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THE CONTRIBUTION OF DISCONTINUOUS ROCK-MASS FAILURE TO GLACIER EROSION

by

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ABSTRACT

Geomechanical rock-mass properties control the response of bedrock to applied stresses and can be summarized in a linear Mohr-Coulomb equation, which defines the principal parameters determining failure. Nevertheless, in studying the erosion of bedrock by glacier ice, little attention has been paid to failure criteria although a coincidence of erosional landforms with fracture systems at regional and local scales has been demonstrated. Few studies have analysed the precise nature of the fracture geometry, or proposed its mechanical impact in association with glacier ice.

This investigation proposes that, since almost all bedrock possesses identifiable fracture systems, the properties of discontinuous rock mass (DRM) be regarded as defining primary conditions of stress and stability which are subsequently modified directly and indirectly by glacier ice. Consequent rock-mass failure modes are prescribed by discontinuity geometry and applied stresses, and evidence from North Wales confirms the validity of the theoretical treatment of rock-mass properties, and explains the accordance of landforms with structure.

INTRODUCTION

Glacier erosion of hard rock is a complex process controlled by material properties interacting at what Weertman (1979) termed the bed-water-ice interface. Bedrock properties determine exclusively the first of these components and hydraulic conductivity influences the second. Although many ice-flow problems have been resolved, rock-mass performance under stress beneath and adjacent to glaciers has received little attention, although the extent to which the close control on glacier erosion exerted by geological structure has been recognized, especially by geomorphologists. Randall (1961), Holtedahl (1967), and Nilsen (1973) considered that large-scale fractures or joints of Caledonian age determined fjord and other glacially-eroded valley alignment in Norway; Trainer (1973) described incipient joints opened by ice flow in a wide range of rock from California, Maine, and New York State, and Zumberge (1955) demonstrated structurally-aligned glacier scouring around western Lake Superior. In all cases, structural elements involved are clearly of pre-glacial tectonic origin, whereas relaxation of overburden-confining stresses was believed by some authors to cause rock fracture immediately preceding or during glaciation, and hence to facilitate "quarrying", often enhanced by freeze-thaw loosening (Jahns 1943, Lewis 1954, Chapman and Rioux 1958, Battey 1960, Whillans 1978). Although the age, formation, and significance of the resultant sheeting structures (supposedly formed irrespective of any existing anisotropy) are sometimes qualified, preoccupation with "pressure release" demonstrates a simplistic and frequently inaccurate view of rock-mass properties and response to stress, as other authors have indicated (Harland 1957, Twidale 1972, 1973, Brunner and Scheidegger 1973). Occasionally, absence of serious attention to rock-mass performance under stress has led to many omissions. The "melt-water hypothesis" of cirque erosion (Lewis 1938, 1940) is one clear example, where the effect of water pressure on stability is ignored, often despite substantial evidence of its abundant presence in rock mass; another is the notable avoidance of suggested failure mechanisms in studies which otherwise demonstrate intimate structural control over erosion (Haynes 1968, Sugden 1974).

Bedrock performance has been examined in more detail recently. Broster and others (1979) give qualified support to the fracture of intact rock by glacier ice; this is questioned later in this paper. Although primarily not investigating nor modelling rock properties, Morland and Boulton (1975), Morland and Morris (1977), and Boulton (1979) consider that a jointed bedrock model responding to basal ice shear would be more appropriate. Up to now, studies of bedrock response to specific stress conditions induced by glacier ice lack an understanding of the principles of rock mechanics and resulting failure mechanisms. Those principles considered by the present author to be important will now be outlined.

PRINCIPAL GEOMECHANICAL ROCK-MASS PROPERTIES

A major problem in assessing the erodibility of rock stems from the gross inequality between the internal shear strength of rock and glacier ice; this is partially resolved for abrasion by regarding the glacier sole as an ice-rock-debris mix, but large-scale block removal or "quarrying" is not so effectively explained.

Intact rock-mass strength (IRMS)

The failure criteria for rock is usually defined by a simple linear Mohr-Coulomb equation (Fig.1):

$$\tau = c + \sigma \tan \phi , \qquad (1)$$

where τ and σ are shear and normal stresses, respectively, c is the value for internal

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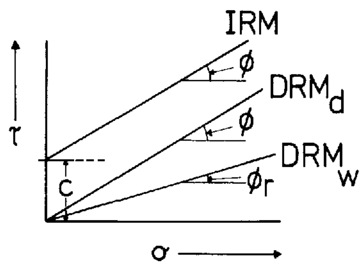

Fig.1. Linear Mohr-Coulomb relationships between shear stress and normal stress for intact rock mass (IRM); the progressive reduction in required shear stress is shown for dry discontinuous rock mass (DRM_d) where $C = 0$, and wetted discontinuous rock mass (DRM_w), where a given friction angle ϕ is reduced to an effective friction angle ϕ_r.

cohesion, and ϕ is the angle of friction along the eventual failure plane (Hoek 1970). A distinction is made between *peak* shear strength, beyond which the rock deforms, and the *residual* shear strength of the deformed mass. These may be similar for soft rock, whereas residual strength may be as little as half the peak strength for hard igneous rock (Hoek and Bray 1974). Typical intact rock shear strengths and other properties are shown in Table I.

the failure criteria are for dry rock and a further significant modification afforded by discontinuous rock mass (DRM) is high secondary permeability (Witherspoon and Gale 1977). As well as contributing to shear stress, water reduces normal stress σ to effective normal stress $\bar{\sigma}_n$ by a value u (Hoek and Bray 1974), and for practical purposes the modified Mohr-Coulomb equation may be written as

$$\tau = c + (\sigma - u) \tan (\phi + \phi_f) , \qquad (2)$$

or, in a simplified form, as

$$\tau = c + \bar{\sigma}_n \tan \phi_r , \qquad (3)$$

where ϕ_r is the effective friction angle. Roughness increases the friction angle ϕ by an amount ϕ_f, and the plane possesses, more correctly, bi-linear shear strength, which assumes the lower (residual) value upon shearing of asperities (Witherspoon and Gale 1977).

In practice, all rock mass possesses internal fractures which normally demonstrate a strongly preferred geometry, determined by geological (principally tectonic) history (Attewell and Farmer 1976). Marked planar anisotropy renders DRM liable to simple failure in a co-axial stress field and to complex failure, involving multiple planes, elsewhere. Compound failure along discontinuities and cracks propagated across rock bridges was reported in laboratory tests (Brown 1970). Brown also suggested that discontinuous rock-mass failure (DRMF) only

TABLE I. SOME TYPICAL ROCK-MASS PROPERTIES (after Hoek and Bray (1974), Kulhawy (1975), among others)

	Uni-axial compressive strength	Friction angle ϕ (tri-axial load)		Residual friction angle ϕ_r	Cohesion C (tri-axial load)
	$MN\ m^{-2}$		deg		$MN\ m^{-2}$
Plutonics	146.4	45	(granite)	35	56.1
Volcanics	123.9	25		-	32.2
Metamorphics	79.6	27	(slate)	25	22.9
Clastic sediments	96.3	29	(sandstone)	25	31.7

Discontinuous rock-mass strength (DRMS)

Intact strength offers little scope for low-magnitude shear stress, of the order of $0.1 MN\ m^{-2}$ (Weertman 1979), at the glacier sole, and a substantial reduction in strength is required to permit large-scale erosion. Discontinuities* render rock mechanically and hydraulically defective to an extent where this is possible, by altering stress relationships in the rock mass and providing release planes requiring much lower disturbing forces (Hoek and Bray 1974). IRMS values become less meaningful in discontinuous rock and are replaced by DRMS.

The principal modification to the Mohr-Coulomb criterion lies initially in lower values for the parameters of cohesion c, and friction angle ϕ, and a comparison of typical values is made in Table I. The cohesion is now solely that of the discontinuity plane and is effectively zero, except in the presence of fill. However, shears through intact rock and ignores discontinuities under very high confining pressures ($1\ 400\ MN\ m^{-2}$), thus tending to confirm that glacier ice can only "quarry" DRM and that failure of supposedly intact isotropic rock (Broster and others 1979) may be in error, overlooking pre-existing anistropy (Hoek 1964).

* The term *discontinuity* is used here to describe systematic fractures regardless of origin.

Conditions of DRM stability and failure

Practical application of the modified failure criterion permits assessment of stability under gravitational and dynamic loading. Design in engineered slopes is particularly concerned with the former, and failure is controlled generally by (i) stress relations in slopes related to discontinuity geometry (Hoek 1973), (ii) individual block size and shape, and (iii) cohesion of any infilling material. Calculation of stability or predicted failure mode is then relatively straightforward. From the Mohr-Coulomb criterion, resistance to gravitational sliding is defined (after Hoek and Bray 1974) as

$$R = cA + W\cos \psi_d \tan \phi , \qquad (4)$$

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where A is the block/slope contact area, W is the block weight and ψ_d is the discontinuity angle. If shearing and resisting forces are exactly balanced, the block is said to be in *limiting equilibrium* for dry slopes when

$$W\sin\psi_d = cA + W\cos\psi_d \tan\phi \ , \qquad (5)$$

and for wet slopes when

$$W\sin\psi_d + V = cA + (W\cos\psi_d - u)\tan\phi \ , \qquad (6)$$

where V is the additional loading due to the weight of water behind the block, and u is the reduction of normal stress due to uplifting pressure of water under the block.

Failure modes

Probable failure modes on unstable slopes can be determined from the relationship between the excavated slope and discontinuity geometry. Three of four principal failure mechanisms recognized in slope engineering are considered here (Fig.2). (*Circular failure* is disregarded for DRM with well-defined discontinuities.)

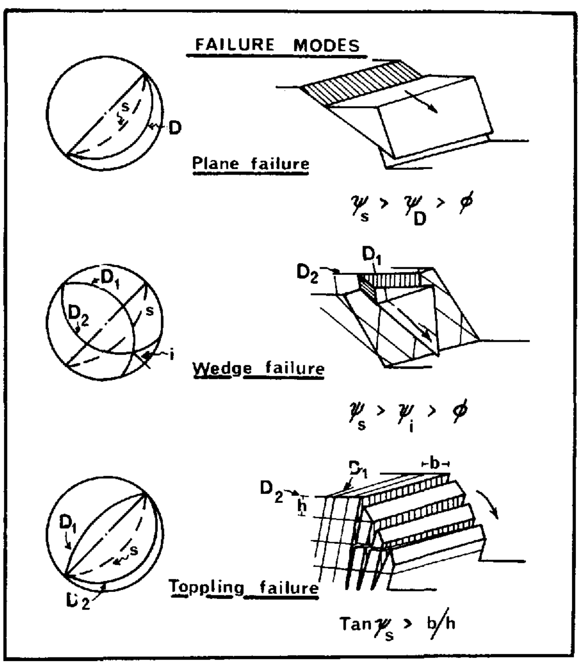

Fig.2. Failure modes and their related discontinuity stereonet (equatorial equal-area lower hemisphere projection).

Plane failure (of single or multiple slabs) occurs when

$$\psi_s > \psi_d > \phi \ , \qquad (7)$$

and *wedge failure* occurs when

$$\psi_s > \psi_i > \phi \ , \qquad (8)$$

where ψ_s and ψ_d are the slope and discontinuity angles and ψ_i is the angle of the slope of intersection of two planes defining a wedge. (The excavated slope must permit the potential failure planes to "daylight".) Failure, particularly in the case of planar slides, requires the presence of other release surfaces provided by other discontinuities.

Toppling failure occurs when the primary plane D_1 dips into the slope and is apparently stable, but also when a secondary stable plane D_2 is so spaced as to define a block whose centre of gravity overhangs a pivot point (de Freitas and Watters 1973).

It is emphasized that, although actual slope stability may be complex, practical application of theoretical analysis is generally successful (Hoek 1973). Also, whilst its primary application is for gravitational loading, an extension of principles to dynamic glacier loading may be appropriate and theoretical modifications to stress relationships induced by glacier ice are now proposed.

$$\psi_s < \psi_{d,i} \gtrless \phi \ . \qquad (9)$$

STRESS MODIFICATIONS BY GLACIER ICE

A glacier must activate inherent rock-mass instability for erosion to occur (Terzaghi 1962); this investigation restricts itself to suggested de-stabilizing processes and not to the necessary resultant entrainment or incorporation with the glacier. Two quite different domains are recognized; (i) rock mass confined by ice and under dynamic load, and (ii) rock mass unconfined and primarily loaded by gravity.

Rock mass confined by ice

This is the more difficult to analyse because of the relative inaccessibility of the ice-rock contact, and also because DRM is inherently stable in its primary valley-floor position. Equations (7) and (8) do not apply, and discontinuity-stress relationships show

Although gravitational load does not meet limiting equilibrium requirements, two factors increase shear stress. First, ice flow generates a low-magnitude shear stress of about 0.1 MN m^{-2} (Weertman 1979) enhanced for an ice-rock mix. Second, melt water at the ice-rock mass contact penetrates discontinuities, contributing a force V and reducing normal stress by a value u (Equation 6). However, it is recognized that a complex feedback relationship exists here, whereby secondary permeability afforded by DRM may alter critically the basal pressure-melting balance. Two further qualifications are made to this domain. Once begun, block removal permitting low-angled planes to "daylight", and also removing the restraining presence of the block, may reduce sliding resistance sufficiently under dynamic load, where $\psi_{d,i} < \phi$. More significantly, the primary subglacial loading mode assumes a low-angled bedrock floor; in practice this is probably unnecessarily conservative, since steep slopes occur frequently beneath ice for short distances, and DRMF may approach more closely that of the unconfined domain discussed below.

Rock mass unconfined by ice

Glacier erosion in this domain is in two parts: (i) an initial amount of vertical or horizontal excavation in the confined domain, cutting the slope beyond the limiting equilibrium, followed by (ii) unconfined DRMF of a mode determined by slope-discontinuity geometries. Equations (7) or (8) must apply. The amount of confined excavation need not be large, as will be shown later. Progressive failure in one mode may destabilize other blocks unmoved by initial disturbance, and very large volumes of rock mass may be involved in such compound translation failures; this is also shown in field examples presented later.

Water derived from ice-melt and also precipitation beyond the glacier margin assumes a considerable significance in destabilizing unconfined rock. Barton (1973) states that water may reduce the friction angle ϕ by as much as 30°, and therefore the presence of water throughout

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the back-wall zone of cirque glaciers must be considered to make a major contribution to DRMF without recourse to freeze-thaw mechanisms.

Again, further qualifications may be made with respect to the destabilizing mechanism.
(i) Unconfined failure can only apply to glaciers confined within bedrock channels, limiting the mechanism almost entirely to valley and cirque glaciers, and thus accounting in part for their significantly greater erosive power.
(ii) Once initiated, progressive failure is controlled primarily by the DRM geometry; unlike engineering applications, where the required slope and discontinuity geometries may or may not coincide favourably, it is suggested that glacier erosion will always show close conformation. Principal applied stress will seek out the most closely related potential failure planes, and hence structure controls glacier erosion.

Geomechanical principles, modified for the glacier environment, are now investigated for application to glacier-eroded rock mass in Snowdonia, North Wales, after reviewing the general structural geology of the region.

STRUCTURAL GEOLOGY OF SNOWDONIA, NORTH WALES

Clastic marine sediments, progressively interstratified with ignimbrites and later intruded by dolerites, rhyolites, and microgranites, form almost all of the 1 200 km^2 study area, and represent a complex Lower Palaeozoic (late Cambrian to late Ordovician) synclinal accumulation whose axis forms the mountain core above 1 000 m.

The pile was subjected to pronounced polyphase deformation of Caledonian tectonic origin (late Silurian-early Devonian (Shackleton 1954)), and four distinct structural components are recognized, represented by four fold axes (F_{1-4}) and associated syngenetic axial-planar cleavage (S_{1-4}) (Helm and others 1963, Lynas 1970). The regional structure is dominated by F_2, S_2, with their typical Caledonoid NNE-SSW strike, mainly dipping steeply north-west.

A primary fracture geometry of steep-vertical discontinuities, which confirms the Caledonoid tectonic stress field, has been described (Addison, unpublished). Over 2 900 km of principal fractures were recorded. The systematic regional ("master") fracture pattern (Fig.3) corresponds to expected tectonic configuration (Badgley 1965, Fookes and Wilson 1966, Price 1966, Causay 1977); in the field, the three-dimensional discontinuity geometry measured in bedrock outcrops replicates the established regional pattern, and continues within rock slabs with close facsimile planar anistropy. Strength and spacing depend on lithology at the smaller scales, but otherwise the fracture network disregards lithological boundaries.

Previous research on glacier erosion in Snowdonia concentrated on the significance of the orientation and elevation of nearly 50 cirques in reconstructing Pleistocene glacio-climatology (Seddon 1957, Unwin, unpublished), and, whilst distribution conforms to a north-west European pattern, it also corresponds intimately to the fracture geometry (Addison 1977). Moreover, a recently reconstructed Pleistocene "Merioneth" ice cap, centred to the south-east of Snowdonia (Addison, unpublished, Foster, unpublished, Rowlands, unpublished), was shown to have been the source of radial outlet glaciers which breached the mountain axis with transfluent troughs up to 600 m deep. As with the cirques, they too show a marked conformity to the regional

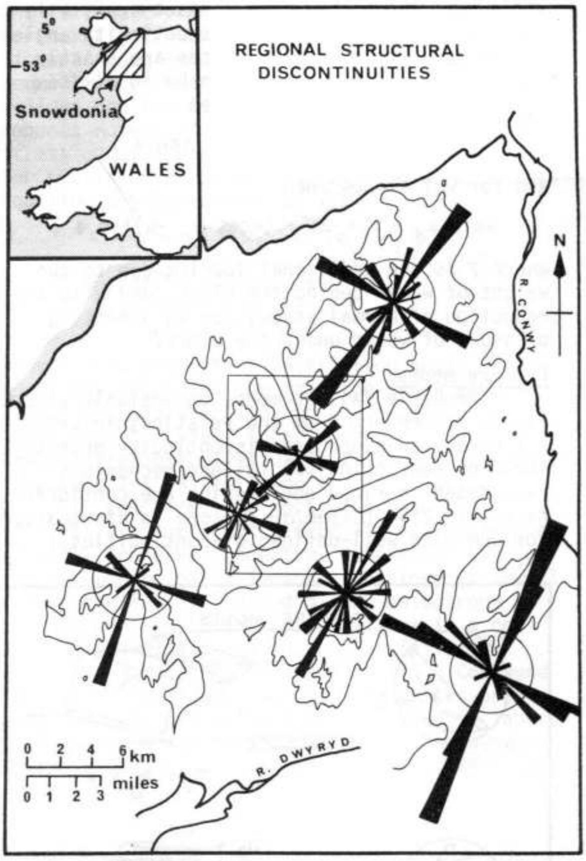

Fig.3. Frequency orientation diagrams of regional fracture systems for each of the six mountain groups of Snowdonia, mapped from stereographic air photograph cover. Circular scale shows 5 km. Inset outline shows location of Figure 4.

fracture geometry (Fig.4). In both cases, structurally controlled DRMF beneath and adjacent to the glacier bed is believed to have been the principal mechanism of excavation.

FIELD EVIDENCE OF GLACIER-INDUCED DISCONTINUOUS ROCK-MASS FAILURE

A combination of inferred and calculated conditions identifies failure in a previously-glaciated environment. The difficulties of observing rock-mass failure and erosion around existing glaciers, especially under the ice, justify the study of failure at previously glaciated sites (where a comprehensive survey of the fracture systems is possible), provided that the evidence for a glacial origin of failure is convincing. Location and mode of failure is easily recognized by residual rock-wall elements representing the release surfaces, block debris where present, and visual comparisons of the slope and discontinuity geometries (de Freitas and Watters 1973, Addison, unpublished, Causay and Farrar, in preparation*). Detailed confirmation may be calculated from measurement of the discontinuity geometry (Silveira and others 1966, Young and Fowell 1978) with typical values of geomechanical properties, or specific values obtained from *in situ* and laboratory tests, and

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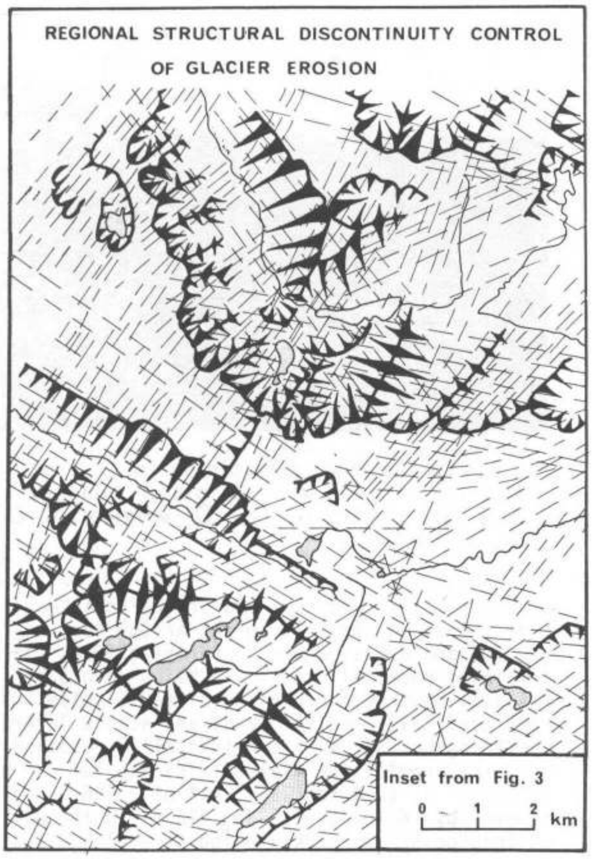

Fig.4. Primary fractures in the Snowdon (SW) and Glyder (NE) groups and principal glacier-eroded cirques and troughs. Fractures are shown by broken lines, cliffs by toothed shading, and lakes by stippling.

expressed as a factor of safety F where $F = 1$ represents limiting equilibrium (Hoek 1970, 1973).

A *glacial* origin for DRMF is inferred from the glacial history of the site, contemporary stability in the absence of glacier-related disturbing forces, and, in particular, absence of the failed mass at the toe of the slope. Site examples from Snowdonia are now presented.

Confined failure

Slope-failure criteria do not apply so readily here as stated earlier. At the three chosen sites, DRMF was compound, being induced dynamically in otherwise stable rock mass by basal shear, and then, once block separation began, local small-scale slab, wedge, and toppling failures occurred along destabilized discontinuities.

(i) *Cwm Stwlan*

Excavation for the upper dam foundations of the Ffestiniog pumped-storage hydro-electric scheme, constructed on the bedrock threshold of a glacial cirque, revealed considerably disturbed, hard, unweathered rhyolite dislocated along pre-existing discontinuities to a depth of 13 m across a front 150 m wide, which necessitated design modifications. Anderson (1969:193) considered the dislocation to have been caused by glacier drag across the threshold: "...facilitated by the presence of five faults in the part most affected and by joints almost at right angles to the rock-lip... The affected zone does not tail off but ends abruptly on both sides. The limits may be partly related to the faults, but they may also mark the width within which the glacier was thick enough to exert drag".

(ii) *Ogwen*

Bedrock floor in a major glacier-breached watershed is shown in Figure 5. Ice flowing from left to right first abraded the rock, followed by "quarrying" (displaced blocks show striations on one surface only) which removed some blocks altogether and displaced others; thereafter, gravitationally loaded secondary failure further dislocated the rock mass, at least in part sub-

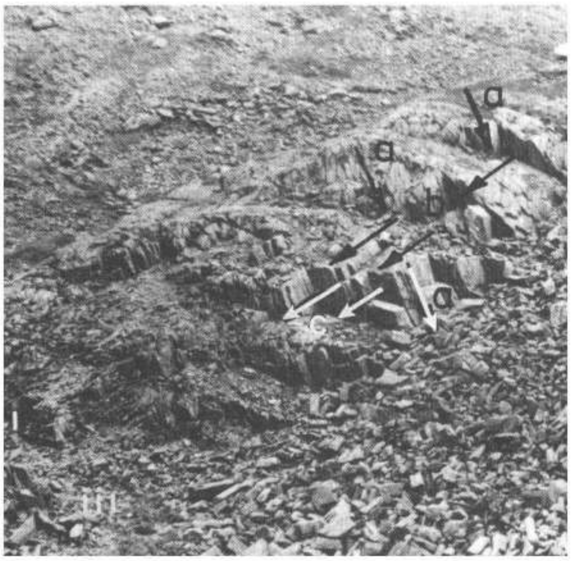

Fig.5. Ogwen valley floor. Sub-glacier confined DRMF, with secondary failure evident in excavated sections. Slab failure occurred along two planar sets (a, b) and toppling failure away from (c).

Fig.6. Toppling failure in Nant Peris; destabilization caused the parting of blocks along arrowed discontinuities.

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glacially since many blocks are missing. Failure surfaces were entirely controlled by the discontinuity geometry, and primary and modified confined failure is indicated by the displacement of debris down-glacier and down-slope.

(iii) *Nant Peris*

Figure 6 shows an example of toppling failure towards the valley floor generated by the removal of adjacent rock mass under glacier confinement close to the valley floor. Cliff elements such as these are common, with at least the greater part of the failed rock mass absent from the toe; by comparison, the few remaining instable blocks which have recently toppled from the now unconfined face are all present at the toe, and exhibit less-weathered contact planes.

Unconfined failure

Cwm Graianog

This cirque basin affords one of the finest site concentrations of all modes of rock-mass failure in Snowdonia. It is excavated in Ffestiniog grit, and failure modes are discussed with reference to a standard structural presentation (Hoek and Bray 1974) shown in Figure 7.

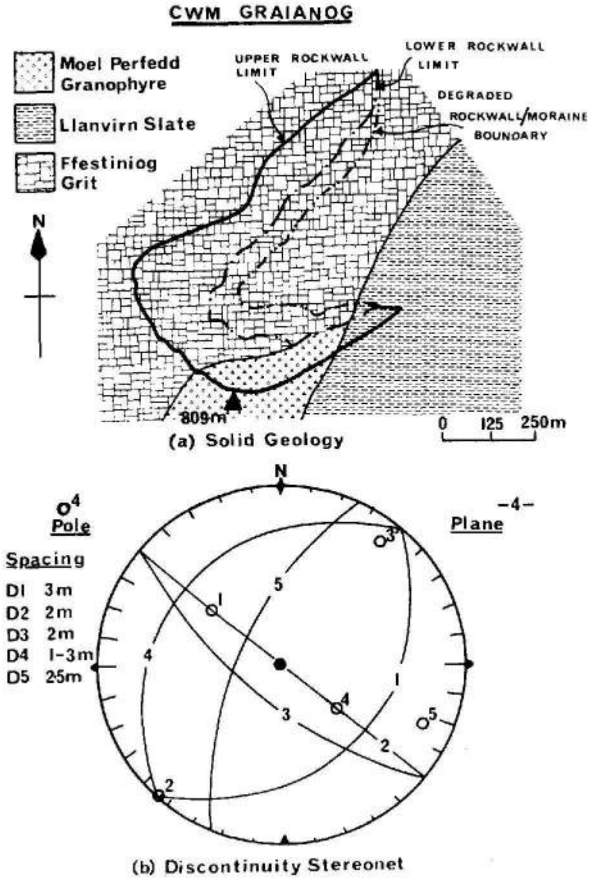

Fig.7. Bedrock map and discontinuity stereonet for Cwm Graianog.

The north side wall consists almost entirely of a spectacular series of D_1 surfaces (Fig.8) and the slope angle is effectively the same as the discontinuity dip of 38-40° to the south-east. Slab failure down D_1 was released along D_2, which frequently possesses an injected quartz fill, and D_3, and the vertical extent of individual slabs is limited by D_4 with the same strike, but opposite dip, as D_1. One entire

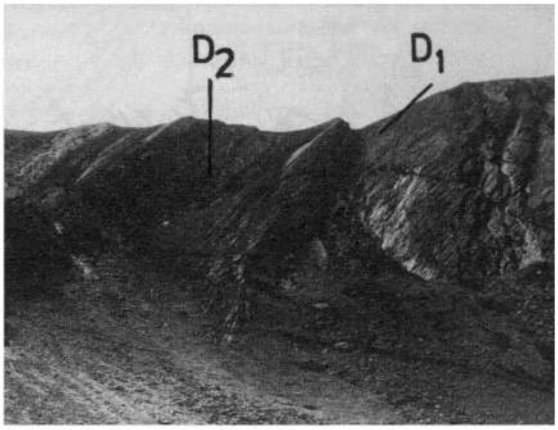

Fig.8. Cwm Graianog (Ffestiniog grit). North side wall (right) with D_1 planar surfaces; head wall (left) with D_1- D_2 wedging and D_2 planar surfaces.

slab towards the western end of the basin may have failed to the full height of the rock wall (200 m) and across a width averaging 60 m. The remaining rock wall is clean, being devoid of residual blocks, overhanging elements below which rock mass have been released, and stable laterally-confining units. With a principal D_1 spacing of 3 m, this would have yielded a single failure of 36 000 m^3 of the side wall, all of which was removed by the glacier. D_1 planes in the wall at this point are marked uniquely by large-scale bedding-plane ripples (Fig.9), and the only debris

Fig.9. Cwm Graianog. Single D_1 major planar-slide release surface, (showing ripple marks).

blocks so marked are found several hundred metres away in, and resting upon, cirque moraines in positions where they could have been deposited only by glacier ice.

The irregular strength and spacing of D_5 renders it less apparent as a control, but D_2 and D_4 become more important as the back wall is approached. The "curved" transition is effected by D_1- D_2 wedge failure (ψ_i =39°, orientated at 130°) producing a series of buttresses, and the extent to which the geometry predetermined failure on excavated slopes is completed by the superimposition of toppling failure released from D_1 and low-angled D_4 (itself below the assumed friction angle) on more complex slab and

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wedge failure in the south wall. A rapid assessment of current stability (after Hoek 1970) suggests that D_1 has a factor of safety $F \geq 1$ for typical assumed mechanical values, which has two important implications. (i) Excavation at the toe would rapidly cause D_1 to "daylight" and generate further slab failure; this is considered to be typical of the effect of glacier erosion. (ii) Other modifications to Mohr-Coulomb parameters would result in failure; locally small contemporary slides are evident, considered to be the smoothing effect of weathering on roughnesses along the D_1 planes.

There is a dramatic decline in side-wall height at the Llanvirn slates-granophyre contact; it is suggested that the lower DRMS of slates permitted greater excavation of the side wall, and it is further noted here and elsewhere that cleavage planes do not appear to have provided significant failure surfaces during glacier erosion.

CONCLUSION

Geomechanical rock-mass properties have been neglected in examining processes of glacier erosion, and it is proposed that alteration of stress relationships in discontinuous rock mass directly or indirectly by glacier ice provides a realistic principal mechanism for the study of bedrock excavation by glaciers. Theoretical failure criteria applied to specific rock-mass properties are sustained by field evidence, and support the following conclusions.

1. Failure of rock slabs occurs along pre-existing discontinuities, and the relative disposition and strength of the discontinuity geometry provides an exclusive framework for excavation and is manifest in structurally-controlled erosional landforms at all scales.
2. Failure in confined rock is due primarily to the dynamic loading potential of the conditions at the ice-rock mass contact, and in unconfined rock to the activation of gravitational loading on otherwise stable slopes.
3. DRMF re-defines in more appropriate mechanical terms conditions which in certain circumstances have been identified as erosion processes involving "pressure release" and "melt-water sapping". It is contended that many quoted instances of pressure release in fact describe parallel slope facets determined by pre-existing discontinuity geometry, where forms of glacial erosion have been controlled by structure rather than vice versa.
4. Stress conditions in discontinuous rock mass can be incorporated usefully into theoretical and practical examination of ice flow patterns and behaviour at the rock-ice interface.

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