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Exposure dating and glacial reconstruction at Mt. Field, Tasmania, Australia, identifies MIS 3 and MIS 2 glacial advances and climatic variability

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ABSTRACT: Tasmania is important for understanding Quaternary climatic change because it is one of only three areas that experienced extensive mid-latitude Southern Hemisphere glaciation and it lies in a dominantly oceanic environment at a great distance from Northern Hemisphere ice sheet feedbacks. We applied exposure dating using ^{36}Cl to an extensive sequence of moraines from the last glacial at Mt. Field, Tasmania. Glaciers advanced at 41–44 ka during Marine oxygen Isotope Stage (MIS) 3 and at 18 ka during MIS 2. Both advances occurred in response to an ELA lowering greater than 1100 m below the present-day mean summer freezing level, and a possible temperature reduction of 7–8 °C. Deglaciation was rapid and complete by ca. 16 ka. The overall story emerging from studies of former Tasmanian glaciers is that the MIS 2 glaciation was of limited extent and that some glaciers were more extensive during earlier parts of the last glacial cycle.

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KEYWORDS: Tasmania; Mt. Field; Last Glacial Maximum; exposure dating; ^{36}Cl; climatic change.

Introduction

Tasmania, at 42–44 °S, together with New Zealand and South America, are the only areas to have experienced extensive Quaternary mid-latitude glaciation in the Southern Hemisphere. At a great distance from Northern Hemisphere insolation forcing and associated ice sheet feedbacks, Tasmania offers insight into terrestrial climate in a mid-latitude southern oceanic domain. The mountains of Tasmania reach a maximum elevation of ca. 1600 m, lower than those of New Zealand and South America, and consequently glaciation was more restricted. Valley glaciers and small icecaps developed in the western parts of the island during the last glaciation, covering more than 1000 km^2 (Colhoun *et al.,* 1996).

The first glacial stratigraphy was established early in the 20th century. Lewis (1945) initially proposed a model of three separate glaciations: an ice-sheet, a valley-glacier and a cirque glaciation. Each glaciation was envisaged to have been less extensive ice than the previous one. The scheme was examined and extensively modified by later workers (Colhoun, 2004). Radiocarbon dates of ca. 19 ka on an outwash sequence at Dante Rivulet in the West Coast Range (Gibson *et al*., 1987, Colhoun and Fitzsimons, 1996) (Fig. 1) placed the most recent glaciation within Marine oxygen Isotope Stage (MIS) 2. However, there were no direct dates on moraines until the advent of exposure dating using cosmogenic isotopes. Of particular importance was the dating of the Hamilton Moraine (Fig. 1), in the West Coast Range, which was regarded as the 'type site' for the last glaciation in Tasmania. This moraine was found to have a minimum age of 190 ka (Barrows *et al*., 2002). Although this deceptively well-preserved moraine pre-dates the last glaciation, exposure ages on nearby moraines at Poets Hill (Fig. 1) and numerous other moraines across Tasmania demonstrated that most glaciers reached their maximum extent during a brief period of 17–21 ka (Barrows *et al*., 2002). This advance is coeval with the Blue Lake Advance of the Late Kosciuszko glaciation (Barrows *et al*., 2001).

In Tasmania there is evidence for at least three earlier Pleistocene glaciations pre-dating MIS 2 (Colhoun and Fitzsimons, 1996). A few locations provide a hint that glaciers were also more extensive during an earlier part of the last glacial cycle. Fitzsimons and Colhoun (1991) suggested a glacial advance prior to 40 ka in the King Valley (Fig. 1) based on stratigraphic evidence. Exposure dating at Mt. Field, Mt. Jukes and the Hartz Mountains (Fig. 1) indicates that some glaciers might have been more extensive between 39 and 46 ka (Barrows *et al*., 2002), whereas glaciers expanded at Mt. Kosciuszko (Fig. 1) at 32 ka and 59 ka (Barrows *et al*., 2001).

Mt. Field is the target of this study because there has been no modern assessment of the large (>15) number of moraines that date to the last glacial cycle. Landform maps, four new ^{36}Cl

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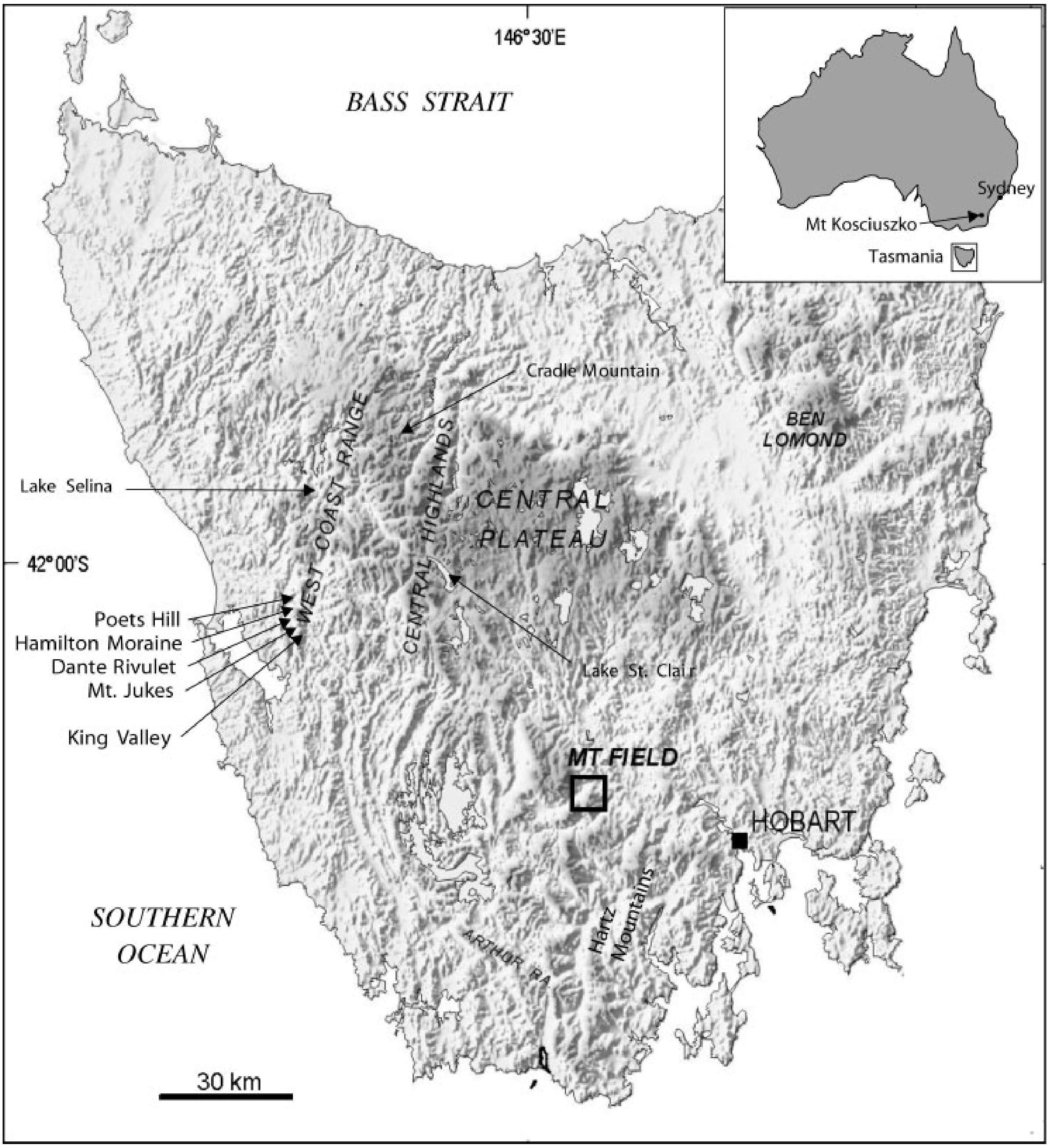


Figure 1 Location of Mt. Field in Tasmania, Australia. The main mountain ranges and other important areas of former Quaternary glaciation are also shown

exposure ages and twelve other published exposure ages (Barrows *et al.*, 2002) allow the extent and timing of glaciation to be established. ELA reconstructions of the cirque and short valley glaciers are made for four time periods, and we examine the likely deglaciation sequence at Mt. Field in the broader context of the retreat of ice across Tasmania during the last glaciation. Finally, we investigate some of the possibilities regarding the amount of climatic change necessary to produce glaciation on these mountains.

Environment and previous work

Mount Field National Park 50 km northwest of Hobart is a well-known area of former glaciation (Griffith Taylor, 1921; Fig. 1). Situated at altitudes of 850 to 1434 m, Mt. Field plateau is dominated by a 300-m thick sill of Jurassic dolerite. The plateau lies in the rain shadow of the ranges farther west (Fig. 1). The highest summits, deepest valleys and most obvious glacial landforms occur in the west and central part of the plateau where annual precipitation is high at 2000–3000 mm (Gibson, 1990). Farther east, annual precipitation is lower at 1000–2000 mm and glacial landforms are restricted to small cirques in the lee of the plateau scarp below Mt. Field East. The plateau surface around Mt. Field East is dominated by periglacial landforms including extensive solifluction deposits and blockfields (Davies, 1969).

Griffith Taylor (1921) and Lewis (1921) first noted glacial landforms and suggested that three glacial advances occurred, although their conclusions were based on erosional evidence rather than on stratigraphic division of the glacial deposits. Jennings and Banks (1959) considered that the glacial landforms at Mt. Field belonged to the last glaciation and did not represent three separate stages. Radiocarbon dating of cirque lake sediments carried out in pollen studies at Mt. Field indicate basal organic ages of 12 960 ± 950 ^{14}C yrs BP (I-7648) at Eagle Tarn, 9725 ± 190 ^{14}C yr BP (I-8008) at Tarn Shelf and 11 420 ± 205 ^{14}C yr BP (SUA-325) at Beatties Tarn (Macphail, 1979). The oldest of these dates, when calibrated, indicates that deglaciation occurred prior to 14.1–16.6 cal. years BP (Barrows *et al.*, 2002). Kiernan *et al.* (2001) studied older degraded moraines and cave deposits on the margin of the Mt. Field plateau, and suggested that at least four Quaternary glaciations preceded the Last Glacial Maximum (LGM), the most recent during MIS 4. No attempt has been made to determine the extent, timing and climatic significance of the more recent glacial landforms which form the focus of this study.

Methods

Mapping

A morpho-stratigraphic approach for mapping was employed at Mt. Field because glacial landforms are well preserved but their associated sediments are poorly exposed. We concentrated on delineating the former upper and lower limits of ice cover and the number and sequence of depositional phases (Fig. 2). In former ice accumulation areas, trimlines were identified as linear boundaries between periglacial blockfields and ice-smoothed bedrock surfaces (Thorp, 1986; Stone *et al.*, 1998). In lower areas we used cross-cutting relationships of moraines and associated outwash surfaces to delineate the sequence and extent of depositional phases. Aerial photographs aided in identification of the morphological features. Landforms were mapped at a scale of 1:25 000 in combination with field evidence.

Exposure dating

Four boulders at two locations were dated in this study using *in situ* ^{36}Cl to extend the previous dating of Barrows *et al.* (2002) at Mt. Field. Two samples were collected from Lake Newdegate where a block moraine with a high protalus component at 1100 m altitude could have formed after the main deglaciation (Colhoun *et al.*, 1996). Another two were collected from the glacial boulders 'Griffith and Taylor' from the Broad River Valley belonging to an ice advance that predates

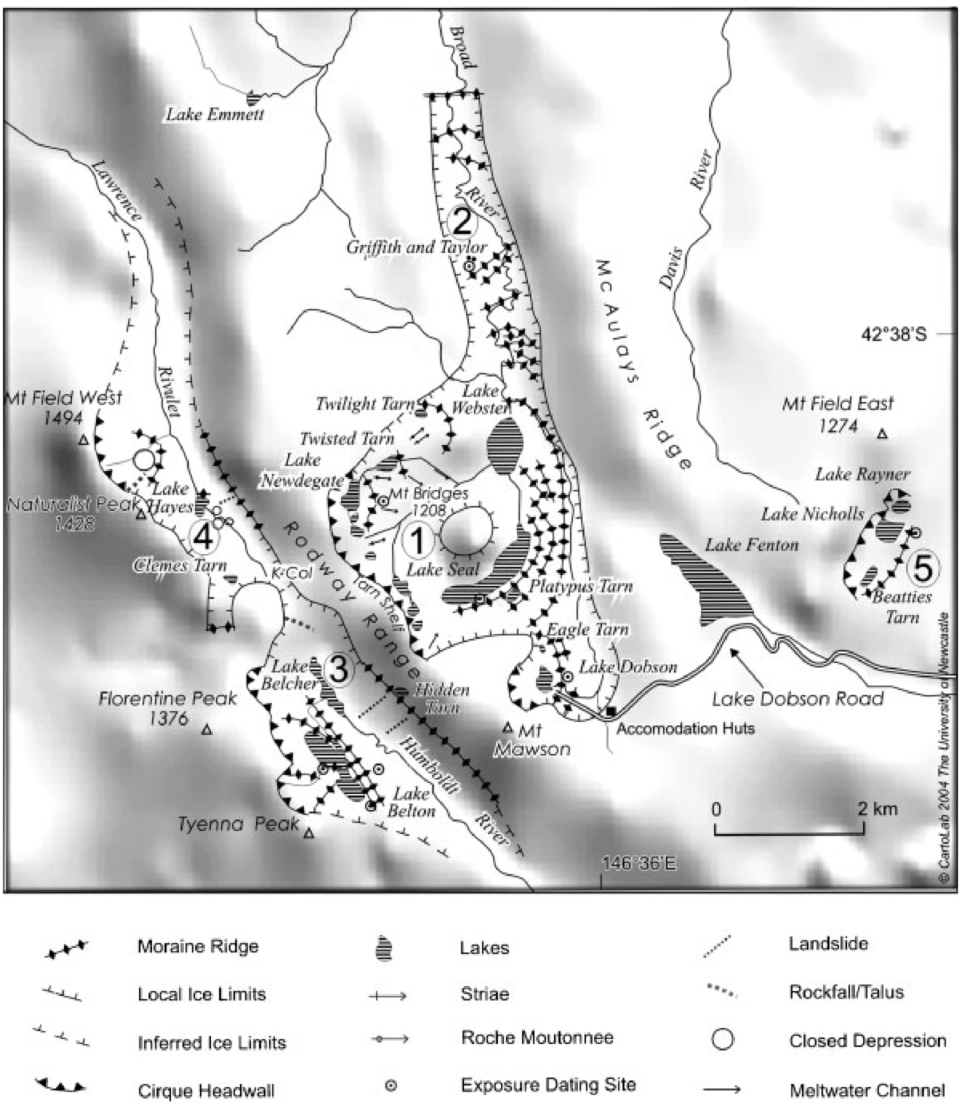


Figure 2 Geomorphological map of Mt. Field**.** The location of glacial landforms, major ridges, valleys and lakes are shown. The main sites mentioned in the text are numbered: Tarn Shelf (1), Broad Valley (2), Lake Belcher and Belton (3), Lake Hayes (4) and Beatties Tarn and Lake Nicholls (5)

Tables 1 Site data

Sample	Longitude (°E)	Latitude (°S)	Latitude[a] (°S)	Altitude (m)	Scaling factor (nucleons)[b]	Scaling factor (muons)[b]	Horizon correction	Thickness correction[c]
Lake Newdegate moraine								
NEW-002	146.5611	42.6667	42.33	1160	2.574/2.561	1.643/1.638	0.9846	0.9584, 1.357, 1.055
NEW-003	146.5611	42.6667	42.44	1165	2.584/2.575	1.646/1.643	0.9846	0.9611, 1.338, 1.055
Broad valley boulders								
G + T-001	146.5792	42.6333	45.87	825	1.970/2.052	1.413/1.451	0.9355	0.9523, 1.396, 1.063
G + T-002	146.5792	42.6333	45.53	825	1.970/2.044	1.413/1.447	0.9355	0.9523, 1.395, 1.063

[a]Effective geomagnetic latitude.
[b]First number for geographic latitude, second number for effective geomagnetic latitude.
[c]Correction factors for spallation, thermal neutrons, and epithermal neutrons respectively; $\rho = 3.0\,g\,cm^{-3}$; $\Lambda = 160\,g\,cm^{-1}$.

18.8 ka, the age of the innermost lateral moraine at Lake Seal (Barrows *et al.*, 2002). At all sites the largest boulders were selected, as these are likely to have experienced minimal snow cover. Boulders with spalled or weathered surfaces were avoided. Site data for the samples are listed in Table 1. Sample preparation techniques are described in Barrows *et al.* (2002). The isotopic ratio of $^{36}Cl/Cl$ was measured by accelerator mass spectrometry on the 14UD accelerator at the Australian National University (Fifield *et al.*, 1994). Chemical data for the samples are presented in Table 2.

Exposure ages were calculated using the conventional approach (Cerling and Craig, 1994). Production pathways for cosmogenic ^{36}Cl and production rates follow Barrows *et al.* (2002). Age calculations are presented in two forms, an 'apparent' age and a 'corrected' age. The apparent age is calculated using geographic latitude and the site data in Table 1. The corrected ^{36}Cl age is calculated using effective geomagnetic latitude and includes theoretical production from minor elements. All ages are calculated on a common basis assuming no significant erosion since initial exposure. Corrections due to geomagnetic changes are made individually on each age. Effective geomagnetic latitude was calculated by the same methods and records used in Barrows *et al.* (2002). All references in the text are to the corrected ages, because we consider these to be the most accurate.

Glacial reconstruction

The pattern and relative position of glacial (moraines and trimlines) and non-glacial landforms (blockfields, deeply weathered bedrock and solifluction deposits) allows reconstruction of former ice limits, glacial surface profiles and Equilibrium-Line Altitudes (ELAs). A conventional Accumulation Area Ratio (AAR) of 0.65 was used on the Broad Valley glacier and a Toe to Headwall Altitude Ratio (THAR) of 0.4 was used on former cirque glaciers following Meierding (1982) because these values have been shown to involve the lowest uncertainty. Surface debris in the ablation zone can modify the AAR, but the large linear moraines and lack of hummocky till at Mt. Field suggests that the glaciers were free of major debris mantles. As a further check, an area/altitude graph was drawn for the Broad Valley glacier and the uncertainty associated with a range of AAR values was calculated.

Results

Erosional landforms and trimlines

The most impressive landforms of glacial erosion occur within the Broad Valley drainage basin (Fig. 2, site 2) and on the higher slopes below Mt. Field West and Naturalist Peak (Fig. 2, site 4). Tarn Shelf, an elongate cirque at the head of the Broad Valley (site 1) was the accumulation area of the largest glacier at Mt. Field and it has well-developed erosional landforms (Fig. 3). The major route of ice flow from Tarn Shelf towards the Broad Valley was via Lake Seal (site 1). Lake Seal is overdeepened and trimlines on Mt. Bridges indicate that the valley was ca. 80% full of ice at maximum extent. Sandstone clasts in nearby moraines indicate that glacial erosion has excavated to below the 300 m-thick dolerite sill in this area. The lower Broad Valley is straight and devoid of spurs for ca. 5 km downstream of Lake Webster to an elevation of ca. 900 m, with steep linear slopes and a flat aggradation surface at its base.

Ice also flowed eastward toward the Twisted and Twilight Tarn areas (Fig. 2) from the northern part of Tarn Shelf (Fig. 3). Glacial landforms are preserved, including striae and degraded moraines, but glaciated bedrock shows evidence of postglacial

Table 2 Chemical data[a]

Sample	[CaO] (wt%)	[K_2O] (wt%)	[Cl] (ppm)	[TiO_2] (wt%)	[Fe_2O_3] (wt%)	Cross-section (10^{-3} $cm^2\,g^{-1}$)
Lake Newdegate moraine						
NEW-002	10.914 ± 0.00	0.553 ± 0.02	8.0 ± 1.67	0.539 ± 0.00	10.070 ± 0.01	5.445 ± 0.114
NEW-003	11.173 ± 0.00	0.554 ± 0.01	15.7 ± 0.50	0.527 ± 0.02	11.259 ± 0.00	5.714 ± 0.112
Broad valley boulders						
G + T-001	11.193 ± 0.01	0.590 ± 0.02	10.7 ± 0.59	0.553 ± 0.01	10.602 ± 0.01	5.693 ± 0.114
G + T-002	10.035 ± 0.00	0.677 ± 0.02	4.3 ± 0.45	0.567 ± 0.02	11.158 ± 0.01	5.683 ± 0.114

[a]The abundance of major target elements was determined using X-ray fluorescence. Chlorine content was determined by isotope dilution. The concentrations of trace elements used to determine the cross-section were measured by inductively coupled plasma mass spectrometry.

I)

II)

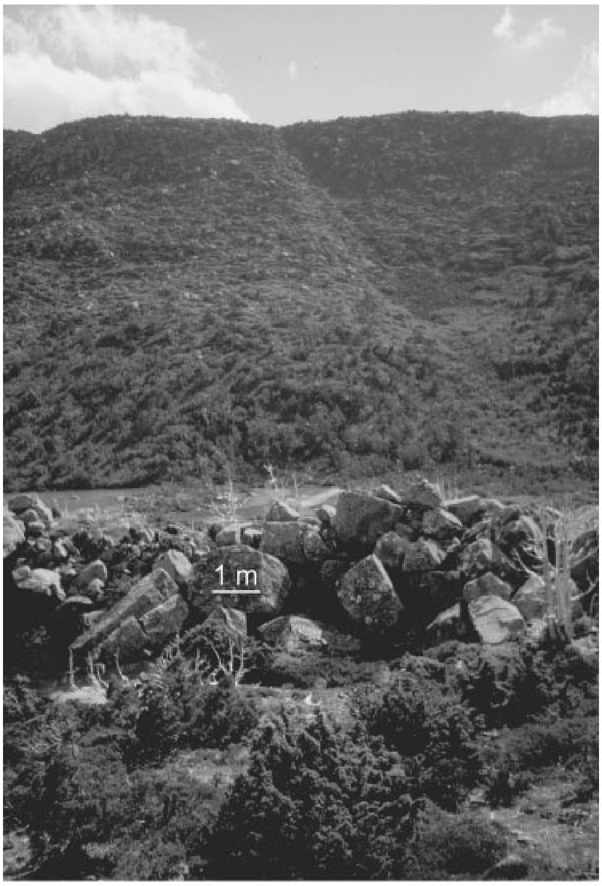
Figure 3 Landscapes of glacial erosion and trimlines. Glacial erosion is most evident on the east-facing slopes of ridges at Mt. Field. In contrast the west-facing slopes are mantled in periglacial blockfields and they preserve excellent trimlines. (I) The Tarn Shelf (viewed from above). Glacial erosion has exploited structural weaknesses in the dolerite bedrock, resulting in hundreds of small tarns and intervening roches moutonnées. Regolith is absent from these areas, and periglacial landforms are absent or poorly developed. The unnamed trough between Mt. Bridges (centre right) and the hills at Twisted Tarn and Twilight Tarn (centre left) is also evident. This valley has a V-shaped profile, but large meltwater channels at its head and abundant ice-smoothed bedrock indicates recent occupation by glacier ice. Striations occur on the hills above Twisted Tarn, providing evidence for older (undated) glacial erosion. (II) Trimline on the west-facing slopes of Rodway Range. The upper slopes are mantled by periglacial blockfields. The trimline occurs about one-third of the way down the slope. Such well-developed blockfields on the summit ridges probably took more than one glacial cycle to form—also see Fig. 4(iv). Smoothed bedrock indicates that ice once covered K Col (foreground), although the former direction of ice motion is not evident weathering and periglacial landforms also occur in this area. The area was probably last glaciated prior to MIS 2, although further exposure dating is required to test this hypothesis.

Dolerite blockfields mantle ridge tops and plateau surfaces at Mt. Field (Figs 3 and 4). Blockfields occur elsewhere in Tasmania including Ben Lomond and the Central Plateau (Fig. 1) but they are considered to be inactive in today's climate and mostly occur outside of MIS 2 ice limits (Caine, 1983; Colhoun *et al.*, 1996; Barrows *et al.*, 2004). The occurrence of extensive blockfields at Mt. Field suggests that glaciation was limited to cirques and valley heads during the late Quaternary. There are two places where ice may have crossed a drainage divide—at K Col (Fig. 3, site 3) and also at Clemes Tarn where glacially sculpted bedrock occurs on the drainage divide between Lake Hayes and a small basin between Naturalist and Florentine Peaks (Fig. 2, site 3).

I)

II)

Figure 4 Moraine stratigraphy. (I) The Griffith and Taylor glacial boulders, located on an outwash surface in the lower Broad Valley. The boulder on the right of the photograph (the true right of the valley) gives a ^{36}Cl age of 44.1 ± 2.2 and the boulder on the true left gives 41.0 ± 2.0 ka. The Broad Valley consists of moraine ridges (forested moraine in distance) and intervening outwash plains (foreground, vegetation is native buttongrass, *Gymnoschoenus sphaerocephalus*). Ten moraines occur downstream of Lake Webster and each has a steep ice proximal slope, while ice distal slopes grade gently into outwash surfaces. (II) A series of moraines occur on the eastern shore of Lake Seal. Platypus Tarn (small lake in centre) is dammed between a smaller inner moraine and a larger compound outer moraine. A sample from a boulder on the inner moraine has a ^{36}Cl age of 18.8 ± 3.0 ka. (III) The moraine at Lake Newdegate on Tarn Shelf consists of dolerite blocks >1 m in diameter. Two of the highest boulders on the moraine crest yield ^{36}Cl ages of 18.0 ± 1.0 and 18.7 ± 1.3 ka. (IV) Moraines on the shore of Lake Belton (centre) are evidence for two adjacent cirque glaciers occupying the slopes below Naturalist Peak (centre background). A retreat moraine also occurs above Lake Belton. The closely spaced terminal moraines have similar ages ca. 18–21 ka. The Rodway Range blockfields are visible in the foreground



III)

IV)

Figure 4 *(Continues)*

Moraine stratigraphy

The major landforms of glacial deposition are illustrated in Fig. 2. There is evidence for valley glaciation and a subsequent less extensive cirque phase. Sites of former valley glaciation include the Broad Valley and the western valleys containing Lake Hayes and Lakes Belton and Belcher. Cirques, often containing moraines, occur at many sites including Lake Dobson, Lake Nicholls, Beatties Tarn and Clemes Tarn and inside the valley glacier ice limits at Lake Belton and Lake Hayes and on the Tarn Shelf at Lake Newdegate.

Seventeen moraines occur in the Broad Valley drainage system between Tarn Shelf and the lower Broad Valley (Fig. 4). This includes eleven distinct end-moraine ridges in the lower part of the Broad Valley below Lake Webster, a 100-m high compound moraine sequence with five crests on the eastern

Table 3 ^{36}Cl Exposure ages for Lake Newdegate and the Broad Valley

Sample	Laboratory code	$[^{36}Cl]_c$ ($\times 10^5$ g^{-1})[a]	$[^{36}Cl]_r$ ($\times 10^3$ g^{-1})[b]	Production rate (g^{-1} yr^{-1})[c]	Production rate (g^{-1} yr^{-1})[d]	Apparent age (ka)	Corrected age (ka)
Lake Newdegate moraine							
NEW-002	ANU-C013-24	2.262 ± 0.105	6.4 ± 1.3	12.56 ± 0.407	12.74 ± 0.405	18.4 ± 1.1	**18.1 ± 1.0**
NEW-003	ANU-C013-25	2.513 ± 0.15	1.27 ± 0.048	13.48 ± 0.427	13.69 ± 0.426	19.1 ± 1.3	**18.8 ± 1.3**
Broad valley boulders							
G + T-001	ANU-C013-26	4.269 ± 0.156	0.871 ± 0.051	9.6 ± 0.3	10.18 ± 0.312	46.9 ± 2.4	**44.1 ± 2.2**
G + T-002	ANU-C013-27	3.586 ± 0.121	0.313 ± 0.033	8.668 ± 0.271	9.178 ± 0.281	43.5 ± 2.1	**41.0 ± 2.0**

[a]C = cosmogenic component.
[b]R = radiogenic component.
[c]Production rate for apparent age.
[d]Production rate for corrected age.

shore of Lake Seal (Fig. 3) and a final retreat moraine at 1140 m at Lake Newdegate on Tarn Shelf (Fig. 4).

Prominent lateral moraines occur at ca. 1100 m in both the Lake Belcher/Belton (Fig. 4) and Lake Hayes valleys. In the Lake Hayes Valley, the moraine extends downvalley for 4 km, providing evidence for a short valley glacier (Fig. 2, site 3). In the Lake Belcher/Belton Valley, the moraine is slightly larger and is approximately 5 km long. Kiernan *et al.* (2001) indicated that these moraines formed before MIS 2.

Many small cirque moraines at Mt. Field provide evidence for less extensive glaciation (Fig. 2). Some cirques contain several moraines or a compound ridge, indicating multiple advances (Fig. 4).

Exposure dating

New exposure ages are presented in Table 3 and earlier ages are listed in Table 4. Twelve of the sixteen exposure ages cluster between ca. 16 and 21 ka, dating them to MIS 2. The remaining four ages date from ca. 33–44 ka during MIS 3.

Similar ages within MIS 2 occur on both terminal and recessional moraines, indicating that a number of advances occurred during a short period. The best-dated moraine sequence is at Lake Belton (Fig. 4), where eight exposure ages from closely spaced moraines show little variation. A similar situation occurs in the upper Broad Valley where there is no statistical difference between the ages of boulders on the innermost moraine at Lake Seal and Lake Newdegate (Fig. 4), providing evidence for early deglaciation at around ca. 18 ka.

Table 4 Corrected exposure ages for Mt. Field from Barrows *et al.* (2002). All samples are ^{36}Cl ages from dolerite boulders except sample MTF-043 (*) which is a ^{10}Be age from a sandstone boulder

Location	Sample	Apparent age (ka)	Corrected age (ka)
Lake Belton	MTF-043*	15.9 ± 1.5	**16.1 ± 1.5**
Lake Belton	MTF-042	18.7 ± 1.3	**18.4 ± 1.3**
Lake Belton	MTF-046	20.0 ± 1.6	**20.6 ± 1.6**
Lake Belton	MTF-047	18.9 ± 1.3	**18.6 ± 1.3**
Lake Belton	MTF-041	20.3 ± 1.4	**19.9 ± 1.3**
Lake Belton	MTF-044	16.8 ± 1.0	**16.6 ± 1.0**
Lake Belton	MTF-045	18.8 ± 1.3	**18.5 ± 1.2**
Lake Belton	MTF-049	18.4 ± 1.3	**18.1 ± 1.3**
Lake Seal	MTF-054	19.1 ± 3.1	**18.8 ± 3.0**
Eagle Tarn	MTF-055	18.9 ± 1.9	**18.6 ± 1.9**
Lake Nicholls	MTF-051	34.7 ± 2.5	**33.1 ± 2.4**
Lake Nicholls	MTF-052	46.3 ± 3.2	**43.1 ± 3.0**

The Griffith and Taylor boulders, dated to 44.1 ± 2.2 and 41.0 ± 2.0 ka, occur on an outwash surface, tens of metres beyond an associated double-crested end moraine in the Broad Valley (Fig. 4). Although we only have two ages and this limits our ability to generalise, the dates are similar to an age of 43.1 ± 3.0 for a boulder on the Beatties Tarn–Lake Nicholls moraine near Mt. Field East (Barrows *et al.*, 2002). The surfaces of the boulders retain primary dolerite structures including hexagonal cooling joints, eliminating any significant post-depositional weathering. Additionally, the chance of producing two statistically identical ages on adjacent boulders by cosmogenic isotope inherhitance is extremely small.

Up to twelve moraines in the Broad Valley occur in a position lying stratigraphically between the dated Lake Seal moraine (Fig. 4) and the Griffith and Taylor boulders. Although moraine ages are unable to be further constrained at present, they date from the interval between ca. 41 and 21 ka. The moraines may have formed during a stepped glacial retreat but a complete retreat after 41 ka and the subsequent establishment of another glacier during MIS 2 cannot be ruled out. A further three moraines and associated outwash terraces occur up to 2.5 km beyond the Griffith and Taylor erratics, after which the river enters a gorge. These moraines have not been dated but must be older than 41–44 ka.

Glacial reconstruction

Moraine limits and trimlines have been used to reconstruct the former glacier surface profiles for four periods at Mt. Field (Fig. 5). The phases are based on exposure dating but there is some uncertainty because not all moraines have been dated. The ELAs for each former glacier at Mt. Field are presented in Table 5 with supporting information on glacier area. In addition, an area/altitude graph for the Broad Valley glacier (Fig. 6) indicates that the uncertainty associated within a realistic range of AAR values from 0.6 to 0.7 is approximately 50 m and the ELA is modified by only 100 m if an unrealistically low AAR value of 0.5 is chosen. We conservatively quote the uncertainty associated with the choice of AAR as ± 50 m in this paper.

The glacial reconstruction reveals that small changes in the ELA result in dramatic changes in ice cover at Mt. Field. Ice covered ca. 17–20 km^2 between 41 and 44 ka, and the ELA of the Broad Valley glacier was at 940 ± 50 m. At 19–21 ka, ice cover was ca. 8 km^2 and the regional ELA was at ca. 1040 ± 50 m. A 120-m rise in the ELA at ca. 18 ka resulted in a reduction of glacial area to less than 1 km^2. At this time, two small cirque glaciers remained above Lake Belton and at Lake Newdegate and the ELA was at 1120–1160 m.

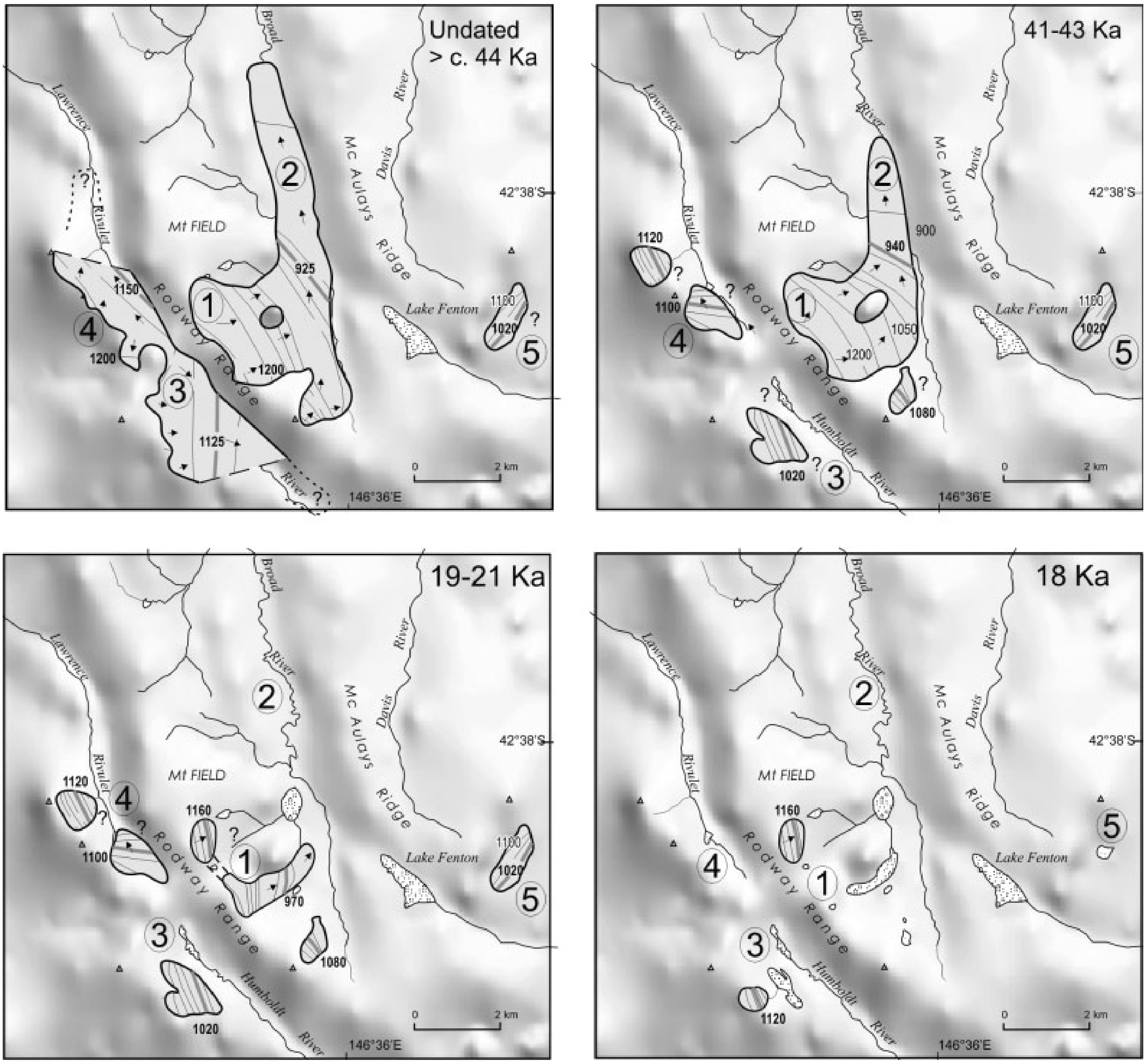


Figure 5 Reconstructed ELAs, glacier elevation and flow direction for the >ca. 44 ka, ca. 41–44 ka, < ca. 19–21 ka, and ca. 18 ka ice limits. Question marks indicate areas where precise ice extent is not known, or where an age is inferred. The main sites mentioned in the text are numbered: Tarn Shelf (1), Broad Valley (2), Lake Belcher and Belton (3), Lake Hayes (4) and Beatties Tarn and Lake Nicholls (5)

The reconstructed glaciers show an interesting pattern that appears to reflect the role of topography on wind-drifted snow accumulation and shading from insolation. An example of topographic shading is the anomalously low ELA of the Broad Valley glacier (970 ± 50 m) during MIS 2 when it was confined within the deeply shaded glacial trough at Lake Seal. The role of snow drifting on accumulation is evident because glacier surfaces at Mt. Field were inclined transversely from west to east rather than sloping downvalley, and cirque glaciers formed in easterly and shaded niches on the valley sides rather than in the valley heads (Fig. 5). This pattern indicates prevailing westerly airflow and favourable sites for snow accumulation in the lee of north–south trending mountain ridges such as Mt. Field West and the Rodway Range.

Temperature and precipitation reconstruction

The extent of valley glaciers and their associated ELAs depends on air temperature, precipitation rate, insolation, cloudiness, near-surface wind velocity and humidity (Oerlemans, 1991; Ohmura *et al.*, 1992; Kerr and Sugden, 1994). It is not possible to reconstruct any one variable from glacial evidence, but the change in dominant variables (temperature and precipitation) can be reasoned with some confidence by considering contemporary glacier–climate relationships and wider proxy evidence for environmental change during the last glaciation. In this section we reconstruct the climate of MIS 2 and discuss the uncertainty and limitations of the methodology.

A widely used method for reconstructing climatic change is to calculate an ELA depression between glacial times and the present, by comparing Quaternary and contemporary ELAs on the same mountain range (e.g. Porter, 1975). Unfortunately Tasmania lacks present-day glaciers and estimating a current ELA is problematic. It has previously been calculated by using an average atmospheric freezing level as a proxy (Colhoun, 1985). This approach provides a rough indication only, because there is uncertainty concerning the temperature lapse rates and the relationship between the freezing level and the ELA. We chose the mean summer freezing level because it has a closer relationship to the ELA on contemporary glaciers (Ohmura *et al.*, 1992).

Table 5 Equilibrium-Line Altitude (ELA) estimates for former glaciers at Mt. Field. The ELAs show spatial and temporal variability in response to a climatic amelioration during deglaciation and orientation with respect to snow-bearing winds and insolation as controlled by local topography. Figure 5 shows the glacier reconstructions from which these ELA figures are estimated

Reconstructed glacier	Age	Area (km^2)	ELA (m)
Lake Hayes glacier	Undated, >MIS 3 likely	2.6	1150
Belton/Belcher glacier	Undated, >MIS 3 likely	4.8	1125
Clemes Tarn	Undated. Possibly active in MIS 2	0.3	1200
Broad Valley glacier	Undated, >MIS 3	12	925
Broad Valley glacier	MIS 3	9.5	940
Lake Nicholls/Beatties Tarn glacier	MIS 3	0.7	1020
Lake Seal advance (youngest)	MIS 2	1.9	970
Lake Dobson glacier	MIS 2	0.4	1080
Mt Field West glacier	Undated, MIS 2 age likely	0.6	1120
Lake Hayes glacier	Undated, MIS 2 age likely	0.9	1100
Lake Belton glacier	MIS 2	1.0	1020
Lake Newdegate glacier	MIS 2	0.4	1160
Lake Belton advance (youngest)	MIS 2	0.25	1120

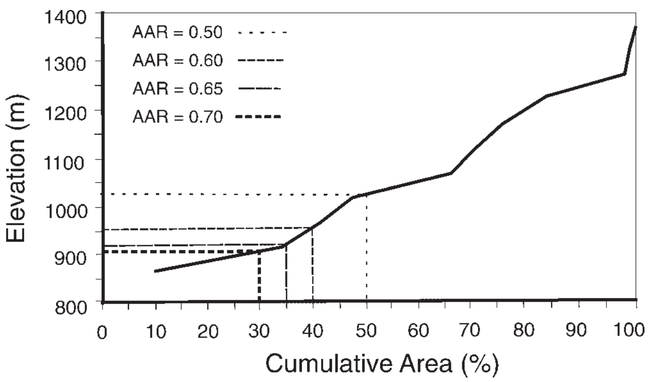


Figure 6 Area–elevation plot for the former Broad Valley Glacier. An Accumulation Area Ratio (AAR) of 0.65 is used in this study. Adjusting the AAR between 0.6 and 0.7 causes the ELA to vary by ca. 50 m, providing an estimate of the uncertainty associated with our choice. An unrealistically low AAR of 0.5 (typical of debris-covered glaciers), results in an ELA variation of only ca. 100 m

The mean summer freezing level for Mt. Field was calculated at 2300 m using temperature data from 1988 to 1992 at Maydena, 10 km from Mt. Field and a temperature lapse rate of 6.5 °C km^{-1} (Nunez and Colhoun, 1986). This lapse rate, based on contemporary data from Tasmanian mountains, may have changed during glacial times and is another source of uncertainty. Using the Broad Valley glacier at ca. 41–44 ka as an example (ELA of 940 ± 50 m), the ELA depression is calculated at 1360 ± 50 m. At ca. 18 ka (ELA of 1160 m) the ELA depression is calculated as 1140 ± 50 m.

Our ELA calculations can be translated to temperature changes if constant precipitation is assumed for the glacial advances. Using the temperature lapse rate, the ELA differences translate to mean temperature differences relative to present of −8.0 °C during MIS 3 and −7.4 °C during MIS 2. Determining past precipitation levels is difficult, but a few comments can be made. Diatom and pollen evidence from Eagle Tarn indicates that the latest Pleistocene climate of Mt. Field was drier than the Holocene climate (Bradbury, 1986). Evidence for drier conditions is also evident in dune sequences in eastern Tasmania, which were activated during glacial times (Bowden, 1983). Little information about past precipitation levels during MIS 3 is available and an increase in precipitation cannot be ruled out. The uncertainty in quantifying past precipitation places a limitation on our temperature reconstructions and means that we cannot state that temperatures were colder during MIS 3 than during MIS 2, despite a greater ELA depression during this time. We quote the temperature lowering associated with both the MIS 3 and MIS 2 advances as 7–8 °C.

Discussion

The exposure ages and geomorphic map presented in this study provide evidence for glacial advances at Mt. Field between ca. 41–44 ka (MIS 3) and 16 ka (MIS 2). Evidence for the MIS 3 advance occurs in two locations, the Broad Valley and at Lake Nicholls. Many undated retreat moraines occur in the Broad Valley, but exposure dating on older and younger moraines provides limiting ages for these moraines of >19 ka and <41 ka. Widespread cirque glacier advances occurred during the LGM at ca. 19 ka, and the youngest moraines at Lakes Newdegate and Belton are 18 ka old although one boulder at Lake Belton dated using ^{10}Be has a younger age of 16 ka.

Extent of MIS 3 advances

With the exception of the Broad Valley glacier, MIS 3 advances at Mt. Field were probably of similar extent to those of MIS 2 and are preserved in fortuitous situations only. Moraine survival depends on many factors including the extent of each successive advance and the topography of the terminal environment (Rothlisberger and Schneebeli, 1979). The cirque glaciers at Mt. Field may have removed their MIS 3 moraine records by 'self-censoring' during successive periods of glacial advance and retreat (Gibbons *et al.*, 1984; Kirkbride and Brazier, 1998). The MIS 3 advance may have been preserved in the Broad Valley because the glacier had a gently inclined surface profile in its former ablation zone, declining at only 2°. Low-gradient glaciers undergo large changes in extent for relatively small changes in climate (Oerlemans, 1989; Mackintosh *et al.*, 2002). A broad accumulation area and long narrow snout further enhance this sensitivity (Furbish and Andrews, 1984). This geometric effect explains why a small change in climate, reflected in the 100-m shift in ELA of the Broad Valley glacier, could result in a 4-km change in glacier length. Such an enhanced response would spread out the moraine sequence and facilitate preservation of landforms and deposits that reflect minor fluctuations of the terminus.

Many undated moraines occur between Lake Seal, and the Griffith and Taylor erratics. The formation of these large moraines (>100 m above surrounding topography at Lake Seal) requires a long period of glacial equilibrium, even if they rest on bedrock at depth. Short valley glaciers today (even in subpolar environments) tend to respond to climatic changes within ca. 100 years (Oerlemans and Fortuin, 1992), and thus each large moraine may represent hundreds or possibly thousands of years of deposition. This moraine complex is a target for further exposure dating.

Comparison with previous work at Mt. Field

Kiernan *et al*. (2001) identified five Quaternary ice advances at Mt. Field. We did not attempt to determine the age of the oldest three advances (Westfield, Lawrence, Junee) with exposure dating, but a comparison between our results and this study is revealing for the youngest advances, the Humboldt and Belton. It also allows us to highlight the strengths and limitations of different dating techniques employed at Mt. Field.

Kiernan *et al*. (2001) argued that the 'Humboldt advance' occurred during the last glacial cycle, and probably during MIS 4. A glacier in the Humboldt Valley was large enough to breach a local divide and drain into the Junee Valley. Based on the U-series ages in Threefortyone Cave they argued that outwash gravel was deposited after 132 ka and before 16.7 ka. A further U-series date from the Welcome Stranger Cave, associated with the Humboldt advance indicates a minimum age for outwash gravels of 41.1 ka. As their date is very similar to our MIS 3 exposure ages, we suspect that the 'Humboldt advance' occurred between ca. 41 and 44 ka at Mt. Field during MIS 3 rather than MIS 4.

In the Broad Valley, Kiernan *et al*. (2001) used weathering evidence to delimit the boundary between the LGM 'Belton' advance and the 'Humboldt' advance (presumed MIS 4) as approximately 5 km downstream of Lake Webster, whereas our exposure ages from Griffith and Taylor boulders indicate that the LGM advance was much less extensive (Fig. 5, site 2). Kiernan *et al*. (2001) also used weathering evidence on the moraine bounding Lake Nicholls to assign it to the LGM 'Belton' advance, whereas our exposure age indicates that the moraine dates from MIS 3. However in this case, a basal limiting ^{14}C date of 13.1–13.5 cal. ka at Beatties Tarn, a nearby cirque basin impounded by the same moraine, indicates that ice might have been present during both MIS 2 and 3 and that the moraine may be a compound feature.

Exposure dating provides a direct constraint on the deposition of glacial boulders and moraines, has good age resolution for this period and a degree of precision that is not possible using weathering evidence alone. Weathering evidence is useful for determining a relative chronology when glacial advances are vastly different in age (Kiernan, 1990), but we have found that it is not suitable for the purpose of differentiating between glacial advances from within one glacial cycle.

Comparison with wider Tasmania and other Southern Hemisphere sites

Landforms dating from the last glacial cycle have been identified in many parts of Tasmania (Colhoun *et al*., 1996; Barrows *et al*., 2002). The most studied are the West Coast Range, and the former outlet valleys from the large glacial systems in central Tasmania, including Lake St. Clair and Cradle Mountain, and several outlying areas of former cirque glaciation including Lake Ouse, Ben Lomond and the Hartz Mountains. Within this context, Mt. Field is important because it is a well-constrained glacial system, it contained small ice masses responsive to minor climate changes and now has a high density of absolute ages.

The overall story emerging from studies of former Tasmanian glaciers is that the MIS 2 glaciation was of limited extent and that earlier Quaternary glaciations were much more extensive (Colhoun, 1985). Our study indicates the possibility that some glaciers were at least as extensive during MIS 3 as during MIS 2. Further afield in Tasmania, exposure ages from the Hartz Mountains and Mt. Jukes indicate that some glaciers might also have been extensive between 39 and 46 ka (Barrows *et al*., 2002). Many mountain glaciers appear to have reached a greater extent during earlier parts of the last glacial cycle (Gillespie and Molnar, 1995). For example, in New Zealand, glacial advances have been dated to 40–41 and 46–48 ka at Aurora Cave on Lake Te Anau in Fiordland (Williams, 1996).

Little is known about the wider structure and timing of glacial retreat across Tasmania leading into the Holocene. Limiting radiocarbon dates from glacial lake sediments range from as early as 17–18 ka ^{14}C yr BP (Ooze Lake and Lake St Clair), indicating early and rapid retreat of ice without any further advance, to as late as the Holocene (Macphail and Colhoun, 1985; Hopf *et al*., 2000). However, many of these dates considerably postdate the complete retreat of ice (Barrows *et al*., 2002). The youngest directly dated glacial features are at Mt. Field (Barrows *et al*., 2002). At Mt. Kosciuszko, the Twynam advance of the Blue Lake glacier is dated at 16.8 ka. Similarly, in the higher altitude mountains of New Zealand and Chile where glaciers are still found today, there is clear evidence for an early deglacial advance at about the same time (Fitzsimons, 1997; Lowell *et al*., 1995).

Colhoun *et al*. (1996) argued that some younger moraines might exist in Tasmania and that the Newdegate moraine at Mt. Field possibly formed after the main MIS 2 advance. Exposure dating in this study allowed us to test this hypothesis. It appears clear that deglaciation occurred early, by 18 ka in most places and at 16 ka at the very latest. In New Zealand there is evidence for a late glacial advance, possibly at the same time as the Younger Dryas (Denton and Hendy, 1994), but no advance of this age has been identified in Australia.

Climatic implications

The MIS 3 climate in Tasmania was of a cool temperate nature, intermediate between interglacial and glacial conditions (Colhoun *et al*., 1999). The best record of MIS 3 climatic variability is a pollen diagram from Lake Selina on the West Coast Range. Although the ages are poorly constrained, the record shows numerous fluctuations that are reminiscent of the δ^{18}O variations in the Vostok ice core (Petit *et al*., 1999; Colhoun *et al*., 1999; Fig. 7). The pollen diagram is interpreted to show overall cold increasing during MIS 3 towards MIS 2 with fluctuations between cool and cold periods. Hence, the MIS 3 downturns in Lake Selina core may coincide with glacial advances at Mt. Field. Further a field, a sea-surface reconstruction from adjacent to the east coast of New Zealand at Deep Sea Drilling Project (DSDP) Site 594 exhibits a clear decrease in reconstructed sea-surface temperature during MIS 3 at ca. 45 ka (Barrows *et al*., 2001; Fig. 7). Process-based modelling studies of glacial mass balance indicate that maritime glaciers are sensitive to temperature changes (Oerlemans and Fortuin, 1992; Kerr and Sugden, 1994) and we suspect that the ELA changes at Mt. Field are dominated by past temperature changes.

Our findings suggest that the advance and retreat of the Broad Valley glacier between 45 ka and the LGM reflects a period of transitional climate, with several cold periods that may have involved changes in precipitation. These cold spikes during MIS 3 might have approached the level of cooling reached during the peak of MIS 2. The reconstructed sea-surface temperature record from DSDP Site 594 shows several sharp reductions between ca. 32 ka and 20 ka (Fig. 7). Although evidence for glacier advances from this period have not been

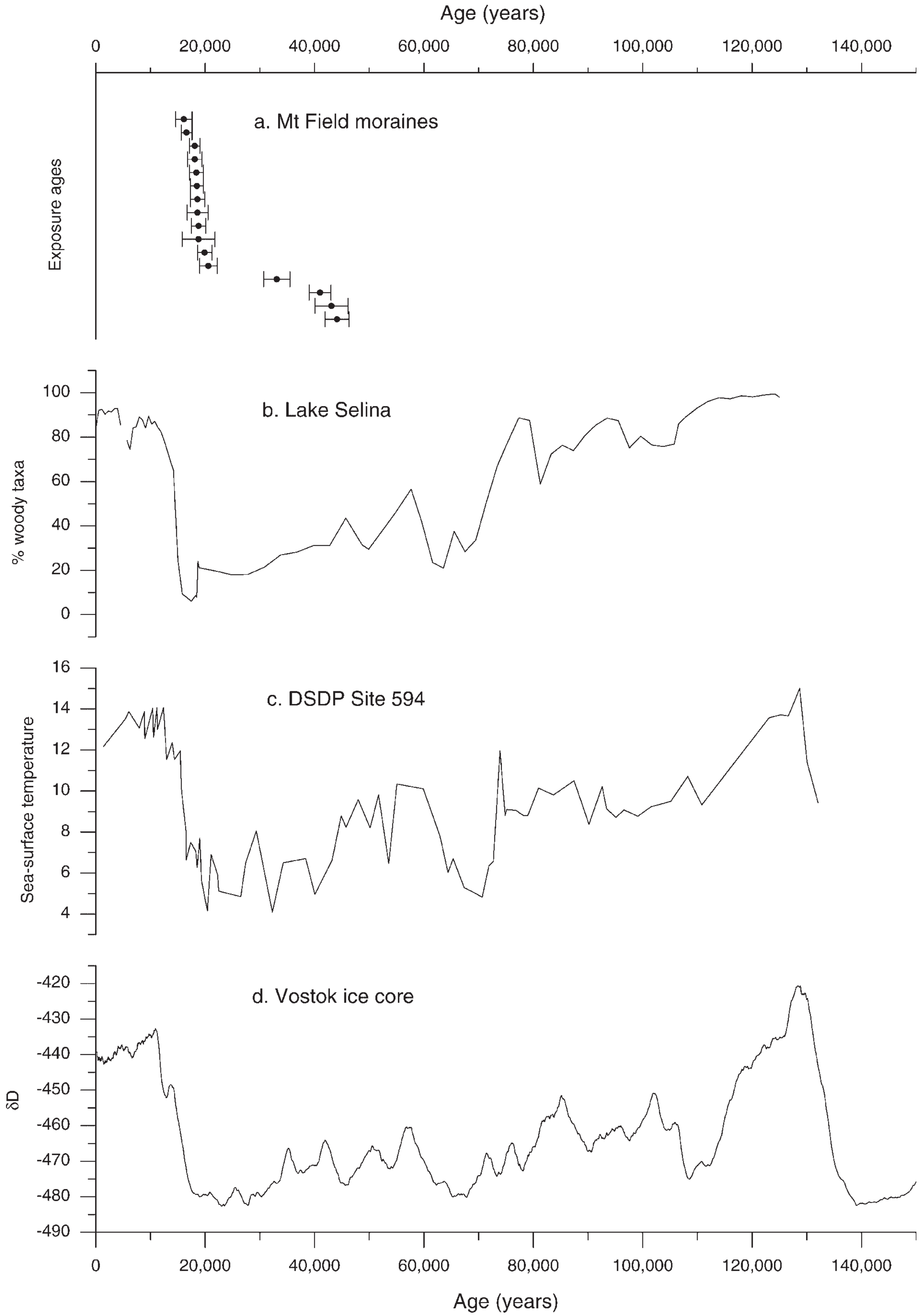


Figure 7 Comparison between the exposure ages at Mt. Field (a) and wider proxy evidence for climatic changes including (b) Lake Selina pollen record in Tasmania (Colhoun *et al.*, 1999), (c) sea-surface temperatures reconstructed for DSDP Site 594 (Barrows *et al.*, 2001), a marine core off the east coast of New Zealand and (d) the deuterium record from the Vostok ice core from central Antarctica (Petit *et al.*, 1999)

found widely, moraines from Mt. Kosciusko (Fig. 1) have been dated to 32 ka (Barrows *et al.*, 2001).

Our findings indicate that a temperature decline of ca. 7 °C may have occurred during MIS 2. The timing of this possible temperature drop coincides with the global peak in ice volume and sea-level lowering at ca. 20 ka (Fleming *et al.*, 1998, Yokoyama *et al.*, 2000) when sea-surface temperature in the south Pacific also reached a minimum (Barrows *et al.*, 2000; Barrows and Juggins, 2005). Temperature probably increased dramatically after 18 ka, causing widespread deglaciation at Mt. Field. This increase in temperature occurred at approximately the same time as the warming evident in Antarctic ice cores (Fig. 7).

The orientation and location of former glaciers at Mt. Field indicates that, as today, most precipitation arrived from the west. The dominant role of the southern westerlies is also evident in the broad pattern of reconstructed ELAs in Tasmania during MIS 2. Previous ELA reconstructions in Tasmania have been based on single glaciers or icecaps and it has not always been clear whether they represent regional climatic conditions. To complicate matters further, different methods are used to reconstruct the ELAs and comparisons are made between features, which are not always well dated. Nevertheless, a broad pattern is obvious. Colhoun (1985) indicated that the ELA of the coastal maritime West Coast Range icecap was at 835 m during the peak of the last glaciation.

Farther east at the more continental extreme, cirque glaciers on Ben Lomond had an ELA of ca. 1400 m (Caine, 1983). Mt. Field, in central Tasmania sits in an intermediate position—the mean ELA for well-dated MIS 2 glaciers is 1057 ± 50 m. This west to east increase in ELA across Tasmania, first identified by cirque floor mapping by Peterson and Robinson (1969), mimics the present-day precipitation gradient and confirms that westerly winds were as important during the Last Glacial Maximum as they are today (Derbyshire, 1971).

Conclusions

We have applied exposure dating, mapping and ELA reconstruction to the glaciated landscape of Mt. Field, Tasmania. Exposure dating has allowed for a precise sequence of events to be resolved. It appears that during the last glaciation ice advances were smaller than those mapped by Kiernan *et al.* (2001) using weathering evidence, and we directly dated a new glacial advance to MIS 3. In summary:

1. Some glaciers at Mt. Field were more extensive during MIS 3 than during the global peak in ice volume during MIS 2.
2. A glacial advance occurred between 41 and 44 ka BP, associated with a ELA reduction of 1360 ± 50 m and a possible temperature reduction of 7–8 °C. It appears that wider glacial advances in Tasmania and also New Zealand occurred at this time. The Lake Selina pollen record and the DSDP 594 sea surface temperature reconstruction provide wider evidence of cooling.
3. Cirque glaciers developed between ca. 21 and 18 ka during MIS 2 in response to a decline in air temperature at the LGM. ELAs were depressed by around 1140 ± 50 m. A local and regional ELA trend indicates that a west to east precipitation gradient existed during the last glaciation, as it does today.
4 Deglaciation occurred rapidly after this time, and no readvance occurred after 16–18 ka. This signal is similar to the temperature record in Antarctic ice cores.

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