Rock glaciers, protalus ramparts and related phenomena, Rondane, Norway: a continuum of large-scale talus-derived landforms

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Talus-derived landforms from Rondane National Park, southern Norway, are described and classified as protalus ramparts, valley-floor and valley-side talus-foot rock glaciers, and a 'push-deformation' moraine. A morphological and developmental continuum of talus and derivative large-scale landforms is proposed, with simple talus slopes at one end and more complex ridge, lobe and bench forms at the other. The various types of feature probably develop from simple talus slopes via separate developmental routes, rather than as a linear sequence. Lichen size and Schmidt hammer R-values were used to indicate the relative ages of the features. Although all are thought to have originated during the early Holocene, they differ in the presence or extent of recent activity. Hence an age and activity continuum is also suggested, the recency of activity increasing in the direction protalus rampart → rock glacier → 'push-deformation' moraine.

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During the last two decades, interest in rock glaciers, protalus ramparts and related landforms has increased markedly, but our understanding remains limited. Rock glaciers in particular have attracted increased attention but disagreement continues about their definition and classification (cf. Østrem 1971; Johnson 1973; Barsch 1971, 1977; Whalley 1979) and about their origin and sensitivity to environmental change (e.g. Swett *et al.* 1980; Humlum 1982; Giardino 1983). For the purposes of this study talus-foot or lobate rock glaciers are defined as being broader than they are long and composed of deformed talus developed along valley walls below cliffs. Various theories have been proposed to explain their movement down valley sides and onto valley floors, including creep of an ice core or of interstitial ice, or basal shearing which may be aided by hydrostatic pressure or by pore water trapped beneath a frozen veneer (Giardino 1983; Giardino & Vick 1985). A range of indicators of activity and inactivity of rock glaciers has been proposed. Indicators of activity have included the presence of an ice core (Corté 1976), the considerable thickness of a feature, the presence of steep boundary slopes with sharp breaks of slope, the existence of fine material or the lack of vegetation on the front slope (Wahrhaftig & Cox 1959; Barsch 1977), and fresh breaks in the surface (Foster & Holmes 1965). Supposed indicators of inactivity have ranged from low-angle boundary slopes, presence of collapse structures (Barsch & Treter 1976; Sissons 1976), large lichens (Luckman & Crockett 1978), continuity of lichen cover (Wahrhaftig & Cox 1959) to a well-established soil and vegetation cover (Barsch & Treter 1976).

Protalus ramparts also present problems of definition and origin. They are generally assumed to form by debris sliding over the snow and accumulating at the foot of a perennial snowbank (Richmond 1962), but this remains unsubstantiated by field observation (Johnson 1983) and similarities or connections have been proposed in the development of protalus ramparts and rock glaciers (Grötzbach 1965; Corté 1976; Sissons 1976; Ballantyne & Kirkbride 1987).

With a few exceptions (e.g. Griffey & Whalley 1979; Matthews & Petch 1982; Lindner & Marks 1985; Vere & Matthews 1985), little is known about rock glaciers and related forms in Scandinavia. This was emphasized by the debate on ice-cored moraines between Østrem (1971) and Barsch

(1971). In Rondane, Strøm (1945) described 'debris ledges' formed in a similar manner to that assumed for protalus ramparts while Barsch & Treter (1976) used mainly aerial photographs to identify fourteen rock glaciers. We present here the results of a more detailed investigation carried out in Rondane of five landforms identified as active rock glaciers and one as inactive according to these authors, together with an additional three landforms. Emphasis is given to the morphology, age and activity of these features with special reference to their classification, development and interrelationships.

Background

The central massif of Rondane National Park is a mountain range of some 200 km^2 with a number of peaks exceeding 2,000 m and a highest point of 2,178 m (Rondslottet) (Fig. 1). The mean annual temperature is *c.* −5°C at 1,500 m and mean annual precipitation amounts to about 460 mm (Dahl 1956). Glacier ice is absent except for a possible residual patch in Smedbotn. According to Sollid & Reite (1983:50), the last ice sheet covered Rondane up to *c.* 1,800 m in the Preboreal Chronozone. At that time local cirque glaciers occupying the higher valleys converged with the main ice sheet, giving rise on deglaciation to extensive fluvioglacial deposits in the valley bottoms of Döråen and its tributaries.

The area comprises mainly an arkosic sandstone known as sparagmite. The combination of steep valley sides, well-jointed rock, freeze–thaw conditions and low stream activity in the upper valleys has led to talus-covered lower slopes and block-field-covered floors. The features on which this study focuses are located in the valleys of Langholet, Smedbotn and Bergedalen at altitudes of *c.* 1,300–1,600 m (Fig. 1).

Morphology

Selected long profiles for the features were determined using an Abney level and 30 m tape. Readings were recorded to marked breaks of slope or to 30 m ground lengths (Fig. 2). All features are characterized by angular blocks up to about 6 m in size. Morphological details of each feature are given in Table 1.

Langholet. – Four landforms along the W slope of Langholet valley were studied (Fig. 1; Table 1). Langholet I has a crenulate plan form partly obscured by snow when measured. Langholet II, III and IV have not been previously referred to in

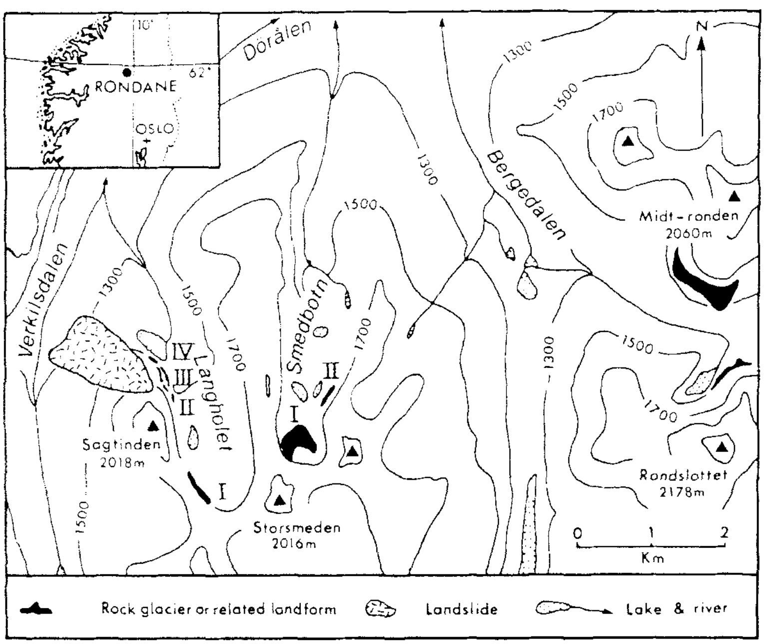

Fig. 1. Location of talus-derived landforms in Rondane, central southern Norway.

Table 1. Characteristics and classification of talus-derived landforms, Rondane.

Feature	Aspect	Altitude (m)	Max. length (m)	Breadth (m)	Max. talus slope angle (°)	Distal slope: Overall angle (°)	Distal slope: Max. angle (°)	Morphological characteristics	Classification
Langholet I	ENE	1,580	230	550	37	29	36	2 ridges	Talus-foot rock glacier
Langholet II	E	1,520	6	280	35	33	34	1 ridge	Protalus rampart
Langholet III	E	1,480	56	590	34	25	35	2 ridges	Protalus rampart
Langholet IV	NE	1,480	23	305	31	31	31	1 ridge	Protalus rampart
Smedbotn I	N	1,600	350	580	34	25	41	Multiple ridges	Push-deformation moraine
Smedbotn II	W	1,580	180	420	33	41	54	Bench + surface ridges	Talus-foot rock glacier
Rondslottet	N	1,520	230	750	34	37	50	Bench + lobes	Talus-foot rock glacier
Midtronden	SW	1,540	190	1,100	38	34	43	Bench, lobes + surface ridges	Talus-foot rock glacier
Verkilsdalen	NW	1,300	1,600	750	—	—	—	Lobate ridge complex	Landslide

Note: Altitude = altitude of toe.
Maximum length = max. length from the talus foot measured to the outer ridge/bench crest.
Full details on the Verkilsdalen feature are given in Dawson *et al.* 1986.

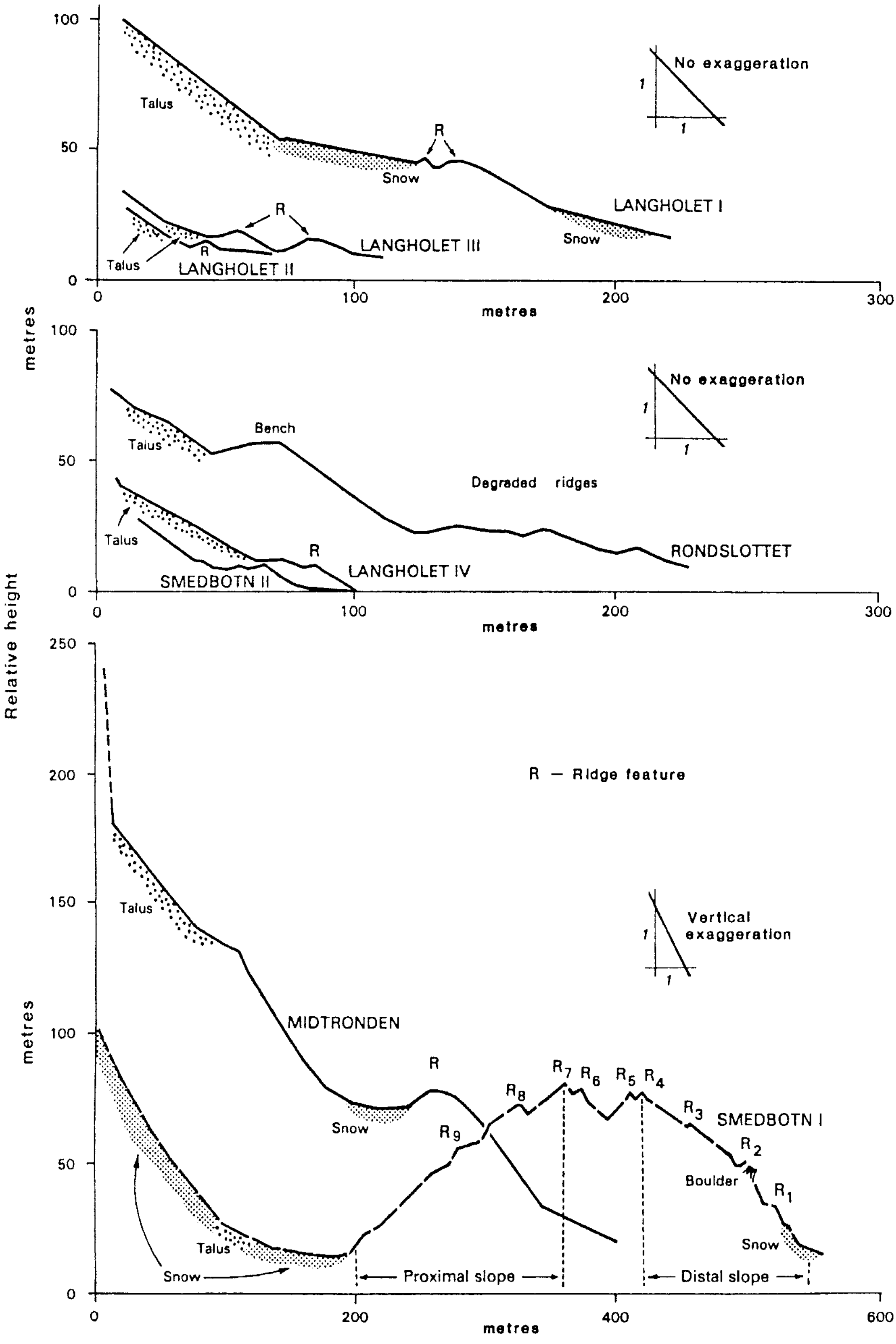
No exaggeration
Talus
R
Snow
LANGHOLET I
LANGHOLET III
LANGHOLET II
Talus
Snow
metres
Relative height
Bench
Degraded ridges
RONDSLOTTET
LANGHOLET IV
SMEDBOTN II
R — Ridge feature
Vertical exaggeration
MIDTRONDEN
SMEDBOTN I
Boulder
Proximal slope
Distal slope

Table 2. Lichen size data for the talus-derived landforms in Rondane. Results are given for the diameter (mm) of the single largest (1.1) and the mean diameter of the five largest (5.1) lichens in 250 m^2 search areas.

Location	1.1	5.1
Smedbotn I		
Outside	270	251
Ridge 1	235	206
Ridge 2	225	212
Ridge 5	260	222
Ridge 6	235	220
Ridge 7	180	158
Ridge 8	115	100
Ridge 9	95	95
Proximal slope (top)	93	79
Proximal slope	65	55
Smedbotn II		
Outside	265	232
Outer ridge	370	280
Inner ridge	325	274
Langholet I		
Outside	285	216
Outer ridge	250	226
Inner ridge	220	181
Talus foot	120	69
Langholet II		
Outside	280	241
Ridge	235	217
Talus foot	190	174
Langholet III		
Outside	288	239
Outer ridge	220	205
Inner ridge	285	264
Talus foot	155	137
Langholet IV		
Outside	250	227
Ridge	240	213
Talus foot	145	133
Midtronden		
Outside	355	298
Outer ridge	400	329
Inner ridge	445	254
Talus foot	115	98
Rondslottet		
Outside	245	237
Degraded ridge	310	248
Bench	240	224
Talus foot	220	187

the literature. They consist of well-defined single or double ridges (Fig. 3).

Smedbotn. – Two landforms were investigated in Smedbotn (Fig. 1). Smedbotn I forms a large, high, arcuate, multiple-ridged structure enclosing a deep hollow near the valley headwall (Fig. 5C). Proximal slope angles range from 8° to 48° with an overall angle of 24°. Smedbotn II, located *c.* 0.5 km downvalley from Smedbotn I (Fig. 1), comprises a broad, undulating bench at its S end from where it narrows northwards to form two ridges (Fig. 2).

Bergedalen. – Two landforms were analysed in Bergedalen (Fig. 1). The Rondslottet feature is an arcuate bench, ridge and lobe complex below the N-facing spur of Rondslottet peak (Fig. 4). At its S end, it forms a narrow bench emanating from an area of two small, ill-defined lobes (Fig. 2). Below the bench, the valley floor comprises up to three low, ill-defined ridges (<3 m high) paralleling the bench. Farther N and E, as the bench curves around the talus slope, it descends and gives way to two-steep-fronted talus lobes (Fig. 4A). On the opposite valley side lies the Midtronden feature. It forms an apron below a broad bedrock spur (Fig. 5B). It consists of an outer broad ridge, four lobes and several short, bench-like features.

Verkilsdalen. – A large feature occupies the entire NW-facing, wedge-shaped spur end slope of Sagtinden overlooking the Verkils valley. Boulders up to 10 m in size form a complex of lobe-like ridges extending downslope.

Dating techniques

Lichenometry

Measurements were made of the lichen *Rhizocarpon geographicum* agg. (including *R. alpicola*), using methods closely related to those adopted for dating end moraines in southern Norway (Anderson & Sollid 1971; Matthews 1974, 1975, 1977; Matthews & Shakesby 1984). Long axes of at least

Fig. 2. Long profiles of features in Langholet, Smedbotn and Bergedalen. See Fig. 1 for location. Note degree of vertical exaggeration for the Smedbotn I and Midtronden features.

Table 3. Schmidt hammer R-values: means, standard deviations and 95% confidence limits.

Location	$\bar{X}$	S	$(\pm t.\hat{\sigma}_{\bar{x}})$
Smedbotn I			
Outside	34.16	10.26	2.94
Ridge 1	38.54	9.98	2.86
Ridge 2	39.30	9.70	2.78
Ridge 7	40.18	11.12	3.19
Ridge 8	42.56	9.51	2.73
Smedbotn II			
Outside	37.32	11.97	3.43
Outer ridge	41.12	10.10	2.90
Inner ridge	39.16	10.61	3.04
Talus	43.92	8.78	2.52
Langholet I			
Outside	35.84	12.04	3.45
Outer ridge	37.10	11.41	3.27
Inner ridge	35.82	10.33	2.96
Talus	40.44	10.78	3.09
Langholet II			
Outside	37.26	12.71	3.65
Ridge	39.68	12.27	3.52
Talus	41.62	9.86	2.83
Langholet III			
Outside	35.88	9.94	2.85
Outer ridge	35.32	11.03	3.17
Inner ridge	39.02	12.61	3.62
Talus	44.34	10.35	2.97
Langholet IV			
Outside	36.40	9.97	2.86
Outer ridge	45.32	9.27	2.66
Talus	42.86	7.00	2.01
Midtronden			
Outside	35.38	9.02	2.59
Outer ridge	39.32	10.87	3.12
Inner ridge	36.56	11.74	3.37
Talus	40.00	9.36	2.69
Rondslottet			
Outside	37.16	9.15	2.63
Outer ridges	37.38	7.89	2.26
Bench	37.60	10.06	2.89
Talus	38.24	10.04	2.88

the ten largest individuals were recorded along 25 m lengths of ridge (area = 25 × 10 m). Three types of site were searched: (1) various 'ridge' sites on the landforms *sensu stricto*; (2) 'talus' sites, located in talus-foot positions to the rear of the landforms; and (3) 'outside' sites beyond the fronts of the landforms. At each 'ridge' site, ridge crest and proximal slope were searched. Where a landform comprised more than one ridge, at least the outer and inner ridges were searched separately.

Results in Table 2 show that most sites yielded lichens at least 200 mm in diameter. The largest individual lichen from a hollow on the Midtronden feature reached 605 mm. Lichens from 'outside' sites and outer ridges are similarly large. Indeed, on four landforms, lichens tend to be smaller than on adjacent 'outside' sites. Similarly, lichen size does not differ between inner and outer ridges, except for the inner ridge of Smedbotn I, where the largest lichen was only 95 mm in diameter. Although 'talus' sites are variable, lichens are generally smaller than those on 'ridge' and 'outside' sites.

Schmidt hammer R-values

Matthews & Shakesby (1984) showed the potential of the Schmidt hammer R-value for relative age-dating of Neoglacial rock surfaces, greater surface weathering and hence greater age being reflected in lower R-values. In this study, 50 R-value readings were obtained at 'outside' sites, various 'ridge' sites and 'talus' sites on each of the features investigated. Each reading was taken from lichen-free, horizontal surfaces on separate stable boulders. One operator used a single Schmidt hammer for all 1,500 readings and checks were made on the effects of instrument wear before and after fieldwork (McCarroll 1987).

Overall, mean R-values tend to increase slightly from 'outside' sites ($\bar{x} = 36.2$), to 'outer ridges' ($\bar{x} = 39.2$) to 'talus' sites ($\bar{x} = 41.7$) (Table 3), although there are exceptions (e.g. Langholet IV). With regard to 95% confidence intervals ($\pm t.\hat{\sigma}_{\bar{x}}$), R-values from individual landforms generally overlap with those from the corresponding 'outside' sites indicating no significant difference. The exceptions are: Smedbotn I, between the innermost ridge and the 'outside' site; Langholet III and IV, between 'talus' and 'outside' sites; and for Langholet IV between 'ridge' and 'outside' sites. For sites where both R-values and lichen sizes were obtained, the regression of mean R-value against the single largest, and five largest lichens measured was weak but statistically significant (e.g. for the five largest lichens ($r = -0.41$, $p < 0.02$, $n = 37$)).

Classification

Barsch & Treter (1976) interpreted the Verkilsdalen feature as a rock glacier. On the basis of several distinctive characteristics, we reject this interpretation and favour a landslide origin. These characteristics are: its position beneath a hillslope scar extending to the ridge crest with no talus slope to the rear; an area of displaced hillside and fissured rock attesting to the catastrophic nature of the landslide; and, significantly, a debris apron beyond the main body of the landform consisting of finer particles and large boulders sprayed out in advance of the landslide. See Dawson *et al.* (1986) for a full discussion.

Langholet II and III are regarded as protalus ramparts in view of the well-defined front ridges entirely separate from the talus foot. The maximum measured slope angles on the ridges approximate those of the talus and are just below the minimum angle of shearing resistance (ϕ' cv) for talus (39–40°; Chandler 1973). Langholet IV is also regarded as a protalus rampart as there are no signs of talus deformation and it is continuous with Langholet II (Fig. 3B).

The location of these features is favourable as regards debris supply, for they lie directly below the near-vertical cliffs forming the E boundary of the Verkilsdalen landslide which could have contributed to their formation in one of two ways. First, they could date from the time of the landslide event itself and have formed from debris falling over the cliff. Second, they could have formed through increased availability of loosened, frost-susceptible joint-bound debris following the landslide event. The two discrete ridges of Langholet III (Fig. 3A) and the smaller size of ridge debris compared with that of the landslide favour the second alternative.

Langholet I, Smedbotn II, Midtronden and Rondslottet are regarded as rock glaciers for the following reasons. First, they all represent marked extensions of deformed talus beyond the talus foot compared with the separate ridges of the protalus ramparts. Talus deformation is most clearly seen in Langholet I and Smedbotn II (Fig. 2) where the talus foot appears to have 'bulged' onto the valley floor, unlike the Langholet IV protalus rampart where the ridge merges with part of the talus slope but represents no talus deformation (Fig. 3B). Second, all four have lobes and surface ridges which are interpreted as flow structures, the latter also possibly resulting from thrusting along shear surfaces. Third, the front slopes are characterized by oversteepened zones, particularly the upper 2–3 m (Fig. 4B). Overall angles tend to be steeper (28–41°) than on the protalus ramparts (25–33°). Fourth, the front slopes have a crenulate plan form suggesting irregular forward motion whereas the protalus ramparts are smoothly linear or gently-curving, supporting the idea of debris accumulation at the base of a snowbank.

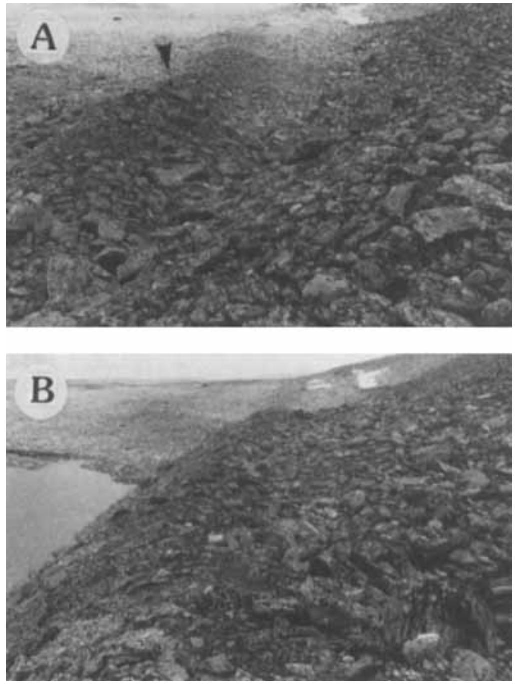

Fig. 3. A. – Langholet III protalus rampart. Double ridges can be seen. Figure (arrowed) is standing on the outer ridge. B. – Langholet IV protalus rampart. Small size of ridge (*c.* 2 m) and stability of feature are apparent. The ridges of Langholet III and II can be seen in the upper right centre of the photograph.

Rondslottet is arguably the least typical rock glacier. Its variable morphology could reflect a two-stage origin; initiation as a protalus rampart or avalanche bench (Johnson 1975), followed later, where shear stress increased, by rock glacier development (Grötzbach 1965; Lindner & Marks 1985). However, this view can be rejected. First, its location high above the valley floor combined with its considerable width and continuity around a spur end seems to exclude a protalus origin. The disposition of the lobes and bench seems closely related to debris supply, length of talus slope and proximity to the valley floor, important factors in determining the propensity for mass movement whether by creep of interstitial ice or basal shearing. Second, the bench slope steepens in the upper 2–3 m (Fig. 4B), a reflection of forward motion but not of debris accumulation at the base of a snowbank. It is suggested that this feature developed as

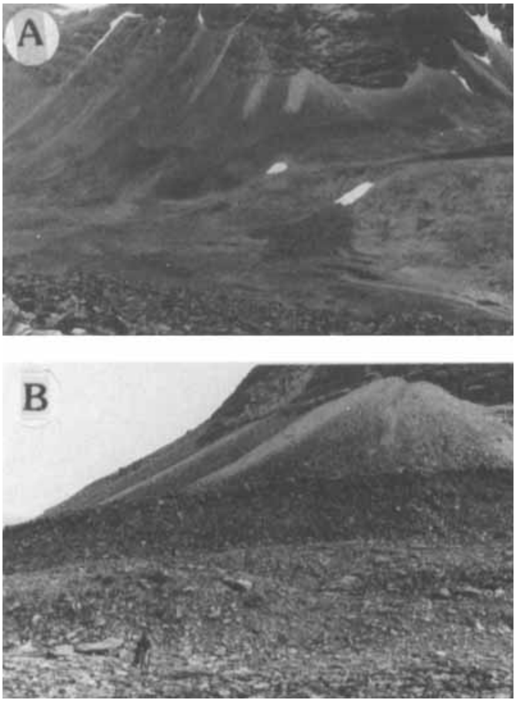

Fig. 4. A. – Rondslottet talus-foot rock glacier (valley-side type). Central bench form and flanking lobes are clearly visible. Lighter streaks of relatively fresh talus can be seen on the talus slopes and draped over ledges on the cliffs above. B. – Bench section of the Rondslottet rock glacier with degraded ridges in the foreground. Note steeper upper 2–3 m section of the frontal slope of the bench.

a bench which became in part unstable leading to the development of lobes where the talus foot failed to reach the valley floor and where debris supply remained sufficient. The form of the other rock glaciers supports this interpretation: Midtronden has a valley-side location and well-developed lobes, whereas Smedbotn II and Langholet I have a valley-floor location resulting in restricted forward motion.

Barsch & Treter (1976) regarded Smedbotn I as a rock glacier developed from an ice-cored moraine, being formed by extrusion of plastically-deformed frozen material at the base of the distal slope. A snowbank against the base of the distal slope prevented a direct assessment of Barsch & Treter's assertion that fresh material was emerging at this point. Nevertheless, lichenometric and Schmidt hammer data for the ridges show that distal slope ridges are older than those on the proximal slope, suggesting instead a glacial origin which has already been proposed for similar large features termed 'push-deformation' moraines in E Jotunheimen (Matthews & Shakesby 1984). During successive Neoglacial glacier advances, the relatively small Smedbotn glacier would have been confined by an increasingly large end moraine. Considerable force would have been exerted on the moraine by the expanding glacier, leading to ridges being formed by pushing and deformation. Surface ridges thus represent both depositional and deformational structures; anastomosing ridges reflecting modified older deposits and newly-created structures caused by glacier push. Evidence for this origin is seen in angles exceeding ϕ' cv on both the proximal (up to 48°) and distal slopes (up to 41°).

A morphological and developmental continuum

Talus and derivative landforms in Rondane can be viewed as a continuum of form (Johnson 1983), with different forms originating from simple talus slopes via separate developmental routes (Fig. 6). Rockfall talus slopes represent the ubiquitous form of debris mass movement in the upper, steep-sided valleys of Rondane. Snow cover seems to be insufficient for the development of protalus ramparts in most situations; their formation in Langholet apparently depending on favourable debris supply. Simple talus slopes and rock glaciers, therefore, may be the 'normal' talus-derived landforms in Rondane, leaving the protalus ramparts as special cases. The 'push-deformation' moraine (Smedbotn I) is distinct by virtue of its association with glacier ice; it may also be regarded as the most complex type of landform, the debris having undergone glacial entrainment and deposition followed by glacial pushing and deformation.

The rock glaciers appear to have developed in three ways. First, a bench may form (cf. Åkerman 1984). Second, where benches form relatively high on a talus slope, it appears that a shear stress threshold can be surpassed and a 'break-away' lobe may extend downslope, carrying most debris near the front crest (Fig. 5B). For the Rondslottet feature this threshold seems to have been exceeded at different locations and at different times, in view of the low, degraded ridges beyond the bench foot (Fig. 2). This type of rock glacier can be expected to comprise portions of bench and lobe depending on the stability and position on the talus slope. Third, where rock glacier development has

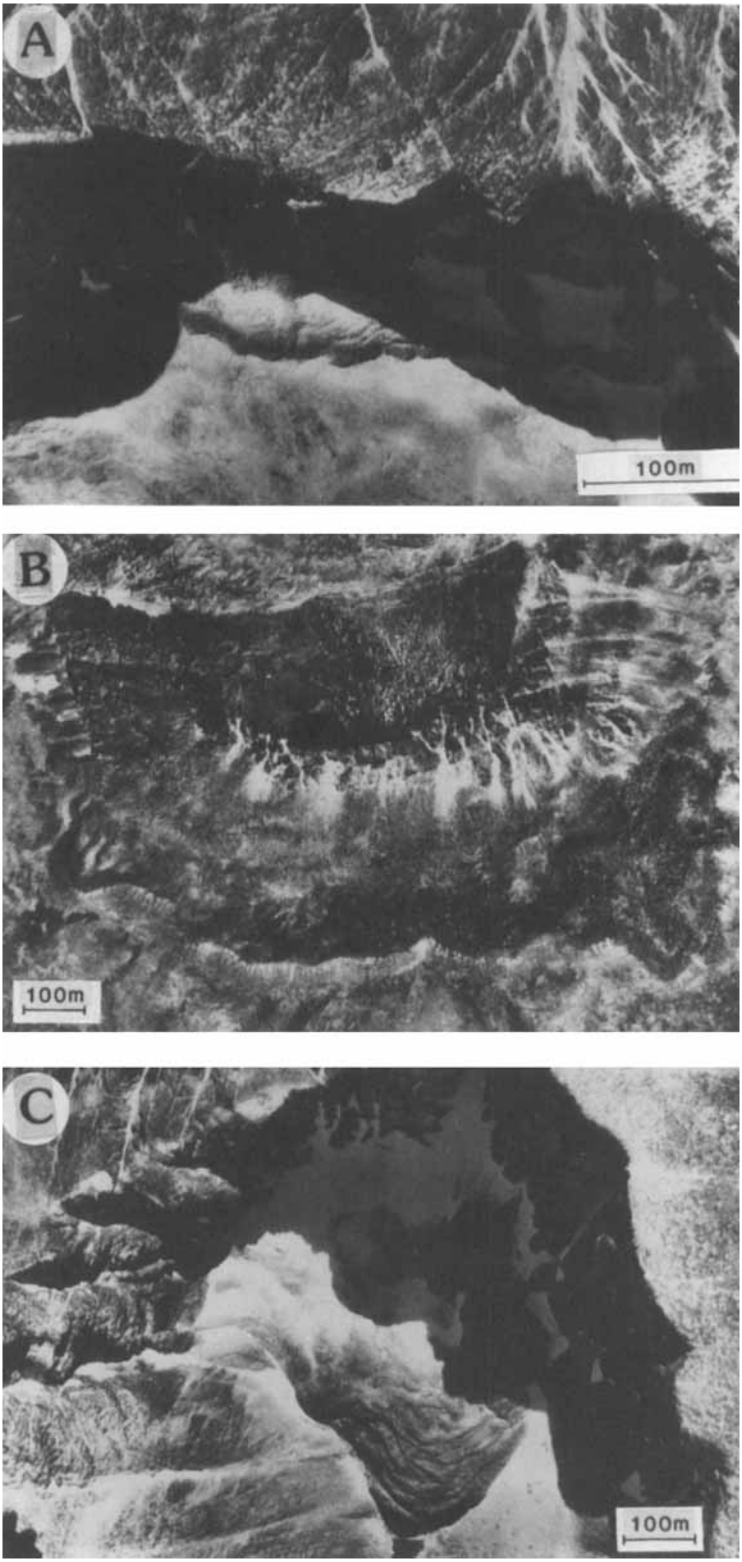

Fig. 5. A. – Vertical aerial photograph of Langholet I talus-foot rock glacier (valley-floor type). Note restricted lobe development in the valley bottom location. (Widerøe's Flyveselskap A/S 1967.) B. – Vertical aerial photograph of Midtronden talus-foot rock glacier (valley-side type). Lighter streaks of comparatively fresh talus (centre) define the base of the cliffs of the spur from Midtronden peak. The highly crenulate plan form of the frontal slope of the feature itself is seen across the lower part of the photograph. (Widerøe's Flyveselskap 1967). C. – Vertical aerial photograph of Smedbotn I 'push-deformation' moraine. Between the moraine complex and the headwall lies a large depression which, at the time this photograph was taken, contained remnants of glacier ice. Note also the anastomosing pattern of surface ridges. (Widerøe's Flyveselskap A/S 1967.)

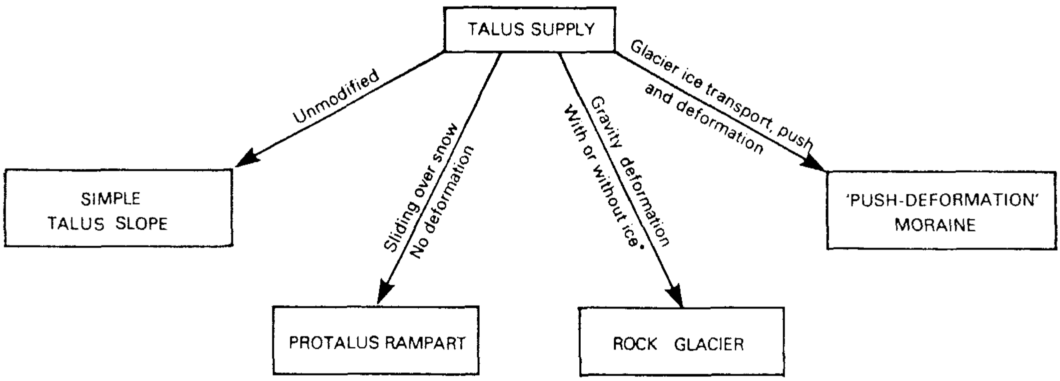

Fig. 6. The non-linear morphological and developmental continuum of talus-derived landforms in Rondane. In addition, valley-side and valley-floor rock glaciers are recognized in this study. *Most theories of rock glacier formation assume the presence of interstitial ice, ground ice or an ice core.

occurred entirely on the valley floor, extension has been restricted (e.g. Smedbotn II and Langholet I).

An age and activity continuum

Great age and inactivity of the features is suggested by the consistently large lichens and the often continuous lichen cover on surface boulders. Previous work in southern Norway suggests that maximum lichen sizes over *c.* 150 mm predate the 'Little Ice Age' (Matthews & Shakesby 1984), and in view of the relatively continental climate of Rondane and assuming declining lichen growth rates with time, many surfaces must be considerably older than the 'Little Ice Age'.

That lichen sizes on the landforms do not differ significantly from those characteristic of 'outside' sites suggests relatively uninterrupted growth on the landforms for a considerable time. With no consistent pattern of lichen sizes and Schmidt hammer R-values between inner and outer ridges, differential ages for ridges associated with all but one feature (Smedbotn I) can be rejected. Lichen sizes from 'talus' sites, however, suggest that talus inputs occurred during the 'Little Ice Age' and continue today. Present-day talus production is also shown by 'talus' boulders with either an incomplete or absent lichen cover. Although lichen-free boulders are common, they are not reflected in the data of Table 2 because only the largest lichens were measured.

When the combined Schmidt hammer results for rock glaciers and protalus ramparts were examined for differences between 'outside', 'outer ridge' and 'talus' sites using Kolmogorov-Smirnov two-sample tests, the following results were obtained. For rock glaciers, 'outer ridges' could be distinguished statistically from 'outside' sites ($p < 0.05$) but not from 'talus' sites ($p > 0.05$). For protalus ramparts the ramparts were distinguishable from 'talus' sites ($p < 0.05$) but not from 'outside' sites. This implies that the protalus ramparts are older or have been stable for longer than the rock glaciers. Support for this conclusion is given by a complete lichen cover on all protalus rampart boulders compared with small quantities of fresh material on the rock glaciers near 'talus' zones and by the stability of all protalus rampart slopes compared with rock glacier front slopes, which (except for Langholet I and parts of Smedbotn II) comprise easily dislodged debris. The small sizes of lichens on the innermost ridge (and on the long proximal slope) indicate that a major reactivation of Smedbotn I occurred during the 'Little Ice Age'. In addition, the steepness of the proximal slope suggests comparatively recent glacier retreat, with only a slightly less steep distal slope suggesting comparatively recent glacier push.

From these observations an activity continuum can be proposed, with the 'push-deformation' moraine being the most active, followed in turn by the rock glaciers and the inactive protalus ramparts. The 'push-deformation' moraine was active during the 'Little Ice Age' whereas the protalus ramparts, being fossil features, clearly were not. Four possibilities for the origin of the rock glaciers can be put forward. First, if Rondane was deglaciated during Preboreal times, the rock glaciers may have developed then, when conditions were perhaps particularly favourable. However, rapid deglaciation of Rondane (cf. Barth *et al.* 1980; Hafsten 1981) suggests, second, that they remained active throughout the Holocene, the large lichens reflecting stable upper surfaces to otherwise active rock glaciers, the lower layers of which continued to move. Third, they may have been intermittently active in the Holocene. Fourth, just as Smedbotn I and the protalus ramparts differ in their periods of activity so might the rock glaciers (cf. Johnson 1984), both with respect to different features and parts of the same feature.

If ice has been directly or indirectly involved in the motion of the rock glaciers, the possibility of continuous or periodic activity through the Holocene is to be favoured since Holocene temperatures have been slight and climatic conditions today remain relatively severe. Even during the Climatic Optimum (*c.* 8,000–5,000 B.P.), with temperatures 2–3°C higher than today (Barth *et al.* 1980; Hafsten 1981; Caseldine & Matthews 1985), mean annual air temperatures would only just have reached the suggested upper temperature limit of −2°C for rock glacier activity in the Swiss Alps (Barsch 1977). During the 'Little Ice Age', temperatures were probably 1–2°C lower than today (Matthews 1976, 1977) so that the features could well have been more active during that period and in other Neoglacial cool phases.

Implications for assessing the activity of talus-derived landforms

The indicators of rock glacier activity used in this paper require careful interpretation. The spread of mean Schmidt hammer R-values is low for sites where lichen sizes show considerable age variation and this is attributed largely to boulder surface characteristics. First, freeze–thaw shattering or rockfall leads to an initial rough surface texture which yields similar R-values to weathered boulders. By contrast, 50 boulders from the modern Dörålen stream and 50 weathered boulders from a nearby fluvioglacial terrace yielded significantly different mean R-values of 52.4 and 36.7 respectively (Kolmogorov-Smirnov two-sample test; $p < 0.001$). This can be explained by the initial smooth surface compared with the rough surface developed through weathering. Second, sparagmite surfaces weather partly by flaking, leading to continual renewal of 'fresh' surfaces. Third, many boulders obviously weakened by weathering along bedding planes were omitted from consideration as Schmidt hammer readings would have reflected sub-surface weaknesses rather than surface hardness.

Lichen sizes from the rock glaciers need to be interpreted with caution in view of the ability of lichens to thrive in relatively unstable conditions (Matthews 1973; Griffey 1978). Continuity of lichens across adjacent surface debris (Luckman & Crockett 1978) or the presence of lichen-covered boulders in the surface hollows otherwise occupied by lichen-free boulders as a result of persistent snow drifts (Foster & Holmes 1965), though not applicable here, would seem more appropriate as diagnostic criteria.

Other frequently-cited indicators of rock glacier age also require cautious use. For example, Smedbotn II (with angles up to 54°) had the steepest front, yet paradoxically this was the most stable because of interlocking boulders. The other rock glacier fronts reclined mostly at angles < Ø' cv. Surprisingly, one of the most active talus slopes, with angles up to 37°, occurred upslope of the rock glacier with the lowest-angled front slope (28° overall; Langholet I). Clearly, front slope angles are not always reliable indicators of rock glacier activity.

Conclusion

This investigation has highlighted areas of debate concerning the morphology, classification, age and state of activity of rock glaciers, protalus ramparts and related landforms. A morphological and developmental continuum of these landforms is proposed. Rather than a linear, sequential development of one class of talus-derived landforms to the next (cf. Grötzbach 1965; Corté 1976; Ballantyne & Kirkbride 1987), a number of alternative routes originating from a simple talus slope is envisaged (Fig. 6). In Rondane, rock glaciers seem to be the 'normal' talus-derived landform with protalus rampart development depending on special conditions of debris supply. Variation in talus-foot rock glacier form is well illustrated in the Rondslottet feature with lobes developing from a bench form where debris supply and slope conditions have allowed. Lobe extensions are better developed in the Midtronden feature because the talus foot terminates above the valley floor along the entire talus slope; consequently, potential for rock glacier movement is greater. By contrast, for talus-foot rock glaciers at the talus slope/valley floor junction (Langholet I and Smedbotn II), forward motion and therefore extension from the talus foot are limited. Sufficient snowbed growth for restricted glacier development was instrumental in the formation of the Smedbotn I 'push-deformation' moraine.

A separate age and activity continuum has also been recognized with the recency of activity increasing in the direction: protalus rampart → rock glacier → 'push-deformation' moraine. It is suggested that all the talus-derived landforms in Rondane probably originated in the early Holocene. The protalus ramparts are 'fossil' features while the rock glaciers may have been active, perhaps intermittently, throughout the Holocene. The 'push-deformation' moraine is regarded as the most recently active of the landforms investigated as it experienced a major phase of activity, and hence major changes in form, during the 'Little Ice Age'.

Generally-accepted diagnostic criteria for distinguishing rock glaciers from other talus-derived landforms are found inadequate. 'Porridge-like appearance' (Barsch 1977:231) and 'tongue-shaped or lobate masses of poorly-sorted angular debris' (Wahrhaftig & Cox 1959:387) are not descriptions exclusive to rock glaciers: the morphology of the Verkilsdalen feature matched this description and whilst thought to be a rock glacier by Barsch & Treter (1976), has been shown by Dawson *et al.* (1986) to be a landslide. These descriptions are equally appropriate for Smedbotn I, also viewed as a rock glacier by Barsch & Treter (1976), yet our work indicates a glacial origin. The description of a protalus rampart as a 'ridge of rubble or debris that has accumulated piecemeal by rock-fall or debris-fall across a perennial snowbank, commonly at the foot of talus' (Richmond 1962:20) would apply to the Rondane features ascribed to this origin. However, features regarded as such by Ballantyne & Kirkbride (1987) in several respects (talus-foot extension, constituent material, distal slope angle) resemble features identified here as rock glaciers. Clearly, unambiguous diagnostic criteria for differentiating between these landforms are needed. Because rock glaciers are slow-moving, lichen sizes and weathering indices are unlikely to be unambiguous in determining activity. Furthermore, a simple correlation between activity and front slope angle seems doubtful. Instability of the uppermost part of the front slope, continuity of lichens across surface debris and lichen-covered boulders in otherwise lichen-free hollows might offer better indices of inactivity where no vegetation nor surface fines occur.

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