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Late Cenozoic deposits at Reedy Glacier, Transantarctic Mountains: implications for former thickness of the West Antarctic Ice Sheet

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ABSTRACT

Deposits corresponding to multiple periods of glaciation are preserved in ice-free areas adjacent to Reedy Glacier, southern Transantarctic Mountains. Glacial geologic mapping, supported by ^{10}Be surface-exposure dating, shows that Reedy Glacier was significantly thicker than today multiple times during the mid-to-late Cenozoic. Longitudinal-surface profiles reconstructed from the upper limits of deposits indicate greater thickening at the glacier mouth than at the head during these episodes, indicating that Reedy Glacier responded primarily to changes in the thickness of the West Antarctic Ice Sheet. Surface-exposure ages suggest this relationship has been in place since at least 5 Ma. The last period of thickening of Reedy Glacier occurred during Marine Isotope Stage 2, at which time the glacier surface near its confluence with the West Antarctic Ice Sheet was at least 500 m higher than today.

1. Introduction

East Antarctic Ice Sheet (EAIS) outlet glaciers flowing through the Transantarctic Mountains (TAM) have fluctuated in volume throughout the Cenozoic (Mercer, 1968a; Denton et al., 1989a; Bockheim et al., 1989; Orombelli et al., 1990). During the Late Pleistocene, growth of the Ross Sea ice sheet caused the lower reaches of these glaciers flowing into the Ross Sea Embayment (RSE) to thicken by as much as 1000 m (Bockheim et al., 1989; Denton et al., 1989b; Denton and Marchant, 2000). Holocene deglaciation of the RSE resulted in thinning and steepening of outlet glaciers to their modern profiles and the isolation of fresh lateral drift sheets and moraines on adjacent mountainsides (Mercer, 1968b; Denton et al., 1989a and refs. therein). Weathered drift sheets preserved alongside outlet glaciers (Mercer, 1968b; Denton et al., 1989a,b; Ackert and Kurz, 2004) represent previous periods of glacier expansion and are more extensive than the Late Pleistocene drift.

In order to address questions of former ice thickness, we examined deposits from Reedy Glacier, a large (>120 km long) outlet glacier of the EAIS in the southern TAM. Reedy Glacier (86°30′–85°00′S, 124°00–138°00′E; Fig. 1) merges with the West Antarctic Ice Sheet (WAIS) ~50 km inland of the Siple Coast grounding line and forms a major tributary of Mercer Ice Stream (Fig. 1). The elevation profile of Reedy Glacier, therefore, is controlled to a large degree by the thickness of the WAIS and to a lesser degree by the level of the EAIS (Mercer, 1968b). Thus, changes in Reedy Glacier, reconstructed from the geologic record, can be used to infer past fluctuations of the ice sheets.

2. Methodology and site locations

Well-preserved drift sheets and moraines are exposed in ice-free areas adjacent to Reedy Glacier. Mercer (1968a,b) identified three distinct groups – Reedy I, Reedy II, and Reedy III, in order of decreasing age, based on position, composition, and relative weathering. Our mapping revealed a greater number of drift units, described below. We focussed on three large, ice-free areas adjacent to Reedy Glacier – the Quartz Hills, Caloplaca Hills, and Polygon Spur (Fig. 1) – but also visited five nunataks (Fig. 1). At each site, we mapped the distribution, elevation, morphology, and geometry of moraines, drift sheets, erratics, and erosional features on vertical aerial photos (~1:20,000 scale). Excavations enabled us to take clast and sediment samples from each unit. We categorized and correlated glacial drifts in the field through comparison of physical characteristics (e.g. weathering extent, composition), morphology, and position relative to the modern margin, and in the laboratory using clast and grain-size analyses (see Appendix I).

Cosmogenic ^{10}Be ages from granite erratics at numerous sites along the glacier provide chronologic constraints. While the bulk of

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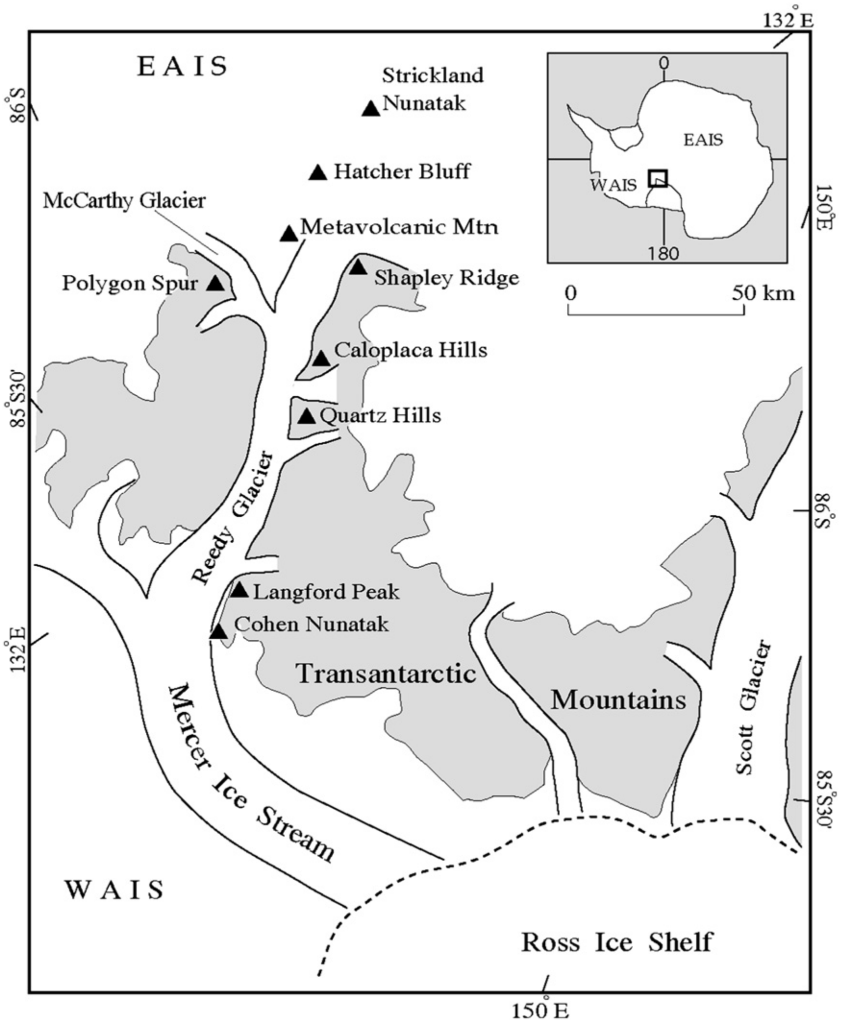

Fig. 1. Reedy Glacier is an outlet of the EAIS flowing through the Transantarctic Mountains into Mercer Ice Stream, ~50 km upstream from the present-day WAIS grounding line (dashed line) in the Ross Sea Embayment. Field sites are shown.

this work focussed on the timing of the last glacial maximum (LGM) and subsequent recession (see Todd et al., personal communication), we dated twenty-four samples from older deposits and their ages help to elucidate the mapping described below. These ages typically are from boulders perched on bedrock or stable surfaces, to avoid the effects of exhumation, and have been calculated assuming zero erosion. We provide details of those older samples in Table 1 and Appendix II; for samples dating to the LGM, see Todd et al. (personal communication).

The Quartz Hills (85°56′S, 132°50′W; 25 km^2), located midway along the southwest margin of Reedy Glacier (Fig. 1), overlook the confluence of Reedy and a minor tributary, Colorado Glacier (Fig. 2a). Bedrock is predominantly coarse-grained granite gneiss, with smaller amounts of orthoclase–feldspar and plagioclase–feldspar granites, as well as dark, fine-grained mafic rocks. The landscape has alpine relief, including horns, arêtes, cirques, and glacially carved valleys, and ranges from 1180 m (modern glacier surface) to ~2200 m elevation. An extensive, low-angled slope (hereafter referred to as the Quartz Hills bench; Figs. 2a and 3) rises southward ~4.5 km from ~1300 m to more that 1700 m. With the exception of one small, isolated glacier in the Valley of Doubt (*informal name*; Fig. 2a), ice cover at present is limited to perennial patches. The surfaces of both Reedy and Colorado Glaciers at the Quartz Hills are blue-ice ablation zones; our stake measurements made between December 2003 and December 2004 indicate ablation is ~0.2 m/yr ice equivalent. Our radar transects of both Reedy and Colorado Glaciers in this region reveal maximum ice thickness of 2100 m and 1300 m, respectively, with the former maintaining a surface centre-line velocity of ~170 m/yr.

The Caloplaca Hills (86°04′S, 131°00′E; 20 km^2; Fig. 1), located 20 km up-glacier from the Quartz Hills, are underlain by crystalline granite and granite gneiss and form a high relief (~800 m), ice-free alpine topography. Two tributaries of Reedy Glacier, flowing northeast from the Watson Escarpment, bound the Caloplaca Hills both to the northwest (Wotkyns Glacier) and southeast (unnamed glacier). A prominent feature is the 2-km-long valley (Caloplaca Valley) paralleling Reedy Glacier, into which a southeast-flowing lobe of Wotkyns Glacier (Wotkyns Lobe) protrudes. At the valley's south-eastern end, a small (~1 km long) alpine glacier descends from the ridgeline and terminates on the valley bottom.

Polygon Spur (86°00′S, 126°00′W; ~37 km^2) and adjacent Mims and Tillite Spurs (combined area of ~3 km^2) are situated below the southern edge of the Wisconsin Plateau northeast of Reedy Glacier (Fig. 1). Polygon Spur is bound on two sides by McCarthy Glacier (a major tributary of Reedy Glacier) and on a third by Olentangy Glacier (Fig. 2b), which drains the southern Horlick Mountains and flows into Reedy Glacier. The ice margin forms a series of eastward-flowing lobes. An ancient undulating surface (~15 km^2) of glacially

Table 1
Sample details and ^{10}Be surface-exposure ages. Sample names ending with QZH, PGN, TLL collected from the Quartz Hills, Polygon Spur, and Tillite Spur, respectively. Italics denote outlier. Age calculations do not account for erosion.

Sample	Latitude (deg. S)	Longitude (deg. W)	Altitude (m.a.s.l.)	Scaling (spallation)	Scaling (muons)	Thickness correction	Horizon correction	^{10}Be production rate (atom/g/yr)	^{10}Be concentration (10^4 atom/g)	Exposure age (ka)	Internal error (ka)
Reedy B drift											
03-RDY-083-QZH	85.90787	132.53595	1434	4.684	2.232	0.927	0.997	21.69 ± 1.29	347.3 ± 9.6	166 ± 11	4.8
03-RDY-084-QZH	85.90787	132.53595	1434	4.684	2.232	0.919	0.992	21.38 ± 1.27	331.2 ± 14.1	161 ± 12	7.1
03-RDY-085-QZH	85.90475	132.54282	1390	4.523	2.189	0.935	0.999	21.15 ± 1.25	276.1 ± 7.7	135 ± 09	3.9
03-RDY-086-QZH	85.90572	132.52933	1399	4.554	2.197	0.915	0.998	20.83 ± 1.23	284.2 ± 6.6	141 ± 09	7.8
03-RDY-087-QZH	85.90620	132.52293	1403	4.571	2.202	0.935	0.999	21.39 ± 1.27	342.6 ± 8.3	166 ± 11	4.2
03-RDY-089-QZH	*85.90578*	*132.51122*	*1397*	*4.548*	*2.196*	*0.953*	*0.999*	*21.67 ± 1.28*	*864 ± 14*	*441 ± 30*	*7.8*
Reedy C drift											
03-RDY-078-QZH	85.91297	132.43628	1493	4.911	2.292	0.987	0.997	24.12 ± 1.43	1434 ± 44	695 ± 55	25.1
03-RDY-081-QZH	85.90855	132.53355	1442	4.713	2.240	0.956	0.995	22.44 ± 1.33	1466 ± 36	778 ± 60	22.9
Reedy *D* drift											
03-RDY-063-QZH	85.92493	132.75775	1487	4.888	2.286	0.982	0.983	23.62 ± 1.4	3470 ± 16	2459 ± 272	21.3
Reedy E drift											
03-RDY-011-QZH	85.92895	132.51148	1739	5.942	2.550	0.978	0.997	28.94 ± 1.72	5621 ± 26	4932 ± 1128	88.3
03-RDY-012-QZH	85.92906	132.50626	1743	5.962	2.555	0.965	0.997	28.65 ± 1.7	4181 ± 44	2428 ± 270	46.9
03-RDY-013-QZH	85.92905	132.50617	1743	5.960	2.555	0.982	0.997	29.15 ± 1.73	3649 ± 44	1869 ± 180	36
03-RDY-016-QZH	85.92905	132.50617	1742	5.955	2.553	0.952	0.997	28.24 ± 1.67	3955 ± 62	2254 ± 243	61.7
03-RDY-069-QZH	85.93980	132.40382	1798	6.214	2.616	0.982	0.988	30.12 ± 1.79	4281 ± 56	2313 ± 251	53.9
03-RDY-070-QZH	85.93795	132.40998	1784	6.148	2.600	0.982	0.991	29.91 ± 1.77	4617 ± 48	2703 ± 324	55.4
03-RDY-072-QZH	85.93775	132.41812	1778	6.121	2.593	0.956	0.992	29.01 ± 1.72	4271 ± 48	2468 ± 278	51.5
03-RDY-073-QZH	85.93812	132.42310	1778	6.121	2.593	0.978	0.992	29.66 ± 1.76	5737 ± 22	4857 ± 1084	69.8
03-RDY-074-QZH	85.92718	132.34662	1715	5.834	2.524	0.986	0.998	28.68 ± 1.7	4794 ± 28	3204 ± 438	42.8
04-RDY-113-PGN	85.98945	126.05957	2166	8.108	3.046	0.980	0.94	39.42 ± 2.34	7334 ± 41	4249 ± 789	73.4
04-RDY-114-PGN	85.99057	126.05088	2154	8.040	3.031	0.948	0.997	37.92 ± 2.25	3433 ± 19	1173 ± 93	8.8
04-RDY-118-PGN	85.99018	126.05593	2156	8.051	3.034	0.983	0.996	39.31 ± 2.33	5960 ± 23	2610 ± 301	19.4
04-RDY-164-TLL	85.97897	126.64477	2139	7.956	3.013	0.969	0.999	38.46 ± 2.28	7252 ± 30	4439 ± 871	60.6
04-RDY-165-TLL	85.97893	126.65010	2145	7.990	3.020	0.979	0.979	38.9 ± 2.31	4413 ± 30	1608 ± 142	16
04-RDY-166-TLL	85.97860	126.64822	2146	7.995	3.022	0.979	0.999	39.02 ± 2.31	5823 ± 33	2532 ± 286	27.2
04-RDY-167-TLL	85.97834	126.63729	2163	8.091	3.042	0.983	1.000	39.7 ± 2.35	7670 ± 32	4831 ± 1070	74.3

scoured, striated, and heavily stained and varnished granite bedrock knolls and shallow valleys (Fig. 4) rises 3 km inland from the ice margin. Farther upslope, a series of steep colluvial slopes and two low-angle benches ('lower and middle' terraces; Fig. 2b) extend up to a ∼400 m-high escarpment separating Polygon Spur from an upper terrace (2670 m), located ∼200 m below the Wisconsin Plateau (Fig. 2b). Middle Palaeozoic granite and Late Palaeozoic sedimentary rocks, including tillite (Mercer, 1968b), underlie

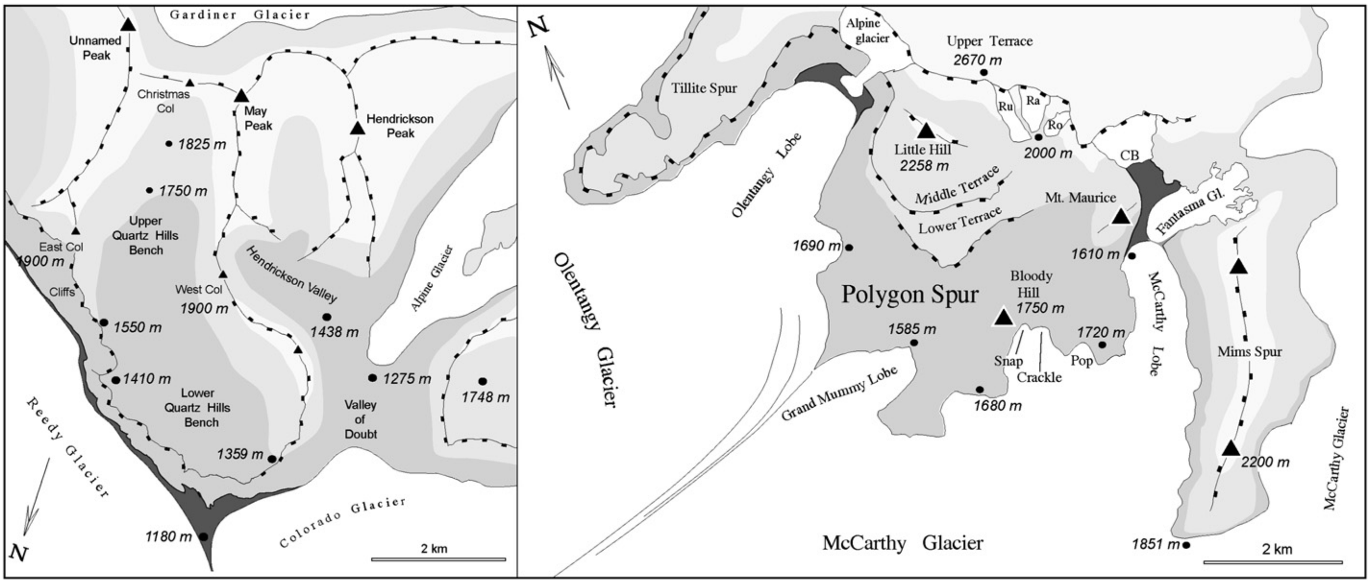

Fig. 2. a. (Left) Map of Quartz Hills showing locations mentioned in text. An indication of relief is given by shading: lower elevations are darker, higher elevations are lighter. Spot heights were measured by GPS. b. (Right) Polygon Spur map showing features mentioned in text: S – Snap lobe; C – Crackle lobe; P – Pop lobe; Ru – Rum Glacier; Ra – Raasay Glacier; Ro – Rona Glacier; CB – Cold Bowl. Blocked lines denote ridges and escarpments, and dark grey areas drift-mantled glacier ice. Shading in both areas represents relative elevation.

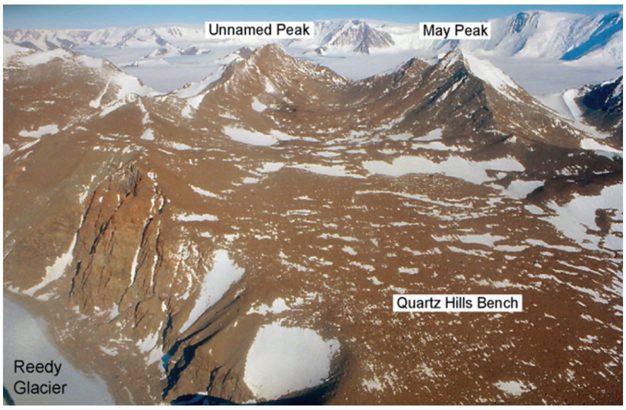

Fig. 3. Aerial view of the Quartz Hills from the north, showing the broad bench (Quartz Hills bench) sloping up to Unnamed Peak and May Peak. Reedy Glacier is visible in the bottom left of the image. Gardiner Glacier separates the Quartz Hills from the Watson Escarpment (background).

this terrace. Discussion of the tillite is beyond the scope of this paper, though reworked fragments, including septarian nodules, occur in younger deposits.

3. Surficial geomorphology

We identified nine drift units at Reedy Glacier and describe them from youngest to oldest. At least five additional glacial episodes are represented by isolated drift patches. Table 2 shows the relationship between our terminology and that of Mercer (1968b). Most glacial deposits are loose, coarse-grained diamictons containing abundant angular clasts. Sedimentologic and drift-weathering characteristics are in Table 3 and clast characteristics in Table 4.

3.1. Modern and recent deposits

Modern and recent (late Holocene) deposits typically consist of thick, loose blankets of granitic boulders and gravel overlying the present glacier, as well as ice-cored lateral moraines at the margin (Table 4). In the Quartz Hills, the most extensive ice-cored drift forms the medial moraine at the confluence of Reedy and Colorado Glaciers (Fig. 5) and features conical, ice-cored mounds and small, irregular (1–1.5 m high) ridges. A large (3 m high), ice-cored lateral moraine emerges from this medial moraine and extends southwest along the Colorado Glacier margin for 1.5 km, whereupon it bifurcates and extends for a further kilometre as two closely spaced moraines. In the Caloplaca Hills, a single ice-cored moraine, as much as 3 m high, bounds the Wotkyns Lobe (Fig. 6) and continues along the eastern margin of Wotkyns Glacier. Sinuous medial moraines, as much as 4 m high and 1 km in length, occur on the Wotkyns Lobe surface. At Polygon Spur, a large (2–4 m high) ice-cored ridge bounds the McCarthy lobe, but, in general, modern and recent moraines are scarce, reflecting the low volume of transported material. Nevertheless, sections of a single ridge can be traced within the valleys of the Grand Mummy, Snap, and Pop Lobes (*informal names*; Fig. 2b). In each location, these moraines are less than 10 m from the ice margin and comprise narrow (~1 m wide) accumulations of material. The presence of highly weathered clasts in the moraines indicates reworked material has been transported by McCarthy Glacier.

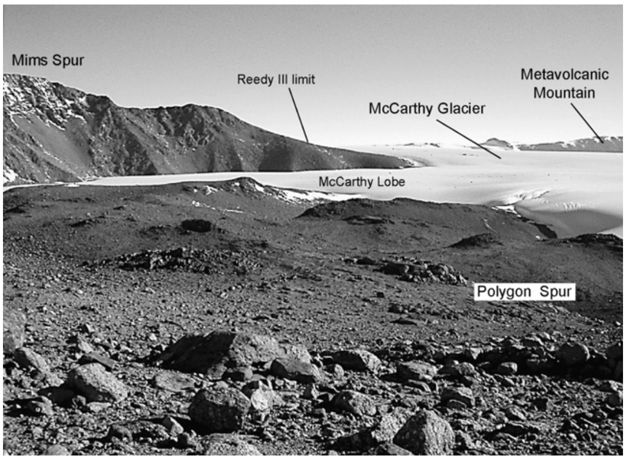

Fig. 4. Photograph of Polygon Spur taken from Bloody Hill, looking south. Mims Spur on the left is separated from Polygon Spur by the McCarthy Lobe. Striated bedrock knolls and shallow valleys can be seen on lower Polygon Spur. Metavolcanic Mountain is visible in the distance.

3.2. Reedy III drift

Throughout the Quartz Hills, Reedy III drift (Mercer's (1968b) terminology) forms a conspicuous, thick (>1 m in places) sheet of granitic boulders and gravel (Table 3) overlying more-weathered material (Fig. 7) and pre-existing moraines. The drift, which is grey in colour and generally unweathered, extends from the modern glacier surface (~1180 m) to 1410 m in the eastern Quartz Hills and to 1359 m above Colorado Glacier (Fig. 5). Well-defined lateral moraines (1–3 m high) form the limit at two sites. One moraine continues for more than a kilometre along the cliff top above Reedy Glacier, dropping from 1396 m to 1390 m to the southwest. The second, ~100 m in length, overlooks the confluence of Reedy and Colorado Glaciers. A prominent drift edge occurs 50 m below the Reedy III drift limit; we interpret it as a still-stand or minor readvance during deglaciation. Slope processes have disturbed deposits below the drift limit, especially where buried ice is present.

In the Valley of Doubt, the upper limit descends gradually 1.3 km towards the valley apex, indicating that ice flow was from Colorado Glacier rather than local valley ice. A complex of irregular, closely spaced, discontinuous ice-cored ridges (1–2 m in relief, 2–8 m wide) lies ~100 m inside the drift limit on the valley bottom; two continuous ridges also inside the drift limit descend both valley walls. Together, these ridges occupy a position similar to the recessional limit on the bench.

Reedy III drift is thin and discontinuous in the Caloplaca Hills. On the north ridge of Mt Carmer (Fig. 6), fresh granite erratics extend to at least ~1550 m elevation, roughly 40 m above Wotkyns Glacier. We did not detect a drift limit on the eastern slopes of the mountain, but a narrow band of erratics with a distinct upper limit is exposed on the valley floor at ~1550 m, ~140 m above Wotkyns

Table 2
Comparison of Reedy Glacier drifts (this study) to Mercer's (1968b) terminology, arranged from youngest (Reedy III) to oldest (Middle Horlick Unit 5).

Unit name (this study)	Unit name (Mercer, 1968b)
Reedy III drift	*Reedy III drift*
Reedy *A* drift	*Reedy II drift*
Reedy *B* drift	
Reedy *C* drift	
Reedy *D* drift	*Reedy I drift*
Reedy *E* drift	
Red drift	*No equivalent*
Middle Horlick Unit 5	*Middle Horlick Unit 5*

Table 3
Sedimentology and weathering characteristics of drift units at Reedy Glacier. CsD: clast-supported diamicton; MsD: matrix-supported diamicton; (ms): moderately sorted; (us): unsorted; (sr): silt-rich; (sd): sand-rich; (cr): clay-rich; (sr/sd): (silty–sandy); (gr): gravel rich. 'Ghosts' are highly rotten clasts lacking structural integrity.

Unit	Sedimentology	Weathering depth (cm)	Deflation pavement thickness (cm)	Cavernous weathering of surface boulders	Planed boulders	Patterned ground	Ghosts	Description
Quartz Hills								
Reedy III	(us) CsD	0	0	No	No	Frost cracks	No	Boulders largely confined to surface. Sand fines with depth.
Reedy *A*	Boulder	0	0	No	No	No	No	No fine sediments. Boulders angular and lightly stained.
Reedy *B*	CsD	60	20	Minor	No	No	No	Unit thickness ranges from one clast to 1 m, includes pockets of sorted sand.
Reedy *C*	(us) CSD	Unknown	Unknown	Moderate	No	No	No	Drift dominated by boulders.
Reedy *D*	(ms) CsD	80	10	Extreme	Yes	No	Yes	Deeply stained sand fines with depth. 4 cm salt lens at 10 cm depth, salt flecks common to 15 cm depth.
Reedy *E*	(sr) MsD	≥50	20	Extreme	Yes	No	Yes	Sand & gravel confined to upper 5 cm and probably products of weathering of surface boulders.
Caloplaca Hills								
Reedy III	–	0	No	No	No	No	–	Unit consists of occasional fresh boulders and cobbles.
Reedy *B*	–	–	No	Minor	No	No	–	Surface of frost-shattered boulders, sand and weathering detritus.
Reedy *D*	–	–	–	Extensive	No	Yes	–	Surface formed of deeply stained, angular boulders, weathering detritus and coarse gravel. Boulders exfoliating.
Reedy *E*	–	–	–	Extreme	Yes	No	–	Deflated surface dominated by coarse weathering detritus. Silty sand below surface.
Polygon Spur								
Reedy III	–	–	–	No	No	No	No	Unit consists of occasional fresh boulders and cobbles.
Reedy *B*	CsD	–	–	No	No	No	No	Clast types exotic to lower Polygon Spur. Unit very loose. Salt flecks common to 60 cm.
Reedy *C*	(us) MsD	30	20	Moderate	No	No	No	Highly compacted silty–sand matrix to 70 cm. Salt throughout.
Reedy *D*	(gr) CsD	>100	–	Moderate-Extensive	No	No	No	Matrix tightly packed. Fractured clasts throughout unit. Salt beneath surface boulders.
Reedy *E*	(sr) MsD	>100	–	Extreme	No	No	–	Many granite boulders rest on pedestals of underlying sedimentary bedrock protected from wind erosion.
Red	(sr/sd) MsD	>100	5	No	No	Relict frost cracks	No	Matrix varies from silt to silt-rich gravel. Exotic clasts on surface and throughout depth.
Horlick Unit 5	(cr) MsD	–	No	No	No	No	–	Surface dominated by weathered clay and exotic clasts. Clay highly compacted. Granite and large boulders absent.
Cirque I	CsD	–	–	No	No	Frost cracks	No	Unit overlies buried glacier ice.
Cirque II	(sd) MsD	≥50	10	No	No	Polygons (>2 m)	No	Unit overlies buried glacier ice. Surface of small, moderately stained and exfoliating boulders.
Cirque III	(sd) MsD	≥50	10	No	No	Polygons (>2 m)	No	Unit overlies buried glacier ice. Greater abundance of surface boulders. Fresher clasts in frost cracks.

Lobe (due to variations in glacier topography, the surface of Wotkyns Lobe is as much as ~100 m lower than that of Wotkyns Glacier). Above the east margin of the lobe, the upper limit of Reedy III drift occurs at ~1570 m. A separate deposit occurs on the lip of Mercer Col (*informal name*; 1700 m; Fig. 6) ~200 m above Reedy Glacier. Because this was deposited by Reedy Glacier, rather than Wotkyns Lobe, we have used this elevation to reconstruct the former level of Reedy Glacier in the Caloplaca Hills.

On Polygon Spur, Reedy III drift is thin, patchy, and, in places, consists only of erratics. We employed the upper limit of fresh erratics to determine the extent of this unit. On the northwest slopes, the uppermost erratics occur at 1717 m, roughly 100 m above the present glacier surface (Fig. 8). From there, the drift limit slopes southeast and is indistinct until reappearing at 1647 m as ice-cored drift in a gulch beneath Mt. Maurice (*informal name*; Fig. 2b). From here, ice-cored drift and a prominent lateral moraine rise to 1809 m at the base of the upper terrace escarpment in Cold Bowl (*informal name*; Fig. 2b), indicating that ice flowed out of Cold Bowl and coalesced with the McCarthy Lobe. Ice-cored Reedy III drift extends ~40 m above the southeast margin of Fantasma Glacier (*informal name*; Fig. 2b), but is buried by talus beneath the summit of Mims Spur (Fig. 8). The limit continues 3 km farther south and ~190 m above the surface of McCarthy Glacier as a distinct (1.5 m relief), ice-cored lateral moraine on the southern end of Mims Spur.

Table 4
Clast lithology and weathering characteristics of Reedy Glacier deposits. W1–W4: % clasts in each weathering stage (Appendix I and II); Bkn: % broken clasts; GM: % glacially moulded clasts; GS: % striated clasts; Ptt: % pitted clasts; Cal: % clasts with calcite accumulations; DV: % desert-varnished clasts; Vnt: % ventifacts; S1–S4: % clasts in each surface oxidation stage; Salt; % clasts with surface salt accumulations. Also see Appendix I and II for clast lithology. In Description, A: Angular clasts; SA: Sub-angular clasts.

Unit	No.	Lithology	W1	W2	W3	W4	Bkn	GM	GS	Ptt	Cal	DV	Vnt	S1	S2	S3	S4	Salt	Description
Quartz Hills																			
Modern	100	Gngr/Gr	7	0	0	0	67	43	11	0	0	0	0	0	0	0	0	0	Clasts lack significant weathering. Many are glacially moulded though striations are restricted to finer-grained lithologies. Frost-shattering of surface clasts common
Reedy III	459	Gngr/Gr/Maf	26	7	0	0	96	73	7	6	0	10	0	43	4	0	0	8	Clasts lack significant weathering. Many are glacially moulded though striations are restricted to finer-grained lithologies. Frost-shattering of surface clasts common
Reedy *A*	0	Gngr/Gr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Clasts predominantly angular, lightly stained
Reedy *B*	150	Gngr/Gr	18	61	21	0	41	55	0	7	0	0	0	0	17	77	6	11	Clasts weathered to 60 cm
Reedy *C*	0	Gngr/Gr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Fractured clasts throughout, rotten in upper 5 cm
Reedy *D*	152	Gngr/Gr	0	38	44	17	32	66	0	16	0	0	0	0	27	48	25	79	Fractured, rotten clasts common to 80 cm depth
Reedy *E*	100	Gngr/Gr	31	2	57	10	27	35	0	27	0	0	0	7	31	49	13	68	Fractured clasts common throughout unit
Polygon Spur																			
Modern	150	Gr	20	27	19	0	25	43	0	7	0	0	0	41	33	13	0	0	Majority of clasts moulded. Many are weathered due to prior exposure.
Reedy III	0	Gr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	In Cold Bowl clasts are predominantly local pegmatites, all A in shape
Reedy *B*	100	Gngr/Mcgr/Grdi	79	19	2	0	7	19	0	0	0	0	0	64	31	5	0	62	Clasts typically A. Salt flecks common to 60 cm
Reedy *C*	150	Gr	47	31	22	0	31	20	0	0	0	0	0	25	55	21	0	21	Clasts typically A-SA, exhibit faceting & are moderately stained. Some are rotten
Reedy *D*	100	Gngr	0	36	55	9	69	1	0	21	0	0	0	0	23	52	25	51	All clasts deeply stained, some exfoliated. Clasts predominantly A (though one faceted clast was found), most are fractured
Reedy *E*	50	Gngr	0	21	8	4	15	60	0	2	16	0	0	20	36	18	12	42	Fractured clasts common throughout unit
Red	50	Maf/Gr	88	12	0	0	10	64	0	10	1	65	1	0	21	0	79	0	Surface clasts weathered to a bright red colour & highly varnished. Many pieces of shattered concretion, probably from Kentmere tillite. Majority SA, though faceting & striations are common. One ventifact found below surface
Horlick 5	0	Maf/Shale/SS/Qtz	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	Clasts mostly exotic to Polygon Spur. All extremely desert-varnished
Cirque I	50	Gr/SS/Shale	0	0	0	0	39	0	0	0	0	0	0	18	0	0	0	0	Clasts predominantly A
Cirque II	50	Gr/SS/Shale	62	5	0	0	82	14	0	0	0	0	0	40	60	0	0	0	Clasts predominantly A, though some show faceting. Most are stained
Cirque III	52	Gngr/Gr/Shale	58	0	4	0	78	20	0	0	0	0	0	24	58	18	0	0	Clasts predominantly A, more stained than Cirque II

Reedy III drift also occurs on nunataks near the mouth and head of Reedy Glacier. Near the confluence of Reedy Glacier and Mercer Ice Stream, fresh erratics on the summit of Cohen Nunatak (730 m elevation; 110 m above glacier surface; Fig. 1) indicate it was overrun during the Reedy III period. The lower summit (1060 m elevation) of nearby Langford Peak (1126 m elevation) also is mantled by unweathered erratics, indicating that most if not all of this nunatak, rising more than 300 m above the ice surface, was overridden. Towards the head of Reedy Glacier, in the westernmost valley of Metavolcanic Mountain (Fig. 1), Reedy III drift extends to a distinct limit 120 m above the ice surface. Directly across the glacier, fresh erratics on bedrock on Shapley Ridge (Fig. 1) are ~100 m above the ice surface. Farther up-glacier, fresh erratics are perched on deeply weathered bedrock on Hatcher Bluffs (Fig. 1) as much as 70 m above the glacier surface. Mercer (1968b) reported finding Reedy III material ~40 m above the glacier surface at Strickland Nunatak, 20 km farther up-glacier. However, the only fresh material we observed there occurred in association with periglacial mounds.

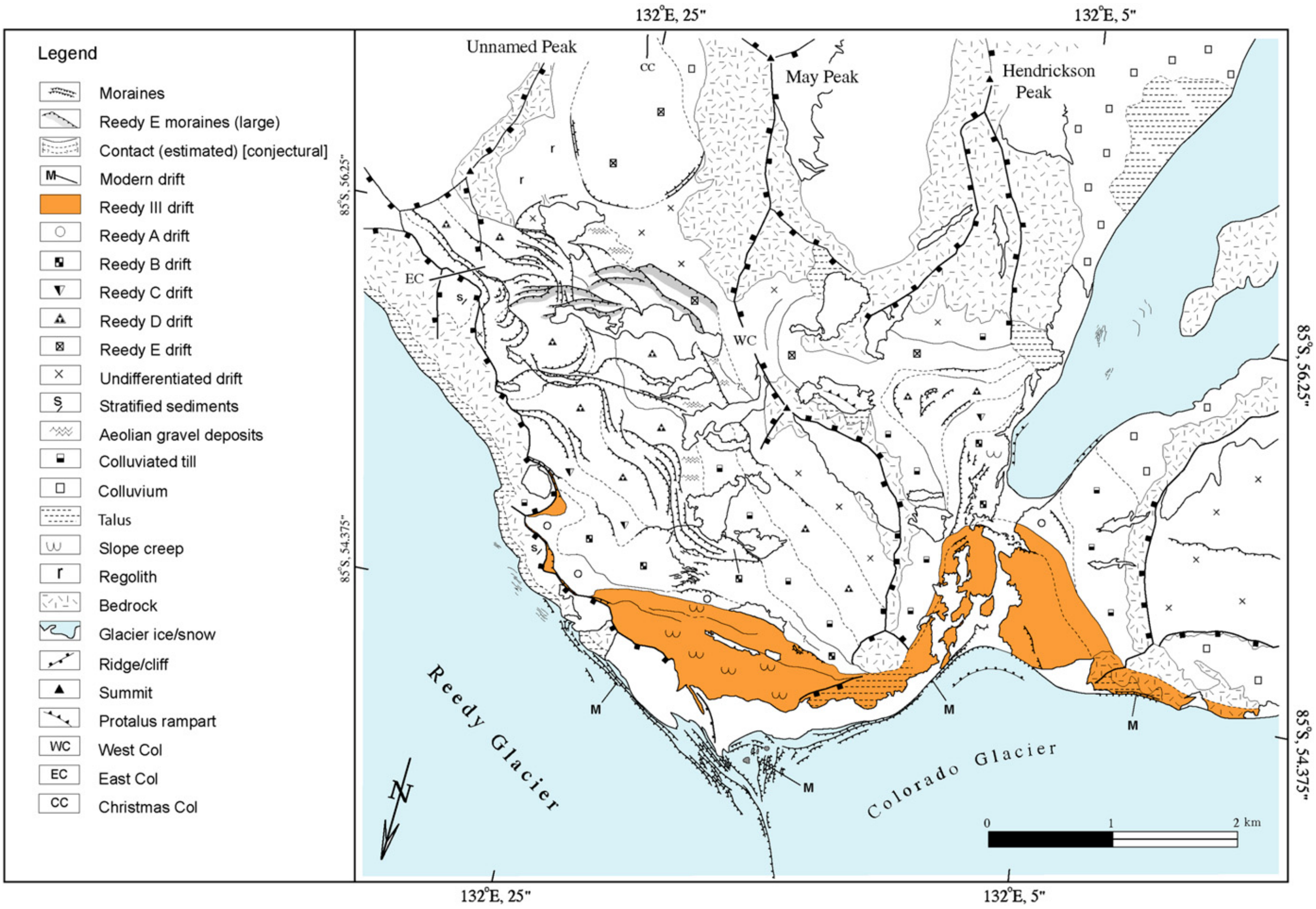

Fig. 5. Glacial geomorphologic map of the Quartz Hills.

Surface-exposure ages from the upper limit of Reedy III drift fall between 17.3 and 14.3 ka in the Quartz Hills, between 14.8 and 10.5 ka in the Caloplaca Hills, and between 9.2 ka and 7.8 ka on Mims Spur (see Todd et al., personal communication).

3.3. *Reedy* A *drift*

Reedy *A* drift occurs only in the Quartz Hills, as narrow patches of boulders immediately outside and upslope from Reedy III deposits. The unit extends to ~1480 m elevation on the bench where an indistinct drift limit descends westward for 1 km before passing under Reedy III drift at 1450 m. In the Valley of Doubt, Reedy *A* drift comprises rare boulders on the east valley wall, as much as 0.5 km up-valley of the maximum LGM limit. Boulder surfaces exhibit only minor granular disaggregation and patchy surface staining.

3.4. *Reedy* B *drift*

Reedy *B* drift comprises boulders and clasts exhibiting moderate surface staining, granular disaggregation, shallow (<1 cm) pitting, minor cavernous weathering and, rarely, desert varnish (Tables 3 and 4). In the Quartz Hills, the drift extends to 1513 m elevation on the east bench, where a small (<2 m high), discontinuous moraine ridge marks the upper limit. The drift edge descends gradually westward, reaching 1500 m on the west bench before merging into colluviated-till slopes (Fig. 5). Reedy *B* drift is thicker on this side of the bench than to the east and forms moraines and mounds.

In the eastern part of Valley of Doubt, Reedy *B* drift occurs to ~1390 m elevation. The unit has been modified extensively by slope processes and is characterised by large, but stable, lobate terraces. A prominent lateral moraine, comprising a narrow (2 m wide) ridge of boulders and extending almost horizontally for about 1 km, likely marks the upper drift limit (Fig. 5). The uniform elevation suggests that the moraine may have been deposited when the lobe of Colorado Glacier coalesced with northward-flowing alpine ice. Reedy *B* drift is not preserved on the west valley wall, likely due to the unstable slope.

In the Caloplaca Hills, Reedy *B* drift extends from near the terminus of Wotkyns Lobe, where it is overlain by Reedy III erratics, to roughly 100 m beyond the Reedy III drift limit (Fig. 6). Three closely spaced lateral moraines occur on the valley floor, ~150 m above the present lobe terminus and likely mark recessional stages. A separate patch of Reedy *B* drift is present on Mercer Col at 1700 m, a few metres distal to Reedy III deposits.

Reedy *B* drift on Polygon Spur is thin and patchy. A faint upper drift limit crosses Polygon Spur at 1710 m elevation. Inside this limit, however, the drift crops out to as much as 1755 m elevation on the summit of Bloody Hill (*informal name*; Fig. 2b). Low-relief (0.5 m) moraines of are concentrated in shallow valleys containing the Grand Mummy, Snap, Crackle (*informal name*; Fig. 2b), and Pop ice lobes and on either side of Bloody Hill (Fig. 8). Because they lie below the upper drift limit, these are interpreted as recessional landforms.

Five perched cobbles from Reedy *B* drift in the Quartz Hills gave exposure ages ranging from 135 ± 9 ka to 166 ± 11 ka (Table 1), with the youngest samples being at lower elevations. We reject an age of 441 ± 30 ka as an outlier, suggesting that the sample had prior exposure.

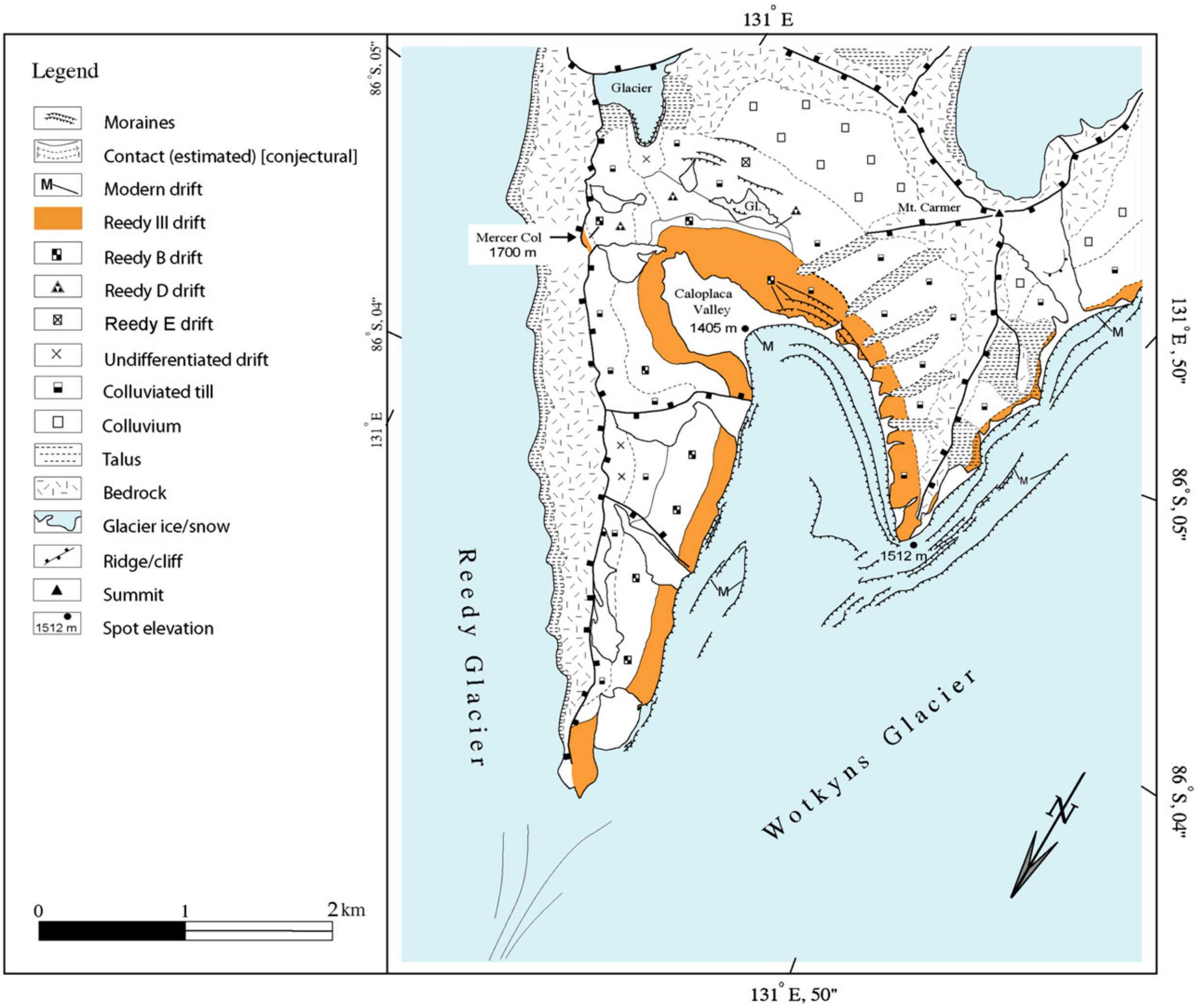

Fig. 6. Glacial geomorphologic map of the Caloplaca Hills.

3.5. *Reedy* C *drift*

Reedy *C* drift (Table 2) is characterised by boulders exhibiting moderate surface staining, granular disaggregation, and fist-sized caverns (Table 3). In the Quartz Hills, the drift is perched on the lip of Hendrickson Valley (*informal name*; Fig. 2a) and overlies an older (likely Reedy *E* drift) moraine. The upper drift edge is defined clearly, but slope processes have modified much of the sheet below. On the eastern bench, thin Reedy *C* drift occurs to ~1550 m elevation. Two boulders from Reedy *C* drift in the Quartz Hills gave apparent (zero erosion) surface-exposure ages of 695 ± 55 and 778 ± 60 ka (Table 1).

On Polygon Spur, Reedy *C* drift is conspicuous due to its light colour, the result of abundant pale, fine-grained granite. On the lower terrace, the drift extends to 1926 m elevation (Fig. 8) where it forms a double moraine, 1–1.5 m high and ~150 m long. The drift edge descends to the southeast for 1 km and becomes a single bouldery moraine at ~1810 m elevation. The moraine maintains this elevation for almost 2 km as it crosses Polygon Spur, before disappearing below the west summit of Mt Maurice. A prominent moraine splits from this drift edge at 1798 m (Fig. 8) and is interpreted as a recessional landform. At lower elevations, the drift forms a thick sheet extending to the modern ice margin. In the shallow valleys adjacent to the Snap, Crackle, and Pop ice lobes, 1 m-high ridges occur in the lee of bedrock

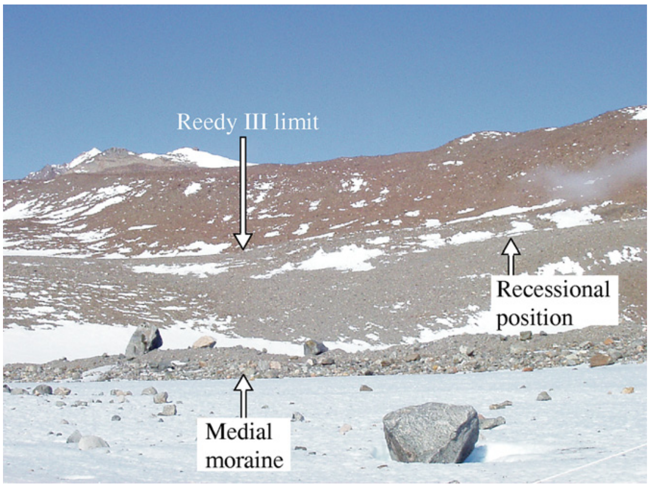

Fig. 7. Reedy III drift overlying weathered deposits in the Quartz Hills. The conspicuous upper limit of this unit occurs ~300 m above the modern glacier surface (foreground) and represents the last glacial maximum of Reedy Glacier. The bouldery landform in the middle distance is a medial moraine marking the confluence of Reedy and Colorado Glaciers.

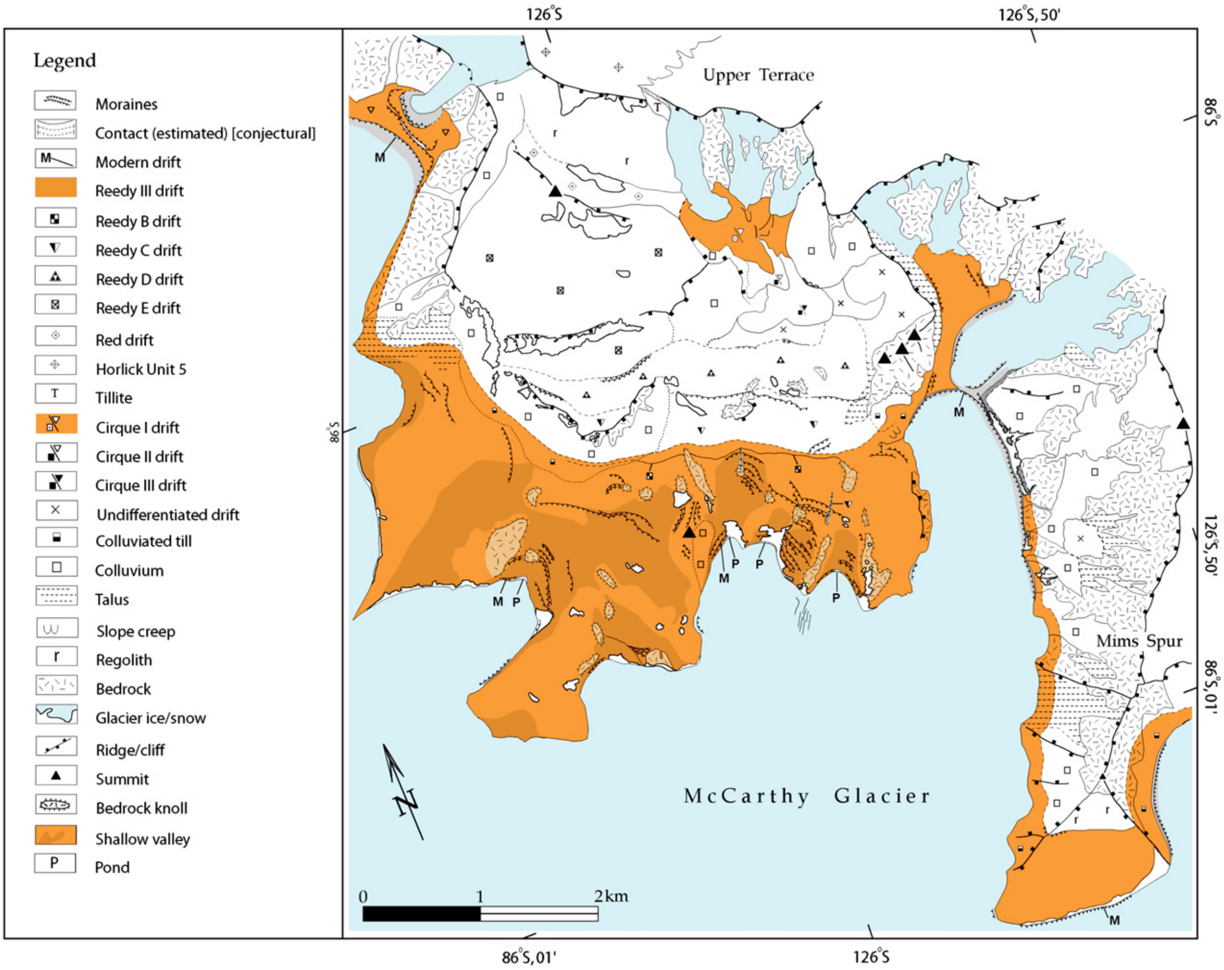

Fig. 8. Glacial geomorphologic map of Polygon Spur.

knolls and are oriented parallel to the valley axes. Because these landforms comprise material distinct from the local bedrock, they are not the products of local lee-side plucking. Rather, they might represent interlobate moraines formed during thinning and separation of ice lobes into their respective valleys.

3.6. Reedy *D* drift

Reedy *D* drift includes clasts that are deeply stained, exhibit granular disaggregation, and are cavernously weathered (~75 cm diameter caverns; Tables 3 and 4). Fine-grained sediments are

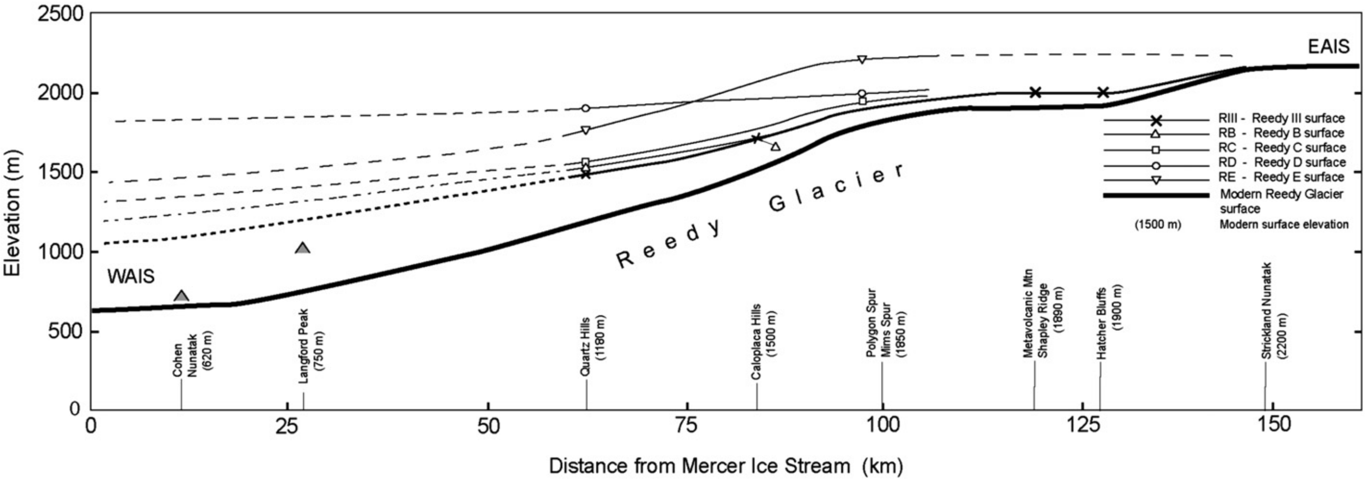

Fig. 9. Present and former longitudinal-surface profiles of Reedy Glacier. Reconstructions are based on the upper limits of deposits at the glacier margins. Symbols denote the sites used in each reconstruction. Profiles have been extrapolated down-glacier (dashed lines) to estimate surface elevations at the confluence of Reedy Glacier and Mercer Ice Stream.

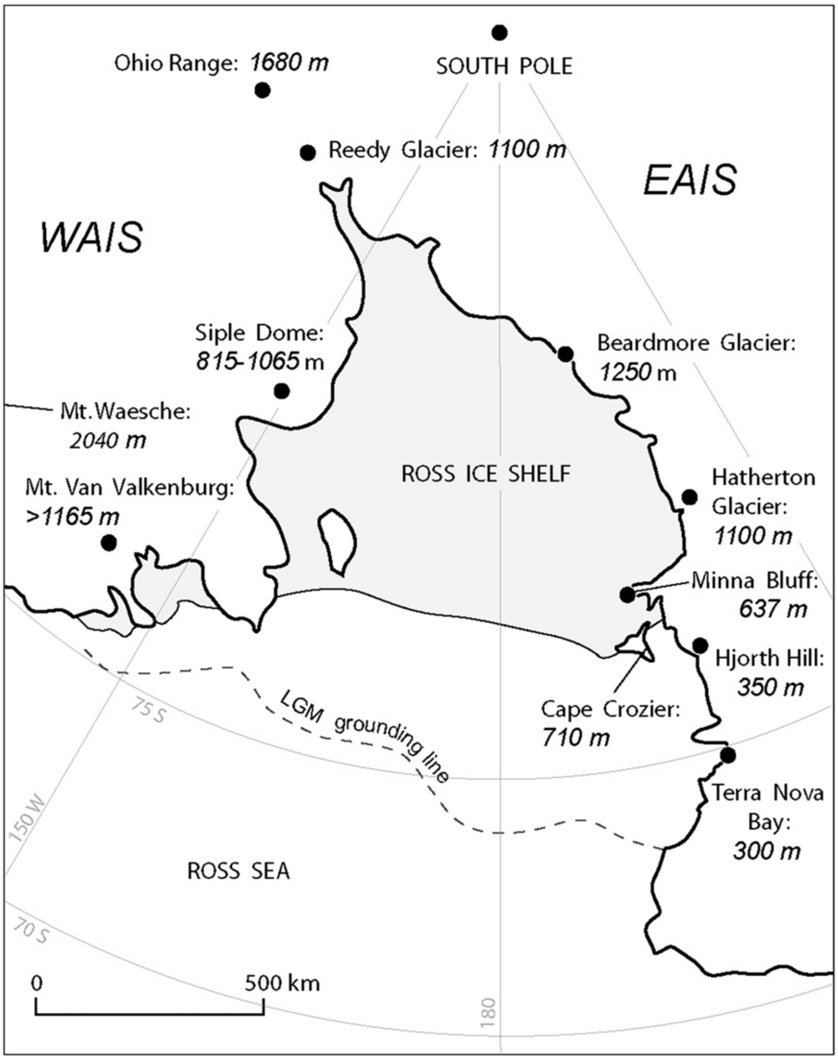

Fig. 10. Former ice-surface elevations for the Ross Sea Embayment during the LGM, based on glacial geologic data (Transantarctic Mountains and Marie Byrd Land) and flow model data (Siple Dome).

oxidised. In general, the drift becomes progressively more weathered with increasing elevation and distance from the present-day ice. An apparent (no erosion) age of 2.5 Ma from a boulder in the Quartz Hills provides a minimum age for this deposit (Table 1).

In the Quartz Hills, Reedy *D* drift forms a profusion of moraine ridges and mounds, many of which are cross-cutting. Ice moving over East Col (1900 m; *informal name*; Fig. 2a) from the main trunk of Reedy Glacier deposited looped drift edges and small moraines (Fig. 5). In addition, lobes from Reedy Glacier flowed southwest across the bench, depositing large drift sheets and extensive moraines (Fig. 5). Coalescence of these two ice lobes at one time is suggested by the distribution of moraines. We also identified Reedy *D* drift in Hendrickson Valley, where it forms patches and discontinuous moraine ridges up to 1550 m. The orientation of these landforms (e.g. lateral moraines and drift edges rise in a down-valley direction) indicates an up-valley flow of ice from the Valley of Doubt (Fig. 5).

In the Caloplaca Hills, Reedy *D* drift forms a continuous sheet on the valley floor from the Reedy *B* drift edge to ∼1600 m elevation (Fig. 6). A veneer of large boulders correlated with this unit on the basis of weathering condition also mantles Mercer Col.

At 1971 m elevation on Polygon Spur, a pair of parallel moraines (1–1.5 m high) marks the upper limit of Reedy *D* drift (Fig. 8). From here, an indistinct drift edge can be traced eastward and occurs ∼500 m farther southeast and 100 m lower in elevation as a single moraine. Southeast of this landform, a second pair of parallel ridges forms the drift edge before becoming indistinct ∼500 m northwest of Mt Maurice. The Reedy *D* drift limit loops around the base of the peak before disappearing beneath Reedy *C* drift.

3.7. *Reedy* E *drift*

Reedy *E* drift is a severely weathered, yellow–green silty diamicton with a surface dominated by coarse, heavily stained gravel, weathering detritus, and planed granitic boulders (Tables 3 and 4). The drift occurs on the uppermost bench in the Quartz Hills (Fig. 5) and includes the largest moraines at that site (as much as 50 m high). Maintaining an elevation of ∼1750 m, the moraines form a closely spaced suite of arcuate ridges that extends for more than 1 km across the upper bench (Fig. 5). The orientation of these landforms indicates deposition by a lobe of Reedy Glacier ice flowing southwest across the bench. The moraines are overlain extensively by Reedy *D* drift, with the exception of the highest and westernmost ridge. Reedy *E* drift also is exposed at 1825 m as a sheet descending gradually ∼0.5 km from the base of Christmas Col (*informal name*; Fig. 2a) to an arcuate line of granite boulders (Fig. 5). This outer limit can be traced to two severely degraded lateral moraines that descend northwest across the flanks of both May Peak and Unnamed Peak (*informal name*; Fig. 2a). The orientation of these landforms indicates ice flow from the southwest (Fig. 5), supplied either by a thickened Gardiner Glacier overtopping the col or by a local cirque glacier. Sections of arcuate moraines (2 m high) also composed of Reedy *E* material occur on the lip of Hendrickson Valley below the maximum Reedy *E* limit.

In the Caloplaca Hills, Reedy *E* drift occurs on Mercer Col as an extensive sheet overlain by patchy younger deposits. At a similar elevation on the opposite side of Caloplaca Valley, a series of large (as much as 5 m high) lateral moraines marks the upper limit of Reedy *E* drift. Elsewhere in Caloplaca Valley, Reedy *E* drift is exposed only where overlying drift is thin or patchy.

On Polygon Spur, the drift mantles the entire middle terrace and some of the lower terrace and extends to a clear limit at ~2200 m elevation, marked by granite boulders (1–2 m high) (Fig. 8). This limit rises northwest to 2260 m on the summit of Little Hill (*informal name*; Fig. 2b) and drops slightly in elevation on the hill's north ridge. At its northernmost extent, the drift is sufficiently thick for abundant large (>2 m diameter, 0.5–1 m depth) polygons to have formed. The unit thins progressively to the southeast, where it is a veneer of boulders overlying Red drift. On nearby Tillite Spur, Reedy *E* drift forms a spread of boulders on Late Palaeozoic bedrock. On both spurs, boulders have shielded underlying sedimentary rocks from weathering to the extent that many are now on pedestals.

Nine boulders from Reedy *E* drift in the Quartz Hills have apparent exposure ages ranging from 1.9 Ma and 5.0 Ma (Table 1). Three on Polygon Spur are between 1.2 and 4.2 Ma and four boulders on Tillite Spur range from 1.7 to 4.8 Ma. The surfaces of these boulders range from heavily corroded and exfoliated to varnished and case-hardened, but all have experienced significant erosion. We treat their ages as minimum-limiting values; erosion rates ranging between 10 and 15 cm/Ma would be sufficient to account for the observed spread of ^{10}Be concentration among a set of rocks with a similar depositional age. Assuming that the sample of the greatest apparent age has undergone the least erosion, we infer a depositional age of >5 Ma for Reedy *E* drift.

3.8. *Red drift*

Red drift occurs only on Polygon Spur. This silt-rich diamicton forms a sheet in the shallow valley east of Little Hill and lacks moraines. The deflated surface is characterised by devitrified volcanic pebbles, many of which have weathered to a vibrant red colour and exhibit desert varnish (Tables 3 and 4). Small quantities of granite blocks, sandstone plates, and blue–grey cobbles of an unidentified, fine-grained igneous lithology are set into this surface. Additionally, pieces of degraded concretions, eroded out of the Permian tillite upslope (Mercer, 1968b), occur on Red drift. Parts of the surface have been modified into ripples, ~10 cm in relief.

3.9. *Middle Horlick Unit 5*

The oldest surficial deposit, Mercer's (1968b) Middle Horlick Unit 5, forms an extensive, sub-horizontal sheet on the upper terrace (~2670 m elevation) above Polygon Spur (Fig. 8). According to Mercer (1968b), the unit overlies striated granite bedrock. Downcutting of the plateau to the present topography, in particular the carving of the Olentangy Lobe valley, has cut a slope through this tillite, exposing it in section at the edge of the upper terrace. Although here the tillite is only 7 m thick, Wilson et al. (1998) reported deposits as much as 32 m thick on the edge of the Wisconsin Plateau overlooking Tillite Spur. Middle Horlick Unit 5 is dominated by weathered clay and by clasts (Table 3) of many different lithologies, including sandstone, quartz, and unidentified volcanic rocks. Unlike all other deposits at Reedy Glacier, most clasts exhibit clear striations and/or glacial moulding beneath desert varnish (Table 4).

3.10. *Cirque drifts*

Three small alpine glaciers (Rum, Raasay, and Rona Glaciers; *informal names*; Fig. 2b), originating in shallow bowls cut into the upper terrace escarpment, coalesced in the past and advanced southward over Polygon Spur. Multiple ice-cored drift sheets mark the former extents of this ice tongue. Today, fresh grey material is emerging along shear planes at the base of each glacier and likely originated on the headwalls. Drift deposited by the coalesced tongue spans a range of ages, but can be assigned to three broad groups – Cirque drifts I–III, in order of increasing age (Tables 3 and 4). Cirque I drift, defined by the limit of fresh, unweathered clasts, occurs as much as ~500 m from the modern glacier margin. The unit overlies ice which, due to its clear nature and the presence of flattened air bubbles, likely is of glacial origin. Cirque II drift extends roughly 100 m beyond the Cirque I drift limit (Fig. 8) and terminates in a low (1–2 m high) scarp. This unit is ~50 cm thick, overlies ice, and is fretted with large (>2 m diameter, ≥30 cm deep) polygons. Surface clasts are moderately stained and exfoliated, but lack caverns. Cirque III drift is a bouldery sheet exposed from the Cirque II drift edge, ~900 m from the present glacier margins (Fig. 8). The surface is similar to that of Cirque II drift, including many large (>2 m diameter, 30–40 cm deep) polygons (Table 3) and differing only in a greater abundance of boulders and a greater degree of clast weathering (Table 4). Cirque III drift is ~50 cm thick and also overlies ice.

3.11. *Undifferentiated deposits*

Thin patches of undifferentiated drift lacking definite limits occur in the Quartz Hills west of the Valley of Doubt, on the north flank of Hendrickson Peak, on West Col, and on the slopes both north and south of West Col. These deposits comprise highly weathered granite material and, in places, have been modified by slope processes. In addition, erosion of the eastern edge of the bench above Reedy Glacier has exposed in section a stratified diamicton, described in more detail by Wilson et al. (1998). The unit exhibits finely laminated silts and sands, both with and without dropstones (Fig. 5), affording evidence of ice-marginal water at Reedy Glacier in the past.

On Polygon Spur, an extensive patch of severely weathered, undifferentiated drift occurs between the lower limit of Cirque III drift and the upper limit of Reedy *D* drift (Fig. 8). The drift surface has high concentrations of large, cavernously weathered boulders, abundant coarse sand and weathering detritus. Because this unit is surrounded by younger deposits, the exact areal extent and origin of the drift is unknown.

4. Ice extent and palaeoenvironment

4.1. *Reedy Glacier drifts*

The areal distribution, fresh, virtually unweathered nature of the drift, and widespread presence of buried ice all indicate that Reedy III drift was deposited during the last major expansion of Reedy Glacier. On the basis of these physical characteristics, we correlate Reedy III drift with similar deposits throughout the TAM, including Beardmore drift (Denton et al., 1989b; Denton and Hughes, 2000), Britannia II drift (Bockheim et al., 1989), Terra Nova drift (Orombelli et al., 1990), and Ross Sea drift (Stuiver et al., 1981; Hall et al., 2000; Hall and Denton, 2000), all of which were deposited during the LGM. This geologic correlation is supported by surface-exposure ages that constrain the Reedy III limit to this time period (Todd et al., personal communication). We suggest the prominent, undated drift edge ~50 m below the maximum limit in the Quartz Hills represents a still-stand or readvance during deglaciation. The event might correspond to similar recessional landforms at Hatherton Glacier (Britannia I drift, >9.3 ka Bockheim et al., 1989), and on Hjorth Hill, southern Scott Coast (~12.8 ka; Hall and Denton, 2000).

Ice-cored drift and moraines on Polygon Spur indicate the coeval expansion of small, independent glaciers. For instance, the presence of local ice in Cold Bowl during the Reedy III maximum is indicated by the steep drop (by more than 150 m) of the Cold Bowl lateral moraine towards the McCarthy Lobe. Given that this lateral moraine joins the Reedy III limit of the McCarthy Lobe, we conclude that the Cold Bowl and McCarthy Glaciers were confluent during the Reedy III maximum. This scenario might be consistent with the hypothesis of increased precipitation over the EAIS during the early Holocene.

Reedy *A* drift extends only slightly beyond the Reedy III deposits in the Quartz Hills and must have been deposited between ~17 ka and ~135 ka, the bracketing ages from Reedy III and Reedy *B* drifts, respectively.

The areal distribution of Reedy *B* drift indicates that the surface of Reedy Glacier was ~300 m higher than today in the Quartz Hills. Reedy ice in the Caloplaca Hills thickened to, but did not overtop, Mercer Col (~1700 m; elevation of drift limit 1666 m), and at Polygon Spur, Reedy Glacier was less extensive during the Reedy B period than during the subsequent Reedy III advance. Five surface-exposure ages from boulders from Reedy *B* drift constrain the deposits to Marine Isotope Stage 6. The only other confirmed deposits of this age in the TAM are in Marshall Valley in the Royal Society Range (Hendy, 2000).

In the Quartz Hills, Reedy *C* and *D* drifts occur as much as ~40 m and ~390 m (elevation) upslope of the Reedy *B* deposits, respectively. The two samples from Reedy *C* drift give ages (695 ka and 778 ka) that are significantly older than MIS 6. Despite their general consistency, these ages are sufficiently old that erosion probably had a significant effect on ^{10}Be concentrations. Therefore, we suggest that these are minimum ages.

Reedy *E* drift represents the earliest identified expansion of Reedy Glacier and the earliest preserved record of ice thickening conformable with the present landscape. In the Quartz Hills, Reedy Glacier ice flowing southward across the bench deposited a series of large moraines on the upper bench, more than 600 m above the modern glacier surface. At roughly the same time, thickening of Gardiner Glacier enabled ice to overtop Christmas Col and flow northward onto the upper bench. Farther west, Reedy/Colorado Glacier ice coalesced with ice in the Valley of Doubt and pushed a lobe into Hendrickson Valley. In the Caloplaca Hills, Reedy Glacier filled Caloplaca Valley. Farther up-glacier, thickening of Olentangy and McCarthy Glaciers by as much as 580 m inundated Polygon and Tillite Spurs and likely much of Mims Spur. Exposure ages of as much as ~5 Ma indicate a Pliocene or earlier deposition of the drift. However, because these ^{10}Be concentrations probably are in steady state with respect to erosion, 5 Ma is a conservative lower age limit.

Reedy drifts *A*–*D* represent expansions more extensive that that during Reedy III time. Clast characteristics, drift thickness, and sedimentology suggest these units were deposited in a polar environment similar to today. Both the abundant silt in Reedy *E* drift and the large size of the Quartz Hills moraines are uncommon for polar glacier margins but characteristic of deposition by temperate ice. However, the absence of outwash, along with other indicators of water, such as kame terraces, indicates that Reedy Glacier was not temperate at this time. Moreover, the deep basin distal to the moraines is not filled with outwash, as would surely have happened had the glacier margin been temperate. The absence of striated clasts and the morphology and sedimentology of Reedy *E* deposits on Polygon and Tillite Spurs (which consist of thin ablation till) suggest deposition by a polar glacier. We therefore propose that the margins of Reedy Glacier were cold-based at this time. The size and composition of the Reedy *E* moraines in the Quartz Hills probably represent one of two scenarios: 1) pre-existing, silty glacial, glaciomarine, or glaciolacustrine deposits in the Reedy trough were reworked during Reedy *E* time or 2), isolated wet patches existed beneath very thick ice and provided a source of basal material for the Quartz Hills moraines.

4.2. *Wisconsin Plateau drifts*

Red drift is dominated by lithologies found only on the Wisconsin Plateau. This composition, as well as areal distribution, suggests it was deposited by ice flowing off the Wisconsin Plateau.

The areal distribution of drift and wealth of exotic clast lithologies indicate Middle Horlick Unit 5 also was deposited by ice originating on the Wisconsin Plateau and not from Reedy Glacier. The fine-grained volcanic clasts found in the drifts on the upper terrace have no source on Polygon Spur and likely originate from outcrops to the northeast (Mercer, 1968b). Striated and moulded clasts are almost ubiquitous within the compacted silt-rich matrix and suggest Middle Horlick Unit 5 was deposited as basal till beneath wet-based ice. Although wet-based ice can exist in a polar climate, it is restricted to the base of very thick or fast-moving ice, and we suggest it is unlikely that such conditions occurred at this elevation (>2500 m) in the TAM. A more plausible scenario is that ice on the upper terrace was temperate when Middle Horlick Unit 5 was deposited (Mercer, 1968b). The thickness of the unit (>7 m) is more typical of temperate glaciers than of polar glaciers and supports this conclusion.

Stratigraphic data and geometric relationships indicate that Middle Horlick Unit 5 is pre-Pliocene in age. First, clasts of Middle Horlick Unit 5 are extremely varnished and pitted compared to Reedy *E* and younger drifts at Reedy Glacier, suggesting that the former has been exposed to weathering for a considerably longer time. Second, the Reedy *E* drift conforms to the present topography and therefore must postdate both the Olentangy valley and Middle Horlick Unit 5, into which Olentangy Glacier has cut. Thus, available evidence indicates that Reedy *E* drift is younger than Middle Horlick Unit 5, a conclusion also reached by Mercer (1968b). Considering that the Reedy *E* moraines are older than 5 Ma, Middle Horlick Unit 5 must predate this time.

In terms of geomorphologic setting and sediment characteristics, Middle Horlick Unit 5 is similar to the Sirius Group. Remnants of these glacial deposits occur to 4000 m elevation throughout the TAM and are widely believed to represent a period of temperate, most likely alpine, glaciation (Denton et al., 1993; Stroeven et al., 1996; Barrett, 1999; Goff et al., 2002). Similar to the Middle Horlick Unit 5, Sirius Group tills consistently form the oldest post-Permian glacial deposits overlying striated erosional surfaces (Brady and McKelvey, 1979; Prentice et al., 1986; Denton et al., 1993). Furthermore, both Middle Horlick Unit 5 and Sirius Group deposits are severely weathered erosional remnants that have been dissected during downcutting of the present landscape (Prentice et al., 1986). Both units are relatively thick (as much as 150 m at Beardmore Glacier; Prentice et al., 1986) and contain abundant glacially moulded and striated clasts.

Sirius Group deposits in the Dry Valleys have been constrained to ~10 Ma using cosmogenic ^{3}He and ^{21}Ne dating (Schäfer et al., 1999: assuming zero erosion), to >15 Ma on the basis of ^{40}Ar/^{39}Ar dating of volcanic ashes (Marchant et al., 1996), and to ~20 Ma using estimated rates of TAM uplift (Hicock et al., 2003). At Beardmore Glacier, Ackert and Kurz (2004) used cosmogenic ^{3}He dating of overlying moraines to calculate a minimum age of ~5 Ma for Sirius Group deposits in the Dominion Range. However, the authors stress that the deposits likely are much older (Ackert and Kurz, 2004). If our correlation with the Sirius Group is correct, Middle Horlick Unit 5 might be as old as Oligocene in age. We note here, however, that Sirius Group deposits may be of different ages, and we can constrain the Middle Horlick Unit 5 only to >5 Ma.

4.3. *Cirque drifts*

Sedimentology, morphology, drift thickness, and clast characteristics all suggest that cirque deposits on Polygon Spur are polar ablation tills. Given the absence today of ice on the plateau above Polygon Spur and the lack of evidence for any such ice since the deposition of Middle Horlick Unit 5, these glaciers likely were nourished either by increased snowfall or by drifting of snow. While it is possible that plateau ice spilled over the rim to nourish the cirque glaciers, our observations of intense local drifting events and the presence of large cornices suggest that drifting plays a major role in glacier expansion. Intensified drifting likely would result from enhanced snowfall on the upper terrace, possibly corresponding to increased precipitation over East Antarctica since the LGM, or from increased windiness. The cirque glaciers probably fluctuated concurrently with the Cold Bowl glacier, also fed by drifting plateau snow. The most recent deposits – Cirque I drift – likely correspond to the Reedy III drift in Cold Bowl and represent broadly simultaneous advance of alpine glaciers and the upper parts of an EAIS outlet glacier. The distribution of drifts suggests that, similar to Reedy Glacier, the cirque glaciers have become smaller with time.

5. Effects of WAIS thickening on Reedy Glacier

We reconstructed former surface profiles of Reedy Glacier using the upper limits of glacial deposits. For the Reedy III profile, we used data from Mims Spur instead of Polygon Spur because ice-surface elevations at the latter site are strongly controlled by the complex local topography. Reedy III drift on Mims Spur was deposited by the main trunk of McCarthy Glacier and represents a more accurate measure of the level of Reedy Glacier.

The surface profiles in Fig. 9 show that ice thickening was much greater at the mouth than at the head of the glacier. This same pattern also has been observed alongside EAIS outlet glaciers elsewhere in the TAM (Bockheim et al., 1989; Denton et al., 1989b; Orombelli et al., 1990; Denton and Hall, 2000; Ackert and Kurz, 2004). Both Mercer (1968a,b) and Bockheim et al. (1989) argued that the asymmetric thickening reflects the influence of thick grounded ice in the Ross Sea rather than changes in basal hydrology or increased precipitation over the EAIS. Our evidence for only minor change at the EAIS plateau is in accord with that hypothesis. On this basis, we suggest the WAIS almost certainly was influencing the profile of Reedy Glacier by Reedy *D* time, when this asymmetric thickening first becomes apparent in our profiles. Moreover, considering this pattern is associated with each subsequent period of glaciation (Fig. 9), we suggest that all major expansions of Reedy Glacier since Reedy *D* time have been caused largely by fluctuations in the thickness and extent of the WAIS. During episodes of deglaciation, the effect of the WAIS on Reedy Glacier was reduced, if not removed entirely, resulting in thinning and steepening of the glacier. The occurrence of heavily weathered clasts incorporated in modern glacier thrust planes at Polygon Spur indicates that Reedy Glacier has been less extensive than today at least once in the past and that this low stand was of sufficient duration for clasts to become heavily weathered.

On the basis of our Reedy III profile (Fig. 9), we suggest that the glacier surface near its mouth was at least 500 m higher during the LGM than today, corresponding to a surface elevation of ~1100 m for the adjacent WAIS. This is similar to the modelled reconstruction presented by Todd et al. (personal communication). Due to the necessary extrapolation of this profile, we cannot preclude that the surface gradient of Reedy Glacier somehow was steeper than shown in its lower reaches. However, this is unlikely for two reasons. First, the modern profile of Reedy Glacier is smooth and becomes progressively less steep towards the glacier mouth, indicating the absence of basal topography that could cause the profile to steepen towards the mouth. Second, for the extrapolated profile to be any steeper than shown in Fig. 9, LGM thickening of Reedy Glacier actually would have to have increased with distance up-glacier, a scenario that does not fit with the suggested model of WAIS-induced profile change.

It is important to note that the LGM reconstruction depicted in Fig. 9 is time-transgressive. Maximum ice thickness occurred earlier at the mouth than at the head of Reedy Glacier (see Todd et al., personal communication) and, therefore, the surface profile was shallower than drawn here. As the value of ~1100 m is based on extrapolation of the longitudinal profile, if the gradient becomes shallower, the extrapolated thickness at the mouth of Reedy Glacier increases. Consequently, the ice elevation at the mouth of Reedy Glacier probably exceeded 1100 m. A maximum limit of ~1400 m is provided by the Reedy III drift limit in the Quartz Hills.

Our reconstruction is in accord with geologic evidence from outlet glaciers elsewhere in the TAM (Bockheim et al., 1989; Denton et al., 1989b) and from Marie Byrd Land (Stone et al., 2003), all of which suggest the WAIS was considerably thicker at the LGM than it is today. Moreover, ice-surface elevations derived from our Reedy III profile are similar to, though less than, the modelled reconstructions of Denton and Hughes (2002). In contrast, ice thickness reconstructions from Mt. Waesche (Ackert et al., 1999) and Siple Dome (Waddington et al., 2005) advocate only modest LGM thickening (50 m and as little as 200 m, respectively) of the WAIS. Similarly, Ackert et al. (2007) reported geologic evidence from the Ohio Range suggesting the WAIS was only ~125 m thicker at the LGM than today. However, minor thickening near the WAIS summit does not preclude major thickening elsewhere within the RSE. Indeed, the amount of ice thickening during the LGM likely decreased up flow lines both in West and East Antarctica, as illustrated by the asymmetrical expansion of Reedy Glacier (Fig. 9). Therefore, since the bulk of post-LGM deglaciation has taken place at the ice-sheet margins in response to grounding-line retreat and replacement of the Ross Sea ice sheet with the floating ice shelf, the greatest changes in relative ice thickness have occurred at locations farthest from the WAIS summit, such as along the TAM front.

The ice sheet's former volume is important for understanding not only the dynamic nature of the WAIS, but also Antarctica's contribution to sea-level change during the LGM and Holocene. Fig. 10 shows LGM surface elevations for the RSE reconstructed on the basis of glacial deposits and ice-flow modelling. Along the TAM, geologic estimates include 1100–1400 m at Reedy Glacier (this study), as much as 1250 m at Beardmore Glacier (Denton et al., 1989b), 1100 m at Hatherton Glacier (Bockheim et al., 1989), 710 m at Cape Crozier, Ross Island (Denton and Marchant, 2000), 637 m on Minna Bluff (Denton and Marchant, 2000), 350 m on Hjorth Hill (Hall and Denton, 2000), and ~300 m at Terra Nova Bay (Orombelli et al., 1990). In Marie Byrd Land (Fig. 10), Stone et al. (2003) observed LGM material on the summit of Mt. Van Valkenburg (1165 m) but, on the basis of surface-exposure ages, concluded that the maximum surface elevation of the WAIS likely was considerably higher, as suggested by the reconstruction of Denton and Hughes (2000). Reconstructions of Siple Dome (Fig 10) based on ice-flow modelling and ice core data suggest that ice-surface elevations there were 800–1100 m during the LGM (Waddington et al., 2005;

Price et al., 2007). Although this is lower than reconstructions based on geologic data from (Fig. 10), both datasets could be accommodated if thick ice occurred along the front of the TAM and in Marie Byrd Land and thinner grounded ice occupied the central RSE. This scenario likely would occur if the ice streams remained active during the LGM (Parizek and Alley, 2004). Alternatively, if ice streams were not active throughout the centre of the RSE, the flow models may be underestimating the former surface elevation of Siple Dome.

6. Declining ice volume at Reedy Glacier?

Drifts at Reedy Glacier become progressively older with increasing elevation (Fig. 9), a pattern also observed at Beardmore and Hatherton Glaciers (Denton et al., 1989b; Bockheim et al., 1989). At face value, this pattern suggests that earlier expansions of Reedy Glacier were more extensive than later episodes. Indeed, the global pattern of glaciation for both alpine glaciers and ice sheets alike appears to have been one of steadily diminishing areal extent over the course of the Quaternary (e.g. Mercer, 1976; Phillips et al., 1990; Barrows et al., 2002; Singer et al., 2004), despite evidence for steadily increasing global ice volume (Shackleton and Kennett, 1975; Lear et al., 2000; Dongsheng and Jimin, 2002).

We discuss four hypotheses to account for the progressive changes observed at Reedy Glacier. The first invokes tectonic uplift, raising both the glacier and the adjacent mountains relative to the WAIS. This contrasts with evidence indicating that significant TAM uplift has ended (Stump et al., 1980; Hall et al., 1993; Wilch et al., 1993; Sugden et al., 1999; Ackert and Kurz, 2004) and that average exhumation rates have been low over the past few million years (Gleadow and Fitzgerald, 1987). Therefore, although uplift might have displaced some of the oldest glacial deposits, we reject a purely tectonic mechanism as the cause of apparent long-term thinning of Reedy Glacier. A second possibility is that downcutting by Reedy Glacier and the consequent isostatic uplift of the surrounding TAM would give the impression of glacier thinning without any change in ice volume. Although downcutting would have been most effective when the glacier was temperate, Stern et al. (2005), modelling the long-term incision by southern TAM outlet glaciers, estimated that downcutting since the inception of polar conditions has been accompanied by as much as 1500 m of isostatic rebound. A third hypothesis is shrinkage of the WAIS due to climate change. Thickening and advance of the WAIS generally is believed to be driven by sea-level lowering resulting from the growth of Northern Hemisphere ice sheets. A long-term cooling trend, such as has occurred during the late Cenozoic, would thus promote rather than impede growth of the WAIS. Therefore, a climate-driven decline in ice-sheet volume is unlikely.

Our final hypothesis invokes long-term evolution of ice-sheet drainage in West Antarctica. Widening, straightening, and deepening of subglacial troughs all increase flow velocity and thus the efficiency of ice transport (e.g. Evans, 1969). Successive expansions of the WAIS would become smaller, thereby lessening the influence of the ice sheet on Reedy Glacier.

Given the discussion above, we suggest that the apparent thinning of Reedy Glacier is the product of both glacial downcutting (along with any accompanying isostatic uplift) and enhanced drainage efficiency of the WAIS. There is at present little evidence to support an overall decreased in ice volume due to climatic or purely tectonic reasons.

7. Conclusions

- The last thickening of Reedy Glacier occurred during the LGM. We correlate Reedy III drift with Britannia drift at Hatherton Glacier (Bockheim et al., 1989), Beardmore drift at Beardmore Glacier (Denton et al., 1989b), Terra Nova drift at Reeves Glacier (Orombelli et al., 1990), and Ross Sea drift in the McMurdo Sound region (Stuiver et al., 1981; Hall et al., 2000; Hall and Denton, 2000).
- During the LGM, ice thickening was asymmetric. Whereas the ice surface near the head of the glacier was ~40 m higher than today, the mouth of Reedy Glacier thickened by ≥500 m. Extrapolation of the glacier profile suggests the surface of Reedy Glacier at its confluence with Mercer Ice Stream had an elevation of ≥1100 m during the LGM. This observation is in agreement with other geologic data from the TAM and Marie Byrd Land, but contradicts more modest reconstructions from glaciologic modelling.
- Surface-exposure ages from Reedy *B* drift indicate thickening occurred during MIS 6 and that this event was slightly more extensive than during the LGM.
- The profile of Reedy Glacier has been influenced strongly by the elevation of the WAIS, at least periodically, since Reedy *D* time (>2.5 Ma). Progressive lowering of the glacier surface since then is attributed, in uncertain proportions, to both downcutting and long-term thinning of the WAIS due to increased efficiency of ice-sheet drainage.
- On the basis of minimum-limiting surface-exposure ages from Reedy *E* moraines, Reedy Glacier has been a polar glacier for at least the last 5 Ma. Areas of wet-based ice might have occurred beneath thicker or faster-moving sections.
- Middle Horlick Unit 5 (Mercer, 1968b) is inferred to be part of the Sirius Group on the basis of composition, position, and relative stratigraphy. The geomorphic and stratigraphic relationships of this unit with younger drifts, as well as minimum surface-exposure ages, indicate that Middle Horlick Unit 5 was deposited prior to 5 Ma.

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Appendix I

We collected samples of approximately fifty pebbles (≤10 cm in length) from each excavation. Each clast was washed, dried, and subsequently described on the basis of a number of clast characteristics including the occurrence of fractures, glacial moulding, striations, surface pitting, weathering rinds, calcium carbonate/salt accumulations, desert varnish, and ventifacts. Common lithologies include gneissic granite (Gngr), granite (Gr), granodiorite (Grdi), microgranite (Mcgr), mafics (Maf), shales, sandstone (SS), and quartz (Qtz). We measured the degree of structural degradation due to weathering by scraping the clast with a blunt steel point. Clasts from which only individual grains could be removed are classed W1 while those that crumble are W4. Similarly, the degree to which clasts are stained range from S1 (slight discolouration) to S4 (deep staining).

We employed wet and dry sieves to conduct grain-size analyses on sediment samples. Approximately 200 g of sediment was sampled from each excavation. Each sample was dry-sieved for fifteen minutes in a stacked unit comprising 4 ϕ mesh (gravel), 2 ϕ mesh (sand), and 0 ϕ mesh (silt). We calculated percentage abundances from these values.

Appendix II

We used the concentration of cosmogenic ^{10}Be in coarse-grained granite to calculate surface-exposure ages. Samples were collected from flat, stable surfaces with no signs of post-depositional modification. To avoid the effects of prior exposure, we focussed on samples exhibiting clear glacial moulding and faceting. We minimised the potential for snow shielding by avoiding sites located close to the margins of snow banks, acknowledging that snow cover might have changed over time.

We used heavy liquids and etching in diluted hydrofluoric acid to separate the quartz. ^{10}Be was extracted following the standard method described by Stone (2004) and ratios measured at the Lawrence Livermore Laboratory Center for Accelerator Mass Spectrometry. Exposure ages were calculated using production rates scaled with latitude and altitude after Lal (1991) and Stone (2000), and corrected for sample thickness and horizon shielding (Table 4).

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