Quaternary changes in level of the upper Taylor Glacier, Antarctica: implications for paleoclimate and East Antarctic Ice Sheet dynamics

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Glacial drifts perched alongside outlet glaciers that drain through the Transantarctic Mountains constrain inland polar plateau ice elevations. The Taylor Glacier, which heads in the Taylor Dome (a peripheral dome of the East Antarctic Ice Sheet), drains East Antarctic ice into the Dry Valleys sector of Transantarctic Mountains and terminates in central Taylor Valley, about 24 km west of the Ross Sea. Five gravel-rich drifts (including 39 distinct moraine ridges) fringe a lateral lobe of the Taylor Glacier in the lower Arena Valley, Quartermain Mountains, southern Victoria Land. ^{3}He and ^{10}Be exposure age dating (from Brook *et al.* 1992), together with Arena Valley stratigraphy and soil morphologic data, provide chronologic control for these drifts and constrain maximum Quaternary thickening of the inland Taylor ice dome to less than 160 m. These minor Quaternary expansions of Taylor Glacier were out-of-phase with outlet glaciers that pass through the Transantarctic Mountains and terminate in the Ross Sea north and south of the Dry Valleys region. Textural analyses suggest that drift deposition occurred from cold-based ice, even though Taylor Glacier advances most likely occurred during global interglaciations. The thermal regime of former Taylor Glacier ice lobes, the character of geomorphic features superimposed on individual drifts, the chemical composition of soils developed on Taylor drifts, and the stability of *in situ* moraine ridges on steep valley walls suggest that the present cold-desert climate in Arena Valley has persisted for at least the last 2.2 Ma.

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Quaternary East Antarctic Ice Sheet dynamics and paleoclimate are central to interpretations of coeval eustatic sea level and marine oxygen isotopes. Glacial drifts perched alongside outlet glaciers that drain through the Transantarctic Mountains limit changes in East Antarctic ice-surface elevation inland of the Transantarctic Mountains. Here we describe glacial drifts in the Arena Valley adjacent to the Taylor Glacier, an outlet glacier that drains Taylor Dome (a peripheral dome of the East Antarctic Ice Sheet) and terminates in the ice-free region of southern Victoria Land. Arena Valley is unique in the Transantarctic Mountains because it is adjacent to the western margin of the East Antarctic Ice Sheet and contains an extraordinarily complete sequence of glacial drifts representing former ice-sheet fluctuations.

Throughout late Quaternary time, Taylor Glacier terminated on land and did not merge with ice masses that periodically grounded in the Ross Sea (Denton *et al.* 1989a). Therefore, it is one of the few Transantarctic outlet glaciers that record fluctuations of East Antarctic ice independent of ice grounded in the Ross Sea. Thus, Quaternary fluctuations of Taylor Glacier reveal the relative timing of ice-level changes of Taylor Dome and ice grounding in the Ross Sea (Denton *et al.* 1989a), constrain glacial overriding of the Transantarctic Mountains (Denton *et al.* 1984), monitor major East Antarctic Ice Sheet fluctuations along an ice divide that extends inland from Taylor Dome to Dome Circe (Drewry 1982), and bear on questions of regional paleoclimate. Our results are based on pedologic examination of 150 soil profiles along with geomorphic and glacial geologic mapping of 39 well-preserved moraines adjacent to a peripheral lobe of the present Taylor Glacier in Arena Valley. ^{3}He and ^{10}Be exposure age dating (Brook *et al.* 1992; Brown *et al.* 1991), along with Arena Valley stratigraphy and soil weathering data, provide chronologic control.

Physical setting

The ice-free Dry Valleys region of southern Victoria Land features about 4000 km^2 of high-relief desert topography on the east flank of the Transantarctic Mountains between the McMurdo Sound sector of the Ross Sea and the East Antarctic polar plateau (Fig. 1).

The glaciers

The polar glaciers of southern Victoria Land are cold and predominantly dry based (Chinn 1980). They lack well-defined accumulation zones, show little to no surface melting, and are nowhere associated with widespread outwash sediments. Most of the Dry Valleys glaciers are strikingly free of surficial and basal

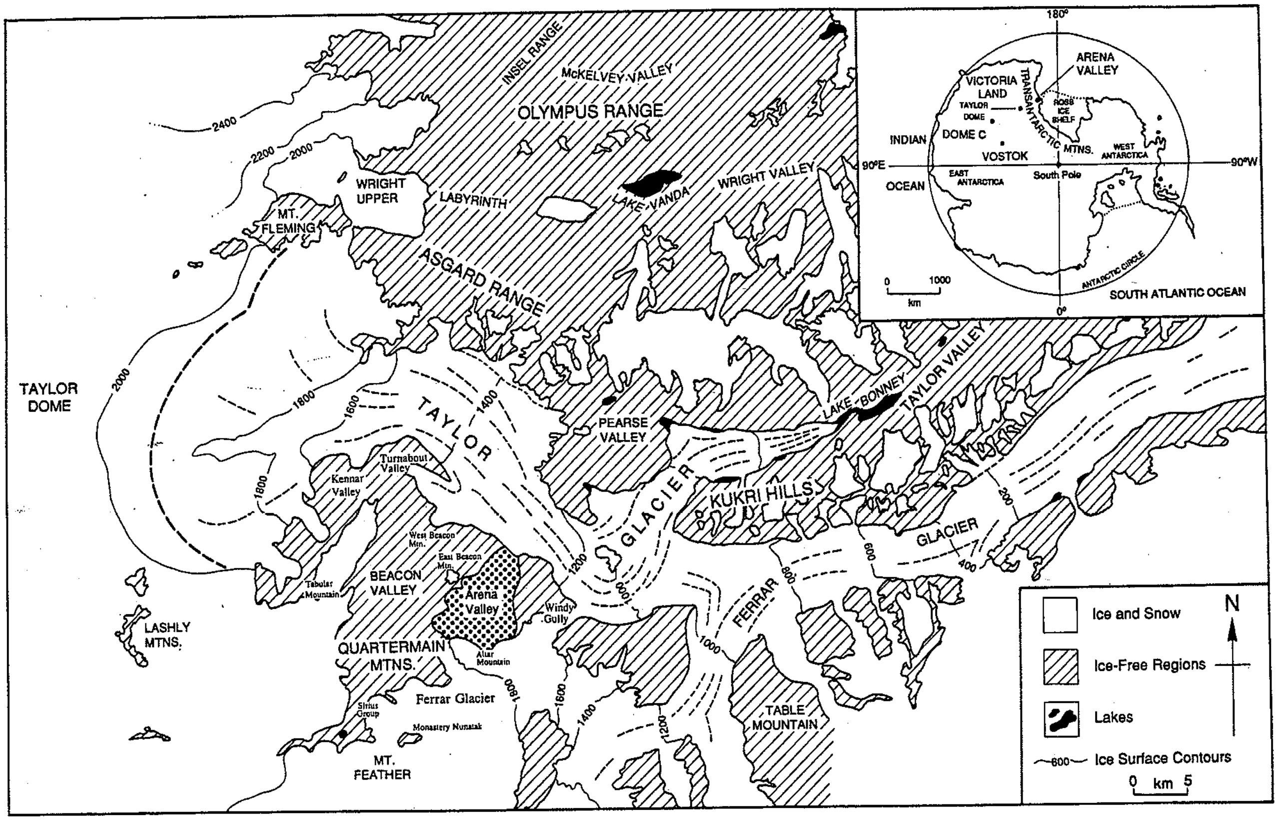

Fig. 1. Location map showing ice-free Dry Valleys and present Taylor Glacier. The polar equilibrium line (bold dashed line), as defined by the irregular geographic boundary between dry snow and blue ice on the glacier surface (Muller 1962), lies at about 2000 m elevation (Robinson 1984).

debris and are nearly everywhere frozen to their bed. They occur in a cold-desert climate, where mean annual temperatures are well below −20°C and precipitation values are less than 45 mm water equivalent per year (Schwerdtfegger 1984). Robin (1988) calculated that the 0°C isotherm in the Dry Valleys region lies about 600 m below sea level. As a result, ablation in the present cold-desert climate occurs almost entirely by sublimation, with less than 10% derived from surface meltwater run-off (Chinn 1980). Thus, the geographic distribution of glacier accumulation and ablation zones is governed solely by local wind patterns and the resulting concentration of transient snow drifts in topographically favored areas and sporadic blue-ice sublimation patches in windswept zones (Chinn 1980). This is different from the situation on temperate glaciers, where excess precipitation and extensive surface-melting zones control glacier accumulation and ablation (Sugden & John 1976). Hence, polar glaciers lack well-defined equilibrium lines and, if present, such lines reflect only local wind patterns. They are not related to the position of the 0°C isotherm. In fact, the Taylor Glacier equilibrium line, as defined by the irregular geographic boundary between dry snow and blue ice on the glacier surface (Muller 1962; Robinson 1984), lies at about 2000 m elevation (Fig. 1), 2600 m above the 0°C isotherm, where mean annual temperatures approach −35°C.

The polar Taylor Glacier, which today drains an ice surface of about 750 km^2 (Robinson 1984) originates in the peripheral Taylor Dome on the East Antarctic Plateau (Fig. 1). The bedrock-controlled Taylor Dome rises 100 m above the surrounding ice-sheet surface and merges with a broad ice divide that extends far inland to Dome Circe (Drewry 1982). Such an ice configuration indicates that Taylor Glacier monitors local ice-surface fluctuations of the Taylor Dome and suggests that it may also monitor major ice-sheet fluctuations along the ice divide between Dome Circe and Taylor Dome. The present Taylor Glacier is about 100 km long. Ablation on the upper Taylor Glacier is entirely from sublimation and averages about 0.18 m water equivalent/year (measured at 1000 m elevation) (Robinson 1984). Dry-based conditions exist at the base of the upper Taylor Glacier ablation zone, although about 50% of the lower ablation zone may be at the pressure melting point (Robinson 1984). Such pressure-melting zones are concentrated towards the Taylor Glacier center, where horizontal ice velocity and ice thickness are greatest (maximum Taylor Glacier horizontal velocity is 14.4 m/year. This figure is based on measured dislocation of surface stakes positioned along the Taylor Glacier center adjacent to Arena Valley (Robinson 1984)). Peripheral Taylor Glacier lobes that project outward from the main glacier trunk into tributary valleys are today entirely cold-based (Robinson 1984).

Arena Valley

Arena Valley, which lies in the Quartermain Mountains alongside the southern edge of the upper Taylor Glacier, is a small (2.5–5.0 km wide and 8 km long) and predominantly ice-free valley (Figs. 1 & 2). Its walls are well-developed rectilinear slopes cut in Beacon Supergroup sandstones and Ferrar Dolerite intrusives. Average valley floor elevations range between 1000 m and 1400 m. Mean annual temperatures approach −30°C. A cold-based peripheral lobe of the present Taylor Glacier extends about 0.5 km southward into the lower Arena Valley and terminates in a steep ice cliff about 25 m high. A remarkably well-preserved sequence of drifts with numerous arcuate moraines occurs alongside this Taylor Glacier lobe.

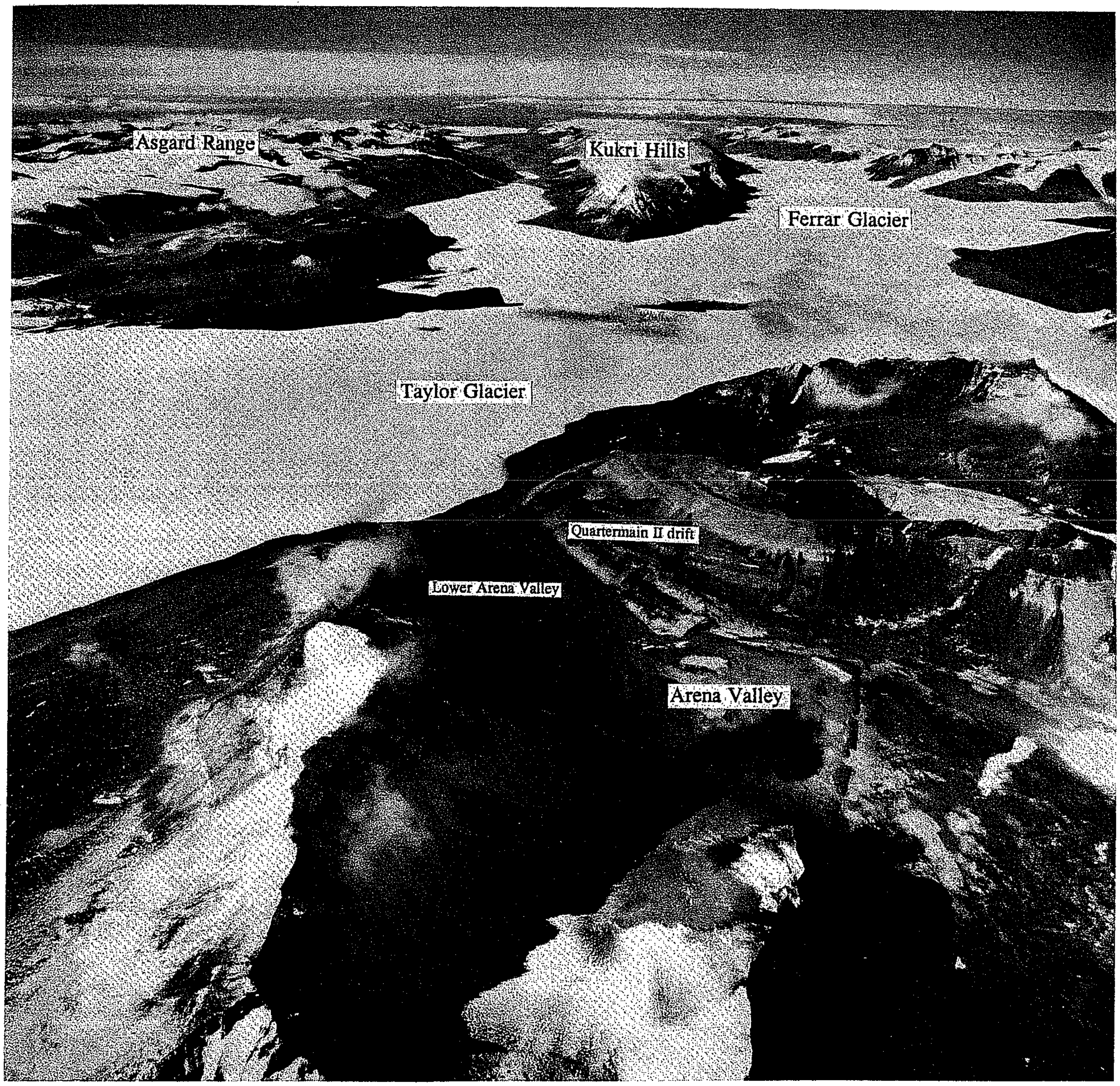

Fig. 2. High-elevation oblique aerial photograph of lower Arena Valley, showing the Taylor and Ferrar Glaciers, the Asgard Range, and the Kukri Hills. (US Navy VXE-6 photograph, TMA 2448, no. 0224, F-33).

The present ice-surface of Taylor Glacier at the mouth of Arena Valley is at about 1050 m elevation.

Glacial deposits in the lower Arena Valley

General description

Two very different drift types crop out in the lower Arena Valley. Quartermain II drift, the oldest, is a highly dissected and eroded granite-rich drift that crops out in a mosaic of 1–1.5 m high patches separated by intervening sandstone bedrock hollows (Fig. 3, Marchant *et al.* 1993a). This unit pre-dates Quaternary time (see below) and may represent regional expansion of the East Antarctic Ice Sheet with possible glacial overriding of the Transantarctic Mountains (Marchant *et al.* 1993a). The second drift type, the subject of this paper, occurs as a series of loose and unconsolidated gravel-rich drifts that, in places, are superimposed on Quartermain II drift. These drifts, which contain numerous granite erratics, crop out between 1000 and 1500 m elevation in the lower Arena Valley. They include 39 arcuate moraines that project southward from the present Taylor Glacier lobe into the lower Arena Valley (Figs. 2 & 4). Moraines vary in size and shape from continuous ridges up to 4 m high to narrow boulder-belt moraines composed of only a single arc of perched cobbles and boulders. The drifts rest cleanly on pre-existing morphologic features and unconsolidated sediments. They lack striated clasts and silt-sized matrix sediments. Instead, moraine ridges are composed predominantly of unsorted medium-to-coarse-grained sands and angular cobble and gravel-sized clasts of local Ferrar Dolerite and Beacon Supergroup Sandstone. Many clasts within the drifts show desert varnish and/or well-preserved ventifacted facets, suggesting an episode(s) of previous subaerial exposure. There are no ice-marginal channels, kame terraces, or outwash trains associated with these drifts in lower Arena Valley.

Relative chronology

The outcrop pattern, surface morphology, cross-cutting relations, and soil development within moraines allow separation of four distinct drifts. The four drifts are termed Taylor II, III, IVa, and IVb drifts (Fig. 4) (Denton *et al.* 1989a; Bockheim 1977, 1982; Brook *et al.* 1993; Brook & Kurz 1993). Below, we describe first the general morphology of lower Arena Valley drifts and then outline soil development within each unit.

Geomorphological data

The Taylor II drift crops out within 0.75 km of the present Taylor Glacier lobe in the lower Arena Valley and includes 15 well-preserved and continuous arcuate moraines between 1000 and 1200 m elevation (100–200 m above the edge of the present Taylor Glacier surface at the Arena Valley mouth). Sharp-crested moraines of the Taylor II drift stand 2–4 m in relief and are among the largest in the Arena Valley. Moraines nearest the Taylor ice lobe reflect the present outline of the glacier margin. The up-valley limit of Taylor II drift is delineated by a well-defined

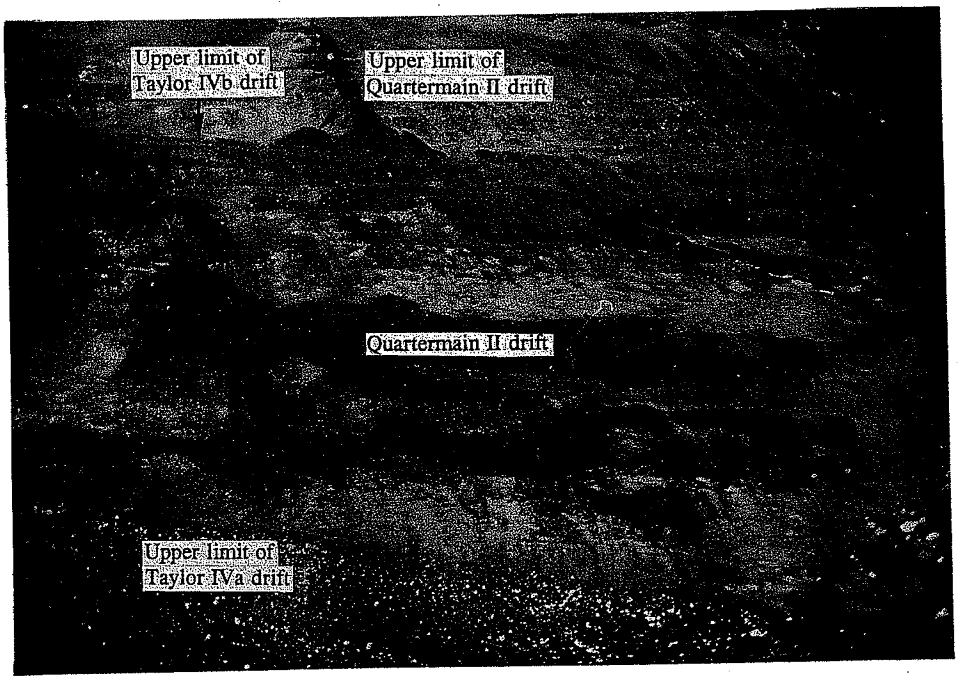

Fig. 3. East wall of lower Arena Valley showing etched and eroded patches of Quartermain II drift (upper limit arrowed) and intervening sandstone bedrock (Arena Sandstone) hollows. The upper limit of Taylor IVb moraines (arrowed) lies at about 1500 m elevation. Note that Taylor IVb moraines extend across Quartermain II drift patches and intervening bedrock hollows without modification.

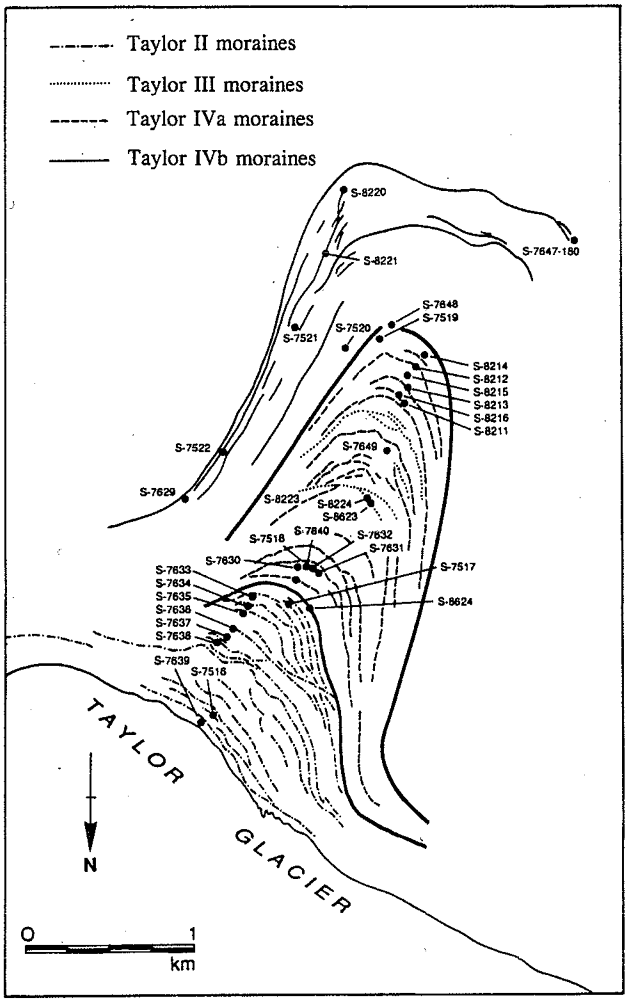

Fig. 4. Taylor moraines in lower Arena Valley. S-82-20 and other numbers refer to soil pit localities. Bold lines on map mark upvalley limit of Taylor II and Taylor IVa moraines. Taylor III moraines are superimposed on Taylor IVa drift and moraines.

moraine ridge that rises over 4 m above the valley floor (Fig. 5).

The Taylor III drift comprises only three discontinuous moraine segments that occur distal and parallel to the Taylor II drift (Fig. 6). These three moraines, which crop out on the valley floor at between 100 m and 250 m elevation above the present Taylor Glacier surface at the Arena Valley mouth, show sharp ridge crests but have only 1–2 m of relief. Moraines drape across pre-existing topography and rest without modification on top of older Taylor IVa drift. In stratigraphic section, the contact between Taylor III drift and Taylor IVa drift is sharp. In one hand-dug excavation a buried *in situ* desert pavement (composed of an interlocking mosaic of gravel and cobble-sized ventifacts) and relict soil horizon stratigraphically separates the Taylor III drift from underlying Taylor IVa drift (Bockheim 1977, 1982).

Taylor IVa drift blankets most of the floor and walls of the lower Arena Valley and includes 16 low-relief moraines that are exposed between 100 and 325 m elevation above the present Taylor Glacier surface at the Arena Valley mouth (Fig. 6). Taylor IVa drift rests without disturbance on pre-existing morphology of unconsolidated colluvial deposits on the west wall of the lower Arena Valley. At one locality, the lobate morphology of an unconsolidated and silt-rich debris lobe in these colluvial deposits is clearly preserved beneath six separate moraines of Taylor IVa drift (Fig. 7). Granulometric analyses of matrix sediments from within Taylor IVa drift superimposed on this silt-rich debris lobe show only coarse-sandy textures (Table 1), and indicate that the advancing ice failed to erode and incorporate the underlying silt-rich sediments.

The Taylor IVb drift consists of eight linear boulder moraines that crop out in lower and central Arena Valley between 125 m and 475 m elevation above the Taylor Glacier (Figs. 3 & 6). These bouldery moraines lack matrix and each comprises only a single row of aligned boulders and cobbles. The up-valley limit of the Taylor IVb drift, which forms the outermost intact moraine loop in the lower Arena Valley, lies about 3.0 km south of the present Taylor Glacier (Fig. 8). The Taylor IVb drift overlies eroded patches of Quartermain II drift and intervening hollows in sandstone bedrock along the east wall of the lower Arena Valley (Fig. 3). Quartermain II drift patches show a highly irregular outcrop pattern that represents post- or syndepositional erosion. Because continuous moraines of the Taylor IVb drift extend across the Quartermain II drift patches and the intervening sandstone hollows, without any modification of them, we suggest that the Taylor IVb drift postdates the deposition (and selective erosion) of the Quartermain II drift. On the basis of ^{3}He and ^{10}Be exposure-age dates on overlying Taylor IVb drift and on Quartermain II drift in central Arena Valley (Brook *et al.* 1993), we consider the Quartermain II drift to be pre-Quaternary (most likely at least 3 to 5 Ma in age, Table 2), and therefore do not address it further here.

In summary, Taylor II, III, IVa, and IVb drifts feature thin bouldery moraines (with a preponderance of gravel clasts exhibiting desert varnish and/or ventifacted facets), and rest without disturbance on the surface of pre-existing morphologic forms, relict soil horizons, and delicate *in situ* desert pavements. They lack striated and polished clasts, fine-grained stratification, associated outwash trains, and/or other features indicating the presence of glacial meltwater. As such, these drifts are characteristic of sediments deposited from non-erosive cold-based ice. The lobate moraine morphology and proximity of drifts to the present Taylor Glacier ice lobe in lower Arena Valley suggest glacial deposition from an expanded cold-based lobe of the Taylor Glacier. The ubiquitous

Fig. 5. Outer limit of Taylor II moraines in lower Arena Valley. Note figure (circled in black) for scale.

granite erratics also support deposition from the Taylor Glacier. For example, though numerous granite clasts occur in the lower Arena Valley, there are no such erratics in upper Arena Valley. This, along with the fact that Taylor Glacier today transports granite clasts (presumably eroded from granite bedrock exposed along the margins of the Taylor Glacier), strongly suggests that the Taylor II, III, IVa, and IVb drifts represent deposition from southward incursions of Taylor Glacier into the lower Arena Valley.

Soil data

Soil morphological properties are uniform within individual drift sheets but show abrupt changes (in some cases order of magnitude changes) between mapped units.

The following soil morphological properties show major breaks at drift boundaries: depths of staining, coherence and matrix salts, salt stage, and weathering stage (Table 3). The staining is due to release of iron from weathering of mafic minerals present in the drifts. The accumulation of soluble salts enables the soils to become coherent at greater depths with increasing age. The accumulation of these salts is reflected by an increase in the morphologic salt stage (Bockheim 1990) from salt encrustations beneath coarse fragments on Taylor II drift to discrete aggregations of salts in Taylor III drift, and eventually to strongly cemented salt pans in Taylor IVa drift.

There are insufficient data to draw any conclusive age-related trends in surface boulder weathering features, but the percentage of surface clasts that show desert varnish, ventifact development, spalling, and pitting appears to increase with relative drift ages (Table 4). The percentage of clasts showing ventifacted facets increases from about 1% on Taylor II drift to greater than 70% on Taylor III and older drifts. Clasts exhibiting desert varnish, which forms rapidly on the surface of exposed boulders under the cold desert weathering conditions prevalent in Arena Valley, increase from 80% on Taylor II drift to nearly 100% on Taylor III and older drifts.

Table 1 gives analytical data for representative soil profiles. All soils are slightly acid to neutral (pH 6.2–7.2) due to the accumulation of soluble salts. Based on electrical conductivity values, the amount of water-soluble salts increases sharply from the Taylor III drift to the Taylor IVa drift. The dominant cation and anion in soil:water extracts from the soils are Na

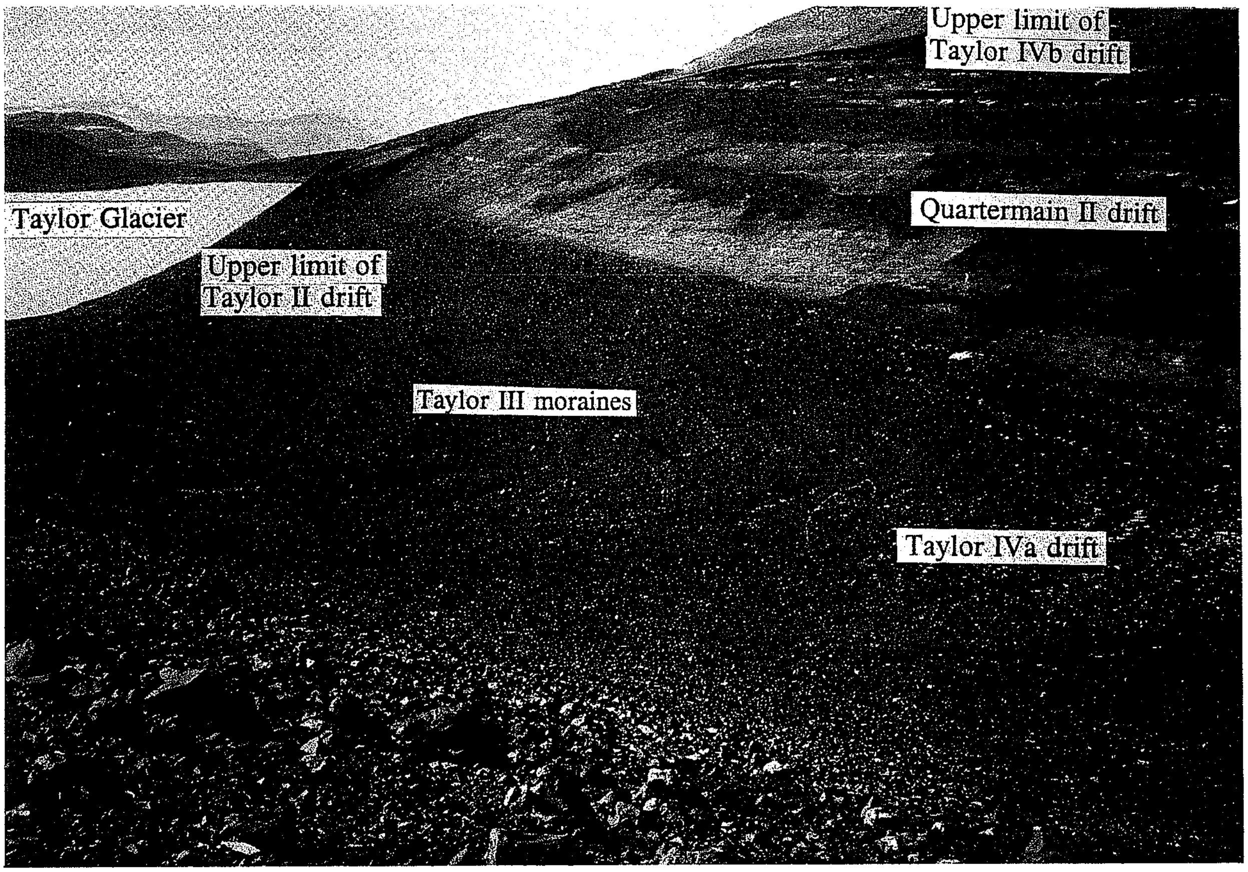

Fig. 6. Oblique aerial photograph of the lower Arena Valley, showing distribution of Taylor II, III, IVa, and IVb drifts as well as Quartermain II drift. Arrows define the upper limit of Taylor II and IVb drifts, and point out two of the three moraines exposed on the floor of lower Arena Valley that comprise Taylor III drift. Most of the moraines shown on the valley floor are composed of Taylor IVa drift.

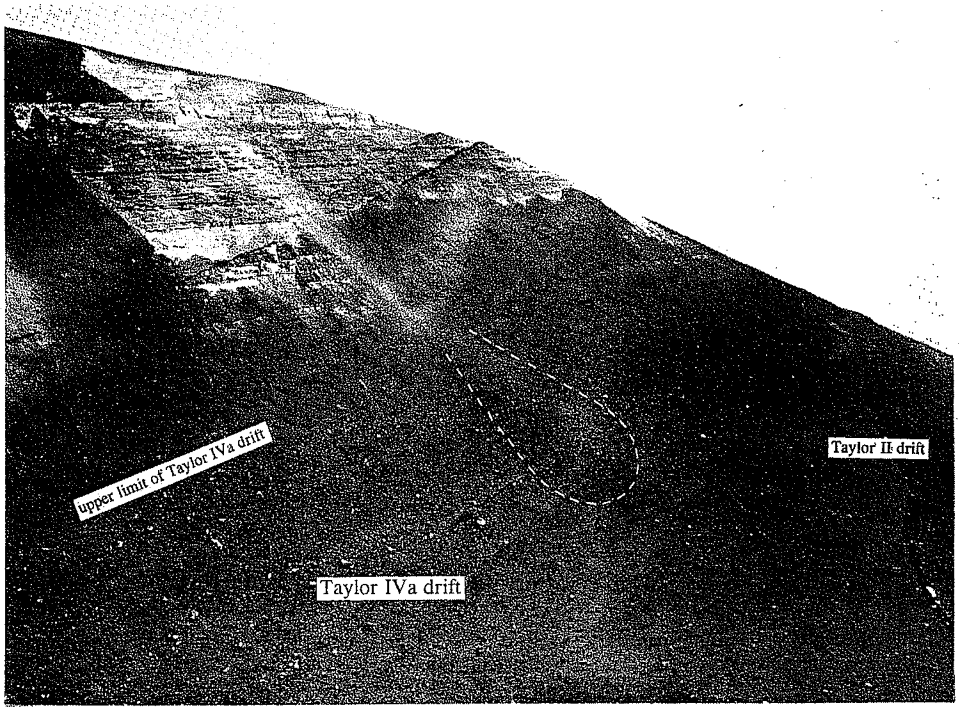

Fig. 7. Oblique aerial view of the lower Arena Valley showing an avalanche deposit overlain by Taylor IVa drift. The geomorphic form of the avalanche deposit is preserved beneath that drift.

Table 1. Chemical and physical properties of soils on drift sheets in the lower Arena Valley.

				Water-soluble ions (mmol/l)[2]								%[3]		
Horizon[1]	Depth (cm)	pH[2]	EC[2] dS/m	Na	Ca	Mg	K	SO_4	Cl	NO_3	%Fe*	Sand	Silt	Clay
						Taylor II drift 76-33								
Bw	0–14	6.2	2.4	4.6	25.6	6.0	0.36	33.7	3.2	0	–	92	5	3
Cu	14–77	6.3	1.0	3.1	6.6	2.1	0.18	7.6	2.3	3.1	–	96	1	3
						Taylor III drift 82-24								
Bw	0–10	6.9	4.4	33.8	10.3	8.5	0.32	14.3	6.3	31.5	0.34	82	8	10
Cox	10–20	7.2	4.0	25.4	12.5	9.7	0.38	14.3	8.2	32.7	0.28	84	9	7
Cu	20–100	7.0	2.0	5.6	10.2	3.1	0.30	4.3	7.3	10.9	0.23	86	8	6
						Taylor IVa drift 82-16								
Bw	0–5	6.2	4.0	23.8	18.6	15.4	0.66	44.3	68.4	15.4	0.29	90	3	7
Bsam	5–21	6.2	31.3	417	8.9	115	1.8	144	6.5	414	0.18	89	3	8
BC	21–39	6.6	2.2	11.7	4.0	8.6	0.35	11.2	7.6	8.8	0.27	86	4	10
Cu	39–87	6.3	1.8	8.4	6.6	4.8	0.36	40.5	4.0	5.5	0.24	88	5	7
2Db	87–90	6.2	2.8	7.7	31.0	4.1	0.52	34.3	1.8	4.3	0.21	90	6	4
2Bwb	90–100	6.3	2.0	7.9	14.8	5.5	0.25	20.9	2.5	5.2	0.22	87	6	7

[1] Soil horizon nomenclature follows Birkeland (1984). [2] Methods follow American Public Health Assn. *et al.* (1975). [3] Sand (2.0–0.05 mm), silt (50-2 microns), clay (<2 microns). * Dithionite-extractable iron from Mehra & Jackson (1960).

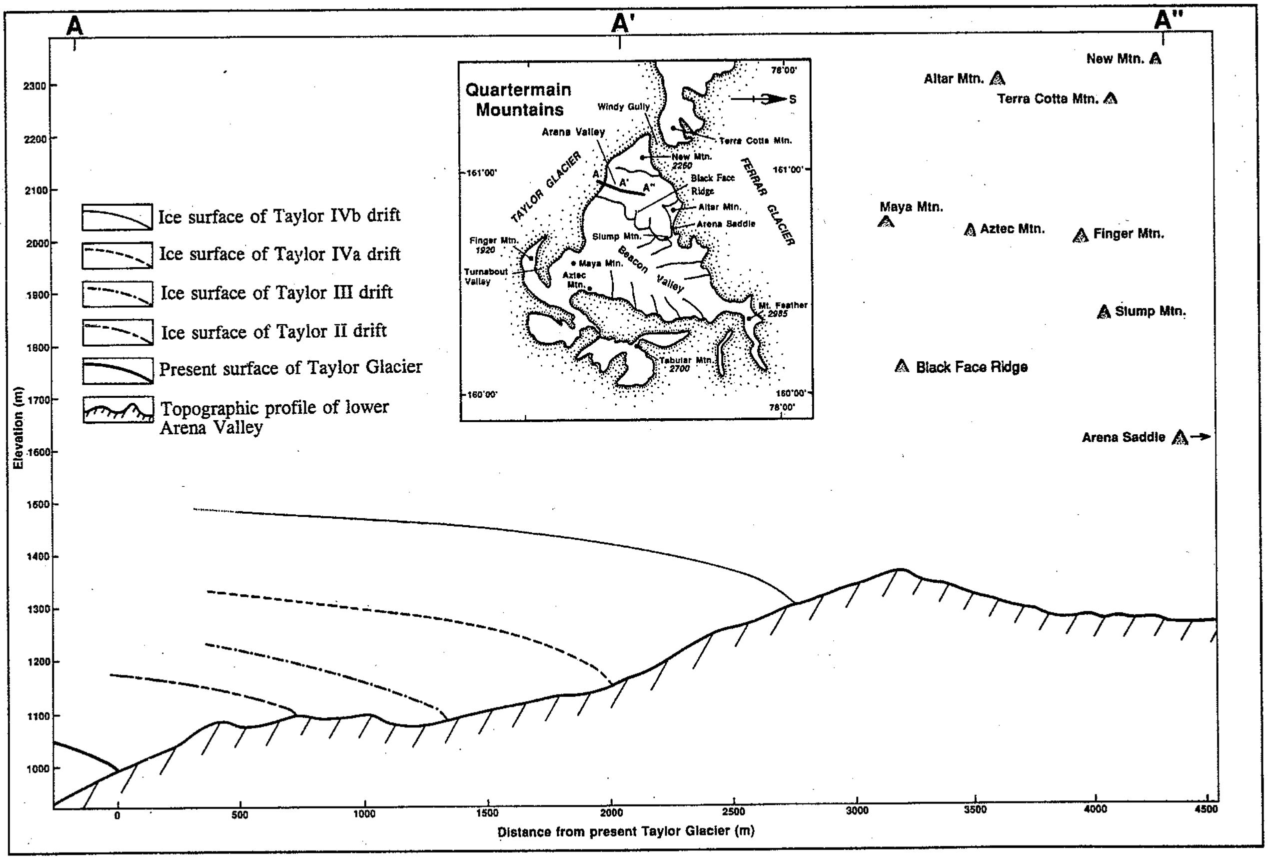

Fig. 8. Longitudinal profile of the lower Arena Valley and former ice-surface elevations of the Taylor Glacier. Inset shows location of cross-section.

and NO_3^-, respectively. The presence of sodium nitrate is consistent with the ultraxerous nature of the soils in Arena Valley (Bockheim 1982; Campbell & Claridge 1969). With the exception of soils in the Taylor II drift, ice cement was seldom observed. The ultraxerous soils of Arena Valley have dry permafrost because there is insufficient moisture to cause cementation (Bockheim 1982). All soils on Taylor II, III, and IVa drifts are skeletal (rock fragments greater than 2.0 mm in diameter comprise 35% or more of

Table 2. Exposure-age chronology of the lower Arena Valley drifts.

Exposure ages[1]			Max. drift elevation (m)		
Drift name	Mean ages[2]	Method	N[3]	Above Taylor Glacier[4]	Absolute Elevation
Taylor II	113 ± 45	^{3}He	6	200	1200
	117 ± 51	^{10}Be	5		
Taylor III	208 ± 67	^{3}He	7	250	1250
Taylor IVa	335 ± 18	^{3}He	6	325	1325
	1.0 + 0.4 − 0.5 Ma	^{10}Be	1		
	1.1 Ma[5]	^{10}Be	1		
Taylor IVb	1.1 ± 0.1 Ma	^{3}He	6	475	1475
	2.1 ± 0.1 Ma	^{10}Be	4		
	2.2 ± 0.1 Ma[6]	^{21}Ne	1		
Quartermain II till	3–5 Ma[7]	^{10}Be		>475	>1474

[1] Data from Brook *et al.* (1993) unless otherwise noted. [2] Mean ages are in 10^3 yr unless otherwise noted. [3] N = number of samples analyzed. [4] Elevations above present Taylor Glacier ice surface adjacent to Arena Valley. [5] This sample has an upper-age limit of about 1.59 Ma and a lower-age limit of 0.823 Ma (Brown *et al.* 1991). [6] Data from Staudacher & Allegre (1991). [7] Data from Brown *et al.* (1991) suggest a ^{10}Be age of around 4.4 Ma. Actual age of Quartermain II till may be significantly older than 3–5 Ma (Brook *et al.* 1993). Absolute drift elevations differ slightly from elevations given in Brook *et al.* (1993); the above elevation data are based on a new topographic map (unpublished) of Arena Valley at a scale of 1:10,000.

Table 3. Morphological properties of drift sheets in the lower Arena Valley.

Depth (cm)									
Profile	COH	STN	Salts	Ghosts	Ice cement	Salt stage[1]	W[2]	CDE[3]	Max. TEX
				Taylor II drift					
75-16	19	33	0	10	>71	0	1	40	s
75-17	10	0	0	15	28	0	1	30	s
76-33	14	14	0	0	>80	1	1	24	vks
76-34	5	5	8	5	>50	1	1	16	sts
76-35	6	6	0	16	>60	1	1	24	gls
76-36	16	16	0	0	>51	1	1	24	ls
76-37	5	5	0	0	>55	1	1	24	gs
76-38	8	8	0	14	>62	1	1	24	gs
76-39	21	21	0	0	21	0	1	24	gs
86-25	7	7	0	0	>100	0	1	16	vgs
AVG.	12	12	1	6	–	0.6	1.0	25	
				Taylor III drift					
82-24	10	20	10	13	>100	2	3	18	s
86-23	14	14	6	0	>100	2	2	9	vgs
AVG.	12	17	8	7	>100	2.0	2.5	14	
				Taylor IVa drift					
82-11	25	25	25	11	>100	5.5	5	18	stscl
82-12	29	29	18	29	>90	5	5	24	sts
82-13	19	19	19	19	>77	5	5	24	ls
82-14	37	45	37	58	>120	5	5	24	s
82-15	40	>100	20	41	>100	5	5	24	s
82-16	39	>100	21	22	>100	5	5	24	s
AVG.	32	>30	23	30	>98	5.0	5.0	23	

COH = coherence. STN = staining. SALTS = visible salts. GHOSTS = sandstone pseudomorphs.
[1] Morphologic salt stage from Bockheim (1990). [2] Weathering stage from Campbell & Claridge (1975). [3] Color-development equivalence (Bockheim 1990).

the profile by volume) with a loamy sand or sandy matrix.

The sharp breaks in soil development and in moraine morphology across drift boundaries, together with direct evidence for Taylor glacier readvance (Taylor III moraines overlie and cross-cut older Taylor IVa moraines) indicate that lower Arena Valley drifts represent distinct glacial advances and retreats

Table 4. Surface boulder weathering features on drift sheets in the lower Arena Valley.

Site No.	Boulder frequency[2]	Dolerite sandstone[2]	% Varnished	% Faceted[3]	% Spalled	% Pitted
			Taylor II drift			
75-16	560	46	80	0	–	–
75-17	856	106	94	1	–	–
AVG.	708	76	87	1	–	–
			Taylor III drift			
82-24	1105	173	100	83	39	2
			Taylor IVa drift			
82-11	570	>218	100	75	26	12
82-12	771	221	100	63	53	19
82-13	897	>200	100	82	38	16
82-14	615	>235	100	95	43	9
82-15	764	>219	100	74	48	11
82-16	906	202	100	70	37	11
AVG.	754	>218	100	76	41	13
			Taylor IVb drift			
75-20	260	64	98	73	–	–
75-21	380	>95	97	67	–	–
75-22	285	13	93	66	–	–
82-20	1083	27	100	76	57	10
82-21	710	8	100	87	46	11
AVG.	544	41	98	74	52	10

[1] Boulder frequency equals the total number of surface clasts greater than 35 cm (as measured along the a-axis) along a transect 100 m long and 3 m wide. [2] Number of dolerite clasts to sandstone clasts. For example, if a total of 700 dolerite and sandstone boulders were counted and all were dolerite, then the ratio would be >700. [3] Percentage of surface clasts showing ventifacted facets.

of several Taylor Glacier lobes into the lower Arena Valley, rather than continual retreat of a single lobe.

Numerical chronology

A numerical chronology for the Taylor II, III, IVa, IVb drifts, based on ^{3}He and ^{10}Be exposure-age dates (Brook *et al.* 1993; Brown *et al.* 1991) on surface clasts removed from the top of individual moraine crests corroborates our relative chronology from soil morphologic data. The numerical ages listed in Table 2 (from Brook *et al.* 1993) differentiate five drifts that range back through the Quaternary to at least late Pliocene time. The results show that Taylor II, III, and IVa are Quaternary-age drifts, whereas the Taylor IVb drift may be late Pliocene or older. (Preliminary age data from analyses of cosmogenic ^{21}Ne from quartz sandstones on Taylor IVb drift are consistent with ages derived from ^{10}Be analyses and indicate an exposure age of at least 2.2 Ma (Staudacher & Allegre 1991) (Table 2). Quartermain II drift is older than 3 to 5 Ma. Taylor IVa drift, the oldest Quaternary-age drift in Arena Valley, represents the maximum advance of the Taylor Glacier in the last 1.1 Ma (Table 2). An important point is that all the drift sheets in lower Arena Valley pre-date late Wisconsin time. There are no glacial deposits coeval with the last major global glaciation (Stage 2) in the lower Arena Valley (see discussion below).

Discussion

Ice dynamics

Taylor Glacier. – The outcrop patterns, sediment textures, stratigraphic relationships, and granite erratics within the Taylor II, III, IVa, and IVb drifts suggest glacial deposition from successive expansions of a cold-based Taylor Glacier ice lobe into the lower Arena Valley. Figure 8 shows longitudinal ice-surface profiles of former and present Taylor ice lobes in lower Arena Valley. Such profiles reflect outcrop elevations of individual drift sheets and outer moraine ridges. Measured ice-surface profiles along with exposure-age data indicate that the maximum Quaternary thickening of Taylor Glacier, represented by the Taylor IVa drift, was only about 325 m above the present Taylor Glacier ice-surface at the Arena Valley mouth. Because former Taylor Glacier ice lobes in the lower Arena Valley were situated within the Taylor Glacier ablation zone (where ice-surface thickening in response to glacial advance exceeds coeval ice-thickening in the accumulation area (Nye 1960)), we argue that maximum Quaternary thickening of the Taylor Dome (35 km west of Arena Valley) was probably much less than the 325 m rise in the Taylor Glacier in the lower Arena Valley (as measured from the distribution of Taylor IVa moraines in the lower Arena Valley). Following procedures outlined in Nye (1960), we calculate that maximum thickening of Taylor

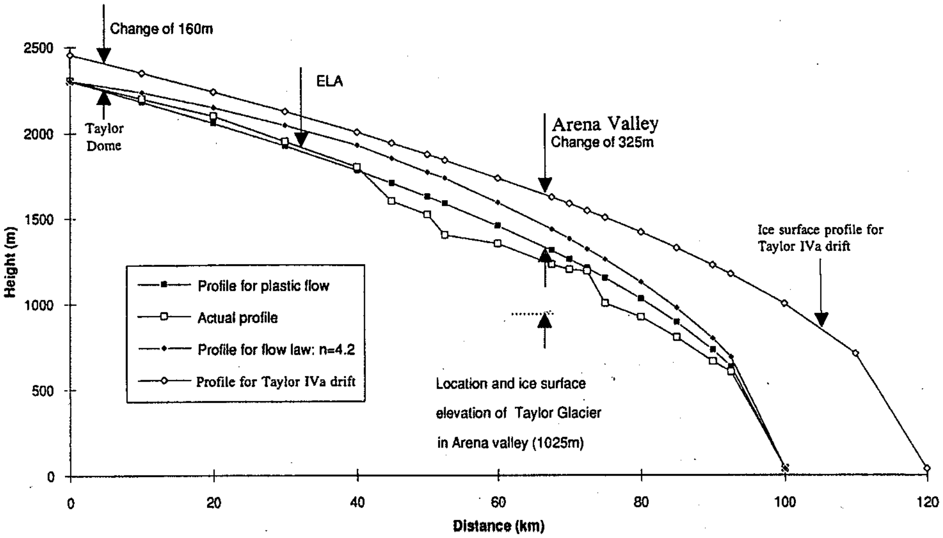

Fig. 9. Present and former ice-surface profiles for Taylor Glacier. Glaciological models that assume plastic flow closely approximate the present ice-surface profile of Taylor Glacier and show that a 325 m ice-surface elevation rise of Taylor Glacier at the mouth of Arena Valley yields a corresponding ice-surface rise at Taylor Dome of only about 160 m.

Dome during Quaternary time would be about one-half of that observed in Arena Valley, or about 160 m.

Figure 9 shows numerical reconstructions of the Taylor Glacier and inland Taylor Dome assuming (1) plastic flow and (2) a flow law with $n = 4.2$ (Robinson 1984). Reconstructions that assume plastic flow closely approximate the present ice-surface profile of Taylor Glacier and show that a 325 m thickening at Arena Valley yields a corresponding ice-surface rise at Taylor Dome of about 160 m. Because Taylor Glacier narrows dramatically as it enters Taylor Valley (Fig. 1), we argue, on the basis of mass conservation (i.e. Furbish & Andrews 1984), that significant ice thickening in the ablation zone could result from only slight thickening in the accumulation zone. As such, maximum Quaternary thickening of the Taylor Dome was most probably less than our calculated maximum estimate of 160 m. These results are consistent with limited late Quaternary interior ice-sheet fluctuations prescribed by ice-core studies (Lorius *et al.* 1984, 1985) and glacial geologic data (Denton *et al.* 1989a; Bockheim *et al.* 1989).

^{3}He and ^{10}Be exposure ages listed in Table 2 show that Taylor II, III, IVa, and IVb drifts all antedate late Wisconsin time. Accordingly, we argue that during late Wisconsin time Taylor Glacier was no larger, and perhaps even slightly smaller, than its present size. Data from outside the Arena Valley show that Taylor Glacier is now at its maximum position since late Wisconsin time, with the exception of minor fluctuations delineated by small Holocene-age ice-cored moraines that occur sporadically alongside the margin of Taylor Glacier (Denton *et al.* 1971, 1989a).

Correlation of lower Arena Valley drifts with glacial deposits exposed elsewhere in ice-free regions alongside the present Taylor Glacier allow construction of longitudinal ice-surface profiles of former Taylor Glaciers and, in certain instances, reveal the relative phasing of Ross Sea glaciations and Taylor Glacier fluctuations during late Quaternary time (Denton *et al.* 1989a). For example, on the basis of soil morphological properties and isotopic dating, Denton *et al.* (1989a) correlated Bonney Drift (a widespread silt-rich drift that crops out along the floor and walls of central Taylor Valley up to 300 m above the present Taylor Glacier surface) with Taylor II drift in lower Arena Valley. Bonney Drift, in turn, is cut by Ross Sea Drift in lower Taylor Valley (Ross Sea Drift represents expansion of grounded ice in the Ross Sea, with ice tongues flowing westward into dry valleys facing McMurdo Sound (Denton *et al.* 1989a)). On the basis of (1) numerous ^{14}C dates from algae associated with Ross Sea drift, (2) cross-cutting relationships between Bonney and Ross Sea Drift, and (3) U/Th dates on carbonates deposited in lakes dammed alongside the Taylor Glacier during its Bonney advance (Hendy *et al.* 1979), Denton *et al.* (1989a) argued that the most recent expansion of grounded ice in the Ross Sea occurred during the last major global glaciation (Stage 2 of the marine oxygen-isotope record), whereas the most recent advance of Taylor Glacier (represented by Bonney Drift/Taylor II drift) occurred during the last major global interglaciation (Stage 5e). This age assignment for Bonney Drift/Taylor II drift is in accord with exposure-age data from Arena Valley (Table 2) (Brook *et al.* 1993) and shows that Taylor Glacier expansion occurred out-of-phase with the last Ross Sea glaciation during late Wisconsin time. By extension, we suggest that the Taylor III, IVa, and IVb drifts represent Taylor Glacier expansion during global interglaciations preceding Stage 5e. However, our present chronology does not permit detailed correlations with specific global interglaciations.

Other Transantarctic outlet glaciers. – Thin and unconsolidated gravel-rich drifts are widespread in ice-free areas alongside the Beardmore, Hatherton, Darwin, and Reedy Glaciers (Mercer 1972; Mayeski 1975; Denton *et al.* 1989b; Bockheim *et al.* 1989). All of these outlet glaciers, which drain East Antarctic polar plateau ice through the Transantarctic Mountains, are different from the Taylor Glacier in that they flow directly into the Ross Ice Shelf and do not terminate on land. Soil data show significant difference in soil morphological properties between the youngest drifts alongside Beardmore, Hatherton, Darwin, and Reedy Glaciers and the youngest drift (Bonney Drift/Taylor II drift) alongside Taylor Glacier (Denton *et al.* 1989a, b; Bockheim *et al.* 1989). Bonney Drift/Taylor II drift shows moderate weathering consistent with deposition sometime during Stage 5e time, whereas the youngest drifts alongside Beardmore, Hatherton, Darwin, and Reedy Glaciers show only very slight surface and internal weathering and are most probably late Wisconsin in age (Denton *et al.* 1989a, b; Bockheim *et al.* 1989). This suggests that Taylor Glacier fluctuated asynchronously with these outlet glaciers during late Quaternary time. The out-of-phase behavior most likely reflects grounding of a late Wisconsin ice sheet in the Ross Sea that dammed outflow of Beardmore, Hatherton, Darwin, and Reedy Glaciers but failed to effect the fully terrestrial Taylor Glacier (Denton *et al.* 1989a, b; Bockheim *et al.* 1989). The effect of a grounded ice sheet in the Ross Sea would most likely result in thickening along the middle and lower reaches of dammed outlet glaciers (if sufficient time elapsed between ice build-up and ice retreat). Because Taylor Glacier failed to merge with Ross Sea ice during late Quaternary time, it could fluctuate independently of ice-shelf grounding episodes in the Ross Sea. Major changes in eustatic sea level caused by the waxing and waning of Northern Hemisphere ice sheets are the most likely cause of ice-sheet grounding in the Ross Sea (Hollin 1962; Stuiver *et al.* 1981). The exact mechanism for Taylor Glacier expansion and contraction during interglacial and glacial conditions is unknown. One possibility is that expansion occurs during episodes of increased precipitation triggered by diminished ice in the Ross Sea (Denton *et al.* 1989a).

The above data imply that glaciers in the Transantarctic Mountains which failed to merge with expanded Ross Sea ice during late Quaternary time fluctuated out-of-phase with grounded ice in the Ross Sea. However, recent data suggest that alpine and plateau glaciers within the mountains of northern Victoria Land advanced in phase with the most recent episode of ice-sheet grounding in the Ross Embayment (Orombelli *et al.* 1991). Because alpine glacier fluctuations in the Transantarctic Mountains appear to originate from changes in local precipitation, the data from northern Victoria Land suggest a more complex interplay among local precipitation changes, grounding episodes in the Ross Sea, and fluctuations of alpine and plateau glaciers in the Transantarctic Mountains than has been previously suggested.

Quaternary Paleoclimate

The climate of the Arena Valley during the Quaternary is inferred from (1) the thermal regime of expanded Taylor Glacier ice lobes, (2) the character of geomorphic features superimposed on individual drifts and nearby unconsolidated diamictons, (3) the chemical composition of soils developed within Taylor II, III, and IVa drifts and, (4) the stability of *in situ* moraine ridges on steep valley slopes.

The preservation of loose and unconsolidated sediments, *in situ* desert pavements, and relict soil horizons beneath lower Arena Valley drifts suggests deposition from non-erosive cold-based ice. The persistence of thin, Quaternary cold-based ice tongues precludes significant warmth in the Arena Valley, even though Taylor Glacier expansions most probably occurred during global interglaciations. These data indicate that basal ice temperatures within Taylor Glacier lobes in Arena Valley remained below 0°C.

The striking absence of outwash sediments, lacustrine deposits, kame terraces, ice-marginal channels, or other glacio-fluvial/waterlain sediments in the lower Arena Valley indicates that here Quaternary Taylor Glacier ice lobes failed to develop extensive surface-melting ablation zones. Because such surface-melting ablation zones only develop on glaciers that occur near the 0°C isotherm, the lack of outwash or other meltwater features in the lower Arena Valley indicate that throughout the Quaternary the atmospheric 0°C isotherm failed to advance up to 1000 m elevation in the Quartermain Mountains.

A simple calculation shows the maximum allowable mean-annual atmospheric temperature rise in the Arena Valley during Quaternary time. In order to produce temperate-style surface-melting ablation zones near the mouth of Arena Valley the 0°C isotherm (which now theoretically lies about 600 m below sea level in the vicinity of the Quartermain Mountains (Robin 1988)) would have to rise up to at least 1000 m elevation. A 1600 m rise in the 0°C isotherm (sufficient to initiate Taylor Glacier surface melting-ablation zones at 1000 m elevation near the mouth of Arena Valley) corresponds to a rise in atmospheric temperature between 8°C and 22°C over the entire Dry Valleys region, assuming calculated Antarctic surface lapse rates (Fortuin & Oerlemans 1990) between 0.5°C and 1.4°C per 100 m elevation rise, respectively. These figures greatly exceed estimated Quaternary temperatures prescribed by ice-core data, which show similar (or below present) atmospheric temperatures for East Antarctica during late Quaternary time (Lorius *et al.* 1984, 1985).

Our estimates of maximum allowable Quaternary temperature in the Arena Valley are reduced dramatically if we consider that small ice-marginal lakes and surficial geomorphic features characteristic of liquid water (rills, levees, and stream channels) are common below 800 m elevation in the vicinity of the Quartermain Mountains (where minor surface melting accounts for about 10% of the total ablation (Chinn 1980)). The mean annual temperature near Arena Valley approaches −27°C. This estimate is based on a recorded mean annual temperature of −19.8°C at about 100 m elevation at nearby Lake Vanda (Schwerdtfeger 1984) and an average lapse rate of 1.0°C/100 m elevation rise (Robin 1988). Landscape analyses show that surficial sediments in lower Arena Valley are unmarked by rills, levees, stream channels, lacustrine sediments, and/or other geomorphic features indicative of liquid water (e.g. Marchant *et al.* 1993a, b). Hence, we conclude that the mean annual temperature in lower Arena Valley failed to rise above about −27°C during the Quaternary. This of course assumes that geomorphic features indicative of liquid water would be preserved in the Arena Valley record. Because the present mean annual temperature in the lower Arena Valley approaches −30°C, we suggest that the maximum allowable Quaternary temperature rise in Arena Valley is about 3°C, although we see no direct evidence in the record for warmer-than-present temperatures during the Quaternary.

The chemistry of soil:water extracts from Taylor II, III, and IVa drifts also bears on the Quaternary climate in the Arena Valley. Soils on all of the moraines are enriched in sodium nitrate, a salt which is common in ultraxerous soils along the polar plateau (Claridge & Campbell 1977). Soils in less arid regions of Antarctica (e.g. xerous and subxerous climatic zones), contain primarily sulfates and chlorides, respectively, that originate from marine sources. The sodium nitrate that is present in ultraxerous soils is derived from sublimation of snow blown in from the polar plateau. The salts infiltrate into the soil during occasional periods of minor snowmelt on the surface of dark-colored rocks (black body radiation) but tend to accumulate in the upper 25 cm of the profile. Therefore, the presence of sodium nitrate and accumulation of salts in the upper 25 cm of the profile in all of the soils examined attest to the persistence of an ultraxerous climate in Arena Valley during Quaternary time.

Finally, the presence of *in situ* moraine ridges on steep valley walls (28° to 33°) implies little or no slope development in the lower Arena Valley for at least the last 2.2 Ma (age of Taylor IVb drift). Otherwise, the moraine ridges and boulder belts of Quaternary and late Pliocene age would be eroded or buried beneath younger colluvial deposits, which we show here is not the case. Such slope stability is best explained by persistent cold-desert conditions similar to the present Dry Valleys climate. We suggest that maximum temperatures in the lower Arena Valley (since at least 2.2 Ma) remained well below 0°C, inhibiting talus and slope development from freeze–thaw mechanisms.

Conclusions

Taylor Glacier fluctuations were minor during the Quaternary. The age and upper elevation of Taylor IVa drift indicate that the maximum Quaternary thickening of Taylor Glacier at the mouth of lower Arena Valley was only about 325 m. Our numerical modeling of upper Taylor Glacier (Fig. 9, based in part on reconstructed ice-surface profiles from the Arena Valley) shows that the maximum Quaternary rise of Taylor Dome at the head of Taylor Glacier was considerably less than 325 m, and most likely less than 160 m. This implies that Taylor Dome was not overwhelmed by inland ice and calls for very restricted Quaternary interior East Antarctic Ice Sheet thickening of Taylor Dome and the inland ice divide. This conclusion is consistent with limited late Quaternary interior ice-sheet fluctuations prescribed by ice-core studies (Lorius *et al.* 1984, 1985).

Late Quaternary Taylor Glacier fluctuations were out-of-phase with Transantarctic outlet glaciers that terminated in the Ross Sea. During late Quaternary time, the Taylor Glacier failed to advance while the Beardmore, Hatherton, Darwin, and Reedy Glaciers thickened along their middle and lower reaches (Denton *et al.* 1989a, b; Bockheim *et al.* 1989). This asynchronous behavior most likely reflects grounding of a late Wisconsin ice sheet in the Ross Sea that dammed outflow of glaciers with marine components but failed to effect the fully terrestrial Taylor Glacier (Denton *et al.* 1989a, b). Emerging data from northern Victoria Land (Orombelli *et al.* 1991) suggest a more complex interplay between grounding episodes in the Ross Sea and thickening of outlet glaciers draining ice across the Transantarctic Mountains. Our data indicate that Taylor Glacier advanced during the last major global interglaciation (probably Stage 5e) (Taylor II drift/Bonney Drift) and may be expanding during the present interglaciation.

The present cold-desert climate in Arena Valley has persisted throughout the Quaternary. The absence of surficial geomorphic features indicative of liquid water in Arena Valley, which are common below 800 m elevation in the Dry Valleys region, suggests that mean annual air temperatures in the Arena Valley failed to rise above −27°C during the last 2.2 Ma (present mean annual temperature in Arena Valley approaches −30°C). The absence of outwash trains, lacustrine sediments, and ice-marginal channels associated with Taylor Glacier lobes in the Arena Valley and the presence of ubiquitous ultraxerous soils and *in situ* moraine ridges on steep valley slopes are consistent with persistent cold-desert climates during the Quaternary. This conclusion is in accord with interpretations for a Pliocene-age volcanic ash overlying an *in situ* desert pavement in central Arena Valley (3 km south of the Taylor IVb drift limit) suggesting persistent cold-desert conditions in Arena Valley for the last 4.3 Ma (Marchant *et al.* 1993b).

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BOREAS NORDQUA NEWS
Boreas, Vol. 23, p. 43. Oslo, 1994 (March)

NORDQUA 94: Southern Iceland

The NORDQUA excursion will take place in Southern Iceland in August 1994, and will focus on the influence of almost continuous volcanism on sediments and sedimentary formations in both glacial and interglacial times, and on research progress concerning the glacial history of the area. The excursion will start from Reykjavik towards the glaciers in Southeast Iceland, where we will study glacial and geological processes at large. From there the excursion will take us across the South Icelandic Lowland, where the emphasis will be on the formation of the Preboreal Budi Moraine and associated deglaciation and sea-level changes, vegetation history and the settlement of Iceland, and the application of tephrochronology in Lateglacial and Holocene studies. From South Iceland the excursion will travel to West Iceland, where attention will be paid to early signs of glaciation that are contained within a few million years' old bedrock formations, and on the Late Weichselian deglaciation history of West Iceland.

Preliminary excursion programme

Aug. 11:	Arrival Keflavik Airport in the afternoon from Copenhagen and Stockholm/Oslo. Departure from Reykjavik to Kirkjubæjarklaustur (K) about 17:00.
Aug. 12:	Kirkjubæjarklaustur – Breidamerkurjökull – Kirkjubæjarklaustur
Aug. 13:	Kirkjubæjarklaustur – Myrdalsjökull – Skogar area (S).
Aug. 14:	Skogar – Budi moraine complex – Laugarvatn area (L).
Aug. 15:	Laugarvatn – (Borgarfjördur/Hvalfjördur) – Reykjavik. The excursion ends in the afternoon in Reykjavik.
Aug. 16:	Departure from Reykjavik/Keflavik.

Preliminary costs

A return apex airfare from Copenhagen to Keflavik costs about 3500 DKK.

Registration fee will be 3700–4000 DKK, including all transportation (except the bus between Keflavik Airport and the City terminal), meals and sleeping accommodations.

Registration

Preliminary registration must be made before May 1, 1994 to:

Dr. Hreggvidur Norddahl, Science Institute, Dunhaga 3, IS-107 Reykjavik, Iceland,

or

Iceland Tourist Bureau, Skogarhlid 18, IS-101 Reykjavik, Iceland.

All those registered before May 1, 1994 will receive a final programme including exact costs in June. Final registration before July 1, please.

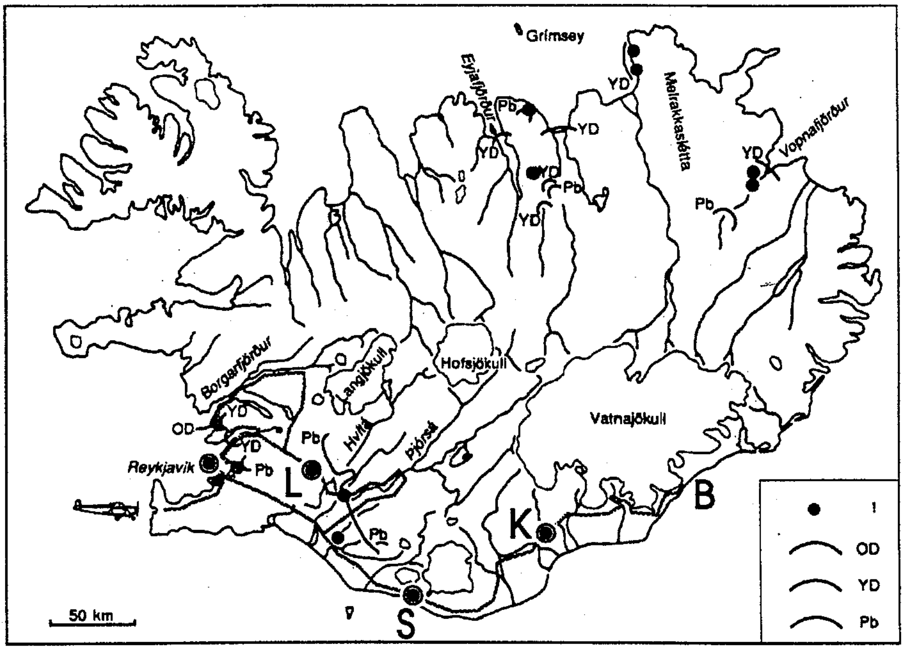

Fig. 1. Late Weichselian and Early Preboreal end-moraines in Iceland with important ^{14}C dated localities and the preliminary excursion route. Legend: 1) ^{14}C dates. OD) Older Dryas position of glacier margin. YD) Younger Dryas position of glacier margin. Pb) Preboreal position of glacier margin. B) Breidamerkurjökull. (K) Kirkjubæjarklaustur. (S) Skogar area. (L) Laugarvatn area.