Ice-marginal geomorphology and Holocene expansion of debris-covered Tasman Glacier, New Zealand

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Abstract The Neoglacial evolution of the Tasman Glacier is reconstructed from the distribution of ice-marginal moraines and from the subglacial topography. The glacier has overridden its margins, creating two shelves of thin ice by *c.* 3700 years before present (BP) and *c.* 2000 years BP. The proglacial foreland is dominated by outwash aggradation and lacks pre-nineteenth century terminal moraines. The glacier has experienced successively larger expansions over the Neoglacial period (*c.* 5000 years), prior to drastic twentieth-century thinning and retreat. Over the same period, uncovered glaciers have shown progressively smaller re-advances. The expansionary tendency of the debris-covered glacier is interpreted as a response to long-term (millennial) accumulation of both subglacial and supraglacial debris. Subglacial aggradation has probably raised the bed of the glacier, promoting debris cover growth and reducing ablation even as less favourable balance regimes developed. Comparison with other glaciers shows that the expansionary tendency is widespread but may be manifest in a variety of sediment-landform associations.

INTRODUCTION

Supraglacial debris covers reverse the ablation gradient and reduce the equilibrium accumulation area ratio, and covered glaciers are often associated with elevated subglacial beds. The longer-term glaciological effects are obscure, yet are important for understanding the climatic significance of dated moraines (Kirkbride & Brazier, 1998), the survival of low-altitude ice tongues, and the evolution of their outwash plains. This paper interprets Neoglacial ice-marginal environments of Tasman Glacier in terms of changes to the 20 km^2 debris-covered ablation area. Fluctuations of uncovered glaciers in the region provide a control sample. The aim is to understand how a persistent debris cover has influenced the magnitude of terminus fluctuations and the style of ice-marginal sedimentation over a period of multiple mass-balance cycles.

ICE-MARGINAL GEOMORPHOLOGY

A schematic view of the lower Tasman Glacier (Fig. 1) has been made from available topographic, velocity and geophysical surveys, and from dated moraines. In Fig. 1, inset sections are based on field observations and interpretation of geophysical profiles.

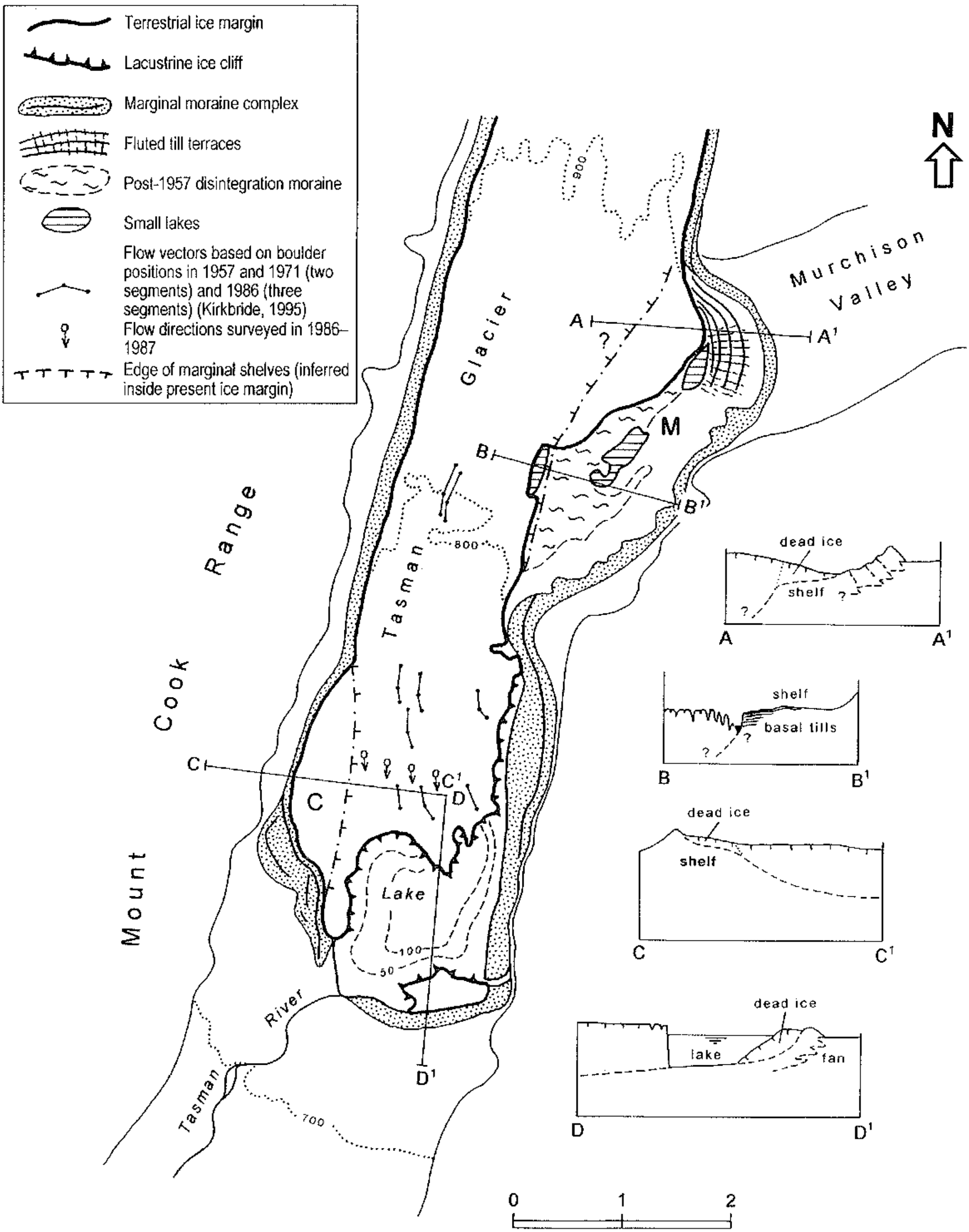

Fig. 1 Map showing the spatial relationships between the present Tasman Glacier and ice-marginal sediment-landform associations, compiled from various sources (see text). Lake bathymetry from Hochstein *et al.* (1995). Inset sections based on 1:50 000 NZMS 260 topomap, with 2.5× vertical exaggeration.

The glacier occupies a trough in the centre of the valley, bounded along the margins by lateral moraines, beneath by subglacial till, and in the proglacial foreland by fluvioglacial sediments. The continuity of the lateral moraines is disrupted at two embayments, informally named the Murchison embayment (M in Fig. 1) and the Celmisia embayment (C in Fig. 1). Within each, surviving ice is thin and stagnant, and appears detached by shear zones from ice in the central trough.

The Murchison embayment has been deglaciated since 1957 aerial photography, revealing to its north end a flight of three fluted, till-mantled benches, and to the south chaotic disintegration moraine (Kirkbride, 1995). Recently deposited tills in the southern area are couplets of a basal melt-out till overlain by supraglacial melt-out till, apparently laid down by post-1957 stagnant-ice wastage. In the northern area where flutes ornament the till surface, deglaciation involved active retreat of mobile ice. The embayment forms a shelf distal to the central trough, created by Tasman ice invading the mouth of the tributary Murchison Valley. The inner shelf edge forms a 40 m cliff of stratified lodgement and basal melt-out tills above a marginal lake (section B–B^1), interpreted as evidence of mobilization/stagnation cycles as the invasive ice thickened and thinned repeatedly. The till benches are interpreted as former lateral moraines behind which aggradation of the Murchison River raised the sandur surface as the Tasman Glacier encroached into the Murchison Valley (see section A–A^1 for interpreted facies structure). Each terrace connects to the north with a bouldery horizon within the lateral moraine, dated by Gellatly *et al.* (1985). Their dates demonstrate moraine building over about the last 3700 ^{14}C years, culminating in the late nineteenth century before drastic thinning of the main glacier. Lateral correlation with the till terraces implies construction of lateral moraines at roughly 3700, 3300, 1600 and <1000 years before present (BP), each being overridden to form a terrace by successive advances until *c.* 100 years BP.

Celmisia embayment (C in Fig. 1) is comparable in form to the Murchison embayment, but remains ice-filled. Velocity surveys up to 1986 detected no significant ice motion (Kirkbride, 1995), and radar survey places the shelf edge beneath the present glacier (section C–C^1) (Hochstein *et al.*, 1995). Weathering-rind dating of lateral moraines provides a minimum age for formation of the embayment of 2160 ± 562 years BP (Gellatly, 1984). The form indicates overfilling of the main trough by Tasman Glacier, causing a thin ice lobe to extend beyond the former glacier margin.

The glacier terminus is an outwash head, in which nearly all the debris from the glacier has been redistributed to form the proglacial fan at the expense of moraine construction. No moraines lie beyond the AD 1890 terminus, from which retreat has only recently begun (section D–D^1). The new proglacial lake is ponded by the ice-contact slope of the outwash head, and in 1995 reached >130 m depth (Hochstein *et al.*, 1995). Moraines are preserved only in a latero-frontal position, and are dated to post 1490 ± 387 years BP (Gellatly, 1984). The terminus environment is one of aggradation of moraines and outwash around the sluggish glacier tongue, which reached its maximum Neoglacial length *c.* AD 1890, but which has oscillated close to this limit for about 1500–2000 years.

MODEL OF NEOGLACIAL EVOLUTION

Evidence for long-term expansion of Tasman Glacier contrasts with chronologies of uncovered glaciers in the region, whose early Neoglacial moraines (*c.* 4000–4500 years BP) lie up to 3.0 km downvalley of the late-nineteenth century ice margins (Wardle, 1973). Samples of 26 uncovered and seven debris-covered glaciers show that the distance between early Neoglacial and late-nineteenth century moraines is less at debris-covered glaciers with a 0.01 significance level. It is proposed that the presence of the debris cover is primarily responsible for these long-term contrasts in climatic response.

If Tasman Glacier has expanded over millennia, coeval with shrinkage of uncovered glaciers, not only is a debris cover necessary to reduce ablation but the cover must itself have expanded. In periods of positive mass balance, faster ice flow and lower bare-ice ablation (*transport-dominant* conditions) cause the cover to contract towards the terminus. Under negative balance, reduced flow and increased ablation (*ablation-dominant* conditions) favour the upstream spread of the debris cover. If, over multiple balance cycles, the covered area oscillates about an "average" state, the glacier would not expand. Therefore, the increase in debris cover under negative balance must have exceeded its shrinkage under positive balance: there must have been a long-term accumulation of supraglacial debris.

Expansion over millennia implies that ablation under the debris cover was not just reduced below that of uncovered ice, but continued to decrease even though the climate became less favourable for glacier survival at low altitudes (as evinced by the retreats of uncovered glaciers). Declining ablation would be achieved by thickening and extension of the debris cover, in turn reflecting some combination of continued addition to the base of the debris cover by englacial melt-out; by strain thickening under longitudinal compression, and by upglacier growth of the cover as englacial particle paths are re-oriented in the evolving glacier tongue (Kirkbride & Warren, 1999). Over multiple mass balance cycles, debris cover growth would be reversed under transport-dominant conditions, and enhanced during ablation-dominant conditions: but over time the effects of growth would exceed those of shrinkage as the glacier itself became longer, gentler and less sensitive to mass balance perturbations.

The model is illustrated in Fig. 2. Growth of the debris cover is related to oscillating transport- and ablation-dominant conditions (Fig. 2(a)). An initial wedge-shaped form (unit 1) is shortened by faster flow, and bare ice extends further downglacier until flow decelerates. Melt-out of englacial debris (unit 2) replaces older debris-cover material which has been transported downstream (unit 1). A return to transport-dominance accretes unit 2 to the thickening debris wedge near the terminus. The process repeats over multiple cycles (units 3–5 *et seq.*), but over time the supraglacial load near the terminus increases as long as marginal deposition is exceeded by additions to the base and upstream edge of the debris layer. The ablational effect will be to lengthen the glacier tongue and reduce surface gradient, promoting further supraglacial debris accumulation. A parallel interpretation is that, if equilibrium mass balance were maintained throughout, long-term supraglacial debris accumulation would cause glacier volume to increase.

Subglacial bed aggradation might also have contributed to a long-term reduction in glacier gradient and increased length, by elevating the glacier bed and inducing a positive mass balance/altitude feedback. Elevated beds are apparent from the morphology of many moraine-dammed glaciers, and have been revealed elsewhere by geophysical surveys (Lliboutry, 1977). Geophysical surveys have shown that the lower

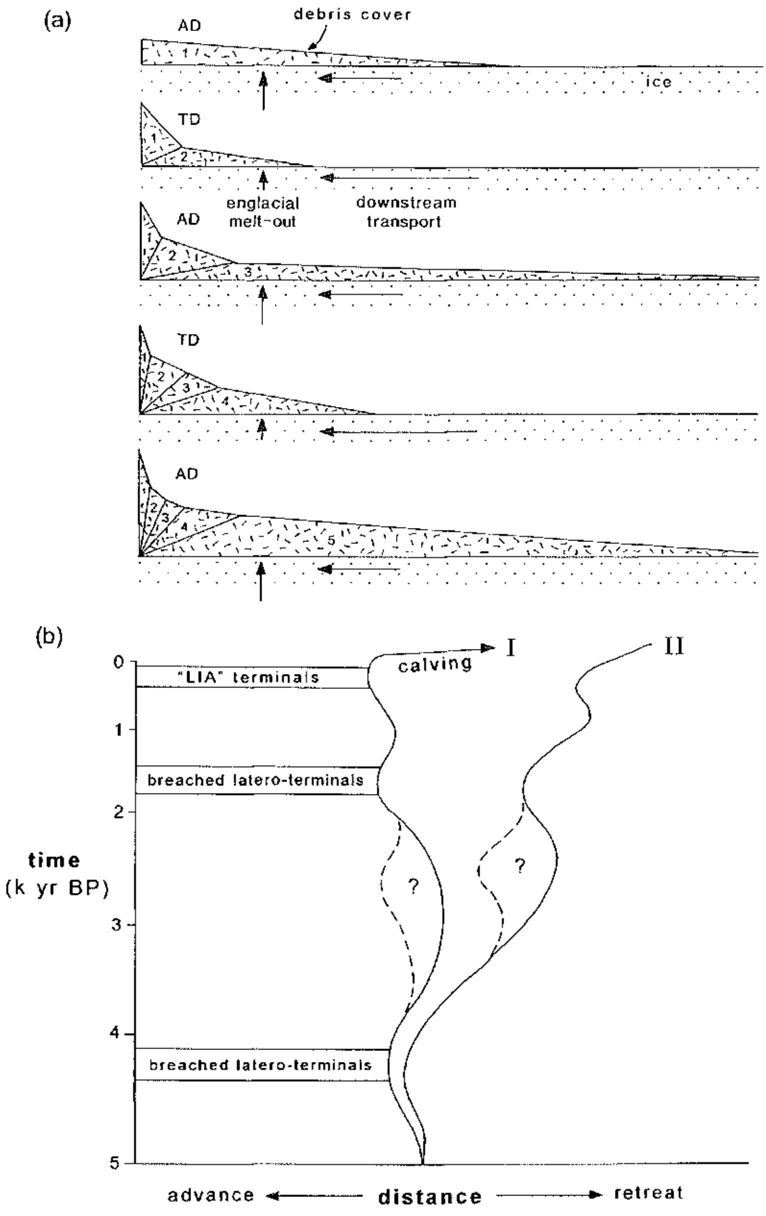

Fig. 2 Schematic evolution of a debris-cover tongue over multiple mass-balance cycles, showing net debris accumulation and glacier expansion.

(a) Incremental accretion to the debris cover under oscillating transport- and ablation-dominance (TD and (AD). Most debris (odd-numbered increments) melts out when mass balance is negative and ablation enhanced, then is accreted to the debris cover by higher ice velocities during positive balance (transport-dominant) phases. The resultant debris cover grows over time, and thickens increasingly towards the terminus. As long as low terminus velocities mean that losses by ice-marginal deposition are exceeded by additions to the debris cover, a lengthening glacier will increasingly favour long-term accumulation.

(b) Comparative distance–time paths for length variations and moraine spacing for debris-covered (line I) and uncovered (II) glaciers. Timing of major advance–retreat phases are tentatively based on published chronologies.

10 km of Tasman Glacier rests on a debris bed of unknown thickness (Broadbent, 1973). For a moraine-dammed glacier to remain constrained by its lateral moraines, the moraine crests must build at least as rapidly as basal aggradation elevates the bed. By implication, long-term thickening of the glacier probably occurs, associated with the supraglacial processes outlined by the model and promoted by the reduced surface gradient of the elevated tongue.

The expansionary model concords with the simplified interpretation of Neoglacial length variations for covered and uncovered glaciers (Fig. 2(b)), whose responses to millennial-scale climate perturbations may follow a similar temporal pattern, but produce the contrasting pattern of moraine spacing.

EVIDENCE FOR EXPANSION OF OTHER DEBRIS-COVERED GLACIERS

It is instructive to examine the margins of debris-covered glaciers in other climatic regions to see whether the expansionary model based on Tasman Glacier has wider applicability. Three types of debris-covered glacier terminus are recognized as evidence of a long-term expansion: (a) outwash heads, exemplified by Tasman Glacier and found in other maritime regions where large glaciers terminate in wide, gentle valleys (e.g. Alaska); (b) elevated, moraine-dammed glaciers exemplified by Hatunraju, Peru (Lliboutry, 1977), and widespread in the Himalaya-Karakoram chain and elsewhere; (c) ice-cored rock glaciers such as Nautardalur, Iceland (Whalley *et al.*, 1995), occurring widely throughout drier alpine areas. The nature of the dynamic differences between types is not fully known, but types will be separated by thresholds related to the competence of outwash to evacuate sediment from the glacier margin (a function of catchment size and climate), and to the ability of the expanding glacier to override its marginal moraines. The first threshold distinguishes the outwash-head type from the other two. The second threshold separates the rock glacier lobe (at which the marginal apron of sediment is being continually overridden) from the moraine-dammed glacier (at which marginal deposition has constructed an obstacle against further expansion). In the latter case, the expansion is accommodated by localized breaching of the moraine dam and formation of overspill lobes. Complex multi-lobed termini can evolve from the basic type. Such lobes are the morphological equivalents in drier areas of the shelf embayments at Tasman Glacier.

The fundamental dynamic of long-term supraglacial debris-cover growth causing glacier expansion appears to be widespread. The main influence on many ice-marginal sediment-landform assemblages appears to have been the dynamics of the individual glaciers rather than climate oscillations in the later Holocene. Individual glaciers express their expansionary tendency as different morphological outcomes, depending on the nature of the linkage between glacial and proglacial sediment transport and moraine construction. Future research should uncover the complex responses of such glaciers within the framework of Holocene climate change.

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