosed in the basaltic pyroclastic rocks that underlie the lavas, and as sparsely distributed shards in interbeds within the lava sequence. This paper presents stratigraphic, isotopic and chronologic data on the silicic rocks, and evaluates the relationship of the silicic magmatism to the Ferrar Large Igneous Province and other possible sources.

Stratigraphy

The only continuous stratigraphic sequences extending from the Upper Triassic strata of the Victoria Group to the Lower Jurassic Ferrar extrusive rocks are exposed in the central Transantarctic Mountains (CTM) (Elliot, 2000 and references therein) and at Shafer peak, Deep Freeze Range, north Victoria Land (NVL) (Schoener et al., this symposium). The Hanson Fm type section, at Mt. Falla (CTM), is a 238-m-thick sequence of volcaniclastic sandstones and siltstones together with tuffaceous beds, which is divided into three informal members, with tuffs and reworked tuffs dominant in the upper member. Hanson strata are thinner elsewhere and the members are less readily recognized, although the upper member everywhere is dominated by tuffs. The overlying basaltic pyroclastic Prebble Fm, ≤204 m thick, includes occasional clasts of silicic tuff, which at Otway Massif are up to 10 m across. The overlying Kirkpatrick Basalt, ≈550 m thick, comprises numerous lava flows with interbeds near the top and bottom of the sequence. Changes in stratigraphic thickness of the Hanson Fm suggest it is disconformity bound.

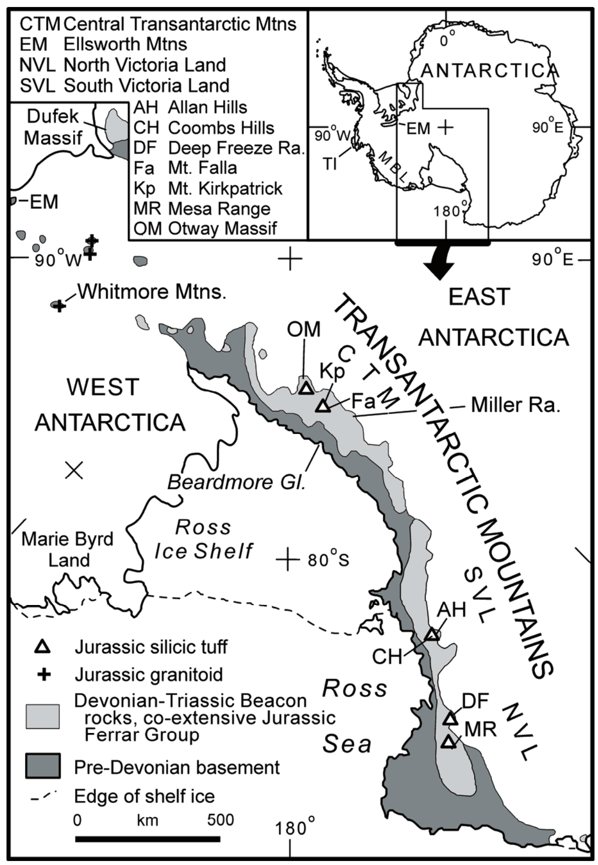

Figure 1. Location map for Lower Jurassic silicic volcanic rocks in the Transantarctic Mountains.

In south Victoria Land (SVL), at Coombs Hills, the Upper Triassic Lashly Fm is overlain by a silicic shard-bearing clastic unit (Fig. 2); however, there is no unequivocal stratigraphic contact with younger rocks (Elliot et al., 2006). Silicic tuff megaclasts have been reported from Allan Hills but none has been found *in situ* in the basaltic pyroclastic Mawson Fm. Near Mt. Weir, Deep Freeze Range (NVL), silicic tuff occurs in the basaltic pyroclastic Exposure Hill Fm (Elliot, unpublished data). At nearby Mt. Shafer siliciclastic shard-bearing sandstones occur within the Exposure Hill Fm; a black shale in this sequence has an Early Jurassic palynological age (Musumeci et al., 2006). In the Mesa Range region (NVL), sandstones with silicic shards overlie the Lower Jurassic Section Peak Fm (Pertusati et al., 2006). The Exposure Hill Fm includes silicic shards and tuff megaclasts. The detailed relationships between the Jurassic units in the Mesa Range region (NVL) are discussed by Schoener et al. (this symposium).

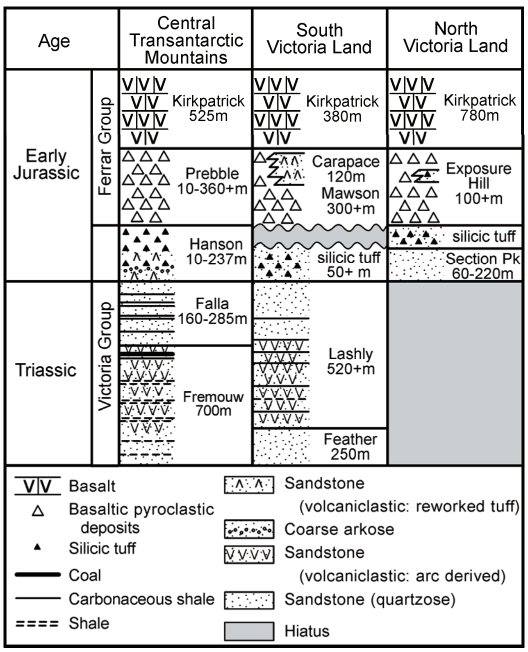

Figure 2. Stratigraphic columns for Triassic and Jurassic strata in the Transantarctic Mountains.

Age

The age of the Hanson Fm is not well constrained. It overlies the upper Triassic (Carnian to Norian) Falla Fm (see Elliot, 2000) and is older than the overlying Ferrar rocks. Four tuffaceous samples from the upper Hanson Fm at Mt. Falla gave an Rb-Sr "isochron" age of 186±8 Ma (Faure and Hill, 1973). The dinosaur from the Hanson Fm has been assigned a Sinemurian-Pliensbachian (Early Jurassic) age (Hammer and Hickerson, 1994). Based on U-Pb zircon and baddeleyite analyses, the Ferrar has an age of 183.6±1.8 Ma (Encarnación et al., 1996), which is close to the Pleinsbachian-Toarcian stage boundary.

A silicic tuff clast from Otway Massif yielded an anomalously young whole rock $^{40}Ar/^{39}Ar$ age of ≈160 Ma (Middle Jurassic), which is attributed to Ar loss by low temperature processes. Zircon, from the same tuff clast, has given a U-Pb SHRIMP age of 182.7±1.8 Ma (Fig. 3; Table 1).

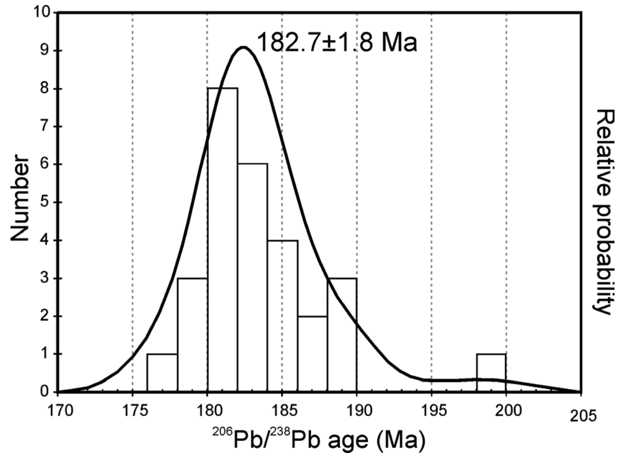

Figure 3. U-Pb zircon age probability plot for a silicic tuff clast from Otway Massif. Analysis performed at the Australian National University, under standard operating and data reduction procedures.

Chemistry

The Hanson Fm silicic rocks are dacite to high-silica rhyolite (SiO_2=67-78%) in composition (see Elliot, 2000; unpublished data). The major elements show considerable scatter, which is attributed, in part, to admixed detrital material (rock fragments and mineral grains) and to alteration (clay minerals and zeolites). High field strength elements show the least scatter, and on chondrite-normalized incompatible element diagrams show Nb-Sr-P-Ti depletions typical of rocks with a strong crustal influence. A crustal signature is also suggested by $^{87}Sr/^{86}Sr$ isotope initial ratios of 0.7091-0.7102 and $^{143}Nd/^{144}Nd$ initial ratios of 0.51220-0.51226 (ϵ_{Nd} values of -2.8 to -4.0 at 183 Ma) for three *in situ* Hanson tuffs and two tuff clasts from the Prebble Fm (Fig. 4; Table 2).

Discussion

The zircon U-Pb SHRIMP age of 182.7±1.8 Ma for the silicic tuff clast enclosed in basaltic tuff breccia is similar to the U-Pb age (by thermal ionization mass spectrometry) assigned to the Ferrar rocks, and therefore temporal association with the Ferrar province is indicated.

The Sr isotope data for the tuffs (Table 2) indicate a crustal influence in their genesis. The Sr isotope initial ratios are significantly lower than most of the underlying upper crustal rocks of the Lower Paleozoic Ross Orogen, which are generally>0.720 at 183 Ma (Borg et al., 1990);this suggests the tuffs were not derived by anatexis of such crust. However the silicic tuff Sr isoptope initial ratios are within the range of lower crustal xenoliths from SVL (Kalamarides et al.,

Table 1. Summary of SHRIMP U-Pb zircon results for sample 96-27-14.

Grain. spot	U (ppm)	Th (ppm)	Th/U	^{206}Pb* (ppm)	^{204}Pb/ ^{206}Pb	f_{206} %	Total ^{238}U/ ^{206}Pb	±	^{207}Pb/ ^{206}Pb	±	Radiogenic ^{206}Pb/ ^{238}U	±	Age (Ma) ^{206}Pb/ ^{238}U	±
Z4420														
1.1	199	359	1.80	5.1	0.000263	<0.01	33.57	0.43	0.0493	0.0011	0.0298	0.0004	189.4	2.4
2.1	256	336	1.32	6.4	0.000431	1.13	34.12	0.42	0.0588	0.0015	0.0290	0.0004	184.2	2.3
3.1	356	425	1.19	8.9	0.000009	0.19	34.34	0.41	0.0513	0.0009	0.0291	0.0004	184.7	2.2
4.1	594	595	1.00	14.9	0.000100	0.14	34.33	0.38	0.0509	0.0007	0.0291	0.0003	184.9	2.0
5.1	366	293	0.80	9.1	0.000103	<0.01	34.61	0.40	0.0495	0.0009	0.0289	0.0003	183.7	2.1
6.1	1194	1115	0.93	30.3	0.001436	2.39	33.90	0.36	0.0688	0.0011	0.0288	0.0003	183.0	2.0
7.1	2143	1012	0.47	54.2	0.000230	0.39	34.00	0.35	0.0529	0.0004	0.0293	0.0003	186.2	1.9
8.1	106	47	0.45	18.1	0.000121	0.30	5.02	0.06	0.0814	0.0008	0.1988	0.0026	1168.9	14.1
9.1	108	121	1.12	2.7	0.000715	0.42	34.84	0.52	0.0530	0.0017	0.0286	0.0004	181.7	2.7
10.1	292	366	1.25	7.2	0.000593	0.77	34.82	0.42	0.0559	0.0010	0.0285	0.0003	181.1	2.2
11.1	442	364	0.82	10.8	0.000267	0.10	35.03	0.40	0.0505	0.0008	0.0285	0.0003	181.3	2.1
12.1	181	290	1.60	4.4	0.000179	0.63	35.11	0.46	0.0547	0.0013	0.0283	0.0004	179.9	2.4
Z4974														
1.1	266	286	1.07	7.2	-	0.36	31.92	0.59	0.0530	0.0011	0.0312	0.0006	198.1	3.6
2.1	100	138	1.39	2.4	-	0.55	35.01	0.53	0.0541	0.0018	0.0284	0.0004	180.6	2.7
3.1	56	56	1.01	1.4	0.000018	0.23	34.96	0.64	0.0515	0.0024	0.0285	0.0005	181.4	3.3
4.1	99	163	1.65	2.4	-	0.16	34.82	0.53	0.0510	0.0017	0.0287	0.0004	182.2	2.8
5.1	2647	3639	1.37	65.8	0.000051	<0.01	34.55	0.36	0.0494	0.0003	0.0290	0.0003	184.0	1.9
6.1	1638	1681	1.03	41.1	0.001246	2.13	34.25	0.36	0.0667	0.0006	0.0286	0.0003	181.6	1.9
7.1	276	388	1.40	7.5	0.007145	12.55	31.61	0.54	0.1497	0.0060	0.0277	0.0005	175.9	3.4
8.1	271	266	0.98	6.7	0.000005	0.20	34.97	0.43	0.0513	0.0011	0.0285	0.0004	181.4	2.2
9.1	548	519	0.95	13.3	-	0.05	35.32	0.40	0.0501	0.0007	0.0283	0.0003	179.9	2.0
10.1	359	108	0.30	51.9	-	0.10	5.93	0.06	0.0734	0.0005	0.1684	0.0019	1003.0	10.4
11.1	1876	2472	1.32	48.1	0.000020	<0.01	33.54	0.35	0.0494	0.0004	0.0298	0.0003	189.5	2.0
12.1	108	144	1.33	2.7	0.000923	0.05	33.68	0.51	0.0503	0.0017	0.0297	0.0005	188.5	2.8
13.1	310	107	0.35	34.5	0.000133	0.17	7.73	0.09	0.0667	0.0006	0.1292	0.0015	783.4	8.4
14.1	468	403	0.86	11.5	0.000392	0.05	34.85	0.40	0.0501	0.0008	0.0287	0.0003	182.3	2.1
15.1	3489	5246	1.50	90.4	0.001417	2.57	33.17	0.34	0.0703	0.0018	0.0294	0.0003	186.6	1.9
16.1	2220	3288	1.48	55.1	0.000041	0.11	34.63	0.37	0.0506	0.0004	0.0288	0.0003	183.3	1.9
17.1	210	321	1.53	5.2	0.000072	0.48	34.74	0.46	0.0535	0.0015	0.0286	0.0004	182.1	2.4
18.1	197	334	1.69	4.7	0.000245	0.18	36.01	0.47	0.0511	0.0013	0.0277	0.0004	176.3	2.3
19.1	184	195	1.06	4.4	0.000354	0.22	35.59	0.48	0.0514	0.0014	0.0280	0.0004	178.2	2.4
20.1	1194	791	0.66	29.5	0.000319	0.51	34.81	0.37	0.0538	0.0006	0.0286	0.0003	181.6	1.9

Notes:
1. Uncertainties given at the one sigma level.
2. Error in Temora reference zircon calibration was 0.65% & 0.58% for the analytical sessions. (not included in above errors but required when comparing data from different mounts).
3. f_{206} % denotes the percentage of ^{206}Pb that is common Pb.
4. Correction for common Pb made using the measured ^{238}U/^{206}Pb and ^{207}Pb/^{206}Pb ratios following Tera and Wasserburg (1972) as outlined in Williams (1998).

Table 2. Rb, Sr, Sm, and Nd concentrations and ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd present day and calculated initial ratios at 183 Ma for silicic tuffs. Samples (all have prefix 85-) 1 (3-24A) and 2 (11-10): Prebble Formation tuff clasts. Samples 3 (16-24), 4 (19-2), and 5 (20-11): Hanson Formation tuffs. Methods are given in Foland and Allen (1991).

#	Rb (ppm)	Sr (ppm)	^{87}Rb/^{86}Sr	^{87}Sr/^{86}Sr	(^{87}Sr/^{86}Sr)$_i$	Sm (ppm)	Nd (ppm)	^{147}Sm/ ^{144}Nd	^{143}Nd/^{144}Nd	(^{143}Nd/^{144}Nd)$_i$	$E_{Nd[T]}$	T_{DM}
1	40.3	100.7	1.157	0.712839 (14)	0.709829 (39)	2.91	11.4	0.1549	0.512420 (6)	0.512235 (6)	-3.28	1893
2	105.0	380.1	0.7998	0.711321 (8)	0.709240 (26)	5.27	27.1	0.1178	0.512337 (6)	0.512196 (6)	-4.03	1294
3	150.6	149.3	2.922	0.716871 (11)	0.709268 (92)	4.36	20.5	0.1286	0.512356 (6)	0.512202 (6)	-3.91	1424
4	117.4	65.3	5.209	0.722702 (9)	0.709147 (163)	7.54	41.6	0.1096	0.512377 (6)	0.512246 (6)	-3.06	1134
5	90.8	199.3	1.318	0.713613 (10)	0.710182 (42)	6.79	35.9	0.1143	0.512394 (7)	0.512257 (7)	-2.84	1162

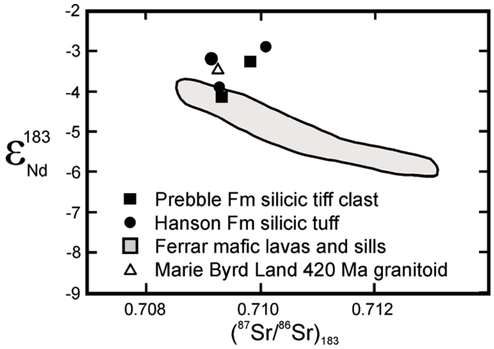

Figure 4. ε_{Nd} versus $^{87}Sr/^{86}Sr$ for silicic tuffs and tuff clasts, together with a Marie Byrd Land granitoid and the field for Ferrar lavas and sills.

1987). Ferrar tholeiites have similar Sr isotope initial ratios but somewhat lower Nd initial isotope ratios (respectively: 0.7085-0.7117 and 0.51213-0.51219; Fleming et al., 1995) than the tuffs; nevertheless, the crustal contaminant contributing to the Ferrar isotope signature must have been significantly more radiogenic than the silicic tuffs and their source region. Further, the tuff ϵ_{Nd} values (-2.8 to -4.0) are distinct from Ferrar rocks (ϵ_{Nd} = -4.0 to -6.0; Fleming et al., 1995). Evolution of Ferrar Ferrar magmas occurred at their site of origin in the proto-Weddell Sea region (Elliot and Fleming, 2004, and references therein) and thus similar characteristics would not be expected. Four of the five silicic tuffs have Nd model ages (T_{DM} of 1.1-1.4 Ga) that differ from those of the underlying Ross orogen (T_{DM} = 1.6-1.9 Ga), but one (T_{DM} = 1.9 Ga) is similar to the adjacent Miller Range block (T_{DM} = 2.0 Ga) (Borg et al., 1990). The silicic tuffs were not derived from the same crustal province as the contaminant for Ferrar magmas, nor by anatexis of Ross orogen crust.

Paleozoic and Mesozoic orogenic belts and magmatic arcs lie outboard of the TAM (Pankhurst et al., 1993, 1998; Mukasa and Dalziel, 2000) but evidence for Early Jurassic magmatism along the Gondwana paleo-Pacific margin is scant (Fig. 5). In the New Zealand region, parts of the Brook Street and Murihiku terranes indicate an Early Jurassic magmatic arc (Adams et al., 2002), and the Bounty Islands granite has an age of 183±9 Ma (Adams and Campbell, 2005). The Jones Mountains granite has an age of 198±2 Ma (Pankhurst et al., 1993), and a pluton in central Antarctic Peninsula an age of 181 Ma (Leat et al., 1995). In the southern Antarctic Peninsula, the Brennecke and Mt. Poster formations record Early Jurassic silicic volcanism (Pankhurst et al., 2000; Riley et al., 2001). The intra-plate granitoids of the Ellsworth-Whitmore Mountains block (EWB) have latest Early Jurassic ages of ca. 175 Ma (Storey et al., 1988).

Of the Lower Jurassic magmatic rocks, none has similar Nd isotope initial ratios and only the Jones Mountains granite has similar Sr isotope initial ratios (Pankhurst et al., 1993). None of these magmatic centers was the source for the Hanson tuffs. Among the analyzed Paleozoic granitoids and gneisses, many having Mesoproterozoic Nd model ages (Pankhurst et al., 1998), only one, a 420 Ma granitoid, has Sr and Nd initial isotope ratios compatible with the Hanson tuffs.

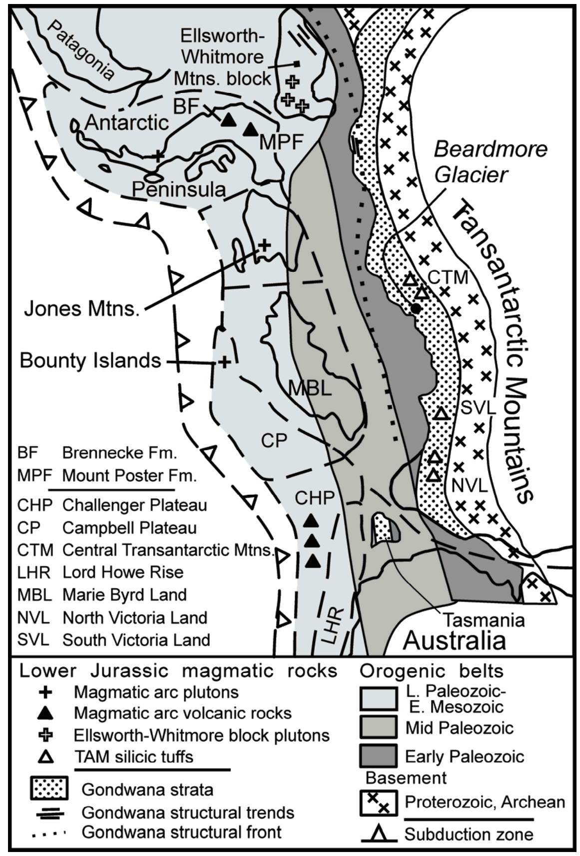

Figure 5. Gondwana reconstruction for the Early Jurassic, showing the distribution of contemporaneous magmatism and Paleozoic orogenic belts.

Although the EWB is close to CTM today, in Jurassic time it was located ca. 2,000 km distant between adjacent southern Africa and Queen Maud Land. The Gondwana margin blocks were similarly displaced toward South America, and were also closer to TAM before break-up, given the extended and thinned crust of West Antarctica (Winberry and Anandakrishnan, 2004) (Fig. 5).

Silicic volcanism in the TAM is a regional phenomenon extending over 1400 km. Although not yet well documented, the rocks in NVL and SVL containing silicic shards are clearly part of the section between Triassic siliciclastic strata and Ferrar lavas. Silicic tuffs from both Coombs Hills and the Deep Freeze Range are high-silica rhyolites (Elliot, unpublished data) and similar to the tuffs from CTM.

The tectonic setting for the Hanson Fm, inferred to have been an active rift, was initiated in early Hanson time, shown by arkosic sandstones in the lower member, and implies that a back-arc extensional setting formed within the previous foreland basin (see Elliot, 2000). The rift extended into NVL, controlling the long distance dispersal of Ferrar magmas (Elliot and Fleming, 2004). In terms of the plate margin, trench roll-back may have caused the extension, but magmatism along the margin did not intensify until the Middle Jurassic with major activity in the Antarctic Peninsula (Leat et al., 1995).

Silicic volcanism recorded in the lower and middle members of the Hanson Fm is inferred to reflect distal Plinian eruptions, whereas in the upper member it was proximal based on the presence of coarse-grained fallout debris. Thick tuff beds, required for the megaclasts, have not yet been recorded in any stratigraphic sequence; nevertheless the megaclasts imply a proximal source. Distal eruptions could have occurred along, or inboard of, the plate margin, yet the available geochemistry and isotope data do not show clear differences in composition between the distal and proximal volcanism.

Summary

The distribution and age of silicic volcanism in the TAM are compatible with an origin related either to Ferrar magmatism or to plate margin processes, the latter including extension in the back-arc region and both distal and proximal volcanism. Available isotopic data suggest the tuffs were derived from a crustal province with the same Nd model age as that of the EWB granitoids and Mount Poster Fm rocks, as well as parts of Marie Byrd Land, but not yet known from the TAM. Ferrar magmas could have caused anatectic melting of appropriate but unexposed CTM crust, in particular for the proximal tuffs, but the source for the distal rhyolitic tuffs might then have been located in West Antarctica and from as-yet-unidentified Early Jurassic magmatic centers, or from more distal centers in the TAM. In conclusion, the data constrain the source(s) to unexposed Early Jurassic magmatic centers in West Antarctica or an unexposed TAM crustal terrain that underwent Ferrar-related anatectic melting.

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