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Preliminary report on the Quaternary geology and palaeo-iceflow in the Bridge of Orchy – Glen Lyon area, SW Scottish Highlands – June 2003

Land and Resources Directorate

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BRITISH GEOLOGICAL SURVEY

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Preliminary report on the Quaternary geology and palaeo-iceflow in the Bridge of Orchy – Glen Lyon area, SW Scottish Highlands – June 2003

N R Golledge

Key words

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Front cover

Cover photo shows Beinn Dorain and Beinn an Dothaidh from Beinn Achaladair ridge.

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) concerning the Quaternary geology of an area of the south-west Scottish Highlands, including reconstructions of former iceflow of the Loch Lomond Stadial ice cap. The report summarises the results of four weeks field work in an area of 160 km^2, and highlights areas where future research may prove useful. The work was undertaken as part of the Moine and Dalradian Basins project, a component of the Highlands and Islands Integrated Surveys (E1263S71). An element of the preparatory and fieldwork time was additionally funded by the SIGMA Toolkit project, (E1258S65).

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Summary

This report describes the Quaternary deposits and geomorphology of an area of the south-west Scottish Highlands. Both the deposits and the landforms can be broadly divided into glacial, periglacial and recent in origin. As far as possible the nature of the deposits and landforms are described as seen in the field, and subsequent interpretations are made concerning their mode of genesis and their significance in the spatial context.

The area has been repeatedly affected by glaciation throughout the Devensian, although most of the evidence remaining reflects only the last stage, the Loch Lomond Stadial glaciation. During this c. 1200 year period, an ice cap is thought to have developed on the mountains to the west of Rannoch Moor and at its maximum extent to have overwhelmed the valleys and many of the mountains of the field area. The extent of the former ice cap has been debated over the last 30 years, and an attempt is made here to assess the various models against the field evidence. A new model is consequently proposed, drawing on many of the findings of earlier workers as well as the new data. An ice cap with a maximum surface altitude of at least 850 m O.D. is suggested to have overwhelmed the area, with a generally east and south-east surface gradient. The ice cap most probably grew from rejuvenated ice that survived throughout the preceding Windermere Interstadial in the high corries and valleys. The ice cap became increasingly influenced by topography as deglaciation ensued, and eventually the valleys of the field area were probably occupied by ice that was being maintained by local accumulation areas.

1 Introduction

1.1 AREA

Fieldwork was carried out during the period 4th – 28th June 2003 in a 160 km^2 area of the south-west Highlands from [NN300000 350000] (SW corner) to [NN460000 450000] (NE corner). The land lies to the south-south-east of Rannoch Moor, is bordered in the west by the village of Bridge of Orchy, and is dissected from west to east by Glen Lyon and Glen Lochay. Within the mountainous area are seven peaks that exceed 914 m (3000ft), and considerably more 'tops' of similar size (Figure 1).

Precipitation in the area is approximately 2500 mm pa (Thorp, 1991), mostly falling to the east of the Beinn a' Chreachain – Beinn Achaladair – Beinn a' Chuirn – Beinn a' Chaisteil watershed and draining east through Glens Lyon and Lochay into the river Tay and ultimately to the Firth of Tay at Perth. The natural drainage of Glen Lyon has been dammed at Lubreoch [NN455 416] to create a much-enlarged Loch Lyon, which is used for hydroelectric power. West of the watershed, runoff drains through Glen Orchy to Loch Awe.

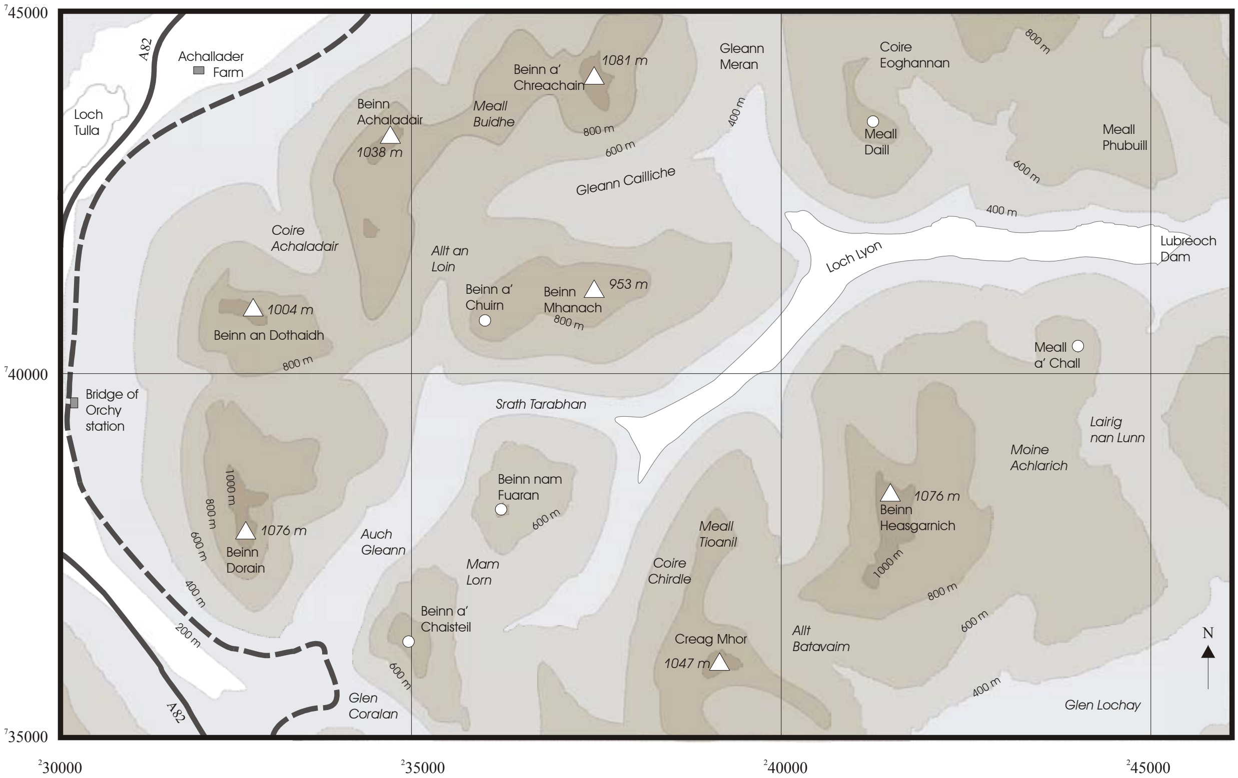

Figure 1: The field area, showing relief (200 m contour intervals), mountain summits, key valleys and lochs. Dashed line shows route of railway.

1.2 LEGACY

Very limited 'Drift' survey had been carried out in the area previously. The existing map (Balquhidder, Sheet 46, 1:63 360, Geological Survey of Scotland, 1900) has a limited number of boundaries marked, generally only alluvium and associated river terraces. A number of striae and roche moutonnée are also recorded. Old Series fieldslips contain a similarly limited amount of information, mainly comprising areal comments such as ‘peat’ or ‘moraines’. The DigMap 50k linework was assessed but deemed too simplistic to be of any use in this survey. This survey was, therefore, almost a primary survey.

1.3 LITERATURE

The area has been similarly neglected in published research, having been the subject of only a small number of Ph.D theses (Thompson, 1972; Horsfield 1983; Thorp, 1984), and cursory consideration by others (e.g. Sissons 1974). North of the area, work has been focussed around Rannoch (e.g. Hinxman *et al.*, 1923; Thorp, 1986, 1987, 1991a), and south around Loch Lomond, (e.g. Rose 1980). Charlesworth, (1955), and Thorp, (1991b), both present regional overviews of the area, but nothing describing the glacial deposits in any detail appears to exist. For a more detailed review of the main research in the area see ‘Quaternary History’ below.

1.4 MAPPING TECHNIQUES

Digital data capture was employed to facilitate rapid mapping and to enable the collection of data to corporate attribution levels. The system used was a Compaq iPAQ 3850 PDA with an ‘Expansion pack’ holding a 128MB Compact Flash card. The Windows CE operating system enabled ESRI ArcPad 6.0.2 to be installed. Data was compiled prior to fieldwork using PC-based ArcGIS 8.3, and exported to ArcPad format using the dedicated tools. Forms were created automatically to enable attribution to be entered in the field for each feature captured. Dropdown menus for rapid population of the forms were generated from GSD dictionary tables to ensure corporate compatibility and effective post-fieldwork data processing. Due to the extent of the field area, Ordnance Survey MasterMap (vector) and Profile (contour) data was used in preference to raster basemaps, allowing quicker screen refresh when panning and zooming between views. A certain amount of pre-processing was necessary to ensure the most effective display of this data, and was carried out under the SIGMA project. Point data was captured directly from a GPS connection (Garmin eTrex via serial port) and attributed accordingly. Linework was initially also captured into separate attributed shapefiles, but was found to be slow when swapping between layers. Subsequently, freehand lines were used to ‘draw’ the map in the same way as a pencil and paper. This far more intuitive method requires later attribution and possible re-capture of many of the lines, but enables a far more efficient means of data capture in the field, and provides much better visual cues when mapping.

2 Overview of the superficial geology

The area, as described above, is one of high mountains and deep ‘U’-shaped valleys typical of a glacially-modified landscape (Figure 2). The high ground is commonly barren bedrock, locally ice-smoothed in places, and elsewhere mantled with thin regolith of frost-shattered rock debris. Where gravitational processes have affected this debris, solifluction terraces can be seen. Scree (talus) derived from frost-shattered rock accumulates on many of the steep slopes directly below rockfaces, and in a number of localities forms cones of angular debris. The lower slopes are variably covered in till, often thin on the valley sides and thick on the valley floors, particularly at valley confluences. Superimposed on the till in many places are moraine mounds of varying sizes and composition, reflecting former ice margin positions. Ice-contact deposits of sand and gravel are also seen in one or two localities. At a limited number of places, glaciofluvial deposits were seen between till sheets or incorporated into moraines. Minor deposits of laminated (glaciolacustrine) sediments were also seen, commonly in association with ice-marginal landforms. Many of the glacial deposits have been gullied and eroded by Holocene processes, producing alluvium and alluvial fans and terraces, and in areas of poorly-drained ground peat has accumulated.

Figure 2: The 'U'-shaped valley of Auch Gleann, looking south from Beinn Mhanach.

3 Description and occurrence of Quaternary deposits

3.1 BEDROCK AT OR NEAR SURFACE

The density of high mountains means that bedrock is commonly exposed or very close to the surface in a large part of the field area. Large areas were mapped where valley-sides or mountain tops were seen to have little or no drift cover. Bedrock was found to outcrop even on the lower slopes of certain valleys, mantled only by a thin layer of till or head, for example along both sides of Auch Gleann, the slopes of Gleann Coralan below Beinn Chaorach, and along the east side of Gleann Meran. An area of linear mounds north-east of Beinn Heasgarnich, originally interpreted (from air photos) as constructional ice-marginal features, were found to be mainly bedrock ridges, probably eroded along strike by glacial meltwater. Bedrock is also commonly exposed in stream gullies and river beds, and at one or two localities forms gorges, for example in upper Gleann Coralan and around Sidh Trom'aidh in Gleann Meran. Frost-shattered bedrock is common on the higher summits, and that it is essentially *in situ* is demonstrated by fractured quartz veins with well-defined margins, as seen in Figure 3.

Figure 3: Frost-shattered *in situ* quartz vein, Beinn Achaladair summit.

The occurrence of such frost-shattered bedrock is indicative of prolonged exposure to freeze-thaw processes, and indeed its presence has been employed (together with other evidence) as an indicator that the locality was ice-free during the last glacial period, the Loch Lomond Stadial (LLS), (e.g. Thorp 1986). Conversely, areas where the bedrock has been obviously smoothed are used as evidence that they were below the last glaciers. The nature of smoothing, in particular the presence of any asymmetry, is important in reconstructing ice-flow directions across the many cols and spurs in the area (see *Geomorphology* below).

3.2 HEAD / REGOLITH

Where bedrock is shattered *in situ* as described above, a mantle of disaggregated rock may develop at the surface, forming regolith. Progressive weathering leads to further shattering and deepening of this mantle, which may therefore consist of large blocks, gravel-grade material, and smaller amounts of interstitial fines. The latter are, however, commonly removed by the winnowing effect of the high winds typical of mountain summits. The remaining blocks are typically angular (A) or very angular (VA) (*sensu* Benn and Ballantyne, 1993), unless composed of a coarse crystalline material such as granite, which readily weathers by granular disintegration. Blocky regolith is not widespread in the region, but is well developed in the psammite and mica-schist at around 950 m O.D. on Beinn Mhanach (Figure 4). Frost-heave may affect such regolith to produce patterned ground, principally stone polygons. Such features were only observed at one locality, [NN35957 43830], at c. 970 m O.D. west of Beinn a' Creachain summit.

Figure 4: Blocky, angular psammite regolith, Beinn Mhanach.

Downslope movement of disaggregated bedrock may take place through solifluction (soil creep) or gelifluction (frost heave), or a combination of the two. Where this occurs, terraces or lobes may build up with sub-horizontal 'treads' and steep downslope 'risers'. Reverse-sorting (resulting from the settling of fines through pore spaces) produces the kind of terrace seen on Beinn Mhanach (Figure 5).

Figure 5: An active solifluction terrace, Beinn Mhanach. Trenching tool (left) for scale.

On steeper slopes, repeated surface wash, soil creep, frost heave, rockfall and occasional small-scale landsliping can produce heterolithic deposits that loosely resemble the parent material and form a variably thick mantle over large areas, without forming any distinctive feature. Such head deposits are ubiquitous, and a pragmatic approach is essential in Highland mapping to avoid over-representation. Thus head is only mapped where it forms a significant and distinct unit. Soliflucted till is generally mapped as till, as this is deemed more useful to the end user. An example of such a deposit, from Glen Lyon, is shown in Figure 6.

Figure 6: Soliflucted till and slope wash over till, Glen Lyon.

3.3 TILL

The term 'till' embraces all diamictons of glacial origin, and can therefore refer to significantly different materials. Three distinct diamictons were identified in the field area, although each is highly variable in texture and composition.

3.3.1 'Morainic' diamicton

This silt and sand, olive-brown or light olive brown (2.5Y 4/4 – 5/6)[1] diamicton is characteristically friable, though more consolidated patches are locally evident. Variably clast-rich, many clasts are sub-angular (SA) although some A and VA clasts are also often seen. Most of the represented lithologies are local metasediments, including mica-schist, quartzite and pelite, which tends to decompose easily. Large boulders are often seen in the deposit. The unit is often the uppermost in a section, is commonly the main component of moraine mounds, and is nearly always stained by iron (orange) or manganese (black) to some degree. It is thought to represent the 'meltout', 'stagnation' or ice-marginal till of the last (LLS) glaciers.

[1] Munsell Soil Colour

3.3.2 Olive-brown till

The most widespread of the till types, this diamicton is likely to represent the sub-glacial till of the last (LLS) glaciers. Although similar in colour to the morainic diamicton, this light olive brown (2.5Y 5/4 – 5/6) firm, silty deposit is characteristically different in that it is considerably more coherent. Oxide staining is typically less pervasive, probably because seepage and throughflow of surface water is impeded by its greater consolidation, finer matrix grain size and consequent lower permeability. Clasts incorporated into the deposit are generally local metasediments of similar provenance to those in the morainic deposits, but typically smaller and less abundant, with almost all clasts being SA.

3.3.3 Grey till

The least often seen till is a blue-grey or greenish-grey (5GY 5/1) clay or silt matrix diamicton containing rounded (R), sub-rounded (SR) or SA clasts (Figure 7). When dug, the till cleaves along distinct, though random, fracture planes. The deposit is variably clast-rich but always appears to be very well consolidated. A section in Allt Tarsuinn, east of Beinn Heasgarnich, exposed a highly weathered upper surface to the grey till, with extensive iron-staining and manganese pans up to 3 cm thick. In Glen Coralan, a raft of the grey till appears to have been incorporated into a later deposit, whilst elsewhere the variable colour of the olive-brown till may in part be due to reworking of this grey till. It is tentatively suggested that the grey till represents the sub-glacial till of the Main Late Devensian (MLD) glaciation, and has been only locally preserved in areas where erosion by LLS glaciers has been restricted. Thorp, (1987), proposed that the Glen Lyon area was the location of one of 3 main domes within the MLD ice centre around Rannoch, and that ice flowed outward from there. It is possible that the grey colour of the till may therefore reflect local rock types, in particular the black, graphitic, Ben Eagach schist. Geochemical analysis may be able to determine whether this is, in fact, the case.

Figure 7: Grey till, Glen Coralan.

Although the tills are considerably different in character, it is not possible to map out individual types unless they form distinctive landforms, such as moraines. The grey till appears to be very restricted in preservation, and may therefore be impossible to map with confidence. Consequently, where areas of till are mapped, they are thought to be mainly comprised of the olive-brown till. Generally, the till is thin on valley sides (< 2 m thick), and bedrock is frequently seen cropping out low down the slopes, for example in Auch Gleann and Glen Coralan. Valley floors may have thin margins of thick till along their sides, but in the majority of glens, fluvial erosion has removed most of the former deposits. One or two areas of notably thick till do occur, however. The confluence of Gleann Cumhang and Glen Coralan, for example, is choked with a c. 10 m thick wedge of mainly grey till with olive brown till on top. When viewed from above, it is clear that the reasonably flat till surface dips gently to the west-north-west, down Glen Coralan. The till mass is deeply dissected by both the Allt Coralan and other, west-trending, channels. It is likely that this material was emplaced in a sub-glacial accretionary environment by decelerating ice, and was later dissected by sub- or proglacial drainage channels, perhaps during LLS deglaciation. Directly to the north, another area of thick till is evident below Mam Lorn, and is dissected by the Abhainn Ghlas flowing north-east into Loch Lyon. On the south side of Glen Lyon, the lower slopes are mantled in variably thick till augmented by overlying morainic deposits. The thickest deposits occur south of Lubreoch Dam at the mouth of the Allt Lairig nan Lunn.

3.4 HUMMOCKY MOUNDY GLACIAL DEPOSITS (MORAINE)

As described above, morainic deposits are composed generally of a friable sandy diamicton. However, there are a number of localities where the heterogeneity of the features is exemplified. For example, sections exposed at c. 550 m O.D. in the Allt an Loin (e.g. [NN352 410]), directly west of Beinn a' Chuirn, illustrate that laminated clay and silt deposited in ice-marginal ponds were commonly 'bulldozed' more-or-less intact into moraines, where diamictons were subsequently emplaced above, (most probably as debris flows from the ice margin) (Figure 8). Such tectonic activity may have occurred some distance proglacially, (through forward propagation of shear stress), but nonetheless confirms that ice retreat, even in the latest stages of deglaciation, was an active process at these altitudes.

Figure 8: Moraine section including highly disrupted laminated silt and clay overlying coarse sand, Allt an Loin.

A similar, perhaps more dramatic example of such ice-marginal tectonics can be seen in Glen Lyon, at the mouth of the Allt Chall [NN4324 4151]. Here, an almost undisturbed raft of bedded sand has been thrust and tectonically emplaced with an erosional lower contact on top of a bouldery diamicton, and has subsequently been buried by a further, clast-rich diamicton (Figure 9). Also on the south side of Glen Lyon [NN4418 4170] is an exposure in ice-marginal sediments that shows bedded, normally-graded outwash that has been substantially folded, most probably by proglacial 'shunting' as the ice margin oscillated (Figure 10). 'Active retreat' therefore seems to have been typical of the waning LLS glaciers in the Glen Lyon region.

Figure 9: Rafted bedded sand unit overlain by angular bouldery diamicton, Glen Lyon.

Figure 10: Folded bedded sand and gravel outwash forming push moraine, Glen Lyon.

The landforms are similarly highly variable, ranging from well developed boulder-topped ridges 10 – 15 m high, as in Srath Tarabhan, to poorly-lineated boulder accumulations formed by rockfall onto the ice margin, as seen on the south-west slopes below Meall a' Chall. Groups of clearly aligned, linear moraine ridges are seen around Badour [NN431 353] and Batavaime [NN422 347] in Glen Lochay, whilst in Auch Gleann the moraine mounds tend to form more ill-defined, bouldery moraine mound complexes.

3.5 GLACIOFLUVIAL AND GLACIOLACUSTRINE DEPOSITS

3.5.1 Ice-contact deposits

Glaciofluvial deposits are limited in extent in the mapped area, and are confined to the head of Auch Gleann, the floor of Glen Lochay, and to Glen Lyon, near Pubil [NN462 421]. The majority of deposits consist of ice-contact mounds of sand and gravel formed subglacially in glacier sole cavities. The linear ridges at the head of Auch Gleann, for example, are interpreted as eskers and reflect subglacial drainage to the south and south-east, somewhat across the valley. One of these particularly well-formed steep-sided ridges [NN354 393] has been dissected by subsequent river action, but its linear trend is still evident. No sections were seen in any of the landforms, however. The deposits in Glens Lyon and Lochay are similarly limited to ice-contact kamiform mounds and valley-parallel esker-like ridges.

3.5.2 Fan deposits

Glaciofluvial fans have been mapped where large fan deposits are found in localities where modern fluvial activity seems inadequate to explain their size. For example, the large, relict fan below Coire na h-Annait in Auch Gleann [NN346 381] is most satisfactorily explained as a glaciofluvial fan formed in the late stages of deglaciation when the main valley was ice free, but ice still sat in the corrie at 500 – 700m O.D. The fan has been partially reworked and recent alluvial fans have developed at its margins. Of greater interest, however, are the four flat-topped, sloping fan fragments seen between 300 and 370 m O.D. on the east side of Allt Coire Achaladair (Figure 11).

Figure 11: Ice-contact (?) fan terraces, Coire Achaladair.

Little of the fans remain, having been largely reworked, but a section at c. 360 – 70 m proved bedded sand and gravel dipping gently downslope (Figure 12). Their formation must predate that of the Tulla delta (see below), as they are significantly laterally reworked, whilst the delta below is not. Since the delta is thought to have been deposited into an ice-dammed lake during deglaciation at the end of the LLS, the higher fans must relate to a time when ice was still present in the main valley, or when the lake was just beginning to form. The lower terraces may relate to the lake levels of 332, 323m, 319m and 315m, whilst the highest terrace may have built up against the former ice surface much earlier. The angular nature of the constituent debris suggests that fluvial travel has been limited, but that it was deposited fluvially is evidenced by the clearly bedded nature of the material. Further work may be required to determine the formation of these features.

Figure 12: Interbedded sand and angular gravel and cobbles, ice-contact (?) fan, Coire Achaladair.

3.5.3 Sheet deposits

No glaciofluvial sheet deposits were mapped.

3.5.4 Glaciolacustrine deposits

Small areas of glaciolacustrine deposits forming at the ice margin have been mentioned above, and appear to have been common during deglaciation of the area. In Auch Gleann, several small exposures of laminated silt and sand were seen, although these are limited in areal extent. Figure 13 illustrates the kind of sediments seen in lower Auch Gleann.

Figure 13: Glaciolacustrine laminated silt and fine sand, Auch Gleann.

3.5.5 Glacial Lake Tulla

The chief interest in the area is the former 'Glacial Lake Tulla' and its associated shorelines and impressive delta on the hillside south of Achallader farm, first noted by Milne, (1847). Several authors have described these features (Hinxman *et al.*, 1923; Mathieson & Bailey 1925; Gregory, 1926; Charlesworth 1955), and the history of the lake is summarised effectively by Ballantyne (1979, 1992). Westward retreating ice dammed meltwater in the depression to the east between Ghlas Beinn and Beinn Achaladair, leading to the formation of shorelines at 332, 323m, 319m, 315m and finally at 248m as the retreating Rannoch Moor ice exposed cols at these heights. The delta formed (presumably) from sediment input from meltwater streams exiting a corrie glacier in Coire Daingean on the north side of Beinn an Dothaidh, also the most likely source for the fans described above. Interestingly, Ballantyne (1979) suggests that the 332 m shoreline may have been formed by a pond between the hillside and the still present, but wasting, ice margin. Up to 6m of laminated sediments are known to exist below alluvium on the floodplain of the present Water of Tulla (Ballantyne, 1992). Laminated sediments were also seen recently exposed in a track-side cutting 0.5 km west of Achallader farm.

3.6 ALLUVIUM

Alluvial deposits are common throughout the mapped area, forming fans, terraces and bouldery spreads. Upland mountain streams typically form steep, bouldery deposits of R and SR cobbles, whilst those lower down meander more extensively and deposit gravel, sand and silt. Many of the valleys exhibit floodplains that are composed of interbedded alluvium and peat, formed when channel migration results in changes in the depositional regime. The floodplain in Glen Lochay reaches a maximum width of c. 300 m near Botaurnie [NN489 368] and in Glen Lyon c. 400 m near Pubil [NN468 418]. A section in a large alluvial fan is exposed in Gleann Meran [NN395 425], and constitutes soft sand and silt beds, and firmer clay layers (Figure 14).

Figure 14: Bedded sand, silt and clay with organic layers, alluvial fan, Gleann Meran.

Shoreface alluvium is widespread around the margins of Loch Lyon, and is exposed when the reservoir level is sufficiently low. Beach terraces and strand lines are evident, and a degree of grain size sorting is seen (Figure 15).

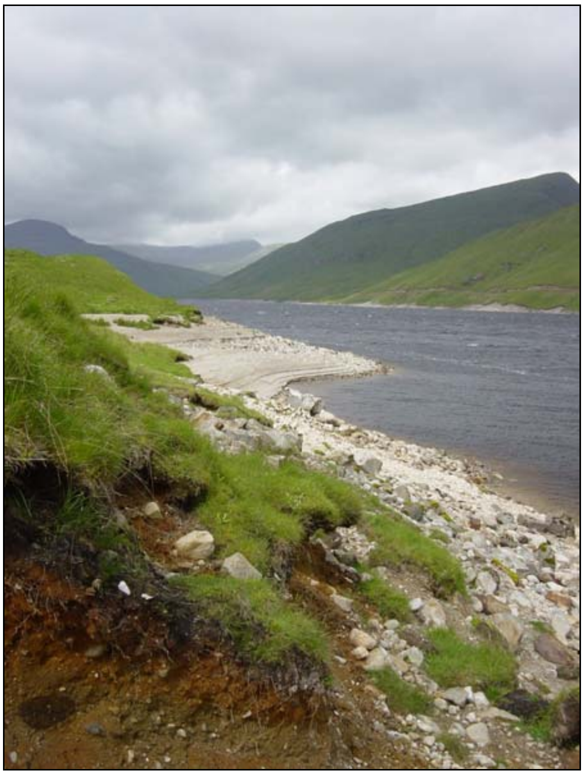

Figure 15: Shoreface sand, gravel and cobble alluvium, Glen Lyon, looking west.

3.7 PEAT

Many of the hillsides are variably covered with peat, ranging from a thin layer of peaty soil to thick, woody, fibrous peat containing abundant pine stumps. Particularly peaty areas are found along much of Allt Batavaim around the watershed between Creag Mhor and Sron Tairbh [NN39 36], and up onto the col at Coire an t-Sneachda [NN38 37]. The east flanks of Beinn Heasgarnich are especially boggy between the boulder and bedrock mounds at Moine Achlarich and Coire Ban Beag [NN43 39]. The flat watershed north of Sidh Trom'aidh in Gleann Meran [NN39 44] is similarly covered in deep peat, as is the 'bench' at 550 – 600 m on the south side of Gleann Cailliche below Beinn Mhanach [NN37 42].

4 Geomorphology

The mapped area has abundant and varied geomorphological features, ranging from purely erosional examples such as the corries and nunataks to the entirely depositional moraines, eskers and fans, and composite features such as the characteristic 'U'-shaped valleys. Whilst the majority of features are glacial in origin and therefore 'relict', current processes are still sufficiently active to significantly modify the landscape.

4.1 CORRIES

Corries are bowl-shaped erosional bedrock depressions high on the mountainsides that once acted as accumulation areas for snow and consequently glacier ice. Rotational ice flow within the corrie results in plucking of the backwall and floor, accentuating the overall form. Corries with well-developed form are sparse in the field area, perhaps the best example being Coire an Lochain on the north side of Beinn a' Chreachain. Coire nan Clach on the south side of Beinn Achaladair has several well-developed arcuate boulder-topped ridges trending transversely to the natural gradient, and these are interpreted as moraines from the last retreating glaciers as they wasted back into their original source areas, although this was probably on the high ground above the corrie itself. Others either form wider, less well-defined bowls, such as Coire a' Mhath ghamhna south-east of Beinn a' Chreachain, or more elongate valleys, such as Coire a' Ghabhalaich south of Beinn an Dothaidh. Some, such as Coire Ban Mor and Coire Ban Beag east of Beinn Heasgarnich have little to define them as true corries, indeed in the latter case ice flowed into and over it, rather than out of it.

4.2 NUNATAKS / ARÊTES

Peaks projecting above the ice surface, nunataks, and ridges connecting these peaks, arêtes, are commonly identified by their lack of glacial deposits or evidence of glacial erosion, and by the presence instead of abundant frost-shattered bedrock and periglacial features. These criteria were used, with others, by Thorp, (1981, 1984, 1986) to propose that such 'trimlines' could be used to determine the upper limit of the last ice sheet to within < 60 m. This model was considered to a certain extent during the mapping, but only at a broad scale due to the speed of reconnaissance. Cols were deemed of particular importance in determining palaeo-iceflow. The lack of abundant angular regolith above the 744 m col between Beinn Dorain and Beinn an Dothaidh suggests that ice overwhelmed this col at one point, although this does not accord with the proposed 700 m upper limit of LLS ice in the Tulla basin of Thorp (1986). The col at 755 m above Coire Daingean (c. 2 km north-east) also appears to have been overtopped (A. G. Leslie, *pers. comm.*).

The Beinn Dorain – Beinn a' Chreachain ridge therefore served as only a partial barrier to the main ice mass centred on Rannoch Moor and filling the Tulla Basin.

The summits of Beinn a' Chuirn and Beinn Mhanach were ice-free, and it is possible that both Beinn nam Fuaran and Beinn a' Chaisteil were only covered by very thin (probably cold-based) ice (< 50 m thick). The 546 m col between these latter two summits was definitely overridden by warm-based, thicker ice, as is evidenced by abundant ice-smoothed bedrock, striae orientated 334° - 154°, and lateral moraines with associated meltwater channels on the north and south hillslopes. Further east, the generally east or south-east sloping ice stream was bolstered by input from the extensive high ground (snow and ice accumulation zones) around Beinn Heasgarnich, Meall Buidhe, and Creag Mhor. The upper peaks of Heasgarnich and Creag Mhor were probably nunataks, but the more rounded summit of Meall Buidhe might well have accumulated ice. The 804m col north of Creag Mhor appears to have low, smooth-topped bouldery ridges along much of its length, but their origin is ambiguous as they appear to coincide with local strike of the bedrock. It is possible that they represent landforms predating the LLS, and were streamlined by LLS ice overtopping the col. The presence of R and SR boulders of varying lithologies suggest that they are not just composed of *in situ* weathered rock. To the east of the col, moraine orientations suggest that ice flowed across Coire an t-Sneachda and then divided, some flowing north down Fionn a' Ghlinne and the rest flowed south down Allt Batavaim, and from there into the main drainage route of Glen Lochay.

4.3 BENCHES

Lateral benches cut into till or bedrock by ice marginal drainage are abundant on many of the hillslopes in the area. Such benches are useful in reconstructing former ice margin positions, and their angle of inclination gives clues as to the direction of dip and gradient of the former ice surface. Good examples exist on the north-west flanks of the Beinn a' Chuirn – Beinn Mhanach massif, which appear to dip both north-eastward and southward from the watershed. It seems likely, therefore, that this area was one of ice divergence. A key problem in assessing the importance of sub-parallel linear features in an area dominated by metasedimentary bedrock is that the benches may reflect preferential weathering along strike of less resistant lithologies. This is particularly difficult in the east of the mapped area, around Beinn Heasgarnich and Creag Mhor, where the bedrock is predominantly Ben Lawers schist, which characteristically forms particularly 'lumpy' ground. Thus few benches were mapped in the eastern area.

4.4 MELTWATER CHANNELS

Sub-glacial channels cut through till have been mentioned previously. It is possible that the bedrock-cut slot gorge in upper Glen Coralan is also a sub-glacial feature, perhaps exploiting a joint or other linear weakness in the rock. Ice-marginal meltwater channels have also been described above, as they tend to exist as 'half-channels', where one side is cut in ice, and hence form benches. Latero-frontal moraine systems are associated with significant drainage, often arcuate and downslope, and have been mapped on the lower western slopes of Gleann Meran, the southern slopes of Srath Tarabhan, and the north-eastern side of Allt Batavaim [NN40 36]. No overflow channels were mapped.

4.5 SHORELINES

Shorelines relating to glacial lakes have been recorded only around the northern flanks of Beinn Achaladair where Glacial Lake Tulla was ponded during LLS deglaciation. These have already been described above.

4.6 LANDSLIPS

A number of landslips of varying sizes were seen in the field area. The most obvious and easily distinguishable is the failure of Coire Chirdle on the west side of Creag Mhor, where an almost perfectly arcuate backscarp is visible between 600 – 800 m O.D. The collapsed strata have remained coherent and little disruption is evident. The landslip is approximately 1300 m in width but appears to have slipped only a few tens of metres downslope. Less immediately obvious is a landslip almost directly opposite, on the south-east side of Beinn nam Fuaran, between c. 500 – 600 m O.D. (Figure 16). The collapsed material is highly disrupted and forms irregular, moundy topography.

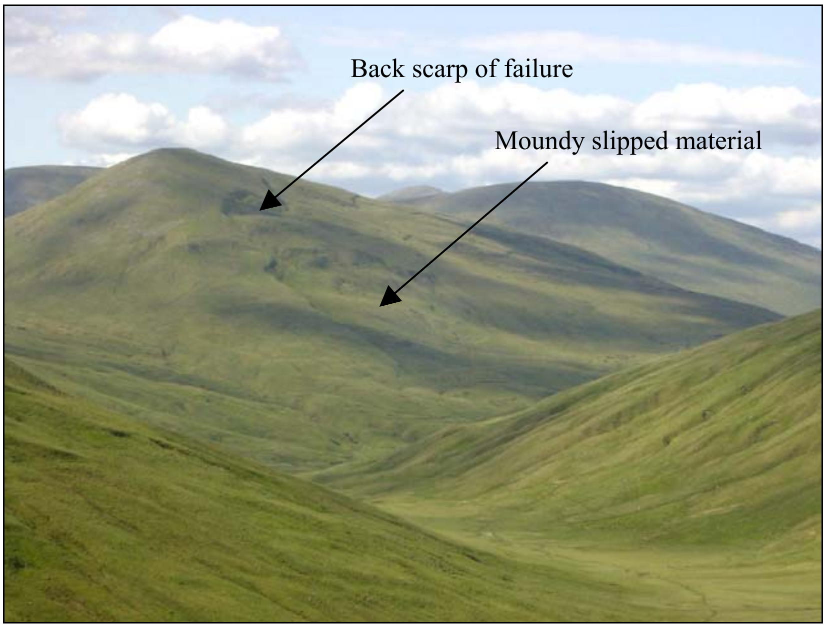

Figure 16: Rock slope failure on east side of Beinn nam Fuaran.

Other examples were seen on Beinn Chaorach, at [NN353 335], and on Beinn a' Chuirn at [NN356 406]. In addition, numerous smaller slumps and slides in superficial deposits were seen. Other workers have identified landslips elsewhere in this area, for example on Beinn Odhar, Beinn Challum, Beinn a' Chaisteil and in Gleann Meran (D. Jarman, *pers.comm.*). A review by Ballantyne, (1986) identified 740 landslides or areas of sliding in Scotland, which can be divided into four main types – non-rotational rock slope failures (RSF), rotational RSF, debris flows, and translational slides in drift or regolith. The first category are suggested to be particularly common in Highland metamorphic rocks, especially schists, and include major rockfalls, rock topples, translational slides and rock sags, often in combination. A more local study suggests that the typical mode of failure in this part of the Highlands is the 'short-travel, semi-intact or coherent arrested slide' (Jarman, 2003).

The distribution of non-rotational RSF, or Category 1 landslides, is closely related to occurrence of Moine and Dalradian metamorphic lithologies, particularly schists, (Ballantyne 1986 and refs therein). This is possibly a result of the lower friction angle of schist compared to granites, for example, and the foliation planes of schist that may form shear planes if dipping into a valley (Holmes 1984). Clustering of landslides is evident in some areas, with approximately a quarter of the > 600 RSF identified in the Scottish Highlands by Ballantyne, (1986), occurring within 30 km of the Highland Boundary Fault west of the Tay (Jarman, 2003). In the recently mapped area, the landslides identified in the field and those reported by Jarman appear to cluster to some extent along segments of the Tyndrum Fault or associated splays (Figure 17).

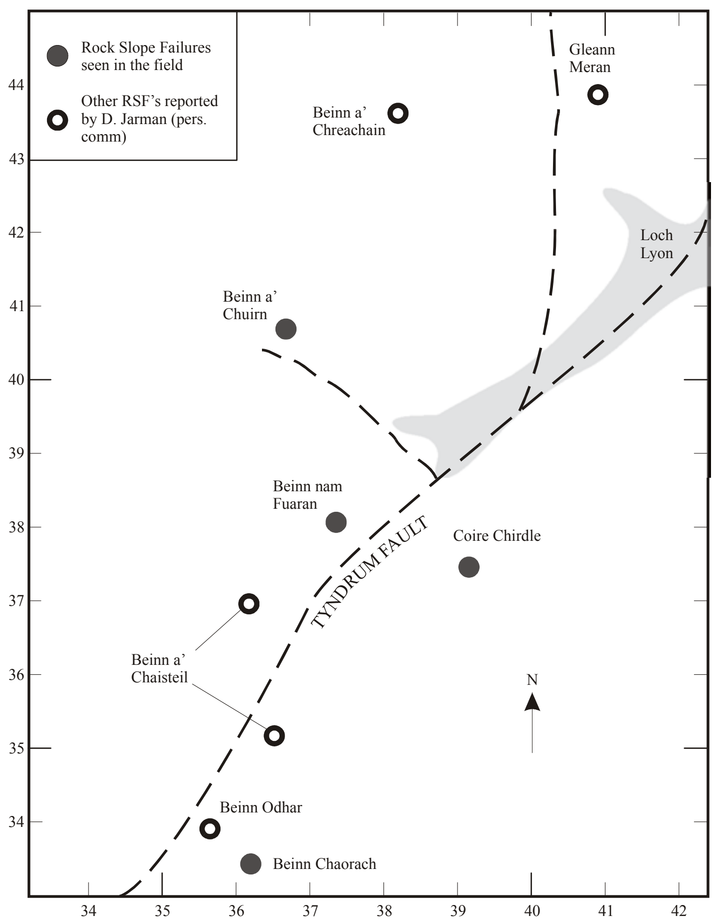

Figure 17: The distribution of Rock Slope Failures in the field area, in relation to the Tyndrum Fault and associated structures.

Although the Scottish Highlands are thought to have been affected by increased seismotectonic activity following MLD deglaciation (Firth and Stewart, 2000), a seismic trigger for landsliding, such as proposed by Ringrose (1989), is generally thought unlikely (Ballantyne, 1986, Jarman, 2003). The correlation between faults and the occurrence of landslides may nevertheless be real, but may simply reflect areas of structurally weakened rock. In general, however, RSF's are likely to occur where valley slopes have been oversteepened by glacial erosion, as this leads to greater slope stresses and consequently a higher likelihood of failure. The relative absence of RSF's in mature valleys may indicate that these glens have readjusted incrementally to post-Tertiary changes in baselevel through progressive glaciations and fluvial periods, whilst valleys resulting from recent breaching and overdeepening are much more likely to show evidence of post-LLS RSF's. Indeed, it may be possible to use the distribution of RSF's to indicate areas of recent breaching (Jarman, 2003). The ages of these failures are uncertain, although it is reasonable to assume that rapid stress release following deglaciation might predispose oversteepened slopes to incipient failure. The trigger would most likely be a period of high rainfall.

4.7 ICE-MOULDING / STRIAE / ROCHE MOUTONNÉE / PERCHED BOULDERS

The metasedimentary rocks that dominate the field area are easily weathered and fracture along foliation planes, producing smooth surfaces even without further erosion. Identifying glacially-smoothed bedrock and striae therefore becomes quite challenging. In the former case, ice-smoothed bedrock was only recorded where there was evidence that the abrasion extended *across* bedding or foliation planes, and where the smoothing appeared to affect the more resistant psammitic beds as well. In some cases, the absence of fractured rock in combination with the above was taken as an indication that the surface had been glacially smoothed. Where two contrasting surfaces are seen within the same lithology, this evidence is fairly convincing, (Figures 18 and 19).

Figure 18: Ice-smoothed bedrock, Beinn Achaladair – Meall Buidhe ridge.

Figure 19: Angular, frost-shattered bedrock, Meall Buidhe.

Striae were only seen at one locality, on Mam Lorn on the east side of Auch Gleann, and were confirmed as such due to their cross-cutting of all lithological / structural lineations seen in the surrounding rock. Roches moutonnée are more numerous, but seem to be confined to particular areas. The majority occur along the ridge at [NN444 388] east of Beinn Heasgarnich, which is composed of thinly bedded garnetiferous mica-schist of the Ben Lui Schist Formation, and has been extensively glacially-smoothed. Significantly, the direction of flow across these outcrops appears to change along the length of the ridge, from 079° – 132°. In the context of their location, these palaeo iceflow indicators suggest divergent ice flow across this watershed area, most probably as a result of (at least partial) deflection by the 806 m high Meall nan Subh. That the surfaces have been glacially-smoothed is further evidenced by the occurrence of perched boulders of Ben Lawers Schist Formation hornblende schist on one or two of them, (Figure 20).

Figure 20: Perched boulder of Ben Lawers Schist Formation hornblende schist resting on Ben Lui Schist Formation mica-schist, Lairig nan Lunn.

4.8 MORAINES AND STREAMLINED MOUNDS

Clear constructional moraines formed at former ice margins are relatively few in the field area. Numerous small mounds are present in many of the glens, but are typically dissected by Holocene slope gullying or are poorly defined as a result of post-depositional settling and later infilling of hollows with peat. Whilst still useful in establishing palaeo-iceflow and the nature of deglaciation, only where sections are available are they of any significant interest. The most well-developed moraines are the two 10 m high elongate ridges in Srath Tarabhan. These steep-sided ridges have bouldery crests and slopes, trend across the valley and their position suggests that ice retreated westwards along Srath Tarabhan, most probably back towards Coire a' Ghabhalaich. A number of arcuate, cross-valley ridges in Glen Coralan are also interpreted as moraines, based on an exposure in diamictons and bedded sand and gravel at [NRG148] [NN34561 35203]. Their overall morphology has been obscured, however, by paraglacial valley-side debris flows and peat infilling of hollows. A particularly well-developed system of retreat moraines was seen on the south side of Glen Lochay, near Batavaime, but was not investigated.

Of potentially greater significance than the moraines described above are the low, smooth-topped streamlined mounds seen in valleys on the north side of Glen Lyon, and on the 638 m col north of Beinn Chaorach. In Coire Eoghannan (north of Loch Lyon) the ubiquitous cross-valley mounds are smooth-topped, bouldery in places, and appear to exhibit a secondary, imposed, down-valley orientation. This drumlinisation of existing deposits is thought to be indicative of LLS glacier-advance over pre-existing (MLD) moraine suites (Wilson and Evans, 2001), and has been noted elsewhere in Scotland (T. Bradwell, *pers. comm.*). These streamlined mounds occur from the 765 m col south of Meall na Feith' Faide south-eastwards along much of the length of Coire Eoghannan (Figure 21). Less well developed examples occur in the adjacent valley to the east, and on the 638 m col north of Beinn Chaorach. This implies that these areas were overwhelmed by warm-based, relatively fast-flowing ice subsequent to initial formation of the mounds. This evidence for warm-based ice overriding the Coire Eoghannan col at 765 m during the LLS is clearly at odds with the 700 m upper limit of ice in the Tulla area proposed by Thorp (1986).

Figure 21: Elongate, streamlined mounds, col west of Coire Eoghannan.

4.9 ESKERS

The linear mounds at the head of Auch Gleann are poorly exposed, and so their composition is unknown. Many of the mounds are thought to be moraines, but two of the ridges are aligned in such a way as to require an alternative explanation. It is suggested, therefore, that the ridges at [NN35189 38939] and [NN35406 39289] are eskers, formed by sub-glacial deposition of sand and gravel in drainage channels cut in basal ice. Their orientation suggests that at the time of formation, late in deglaciation, drainage was generally towards the south-south-east and south-east. The ridges are c. 100 m and c. 250 m long respectively, and approximately 5 m high. A scraping in the former revealed friable sand and gravel.

Table 1, below, summarises some of the most important geomorphological features in the field area, and the implications for the presence of LLS at each locality.

Evidence of the presence of LLS ice			*Evidence of the absence of LLS ice*		
Feature	Grid reference	Height (m O.D.)	Feature	Grid reference	Height (m O.D.)
1) Streamlined mounds above Coire Eoghannan	[NN412 447]	765	1) Ben Lawers Schist Formation erratics west of Beinn a' Chreachain	[NN367 442]	940
2) Mounded deposits on col north of Creag Mhor	[NN388 372]	804	2) Regolith near Beinn Mhanach summit	[NN369 412]	890
3) East-south-east ice flow over Moine Achlarich	[NN434 395]	660	3) Regolith on Meall Daill	[NN409 441]	810
4) Ice-smoothed bedrock on cols at Coire an Dothaidh Coire Daingean Bealach an Aoghlain	[NN325 398] [NN340 405] [NN354 434]	744 750 813	4) Frost-shattered *in situ* quartz vein on Beinn Achaladair	[NN346 433]	1030
5) Ice-marginal benches, north side of Beinn a' Chuirn	[NN360 413]	780	5) Fossil stone polygons on Meall Buidhe	[NN360 438]	970
6) Lateral moraine, Coire a' Mhath-ghamhna	[NN365 433]	730	6) Frost-shattered bedrock on Meall Buidhe	[NN364 442]	970
Maximum height	=	**813**	*Minimum height*	=	**810**

Table 1: Geomorphological features in the field area

5 Quaternary history

5.1 PREVIOUS RESEARCH

5.1.1 Geological Survey

Mapping undertaken by the Geological Survey on Sheet 54 (to the north of the recently mapped area) led Hinxman *et al.*, (1923) to propose a relatively simple, two stage model of glaciation for the region. Using striae, the distribution of granite erratics and the orientation and position of moraines, they suggested that early in the glacial period the axis of ice dispersion lay in the region of the western margin of the Moor of Rannoch. During this phase, only the highest peaks in the area were exposed above the ice sheet, which they estimated to have attained a thickness of at least 2000' (c. 606 m) over the centre of the Moor. They envisaged that during a second phase, following the Last Glacial Maximum (LGM), gradual thinning of the ice led to increased topographic control being exerted on the ice sheet, channelling its drainage eastward through the valleys of the Treig, Ossian, Ericht and Rannoch. This system of large valley glaciers (topographic ice streams) was thought not to have existed west of the ice-shed, where instead the steeper relief may have promoted smaller, more dynamic ice cap outlet glaciers. Importantly, Hinxman *et al*., (1923) considered Glen Lyon to have been filled by ice emanating from the high ground surrounding the glen, and mention the absence of Rannoch granite erratics in the area as evidence against the incursion of ice from Rannoch Moor, and by implication, the mountains to the west.

5.1.2 K.S.R. Thompson

The thesis of Thompson (1972) focused on the mountains of western Perthshire, and considerable attention was given to Glen Lyon, its tributaries, and the surrounding area. Through detailed air photo analysis and ground truthing, Thompson reconstructed the last glaciers in the area based on morphological and sedimentological evidence. Taking the early Geological Survey Memoirs as starting points, he added his own field observations and developed a model for the extent and deglacial nature of the LLS ice in the area. Identifying that Glen Lyon is ringed by high mountains, Thompson proposed that the numerous corries and high valleys surrounding the glen acted as the main accumulation areas for the snow (and ultimately ice) that fed the main 'trunk' glacier that flowed eastward down Glen Lyon. Cols such as that between Beinn Dorain and Beinn an Dothaidh were considered to have been streamlined, forming roche moutonnées, and it was therefore suggested that ice had flowed across this col from east to west, even though the main ice gradient would have been to the east. Similarly it was argued that the considerable thickness of ice in this area prevented Rannoch ice from entering Glen Lyon by way of Gleann Meran. The absence of Rannoch granite erratics in the Glen Lyon area was used to support this reconstruction, and the mounds identified in Coire Eoghannan at 760 m O.D. were taken as evidence for a minimum ice thickness in that area. Ice accumulating on the high ground south of Loch Lyon, around Beinn Heasgarnich, was thought to have flowed generally north-eastward, but bifurcated (due to topographic influence) and acted as a tributary to the Glen Lochay glacier in the south of the area. In summary, it was proposed that the ice in the Glen Lyon area accumulated on much of the high ground and fed a dynamic eastward-flowing valley glacier that may have been sourced at altitudes of > 900 m O.D (Figure 22 a).

5.1.3 B.R. Horsfield

Also focussing (in part) on the Glen Lyon area, Horsfield set out to establish the deglacial pattern in the western Grampians by testing two existing models against the field evidence. The first model was put forward by Charlesworth (1955), who proposed that the moraines and other ice marginal features represented the last glaciers in this area, following his 'Highland Readvance'. The contrasting model was that of Sissons (1965) which instead argued that the 'hummocky moraine' seen throughout the area was a result of *in situ* stagnation of an ice cap that developed in the western Highlands after the main Late Devensian ice sheet had disappeared. Using ice-marginal features to constrain the size and extent of the ice, and palaeo-iceflow indicators to reconstruct its dynamics, Horsfield concluded that the LLS was characterised in this area by the growth of an ice cap that overwhelmed the surrounding mountains (Figure 22 b) and subsequently retreated actively back to its centre on the west side of Rannoch Moor. Whilst accepting many of Charlesworths maximum limits, Horsfield does not agree with the 'valley glaciation' proposed by Charlesworth. No sedimentology is presented, and the issue of the absence of Rannoch granite erratics in Glen Lyon is not addressed.

5.1.4 P.W. Thorp

In order to determine the upper limits, and therefore extent, of the Loch Lomond Stadial ice sheet, Thorp (1984, 1986) mapped moraines, thick drift, fluvioglacial landforms, erratics, ice-smoothed bedrock, striae, friction cracks and relict periglacial forms in an area generally to the north-west of that described here. By carrying out extensive mapping, Thorp was able to reconstruct the LLS icefield in the Western Grampians and describe its extent, morphology and dynamics, including calculations of basal shear stresses for the main outlet glaciers, (Thorp, 1991b). The rationale behind this 'trimline method' was that previous research had always concentrated on depositional landforms on the valley floors, and upper glacier limits had been derived by extrapolation and inference. To avoid the errors inherent in such an approach, Thorp proceeded to define criteria that could be used as direct evidence of an ice limit in the higher areas, without recourse to extrapolation. By adopting this method and undertaking systematic mapping, Thorp concluded that the LLS icefield had ice-shed altitudes of c. 750 m O.D., a maximum width of c. 80 km, and covered an area of c. 2000 km^2. The ice configuration envisaged for the Glen Lyon area is shown in Figure 22 c). Thorp (1987) also reconstructed the Late Devensian ice sheet in the area, and concluded that three main domes existed. These were centred on the Glen Lyon area, the Etive mountains, and the Nevis range. Each dispersal centre contributed to the ice sheet as a whole, without being overwhelmed or influenced by other ice. An ice divide was therefore proposed, trending approximately north-west from the mountains around Glen Lyon, across the Etive mountains and on to the Nevis range. Ice to the east of the shed flowed generally east and north-east, whilst that to the west drained towards the west coast.

5.1.5 Other research

Other workers have contributed to the general understanding of the area, in particular Ballantyne (1979, 1992) and Boulton (1992) who both focussed on the reconstruction of glacial Lake Tulla and associated landforms. Both were in agreement that the general pattern of ice retreat was from east to west, with topography exerting increasing influence as the ice downwasted. Ballantyne (1979) questions the maximum altitude (915 m O.D.) of ice in the Rannoch area proposed by Thompson (1972), and suggests instead that the ice surface was somewhat lower, and that the ice sheet downwasted *in situ*.

5.2 FIELD EVIDENCE

Field mapping carried out during June 2003, together with a preliminary aerial photo interpretation, has yielded the following key evidence. The field area was overwhelmed by ice at several times during the Quaternary. This is evidenced by deposits of at least two distinct (sub-glacial) till units, which are interbedded with sand and gravel outwash at one or two localities. The last stage of glaciation is thought to have occurred during the LLS, and is likely to have been sufficiently erosive to have removed the majority of earlier deposits. The morainic sediments and landforms preserved, therefore, are deemed to represent the decay of the LLS ice. Rafting of sand units within these ice-marginal deposits is taken as evidence of an oscillating margin of actively retreating ice, rather than stagnant ice that downwasted *in situ*. Ice-flow indicators, such as striae and ice-smoothed bedrock, enable a palaeo-iceflow model to be constructed, (Figure 22 d, & Figure 23).

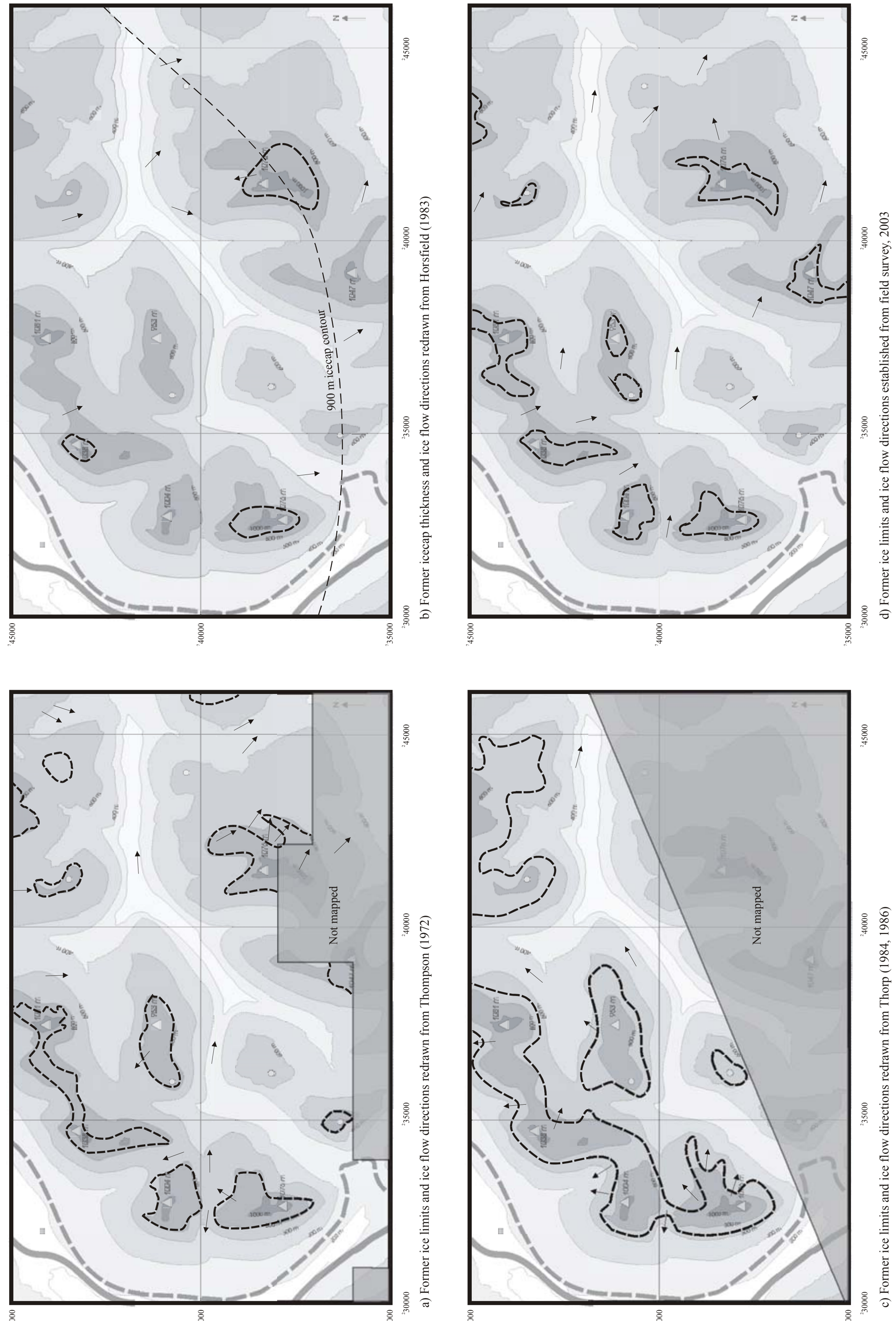

Figure 22: Four contrasting models of ice extent and flow direction in the field area. Dashed line represents upper limits of ice, arrows show inferred direction of flow.

6 Discussion

6.1 PALAEOCLIMATE

Due to prevailing southerly and south-westerly air flow from the Atlantic ocean, the west coast of Scotland is predisposed to receive relatively high precipitation compared to central and eastern areas. The high mountains of the western Highlands present a significant physical barrier to north-eastward moving moist air, and force the air to rise and therefore cool. The resultant orographic precipitation accounts for the area receiving almost five times the national annual average rainfall. It is likely that weather patterns were similar during the last glacial cycle, although a stronger west-east precipitation gradient probably existed across the country (Sissons, 1980). Snow and ice accumulation is therefore likely to have begun relatively early on the high ground of the field area during the gradual cooling of the Early Devensian. By the LGM (c. 22 ka BP), the British Ice Sheet (centred to the west of Rannoch Moor) is thought to have extended as far south as Staffordshire and as far east as the Bosies Bank moraine in the North Sea, beyond the Moray Firth (Merritt *et al.,*1995). This considerable mass of ice was fed in the western Highlands by three ice domes, one of which was centred over Glen Lyon. Radial ice flow from this dome would have scoured mainly schists and quartzites from the Ben Lawers, Ben Lui, Beinn Eagach and Carn Mairg formations, as well as those from the Lochaber Subgroup and Grampian Group psammites. Erratics of Ben Lawers schist found at 940 m O.D. on the col west of Beinn a' Chreachain were probably deposited by north-westward flowing ice from the Beinn Heasgarnich area during this phase. Their preservation suggests that any subsequent ice advance did not reach this altitude in this area. It is also possible that the grey till may relate to this main phase of glaciation, its grey colour deriving from the freshly exposed schists that predominate in the area.

Following the LGM, climatic amelioration led to a gradual thinning and retreat of the MLD ice sheet. This retreat may have been interrupted by stillstands or readvances triggered by increased precipitation (Clapperton, 1997), such as is thought to have occurred at H.E.1 (c. 16 ka BP) (Bowen et al., 2002). Subsequent recession may have taken place rapidly, as a result of increasingly temperatures at the beginning of the Windermere Interstadial (WI). It is not known whether complete deglaciation did, in fact, occur, or whether some ice remained in higher and protected areas. Such a scenario has been postulated for 'the highest catchments of the Scottish mountains' (Clapperton, 1997), and in particular for certain valleys in the Cairngorms, where ice is thought to have simply been 'rejuvenated' during the LLS, (Bennett and Glasser, 1991). It is feasible, therefore, that 'dormant' ice remained in the high corries and valleys surrounding Rannoch Moor and in the Glen Lyon mountains, and maybe even on Rannoch Moor itself, throughout the WI.

At the beginning of the LLS, the cooling climate (possibly a result of iceberg discharge into the North Atlantic from the Laurentide Ice Sheet) led to the regrowth of ice in the Western Highlands. Snowfall would have been fairly even across the area (although strongly influenced by altitude), but ice growth could only have occurred where snow was able to accumulate. Thompson (1972) proposed that the corries on the flanks of Beinn Dorain, Beinn Achaladair and Beinn a' Chreachain acted as accumulation (and therefore source) areas for the Glen Lyon glacier. Identifying that a number of cols in the area showed signs of glacial smoothing he suggested that ice developed in this area flowed outward to coalesce with Rannoch-derived ice. In contrast, Horsfield (1983) favoured the idea of a single ice cap centred to the west of Rannoch that encroached on, and eventually overwhelmed the Glen Lyon area. Thorp (1986) disagreed with both earlier workers and postulated a much lower maximum ice limit, around 750 m O.D., and consequently envisaged considerably less interaction between the ice in the Glen Lyon area and that dispersing from Rannoch Moor.

Using the evidence presented in Table 1, the following model (Figure 23) may be constructed which draws on aspects of all the earlier work, and attempts to reconcile their differences.

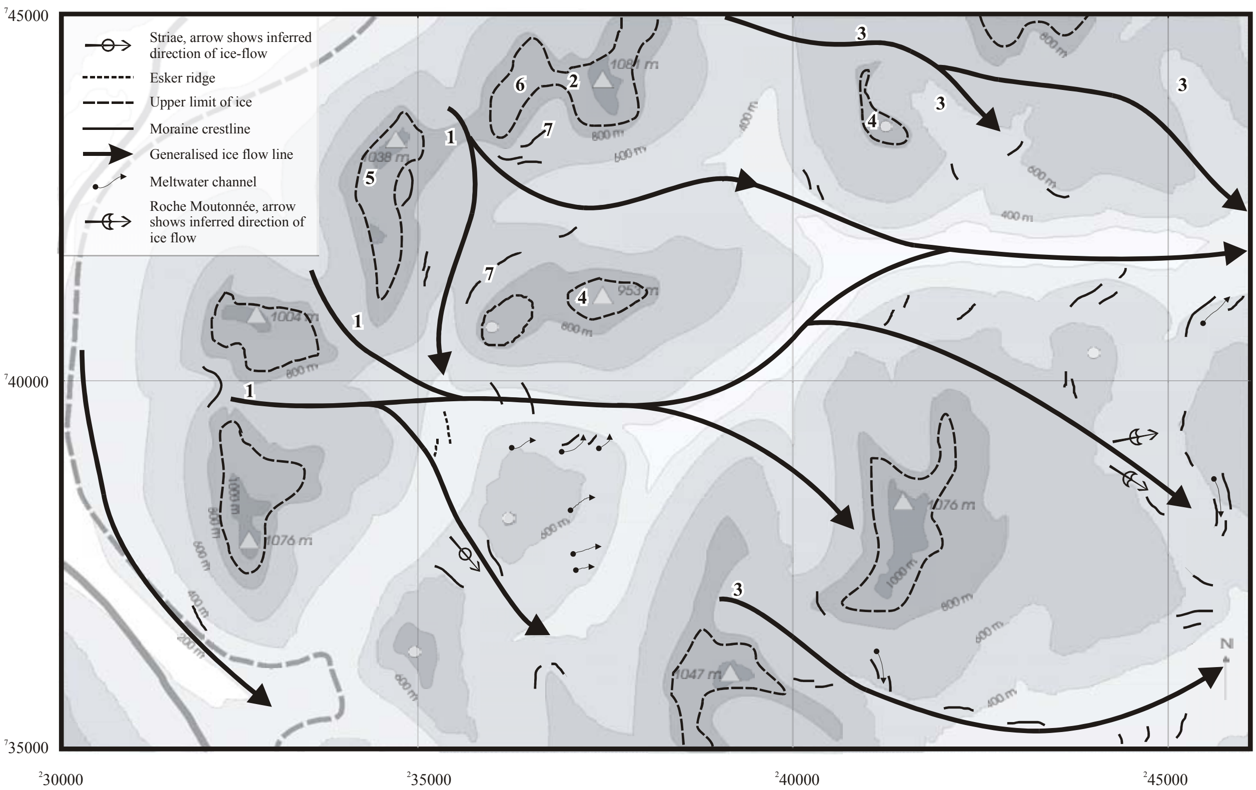

Figure 23: A new model of ice-flow in the Bridge of Orchy – Glen Lyon area.

1 – Ice-smoothed bedrock, 2 – Ben Lawers Schist Formation erratics, 3 – Streamlined mounds, 4 – Regolith, 5 – Frost-shattered quartz vein, 6 – Stone polygons, 7 – Ice-marginal features

6.2 ICE ACCUMULATION

The LLS ice cap accumulated predominantly in the mountains of the Etive and Nevis ranges, although local ice growth must also have occurred in the poorly-developed corries in the Glen Lyon area. The ice in the Etive / Nevis areas may have developed from 'rejuvenated' ice that survived throughout the WI, and in the short period of the LLS managed to attain a maximum surface altitude of > 850 m O.D. in the area of Rannoch Moor and the Tulla Basin. Local source areas would naturally have supported ice at higher altitudes. The ice shed proposed by Thorp (1987) for the MLD ice sheet is likely to have been similar during the LLS, given that the ice cap developed in the same area and was fed by the same south-westerly winds. Consequently, ice flow of the growing ice cap would have been eastward and south-eastward from west of Rannoch, and on reaching the Glen Lyon field area would have encountered the substantial obstacle presented by the Beinn Dorain – Beinn an Dothaidh – Beinn Achaladair – Beinn a' Chreachain ridge. With an ice surface > 850 m O.D., however, the cols identified as showing ice-smoothing would have been breached, and ice would have continued to flow along the natural eastward and south-eastward gradient through Glen Lyon. The cols above this upper ice limit would have blocked the invasive ice, and consequently preserve evidence of MLD glaciation only.

Coire an Dothaidh contains bouldery moraines arcing into the hillside, suggesting that the last ice to occupy the corrie was sourced from Glen Orchy, not from westward flowing ice crossing the col from the Beinn Dorain corries as proposed by Thompson (1972). Having overtopped the cols at 744 m and 750 m O.D., the Rannoch ice then flowed east into Glen Lyon by way of Srath Tarabhan, and south-east across Auch Gleann and the wide col of Mam Lorn, where striae with a south-easterly orientation are preserved. Ice also overtopped the col north-east of Beinn Achaladair (813 m O.D.) and flowed down Gleann Cailliche into Glen Lyon. In the area of Gleann Meran, a c. 400 m thickness of ice may have existed where the Rannoch ice attempted to flow south into Glen Lyon. It seems possible that the ice flowing out of Gleann Cailliche would be sufficient to deflect the Rannoch ice, resulting in flow across the breach rather than through it. The overall gradient may well have been slightly south of east, and this led to the streamlining of the mounded deposits on the col at 760 m O.D. above Coire Eoghannan. These were identified as ice marginal deposits by Thompson (1972) but have been reinterpreted here as sub-glacially modified pre-existing features.

On the south side of Glen Lyon, the advancing ice flowing south-east across Mam Lorn and Beinn nam Fuaran crossed the Abhainn Ghlas and overwhelmed the 804 m O.D. ridge north of Creag Mhor. The summit of Meall Tionail may well have existed as a nunatak, or may have supported relatively immobile cold-based ice. Encountering the western ridge of Beinn Heasgarnich the ice diverged, flowing north-eastward into Fionn a' Ghlinne and across Stob Garbh Leachtir, and south-eastward down Allt Batavaim into Glen Lochay. The high ground surrounding both Beinn Heasgarnich and Creag Mhor no doubt acted as source areas for snow and ice themselves, and would have contributed to the total ice volume flowing through Glen Lyon and also into Glen Lochay. Whilst Thompson (1972) interprets the bedrock mounds east of Beinn Heasgarnich as being streamlined by north-easterly flowing ice, the boulder mounds in Coire Ban Beag (to their north) appear to represent rockfall onto an ice margin, which suggests instead that ice flowed south-eastward into this corrie. The peak of Meall a' Chall was no doubt overwhelmed but may have exerted some influence on ice flow direction, leading to a more easterly overall flow. East of Heasgarnich, ice flow into Glen Lochay occurred as the ice diverged around the (probably overwhelmed) hill of Meall nan Subh. Ice divergence in this area is evidenced by a series of roche moutonnéed crags that show a gradual change in ice flow direction from slightly north of east to south-east.

6.3 DEGLACIATION

The retreat pattern of the LLS ice cap can be reconstructed from the ice marginal features that are preserved. Meltwater channels and moraines were mapped in order to determine the direction of ice retreat, and the sedimentology of the depositional features was examined to understand the nature or style of the retreat. Many of the moraines occur preferentially along one side of a valley, for example in Glen Lyon, and numerous exposures show evidence of ice-marginal tectonism, which suggests dynamic oscillation of the receding margin.

LLS deglaciation was triggered by climatic warming, which resulted in smaller accumulation zones and larger ablation areas for the ice cap. As the mass balance of the ice cap became increasingly negative, thinning and overall recession would have ensued. Two resultant scenarios may be envisaged; either the thinning ice in Glen Lyon became cut off from the main ice cap by the Beinn Dorain – Beinn a' Chreachain ridge, or the ice remained coherent and retreated back to west of Rannoch. In both scenarios, active retreat must be accommodated as evidence of glacitectonism is widespread throughout the field area. If the ice in Glen Lyon had been 'cut-off' from the main ice cap by the mountain ridge to the north-west, the remaining ice mass must have been fed actively by the accumulation areas of the high summits and corries surrounding Glen Lyon. Such a configuration may be possible, and indeed Thompson (1972) suggests that the ice in Glen Lyon was almost completely sourced from this high ground throughout the LLS. This would explain the absence of granite erratics in the area, as the wasting ice would have been locally sourced and therefore carrying only metasediment debris. Erosion by both ice and meltwater may well have 'flushed-out' any earlier granite debris. Alternatively, the model proposed by Horsfield (1983) may also be considered. In his view, the ice cap retreated as a coherent body towards the western margins of Rannoch Moor. To make this possible the ice cap would have required a steep ice front, so that the Glen Lyon ice could remain active throughout the majority of deglaciation. Horsfield's reconstruction suggests an ice surface altitude of c. 900 - 950 m O.D. over Glen Lyon during maximum extent, with an increasingly steep gradient towards the ice margins.

The field evidence suggests that the receding ice became increasingly controlled by topography and retreated up the valleys of Glen Lyon, Gleann Cailliche, Srath Tarabhan and Auch Gleann into Allt an Loin. It appears therefore, that the Beinn an Dothaidh – Beinn Achaladair area was a major source area for the ice. During deglaciation, accumulation in this area may have enabled ice cut-off from the ice cap to remain active in the high corries and valleys. Boulder ridges in Coire nan Clach (Beinn Achaladair) arc across the corrie and up the backwall, suggesting formation by ice derived from the 950 – 1000 m O.D. ridge above. Horsfields reconstruction would accommodate ice at this height during maximum extent of the LLS ice cap, but not at such a late stage in deglaciation. It would also conflict with the evidence of lower cols further along the ridge remaining ice free during the LLS. The most reasonable explanation therefore is that the ice forming the mounds in Coire nan Clach was sourced independently from the summit and ridge area of Beinn Achaladair. At the time these were forming, the main ice cap would have retreated significantly from this area.

7 Conclusions

The glacial deposits of the Bridge of Orchy – Glen Lyon area are mostly the product of the LLS glaciation. This period of renewed glacial activity following the MLD glaciation appears to have been characterised by the growth of an ice cap in the western Highlands that overwhelmed much of the field area. Whilst the underlying topography exerted a certain amount of influence on the flow of the ice, it did not entirely control it. The field evidence suggests that transfluence and divergence occurred as the ice cap encroached on the Glen Lyon area, and also that the general pattern of ice flow was towards the east and south-east along Glens Lyon and Lochay. The size of the ice cap is considered to be closer to that proposed by Horsfield (1983) than the much smaller one presented by Thorp (1986), at least in terms of maximum thickness. The thicker ice cap may well have developed from ice that survived the WI and was 'rejuvenated' in the LLS. As the ice cap receded towards the end of the LLS, it became increasingly influenced by the underlying topography, and may have thinned to a critical thickness at which the ice in the Glen Lyon area became cut-off from the main ice cap. Subsequent retreat then took place actively, the main glacier being sourced predominantly from the high rounded summits and immature corries within the field area.

The periglacial trimline evidence presented by Thorp (1984, 1986) only covered part of the field area, but sufficient evidence was seen to suggest that the trimline approach might not be entirely reliable in this region. It is possible, however, that thermal boundaries with the ice cap may have allowed preservation of, for example, weathering limits that were formed previously (perhaps during a stillstand or readvance of the MLD ice sheet). Periglacial landforms such as stone polygons, solifluction terraces and regolith mantles are abundant in the field area, but are confined to the summits of the higher mountains.

A number of landslides were recorded in the field area and these may be attributable to post-glacial slope adjustment. The most likely trigger for such rock slope failures is high cleft water pressures (from heavy rainfall), which exploit pre-existing weaknesses in the rock mass. Glacial oversteepening of valley sides, together with the abundance of fault and foliation planes in the local lithologies predispose many of the slopes to failure. Other Holocene processes such as debris flow activity, fluvial erosion and deposition, peat accumulation and freeze-thaw weathering continue to modify the landscape and obscure the glacial legacy.

Further work might focus on understanding the temporal framework of this ongoing landscape evolution. Luminescence dating may be employed to constrain the time of deposition of sand units interbedded with tills, such as the sections in Glen Coralan and Coire Chailein [NN31 33]. Cosmogenic surface exposure dating could be used to determine which summits and cols have been exposed the longest, or to date the construction of recessional moraines such as those in Srath Tarabhan. Iceflow models could be refined through the application of geochemical analysis to the tills in the area, which by comparing results with specimens of local lithologies, may provide clues as to their provenance.

8 References

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