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Geotechnical controls on a steep lateral moraine undergoing paraglacial slope adjustment

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Abstract: Sustained post 'Little Ice Age' retreat of the northern lobe of the Feegletscher, Valais, Switzerland, has exposed lateral moraines that show pronounced oversteepening on the upper proximal slopes, with upper-slope segments displaying angles of up to about 70°. Paraglacial processes have eroded gullies into the upper-slope segments, and associated debris-flow deposits result in lower angles of between 34° and 25° in the mid-slope and slope-foot zones, respectively. In order to assess the geotechnical properties of morainic sediments that permit development of quasi-stable, oversteepened slope segments, a standard suite of geotechnical measures was applied to samples of Feegletscher moraine sediments. Shear box testing yielded angles of friction ranging from 35° for loose samples to 52° for dense samples. Although the heterogeneous nature of moraine deposits makes laboratory testing of the whole size range of *in situ* sediments impractical, shear box test results imply that *in situ* upper-slope angles exceed the angles of friction of moraine sediments by 26°–40°. We are unable to replicate angles of friction in shear box tests that correspond to *in situ* angles of the upper-slope sections measured in the field. However, we suggest that distal dipping mica-schist clasts may play an important role in permitting high-angle slope stability. Quasi-stable storage of glacigenic sediments in high-angle moraine sequences over decadal timescales has implications for understanding the period following deglaciation over which paraglacial reworking and redistribution of sediments may operate.

Glacier retreat triggers the progressive modification of glacial sediments, landforms, landscapes and land systems through their exposure to non-glacial Earth-surface processes and conditions. In recently deglaciated mountain areas a wide range of these *paraglacial* processes is responsible for the release, reworking and redeposition of large quantities of unstable glacigenic sediment over a wide range of timescales (Ballantyne 2002*a*). Steep, sediment-mantled valley slopes, for example, are eroded by rapid mass-movement processes, often creating a land system of intersecting gullies, coalescing debris cones and valley-floor deposits of reworked sediment in a matter of decades (e.g. Ballantyne & Benn 1994; Ballantyne 1995; Curry 1999; Curry *et al.* 2005). These phenomena also pose a risk to inhabitants and infrastructure in deglaciated valleys, some of which are frequented by large numbers of visitors. While recent studies have focused attention on the processes, rates, and sedimentological and morphological consequences of this activity, few have specifically considered the geotechnical characteristics of sediments that may be susceptible to failure by paraglacial processes.

High-angle, gullied lateral-terminal moraines are a common feature of deglaciating land systems in the European Alps and elsewhere. Their morphology and steep gradient are strong conditioning factors for rapid and extensive paraglacial slope adjustment (e.g. Curry 2000; Curry *et al.* 2005). Although such lateral-terminal moraines are eroded rapidly following deglaciation, their upper slopes commonly retain a pronounced oversteepened form, at least during the early period of deglaciation and associated paraglacial modification. The detailed geotechnical characteristics of lateral-terminal moraines that permit them to stand in a quasi-stable state at high angles have yet to be adequately explained, however. This lack of detailed understanding arises partly due to the difficulties of accessing steep moraine slopes that are subject to regular paraglacial activity (such as debris flows and release of clastic debris from the fine-grained matrix) and the problems of replicating *in situ* conditions when undertaking geotechnical analysis in the laboratory. This research applies geotechnical methods to a lateral-frontal moraine sequence in an attempt to explain the geotechnical properties

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of glacigenic sediments that may allow them to stand at high angles in a quasi-stable form.

Lateral-frontal moraines are formed as debris falls, slumps, slides or flows down the ice surface and accumulates around the glacier margin (e.g. Small 1983; Owen & Derbyshire 1989; Owen 1994). The relative balance of debris supply from supraglacial and valley-side sources will affect the resultant detailed moraine morphology and sedimentary facies, while successive ice advances may result in superimposition of lateral-frontal moraine structures (Bennett & Glasser 1996). If the glacier remains in a stable position, the accumulation of dumped material often produces a wedge-shaped moraine with strong fabric and crude internal bedding dipping away from the glacier at angles of 10°–40° (Small 1983; Bennett & Glasser 1996). However, the ice-proximal parts of lateral-frontal moraines tend to be structurally complex, reflecting widespread collapse and reworking following removal of ice support, together with ice-marginal glacifluvial activity. Moreover, melt-out of buried ice and post-glacial gravitational reworking may destroy bedding. Sediment facies commonly consist of stacked diamictons with variable clast content intercalated with thin sand and gravel layers, reflecting intermittent glacifluvial deposition and reworking (Benn *et al.* 2005). Most diamicton facies are sandy boulder gravels containing predominantly angular debris from passive transport of rockfall material, although more rounded clasts may be found within lateral moraines where a higher proportion of basal-zone debris is delivered to the terminus (Matthews & Petch 1982), or where proglacial sediment is entrained during glacier advance (Slatt 1971). Where valley-constrained glacier termini repeatedly occupy similar positions, large, multicrested lateral moraines may form, reflecting episodic aggradation separated by periods of erosion or non-deposition. Complex depositional histories may be preserved in the internal moraine structure, with multiple depositional sequences bounded by erosion surfaces. Periods of non-deposition may be indicated by buried palaeosols (e.g. Röthlisberger *et al.* 1980).

The extent, conditioning factors, morphological consequences and rates of recent paraglacial reworking of sediment at this site are considered in detail elsewhere (Curry *et al.* 2005), while geotechnical investigation has previously been undertaken at this locality (Whalley 1975). Whalley applied shear test results from the nearby Allalingletscher lateral moraine to the similar form of moraine slopes at Feegletscher Nord in an attempt to explain the preservation of pronounced oversteepening on the upper moraine slopes. Here we report the results of geotechnical testing of samples drawn directly from the Feegletscher Nord moraine sequence.

Study area

Investigation of the paraglacial modification of valley-side sediment-mantled slopes was undertaken in August 2001 and September 2006 in the forefield of the Feegletscher Nord (46°06′N, 7°54′E), in the Saaser Valley, Valais, Switzerland (Fig. 1). The Feegletscher is a small (<10 km^2) ice-field outlet glacier that descends from an altitude of over 4000 m asl (m above sea level) on the eastern flank of the Mischabel to a terminus at approximately 2200 m asl (as of September 2006). The front of the Feegletscher divides into two distinct tongues; a heavily crevassed ice fall characterizes the top of the wider southern lobe snout area. The northern lobe (hereafter referred to as Feegletscher Nord) is also heavily crevassed in the upper reaches, but becomes increasingly constrained and narrowed by steep rock-walled topography in its lower reaches. Both lobes are orientated in a NE direction. The site is dominated by Bernard nappe mica-schists, with serpentinite, amphibolite and quartzite (Swiss Geological Commission 1980; Hsü 1995). It experiences the inner alpine, relatively dry climate of the Valais surrounded by high mountains, with an estimated 800–1200 mm annual precipitation and mean annual temperatures of approximately $+1.5$ °C (Swiss Meteorological Survey, Zürich). The lower limit of discontinuous permafrost in Valais is approximately 2350 m for north-facing slopes and 2650 m for south-facing slopes (Lambiel pers. comm. 2003).

The site was deglaciated by about 9 ka BP, but was repeatedly reoccupied by ice during the Holocene (e.g. Röthlisberger & Schneebeli 1979; Röthlisberger *et al.* 1980). Feegletscher Nord reached its 'Little Ice Age' maximum position at AD 1818, since when it has experienced overall retreat of *c.* 1200 m and lowered *c.* 90 m (Bircher 1982; GK/SCNAT & VAW/ETZH 2006). After a slight re-advance during the 1970s and 1980s, annual retreat of the Feegletscher Nord has been sustained since 1989 (Schnyder pers. comm. 2006).

The forefield area displays marked within-valley asymmetry, with much larger moraine volume on the northern side reflecting increased debris supply from extensive rockwalls on that side of the valley (Fig. 1). On the northern side of the forefield, the pattern of glacier thinning and retreat has exposed steep glacigenic deposits composed of a stacked, multicrested, lateral moraine, which has subsequently been locally reworked, with deep, intersecting gullies forming on most upper slopes at or just below the moraine crest, and cones or sheets of reworked sediment accumulating at the slope foot (Fig. 2).

The dominant agent of reworking of glacigenic sediment at this site is debris-flow activity and

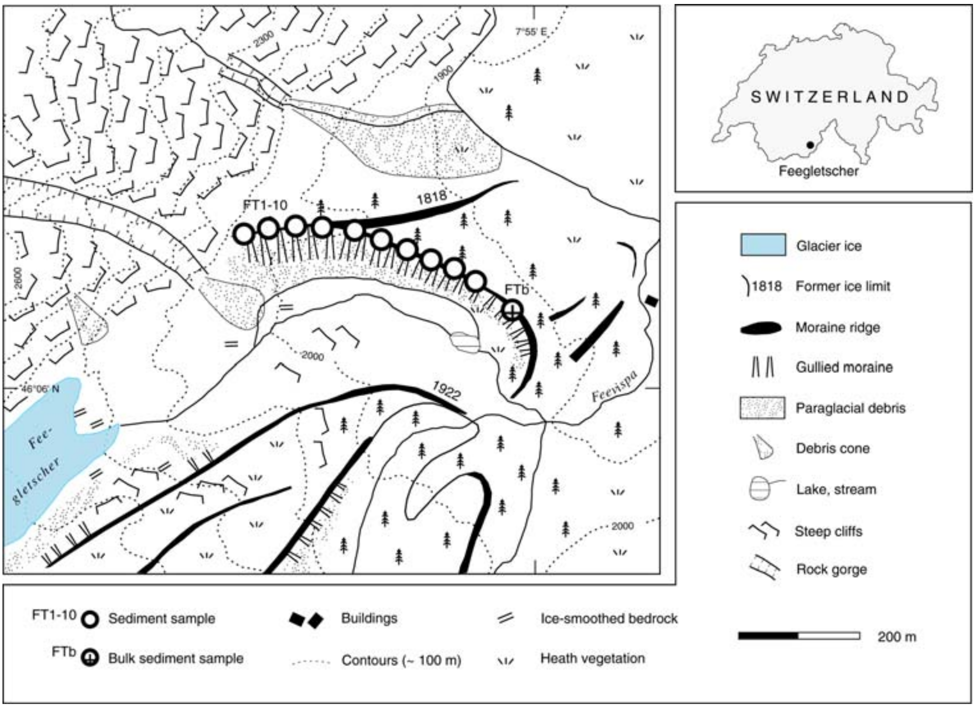


Fig. 1. Location and geomorphology of the Feegletscher Nord study site, Valais, Switzerland.

Fig. 2. Steep lateral moraine proximal slope incised by paraglacial processes operative since AD 1922 in the Feegletscher Nord forefield area. Debris slides and flows descend across the lower slope surfaces. Note crude, distal-dipping stratification exposed in the gully sidewalls.

translational sliding (Curry *et al.* 2005), triggered by rainstorms and snowmelt. There is further localized evidence of snow/slush avalanches, falls and surface wash. The Feevispa outlet stream has incised the lateral-terminal moraine in the SE, and glacifluvial gravel and sand has accumulated on the valley floor within the proximal proglacial zone.

Moraine morphology and evolution at Feegletscher

The stacked lateral moraine on the northern valley side is *c*. 60–120 m high, *c*. 700 m long (down-valley) and has a summit altitude that descends down-valley from 2060 m in the west to 1940 m in the east, considerably below the lower limit of discontinuous permafrost. A pronounced step is visible part-way along the moraine crest, at approximately 2020 m asl. At this point, a separate ridge diverges to the NE and represents the AD 1818 ice limit. Above (west of) this step, proximal slope height exceeds 100 m, but below it the height of the proximal slope is less than 70 m. Historical photographs suggest that the moraine may have been overtopped at this point during the 1890s.

The distal slope is fully vegetated, relatively stable (except for some surface creep as evidenced by curvature of tree trunks) and rests at a gradient of *c*. 33°. In contrast, the proximal slope is largely unvegetated, and steeper, although gradient is more variable, with the most recently deglaciated terrain generally steeper (<80°) than the older ground (<50°). On the oldest terrain, the most mature cones and sheets of reworked debris extend almost to the moraine crest and support a partial grass cover.

Previous investigations of the temporal pattern of moraine-slope adjustment at Feegletscher Nord indicate that following an initial period of gully incision, intervening gully divides are consumed through gully widening, resulting in progressive slope stabilization and levelling of inter-gully relief within 80 years (Curry *et al.* 2005). Thus, a dynamic land system of deep gullies, sharp arêtes and nascent debris cones is being replaced by one of increasingly vegetated coalescing cones and debris aprons, levées, lobes and low-relief scars. The resultant gullied moraine complex is morphologically similar to lateral moraine sequences observed elsewhere in the European Alps (e.g. Curry *et al.* 2005).

Field methods

Initial assessment of the extent of paraglacial reworking of glacigenic sediment comprised detailed geomorphological mapping on 1:5000 scale base maps, produced with the aid of ground and aerial photographs. Access to steep, potentially unstable moraine slopes is problematic. In particular, assessing the slope angles of upper-slope units (interfluves and gullies) that stand at angles of up to 80° is fraught with difficulty. Fifty upper-slope section angles were, therefore, measured by attaching a compass clinometer to a metre rule and placing this over the edge of the cliff at multiple locations along the moraine crest. Compass-clinometer measurements were also made at multiple locations along the moraine on the accumulated lower-angle debris cones. Although these lower-slope units were sufficiently accessible to allow the use of more accurate surveying techniques, in order to maintain a constant level of accuracy/error, compass-clinometer measurements were utilized throughout.

Diamicton facies exposed include sandy boulder gravels containing coarse, angular and subangular material. Distal-dipping of large boulders is clearly evident in the upper moraine slopes, exposed by recent erosion (Fig. 3), although for practical reasons of accessing steep, potentially unstable upper-slope units *in situ* fabric could not be quantitatively assessed. Clearly, the coarsest particles are impractical to sample and test using standard geotechnical laboratory techniques. The sedimentological size characteristics of 11 samples of *in situ* till deposit, each weighing 1 kg, were assessed in terms of fine-fraction (<8 mm, -3Φ) particle-size distributions representative of the finer matrix material within the moraine. Ten samples of massive, poorly sorted, compacted diamicton, spaced 50 m apart along the crest of the moraine ridge were extracted using a trowel, labelled 1–10 from the west to east (FT1-10, Fig. 1). Each of these samples was removed 0.2 m below the ground surface, *c*. 1 m from the proximal slope edge. Sample locations 1–4 are located above a clear step in the moraine crest at an altitude of 2020 m asl, while samples 5–10 are located east of this point. At each of these 10 sediment sampling locations, an *in situ* density test was carried out to BS1377: Part 9: 1990 using the 'sand replacement method'. These *in situ* measurements were carried out for comparison with the densities determined for samples used in the shear tests outlined below. The procedure involved excavating a 0.1 m-diameter hole to a depth of 0.1 m in a levelled area of moraine, using a metal tray with a hole in the middle, and weighing the excavated material. A preweighed pouring cylinder filled with sand of known density was then placed over the hole, and the sand released into the hole to fill it. The cylinder was weighed again and the mass of sand poured into the hole calculated. The volume of the hole was determined from the mass of sand poured, and the

Fig. 3. Flat faces of mica-schist boulders within the upper proximal slope dipping at approximately 33° towards the distal slope (left-hand side).

bulk density of the moraine calculated. The moisture content of a small sample of material taken from the hole was then determined in order to calculate the dry density of the moraine.

Finally, a bulk sample of moraine material weighing 18 kg was removed from a depth of 0.2 m on the moraine crest at a point 80 m SE of sample 10, for laboratory shear tests. An 11th particle-size sample weighing 1 kg was taken from this bulk sample, for granulometric analysis of material finer than 8 mm (-3Φ), as well as clast lithological and form analysis.

Laboratory procedures

To prepare samples for sieving, initial disaggregation was undertaken by prolonged (3 h) agitation in a 4% solution of sodium hexametaphosphate. The particle size distribution of fine gravel to very-fine sand-sized material was determined by wet sieving each of the 11 till samples, with weight per fraction calculated as a percentage of the total. Volume of material finer than 63 μm (4Φ) in each sample was quantified by a Malvern Instruments laser particle-size analyser, and the results converted into % weight data. A total of 167 clasts coarser than 10 mm were sampled from the bulk sediment, described, identified for lithology, and their three principal axes measured to calculate flatness and elongation ratios (Zingg 1935). Aggregate clast shape was also calculated in terms of the percentage of clasts with *c:a* axial ratios ≤ 0.4 (C_{40}) and ≤ 0.5 (C_{50}; Ballantyne 1982), and angularity expressed as the percentage of very angular plus angular clasts (RA; Benn & Ballantyne 1994).

The aim of the direct shear tests was to determine the effective angles of friction for the matrix material for a range of densities and fabric orientations. These values could then be compared with the variety of *in situ* angles of repose, as indicated by the proximal and distal slopes of the moraine, and the redeposited debris at the base of the proximal slope.

To prepare a sample with fabric at a high angle to the shear surface, either an undisturbed sample has to be obtained from the moraine or a reconstituted sample has to be manufactured. The former is virtually impossible because of the lack of cohesion, suction or cement, and the presence of large clasts. The latter method is also impractical because a 300 × 300 mm sample would have to be prepared using a procedure to place flat clasts horizontally, and the entire sample would then have to be rotated through 90° and placed into the shear box intact.

Clearly, a limitation of the shear box tests is that the material (and its fabric) has been disturbed, and then reconstituted within the shear box at densities that may differ from *in situ* densities. Furthermore, the range of matrix particle sizes does not include particles coarser than gravel size, which may affect the shear strength of the reconstituted moraine samples. The two halves of the shear box control the formation of the shear surface or zone. However, the use of a large shear box (300 × 300 mm) is the best available method for laboratory determination of the material shear-strength parameters.

A series of direct shear tests using a large shear box (300 × 300 mm) was carried out on an air-dried sample of the moraine matrix material, using the method in BS1377: Part 7, 1990. For the first series of three tests the lateral moraine sample was loosely placed into the shear box in three layers, to simulate the undisturbed distal and debris slopes. In a second series of three tests, an air-dried sample of material was compacted into the large shear box in three layers, each layer compacted for 60 s with a Kango vibrating hammer and plate rammer. The compaction of the sample is intended to simulate glacial compaction of the moraine during successive advances of Feegletscher Nord. A series of vibrating hammer compaction tests were carried out to BS 1377: Part 4: 1990, to determine the maximum dry density and optimum moisture content of the bulk sample, for comparison with the densities achieved in the shear box. For a third series of shear box tests, the air-dried sample was compacted into the large shear box in three layers and each layer compacted for 30 s with a Kango hammer and plate rammer. After compaction of

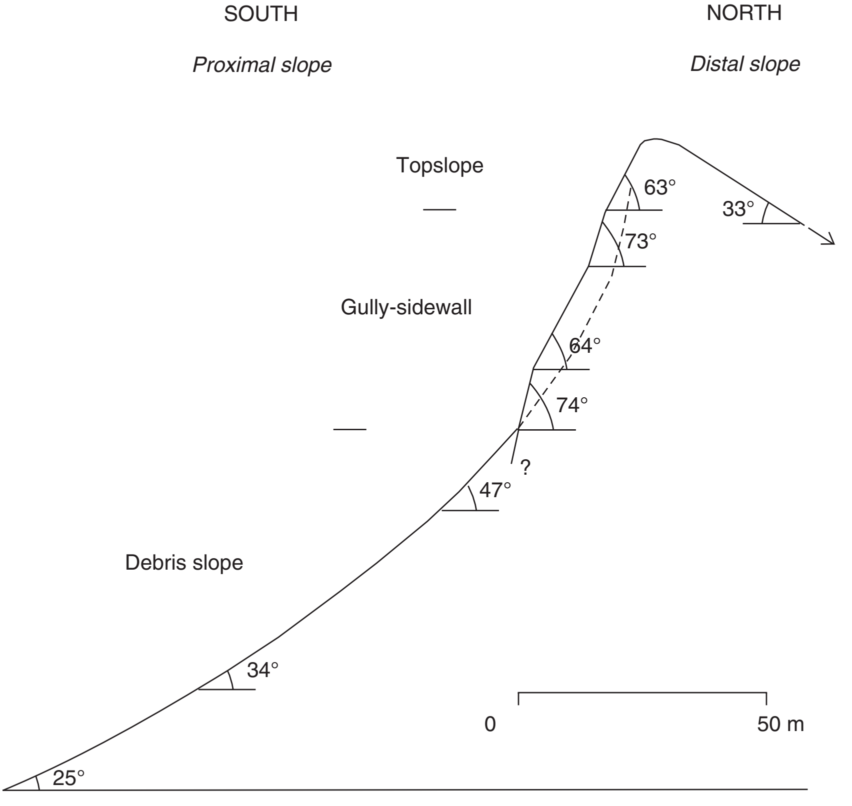


Fig. 4. Characterization of the recently exposed moraine slopes at Feegletscher Nord, based on average survey measurements: an oversteepened top slope, a middle gullied slope zone and a lower-angled basal debris sheet. The dashed line indicates the gully-floor profile. Only the uppermost part of the distal slope is shown.

the second layer 25 gravel-size flat clasts were placed in five rows with their *c*-axes parallel to the direction of shear, to partly simulate the distally dipping fabric of supraglacially derived material emplaced by dumping and gravity-flow deposition at the glacier margins (cf. Small 1983). In each series of tests the air-dried sample was subjected to three normal stresses equivalent to the likely *in situ* stresses within the near-surface sediments of the lateral moraine, based on the densities measured in the field, and then sheared at a rate of 1 mm min^{-1}. The lowest normal stress that could practically be applied by the shear box was used to simulate shear near the surface.

The effective angle of friction was determined from the Mohr–Coulomb failure criterion:

$$\tau_f = c' + \sigma_n' \tan \phi' \quad (1)$$

where τ_f is shear strength, c' is effective apparent cohesion, σ_n' is effective normal stress and ϕ' is effective angle of friction. Assuming that the

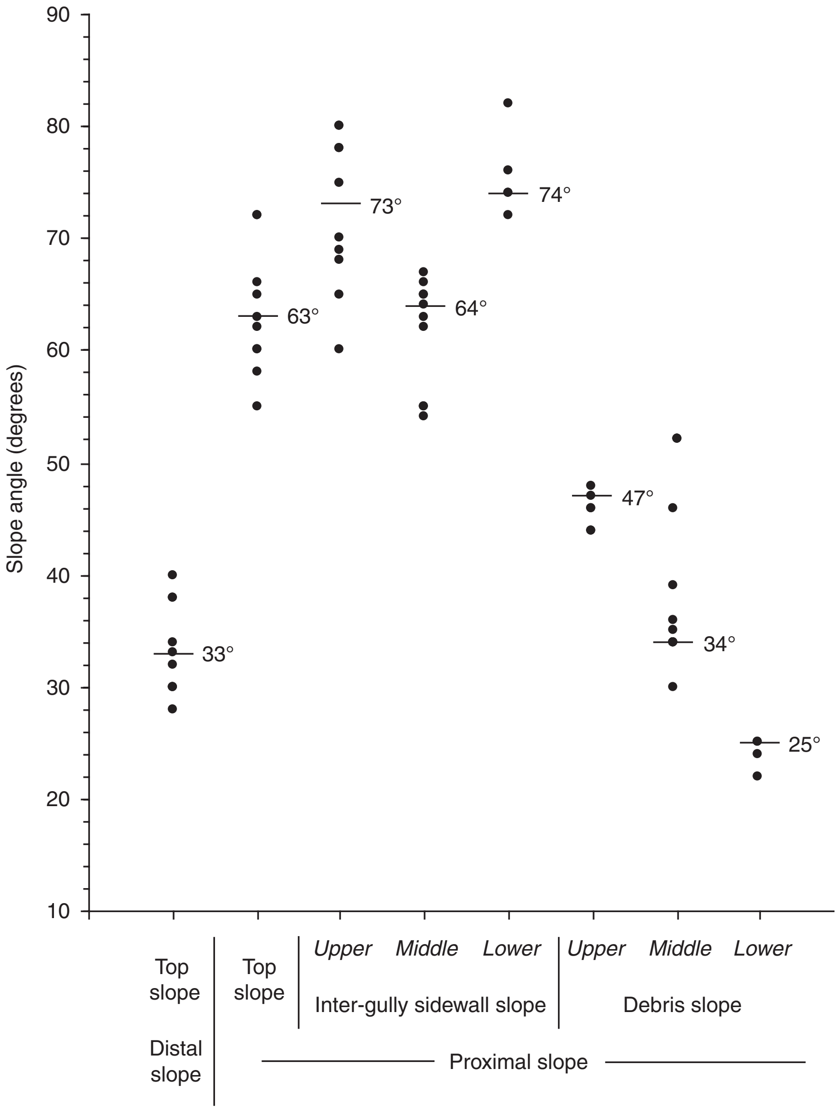


Fig. 5. Dispersion diagrams illustrating moraine slope gradient at Feegletscher Nord. Horizontal bars indicate median values. Each closed circle represents one surveyed slope.

Table 1. In situ *dry densities for samples taken along the crest of the Feegletscher Nord lateral moraine. Sample locations shown in Figure 1*

Sample	Dry density (Mg m^{-3})
1	1.29
2	0.84
3	n/a
4	0.90
5	2.34
6	2.20
7	1.96
8	2.04
9	n/a
10	2.07
Average	1.70

n/a = not available.

effective apparent cohesion of the material is zero, the effective angle of friction is therefore:

$$\phi' = \tan^{-1} \tau_f / \sigma'_n. \quad (2)$$

Results

The proximal slope can be subdivided into three major slope elements, consisting of an oversteepened top slope, a middle gullied slope and a lower-angled debris sheet beneath (Fig. 4). The middle gullied slope section can be further subdivided into upper, middle and lower inter-gully sidewall slopes and gully floor slopes. Results of slope measurements made on the Feegletscher Nord moraine are shown in Figure 5. The median slope angle of the undisturbed and heavily vegetated distal slope is 33°. The median angle of the top proximal slope units was 63°. Median slope angles of the upper, middle and lower inter-gully sidewalls were 73°, 64° and 74°, respectively. The median measured proximal debris cone slopes were 47°, 34° and 25° for the upper, middle and lower sections, respectively.

Results of *in situ* dry density measurements are shown in Table 1. Values range from 0.84 to 2.34 Mg m^{-3} (Mg = 1×10^6 g) with an average of 1.70 Mg m^{-3}. The maximum dry density and optimum moisture content values of the bulk sample, obtained from the vibrating hammer compaction tests, were 2.25 Mg m^{-3} and 7.9%, respectively. *In situ* dry densities derived from the shear box samples range from 1.91 Mg m^{-3} for the loosely packed sample, 2.01–2.20 Mg m^{-3} for the densely packed sample and 2.12–2.16 Mg m^{-3} for the densely packed sample with partial perpendicular fabric (Table 2).

The particle-size distributions for the material finer than 8 mm (−3Φ) of the 10 *in situ* moraine samples and the single bulk moraine sample are shown in Figure 6. Particle-size analysis shows a generally poorly sorted, well-graded range of particle sizes, with clay-size particles making up less than 1% of material finer than 8 mm in all moraine samples. Ninety-four per cent of clasts sampled coarser than 10 mm were mica-schist, 5% were quartz, <1% were mylonite and <1% serpentinite. Clasts were found to be generally subangular (83%; average RA index = 84) and smooth (99%). Clast

Table 2. *Large shear box test results on the Feegletscher Nord moraine bulk sample*

Sample	Dry density (Mg m^{-3})	Normal stress (kPa)	Peak shear stress (kPa)	Critical shear stress (kPa)	Effective angle of friction (°)		Angle of dilation (°)
					Peak ϕ'	Critical ϕ'_{crit}	ψ
Loose	1.91	66.6	48	48	35.8	35.8	0.0
	n/a	133.1	94.2	94.2	35.3	35.3	0.0
	n/a	199.7	138.4	138.4	34.7	34.7	0.0
Average	1.91	–	–	–	35.3	35.3	0.0
Dense	2.09	66.6	51.8	36.7	37.9	28.9	9.0
	2.21	133.1	169.5	100.8	51.9	37.1	14.7
	2.21	199.7	190.2	139.4	43.6	34.9	8.7
Average	2.17	–	–	–	44.4	33.6	10.8
Dense fabric	2.12	66.6	72.5	62.2	47.4	43.0	4.4
	2.13	133.1	146.0	122.4	47.6	42.6	5.0
	2.16	199.7	228.8	168.6	48.9	40.2	8.7
Average	2.13	–	–	–	48.0	41.9	6.1

n/a = not available.

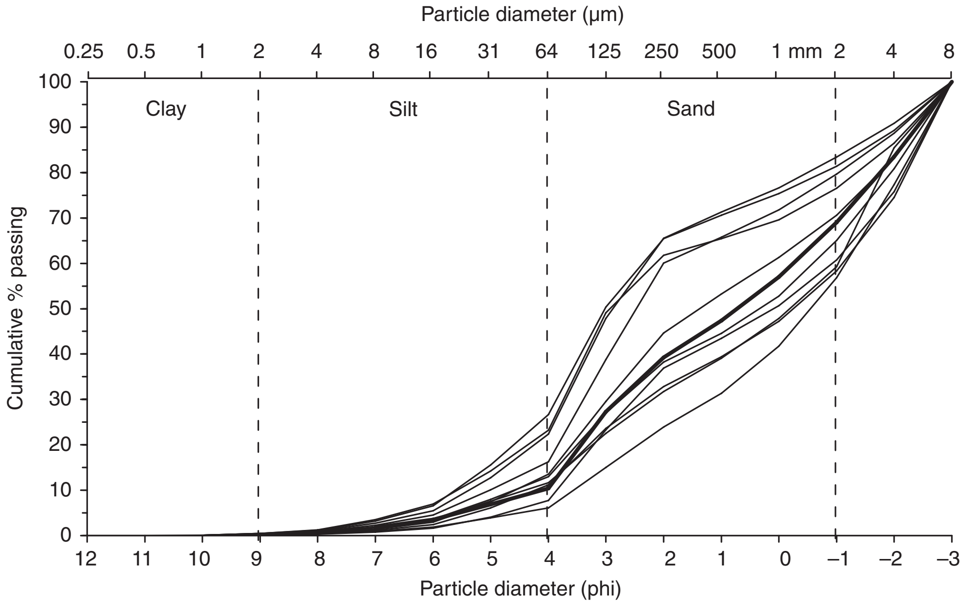


Fig. 6. Cumulative particle-size distributions (material finer than 8 mm/−3Φ) for 11 samples of Feegletscher Nord moraine. The bulk sample is indicated with a bold line.

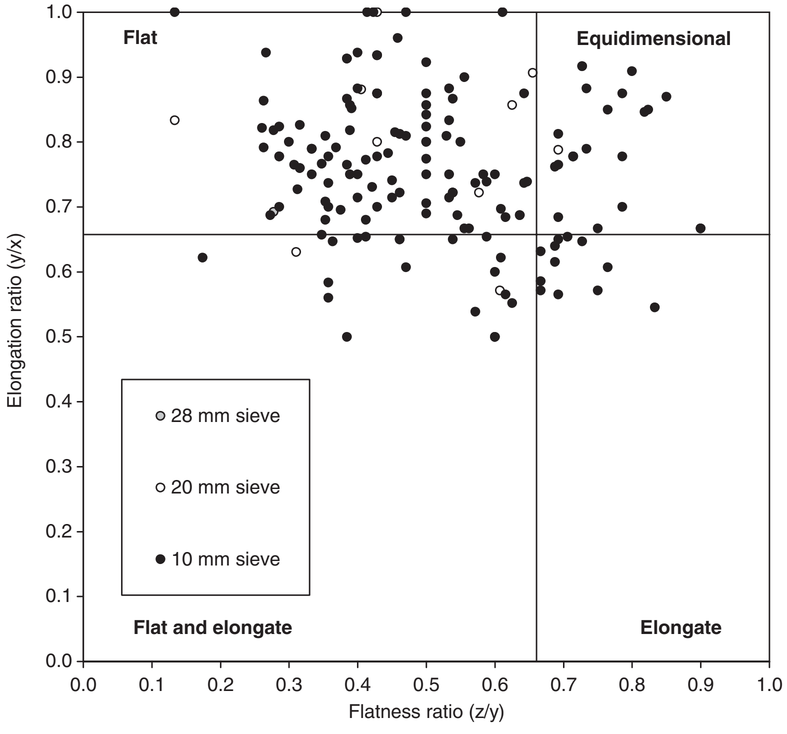
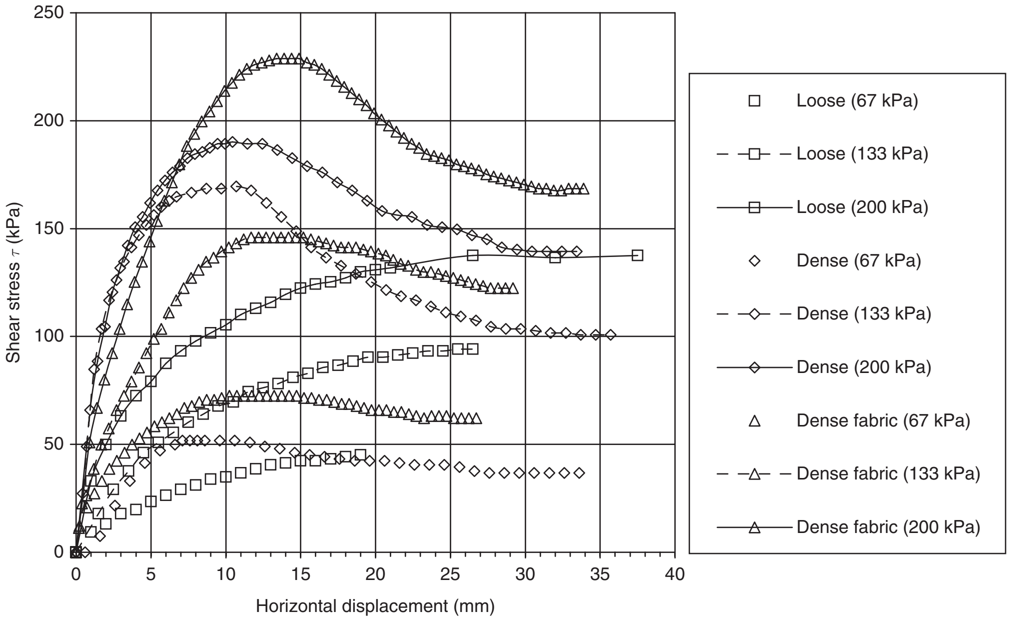


Fig. 7. Shape of 167 clasts taken from the Feegletscher Nord moraine bulk sample, summarized according to Zingg's (1935) flatness and elongation ratios.

(**a**)



(**b**)

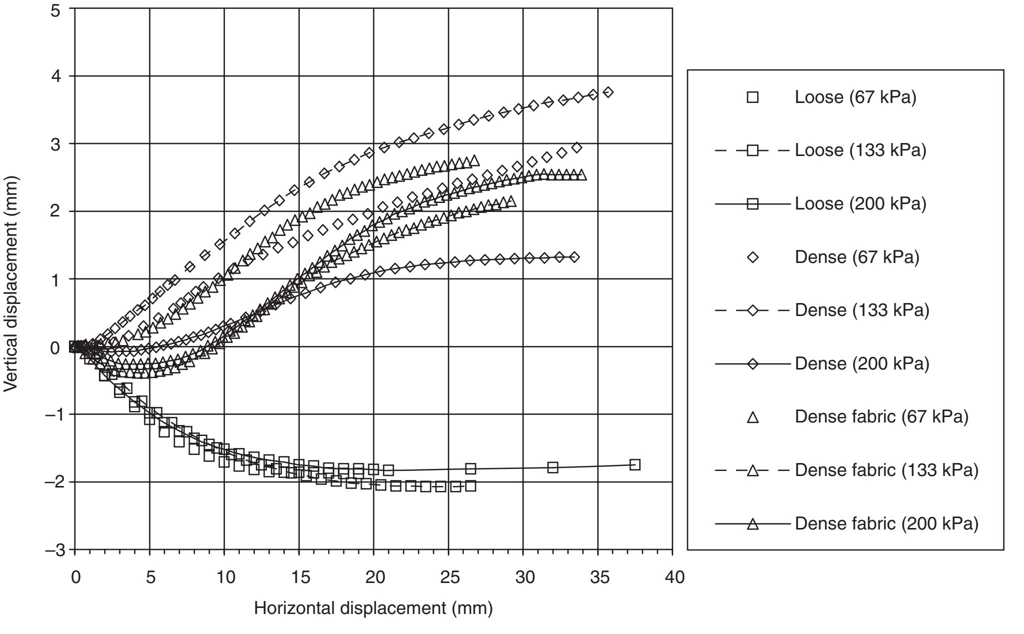


Fig. 8. Large shear box tests on the Feegletscher Nord moraine bulk sample tested ‘loose’, ‘dense’ and ‘dense fabric’ (the latter with a partial fabric perpendicular to the direction of shear). Normal stresses are shown in brackets. (**a**) Shear stress against horizontal displacement. (**b**) Vertical displacement against horizontal displacement. (**c**) Shear stress against effective normal stress.

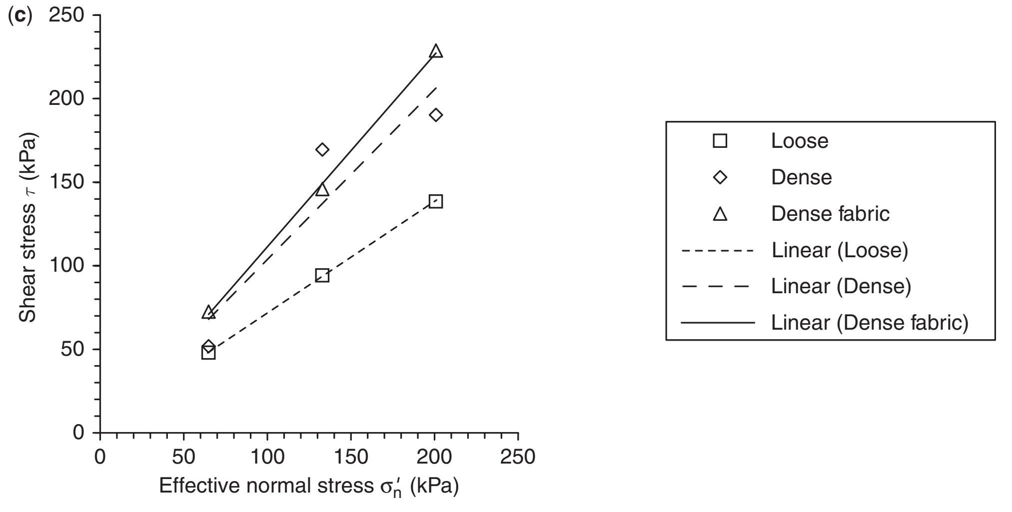


Fig. 8. (*Continued*).

form is described by C_{40} and C_{50} indices of 62 and 85%, respectively, indicating a slabby or elongate form typical of supraglacially transported clasts (Benn & Ballantyne 1994). Following Zingg's (1935) clast form method, 66% of the sampled particles were found to be flat (Fig. 7). Of the remainder, 14% were equidimensional, 13% flat and elongate, and 7% elongate. The average flatness and elongation ratios were 0.506 and 0.760, respectively, which indicates that the average clast form is flat (Zingg 1935). The material finer than 10 mm also contains mica flakes, which by their nature are flat in form.

The shear stress v. displacement and shear stress v. normal stress graphs for the well-graded muddy sandy gravel bulk moraine sample are shown in Figure 8. The effective angle of friction of the loosely packed sample (hereafter referred to as 'loose') ranges from 35° to 36°, with an average of 35° (Table 2). The peak effective angle of friction obtained for the compacted moraine sample (hereafter referred to as 'dense') ranged from 38° to 52°, with an average of 44°, while peak effective angle of friction obtained for the densely packed fabric samples (hereafter referred to as 'dense fabric') ranged from 47° to 49° with an average of 48°. Critical effective angles of friction were 35°, 34° and 42° for the loose, dense and dense fabric samples, respectively. The average dry densities of the loose, dense and dense fabric samples determined at the end of shear box testing were 1.91, 2.17 and 2.13 Mg m^{-3}, respectively. These are all within the range of the *in situ* densities shown in Table 1.

Discussion

This research tests the hypothesis that the angles of friction obtained from shear tests for samples of the lateral moraine prepared to different densities and fabrics should be similar to the natural angles of repose of the lateral moraine, assuming shallow translational failure. The grading of the moraine material supports field observations that suggest the type of failure is likely to be shallow translational sliding, flow and individual clast slide and/or fall, rather than deep-seated rotational slip, because of the very small percentage of clay-sized particles (cf. Selby 1993). Moreover, well-graded, imbricated and overlapping clasts prevent a discrete deep-seated rotational failure surface developing. Translational failure of an 'infinite' cohesionless soil slope is assumed to occur on a plane parallel to the ground surface, at shallow depth. The factor of safety, F, of the slope at the point of translational failure along a potential shear surface is commonly described as:

$$F = \tau_f/\tau = [1 - (u/\gamma z \cos^2 \beta)] \times [\tan \phi'/\tan \beta] = 1 \qquad (3)$$

where τ is shear stress, u is pore-water pressure, γ is unit weight of soil, z the depth of failure surface and β is slope angle.

Assuming that the pore spaces within the moraine are unsaturated and that $u = 0$, then equation (3) yields:

$$\beta = \phi'. \qquad (4)$$

The gradient of the ground surface is therefore equal to the effective angle of friction of the material. If there is a pre-existing slip surface, such as that which may exist between flat clasts with a distinct fabric parallel to the ground surface, then the mobilized effective angle of friction would be equal to the critical effective angle of friction, ϕ'_{crit}, and equation (4) becomes:

$$\beta = \phi'_{\text{crit}}. \tag{5}$$

This appears to be true for the distal and middle proximal debris slopes, which, because of their general flat clast form, are orientated parallel to the slope and have undergone significant shearing during their formation, and so would be expected to be close to the ϕ'_{crit} for loose and dense samples. In fact, the median slope angles of 33° and 36° measured for the distal and middle proximal debris slopes, respectively, and those obtained by Whalley (1975) of 35°, compare well with the ϕ'_{crit} for loose and dense samples of 35° and 34°, respectively.

However, the average peak angle of friction obtained from shear tests on samples of the lateral moraine was 44° for the dense sample and 48° for the dense sample with partial perpendicular fabric. These angles are considerably lower than the maximum median slope angle of 74°, and those found at this site by Curry *et al.* (2005) and Whalley (1975) of 69° and 70°, respectively. This may reflect the fact that the majority of the flat mica-schist clasts in the reconstituted sample were likely to be orientated subhorizontally in the shear box and therefore their fabric was parallel or subparallel to the shear surface. The silt- and sand-sized material, made up of mainly mica particles, may also naturally lie flat when placed in the shear box, as do the gravel-sized particles that were mainly flat mica-schist clasts. In the upper proximal slopes of the lateral moraine, shear of the material near the surface would be at a high angle to the generally distal-dipping imbricated clasts. Therefore, for shallow translational shear to occur parallel with the proximal slope surface, shear would probably be between distally dipping flat clasts in addition to shear of some weak intact clasts. The shearing resistance along this potential shear surface would be significantly increased by the shear surfaces between clasts being at an oblique angle to the slope and by clast intact shear strength. For shear failure to occur parallel to the proximal slope, therefore, significant dilation of the dense distally dipping material is required. This dilation phenomenon is recognized in dense soils, which experience volumetric increase when sheared, until a peak shear stress is reached, followed by a reduction in the rate of dilation until a critical state is reached. At low normal effective stresses many soils exhibit 'dense' characteristics. In the shear box the material dilates and the platen rises at the angle of dilation, ψ. Although the shear surface is horizontal, it can be conceptualized that the microscopic intergranular shear planes are inclined at an angle of ψ. Therefore, the effective angle of friction being measured is:

$$\phi' = \phi'_{\text{crit}} + \psi. \tag{6}$$

This is similar to shear between rock surfaces that are inclined at an angle, i, to the direction of shear (Patton 1966; Barton 1973). Given the presence of interlocking asperities along rough rock-mass discontinuity surfaces, shear stresses along these partings are often inclined to the overall applied shear stress direction. In this case the relationship between applied shear and normal stresses is:

$$\tau_{\text{f}} = \sigma'_{\text{n}} \tan(\phi'_{\text{b}} + i) \tag{7}$$

In equation (7), ϕ'_{b} is the basic angle of friction for the rock, which is similar to the critical angle of friction in soils, since these are the angles measured when there is no volume change, and i is the roughness angle for the joint surface. It can be assumed that the moraine, a well-graded material of densely packed distally dipping clasts, from silt to boulders, behaves somewhere between a dense soil and a weak, highly jointed rock mass. The observed stratification and fabric within the undisturbed moraine might suggest that the geotechnical properties are more closely aligned with those of a highly jointed rock mass than a soil. If it is assumed that the stability of the upper proximal slope is governed by shallow translational failure and equation (4) is rewritten in terms of the angle of friction in equation (7), then:

$$\beta = \phi'_{\text{b}} + i. \tag{8}$$

Barton (1973) presents values of $(\phi'_{\text{b}} + i)$ from several authors for different rock types and rough discontinuity surfaces at low normal stresses, ranging from 66° to 80°, with an average of 72°. This value is close to the gradients of the proximal upper and lower inter-gully sidewall slopes, which have median angles of 73° and 74°, respectively.

Barton (1973) derived an empirical equation for curvilinear peak shear strength along rock joint surfaces:

$$\tau_{\text{f}} = \sigma'_{\text{n}} \tan(\phi'_{\text{b}} + \text{JRC} \ \log_{10}[\text{JCS}/\sigma'_{\text{n}}]) \tag{9}$$

where JRC is the Joint Roughness Coefficient (an empirical measure of joint roughness) and JCS is

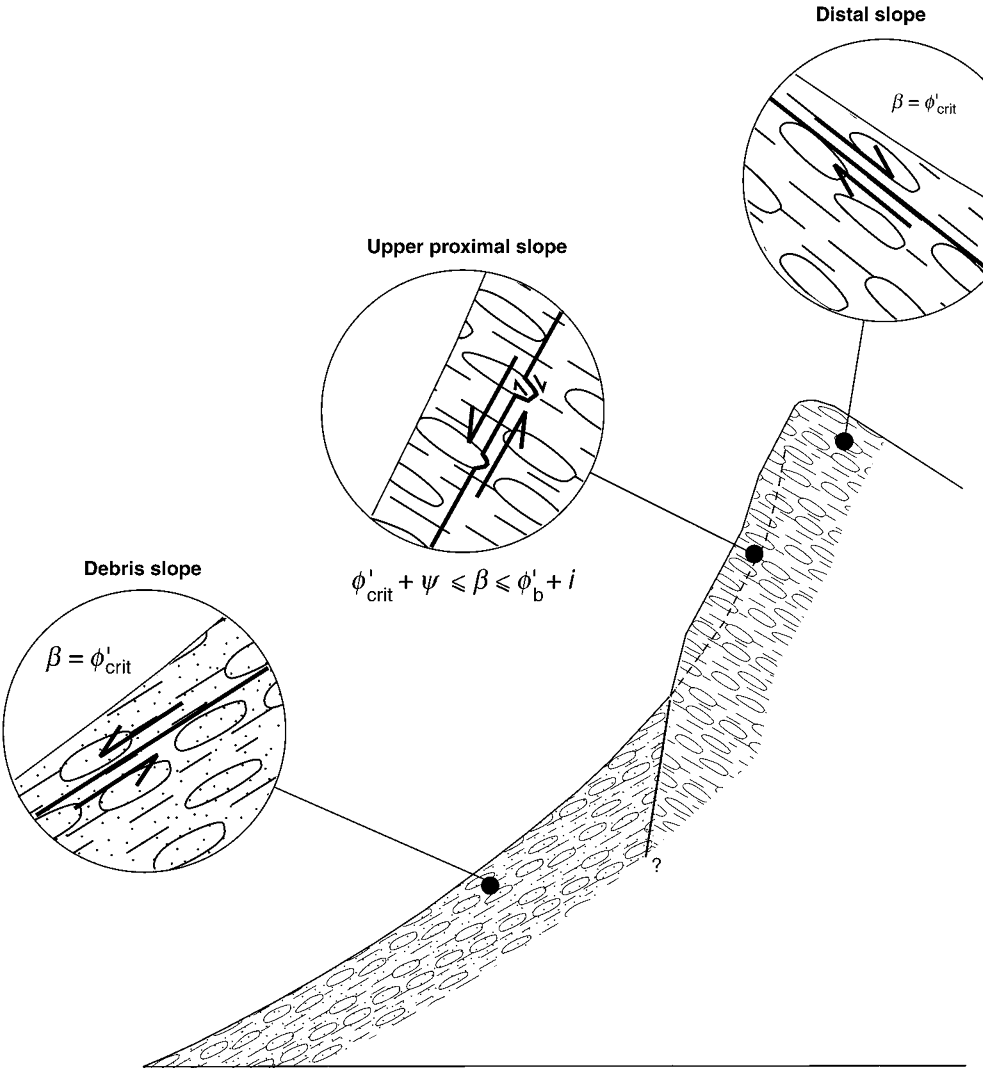


Fig. 9. Idealized section through steep moraine slopes showing the influence of clast shape and fabric on shearing resistance and slope angle. Insets show magnified fabric and potential shear surfaces.

the Joint wall Compressive Strength (compressive strength of weathered joint walls). At low normal stresses the value in parentheses in equation (9) becomes large for rough, undulating joints. Barton suggests that the maximum value for this section of equation (9) ($\phi'_b + \mathrm{JRC}\log_{10}[\mathrm{JCS}/\sigma'_n]$) should be 76° for $\mathrm{JCS}/\sigma_n = 200$. The median angles of the upper proximal slopes lie just below this value.

Consequently, it seems plausible to suggest that the stability of steep, relatively undisturbed upper proximal slopes of the Feegletscher Nord moraine may be controlled by shallow translational failure, with inclined shear stresses and resulting dilation between the generally densely packed, distally dipping clasts (Figs 9 and 10). From the results of the shear box tests, the observations made in the field and the comparisons made with measurements of rock joint shear strengths carried out by others, the upper proximal-slope angles appear to lie between the values given by equations (6) and (8), and hence:

$$\phi'_{crit} + \psi \leq \beta \leq \phi'_b + i. \qquad (10)$$

Indeed, we consider that the major cause of the steep slopes at Feegletscher Nord probably reflects the distal-dipping fabric, whose stabilizing role is significantly enhanced by the generally flat form

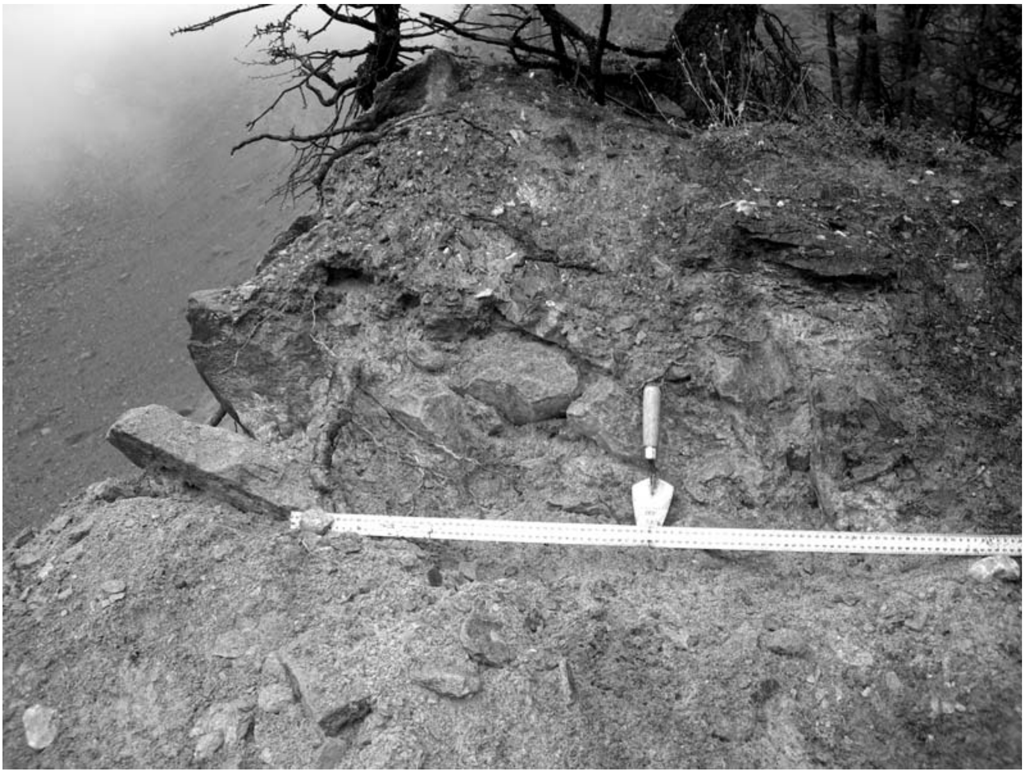


Fig. 10. Naturally eroded, north–south gully section through the top of the middle part of the Feegletscher lateral moraine, showing a south-facing, steep, proximal slope on the left and densely packed, overlapping distally dipping flat clasts in the centre, following rough cleaning of the gully slope. The average dip and dip directions of the larger clasts are 31° and 008°, respectively.

of the mica-schist clasts. Imbrication of these flat-form clasts inhibits shallow translational shear on the proximal slopes and, hence, permits retention of steep slope angles. A further, secondary, temporary slope-stabilizing effect may be the natural 'buttressing' of the moraine material caused by the creation of inter-gully slopes through incision of adjacent gullies, prior to their erosion and removal, although this effect cannot be substantiated without further field investigation.

A possible alternative explanation for the difference between maximum observed slope angles and peak angles of friction concerns the role of cementing and suction (Whalley 1975). Coarse-grained particles, such as gravel and sand-sized material, may be held together by the intermolecular bonds of cementing precipitates such as silica, calcium carbonate and iron oxides, and by bridges of clays. The moraine material observed by the authors, however, was found to be friable and relatively easily broken up by finger pressure, suggesting a lack of suction and/or cementation. There is unlikely to be much cementing owing to the young age of the deposit and the lack of evidence for groundwater flow carrying minerals that could provide cement. There may be some temporary suction pressure holding the fine clasts together during dry periods following evaporation of infiltrated precipitation, because of their flat shape and the silt- and sand-sized matrix. This may explain the weak surface 'crust' that is sometimes observed, which holds finer particles together in larger agglomerates. However, any suction would probably be insufficient to provide a long-term stabilizing effect of the well-graded moraine. This suction is very difficult to measure *in situ* because of the well-graded nature of the sediment.

Two wider implications emerge from this study. The first concerns landform resilience to change and paraglacial sediment transfer rates. Without doubt, paraglacial reworking of glacigenic sediment stores has the potential to substantially modify land-surfaces and sediments during and following deglaciation. Minimum rates of ground-surface lowering on the Feegletscher Nord lateral moraine have averaged approximately 50–100 mm year^{-1}

since ice retreat in AD 1922 (Curry *et al.* 2005). These rates are similar to those calculated for sites in western Norway (Ballantyne & Benn 1994; Curry 1999), although greatly exceed 'normal' erosion rates in other settings (Young & Saunders 1986), emphasizing the extreme rapidity of geomorphic change and sediment transfer on steep, sediment-mantled slopes associated with paraglaciation (cf. Church & Ryder 1972; Church & Slaymaker 1989; Harbor & Warburton 1993). Yet, even within an active paraglacial setting, given favourable lithological conditions, moraine slopes, such as those observed in the lateral-terminus area of the Feegletscher Nord, are able to stand at steep angles in a quasi-stable form on a decadal timescale, resisting wholesale removal and reworking, and delaying the release of glacigenic sediment into the proglacial zone and paraglacial sediment cascade. Thus, while some models of primary paraglacial system behaviour indicate activity rates declining rapidly from a peak at the time of deglaciation (e.g. Matthews 1992), paraglacial sediment movement within the glacigenic sediment-mantled slope land system may in many cases peak shortly after, rather than immediately after, deglaciation.

Moreover, temporary, quasi-stable storage of glacigenic sediments in high-angle moraines, such as those observed in this study, is one of several processes likely to disrupt the simple, monotonic exponential decline of paraglacial sediment transfer rates and add a stochastic element to the timing of forefield sediment delivery by non-glacial processes. Significant levels of paraglacial reworking can take place in primary paraglacial systems some time after deglaciation in response to non-glacial extrinsic perturbations (Ballantyne 2002*b*) and, as this study demonstrates, where lithological conditions are favourable. Storage of sediments in moraine sequences can prevent release of glacigenic material by non-glacial processes for several decades following deglaciation. In general, the post-glacial disintegration processes of morainic deposits remain poorly understood (e.g. Sletten *et al.* 2001), and the ability of moraine slopes to resist wholesale disintegration immediately following deglaciation, as observed in this study, suggests that post-glacial moraine disintegration and associated sediment supply to forefield areas is not a simple linear process.

A second implication relates to the sensitivity of steep, recently deglaciated moraine slopes to future climate change. Clearly, the relevance of the paraglacial concept is particularly evident in the context of recent retreat of mountain glaciers and climatic amelioration. In contrast to the established use of geophysical and geotechnical approaches in the assessment of periglacial slope problems (e.g. Harris *et al.* 2001, 2003; Harris 2005), the application of engineering geology approaches and solutions to paraglacial slope problems is an underdeveloped research field, despite a growing awareness of non-glacial slope hazards associated with recent glacier retreat (e.g. Evans & Clague 1994; Haeberli *et al.* 1997; Holm *et al.* 2004; Huggel *et al.* 2004; Chiarle *et al.* 2007). In this study standard engineering techniques have shed light on controls on paraglacial modification of steep moraines. Further geotechnical work may facilitate improved spatial and temporal prediction of paraglacial mass movement on sediment-mantled slopes. Parameters commonly involved in modelling landslide susceptibility include climatic variables, slope morphology, land use and bedrock lithology. The research presented here highlights the potential role that clast form and fabric may play in enhancing the stability of steep moraine slopes, factors that should be included in landslide (especially debris flow) hazard assessment, monitoring and modelling on steep, glacigenic sediment mantles.

Conclusion

Although paraglacial reworking of sediments clearly has the capacity to induce slope instability and the movement of large volumes of sediment, given favourable lithological conditions, moraine slopes, such as those observed in the lateral-terminus area of the Feegletscher Nord, are able to stand at steep angles in a quasi-stable form on a decadal timescale. The current slope gradients of the lateral moraine reflect the mechanisms of original emplacement, post-glacial (paraglacial) modification, including translational failure, geotechnical properties, stratification and fabric, and high angles of dilation necessary for shallow translational shear to occur on the upper proximal slopes. Results from the shear box testing suggest: (i) that the distal and proximal debris slope angles are similar to the critical effective angles of friction for disturbed samples; and (ii) that a distal slope dip in fabric, throughout the undisturbed moraine, may assist in allowing proximal slopes to exceed peak effective angles of friction measured for disturbed samples in the laboratory. We propose a conceptual model, based on shallow translational shear failure, to explain the mechanisms that enable the preservation of distal, debris and very steep proximal slopes on the Feegletscher Nord and other similar moraines. However, detailed examination of *in situ* fabric samples from steep slope segments would be required to evaluate this model further, and it is difficult to envisage from a logistical point of view, how *in situ* fabric of these steeper slope segments could be quantitatively assessed. Detailed fabric analysis of actively forming lateral moraines at contemporary ice margins may provide additional information without the same level of logistical difficulty, although such studies would be unable to assess the role of factors such as glacifluvial reworking, removal of ice buttressing forces and enhanced paraglacial activity during deglaciation. The role of lithology and fabric in allowing steep slopes to exist in quasi-stable form requires further consideration from both a geomorphological point of view and by those considering the susceptibility of recently deglaciated terrain to mass movement hazards; wholesale slope instability is clearly not always an inevitable and immediate consequence of deglaciation and associated paraglacial activity.

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