The formation and significance of a moraine-mound complex ("hummocky moraine") of Younger Dryas age in Ennerdale, English Lake District

David J. Graham

Centre for Glaciology, Institute of Geography and Earth Sciences, University of Wales, Aberystwyth, Ceredigion SY23 3DB
(now at Department of Geography, Loughborough University, Loughborough, Leicestershire LE113TU)
D.J.Graham@lboro.ac.uk

Ennerdale is a spectacular and beautiful valley in the eastern central Lake District, the upper part of which contains numerous moraines (Fig. 1). These moraines have attracted considerable interest, being described as "perhaps the most complete set of moraines to be found in the district" (Ward, 1873) and "remarkable" (Sissons, 1980). Sissons used the moraines (which he termed "hummocky moraines") to delimit the margins of a glacier in Ennerdale, which he assigned a Younger Dryas age on the basis of the morphological freshness of the features. The reconstructed glacier had an area of 1.28 km^2, a volume of 0.049 km^3 and a firn line elevation of 465 m. The glacier was nourished beneath the cliffs of Great Gable and had a very shallow gradient close to the terminus.

Sissons argued that the moraines in Ennerdale and elsewhere provide evidence of *in situ* glacier stagnation, and thus of rapid climatic amelioration at the end of the Younger Dryas. These inferences have been challenged in recent years and "hummocky moraines" are now considered polygenetic (e.g. Benn, 1992; Bennett, 1993; Hambrey, 1997). This re-evaluation has sparked renewed interest in the processes of moraine formation during the Younger Dryas, and it has become clear that detailed examination of moraine morphology and sedimentology may provide important insights into climatic and glacio-dynamic conditions during the stadial. This poster examines four landform-sediment associations in Ennerdale (Fig. 2) and discusses their significance.

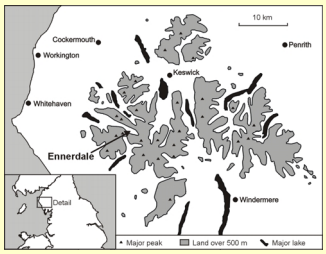

Fig. 1: Location of Ennerdale

Landform-sediment association 1 – Oblique ridges

- Nine sub-parallel, subdued, ridges running obliquely down south-west facing slope of "The Tongue" (Fig. 3).
- Bifurcate in places; sometimes peter out.
- Sedimentary exposures absent so no evidence of constituent facies.

Interpretation

Probably lateral ice-margin moraines on basis of planform morphology, location and anastomosing ridge crests. Insufficient sedimentary exposure makes determination of the mechanism of deposition impossible.

Fig. 3: Oblique ridges, looking upvalley with Great Gable in background

Landform-sediment association 2 – Valley-floor moraine-mound complex

- Moraine-mound complex consisting of many mounds and short crested ridges (Fig. 4).
- Mounds rise sharply from flat ground; surrounding ground apparently infilled.
- Absence of organisation; ridge crests short with no consistent orientation.
- Merges to south into a series of six subdued ridges that rise a short way up valley side.
- Sediment exposures limited, but where present consist predominantly of massive clast-rich sandy diamicton with some massive muddy sandy-gravel.

Interpretation

The planform-morphology does not suggest an ice-marginal origin (except the six subdued ridges on the valley side). Sediments consistent with subglacial origin, but may be reworked pre-existing material. Apparent lack of organisation and valley floor setting suggests that it may represent deposits associated with ice stagnation, similar to those observed on Skye (Benn, 1992). Indistinct ridges on valley side suggest successive ice-marginal positions, but it is not possible to verify this impression.

Fig. 4: Valley-floor moraine-mound complex, viewed from the north

Landform-sediment association 3 – Subdued ridges

- Subdued ridges on northern valley side above/downvalley of "valley-side moraine-mound complex".
- No clear boundary between the "valley-side moraine-mound complex" and the "subdued ridges", but approximately at Youth Hostel.
- Differentiated from "valley-side moraine-mound complex" by: more subdued relief; continuous ridge crests; whaleback morphology; and different ridge-crest orientations.
- Two exposures revealed massive muddy sandy-gravel and clast-rich muddy diamicton.

Interpretation

Valley side location and geometry of ridges suggest they represent ice marginal positions, reflecting retreat stages of a glacier. May represent the Younger Dryas glacier limit or be older. Geometry and location generally consistent with a Younger Dryas age, but the forest makes mapping their full extent impossible. Precise method of genesis not determined due to the poor sedimentary exposure and difficulty of recognising moraines at close quarters in the field for detailed morphological investigations.

Fig. 5: Subdued ridges beneath Scarth Gap pass, looking downvalley

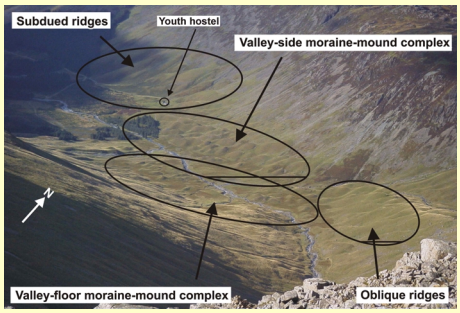

Fig. 2: The key glacio-depositional landform-sediment associations in Ennerdale. The photograph is taken from the summit of Great Gable (899 m), looking down the valley.

Fig. 6: Valley-side moraine-mound complex, looking downvalley. Note rectilinear faces to left and and angular blocks on the surface.

Fig. 7: Individual mounds have an imbricate relationship, being composed of inclined slabs of englacially thrust sediment.

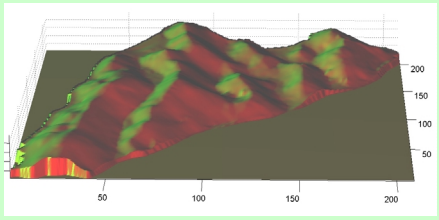

Fig. 8: Digital elevation model of part of the valley-side moraine-mound complex, looking upvalley. South facing faces are commonly rectilinear (lit with red light). North facing slopes are generally irregular (lit with green light). Distances in metres.

Landform-sediment association 4 – Valley-side moraine-mound complex

- Moraine-mound complex consisting of many mounds and ridges (Fig. 6), merging into "subdued ridges" in vicinity of Youth Hostel.
- Complex structure consisting of ridges composed of chains of mounds, with undulating ridge crests (Fig. 8).
- Mounds have imbricate relationships and may be offset from ridge trend (Fig. 7).
- 3/4 of mounds have rectilinear faces on southern side; northern side is irregular.
- Direction of dip of rectilinear faces varies systematically through complex (Fig. 9).
- Exposures uncommon, but reveal massive clast-rich muddy diamicton and massive muddy sandy-gravel. A single mound contained bedded sands and gravels.
- Numerous angular blocks on surface of mounds.

Interpretation

Ice-marginal, lateral, origin unlikely because: (a) moraines entirely absent on opposite valley side; (b) sediments consistent with a predominantly subglacial origin; (c) ridge crest undulating and composed of individual mounds; (d) ridges do not anastomose.

The moraines are similar to those in Svalbard formed by englacial thrusting of basal sediment (Hambrey *et al.*, 1999). Mounds are formed from sediment entrained within individual thrusts, with the rectilinear face of each mound representing the thrust-plane. Debris is released as the glacier recedes, and individual thrust slabs exhibit an imbricate relationship. Supraglacially transported blocks are common on the surface. It is tentatively proposed that the landforms in Ennerdale were formed by this process.

The tectonic structure preserved in Ennerdale suggests oblique ice flow across the valley from the south (Fig. 9). Therefore, it is likely that a subsidiary glacier flowed across Ennerdale from the crags beneath Kirk Fell to the south. This may explain the anomalously low gradient of the Ennerdale glacier identified by Sissons (1980).

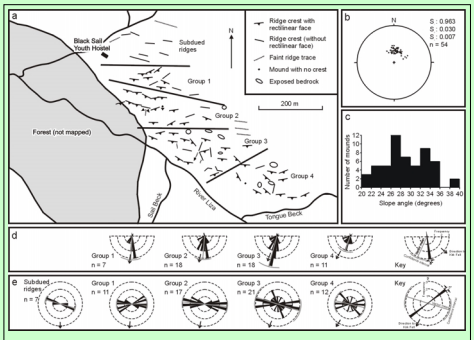

Fig. 9: (a) Structural map of the valley-side moraine-mound complex; (b) Stereographic projection of dip and direction of dip of rectilinear faces; (c) Dips angles of rectilinear faces; (d) Direction of dip of rectilinear faces; (e) Ridge crest orientations.

Causes of thrusting and implications

- Thrusting in glacier ice results from compression approximately normal to the flow direction and is associated with polythermal margins, confluences and reverse bedrock slopes.
- Debris entrainment into thrusts and creation of thrust-moraine complexes are most commonly associated with polythermal glacier margins.
- In Ennerdale, it appears that a combination of a reverse bedrock slope and a confluence may explain thrust initiation.
- The preservation of the tectonic structure in Ennerdale implies that the glacier retreated dynamically, at least initially.
- The full palaeo-climatic implications of the landforms will remain unclear until the importance of polythermal ice for debris entrainment is established.
- The thrust-moraine complex structure reflects the tectonic structure of the glacier and not the ice-margin geometry. It cannot be used to delimit the glacier margin.

Process-form model for Ennerdale

On the basis of the preceding interpretations:

- A glacier formed on the crags of Great Gable to the east and Kirk Fell to the south and flowed down Ennerdale. The "subdued ridges" may mark its maximum extent.
- Ice from Kirk Fell resulted in flow-compression against the northern valley side and the initiation of thrusting.
- Debris was entrained within these thrusts and elevated into the body of the glacier.
- When the glacier receded, the sediment in the thrusts was lowered onto the valley side. The resulting landforms probably represent thrusting that occurred towards the end of the Younger Dryas as the influence of the main Ennerdale glacier weakened.
- The chaotic "valley-floor moraine-mound complex" probably represents the *in situ* wasting of ice from Kirk Fell as it became dynamically separated from its accumulation area. However, the clear ice-marginal moraines ("oblique ridges") higher up Ennerdale, indicate that the main Ennerdale glacier retreated dynamically.

Conclusions

- Four distinct landform-sediment assemblages can be identified in upper Ennerdale associated with a Younger Dryas glacier. Examination of these has allowed the development of a process-form model for the valley.
- The maximum extent of the glacier is unclear, but it may have extended some way into the forest.
- The moraine-mound complex on the northern valley-side probably resulted from englacial thrusting against a reverse bedrock slope opposite the confluence of the main Ennerdale glacier and a subsidiary glacier on Kirk Fell to the south.
- This is the third site in Britain at which evidence of englacial thrusting has been recognised in the Younger Dryas landform record (the others being: Coire a' Cheud-chnoic, Torridon, Bennett *et al.*, 1998; and Cwm Idwal, N. Wales Graham & Midgley, 2000).
- The weight of evidence now suggests that the role of ice-deformation, especially thrusting, in landform genesis has been underestimated. It is likely that other sites will be identified in the future.
- The recognition of englacial thrust-moraine complexes has potential glacio-dynamic and palaeo-climatic implications as it suggests that the glacier retreated dynamically, at least initially. The full palaeo-climatic significance will remain unclear until there is a greater understanding of the importance of polythermal ice in facilitating debris entrainment.

Acknowledgements

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