A glacial geological and geomorphological map of the far NW Highlands, Scotland. Part 1.

SVEN LUKAS[1] and TINA LUKAS

School of Geography and Geosciences, University of St Andrews, Irvine Building, North Street, Fife, KY16 9AL, UK;

[1] Institut für Geologie, Universität Bern, Baltzerstr. 1-3, 3012 Bern, Switzerland; lukas@geo.unibe.ch

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Abstract: The "Glacial geological and geomorphological map of the NW Highlands, Scotland" is the result of detailed aerial photograph interpretation and field mapping at a scale of 1: 25,000 and presents the distribution of glacial deposits and landforms in an area of ca. 1000 km^2 in the far NW Scottish Highlands (58°5"N 4°58"W to 58°29"N 4°34"W; British National Grid: NC 250140 to NC 500 540). This area has never been mapped in detail before, and previous glacier reconstructions have solely been carried out from aerial photographs without much ground-truthing. The present mapping reveals that glacial landforms, most notably recessional "hummocky" moraines attributed to the Younger Dryas (ca. 12.7-11.5 ka BP), are more widely distributed throughout the study area than recognised on earlier overview maps. Detailed mapping enables the detailed reconstruction of part of a large mountain icefield of ca. 211 km^2 which is significantly larger than the 36 km^2 previously envisaged for the NW Highlands. These findings demonstrate that "traditional" mapping from aerial photographs and in the field can result in a high-resolution reconstruction of palaeo-glaciers from which palaeoclimatic variables can then be calculated. Such variables are crucial to validate and further constrain numerical models used to predict future climate change.

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1. Introduction

Mapping the spatial distribution of glacial (geological and geomorphological) features through a combination of remote sensing (aerial photographs, satellite imagery) and fieldwork has a long tradition in Earth Sciences (e.g. Sissons, 1967, 1979; Kronberg, 1984; Boulton and Clark, 1990; Evans et al., 1999; Stokes and Clark, 2001; Jansson, 2002, 2005; Lukas, 2003, 2005a). This combined approach has extensively been utilised to determine the distribution of glacial deposits and landforms throughout large areas of Britain covered by the last ice sheet (see Evans et al., 2005 for a review) and to the subsequent resurgence of local glaciers in the Scottish Highlands during the Loch Lomond Stadial which is equated with the global Younger Dryas (ca. 12.7-11.5 ka BP) (e.g. Sissons, 1967, 1979; Ballantyne, 1989, 2002; Bennett and Boulton, 1993a, 1993b; Benn and Ballantyne, 2005).

Knowledge about the distribution of ice masses during the Younger Dryas is of importance for two reasons: (a) the Younger Dryas was the last period where severe full-glacial conditions persisted globally prior to early Holocene warming, and this period has received special research attention as it serves as a role-model of rapid climate change at decadal and centennial scales (e.g. Anderson, 1997; Rahmstorf, 2002; Tarasov and Peltier, 2005). This holds especially true in the Scottish context since the landscape was glacially shaped during the Younger Dryas for the last time and therefore glacial deposits and landforms are best-preserved here. (b) only carefully-reconstructed ice masses allow palaeoglaciological and palaeoclimatic parameters to be accurately calculated and past atmosphere-cryosphere interactions to be assessed; this information is crucial to constrain numerical models commonly used to understand past and predict future climate change, and the Younger Dryas has also received special research attention in this respect (e.g. Hubbard, 1999; Isarin and Renssen, 1999; Winkler and Haakensen, 1999; McAvaney et al., 2001; Golledge and Hubbard, 2005). Geomorphological and geological field mapping therefore forms the basis for any subsequent numerical modelling exercise.

Contrasting to many other areas in Scotland that have repeatedly been visited by glacial scientists, the study area in the far NW Highlands has been relatively neglected. Following the earliest surveys by the officers of the British Geological Survey (Read et al., 1926; Read, 1931), subsequent overview work by Charlesworth (1955) and Sissons (1977) attempted a synthesis of the glacial history of the area; detailed mapping, however, has never been carried out and published for the area presented here. Knowledge of the glacial history of this area is thus restricted to a published overview map showing the distribution of isolated valley and corrie glaciers that existed during the Younger Dryas in NW Scotland (Fig. 1). The area was investigated as part of a larger study (Lukas, 2005a) that feeds into the Moine Thrust Project of the Onshore Quaternary Mapping Programme of the British Geological Survey.

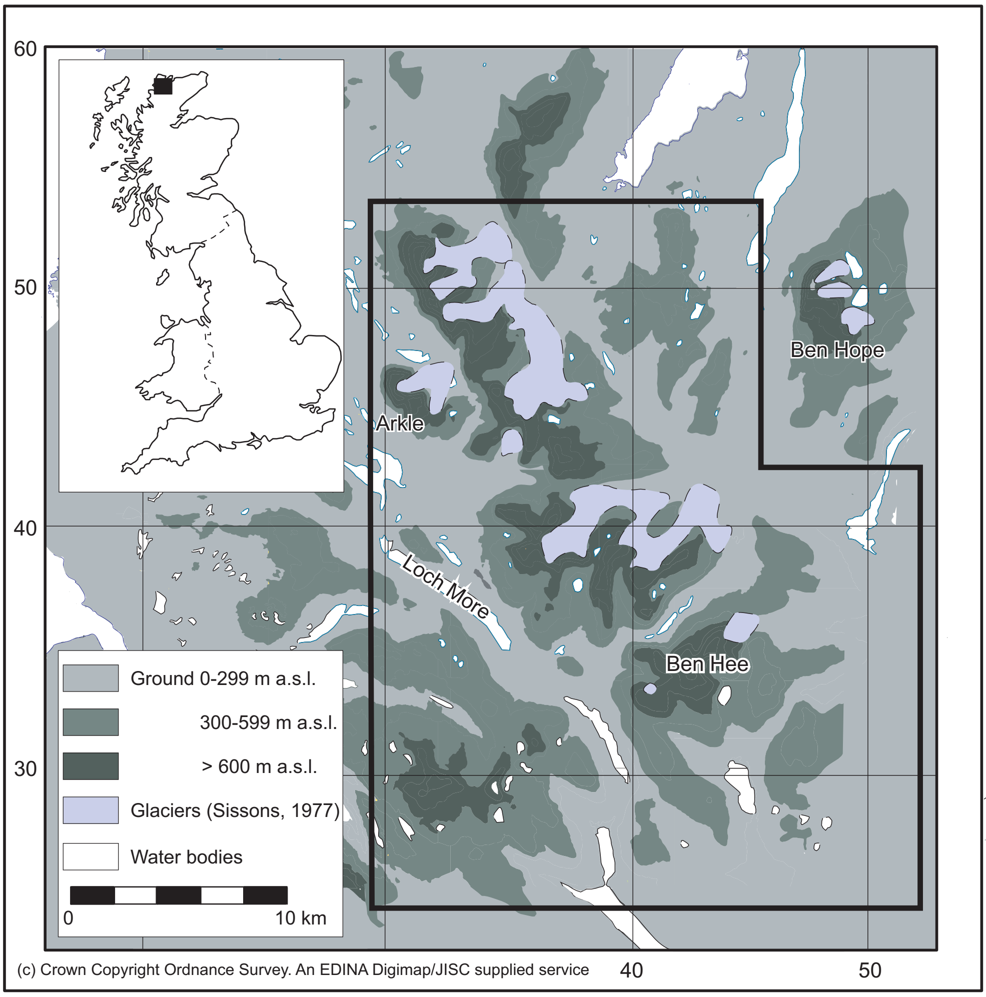

Figure 1 Extent of Younger Dryas glaciers in the far NW Highlands (redrawn from Sissons, 1977). Black frame marks the location of the study area and the map boundary. Grid coordinates correspond to British National Grid tile NC and are spaced at 10 km.

2. Methods

The distribution of moraines, other glacial and periglacial landforms and deposits in the far NW Highlands was mapped onto topographic maps at scales of 1:25,000. Aerial photographs at scales of ca. 1:25,000 were used in addition to determine the exact location, shape and planform of glacial and periglacial landforms. For the study area, aerial photographs of the All Scotland Surveys 1988 and 1989 (RCAHMS Edinburgh) were used as these generally show a good contrast and are valuable tools in locating small features such as moraines with great accuracy.

Aerial photograph interpretation was used prior to and after fieldwork, thereby enhancing the accuracy of the mapping and reducing possible errors that might arise from misinterpretation of features when only viewed once from aerial photographs or on the ground. For example, the recognition of different terrace altitudes from aerial photographs proved difficult so that individual terrace fragments were mapped entirely in the field. Conversely, mapping of moraines from aerial photographs yielded much better results with respect to their orientation and shape, particularly where larger areas of "hummocky moraine" exist. In order to record the location and planform of moraines accurately, mapping was done on an acetate overlying one aerial photograph of a stereopair. Drawing on acetates was carried out while looking through a mirror stereoscope with threefold magnification.

The main problem associated with this method is the geometric distortion present in aerial photographs (Lillesand and Kiefer, 2000; Albertz, 2001) so that the overlays could not simply be transferred to the base maps even though the scales were very similar. In order to get rid of this distortion, datum lines and reference points on the base maps were joined up with those transferred from aerial photographs (cf. Lukas, 2002; Hubbard and Glasser, 2005). Drainage features such as rivers and lakes are the most obvious features that are usually located in lower parts of the relief. Since these objects are farthest away from the camera lens and have relatively low gradients they are the least distorted features on aerial photographs (Kronberg, 1984). Moreover, rivers often show distinct and unique meander bends that enable easy and reliable matching of the information contained on the acetates and the topographic base maps. This is especially the case in the vicinity of river confluences as the number of points that can be used to "lock" the position of a feature increases. Due to the fact that the problem of distortion can be solved quite easily, this method presents a quick and accurate way of mapping geomorphological and geological features (Kronberg, 1984) and proved invaluable for the successful mapping of the study area. A more detailed description of aforementioned method is currently being prepared for publication. The estimated accuracy of the resulting map is between 10 and 20 m horizontally and 5 and 10 m vertically

In the field, geomorphological mapping was conducted with reference to landmarks, with the aid of a compass or, where clear reference points were lacking, a Garmin Summit 12-channel GPS. The orientation of ice flow-directional indicators such as striae, roches moutonnées and ice-moulded bedrock were measured using a compass and corrected from magnetic north to grid north before being placed on the map. In the case of striae, one arrow on the map represents the arithmetic mean of five measurements taken from outcrop areas of not larger than 25 m^2. Single measurements were taken perpendicular to the lee faces of roches moutonnées and parallel to larger-scale grooves in areas of ice-moulded bedrock.

3. Conclusions

The distribution of glacial and periglacial sediments and landforms has been shown to enable the limits of former glaciers to be reconstructed (cf. Sissons, 1979; Ballantyne, 1989, 2002; Benn and Ballantyne, 2005). In the valley bottoms, these include *inter alia* moraines, outwash terraces, till sheets, talus and scree slopes, roches moutonnées, ice-moulded bedrock and striae while on plateaux and mountaintops periglacial processes have produced large-scale periglacial features, such as blockfields, solifluction lobes, patterned ground and mountaintop detritus. Utilising a unified landsystems approach, Lukas (2005a) was able to reconstruct the extent of a coeval mountain icefield (Fig. 2). Radiocarbon dating demonstrates that this icefield existed during the Younger Dryas (Lukas, 2005a). This mountain icefield, which occupies an area of 211 km^2, however, represents only ca. two thirds of the total ice volume in the far NW Highlands as evident from mapping to the southwest and west of the present study area (T. Bradwell, pers. comm., 2005). The findings suggest that the only previous reconstruction available for this area (Sissons, 1977) significantly underestimated regional ice mass extent by at least 6 times (Figs. 1, 2).

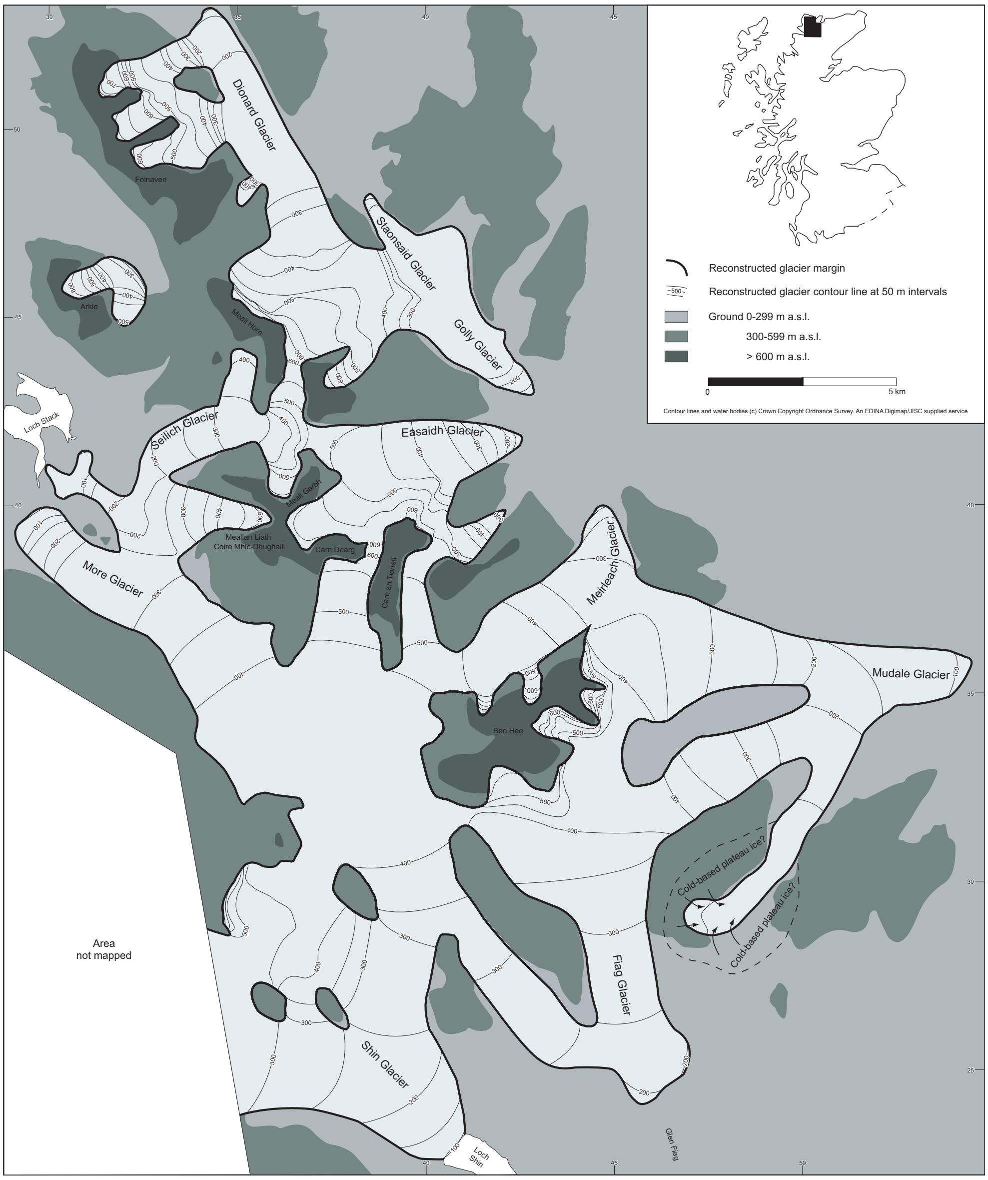

Figure 2 Extent of the Younger Dryas mountain icefield reconstructed for the area covered by the map presented here. The southwestern and western limits of this icefield are outside the present mapping area.

From the distribution of individual glaciers, source areas and a decrease of the equilibrium-line altitudes (ELAs) in an eastward direction (Lukas, 2005a) it is most likely that the dominant wind direction was from the south-west. This data fits the observations from elsewhere in Scotland (cf. Sissons, 1979; Ballantyne, 1989, 2002; Christiansen, 2004; Benn and Ballantyne, 2005). This reconstruction shows a larger internal variability of glacier contours and therefore contrasts with most previous high-resolution reconstructions of Younger Dryas glaciers in Scotland (cf. Ballantyne, 1989, 2002; Benn and Ballantyne, 2005). This is due to the arrangement of the geomorphological evidence and the complexity of the terrain. In one instance, clearly ice-sculpted terrain and mountaintop detritus occurs at the same altitude with a sharp rather than diffuse boundary. This direct association or juxtaposition has previously been interpreted as evidence for thin, cold-based ice feeding into a thicker, warm-based valley glacier (e.g. Rea et al., 1998) and is reflected in the presence of "warped" contours in the southern part of the reconstructed Easaidh Glacier (Fig. 2). Likewise, the southernmost Mudale tributary glacier could be reconstructed using clear geomorphological evidence such as the upslope termination of sediment blankets on either side of the valley, but the local equilibrium line altitude (ELA) is below the regional one (Lukas, 2005a), and, therefore, such a glacier could technically not exist. It is well-known that, in upland areas, peat often covers and blurs the evidence for the transition from former cold-based plateau ice to warm-based ice in glacial troughs (e.g. Rea et al., 1998; McDougall, 2001). It would appear that this is the case for the southernmost tributary of the Mudale Glacier where snowblow alone would yield insufficient quantities to nourish a glacier of this size. In the northernmost parts of the icefield (Dionard Glacier) the surface gradient is unusually low. This appears to be caused by two factors: firstly, the valley floor is similarly gentle and does not show any large undulations; bedrock obstacles are absent from this part of the valley. Secondly, the gentle part coincides with the confluence of the main glacier in the Strath with those sourced in the corries east of Foinaven. This confluence is characterised by steep glacier sections, indicating an ice fall at this point. Since there is no geomorphological evidence to suggest that the glacier surface bulged up as a result of the confluence, the input of additional glacier ice cannot have been sufficient to cause substantial thickening of the main glacier, however. Hence it would appear that the Foinaven corrie glaciers and the main Dionard glacier would have just been confluent at this point, making the glacier atypically long compared to other glaciers (cf. Benn and Evans, 1998: Fig. 9.57).

Detailed mapping and sedimentological analyses of "hummocky moraine" in the study area has furthermore led to a detailed understanding of the modes of moraine formation. These had previously been interpreted as either the result of (a) aerial stagnation (e.g. Sissons, 1977, 1979), (b) active, oscillatory retreat (e.g. Benn, 1992; Bennett and Boulton, 1993a, 1993b; Lukas, 2003) or (c) englacial thrusting (e.g. Hambrey et al., 1997;

Bennett et al., 1998). Sedimentological logging of exposures in 52 moraines clearly demonstrates that the vast majority of these moraines consist of stacked supraglacial debris flow units and intercalated fluvial horizons that were deposited at a temporarily stationary ice margin during overall retreat. Different deformation structures within such terrestrial ice-contact fans allow a continuum ranging from proglacial (ice-marginal) pushing to subglacial shearing to be identified. The remainder of moraines represents pushed outwash fans. Together, the evidence strongly suggests highly active Younger Dryas glaciers that retreated in an oscillatory fashion (Lukas, 2005a, 2005b). Therefore, the sedimentology supports an ice-marginal mode of formation (model (b)) of "hummocky moraines" in the NW Highlands and contradicts models (a) and (c).

The distribution of glacial and periglacial sediments and landforms also enables the dynamics of palaeo-glaciers to be well constrained. For example, the existence of flutes near corrie headwalls and downvalley of bedrock steps, numerous roches moutonnées, outcrops of ice-moulded bedrock and dominantly subglacially-transported clasts indicates a dominantly wet-based thermal regime and highly active valley glaciers with very short response times and high mass turnover (cf. Lukas, 2005a).

Geological and geomorphological mapping is an invaluable tool to understand the distribution of former glaciers from which palaeoclimatic boundary conditions can then be calculated. Only if such parameters are known can numerical models, such as those used to predict future climate change, be reliably constrained, tested and refined. Therefore, traditional mapping must precede or accompany any meaningful numerical modelling exercise.

Software

The process of joining and locking information from acetate overlays and topographic base maps to produce the final map was facilitated electronically in Adobe Photoshop 6.0 using the transform functions. Once un-distorted, the respective layer was dragged into Adobe Illustrator 10.0 where it was aligned with the underlying drainage and road system and digitised together with features such as trimlines, ice-moulded bedrock and roches moutonnées that had been mapped on to the field maps.

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