The glaciation of Dartmoor: the southernmost independent Pleistocene icecap in the British Isles

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Abstract

The granite uplands of Dartmoor have traditionally been considered to be relict permafrost and periglacial landscapes that lay beyond the limits of Quaternary glaciations but a variety of landform evidence indicates that a plateau icefield existed on the northern part of the moor, constituting the southernmost independent icecap in the British Isles. Overdeepened or weakly U-shaped valley segments fringing north Dartmoor document an early, extensive phase of glaciation but the most convincing landform evidence relates to more recent, valley-based glacier occupancy. A moraine ridge on the Slipper Stones represents the most unequivocal palaeo-glacier on north Dartmoor with a palaeo-ELA of c.460 m above sea level (asl), although this relates to the youngest and most restricted phase of glaciation. A longer term ELA is likely to be represented by the Corn Ridge proto-cirque at 370-410 m asl. More extensive valley glaciers are recorded in each of the major drainage basins of north Dartmoor by arcuate and linear bouldery ridges and hummocky valley floor drift, which are interpreted as latero-frontal moraines deposited by outlet lobes of a plateau icefield. Recession of these lobes is marked by inset sequences of such ridges and occasional meltwater channels. Plateau ice was predominantly thin and protective, and snowblow and preferential accumulation in valley heads facilitated the modest glacial erosion and debris transport recorded in the landforms and sediments. It is proposed that the highest plateaux have been occupied by ice for the longest cumulative period of time throughout the Quaternary ("average glacial conditions"), explaining the distribution of different tor types on northern Dartmoor. This also explains the lack of tors on the most expansive of the highest plateau terrain (ice dispersal centres) as the product of: a) average glacial conditions preferentially removing tors or dampening their production rates; b) the survival of high relief (Type 1) tors during glaciation if they occupy summits too narrow to develop significant plateau icefields and/or ridges that are bypassed by faster moving ice in adjacent deep valleys; and c) the survival of subdued (Type 2) tors in areas glaciated less regularly during the Quaternary. Simple ice flow modelling indicates that a plateau ice-field type glaciation is required for significant ice flow to occur and confirms thin ice cover, in particular on narrow summits, thereby supporting the explanation of tor class distribution. The modeling allows to spatially correlate the geomorphological evidence of margin positions into two major stages and further indicates a strong altitude mass balance feedback leading to an ice cap that is not in balance with its climate and with an extent that is limited by the length of the cold phases rather than its severity.

Key words: Glaciation; Dartmoor; plateau icefield; average glacial conditions

Introduction and rationale

Although the granite uplands of Dartmoor (Fig. 1) have long been considered to be relict permafrost and periglacial landscapes that lay beyond the limits of Quaternary glaciations (Linton 1949; Te Punga 1956; Waters 1964, 1965; Gerrard 1988), the notion that glaciers had developed in these areas was entertained by some early researchers (Ormerod 1869; Pillar 1917). The evidence presented at that time was largely circumstantial even anecdotal. For example, Ormerod (1869) reported that "he had not seen any glacial markings on the Dartmoor granite, but that Professor Otto Torrell, when visiting the Moor with him last autumn, gave an unqualified opinion that many of the gravels were the remains of moraines" (p. 99). In contrast, Somervail (1897) suggested that the absence of small lakes on Dartmoor was incompatible with former glaciations and wrote: "It is true that various attempts have from time to time been made by various observers to refer certain phenomena occurring on Dartmoor to local glaciation. None of these, however, are, I think, the result of true glacial action, but must be referred to the more common operations of running water. During the cold of the Pleistocene period, and at its close, the floods from melting snows would perfectly accomplish all the distribution and arrangement of that deposit of angular rocky *debris* surrounding Dartmoor so frequently referred to ice. The same cause would also equally well explain these accumulations of scree matter filling some of the valleys, which some have regarded as the remains of ancient glacial moraines" (p. 388). Pillar (1917) later argued that Dartmoor should have been glaciated given its proximity to the Pleistocene ice sheets: "As the meteorological conditions must have been the same in these contiguous areas, it seems somewhat strange that land in such close proximity should be considered as outside the range of Ice influence" (p. 179).

A more systematic and empirical approach was taken by Pickard (1943), who argued for the former existence of extensive glaciers and small ice caps on Dartmoor during the Quaternary based on a large collection of varied features, some more convincing than others. In particular he presents evidence of amphitheatre-like valley heads or incipient cirques, glacially "worn boulders" and grooved rocks, "moutonnée rocks", perched boulders, moraines comprising ridges of blocky debris, and potential glacifluvial gravels. Although this evidence has never been directly refuted, the predominant view since the 1950s has been that the Dartmoor landscape of summit and valley-side tors is the product of periglacial mechanical weathering and slope processes that have exploited zones of rotten granite and exposed large coherent bedrock residuals, which because of their dilatation joints or pseudo-bedding resemble corestone stacks. The efficacy of these cold climate processes, which must have operated over a large proportion of the Quaternary, was enhanced by pre-existing granite breakdown through deep weathering in the tropical climate of the Tertiary (Linton 1955) and/or pneumatolysis during much earlier periods of deep thermal activity (Palmer & Nielson 1962; Eden & Green 1971). Despite the greater substance of the large volume of work undertaken since Pickard's paper, it is not clear how the present consensus regarding the absence of glacial ice on Dartmoor came about. There are several possibilities, the first of which is the assumption largely championed by Linton (1955) that the development of tors required a lengthy period of ice-free conditions. Palmer and Neilson's (1962) view that the Dartmoor tors reflected prolonged periglacial action, rather than the operation of tropical deep chemical weathering processes as Linton had argued, may also have served to further alienate notions of Dartmoor glaciation and consolidate the periglacial paradigm. The second possibility is that Pickard's views may not have been taken seriously. His 1943 paper was his Presidential address for the Devonshire Association and was, presumably, not refereed. Moreover, although it appears he had a strong interest in natural history and geology, he was an opthalmist by training and was likely regarded as an enthusiastic amateur by later geomorphologists.

However, recent research on Exmoor (Fig. 1) by Harrison et al. (1998, 2001) has demonstrated the existence of tills and associated glacial landforms in the vicinity of The Punchbowl, a north-facing valley near the village of Winsford. The tills have been deposited at altitudes down to 255 m asl probably by a glacier snout that flowed into The Punchbowl from a small ice cap located on the summit plateau of Winsford Hill (426m asl). The presence of glacial ice at relatively low altitudes on Exmoor enabled Harrison (2001) to speculate on the likelihood that Dartmoor had been similarly glaciated at times during the Pleistocene. The Exmoor glaciation evidence is entirely predictable considering that areas of high terrain, such as those located in SW England, are likely to have been cold enough to host small ice caps and glacierets during full glacial periods when British-Irish Ice Sheet limits extended as far south as the Isles of Scilly (Scourse 1991; Scourse et al. 1991; Scourse & Furze 2001; Hiemstra et al. 2006; Fig. 1). Indeed, numerical modeling exercises invariably create ice masses over the SW English uplands during the Last Glacial Maximum (LGM) (Hubbard et al. 2009) merely because the environmental boundary conditions for the model will develop glacier ice where the local equilibrium line intersects the topography. Moreover, the plateau style of topography on Exmoor and Dartmoor is conducive to the accumulation of snow on the broad summits in addition to its build up in the deeper valley heads due to snowblow (cf. Manley 1959; Sissons & Sutherland 1976; Sissons 1979; Sutherland 1984; Mitchell 1996; Rea & Evans 2003, 2007; Coleman et al. 2009). Therefore the style of glaciation will be similar to the plateau icefield glacial landsystem, wherein predominantly thin, largely cold-based and protective ice on upland surfaces would drain into valley heads radiating from the plateaux to form locally thick, warm-based snouts capable of eroding the substrate (Rea et al. 1998; Rea & Evans 2003, 2007). Such erosion would have been responsible for the production of The Punchbowl on Exmoor and potentially the overdeepened valley segments around the high summits of northern Dartmoor, identified by Pickard (1943) as evidence for glacial modification.

The evidence for former glacier ice in marginally glacierized terrains, such as those represented by Exmoor and Dartmoor, is likely to be subtle for a number of reasons. First, the predominantly thin ice located on low-angled slopes would only generate low shear stresses and low flow rates, so the creation of well developed bedrock erosional forms is unlikely. Additionally, the coarse crystalline nature of the Dartmoor granite is not suitable for the preservation of striae and other small scale glacial erosional features. Second, the absence of high bedrock cliffs above the accumulation zones of plateau icefields precludes the provision of extraglacial rock debris, which together with the resistant nature of the granite substrate would have resulted in small glacial debris loads and hence weakly developed moraines and tills. Glaciers would have instead only been able to incorporate periglacial slope deposits, which after at least several hundred thousands of years of weathering and gelifluction will have reached significant thicknesses in valley bottoms (Waters 1964). Moreover, such deposits would have developed into large rock-fronted lobes and possibly rock glaciers in some valley heads in the absence of, or between, glaciations, similar to the stone runs of the Falkland Islands (Joyce 1950; Clapperton 1975; Hansom et al. 2008; Wilson et al. 2008). Harrison et al. (1996) have suggested such an origin for some boulder lobes on Dartmoor. These rock fronted, lobate forms, once their ice content was removed, would resemble thin till sheets and moraines in some settings. Finally, glacier ice that is frozen to its bed effectively protects even delicate periglacial landforms and sediments which therefore can survive one or more glaciations (cf. Clapperton 1970; Whalley et al. 1981; Dyke 1993; Kleman 1994; Kleman & Borgström 1994; Rea et al. 1996a, b). On Dartmoor, the tors and clitter fields were initially regarded by Linton (1949, 1955) as features that could not survive glaciation but he later modified this view by arguing that they could be protected by thin and slow moving ice. This principle of limited glacial erosion has since been used to explain the preservation of tors in the Cairngorms (Sugden 1968; Hall & Phillips 2006; Phillips et al. 2006) and the presence of preglacially weathered *in situ* bedrock and weathering pits in glaciated east and northeast Scotland (Hall & Sugden 1987; Hall & Mellor 1988; Hall and Glasser 2003).

Although Dartmoor has been long established as an exemplar of a mature periglacial landscape, no systematic assessment of potential glacial landform evidence has ever been undertaken, likely due to the overwhelmingly strong periglacial sediment and landform signature. Given the recent advances in our understanding of plateau icefield landsystems and the preservation of tors and associated deposits beneath cold based ice, the systematic survey and mapping of the Dartmoor landscape for potential glacial evidence is warranted. We now show evidence that northern Dartmoor (Fig. 1) was glaciated and discuss the evidence for glaciations in the context of alternative views of landscape inheritance. As the resolution of these issues is critical to the reconstruction of regional glaciation levels and palaeo-equilibrium line altitudes in marginal glacierized terrains and hence the refinement of boundary conditions for numerical ice sheet models, the central aim of this paper is to assess the nature of the Dartmoor landscape in the light of current understandings of plateau ice landsystems.

Methods

Mapping of geomorphological features interpreted as relating to former glaciation was undertaken on stereoscopically viewed aerial photographs taken at a variety of dates since 1945. This information was then transferred on to 1:25,000 scale Ordnance Survey maps. Field checking was performed simultaneously with the mapping process, allowing scrutiny of surface materials at those sites with depositional landforms. A composite glacial geomorphological map covering the whole of north Dartmoor was then compiled and used to produce an outline of glacier snout maximum limits. Tors were also added to the maps and classified according to whether they were high relief/castellated (Type 1) or low relief/subdued (Type 2), and prominent plateau summits with no tors classified as Type 0, in order to determine whether there was any relationship between tor prominence and proposed glacier ice thickness.

Although natural exposures through landforms are rare and restricted in size, we provide some descriptions of sediment characteristics and clast forms in the vicinity of potential moraines on valley bottoms. Very few examples were recovered from any single site due to the bouldery nature of the drift and the rough nature of the surfaces of the granite clasts and so normal quantification procedures for clast form could not be undertaken. We do, however, use the Powers roundness classification scheme (see Benn 2004) to assess the modification of those clasts recovered in the field.

In order to assess the viability and dynamics of glacier ice cover on Dartmoor, a standard time-dependent 2-dimensional ice-flow model is applied. The model also allows an independent assessment of the genesis of the proposed moraines and associated glacigenic landforms. In the model, the flow is calculated from local surface slope and ice thickness using the shallow ice approximation (SIA). Surface evolution is calculated from the principle of mass conservation and is externally forced by a standard altitude-dependent surface mass balance function that is linearly related to surface elevation and equilibrium line altitude *(ELA;* the altitude at which ablation equals accumulation). For the accumulation area the mass balance gradient is reduced by a factor of 0.6 (corresponding to a balance ratio of 1.6). To account for variations in aspect, the surface mass balance is corrected by a term that is proportional to the annual potential solar radiation calculated from surface topography (Kumar et al., 1997) and results in an ELA difference of about 120m between steep north and south facing slopes. Note that the assumed mass balance model intrinsically assumes a plateau ice-field glaciation (accumulation everywhere above ELA) and does not account for wind erosion.

In this study we perform experiments with the ELA remaining constant over time, but it is important to note that the surface mass balance accounts for elevation change of the glacier surface and thereby includes the important mass-balance altitude feedback. For the standard experiment, a conservative ELA estimate of 550m has been used and based on mid-latitude modern analogues (Ohmura et al 1992). We assumed a mass balance gradient of 0.006 y^{-1} in the ablation area and 0.0037 y^{-1} for the accumulation area (balance ratio of 1.6). A uniform ice rheology corresponding to temperate ice has been assumed with an additional flow enhancement factor of 5. Additional experiments with other mass balance parameters (ELA, mass balance gradients) and colder ice rheologies have been undertaken and confirm the robustness of the main findings from the modelling, although timescales of ice cap buildup are slightly different.

Study area

Dartmoor forms part of the Cornubian Batholith which underlies large parts of south-west England. The batholith forms a granitic intrusion related to a Variscan or Hercynian tectonic activity (Campbell *et al.*, 1998). The granite is a coarse-grained megacrystic biotite and the uplands are created by the unroofing of the granite batholith. This rises steeply and abruptly from around 300 m asl on the fluvially incised terrain of the surrounding metamorphic aureole to plateaux with summits above 500 m asl (Fig. 1c). The highest terrain occurs in the northern part of the moor, specifically on the Yes Tor/High Willhays plateau (619m asl) and on the elongate eastern upland spine comprising Cut Hill (603 m asl) and Hangingstone Hill (603 m asl). These uplands are dissected by deep valleys that host the upper reaches of the West Okement River and River Taw in the north, the North Teign River and East Dart River in the east, and the

River Tavy in the west (Fig. 1). The rectilinear pattern of the tributary valleys in these upper catchments reflects the exploitation of major joints in the granite (cf. Gerrard 1974, 1978; Ehlen 1992).

Evidence for glaciation on northern Dartmoor

The evidence for the glaciation of Dartmoor includes landforms relating to both glacial erosion and deposition. Glacial erosional features include incipient or grade 4/5 cirque basins (cf. Evans & Cox 1995). Such features have previously been classified as periglacial altiplanation terraces or "nivation hollows" on Dartmoor (e.g. Te Punga 1956) but are also indicative of the early stages of erosion by glaciers where wind-blown snow prefentially accumulates in pre-existing bedrock hollows or scarp slopes, especially on north or northeast facing hillsides in the northern hemisphere (Evans 1977). Larger erosional features include overdeepened valleys displaying the early development stages of U-shaped profiles (Fig. 2). Although such overdeepening could be the product of fluvial incision and concomitant rock slope failure related to the uplift and antecedent/structurally controlled drainage development on and around the granite batholith (cf. Brunsden 1963, 2007), a tendency towards U-shaped cross profiles is a distinctly glacial signature (cf. Hirano & Aniya 1988; Harbor 1992; Li et al. 2001).

Moraines are often visible as subdued ridges aligned diagonally to slope contours and occasionally crossing valley bottoms, forming the latero-frontal moraines of valley glaciers. In a few locations, hummocky terrain lies on the valley floor, where in the absence of any unequivocal rock slope failures, it is interpreted as the product of supraglacial debris mound accumulation. More common are low amplitude, bouldery drift sheets with lobate fronts, extending from the shallow slopes of the plateau summit edges into the upper reaches of surrounding valleys and often forming a boulder-strewn valley bottom. In many places these drift sheets appear to drape the cliffs of overdeepened valleys in their upper reaches, giving the cliffs a subdued appearance before they merge into the plateau summits. In some locations the drift sheets continue into moraine ridges. Given the long timescale of periglacial landscape change on Dartmoor, an alternative interpretation of some thin drift sheets and possibly some of the more subdued "moraine" ridges, is that they represent large gelifluction sheets, in places being rock-fronted or even rock glacierized, thereby explaining the lobate fronts and modest relief (Ballantyne & Harris 1994; Harrison et al. 1996).

Some valley bottom assemblages of subdued hummocks, boulders and thin drift are associated with evidence of intensive localized human mining by "tinners", who were searching for tin ore as early as the 14th and 15th centuries. The concentration of this activity in valley bottoms reveals that the tinners were using placer mining techniques, locally called "streaming", based on the principle that streams had naturally partially processed the ore or cassiterite once it had been removed from the lodes by weathering. Where streaming has taken place in and around drift hummocks and ridges, the resulting anthropogenic forms can be clearly differentiated from natural landforms because they constitute small scale, closely-spaced parallel ridges or rib-like spoil heaps (Gerrard 1996; Newman 1998).

Deep incisions or dry valleys occur on a number of valley walls and interfluves where they have no relationship with the fluvial drainage pattern. These features are the typical products of glacial meltwater incision, often marking the margins of a receding cold based ice masses or even temperate glaciers in intermediate to high relief settings (Dyke 1993; Greenwood et al. 2007; Syverson & Mickelson 2009; Livingstone et al. 2010) and usually constituting the only evidence of former glaciations characterized by cold based plateau icefields. An alternative interpretation of such features in some locations on Dartmoor is that they mark the locations of major joints in the granite, along which pneumatolysis has resulted in intensive rotting of the bedrock followed by its preferential removal over long periods of nival melt in a periglacial environment.

A subtle feature indicative of glacial activity is the appearance on aerial photographs of streamlining in the form of highly elongate drumlins. This lineation pattern is not aligned slope parallel, and therefore an alternative genetic interpretation that they represent well developed pattern ground or stripes is less valid, especially where they occur in association with other likely glacial features.

The tors of north Dartmoor have been loosely classified according to their morphology and we differentiate tor types in this way by using a three-fold classification scheme. Type 1 or high relief/castellated tors are typified by Yes Tor, Watern Tor and Great Mis Tor and comprise numerous corestone stacks often characterized by precariously balanced or cantilevered blocks and separated by deep "joint avenues" (Fig. 3a). Type 2 or low relief/subdued tors are typified by Quintin's Man and Sittaford Tor and appear as low relief stumps (Fig. 3b). Extensive summit areas that lack tors altogether are classified as Type 0. The use of tors to determine former glacierization of a granite landscape has been successfully employed alongside other glacial landforms and sediments on the Isles of Scilly, where castellated tors lay beyond the LGM ice sheet margin and more subdued tors document the incursion of ice on the north coast of the island of St Martins (Scourse et al. 1991; Scourse & Furze 2001; Hiemstra et al. 2006), as verified by cosmogenic nuclide dating by McCarroll et al. (2010). However, the preservation of relatively delicate tor forms beneath cold based or less vigorously flowing ice has been reported elsewhere and so patterns of tor distribution must be interpreted with caution (e.g. Kleman 1994; Kleman & Borgstrom 1994; Rea et al. 1996a, b; Fabel et al. 2002; Stroeven et al. 2002). Nonetheless, the subtle glacial modification of tors previously regarded as untouched by cold based glacier ice has been identified more recently in the Cairngorms by Hall and Phillips (2006) and Phillips et al. (2006), demonstrating that prolonged glacier occupancy of higher summits could gradually remove tors.

Sedimentary evidence for former glaciations is present at a number of locations and reveals lithofacies associations that are consistent with glacier-marginal deposition and clasts with very crude striae/gouges and convincing faceting and stoss-and-lee or bullet-shaped forms (Sharp 1982; Krüger 1984; Benn & Evans 1996, 2010). Even though the coarse crystalline lithology does not lend itself to the strong development of glacially abraded forms, it appears that the subglacial transport distances along the valleys draining the plateaux were sufficient for the recognizable modification of clasts.

The nature of the evidence for glaciation is now described in detail under sub-headings for each critical location, for which annotated aerial photograph extracts are presented to illustrate the best landform examples. All the evidence is compiled on a geomorphological map (Fig. 4). These data are then compiled as part of the discussion in order to reconstruct the configuration of likely glacier ice cover on northern Dartmoor. Because no datable material has yet been uncovered in the field area, the age of this glaciation is unknown, but we show that the sum of the glacial evidence represents several glaciations.

i) West Okement River valley and Yes Tor

The West Okement River valley is the most deeply incised of the valleys on north Dartmoor, with steep bedrock cliffs rising abruptly from 400 m on the narrow valley floor to 530 m asl on the NE margin of the Great Links Tor/Corn Ridge/Amicombe Hill plateau and to 618 m asl on High Willhays to the east (Figs. 1 & 5). This constitutes a narrow U-shaped cross profile over a distance of <2.5 km, but the only valley bottom ridge of possible morainic origin lies in the upper catchment, on the lower slopes of Amicombe Hill, near Kneeset Foot, at an altitude of 450 m asl (Fig. 4). Down valley of this ridge, on the lower eastern slopes of Amicombe Hill, some small bedrock exposures resemble roches moutonnées (Fig. 6), documenting the passage of glacier ice down the upper West Okement valley.

The cliffs below Corn Ridge form an elongate amphitheatre-like hollow, the base of which is marked by linear and lobate boulder ridges starting at the break of slope at 460 m asl and continuing to the valley bottom and locally named the Slipper Stones (Figs. 1c & 5). The innermost and largest of these ridges runs parallel to the scoured bedrock free face, thereby resembling a protalus rampart (Fig. 7a). However, it lies >100 m from the base of the free face, indicating that the former snow/ice body that occupied the amphitheatre-like hollow was large enough to constitute a small glacier based upon the glaciological constraints identified by Ballantyne and Benn (1994). In addition, the backwall of the hollow comprises smoothed granite slabs, some of which show roche moutonee forms (Fig. 7b). Moreover, the lobate boulder ridges that blanket the lower slopes strongly resemble rock glacierized drift and therefore demarcate the morainic debris of an earlier, more extensive phase of glacier occupation. Although the morphology of the bedrock hollow does not qualify it even as a grade 5 cirque based on the criteria of Evans and Cox (1995), it is nonetheless comparable to the niches occupied by Younger Dryas age glacierets in the Brecon Beacons (Shakesby & Matthews 1993; Carr 2001) and elsewhere in Wales (e.g. Hughes 2009). A further, shallower but also more enclosed amphitheatre-like hollow occurs on the north facing edge of Corn Ridge (Fig. 5). The backwall ranges from 430-460 m asl, subdued hummocks occur on the gently inclined hollow floor at 370-410 m asl, and flat-topped benches drape the lower slopes. A consolidated clast-rich diamicton with sub-rounded to sub-angular forms occurs in stream sections cut through the subdued hummocks. The form of this hollow qualifies it as marginal grade 4 to 5 cirque (Evans & Cox 1995) and its aspect is conducive to cirque development.

The dome of Yes Tor/High Willhays lacks the plateau-like summit form of the other high altitude ridges of north Dartmoor and is capped by type 1 tors (Fig. 4). Its upper and mid slopes are blanketed by rock fronted, lobate gelifluction sheets (Fig. 8) but two of the northward draining valleys (below Homerton Hill and the west tributary of Red-a-ven Brook) contain lobate-fronted, hummocky drift plugs at lower altitudes of 390-400 m OD (Figs. 4, 5 & 9). An exposure through the west Red-a-ven Brook deposits reveals a boulder-rich, gravelly diamicton with a highly fissile structure in its matrix-rich zones and containing numerous weakly facetted cobbles with sub-rounded forms (Fig. 9).

ii) East Okement River and River Taw catchments

The upper East Okement and River Taw valleys drain the northern slopes of Hangingstone Hill (Fig. 1c) and contain evidence for the longest and lowest altitude outlet glacier lobes. The waters of East Okement Head arise in two large bedrock gorges partially cut through the NE trending interfluve of Okement Hill (Fig. 4), indicating a glacial meltwater origin. Low amplitude ridges on the lower slopes of East Mill Tor we argue to be left lateral moraine segments, which appear to be aligned with an arcuate ridge on the valley floor immediately to the north to form a latero-frontal moraine arc. We interpret linear debris stripes striking diagonally downslope and down valley on the slopes below Oke Tor as right lateral moraines of the same glacier lobe but indicative of thicker ice. These stripes disappear at around 400 m asl, the same altitude as subdued hummocks in lower Black-a-ven Brook (Fig. 4). A relict bedrock channel skirts the interfluve between the East Okement Valley and Black-a-ven Brook, descending from 425 m to 400 m asl and terminating in the subdued hummocks. Together with the linear stripes, the channel and the hummocks appear to delineate the outer limit of a glacier that occupied the upper East Okement and spilled into lower Black-a-ven Brook. The only evidence of ice in middle and upper Black-a-ven Brook is a faint linear accumulation of boulders trending diagonally down the SW slopes of East Mill Tor and representing a right lateral moraine of ice flowing from the ridge connecting Okement Hill and the broad SE shoulder of High Willhays (Fig. 4).

Evidence for a glacier lobe in the upper Taw River catchment is restricted to Taw Marsh, a sediment-filled broadening of the main valley between the steep slopes of Belstone Common and Cosdon Hill (Fig. 1c). The left lateral margin of the glacier snout is marked by low amplitude hummocks, the uppermost limits of which descend from 390-360 m asl, whereas the right lateral margin is demarcated by a single thin ridge and associated relict channel descending from 390-380 m asl on the west slopes of Cosdon Hill and terminating in an area of subdued hummocky drift on the east bank of the River Taw below Belstone Common (Figs. 4 & 10). The upper limits of low amplitude hummocks at 450 m asl on the slopes of Metheral Hill and Little Hound Tor demarcate the continuation of the ice margins to the south. Pickard (1943) regarded the silty fill of Taw Marsh to be the deposits of a former lake dammed by a barrier of bouldery drift across the narrowest part of the valley below Belstone Common. An extensive and wide drift bench at 360-365 m asl skirts most of the Taw Marsh depression (Fig. 10) and represents the upper level of the silty fill. Both sets of lateral drift hummocks and ridges converge on the valley narrowing below Belstone Common, indicative of a latero-frontal moraine arc that could have produced a moraine-dammed lake. The right lateral deposits were clearly documented and photographed by Pickard (1943), but he used an earlier spelling of Cawsand for Cosdon Hill.

iii) North Teign River catchment

A variety of landform assemblages in the North Teign catchment document the southward and eastward flow of ice from the Hangingstone Hill elongate plateau. The most convincing suite of glacial landforms occur below the bedrock interfluve called Quintin's Man in lower Great Varracombe (Figs. 4 & 11). The east facing slopes of this interfluve are deeply incised by five steep, relict bedrock channels, the northernmost of which grades downslope into a slightly sinuous, narrow bouldery ridge that trends obliquely across the valley side contours and down valley to an altitude of 485 m asl. The only possible explanation of these landforms is that they represent subglacial meltwater channels and an esker produced at the suture zone of two ice flow units that flowed from west to east across Quintin's Man;

the southernmost flow unit was nourished by ice emanating from the head of the East Dart River and Teign Head and the summits of Black Hill and west Hangingstone Hill, whereas the north flow unit emanated from south Hangingstone Hill and upper Great Varracombe, with the two flow units being forced to flow first north to south and then west to east and finally SW to NE along the upper North Teign River valley (Figs. 1c & 4). The production of meltwater landforms along the suture or confluence zone of two separate ice flow units in a single ice cap is facilitated by the concentration of supraglacial drainage towards the lower ice surface topography created by the suture, especially during the early stages of deglaciation before meltwater pathways become directed more by the underlying topography (Huddart et al. 1999; Evans & Twigg 2002; Benn et al. 2009; Gulley et al. 2009). An alternative, but in our view less likely, explanation for the channels is that they mark the locations of mineral veins and/or pnuematolitically altered bedrock that have been preferentially removed by long periods of periglacial weathering and mass wasting, although this does not explain the sinuous drift ridge.

In addition to these glacifluvial features, the occurrence of arcuate bands of low amplitude drift hummocks on the floors of lower Great Varracombe and Manga Brook at altitudes of 460 m and 480 m asl respectively (Fig. 4) likely demarcate the margins of topographically restricted ice lobes either during recession from the earlier phase of more extensive ice in the North Teign River valley or a later less extensive glaciation. A number of large clasts recovered from a stream cut in Great Varracombe displayed clear facetting and stoss-and-lee or bullet shapes, as well as weakly developed gouges or large striae (Fig. 12), confirming former glacier ice in the valley.

The furthest extent of ice in the North Teign catchment is demarcated by a narrow, arcuate band of low amplitude hummocks in the steep bedrock reach of the main river below the summit of Manga Hill (Fig. 4). Landforms of a likely glacial origin occur in the tributaries to the north of Manga Hill, including arcuate, low amplitude hummocky drift belts and meltwater channels on Hew Down, upper Walla Brook (Fig. 13) and Gallaven Mire, the latter two sites being associated also with extensive flat, marshy areas that represent a localized flattening of the stream long profiles typical of areas of moraine construction. Each of these sites indicate potential ice advance to altitudes of 410-440 m asl. Type 1 tors occupy the summits located between these valley bottom drift assemblages, indicating that the area was characterized by largely topographically confined ice with the high terrain escaping ice coverage or hosting only thin, cold based ice.

iv) East Dart River catchment

Bouldery hummocks suggest that substantial glacier lobes occupied the area of Broad Marsh, on the upper East Dart River, the mouth of Winney's Down Brook and the floor of the valley immediately to the east, below Sittaford Tor (Figs. 4 & 14). These features are arranged in broad arcs on the valley floor which are linked to linear ridges that ascend the surrounding valley walls in a form that closely resembles latero-frontal moraine loops. A well-developed terminal moraine complex underlain by boulder diamict lies to the south of these features (Fig. 14b). The eastern linear ridge continues into an arcuate ridge lying across the col separating Sittaford Tor and White Ridge. The most convincing suite of landforms occurs in the Sittaford Tor valley and lies downslope of a cluster of elongate and tightly spaced linear features located directly south of the tor summit, which is occupied by a type 2 tor (Fig.

14). The linear features strongly resemble small elongate drumlins and if they are subglacial, the ice that created them radiated out from the Sittaford Tor/Winney's Down plateau and was then forced to flow southwards down to 400 m asl by ice occupying the upper North Teign catchment.

Small sections in the Sittaford Tor terminal moraine (Fig. 14c) reveal a range of deposits associated with the construction of the ridge in its valley bottom location. At the down valley end of the landform an exposure 2 m above the stream bed revealed 2 m of gently inclined stratified sand and gravel with several conformable layers or lenses of silty fine sand, overlain unconformably by a thin unconsolidated stratified diamict. The stratified layers are generally inclined towards the down valley margin of the landform at dips that range between 10-15^{o}. At the up valley end of the landform, an exposure near the stream bed revealed highly weathered growan overlain by a thin, homogeneous and massive diamicton, which is in turn overlain by 0.5m of planar stratified sand and gravel. This sequence is unconformably capped by a loose to moderately compact, sandy, clast-supported diamicton, containing sub-rounded clasts and displaying crudely developed up-valley dipping fissility. The same diamicton crops out near the summit of the moraine ridge around 7 m above the stream bed. The sediment exposures support the interpretation of the landform as a terminal moraine, because they resemble the typical lithofacies associations reported from upland moraine ridges elsewhere in Britain and on the forelands of modern glaciers (cf. Boulton & Eyles 1979; Benn 1992; Johnson & Gillam 1995; Lukas 2005, in press). Specifically, subglacial till (fissile diamicton) has been emplaced over a glacifluvial and debris-flow fed ice-contact fan that formed on the distal side of the moraine ridge during glacier snout advance.

The substantial lobate deposit at Broad Marsh, which has been significantly modified by tin mining on the valley floor, documents the incursion of ice radiating out from the high elongate plateau of Cut Hill and flowing down to 490 m asl. A drift line trending across Teign Head to the north, records a later stage of ice recession when Cut Hill plateau ice had separated from Hangingstone Hill/Black Hill ice (Figs. 1c & 4).

v) West Dart River and River Walkham catchments

A prominent linear ridge ascending the east slope of Rough Tor resembles a lateral moraine, and was likely produced by ice descending from the Cut Hill plateau into the upper reaches of the West Dart River (Figs. 4 & 15). This ridge continues across the valley bottom at 465 m asl, affecting a significant diversion of the river, and appears to connect with a faint drift limit on the NW slopes of Lower White Tor and finally into faint arcuate ridges on the floor of an expansive marshy area around Brown's House. If this area was occupied by glacier ice expanding from the confines of the upper West Dart River valley, proglacial drainage would have been diverted down Hollowcombe Bottom, thereby explaining its unusually incised cross profile (Fig. 15).

Immediately to the west, further arcuate drift ridges occupy the upper reaches of the unnamed tributary below the SW slopes of Rough Tor at 470 m asl and the Cowsic River at 500 m asl (Fig. 4). These features strongly resemble latero-frontal moraines deposited by ice descending from the Cut Hill plateau. Similar ridges and associated meltwater channels appear to be present down to 470 m asl in the upper Walkham River valley, demarcating the limit of outlet lobes that descended from the horseshoe-shaped uplands surrounding the valley and connected to the south Cut Hill plateau. The eastern arm of this horseshoe extends southwards to Black Dunghill from which ice appears to have descended into surrounding valley heads to produce arcuate latero-frontal ridges; the most prominent of these lies at 440 m asl in the col separating the River Walkham valley and the upper reach of the Blackbrook River (Figs. 1c & 4). On the east side of Black Dunghill, less extensive lobes are marked by a small lateral moraine fragment at 460 m asl in the upper reach of Conies Down Water and an equivocal bouldery drift limit at 440 m asl in Holming Beam Bottom, the latter being a possible gelifluction sheet. The western arm of the horsehoe-shaped upland, Cocks Hill and Lynch Tor (Type 2), drains into the River Tavy catchment and the only evidence of glacier ice descending from this area westwards comprises small arcuate, inset drift ridges down to 430 m and possibly 420 m asl (Fig. 4).

vi) River Tavy catchment

The River Tavy catchment is the largest on northern Dartmoor and drains the extensive western slopes of the plateaux of Cut Hill and Black Hill and the south slopes of Great Kneeset in addition to the ridges that extend westward from these plateaux. This upland has the potential for accumulating large volumes of snow and ice from the prevailing westerlies and once plateau icefields are established, outlet lobes would descend into the extensive lowlands of the upper River Tavy catchment (Amicombe Brook) from all directions (Fig. 1c).

Small, low relief arcuate ridges documenting plateau ice advance into the upper reaches of small tributaries are apparent on the north and south margins of Standon Down (Fig. 4). Similar ridges occupy the lower slopes of Hare Tor at Tavy Cleave and in Dead Lake valley, although in each of these cases, with the exception of Dead Lake, the development of lobate boulder gelifluction sheets cannot be ruled out as a possible genetic origin. More convincing are the linear and arcuate ridges on the floor of upper Combe Water between 470 and 510 m asl, which resemble latero-frontal moraines deposited by ice descending from Cut Hill and flowing around the Fur Tor promontory (Figs. 4 & 16); similar arcuate ridges produced by the same receding plateau ice occur between 550 and 560 m asl at Tavy Head. Arcuate drift ridges and possible valley-side meltwater channels appear in the upper Rattle Brook. Although localized disruption of the landscape by tinners is evident in this area and therefore some landforms have an ambiguous origin, evidence elsewhere indicates that glacier ice probably descended from the surrounding summits of Amicombe Hill, Hare Tor, Rattlebrook Hill and Great Links Tor (Fig. 4; see also sections *i* and *vii*).

Further arcuate, low relief drift margins exist in the confluence area of upper Amicombe Brook and Black Ridge Brook, indicating that ice lobes descended from Black Hill/Black Ridge in the east and northeast and from Amicombe Hill to the west (Fig. 4). These drift margins lie above the floor of upper Amicombe Brook, which is characterized by an array of complex low relief hummocks and ridges on an expansive marshy floodplain. The clear trimline at 450m asl extends around the floodplain, giving the impression that a lake formerly occupied the site (Figs. 4 & 17). This could only be possible if the drainage of middle Amicombe Brook was dammed, a distinct possibility if glacier lobes had descended from surrounding plateaux to block the westward drainage. Evidence for this ice is sparse, but includes a large drift bluff at the mouth of Western Red Lake and a similar smaller bluff at the mouth of Eastern Red Lake, associated with valley-side meltwater channels in the Eastern Red Lake and lower Fur Tor Brook valleys (Figs. 4 & 18). The origin of the expansive drift-covered bench of Pinswell is unknown, although a conspicuous, narrow ridge running along its summit and appearing as a grey, slightly sinuous line on the aerial photographs can be explained only as a glacial depositional feature, presumably a moraine. Additionally, the existence of a substantial stream and wide channel on the eastern side of Pinswell and running almost parallel with the lower western slopes of Fur Tor is strongly suggestive of ice-marginal meltwater origins. Finally, a 500 m long dry channel running diagonally downslope from 460 to 400 m asl on the northern edge of the Standon Down plateau, directly west of Western Red Lake, strongly resembles a lateral glacial meltwater channel, indicative of a glacier lobe occupying middle Amicombe Brook (Fig. 18). It is thought likely that each of these pieces of evidence collectively records the former occurrence of glacier ice in the Amicombe Brook valley, sourced by ice occupying the extensive elongate plateau surface to the south and east. Recession back onto this surface is recorded by inset arcuate drift ridges (latero-frontal moraines) such as those at Tavy Head and Tavy Hole (Figs. 4 & 19) and upper Cut Combe Water (Fig. 16). The smaller plateaux ridges to the north nourished less extensive glacier lobes that are demarcated by the arcuate drift limits in the Rattle Brook and Little Kneeset/upper Amicombe Brook area (Fig. 4), leaving part of the valley bottom in the latter location to be flooded by ice-dammed lake waters.

vii) Great Links Tor and Walla Brook

The western slopes below the summits of Great Links Tor and Woodcock Hill contain a low amplitude, lobate fronted, bouldery drift sheet that extends into the upper reach of a small tributary of the River Lyd down to 470 m asl (Fig. 4). Although this could represent a very large gelifluction sheet, other evidence for ice on the Great Links Tor upland is manifest in the upper Doctor Brook drainage to the south. Here some extensive and deep incision has taken place in a thick valley fill, documenting significant discharges from the high southern slopes of Great Links Tor (Type 1), around the area of Dick's Well. These discharges have also created an extensively gullied terrain in a cut bank on the lower western slopes of Rattlebrook Hill, which also appear to have contributed water to this system (Fig. 4). Low amplitude ridges and hummocks in the area between Sharp Tor (Type 2) and Doe Tor (Type 1) appear to link to faint linear and arcuate drift limits in the lower Doctor Brook valley and at Wallabrook Head (Fig. 20), representing possible glacier lobes on either side of the Doe Tor upland that reached 380 m asl. Significant incision of a thick valley fill occurs also in Walla Brook, emanating from the outer limit of hummocks at Wallabrook Head. Although tinning activities are apparent in the upper Doctor Brook and Walla Brook catchment, this is distinct and clearly of far less intensity compared to the valley fill and bedrock incisions that document high discharges from the Great Links Tor/Rattlebrook Hill plateau. In combination with the drift limits and hummocks in the lower catchment and the lobate fronted drift sheet north of Great Links Tor, this fluvial incision is regarded as evidence for glacier occupancy and recession on the uplands. The occurrence of Type 1 and Type 2 tors also indicate that the Great Links Tor and Doe Tor uplands escaped glacier overriding whereas Rattlebrook Hill and its subdued Sharp Tor and Chat Tor did not. Based upon these observations and previously presented evidence for ice dispersal from Amicombe Hill, it is considered most likely that the large plateau of Woodcock Hill hosted an icefield, although no unequivocal evidence for ice advance from this upland exists in the Lyd Head valley.

ix) Tor distributions

Although the distributions of tor types have been presented above at a local scale as they pertain to associated glacial evidence, it is important to assess the wider scale pattern of Type 1 and 2 tors (Fig. 4) in order to assess potential indications of glacier erosional intensity. The more delicate, castellated Type 1 tors are indicative of good preservation of landforms that have evolved over prolonged periods of periglacial weathering and mass wasting and therefore reflect locations that have either escaped glaciation or were covered by thin, cold based ice; typically summits that were too narrow to accumulate large plateau icefields or located too far from ice dispersal centres and therefore lying above outlet glacier lobes in surrounding valleys. Type 1 tors do not occur on the wider upland (plateau) surfaces of Hangingstone Hill/Cut Hill and Woodcock Hill/Amicombe Hill but are common on the narrow uplands of Yes Tor/High Willhays and the lower elevation surfaces or ridges surrounding the highest terrain. The latter often stand above glacial features concentrated in adjacent valleys, for example at Fur Tor and Oke Tor.

Type 2 tors predominantly occur on subsidiary summits around the outer margins of high plateaux. This is best illustrated by the Hangingstone Hill/Cut Hill plateau, where Type 2 tors form a largely concentric ring around a central higher terrain characterized by no tors. They also occur on smaller plateau summits such as Woodcock Hill/Amicombe Hill.

Also important in this respect is the occurrence of plateau surfaces with no tors, classified as “Type 0”, where tors have either never formed or have been removed by repeated glaciations during the Quaternary. The tor distribution pattern (Fig. 4) reveals a concentration of Type 0 summit classifications on the most expansive of the highest plateau terrain of the elongate Hangingstone Hill/Cut Hill upland, a prime area for ice inception and dispersal. Another cluster of Type 0 summits occurs to the south on the uplands of Cocks Hill and Black Dunghill, a southerly extension of the Hangingstone Hill/Cut Hill plateau that forms a horseshoe-shaped drainage divide at the head of the River Walkham catchment. An isolated ridge extension of this upland on its southwest margin contains the prominent Type 1 Great Mis Tor, which lies beyond the glacier limits identified for plateau icefield outlet lobes that descended from the Cocks Hill and Black Dunghill uplands.

Numerical modeling results

In the absence of chronological control of the mapped geomorphological features the appropriate palaeo-climatic forcing is unknown and therefore we perform here only experiments that refer to mass balance conditions that are constant in time (e.g. ELA that is constant with time). Starting with ice free conditions and an ELA of 550m, initially ice build-up only occurs on the highest plateau areas where elevations are above the ELA (e.g. Yes Tor plateau and Woodcock Hill in the West and the elongate eastern upland spine comprising Cut Hill and Hangingstone Hill). The ice initially remains stagnant as it is too thin and flat to initiate ice flow. Only after a few hundred years, when the ice has thickened enough, these isolated small ice fields start to flow, advance and join-up in areas of topographic convergence or valleys (Fig 21, 22 and 23). So when neglecting snowblow effects, the modelling indicates that the generally low surface slopes on the Dartmoor plateau necessitate an ice-cap style glaciation as opposed to a valley-type glaciation in order to initiate significant ice flow. A further consequence of the relatively flat topography of the plateau is that the ice cap is highly sensitive to altitude-mass balance feedback. As the ice cap grows in thickness and extent, it moves its surface into higher elevations and therefore into a more positive mass balance regime. This leads to further advance and thereby creates an even larger accumulation area while the ablation area only marginally increases as the elevation of the margin within the main plateau remains elevated (Fig 21). The ice cap would therefore continue to grow until its margin advances down from the main plateau into significantly lower elevations. For a climate (e.g. ELA) that is constant in time, this altitude mass balance feedback does not therefore allow a stable steady state ice cap within the main plateau boundaries in which the described observational evidence of glaciation have been found. The modeled time-slices that are compared here to the geomorphology should therefore not be interpreted as absolute histories of ice extent but as potentially different advance stages over limited time periods, in the order of several hundred to over a thousand years.

The majority of the mapped moraines and geomorphological evidence can be reconciled in the model by two single time-slices of ice cap buildup at 665 years and 1400 years, respectively (Fig 21). Besides giving an estimation of the potential 3-dimensional shape of the ice cap, the modelling further allows us to spatially correlate the different, disconnected geomorphological features into two major stages. The inner extent (665 years) consists of two coalescent small ice caps over the Hangingstone/Cut Hill plateau with maximum divide thicknesses of 100 m (Fig. 23) and two separate and smaller plateau ice fields covering Yes Tor and Woodcock Hill with much thinner ice divide maximum thicknesses of 30 m (fig. 24). Outflow lobes with significant flow occur in most marginal valleys (Fig 22) and in general agree well with the inner set of mapped geomorphological features. Note that the above proposed Slipper Stones glacier is also reproduced by the model due to a strong local depression of ELA (from 550m to 470m) from the aspect correction in the steep NE-facing slope of the West Okement valley.

The more extensive outer and probably earlier stage (1400 years) requires more than a thousand years to build up and produces a major ice cap over the Hangingstone/Black/Cut Hill plateau spine that significantly overruns the topography beneath. This central ice dome has a divide thickness of 150m (Fig. 24) and is coalescent with two separate smaller ice domes over the Yes Tor plateau and Woodcock Hill (Fig. 23). However, the ice thicknesses of these two separate ice domes remain relatively thin and are at locations of major class 1 tors (T1) below 30 m (Fig. 24). Again due to low surface gradients and relatively limited ice thicknesses, ice flow is in general low (below 10m/y) and enhanced flow above 10 m/y only occurs in major valleys (Fig. 22) where ice marginal geomorphological features have been mapped (Fig 4) . This is in line with the assumption that faster flow is more likely to produce depositional features. Distinctly faster ice flow is modeled in the U-shaped West Okement valley, draining a significant part of the central ice cap and indicating the potential for significant erosion in this valley. In the valley of Winney's Down Brook and beneath Sittford Tor, the modeled ice lobes are in good agreement with mapped marginal positions and are fed by ice from the NW, overflowing the topographic ridge of Winney's Down and Sittaford Tor; this is consistent with the mapped small drumlins at that location (Figs. 4 & 21).

In summary, the general agreement of the modeled outlet glacier lobes with the identified marginal geomorphic features in various valleys draining the north Dartmoor plateau strongly supports our palaeoglaciological reconstructions based on the geomorphological mapping. Further, the modelling suggests that the ice caps/fields at the different stages were not in balance with the climate forcing and the extents most likely relate to advance stages of cold periods of limited duration in time (up to a thousand years). As recorded in the GRIP-ice core in Greenland (Dansgaard et al, 1993) such millennia-scale excursions to cold climate seem typical during the last glacial stage and could have driven the repeated build-up of ice-caps that are limited by the length rather than severity of cold phases. Additional modelling experiments with different ELA values and mass balance gradients confirmed this non-steady state extent and spatial correlation and only created slightly different timings for the attainment of the mapped extents.

The modeled ice extent, thickness and flow speed further allows independent assessment of the relationship between tor development and glacier ice cover (see Figs. 21, 22 & 24 for tor styles T0 = pink squares, T1 = red circles, T2 = green triangles). With few exceptions, the distribution of subdued tors (T2) or summits with no tors (T0) in the highest plateau terrain matches the modeled areas of most prolonged cumulative ice cover and relatively thick ice (Fig. 21 and 24), thereby indicating that tor development may have been suppressed during periods of glaciation. Additionally, the locations of subdued or missing tors (T0 and T2) on the central plateau of Hangingstone/Black/Cut Hill correspond to areas modeled as being covered not only by much thicker ice (Fig. 24) but more importantly beneath migrating ice divides where significant ice flow could have played a significant role in eroding tors (Fig. 21). In contrast, the more delicate, high relief type 1 tors (T1) are located mostly outside the margins of the modeled icefields where prolonged periods of periglacial weathering and mass wasting may have only very briefly been interrupted by glaciation. Further, the few T1 tors in locations with prolonged ice cover, such as Yes Tor, Oke Tor and Fur Tor, are in general beneath stagnant ice divides with ice flow very close to zero (Fig. 22) and limited ice thickness (<30m) with high potential for cold based ice (Fig. 24).

Discussion

Overdeepened or weakly U-shaped valley segments that fringe the central uplands of north Dartmoor document the passage of glacier ice that advanced beyond the granite massif, but corroborative evidence for such an extensive glaciation has yet to be identified. If the excavation of the prominently U-shaped West Okement valley for example is glacial in origin then the well defined glacier on the Slipper Stones dates from a later glacial phase and the moraines dating to the period of valley excavation must lie in the lower West Okement River valley. Because the Slipper Stones glacier is the most unequivocal palaeo-glacier on north Dartmoor, we can confidently use it to reconstruct a palaeo-ELA at the time of its development. The small size of the glacier also allows us to employ a simple technique such as maximum elevation of lateral moraines (MELM) in order to determine a palaeo-ELA of c.460 m asl.

More extensive glacier ice has been proposed for each of the major drainage basins of north Dartmoor based upon arcuate and linear bouldery ridges and hummocky valley floor drift, which although often subtle can most simply be explained as the products of latero-frontal moraine deposition by outlet lobes of plateau icefields. Recession of these lobes is also marked by inset sequences of such ridges and occasional meltwater channels. More problematic are situations where boulder fronted gelifluction sheets (Fig. 8) turn lobate and may even become rock glacierized in the upper parts of small valleys, which is especially pertinent where arcuate ridges are in narrowly confined valleys and descend to anomalously low altitudes (e.g. Tavy Cleave). Where origins are ambiguous in this way we have been conservative in our glacial interpretations even though small glacier lobes following the same topographic control could incorporate local bouldery gelifluction debris.

Dispersal centres have been proposed based upon the spatial distribution of moraine distribution relative to topography, numerical flow modelling, and informed by the plateau icefield glacial landsystem model (Rea & Evans 2003), the most likely palaeoglaciology given the physiography of north Dartmoor. Independent verification of the suitability of the north Dartmoor upland surfaces for glacierization can be provided by the application of the Rea and Evans (2003) “Manley curve”, based upon Manley’s (1955) data relating summit breadth to ice cover altitude above the regional firn line (Fig. 25), which lies at 460 m OD based on the moraine of the Slipper Stones glacier, if we assume that the firn line is approximated by the equilibrium line altitude. Manley identified the fact that broad plateaux could sustain glacier icefields even if they were located at elevations close to the ELA. The plateau surfaces of north Dartmoor are relatively narrow and within 150 m of the regional ELA, thereby indicating marginal conditions for glacierization when compared to the glaciated plateaux plotted by Rea and Evans (2003) on the “Manley curve”. This suggests that plateau ice would have been predominantly thin and protective and that snowblow and preferential accumulation in valley heads would have facilitated the modest glacial erosion and debris transport required to deposit the low amplitude morainic landforms. The numerical modelling suggests that even an ELA as high as 550m could lead to the development of larger ice-fields with lobate margins down to 400m, but relies strongly on altitude mass-balance feedback and cold periods of significant length. Furthermore, the numerical modelling confirms relatively thin ice, in particular over the more narrow plateaux and in general with relatively slow flow and therefore limited potential for depositing marginal landforms. The implications of thin plateau ice for tor production are discussed below.

By invoking the concept of “average” glacial conditions (Porter 1989), it is conceivable that Dartmoor’s highest plateaux have been occupied for the longest cumulative period of time throughout the Quaternary and therefore have been subject to the most glacial erosion. This is potentially manifest in the spatial pattern of different tor types on northern Dartmoor, whereby no tors (Type 0) occur on the most expansive of the highest plateau terrain of the elongate Hangingstone Hill/Cut Hill upland, suggesting that this area served as the main ice dispersal centre during periods of glaciation as also indicated by the modelling. In contrast, protection by cold based ice is likely manifest in Type 1 tors on the Yes Tor upland, which was high enough to generate local ice but too small and too narrow to generate a plateau icefield of significant thickness and erosive capability. Type 1 tors also occur on other smaller summits at the outer margins of north Dartmoor which would have escaped inundation by glacier ice because ice would have been topographically confined as outlet lobes from the interior plateau icefields. Type 2 tors occur on the outer margins of the Hangingstone Hill/Cut Hill plateau, where they represent intermediate levels of glacial modification, and on smaller plateaux such as Woodcock Hill/Amicombe Hill where ice coverage was likely less extensive and of shorter duration.

Given the discussion above concerning the likelihood of thin, cold based and protective ice on the north Dartmoor plateaux, an alternative interpretation of the tor distribution pattern is that the highest plateaux have indeed been occupied by glacier ice for the longest cumulative period of time during the Quaternary but this has protected the bedrock from frost weathering and mass wasting by gelifluction, thereby dampening tor formation. In this scenario, Type 1 tors have been produced on summits that have remained ice free for the longest period of Quaternary time. It must be stressed here, however, that the regional palaeo-ELA calculation used above is based upon only one small glacier whose development was almost certainly restricted by bedrock morphology and appears to be the youngest and most restricted of at least two phases of glacier ice development. It is therefore almost certainly anomalously high and is certainly not reflective of the longer term ELA. The latter might be represented by the floor of the weakly developed bedrock amphitheatre or cirque on Corn Ridge; this indicates a potential long term ELA of 370-410 m asl (cf. Evans 1999), thereby making plateau icefield development more viable on north Dartmoor.

The lack of tors on the Hangingstone Hill/Cut Hill upland was noted previously by Palmer and Neilson (1962) who suggested that the concentration of pneumatolysis in this area may explain the absence of coherent granite. They also produced a graph to depict the number of summits with tors in relation to altitude (Fig. 26), illustrating that tors increased in number on summits in the 1400-1500ft (427-457m asl) range, falling off rapidly below that altitude but gradually declining and oscillating in number above that altitude. This pattern of altitudinal distribution was linked by Palmer and Neilson (1962) to several factors thought to be important in dictating tor genesis, including pneumatolysis but predominantly periglacial processes. The latter particularly would have operated most effectively at higher altitudes throughout the Quaternary, explaining the rapid drop in number of summits with tors below 1400ft (427m asl). However, the oscillatory decline in number of summits with tors above 1500ft (457m asl) was not fully explained by Palmer and Neilson (1962). One explanation is simply that the altitudinal range with the largest number of summits with tors (1400-1500ft (427-457m asl)) represents the most extensive upland surface and that further concentrations at around 1650-1750ft and 1850-1950ft (503-533 and 564-594m asl) reflect subordinate surfaces. This concept of dominant long term “planation surfaces” on Dartmoor has been cited also by Gerrard (1974) to explain the distribution of tors. He also demonstrates that tors occur predominantly on summits with higher relative relief. Notwithstanding other equally plausible explanations for tor existence and the concept of polygenetic origins, these patterns of tor distribution with altitude and relative relief support our proposition above that: a) average glacial conditions have either preferentially removed tors from the wider plateau surfaces or dampened their production rates; b) high altitude tors have survived glaciation where they occupy summits too narrow to develop plateau icefields of significant thickness and/or ridges that are bypassed by faster moving ice in adjacent deep valleys; and c) Type 2 tors represent areas glaciated less regularly during the Quaternary. Furthermore, in the case of Hangistone Hill/Cut Hill, the flow modelling indicates migration of the major ice divide as the ice cap builds up and therefore produces significant flow at the location of these topographic highs, which may further prevent survival/development of larger tors.

Age of glaciation

While at present there are no dates on the glaciations described here, on morphostratigraphic grounds we can speculate on the likely ages of the glacial phases. We hypothesise that the development of the plateau icecap and associated valley glaciers occurred during the LGM at a time when the Late Devensian ice sheet reached the northern Scilly Isles to the west and south of Dartmoor. The modelling suggests that such more extensive ice fields with significant ice flow require several hundreds to thousand of years to build up. We further suggest that the restricted glacial advance producing small niche and cirque glaciers in the West Okement Valley occurred during the Younger Dryas. In this scheme the long term ELA at Corn Ridge of 370-410 is slightly higher than that reconstructed by Harrison et al. (1998) for the glaciation of the Punchbowl on Exmoor which had an ELA of 334m asl but remains similarly undated. Similar low values are recorded in parts of South Wales such as the Black Mountains with Younger Dryas ELAs around 290-350m asl (Barclay 1989). Recent unpublished work (Hägg 2009) reports the use of cosmogenic nuclides to assess the age of tors and long-term erosion rates on northern Dartmoor. He used the dates to derive higher long-term catchment denudation rates than present values. Although he recognized the possibility that Dartmoor may have been glaciated especially in the central plateau region where our modeling predicts the existence of plateau icefields, most of his sample sites were on the fringes of this region and therefore do not help test this assertion. However, high rates of catchment denudation may result from glaciation given that burial of surfaces under ice would provide shielding from cosmic radiation and thus lead to underestimation of surface age or overestimation of erosion rates (Hägg 2009, p. 233). Clearly, cosmogenic nuclide dating on selected surfaces will be crucial to provide future information on the age of the Dartmoor glaciations.

Conclusions

The extensive glaciation of Dartmoor is proposed in this paper based upon the interpretations of several geomorphic criteria and simple numerical flow modelling which strongly indicate the development of a plateau icefield landsystem. The glacial evidence is subtle; glaciers flowing at low gradients produce low driving stresses. Nevertheless, we argue here that the glacial evidence comprising moraines, drift limits meltwater channels, ice-scoured bedrock and glacial sediment is compelling. The icecap represents the southernmost independent Pleistocene ice mass in the British Isles and is hypothesized to have last developed during the LGM and Younger Dryas. The palaeoglacier reconstruction with which we have the greatest confidence, the Slipper Stones niche glacier, represents a palaeo-ELA of around 460 m OD based upon the MELM method. When combined with the altitudes and breadths of the main plateau surfaces of north Dartmoor on a “Manley curve”, this palaeo-ELA indicates that upland ice would have been thin and protective and outlet glaciers would have received significant nourishment from snowblow into valley heads, although caution must be exercised when using only one glacieret to determine a regional ELA. If the weakly developed bedrock amphitheatre on Corn Ridge is accepted as a cirque, its floor altitude of 370-410 m OD could be regarded as a long term ELA, thereby making plateau icefield development more viable on north Dartmoor. The flow modelling allows a 3-dimensional reconstruction of a potential ice cap which spatially verifies the mapped marginal moraine features. Due to the low surface gradients of the Dartmoor plateau, the numerical modelling produces a plateau-style rather than a valley glacier style of glaciation in order to initiating significant ice flow. As a further consequence of the low surface gradient, such a potential ice cap is exposed to a strong feedback between surface mass balance and altitude which suggests that the reconstructed glaciation extents do not relate to steady state conditions and that these extents are limited by the length of cold phases. Furthermore, the modeled ice extent, thickness and flow speed are in general consistent with the development and preservation of the observed tor style distribution. Our findings further support the earlier work on glacial deposits and landforms on Exmoor and suggest that other high moorland in the region (such as Bodmin Moor to the west) may also have hosted ice masses during the Quaternary in response to the sub-Milankovitch or millennia-scale excursions to cold climate which seem typical of the last glacial stage and which could have driven the repeated build-up of ice-caps that were limited by the length rather than severity of cold phases.

Acknowledgements

DJAE thanks Mike Walker for introducing him to the problem of the Dartmoor tors during an undergraduate field class back in 1980, thereby demonstrating the invaluable role of fieldwork teaching in Physical Geography! SH thanks Tessa Kingsley with whom he first discussed the glaciation of Exmoor and also David Gilbertson and R.G. (Bob) Thomas. Thanks to Sven Lukas and Phil Hughes for some thorough and very useful comments as referees.

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Figure captions

Figure 1: Location maps of Dartmoor and surrounding area.

Figure 2: An example of an overdeepened and steep-sided valley, illustrated by the River Tavy gorge viewed from Ger Tor, on the western boundary of the north Dartmoor massif.

Figure 3: Major to types: a) Type 1 or castellated tor, illustrated by Watern Tor, which is around 8 m high in the foreground; b) Type 2 or subdued tor, illustrated by bedrock outcrop on Corn Ridge.

Figure 4: Geomorphology map for north Dartmoor, showing main types of proposed glacial landforms, distribution of tor types and summary contour intervals.

Figure 5: Annotated aerial photograph extract of the West Okement valley and the Slipper Stones taken in 1945, before the creation of Meldon Reservoir. North is towards the top in all aerial photograph extracts. Aerial photograph 3G/TUD/T17 – 5064 (crown copyright).

Figure 6: Bedrock exposure resembling a roche moutonnee profile, located on the lower eastern slopes of Amicombe Hill in the upper West Okement River valley.

Figure 7: The Slipper Stones: a) Aerial photograph extract and ground view of the Slipper Stones moraine ridges, with the outermost ridge arrowed. Aerial photograph HSL UK 62 255 – 5845 (Hunting Surveys); b) smoothed granite slabs and subdued roche moutonnee forms on the bedrock backwall.

Figure 8: The east slopes of Yes Tor, showing the Type 1 tor on the summit, clitter on the upper slope, and rock-fronted gelifluction sheet in the foreground.

Figure 9: A lobate-fronted, hummocky drift plug in west Red-a-ven Brook, looking upstream. Inset photographs show details of internal deposits, which are boulder-rich, gravelly diamictons with highly fissile matrix and predominantly weakly facetted sub-rounded cobbles.

Figure 10: Annotated aerial photograph extract of the east side of Taw Marsh. Small scale quarrying of the valley fill along the Taw River is visible on the left. Ordnance Survey aerial photograph 75 369 – 120 (crown copyright).

Figure 11: Annotated aerial photograph extract of lower Great Varracombe, showing the major channels (arrows) and sinuous drift ridge (broken line). Ordnance Survey aerial photograph 75 369 – 123 (crown copyright). The ground photograph shows the drift ridge viewed from upslope and is arrowed with arrow sizes reflecting distance from viewer.

Figure 12: Facetted and weakly striated clasts recovered from stream banks in lower Great Varracombe.

Figure 13: Annotated aerial photograph extract of Walla Brook in the vicinity of Watern Tor (see Fig. 3a) and Wild Tor. The open arrow depicts the direction of meltwater drainage over a nearby col and northwards into Gallaven Mire. Ordnance Survey aerial photograph 75 369 – 122 (crown copyright).

Figure 14: Glacial landforms in the valley to the south of Sittaford Tor: a) Annotated aerial photograph extract of the valley directly south of Sittaford Tor (Fig. 3b). The East Dart River is visible at the bottom of the image. Aerial photograph 3G/TUD/T17 – 5105 (crown copyright); b) ground photograph of large terminal moraine ridge on the west valley side, with ponies for scale; c) vertical profile logs from exposures in the terminal moraine ridge.

Figure 15: Annotated aerial photograph extract of the upper West Dart River, to the east of Rough Tor. The meltwater channel is Hollowcombe Bottom. Aerial photograph 3G/TUD/T17 – 5106 (crown copyright).

Figure 16: Annotated aerial photograph extract and ground view of upper Cut Combe Water and Fur Tor. Possible glacier margins are represented by blue arrows, which mark the outer linear boundary of hummocky drift, and white arrows, which indicate linear assemblage of boulders. Aerial photograph 3G/TUD/T17 – 5067 (crown copyright).

Figure 17: Annotated aerial photograph extract of upper Amicombe Brook, showing complex low relief hummocks and ridges on a marshy floodplain located below a trimline at 450m OD (broken line). Aerial photograph CPE UK 2149 – 3298 (crown copyright).

Figure 18: Annotated aerial photograph extract of Amicombe Brook and Fur Tor, showing the evidence for a glacier lobe that descended from the higher terrain to the south and southeast, damming the local drainage to produce an ice-dammed lake. Aerial photograph 3G/TUD/T17 – 5067 (crown copyright).

Figure 19: Ground views of a typical plateau margin recessional moraine ridge at Tavy Hole.

Figure 20: Annotated aerial photograph extract of Wallabrook Head and Doctor Brook, showing low amplitude ridges and hummocks that mark the wrapping of two glacier lobes around the Doe Tor uplands and the deep incision of thick valley fill and bedrock by meltwater emanating from the Great Links Tor/Rattlebrook Hill uplands to the east and north. Aerial photograph CPE UK 2149 – 3293 (crown copyright).

Figure 21: Time slices of modelled ice surface topography (coloured contours with 25m intervals) for a regional ELA of 550 m after (a) 665years and (b) 1400 years model buildup time. Basal topography is shown as black contours (thick lines for 450, 550 and 600 meter contours) and the pink line marks the ELA position. Locations of tors with their classification (legend) are indicated as coloured symbols. The two fine straight lines indicate the location of profiles shown in Figure 23.

Figure 22: Time slices of modelled ice flow speed in m/y (coloured contours with 1m /y intervals) for the corresponding ice surfaces in Figure 21 for (a) 665 years and (b) 1400 years model buildup time.

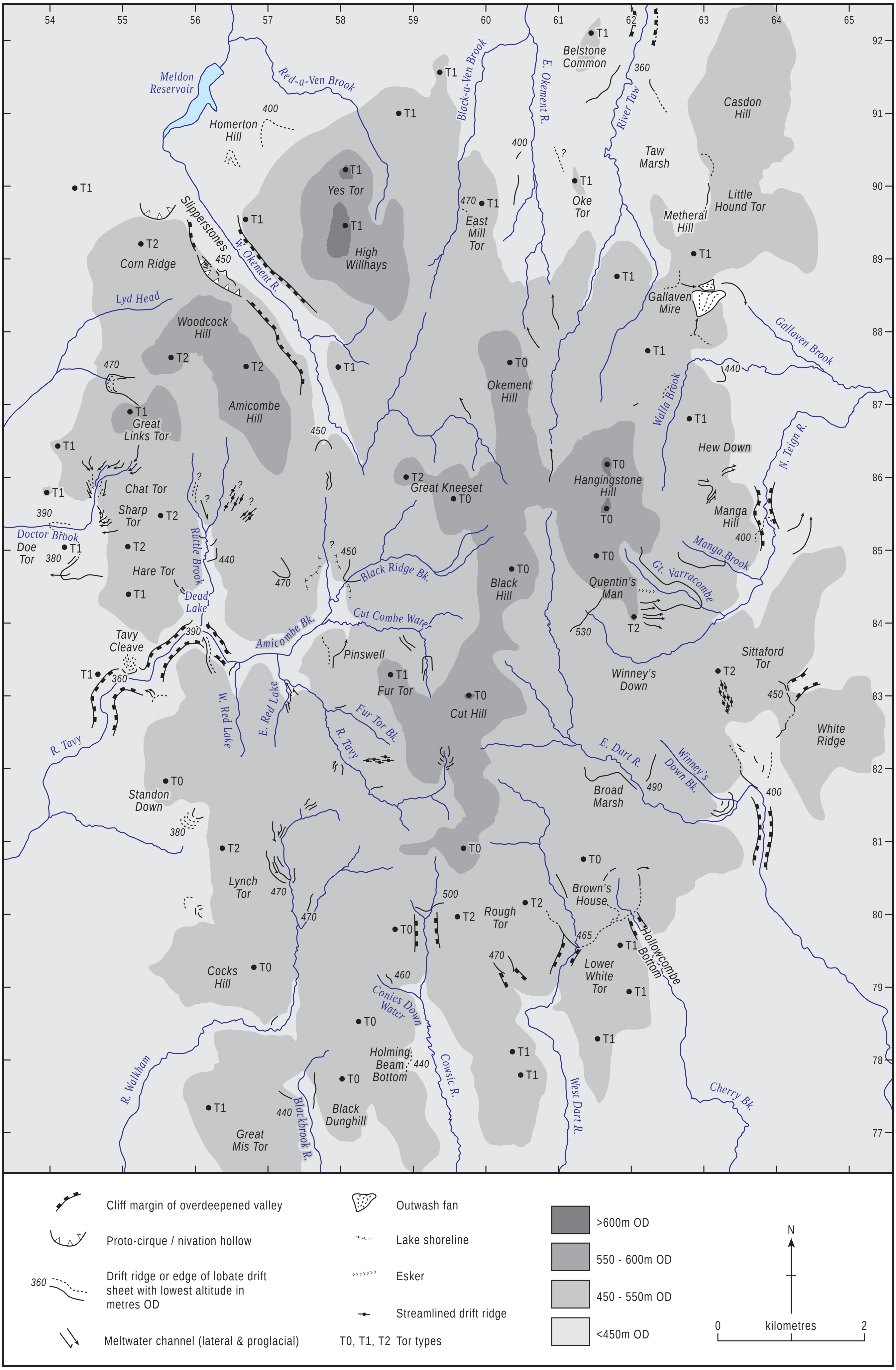
Figure 23: East-West (a) and South-North (b) profiles of modeled ice surfaces during ice cap build up shown at intervals of 200 years (thin solid lines) and at the two chosen timeslices of 665 (dotted line) and 1400 years (dashed line) located as indicated in Figures 21 and 22). The thick black lines refer to the ground topography and the thin dashed line indicates the average ELA (550m).

Figure 24: Time slices of modelled ice thicknesses in m (coloured contours with 10m intervals) for the corresponding ice surfaces in Figure 21 at (a) 665y and (b) 1400y model buildup time.

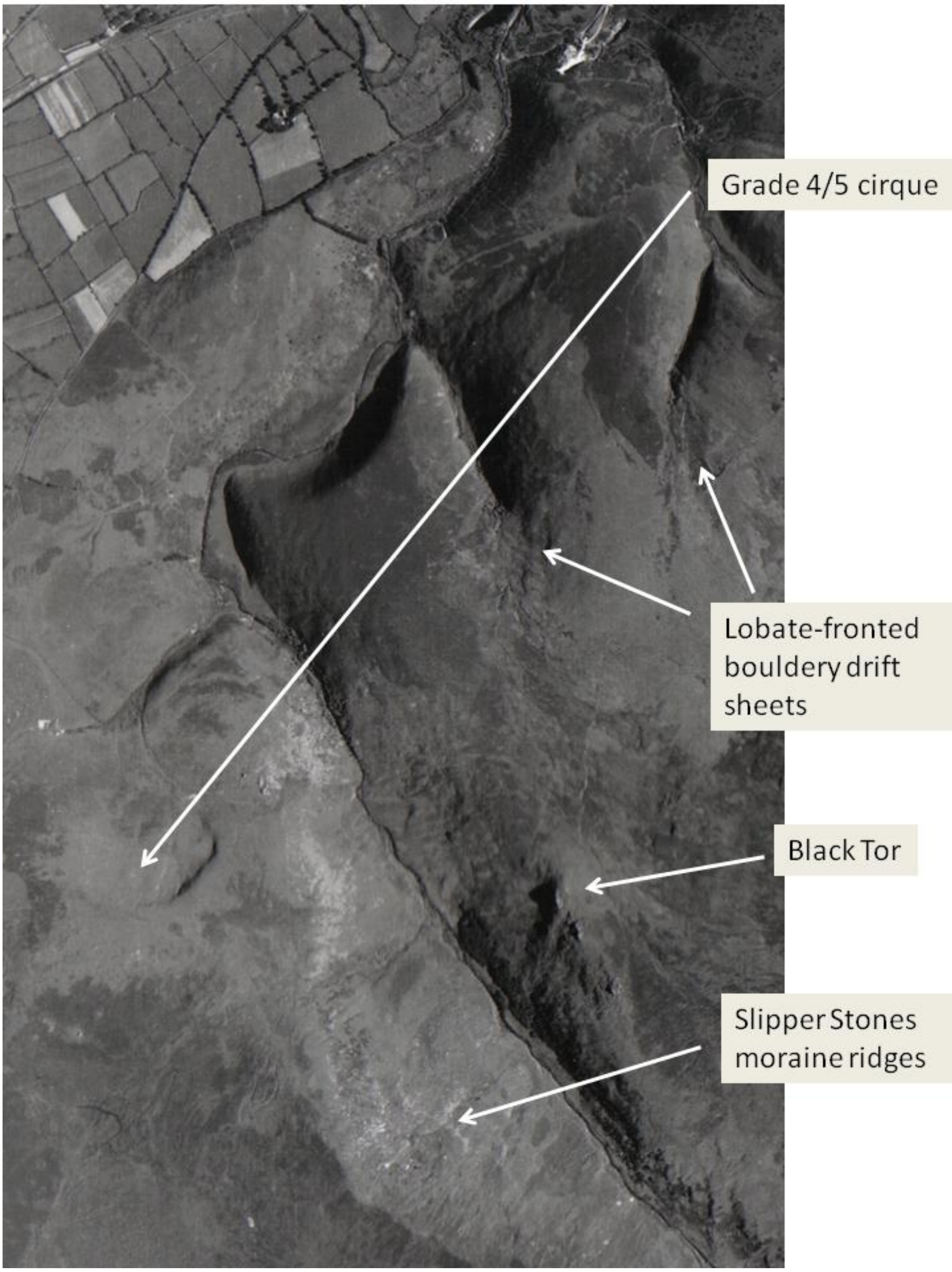
Figure 25: The “Manley curve” from Rea and Evans (2003).

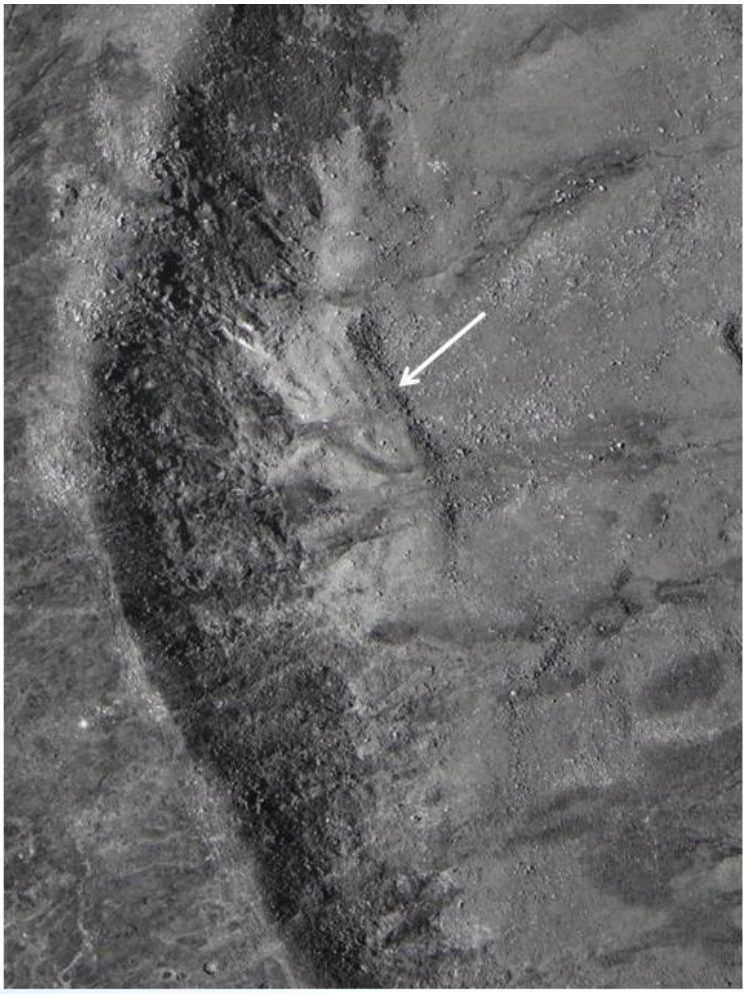
Figure 26: Graph relating number of summits with tors to altitude for Dartmoor, from Palmer and Neilson (1962).

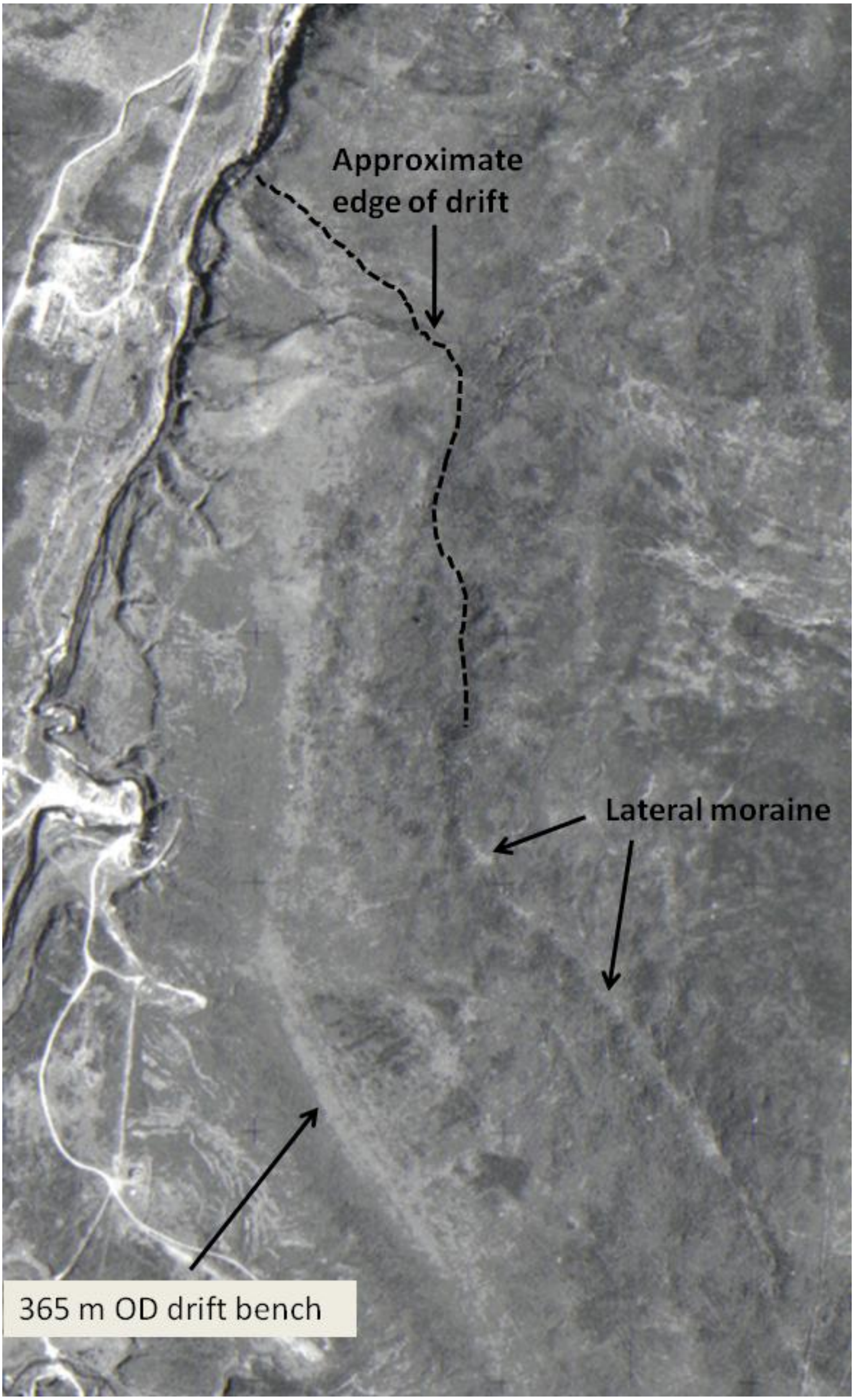

Land above 300m
Dartmoor National Park Boundary
Scotland
N. Ireland
Rep. of Ireland
Wales
England
Exmoor
Isles of Scilly
Tiverton
Crediton
Okehampton
Exeter
Teign
Tavi
Dartmoor
Tavistock
Teignmouth
Newton Abbot
Plym
Buckfastleigh
Torquay
Dart
Totnes
Paignton
Ivybridge
Brixham
Plymouth
Dartmouth
N
0
kilometres
10

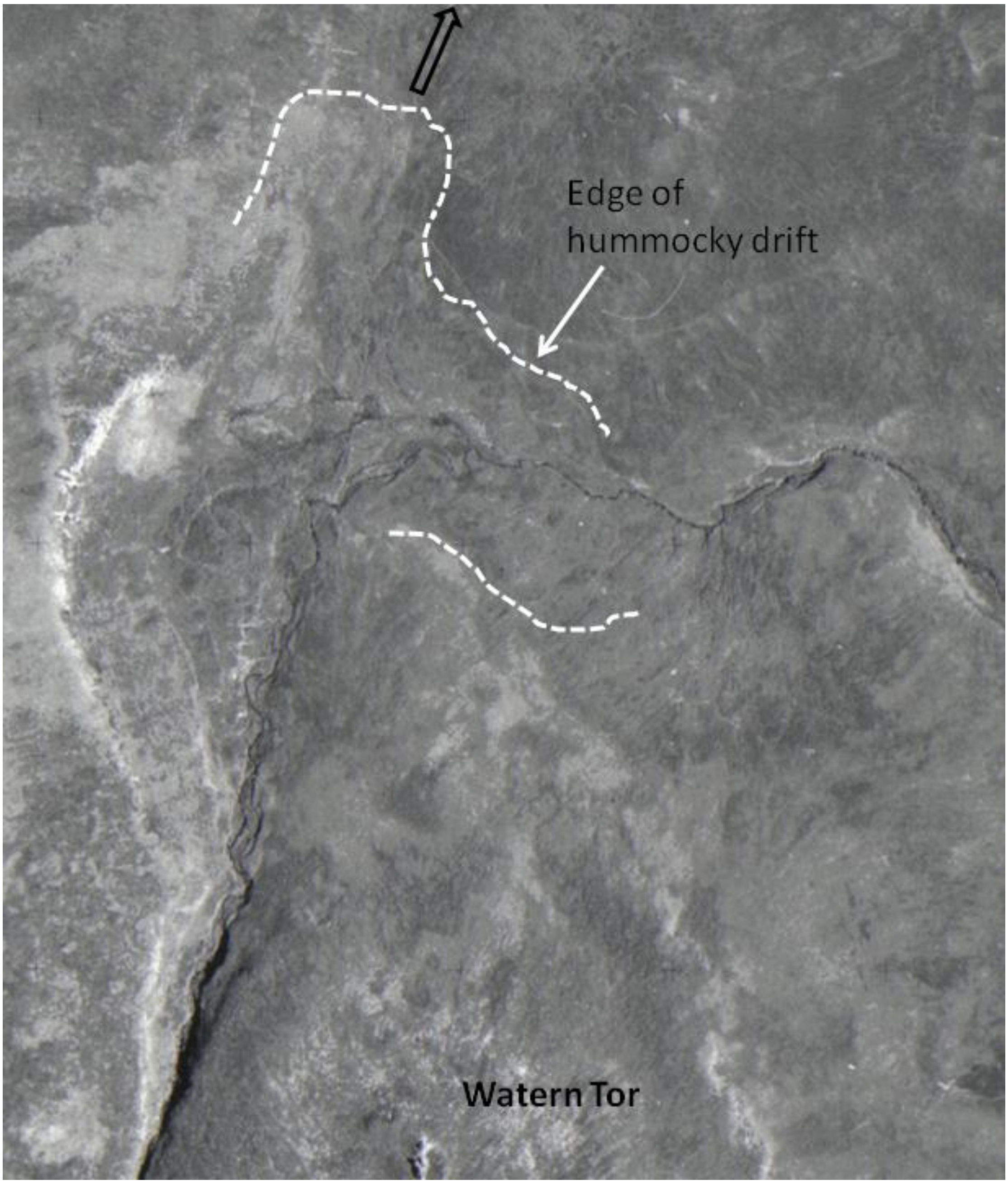


Meldon Reservoir
Red-a-Ven Brook
Black-a-Ven Brook
E. Okement R.
River Taw
Belstone Common
Homerton Hill
Yes Tor
High Willhays
East Mill Tor
Oke Tor
Taw Marsh
Casdon Hill
Little Hound Tor
Metheral Hill
Corn Ridge
Slipperstones
W. Okement R.
Lyd Head
Woodcock Hill
Amicombe Hill
Great Links Tor
Gallaven Mire
Gallaven Brook
Okement Hill
Walla Brook
Hew Down
N. Teign R.
Chat Tor
Sharp Tor
Doctor Brook
Doe Tor
Hare Tor
Rattle Brook
Dead Lake
Great Kneeset
Black Ridge Bk.
Black Hill
Hangingstone Hill
Manga Hill
Manga Brook
Gt. Varracombe
Quentin's Man
Tavy Cleave
Amicombe Bk.
Cut Combe Water
Pinswell
Fur Tor
Cut Hill
Winney's Down
Sittaford Tor
White Ridge
R. Tavy
W. Red Lake
E. Red Lake
Fur Tor Bk.
E. Dart R.
Winney's Down Bk.
Broad Marsh
Standon Down
Lynch Tor
Brown's House
Rough Tor
Hollowcombe Bottom
Lower White Tor
Cocks Hill
Conies Down Water
Holming Beam Bottom
Cowsic R.
West Dart R.
R. Walkham
Great Mis Tor
Blackbrook R.
Black Dunghill
Cherry Bk.
Cliff margin of overdeepened valley
Proto-cirque / nivation hollow
Drift ridge or edge of lobate drift sheet with lowest altitude in metres OD
Meltwater channel (lateral & proglacial)
Outwash fan
Lake shoreline
Esker
Streamlined drift ridge
T0, T1, T2 Tor types
>600m OD
550 - 600m OD
450 - 550m OD
<450m OD
N
0 kilometres 2


Grade 4/5 cirque
Lobate-fronted bouldery drift sheets
Black Tor
Slipper Stones moraine ridges

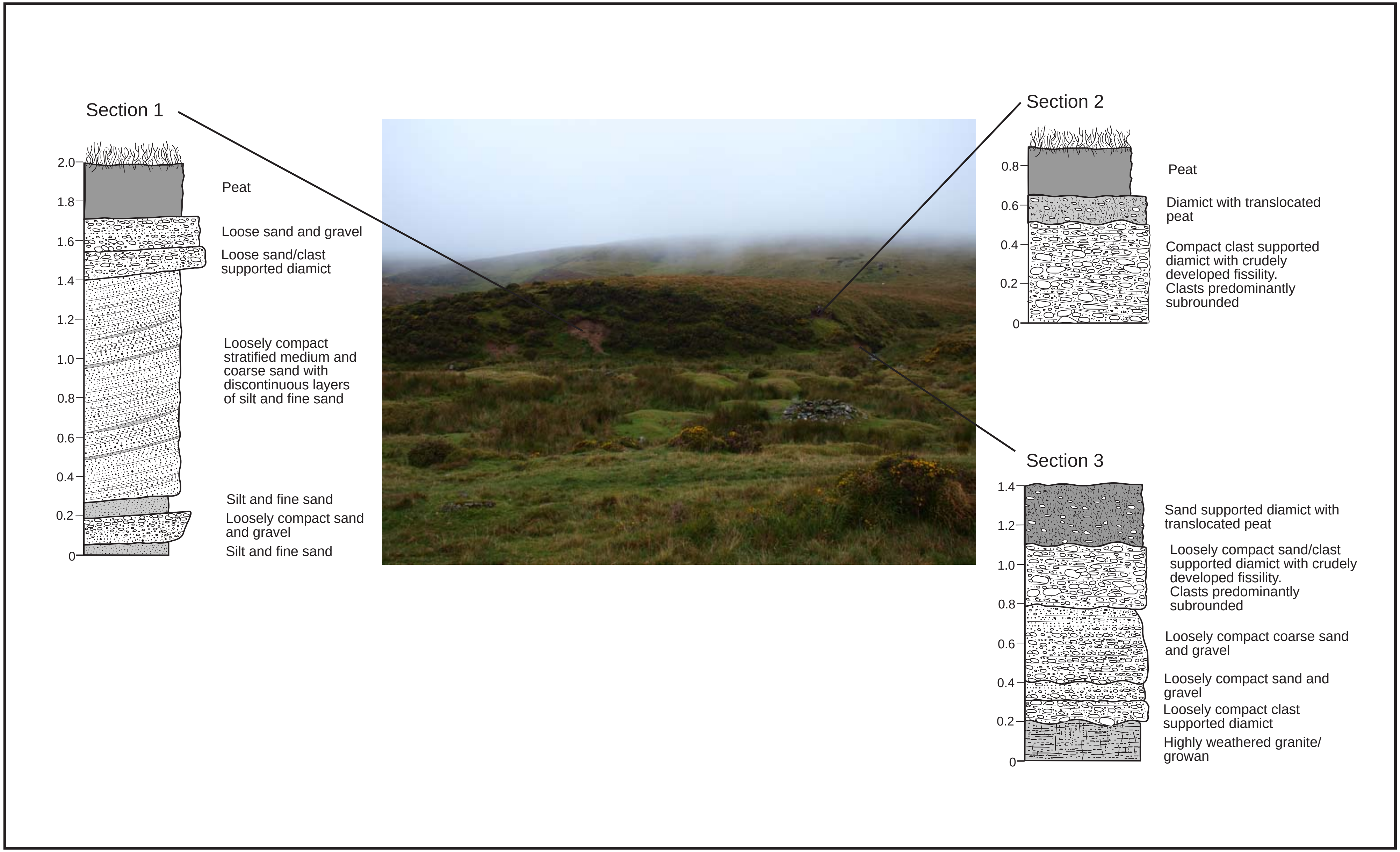


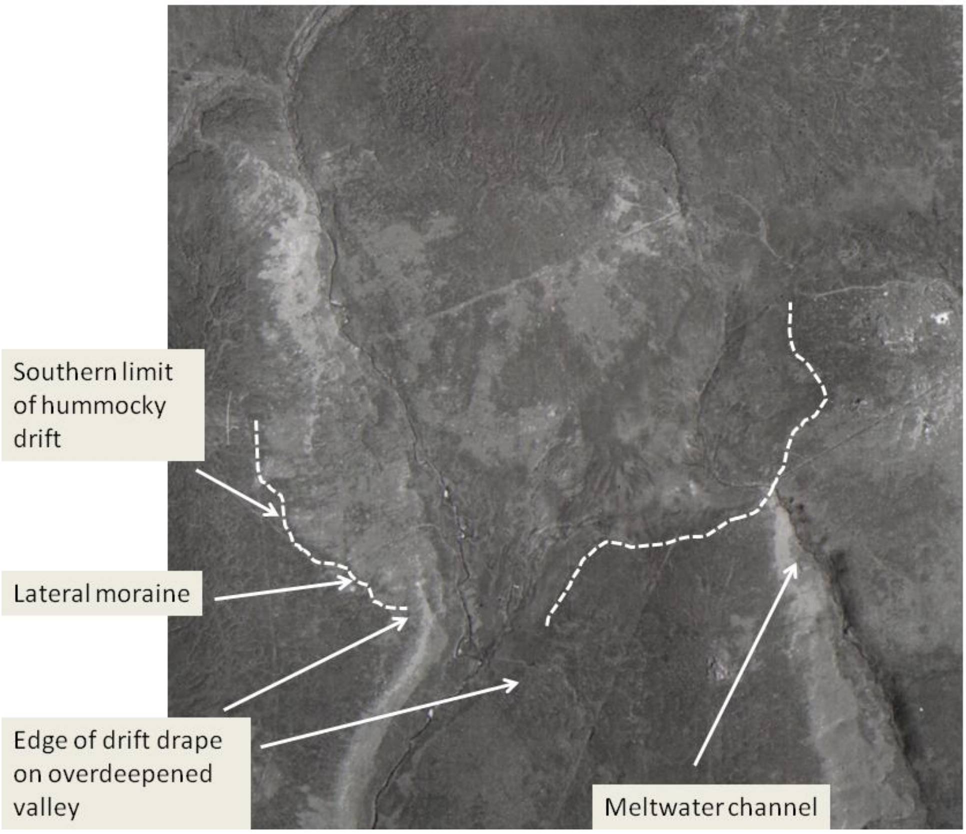

Approximate
edge of drift
Lateral moraine
365 m OD drift bench



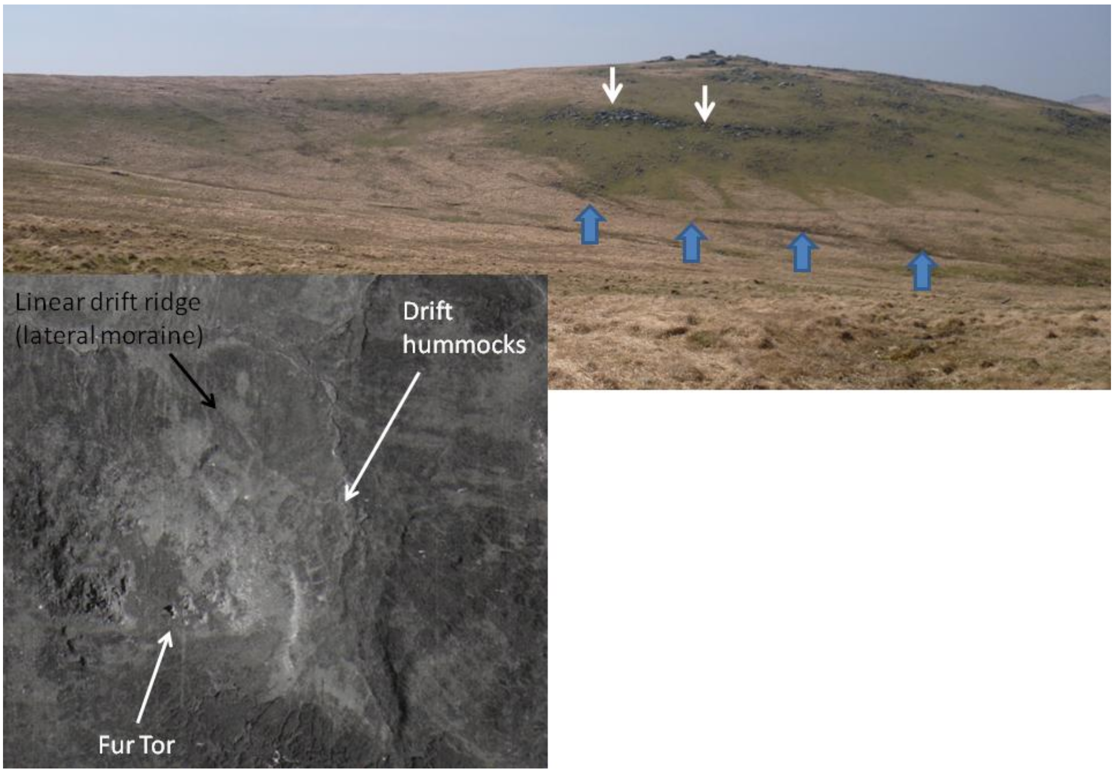
Edge of
hummocky drift
Watern Tor

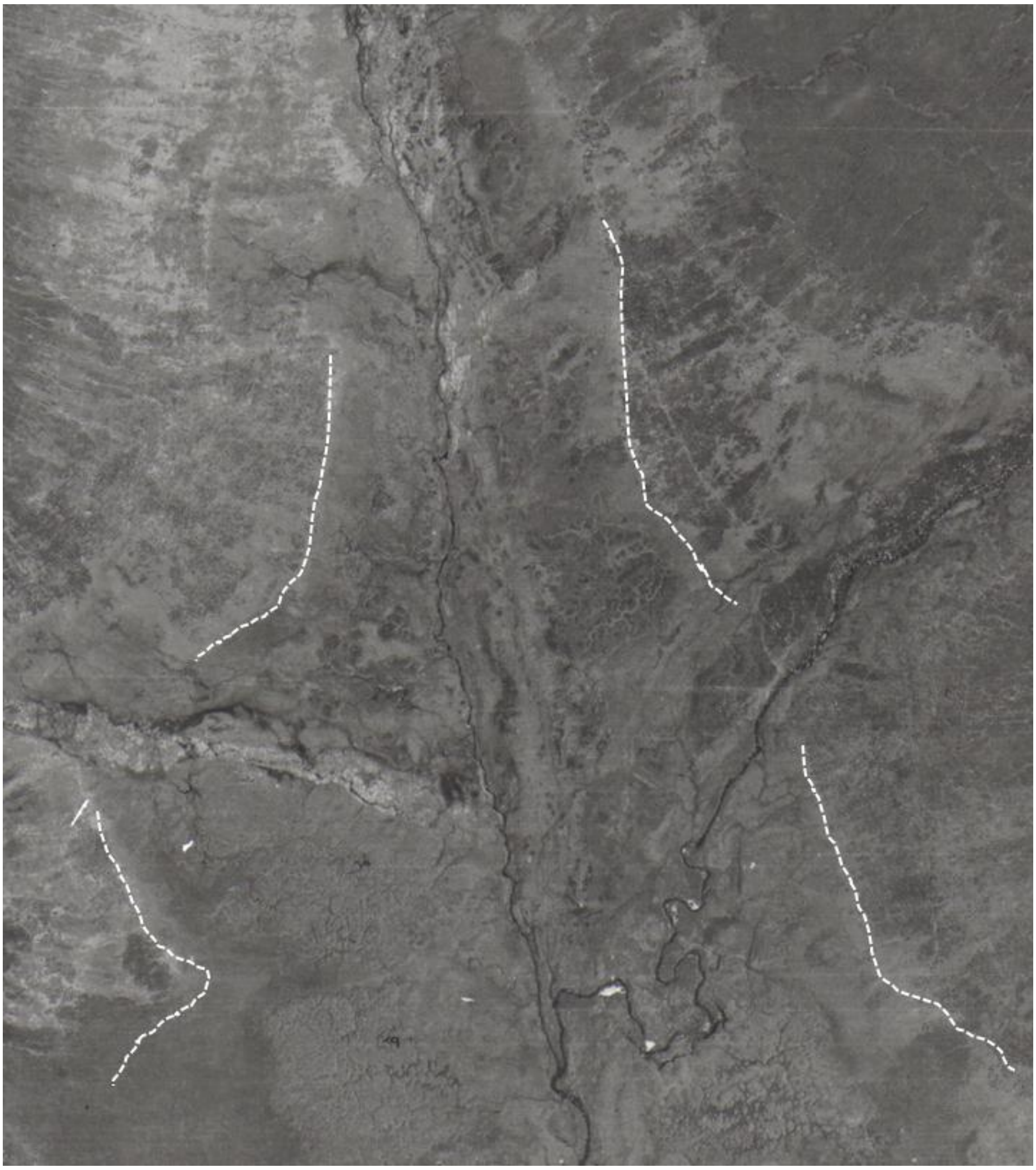

Area of streamlining
Edge of
hummocky drift

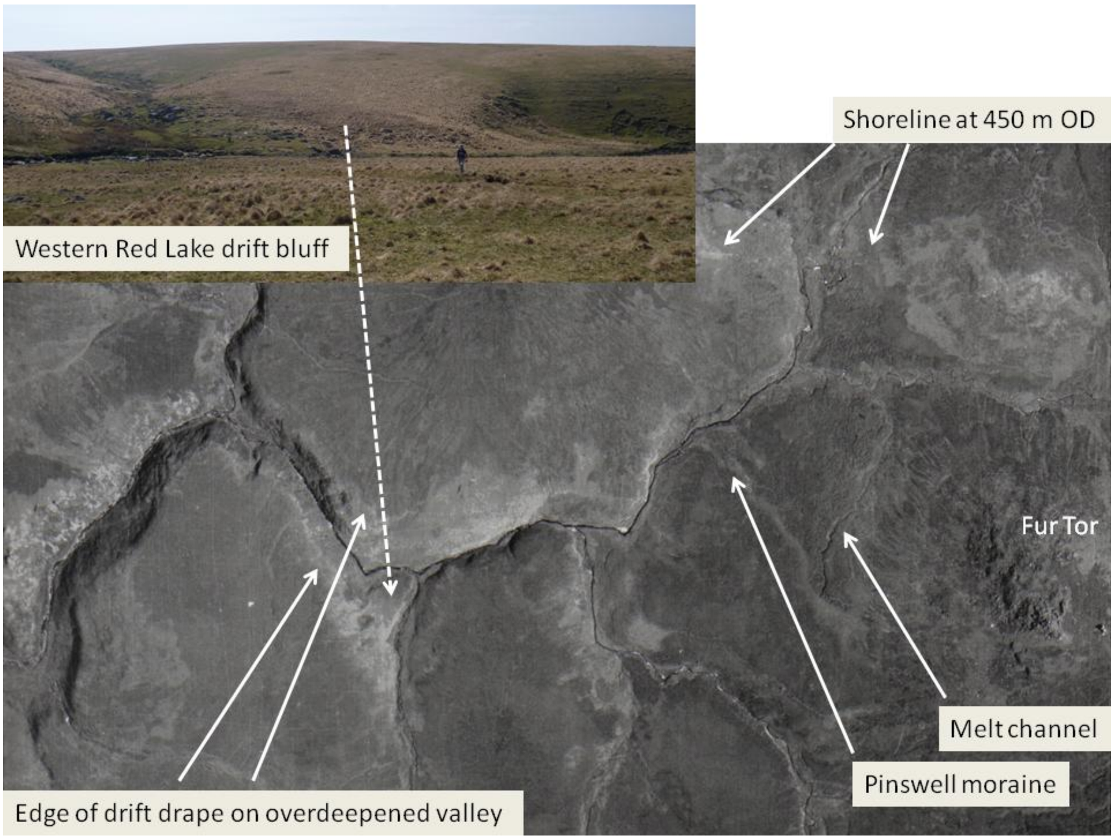

Section 1
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
Peat
Loose sand and gravel
Loose sand/clast supported diamict
Loosely compact stratified medium and coarse sand with discontinuous layers of silt and fine sand
Silt and fine sand
Loosely compact sand and gravel
Silt and fine sand
Section 2
0.8
0.6
0.4
0.2
0
Peat
Diamict with translocated peat
Compact clast supported diamict with crudely developed fissility. Clasts predominantly subrounded
Section 3
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
Sand supported diamict with translocated peat
Loosely compact sand/clast supported diamict with crudely developed fissility. Clasts predominantly subrounded
Loosely compact coarse sand and gravel
Loosely compact sand and gravel
Loosely compact clast supported diamict
Highly weathered granite/ growan

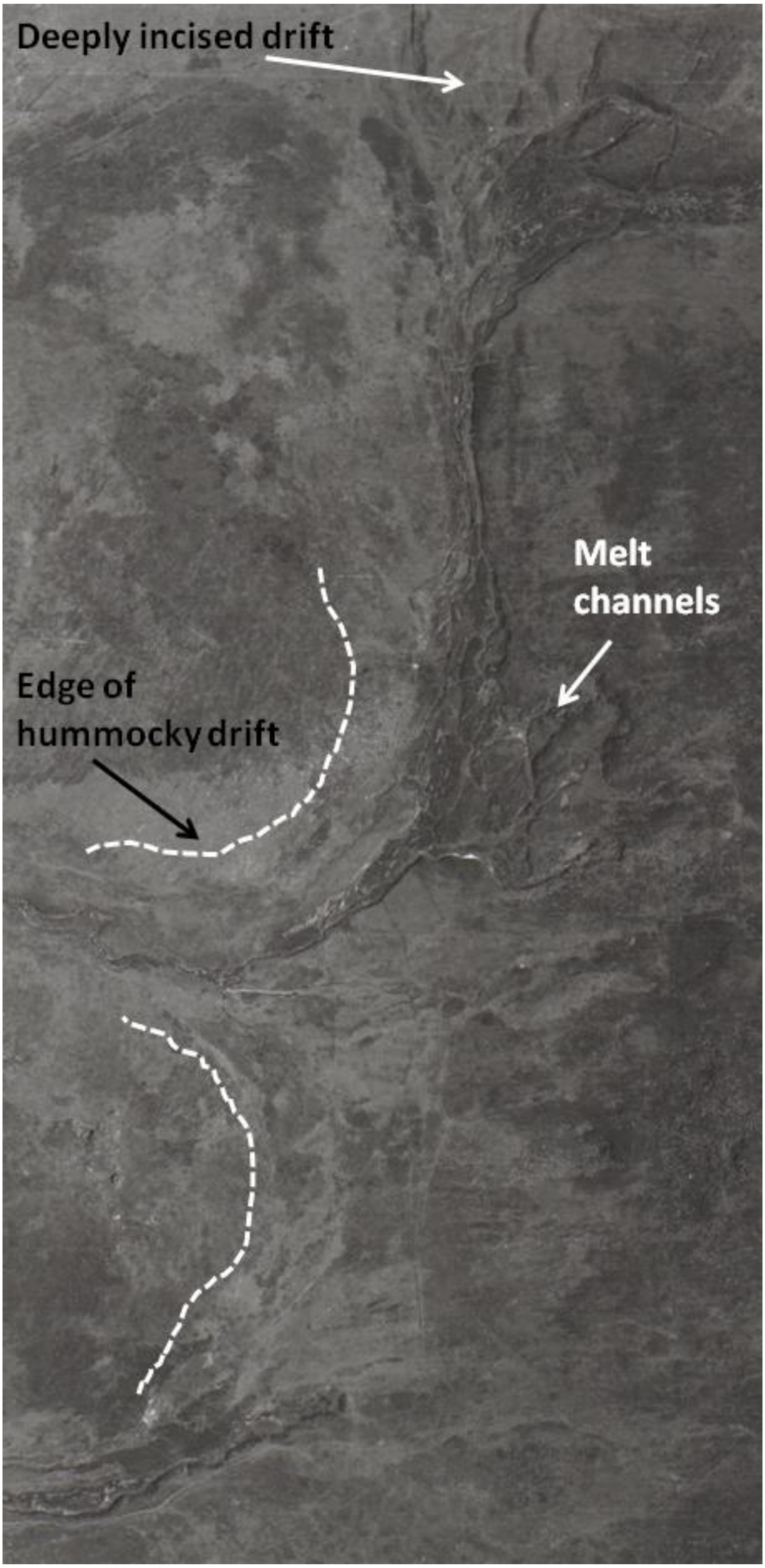


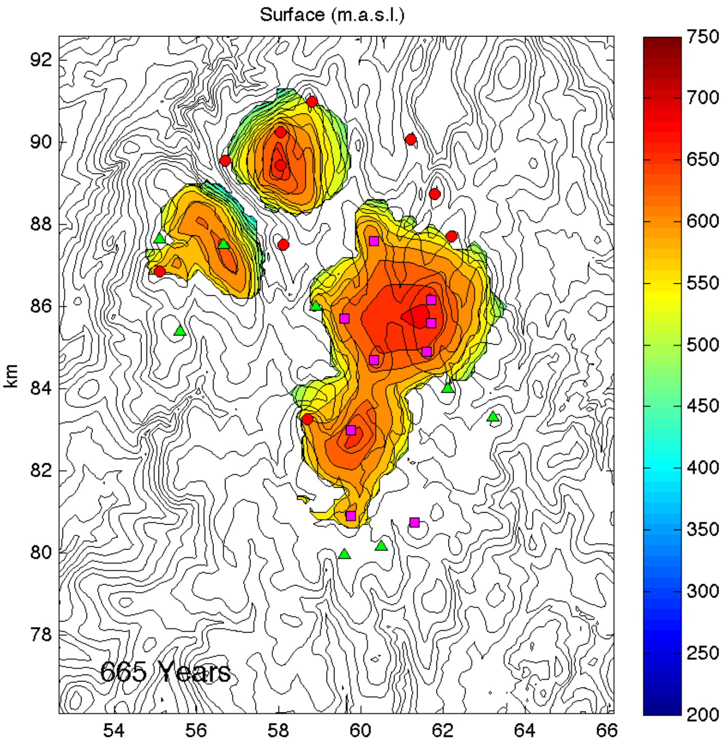
Southern limit of hummocky drift
Lateral moraine
Edge of drift drape on overdeepened valley
Meltwater channel


Linear drift ridge
(lateral moraine)
Drift
hummocks
Fur Tor

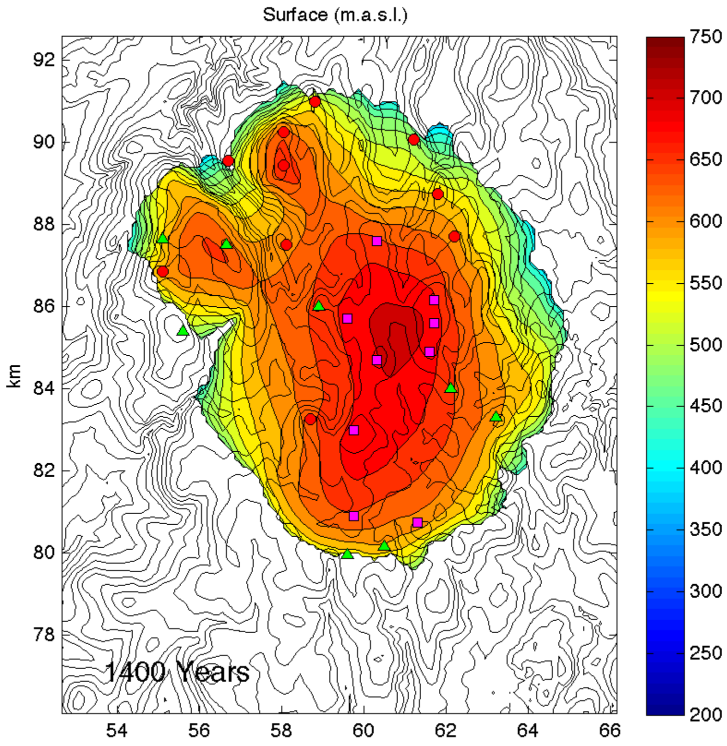


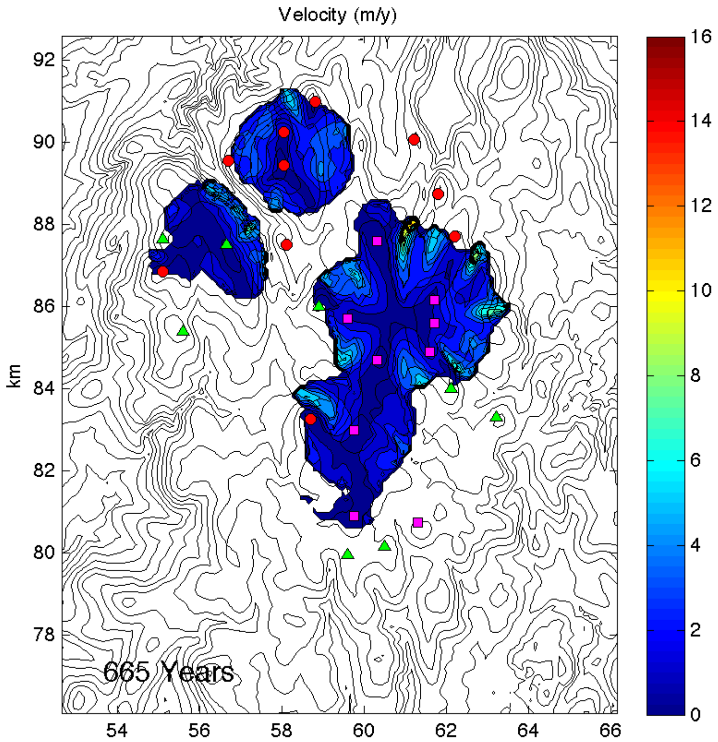

Shoreline at 450 m OD
Western Red Lake drift bluff
Fur Tor
Melt channel
Pinswell moraine
Edge of drift drape on overdeepened valley


Deeply incised drift
Melt
channels
Edge of
hummocky drift

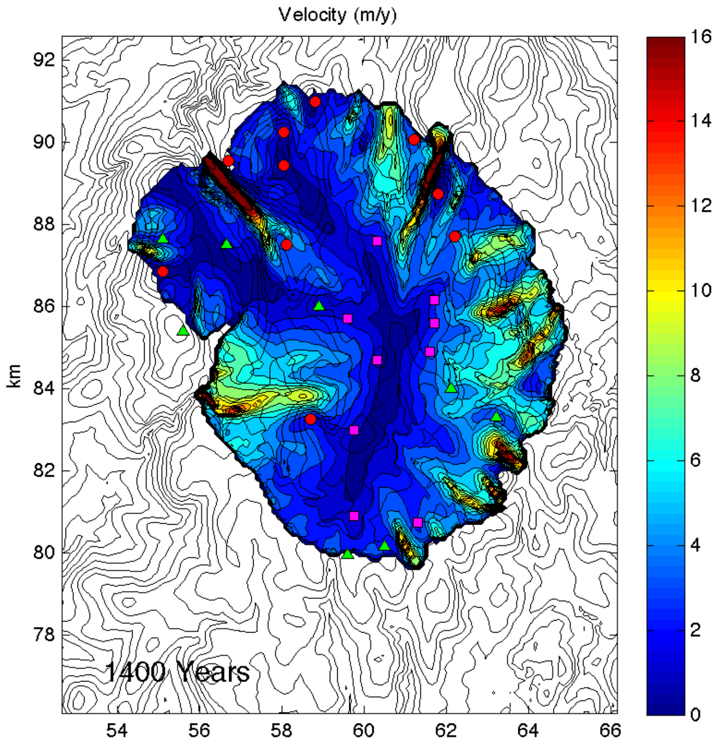


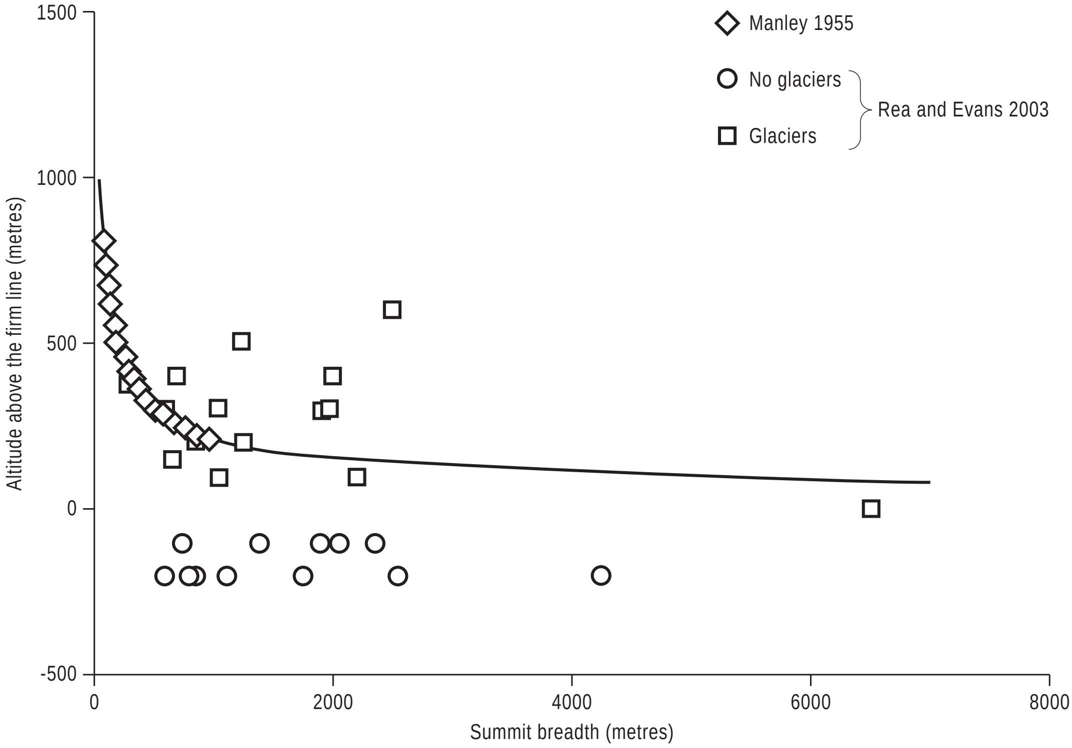
Surface (m.a.s.l.)
km
92
90
88
86
84
82
80
78
54
56
58
60
62
64
66
665 Years
750
700
650
600
550
500
450
400
350
300
250
200


Surface (m.a.s.l.)
km
1400 Years
92
90
88
86
84
82
80
78
54
56
58
60
62
64
66
750
700
650
600
550
500
450
400
350
300
250
200

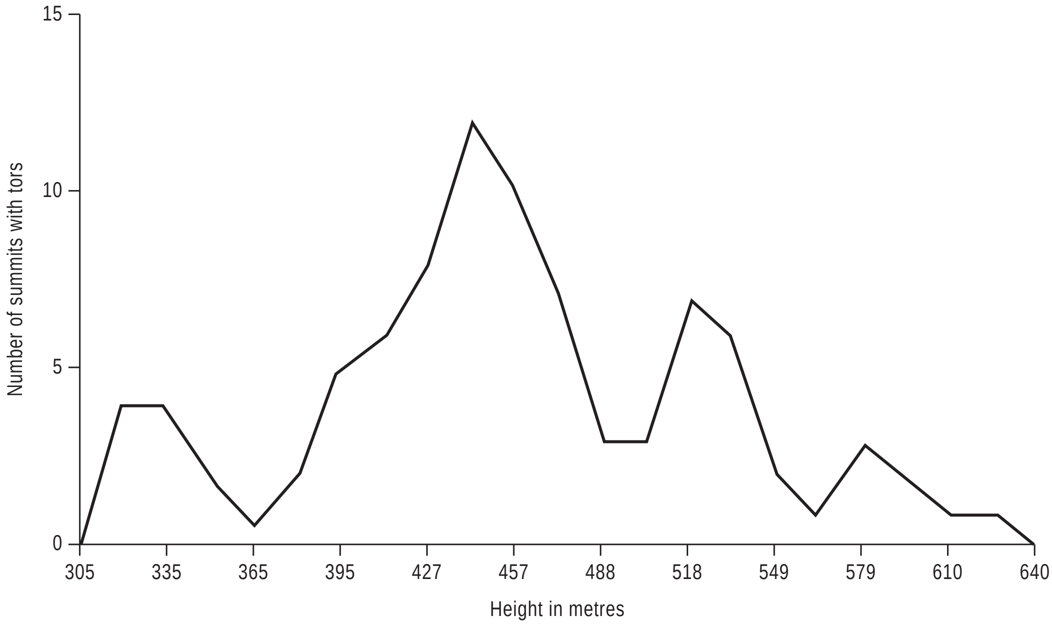


Velocity (m/y)
km
665 Years


Velocity (m/y)
km
1400 Years
92
90
88
86
84
82
80
78
54
56
58
60
62
64
66
16
14
12
10
8
6
4
2
0



Manley 1955
No glaciers
Glaciers
Rea and Evans 2003
1500
1000
500
0
-500
Altitude above the firn line (metres)
0
2000
4000
6000
8000
Summit breadth (metres)


15
10
5
0
Number of summits with tors
305
335
365
395
427
457
488
518
549
579
610
640
Height in metres