Stockholm University

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Degree Project in Geology 15 hp

An exploration of the controls on subglacial bedrock erosion and morphology near Drumnadrochit, Scotland

Ben Jonkman

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Department of Geological Sciences
Stockholm University
SE-106 91 Stockholm

Abstract

Abrasion and plucking are important subglacial erosional processes which create different landforms. This study shows that properties of bedrock control subglacial erosion and bedrock shaping. Denser jointed bedrock and harder bedrock favour plucking, while softer and less jointed bedrock favours abrasion. Field work for this study was done near Drumnadrochit in NE Scotland, where the lithology, geology and morphology of crag and tails and rôches moutonnées were examined. The rôches moutonnées, which have an abraded stoss side, are only shaped out of a soft, biotite rich gneiss, with not much jointing. The crag and tails, which have a plucked stoss side, are more densely jointed and are shaped out of serpentinite and a harder, more felsic gneiss. Foliation appears not to influence subglacial erosion, since the foliation in rôches moutonnées and crag and tails in the study area was similar.

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1 Introduction

Rôches moutonnées and crag and tails are two subglacial erosional landforms, among a wide range of erosional, deformational, and depositional subglacial bedforms. Geoscientists study these morphological features to get a better understanding of ice, the way it flows, and how it influences the underlying bedrock. Since bedforms are widely used to infer properties of palaeo-ice flow (e.g. direction, speed, availability of meltwater, and thermal regime), it is important to understand formation processes so that we make correct palaeo interpretations. The main research questions of this project are: why do these different subglacial erosional landforms form? Is this difference in landform shaping a consequence of ice flow dynamics or is it related to geology or time?

Rôches moutonnées are asymmetric landforms that have been glacially moulded out of pre-existing hummocks or small hills (Huggett 2011, p. 464). They often occur in clusters and have a size ranging from several metres to a few hundred metres (Glasser and Bennett, 2004). The asymmetry is a common factor: rôches moutonnées always have a gently sloping up-ice side and a steep down-ice side. The stoss side (up-ice) of a rôche moutonnée is moulded by abrasion, while the lee side (down-ice) has been plucked. Abrasion is an erosional process where bedrock is polished or scoured by intraglacial clasts or subglacial sediment (e.g. Hallet, 1979; Krabbendam and Glasser, 2011). Plucking, also called quarrying, happens in three steps: the bedrock is fractured by the ice, a bedrock fragment is loosened, and this block is entrained in the ice (e.g. Röthlisberger and Iken, 1981; Hallet, 1996). According to Glasser and Bennett (2004), the asymmetry of rôches moutonnées is caused because they are shaped out of pre-existing hills. On the stoss-side of the hummock, the normal pressure of the ice is high, which causes abrasion. On the lee side cavities can form between the ice sheet and the bedrock, leading to a lower normal pressure. This causes quarrying of the bedrock (Glasser and Bennett, 2004). Because quarrying and the formation of cavities is associated with thin and fast flowing ice (Hallet, 1996), it is suggested that rôches moutonnées preferentially form under those conditions (Glasser and Bennett, 2004). The detailed morphology of rôches moutonnées varies. According to Glasser and Bennett (2004), this is controlled by characteristics of preglacial weathering and jointing or foliation of the bedrock.

Crag and tails also are glacial landforms with a stoss and a lee side, but aside from that they differ significantly from rôches moutonnées. Crag and tails are elongated, tadpole shaped landforms composed of a resistant, plucked knob of bedrock on the steep stoss side (the crag), and a smooth tail on the leeward side. This tail often consists of softer, less resistant bedrock than the crags bedrock, preglacial sediment, or till which is protected from glacial erosion by the crag (e.g. Mäkelä and Illmer, 1992; Evans and Hansom, 1996; Huggett 2011, p. 464).

Differences in glacial landforms could relate to three aspects: time, geological properties of the bedrock (e.g. mineralogy, jointing, foliation), and ice flow properties (e.g. flow speed, meltwater, strain rate). In this project, the importance of the second option, geology, will be tested. Several studies have shown that geology could play an important part in glacial erosion. For example, according to Dühnforth et al. (2010) the degree of joint spacing not only controls the glacial erosion rate, but also whether abrasion or plucking is favoured. Krabbendam and Glasser (2011) state that abrasion is associated with relatively soft rocks with wide joint spacing, where hard rocks with dense joint spacing are linked to erosion by plucking (Glasser and Bennett, 2004). Glasser et al. (1998) add that "glacial abrasion of bedrock surfaces is also favoured where the dominant bedrock foliation is normal to ice flow".

An area in the moorlands northwest of the town of Drumnadrochit in Scotland has been chosen for fieldwork for this research project. It has a varied geology and contains both rôches moutonnées and crag and tails. It therefore gives the opportunity to test whether properties of bedrock govern subglacial erosion and bedform shaping. This shall be done by mapping glacial landforms in the area and examining their internal geology. In addition, serpentinite erratics will be mapped. They can be used as indicators for ice flow direction, since serpentinite is unique to this part of Scotland and the erratic transport can be used to constrain transport pathways and magnitudes.

2 Study area

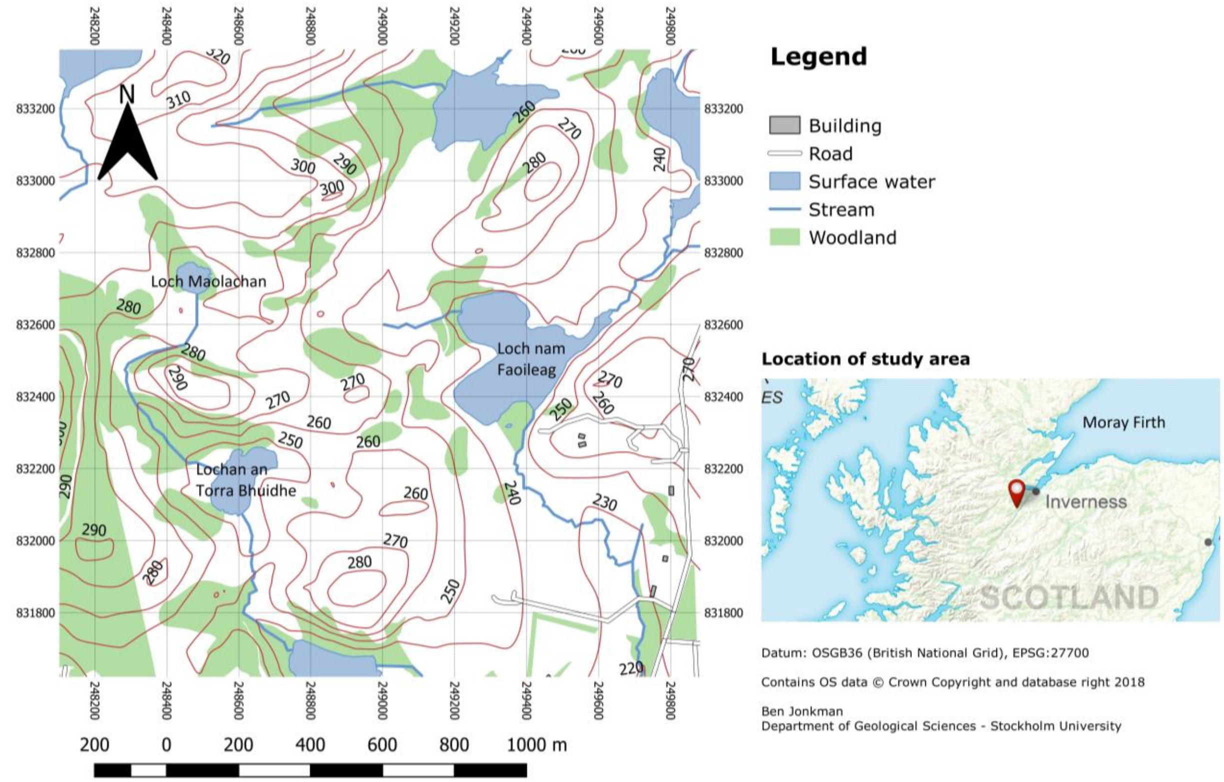

FIGURE 1: A MAP OF THE STUDY AREA (CONTAINS OS DATA ©CROWN COPYRIGHT AND DATABASE RIGHT 2018)

The study area (Figure 1) is an area of 2 km^2 about 3 km northwest of the town of Drumnadrochit, approximately 5 km from Loch Ness. The area is situated in the Scottish Highlands.

The hilly area is on relatively high terrain, more than 200 m higher than Drumnadrochit and Loch Ness, and borders the Great Glen fault. It contains three small lakes: Loch Maolachan, Lochan an Torra Bhuidhe, and Loch nam Faoileag. Loch Maolachan and Lochan an Torra Bhuidhe are linked to each other by a stream. The lowest section of the study area is about 230 m above sea level. The highest parts are more than 300 m above sea level, making the maximum altitude difference approximately 70 m.

The study area is in a moorland with mainly low vegetation. This makes it easier to locate and examine outcrops. The western part of the study area contains many coniferous trees, unlike the rest of the area, where not many trees can be found and most trees are deciduous. These differences in vegetation give clues about the underlying geology, since serpentine soils (derived from weathered serpentinite) are known to be a stressful environment for plants. This is caused by relatively high magnesium and nickel levels (which can be toxic to plants), low availability of nutrients, a high permeability, and shallowness of the soil layer (Roberts and Proctor, 1992; Specht et al., 2001). When trees grow on serpentine soils, they are predominantly coniferous (Oberhuber et al., 1997), so during field work these coniferous areas could be used as an indicator that the underlying bedrock might be serpentinite.

2.1 Geomorphological and palaeoglacial setting

The study area has undergone several periods of glaciation, most recently during the Late Devensian (31-11.5 ka), when the last British Ice Sheet covered the area (Bradwell et al., 2008; Clark et al., 2012). This ice sheet had a maximum extent around 27 ka BP (Clark et al., 2012). Even though there is no scientific consensus on the extent, thickness, and other parameters of the British Ice Sheet during the Last Glacial Maximum (Fretwell et al., 2008), it is believed that during and even after the Last Glacial Maximum of the last British Ice Sheet, up till 17 ka BP, the study area was covered by warm-based ice, with a stable flow-direction (Hughes et al., 2014).

During this period, the ice flowed in a wide stream from the southwest towards the Moray Firth in the northeast (Hughes et al., 2014; Turner et al., 2014). A Digital Surface Model of the wider area surrounding the study area (Figure 2), clearly shows that many landforms in this area are oriented parallel to the ice flow direction in those final stages of the last British Ice Sheet. This widespread bedrock streamlining in the onset area of the Moray Firth ice stream also suggests the ice was well lubricated and therefore warm-based, which is known to cause more bedrock erosion than cold-based ice (Boulton, 1982).

Reconstructions by Clark et al. (2012) indicate that the Moray Firth ice stream had shut down by around 17 ka. Models by Hughes et al. (2014) suggest that during this period most ice had already retreated inland from the northeast Scottish coast, but there still was a glacial lobe which emanated from the Moray Firth and flowed onshore. It is uncertain whether this lobe also covered the study area.

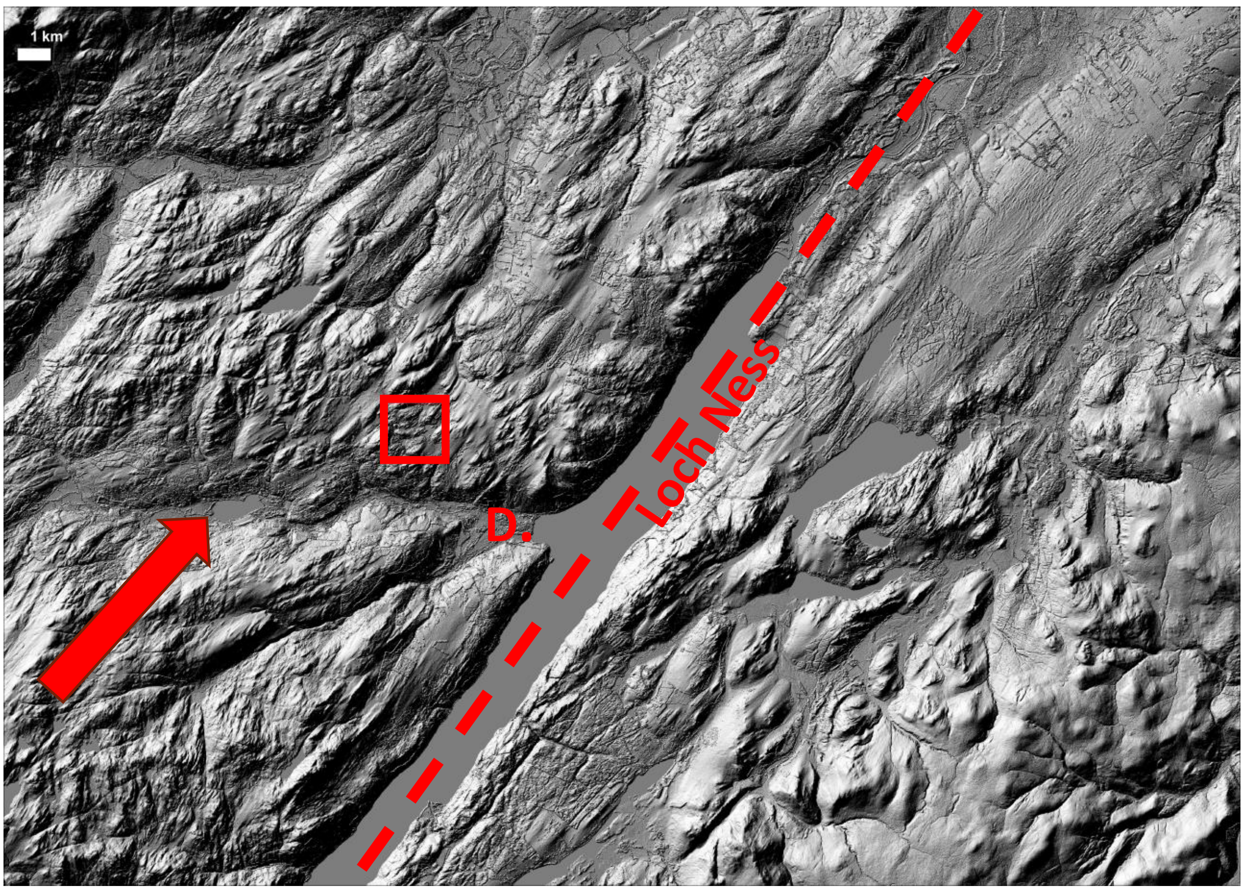

FIGURE 2: NEXTMAP DIGITAL SURFACE MODEL OF THE AREA SURROUNDING THE STUDY AREA (©NERC UK), MODIFIED TO MARK STUDY AREA WITH RED RECTANGLE, MARK ICE FLOW DIRECTION WITH ARROW, MARK GREAT GLEN FAULT WITH DASHED LINE, AND MARK THE LOCATIONS OF LOCH NESS AND DRUMNADROCHIT (D.)

2.2 Geological setting

The study area is located several kilometres west of the Great Glen fault zone. The bedrock in the area is extremely varied. It is composed of sections of schists and gneisses, serpentinite, and metalimestones and Ca-Mg-Fe-silicate rocks (skarns) (Rock et al., 1986). This variety makes the area well-suited to study effects on geomorphology. The distribution of the types of bedrock in the study area can be seen in Figure 3, which is redrawn from Rock et al. (1986).

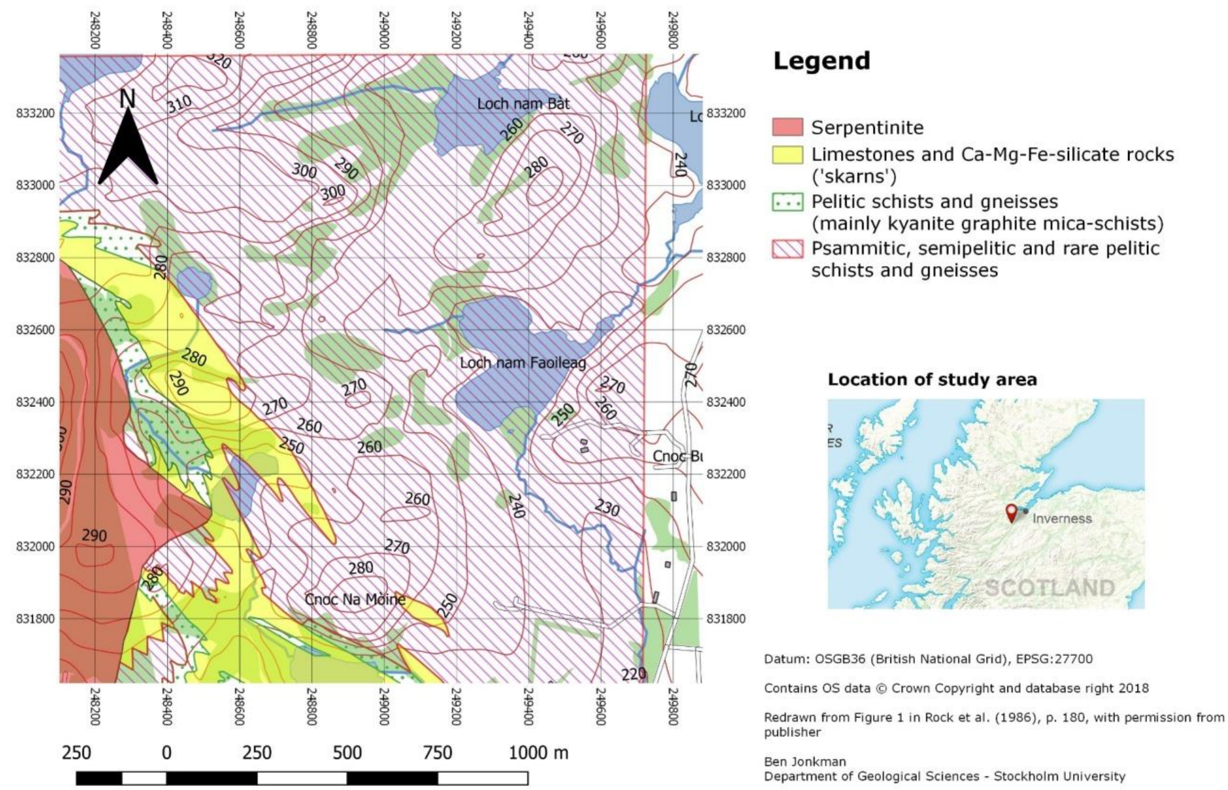

FIGURE 3: GEOLOGICAL MAP OF STUDY AREA (REDRAWN AFTER ROCK ET AL., 1986, P. 180. USED WITH PERMISSION OF SCOTTISH JOURNAL OF GEOLOGY. MAP CONTAINS OS DATA ©CROWN COPYRIGHT AND DATABASE RIGHT 2018)

The psammites belong to the Moine Supergroup, while the pelitic schists and gneisses, the serpentinite and limestones are classified as the Glen Urquhart Complex and are of uncertain origin (Brook and Rock, 1983). Though the exact period of formation of the Glen Urquhart Complex is unclear, Rock et al. (1986) believe it is pre-Caledonian. Rb-Sr dating of biotites in pegmatites in the limestone layers by Brook and Rock (1983) gives a metamorphic age of 428 ± 5 Ma for these rocks.

3 Methods

3.1 Fieldwork

Fieldwork for this degree project was done from 10 to 17 October 2018. During this period glacial landforms in the area were mapped and their internal geology examined.

For the mapping a GNSS device (Garmin 64S) was used to register the exact location of the landform. Because this model GNSS device has an accuracy with an error margin of up to several metres (Garmin, personal communication by email, April 2019), the device was only used to gather the size (length, width and height) of larger landforms (≥12 m). For smaller landforms (<12 m) the extent of the landform was measured using a tape measure. When mapping erratics, the GNSS device was used for gathering location information, while the tape measure was used to measure the size of the erratic.

Lithologies were studied in the field using a hand lens, a tape measure and a compass clinometer. With the hand lens, the rock type and the mineral composition of the rocks were identified. An abundance determination chart from Klein and Philpotts (2013, p. 536) was used on sections of the rocks to determine the approximate modal abundance of felsic minerals versus mafic minerals in the bedrock of gneissose landforms. Because of the size of the landforms (lengths of up to 621 m) only sample sections were used to assess the mineralogy, not the entire landform. For larger landforms more samples were assessed than for smaller landforms. The tape measure was used to measure the joint spacing. Only open joints were measured, since according to Krabbendam and Bradwell (2011) cemented joints rarely seem to represent mechanical weaknesses. Joint spacing was measured on sections of exposed bedrock along transects as long as possible. The compass clinometer was used to measure the dip and strike of the foliation, as well as the orientation of the landform.

Notes were made in the field in a notebook, as well as on a printed Ordnance Survey map of the area.

3.2 Data processing

After the fieldwork, field notes were digitized and ordered in a Microsoft Excel sheet.

QGIS (version 3.0.3 and version 3.2 for Windows) was used to create several maps of the area, including a location map and a geomorphological map. The base layer data (e.g. nature, water bodies, roads, elevation data and buildings) were provided by the Ordnance Survey in the form of their OS OpenData products. The data were downloaded on 17 January 2019.

Geomorphological features and their lithology were mapped in QGIS, based on the field data and a DEM of the area from NEXTMap. For larger landforms the DEM could be used to make corrections for errors that were caused by the inaccuracy of the GNSS device, but for smaller landforms and erratics this was not possible, because of the resolution of the DEM.

4 Results

During the field work for this project, 15 rôches moutonnées and 20 crag and tails were mapped and examined. As can be seen in the Digital Elevation Model (DEM) in Figure 4, not all larger streamlined hills in the area were mapped, but most of these cannot be classified as rôches moutonnées or crag and tails. Almost all accessible large-scaled rôches moutonnées and crag and tails in the area were studied for this project. Figure 5 gives an overview of these landforms on a map.

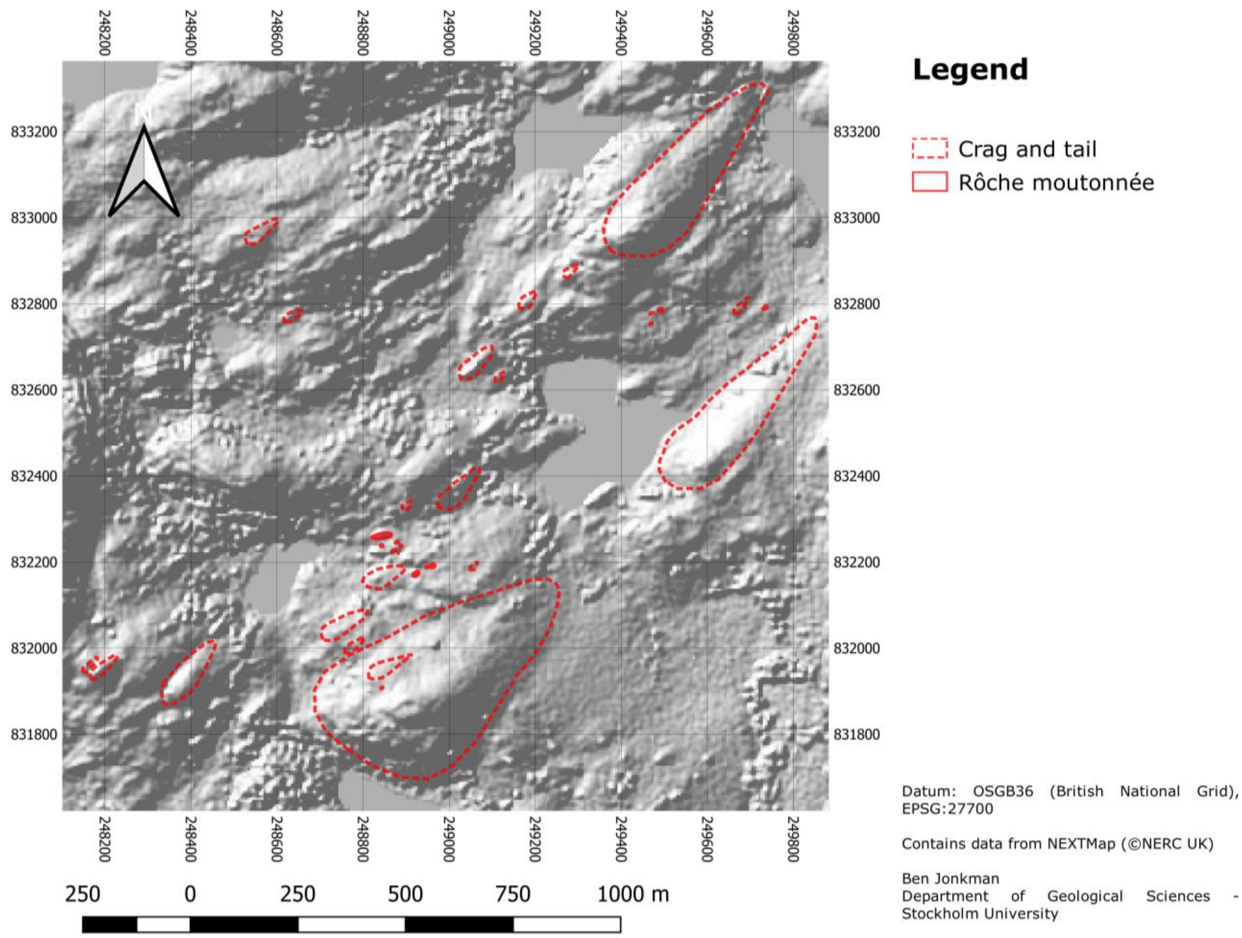

FIGURE 4: THE MAPPED LANDFORMS PROJECTED ON A DEM OF THE STUDY AREA. NEXTMAP (©NERC UK)

While the crag and tails are widely dispersed across the study area, the rôches moutonnées are mostly grouped together. Figure 5 contains an inset of one of these areas, located around 248900 832200 on the British National Grid. Another patch, with three rôches moutonnées, can be found to the northeast, on the other side of Loch nam Faoileag, near 249480 832770.

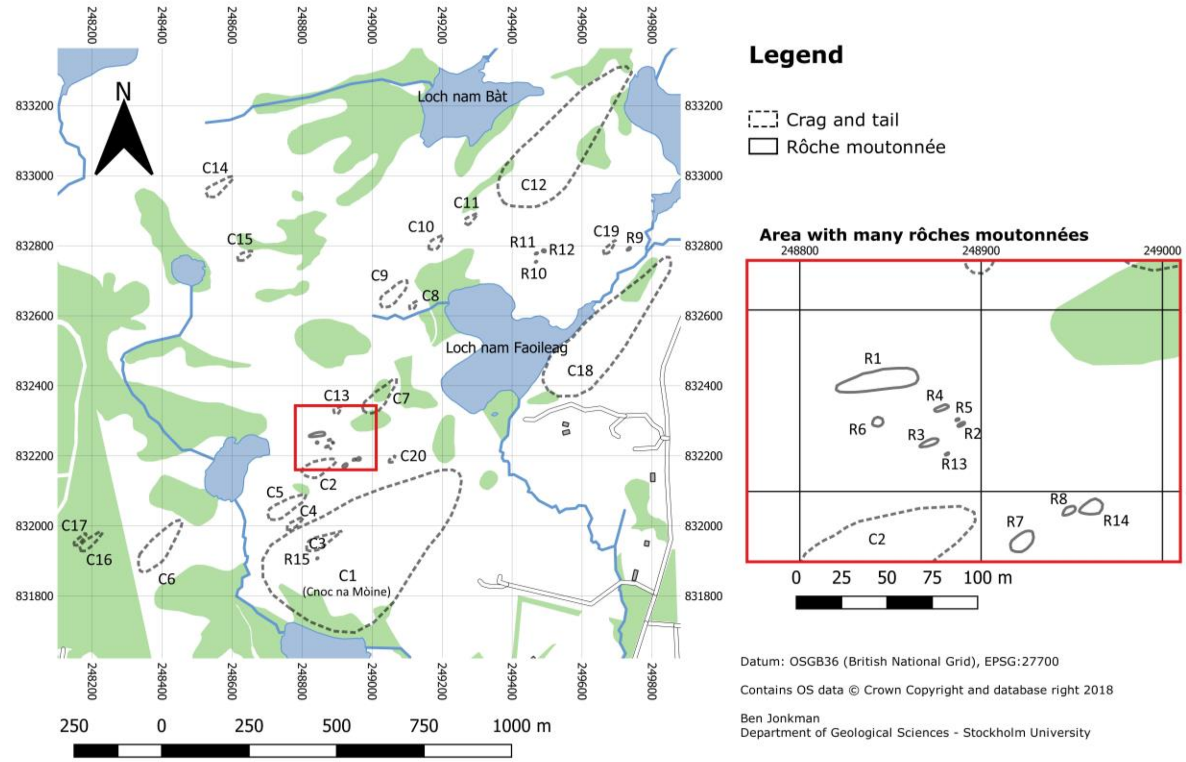

FIGURE 5: MAP SHOWING MAPPED CRAG AND TAILS (C) AND RÔCHES MOUTONNÉES (R) | (CONTAINS OS DATA ©CROWN COPYRIGHT AND DATABASE RIGHT 2018)

4.1 Geomorphology

Most landforms are discrete features, but the largest crag and tail, Cnoc na Mòine, has some small outcrops that are themselves shaped into streamlined landforms, as if these are “piggybacking” on the larger feature. Figure 6 shows one of these landforms, with a rôche moutonnée morphology.

FIGURE 6: A RÔCHE MOUTONNÉE, LOCATED ON THE CRAG SIDE OF THE CRAG AND TAIL CNOC NA MÒINE. HEIGHT OF PERSON IN FRONT OF RÔCHE MOUTONNÉE (INDICATED WITH ARROW) IS APPROXIMATELY 1.75 M. (APPROXIMATE LOCATION ON BRITISH NATIONAL GRID: 248843 831907) PHOTOGRAPHY: BEN JONKMAN

4.1.1 Size of landforms

All crag and tails in the study area are larger in width, length, and height than the rôches moutonnées. The rôches moutonnées have a mean length of 10.5 metres, with a range from 2.4 metres to 45.1 metres. The standard deviation for the length of the rôches moutonnées is 9.8 metres. The crag and tails in the study area have a mean length of 146.3 metres, with a standard deviation of 171.6 metres. The smallest crag and tail is 24.5 metres long, the largest has a length of 621 metres. The height of the studied rôches moutonnées ranges from 30 centimetres to 4 metres. Their mean height is 1.4 metres. The mean height of the crag and tails is more than eight times higher: 12.4 metres. The height of the crag and tails varies from 3 metres to 31 metres.

To compare the elongation and the shape of the two landforms, the length/width ratios and length/height ratios have been calculated. Rôches moutonnées have an average length/width ratio of 2.08, with a standard deviation of 1.13. Crag and tails have an average length/width ratio of 2.65. The standard deviation for the crag and tails is 0.53. So, in terms of elongation crag and tails have a slightly longer, thinner shape, where rôches moutonnées are relatively more rounded. The difference in standard deviation indicates that the crag and tails in this study area are more uniformly shaped, where the length/width ratio of the rôches moutonnées varies more.

The length/height ratios of the landforms indicate that rôches moutonnées tend to be relatively higher than crag and tails. The examined rôches moutonnées have an average length/height ratio of 8.9, where the average length/height ratio of the crag and tails is 11.2. The standard deviations for the length/height ratios are close to each other: 5.1 for the rôches moutonnées and 5.6 for the crag and tails. This shows that the landforms have a uniformity in the length/height ratio that is more or less similar.

These calculations and comparisons indicate that rôches moutonnées in this study area appear to be smaller, slightly rounder, and have a relatively higher amplitude (for their size) than crag and tails in the area.

4.1.2 Landform orientation

Most landforms in the study area trend southwest to northeast with landform heads in the southwest and tails in the northeast. The examined rôches moutonnées and the studied crag and tails both have a fairly narrow window of orientation. For the rôches moutonnées, the landform orientations have a mean of 51.2°, with the northernmost orientation at 44° (NE) and the easternmost orientation at 78° (ENE). The standard deviation of the landform orientation is 8°. The studied crag and tails have an even narrower window of orientation, ranging from 44° to 62°. Measured from head in direction of the tail of the landform, the mean of their orientations is 50.3°, with a standard deviation of 5.4°.

These results show that the rôches moutonnées and the crag and tails are very similarly oriented. On average, the rôche moutonnées are oriented slightly more towards the east, whereas the crag and tails are oriented more northernly. The standard deviation for crag and tails is slightly lower than that of the rôches moutonnées, but the difference is so small that the two are comparable.

More detailed information on the geomorphology of the studied landforms can be found in Table 1, which shows morphological data for the rôches moutonnées, and Table 2, which shows morphological data for the crag and tails.

No glacial striations were found on the examined landforms.

TABLE 1: MORPHOLOGY OF RÔCHES MOUTONNÉES (&=NO DATA AVAILABLE BECAUSE OF TECHNICAL PROBLEMS)

Rôche moutonnée	Landform orientation (measured from head in direction of toe)	Length (m)	Width (m)	Length/width ratio	Height (m)	Length/height ratio
1	78°	45.1	12	3.80	4	11.28
2	55°	10.4	2	5.22	1.75	5.94
3	50°	5	1.9	2.63	0.65	7.69
4	55°	7.7	2.8	2.75	0.70	11.00
5	50°	3.4	1.4	2.39	0.31	10.97
6	50°	6	5	1.20	1.70	3.53
7	48°	14.1	9	1.56	1.70	8.29
8	52°	8.1	5	1.61	&	-
9	45°	12	6.1	1.98	1.70	7.06
10	45°	6.4	4	1.60	0.30	21.33
11	55°	8.1	7.8	1.03	&	-
12	48°	9.2	9.2	1.00	&	-
13	48°	2.40	1.20	2.00	1.10	2.18
14	45°	13.6	8.3	1.64	&	-
15	44°	5.8	6.3	0.92	&	-

TABLE 2: MORPHOLOGY OF CRAG AND TAILS

Crag and tail	Landform orientation (measured from head in direction of toe)	Length (m)	Width (m)	Length/width ratio	Height (m)	Length/height ratio
1 (Cnoc na Mòine)	48°	621	340	1.82	31	20.03
2	50°	100	46	2.17	26	3.84
3	62°	113.8	36	3.16	8	14.23
4	58°	58.5	18	3.25	5	11.70
5	58°	124	42	2.95	7	17.71
6	42°	185	62	2.98	8	23.13
7	50°	129	45	2.87	11	11.73
8	48°	29	15.4	1.88	5	5.80
9	45°	104	40	2.60	13	8.00
10	45°	53.6	27.8	1.93	7	7.66
11	45°	44	19	2.32	9	4.89
12	45°	523.5	177	2.96	30	17.45
13	50°	27.7	16.5	1.68	2.75	10.07
14	55°	91	33.9	2.68	7	13.00
15	55°	47	20.3	2.32	4	11.75
16	55°	79	23	3.44	23	3.43
17	55°	46	14.75	3.12	16	2.88
18	45°	475	147	3.23	29	16.38
19	45°	50.6	16.4	3.09	4	12.65
20	50°	24.5	10	2.45	3	8.17

4.2 Geology

The study area contains several types of bedrock. All studied rôches moutonnées are made of the same rock type: mafic gneiss. For the crag and tails, two rock types were seen: felsic gneiss or schist and serpentinite. Geological attributes of the studied rôches moutonnées and crag and tails can be seen in Table 3 and Table 4, respectively.

What this study classifies as two types of gneiss (mafic and felsic) is placed by Rock et al. (1986) in one category (psammitic, semipelitic and rare pelitic schists and gneisses), as shown on the geological map in Figure 3.

When looking at the geology and the morphology of landforms, it is possible to compare the serpentinite crag and tails with the gneissose ones. The mean length/height ratio for the serpentinite crags and tails is 9.81 and for the gneissose crag and tails 11.47. The mean length/width ratio is 3.18 for the serpentinite crags and tails and 2.55 for the gneissose crag and tails. These numbers indicate that the serpentinite crag and tails have a higher amplitude and are more elongated than the crag and tails which are shaped out of gneiss.

Table 3: Geology of rôches moutonnées (# = no data available, * = dip unmeasurable, ** = no joints visible or measurable)

Rôche moutonnée	Rock type of head	Relative abundance of mafic vs. felsic minerals in gneissose rocks	Mineral composition	Foliation	Foliation orientation (Strike / dip)	Average joint spacing (cm)
1	Mafic gneiss	66 % (n=3)	Quartz, feldspar, biotite, amphibole, garnet	Yes	290° / 58° NE	25.7
2	Mafic gneiss	60 % (n=1)	Quartz, biotite, amphibole, garnet	Yes	326° / 65° NE	8.25
3	Mafic gneiss	#	Quartz, biotite, feldspar, amphibole, garnet	Yes	290° / 80° NE	15.5
4	Mafic gneiss	#	Quartz, muscovite, biotite, garnet	Yes	310° / *	**
5	Mafic gneiss	60 % (n=1)	Quartz, biotite, feldspar, amphibole, garnet	Yes	320° / *	**
6	Mafic gneiss	#	Quartz, muscovite, biotite, amphibole, garnet	Yes	290°/ 75° NE	38.3
7	Mafic gneiss	65 % (n=2)	Quartz, feldspar, biotite, amphibole, garnet	Yes	320° / 85° NE	**
8	Mafic gneiss	55 % (n=2)	Quartz, biotite, amphibole, garnet	Yes	314° / *	**
9	Mafic gneiss	80 % (n=1)	Quartz, garnet, feldspar, amphibole, biotite	Yes	320° / *	**
10	Mafic gneiss	#	Quartz, biotite, garnet	Yes	350° / *	**
11	Mafic gneiss	#	Quartz, garnet, feldspar, biotite	Yes	348° / *	24.6
12	Mafic gneiss	#	Quartz, biotite, garnet	Yes	328° / *	21.9
13	Mafic gneiss	60 % (n=2)	Quartz, garnet, feldspar, biotite, amphibole	Yes	320° / 68° NE	**
14	Mafic gneiss	70 % (n=1)	Quartz, biotite, amphibole, garnet	Yes	312° / *	**
15	Mafic gneiss	60 % (n=1)	Quartz, garnet, feldspar, amphibole, biotite	Yes	320° / 66° NE	**

TABLE 4: GEOLOGY OF CRAG AND TAILS (# = NO DATA AVAILABLE, * = FOLIATION NOT OR PARTIALLY MEASURABLE, ** = NO JOINTS VISIBLE OR MEASURABLE)

Crag and tail	Rock type of head	Relative abundance of mafic vs. felsic minerals in gneissose rocks	Mineral composition	Foliation	Foliation orientation (Strike / dip)	Average joint spacing (cm)
1 (Cnoc na Mòine)	Felsic gneiss	14 % (n=5)	Quartz, feldspar, biotite, garnet	Yes	310° / 85° NE	17
2	Felsic gneiss	14 % (n=4)	Quartz, feldspar, biotite, amphibole, garnet	Yes	325° / 85° NE	16.4
3	Felsic gneiss	#	Quartz, biotite, garnet	Yes	*	18.1
4	Felsic gneiss	#	Quartz, biotite, garnet	Yes	315° / 70° NE	9.3
5	Felsic gneiss	#	Quartz, feldspar, biotite, garnet, muscovite(?)	Yes	320° / 75° NE	12.6
6	Serpentinite	No gneissose bedrock	Serpentinite	*	-	**
7	Felsic gneiss	#	Quartz, feldspar, biotite, muscovite, garnet	No	315° / *	15.1
8	Felsic gneiss	20 % (n=1)	Quartz, K-feldspar, biotite, muscovite, garnet	Yes	10° / 75° NW	16.9
9	Felsic gneiss	2 % (n=1)	Large quartz veins, biotite, garnet	No	-	**
10	Felsic gneiss	#	Quartz, biotite, garnet, K-feldspar	Yes	290° / 65° NE	13.7
11	Felsic gneiss / schist	#	Quartz, K-feldspar, biotite, garnet	Yes	335 / 65 ° ENE	12.5
12	Felsic gneiss	31 % (n=2)	Quartz, biotite, garnet, K-feldspar, amphibole	Yes	345°/ 65° ENE	15.4
13	Felsic gneiss / schist	20 % (n=1)	Quartz, plagioclase, biotite, garnet	Yes	320° / 75° NE	18.9
14	Felsic gneiss	10 % (n=1)	Quartz, plagioclase, biotite, garnet	Yes	315° / 62° NNE	15.6
15	Felsic gneiss	#	Quartz, K-feldspar, biotite, garnet	Yes	*	20.7
16	Serpentinite	No gneissose bedrock	Serpentinite	Yes	300° / *	12.8
17	Serpentinite	No gneissose bedrock	Serpentinite	*	-	12.9
18	Felsic gneiss	#	Quartz, K-feldspar, biotite	Yes	320° / 60° NE	10.3
19	Felsic gneiss	10 % (n=2)	Quartz, K-feldspar, biotite, garnet	Yes	320° / 75° NE	12.4
20	Felsic gneiss	#	Quartz, feldspar, garnet, biotite,	Yes	320° / 65° ENE	13.6

4.2.1 Foliation

Most examined landforms are moulded in foliated bedrock, in which the foliation strike could be measured. But due to features obscuring the rock, such as lichen and vegetation it was not always possible to measure the dip of the foliation.

All 15 rôches moutonnées were made of a foliated bedrock. The mean of the strike of this foliation is 317°, with a standard deviation of 17°. The lowest strike that was measured was 290°, the highest was 350°. For only 7 out of 15 rôches moutonnées it was possible to measure the dip of the foliation. The mean angle of the dip was 71°, with a standard deviation of 9°. The dips ranged from 58° to 85°, all of them in a north-eastern direction.

For the crags, only 15 out of 20 examined landforms were made of a bedrock of which the strike of the foliation can be measured. Most examined crags that are not foliated or of which the foliation is not measurable are shaped out of serpentinite, which only shows very weak foliation. The other, gneissose, landforms showed stronger foliation. The foliation of the crags has an average strike of 321°, with a standard deviation of 18°. The strike ranges from 290° to 10°. The mean of the 13 dip angles that could be taken on the crags is 71°, with a standard deviation of 8°. The dips vary from 65° to 85°, all roughly towards the northeast.

When comparing the measurements of the landforms, it is clear that the foliation is very similar, even though multiple rock types are involved. The mean strike of the foliation on the rôches moutonnées (317°) only differs 4° with the mean strike of the foliation on the crags (321°). The mean dip of the foliation of the two groups of landforms is exactly the same: 71°, dipping towards the northeast.

4.2.2 Joint spacing

The crag and tails in the study area seem to be more jointed than the rôches moutonnées. On only 6 out of the 15 examined rôches moutonnées sufficient joint spacing measurements could be taken. For the crag and tails this was possible on 18 of the 20 studied landforms.

The rocks on the crags have an average joint spacing of 14.7 cm, the rôches moutonnées have an average joint spacing of 22.4 cm. The joint spacing of the crags also has a smaller range (minimum of 9.3 cm, maximum of 20.7 cm, standard deviation of 2.9 cm), where the joint spacing on the rôches moutonnées has a wider focus (minimum of 8.3 cm, maximum 38.3 cm, standard deviation of 9.3 cm).

4.2.3 Mineral composition

The mineral compositions of the rôches moutonnées and the gneissose crag and tails are very similar, though the mineral ratio differs. Most landforms are made of rock which contains quartz, feldspar, amphiboles, micas, and garnet. The rock making up the rôches moutonnées contains relatively more mafic minerals, while the crag and tails by comparison contain more felsic minerals. For 60 % of the rôches moutonnées (9 out of 15) and 47 % of the crag and tails (8 out of 17) it was possible to assess the relative abundance of mafic over felsic minerals. On average, the bedrock of the rôches moutonnées has a composition with 64 % mafic minerals (mainly biotite and some amphibole), while the bedrock of the crags only contains 15 % mafic minerals.

Figure 7 shows a sample of the mineral composition of the felsic gneisses at crag and tail 12 (British National Grid 249401 832958), and crag and tail 13 (National Grid: 248893 832327). Figure 8 shows an example of what this study calls a mafic gneiss: the mineral composition of a rock sample taken at rôche moutonnée 7 (National Grid: 248916 832167).

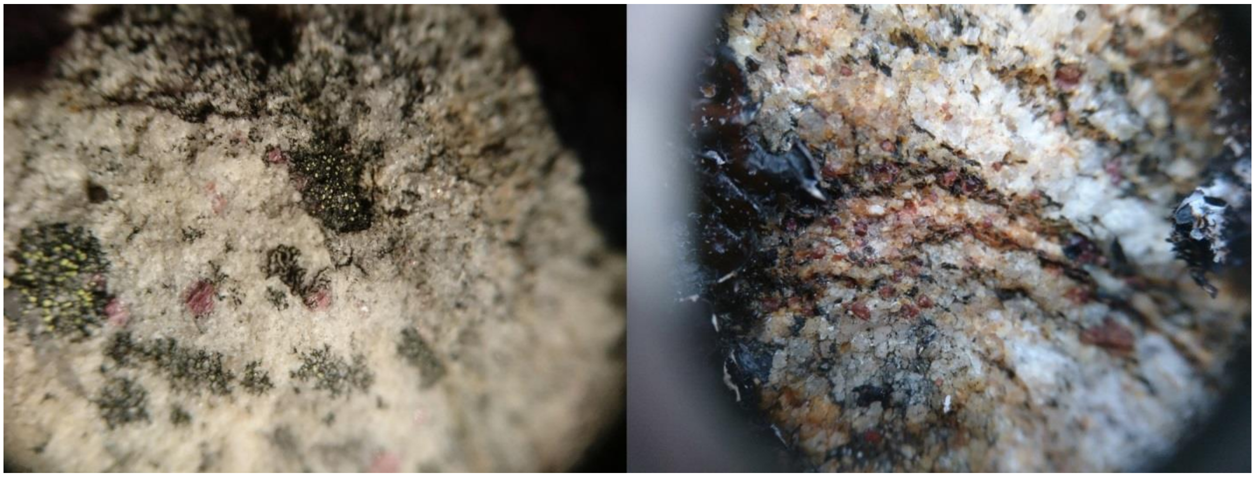

FIGURE 7: PHOTOS OF 2 CM SECTIONS OF BEDROCK TO SHOW MINERAL COMPOSITION OF CRAG AND TAIL 12 (LEFT) AND CRAG AND TAIL 13 (RIGHT). SEVERAL MINERALS CLEARLY CAN BE SEEN, SUCH AS QUARTZ, BIOTITE, AND GARNET. THE SEGMENT OF CRAG AND TAIL 12 SHOWS PREDOMINANTLY FELSIC MINERALS. IT CONTAINS MOSTLY QUARTZ, K-FELDSPAR AND SOME GARNET PORPHYROBLASTS. MOST DARK SPOTS ARE LICHEN. IN THE FRAGMENT OF CRAG AND TAIL 13, SMALL BANDS OF BIOTITE CAN BE SEEN, WITH LARGER BANDS OF QUARTZ AND PLAGIOCLASE. THERE ARE ALSO SOME GARNETS, MOSTLY CLOSE TO THE MAFIC BANDS. PHOTOS: BEN JONKMAN

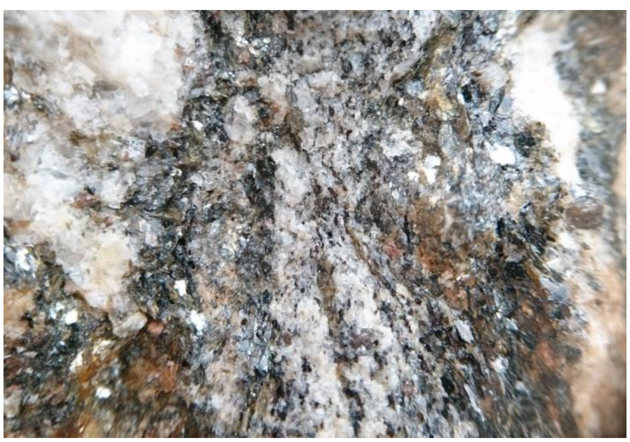

FIGURE 8: A 2 CM SEGMENT OF A ROCK SAMPLE TAKEN AT RÔCHE MOUTONNÉE 7 (NATIONAL GRID: 248916 832167) TO SHOW MINERAL COMPOSITION. BIOTITE IS THE DOMINANT MINERAL, WITH SOME BANDS OF QUARTZ AND K-FELDSPAR, AND HERE AND THERE GARNET. PHOTO: BEN JONKMAN

This difference in felsic and mafic gneiss can also be seen in the colour of the bedrock of the landforms. Figure 9 shows the bedrock surfaces on several landforms. Photos 3, 4, and 5 are taken on rôches moutonnées, 6, 7, and 8 on crag and tails. The bedrock of the rôches moutonnées contains more dark layers, indicating a higher content of mafic minerals, while the crag and tails are lighter because of a relative abundance in felsic minerals.

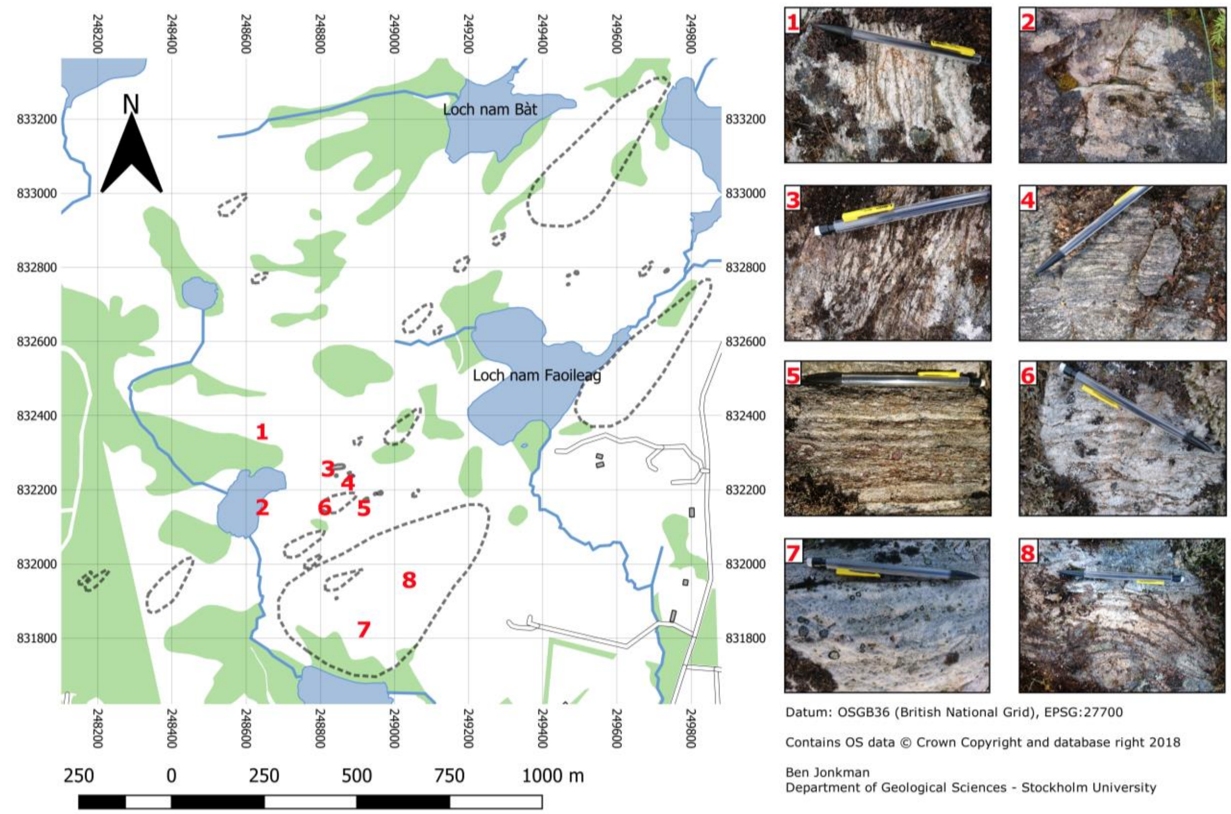

FIGURE 9: PHOTOS SHOWING THE BEDROCK AT CERTAIN LOCATIONS IN THE STUDY AREA. PHOTOS 1, 6, 7, AND 8 SHOW FELSIC GNEISS. PHOTOS 3, 4, AND 5 SHOW MAFIC GNEISS. PHOTO 2 SHOWS METALIMESTONE. THE PENCIL HAS A LENGTH OF 15 CM. (PHOTOGRAPHY: BEN JONKMAN. MAP CONTAINS OS DATA ©CROWN COPYRIGHT AND DATABASE RIGHT 2018)

As shown in Figure 3, the study area contains a sizeable band of (meta)limestone. This rock type appears not to favour glacial bedrock shaping, since neither crag and tail nor rôche moutonnée has been shaped out of (meta)limestone.

4.2.4 Serpentinite erratics

In this study serpentinite erratics in the study area also were mapped. These erratics are shown in Figure 10, as well as serpentinite crag and tails, and the area of which the bedrock is serpentinite according to Rock et al. (1986, p. 180).

As can be seen in Figures 9 and 10, the serpentinite crag and tails are oriented in the same direction (SW-NE), which is similar to the orientation of other crag and tails. The serpentinite erratics can be found in centre of the study area. The source bedrock of these erratics is west and southwest of the erratic distribution. This suggests erratic transport is consistent with the landform orientation.

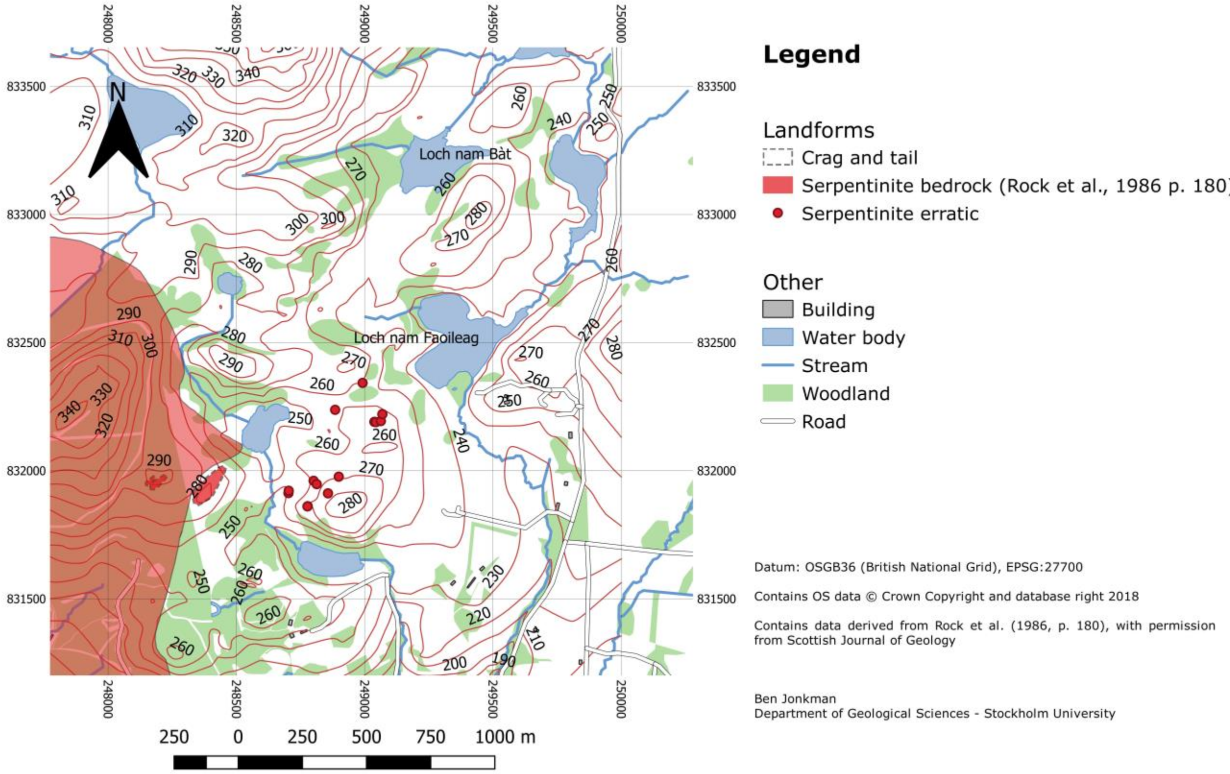

FIGURE 10: A MAP SHOWING MAPPED SERPENTINITE LANDFORMS AND ERRATICS (CONTAINS OS DATA ©CROWN COPYRIGHT AND DATABASE RIGHT 2018, SERPENTINITE BEDROCK REDRAWN AFTER ROCK ET AL., 1986, P. 180. USED WITH PERMISSION FROM SCOTTISH JOURNAL OF GEOLOGY)

TABLE 5: SIZE OF SERPENTINITE ERRATICS

Location of erratic on British National Grid	Size (cm)	Notes
248778 831862	68 x 35 x 45	
248777 831861	-	Three serpentinite rocks, but probably originally one, which broke in parts. The estimated original rock size is 90 x 45. Depth is unsure.
248801 831961	27 x 20 x 15	
248703 831913	23 x 16 x ??	Difficult to measure size because of vegetation
248704 831922	33 x 26 x ??	Difficult to measure size because of vegetation
249038 832191	56 x 38 x ??	Difficult to measure size because of vegetation
249044 832190	43 x 41 x 14	
249063 832194	40 x 100 x 14	
249069 832221	45 x 30 x 15	
248899 831977	66 x 27 x ??	On tail of crag and tail 13
248857 831912	18 x 24 x 25	Near head of crag and tail 3, next to the head of Cnoc na Mòine
248813 831948	32 x 28 x 28	
248992 832343	90 x 80 x 45	
248873 832250	40 x 30 x 25	

4.3 Map

The geological and geomorphological data collected in this study are summarised in Figure 11.

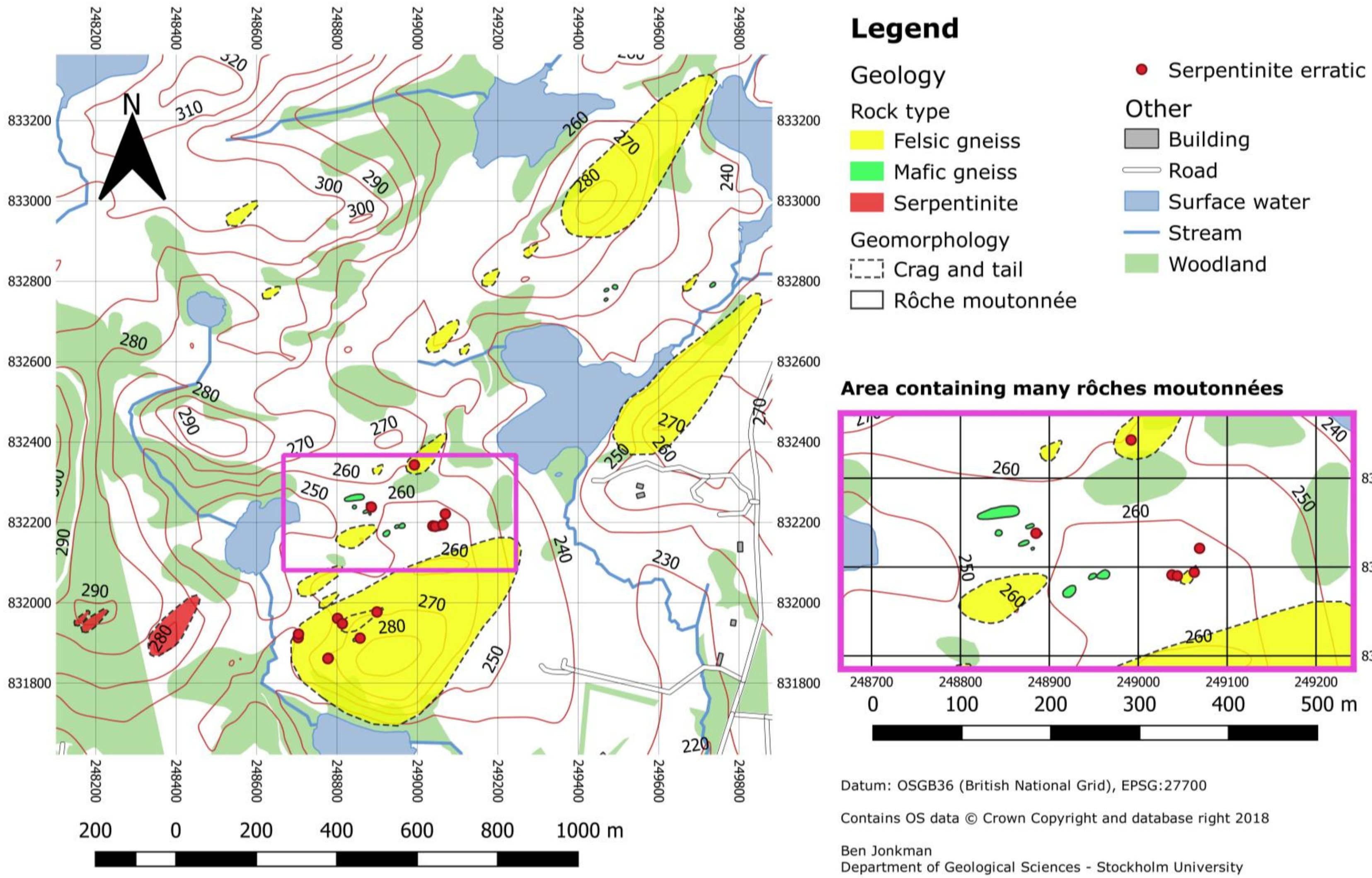

FIGURE 11: GEOMORPHOLOGICAL MAP OF THE STUDY AREA (CONTAINS OS DATA ©CROWN COPYRIGHT AND DATABASE RIGHT 2018)

5 Discussion

5.1 Summary of landform properties

There is a wide range of subglacial erosional landforms. Which type of landform is formed, depends on several factors. Many studies highlight glaciological controls, such as the thickness of the ice, the subglacial meltwater pressure, the thermal regime, and the ice flow velocity (e.g. Gordon, 1981; Hallet, 1996; Glasser and Bennett, 2004; Phillips et al., 2010; Krabbendam and Bradwell, 2011; Krabbendam and Glasser, 2011). In this study I explored the extent to which bedrock properties determine the landform morphology after glaciation. I did so by comparing several geomorphological, geological and lithological properties of rôches moutonnées and crag and tails in a study area in Scotland. Two main character components could be of significance for the formation of different subglacial erosional landforms: the size of the obstacle and the geology of the obstacle.

All studied landforms have a similar orientation, roughly towards the northeast. When looking at their size and shape, some differences can be found between the two types of landform. The studied rôches moutonnées are smaller, slightly rounder and, relative to their length, taller than the studied crag and tails. Because I do not know the preglacial size of the obstacles out of which the landforms were shaped, I cannot assess if there is a relationship between the preglacial height of the obstacle and which landform was formed. However, because there are rôches moutonnées positioned on the stoss side of crag and tails in the study area (e.g. Figure 6), I interpret that the preglacial obstacle height is not the only property controlling subglacial erosion. Otherwise a crag and tail and a rôche moutonnée could not be found at the same location.

In terms of geology there are also several differences and similarities between the two landform types. In the study area, rôches moutonnées are limited to one rock type: mafic gneiss. The crag and tails have been shaped out of felsic gneiss and serpentinite rocks. No crag and tails or rôches moutonnées formed in the metalimestone. The studied crag and tails have denser jointing than the rôches moutonnées. Foliation is similar in both types of landform. These geological properties are discussed in more detail below.

5.2 Geology

5.2.1 Jointing

Joints represent a weakness in the structure of rocks. Several studies have shown that this weakness can have an important effect on glacial erosion. Jointed rocks favour plucking over abrasion, since they are broken up more easily by the ice (e.g. Matthes, 1930; Dühnforth et al., 2010; Krabbendam and Glasser, 2011). I found that different types of landform show different levels of jointing. In the study area, the stoss sides of the crag and tails (i.e. the crags) are more heavily jointed than the stoss sides of rôches moutonnées. So, the steep, plucked crags contain a higher density of joints than the sloping, abraded rôches moutonnées.

When looking at joint spacing as a control for subglacial erosion, the joints themselves could cause an uncertainty. For the joints to be of importance as a control of glacial erosion, they must have been present before glaciation. But some joints could have formed by pressure release after the last glaciation in Britain, which would mean they would not have played any part in the subglacial erosion. The joints used in this study were not dated, so some might have been postglacial.

Jointing appears to be a control of landform type: rocks with many joints have been plucked - resulting in crag and tails, less jointed rocks have been abraded and shaped into rôches moutonnées.

5.2.2 Mineralogy

All rôches moutonnées have the same bedrock (gneiss), while the crags are moulded out of multiple rock types (gneiss and serpentinite). When comparing the mineral composition of the gneisses, a difference in mineralogy is revealed. The rôches moutonnées consist of a gneiss with relatively high proportion of mafic minerals, while the gneissose rocks of the crags contain more felsic minerals. The most dominant mafic mineral is biotite, with minor amphibole. The dominant felsic minerals are quartz, plagioclase and K-feldspar. As shown in Table 6, the mafic minerals, specifically biotite, are relatively soft minerals, while the felsic minerals are harder.

Table 6: Hardness of minerals in gneissose rocks. Left columns are for (ultra)mafic minerals, right columns for felsic minerals (Klein and Philpotts, 2013; A Skelton, 2019, personal communication, 15 June)

Mineral	Mohs hardness		Mineral	Mohs hardness
Biotite	2.5-3		Quartz	7
Amphibole	5-6		Plagioclase	6
Serpentine	2-5		K-feldspar	6

Because the mafic gneisses in the study area, when looking at the mafic minerals, mostly contain biotite and not much amphibole, which is harder, and the felsic gneissose rocks are richer in quartz and feldspars, it is likely that the mafic gneisses are softer than the felsic gneisses. This would mean that the rôches moutonnées are formed out of rock that is softer than the gneissose rock of which the crags are formed. This suggests that softer rocks favour abrasion as an erosional mechanism, resulting in the formation of rôches moutonnées, and harder rocks favour plucking, creating crag and tails.

In the study area, several crag and tails are shaped out of serpentinite, while no serpentinite rôches moutonnées were found. Because the hardness of the serpentinite in the study area is unknown, it cannot be tested whether this is caused by the hardness of the rocks. Serpentine minerals, of which serpentinite mostly is composed, have a broad hardness range: 2 to 5 on Mohs scale of mineral hardness. This makes it hard to make a precise and accurate estimate of the hardness of the serpentinite rocks in the study area. Without knowing the exact hardness of the serpentinite, it is not possible to compare the hardness of the serpentinite crag and tails to the hardness of other examined landforms. Because the felsic gneiss mostly consists of minerals which are harder than serpentine minerals, it is probably harder than the serpentinite. But how the mafic gneiss relates to the serpentinite is unclear. It would be interesting to measure the hardness of the serpentinite in the study area in a future study, so it becomes possible to make these comparisons.

Mineral composition of the bedrock seems to influence subglacial erosion and the formation of subglacial landforms. The gneissose rôche moutonnées in the study area seem to be shaped out of a softer, more mafic gneiss than the gneissose crag and tails. When looking at hardness, the serpentinite rocks cannot be taken into comparison, because their hardness is unknown.

5.2.3 Chemical weathering

The softness of the rocks is not necessarily the only mineralogical aspect in the formation of glacial landforms. Chemical weathering could also play a part. This has not been studied during field work, but it is known to be an important geomorphological process in periglacial environments (e.g. Rea and Whalley, 1996; Matthews and Owen, 2011).

Serpentinite is very susceptible to chemical weathering (e.g. Cleaves et al., 1974). No serpentinite rôches moutonnées were found in the study area, only crag and tails. It therefore appears that for serpentinite rocks, chemical weathering does not favour abrasion as an erosion mechanism nor the formation of rôches moutonnées.

Nicholson (2008) states that the mineralogical composition of bedrock is a very important factor for controlling the rate of postglacial microweathering, especially the relative ratio of quartz, which is a felsic mineral, and the mafic mineral amphibolite. According to Nicholson (2008) rocks with a high proportion of quartz are less susceptible to denudation and weakening, whereas rocks with relatively high amphibolite levels are most susceptible. Biotite is also relatively susceptible to chemical weathering and its vulnerability to water could make glacial sliding and abrasion more likely, because of the meltwater under the warm-based ice sheet. This in turn could favour the development of rôches moutonnées. However, according to White et al. (1999), the weathering rate of biotite is significantly lower at 0 °C than at 20 °C. Aside from this, since weathering in pre- and postglacial environments occurs at rates of several mm ka^{-1} (Nicholson, 2008; Matthews and Owen, 2011), it is not probable that these rates are very different for subglacial chemical weathering. This suggests that these rocks have not been deeply weathered during glaciation. Even so, the weakening of the rock due to chemical weathering could better prime the rock for glacial erosion and thus have consequences for the method of erosion. In the study area the mafic gneissose rocks have been abraded more than the felsic gneissose rocks. This could be because of the difference in rock hardness, but based on the mineral composition of the rocks chemical weathering could also have been important.

Whether chemical weathering plays a part in the formation of different types of glacial landforms remains unclear. For serpentinite rocks it appears not to favour abrasion, but for gneissose rocks it could do so.

5.2.4 Foliation

In terms of foliation the crag and tails and the rôches moutonnées are very similar. Even though multiple rock types are involved, the mean foliation strike of the bedrock of which the landforms are shaped only differs by 4°.

Since the foliation is similar in both types of landform, foliation appears not to have much influence on their morphology.

5.2.5 Landform orientation

Most subglacial landforms in the study area are oriented in the same direction (southwest-northeast). The examined rôches moutonnées have a mean landform orientation towards 51.2°, and the crag and tails towards 50.3°. This similar orientation suggests that in the study area, the ice flowed stably towards the northeast while it was in an erosive mode. This suggested ice flow direction is supported by the distribution of serpentinite erratics in the study area (as shown in Figure 10). All erratics are positioned to the northeast of an area with serpentinite bedrock, according to a geological map by Rock et al. (1986, p. 180).

Because the rôches moutonnées and crag and tails share the same orientation, the ice flow direction does not seem to have influenced the subglacial erosion in the study area.

5.2.6 Comparative summary of the effects of jointing, mineralogy, chemical weathering, foliation, and landform orientation on landform type

Landform type appears to be dictated by jointing and mineral composition and the resulting hardness. Foliation seems to be of no significance. It is unclear if and how chemical weathering is a control for the formation of subglacial erosional landforms.

The findings in this study about the jointing and the hardness of the rocks are in line with other studies (e.g. Glasser et al., 1998; Krabbendam and Glasser, 2011), which associate poorly jointed and softer rocks with abrasion as the most dominant glacial erosion mechanism and hard, densely jointed rocks with plucking. This fits with the formation methods of the two studied types of landform: rôches moutonnées have an abraded stoss side, while crag and tails have a plucked stoss side. However, the rock types about which the mentioned papers reached their conclusions are different than the rock types in the study area for this project: gneiss and serpentinite. Glasser et al. (1998) compared marble, schists and sandstone, Krabbendam and Glasser (2011) studied sandstone and quartzite. Glasser et al. (1998) noticed differences between the softer marble on the one hand and harder schists and sandstone on the other hand. Krabbendam and Glasser (2011) compared the softer sandstone with the harder quartzite. Even though the examined rock types in these studies are different than the ones in this study, the principles are nevertheless the same.

An interesting connection between foliation and landform orientation stands out in this study. Assuming that the crag and tails and rôches moutonnées are oriented parallel to the direction of the erosional ice flow, this would mean that the ice flow direction is more or less perpendicular to the strike of the foliation of the bedrock of the landforms (317° for the rôches moutonnées and 321° for the crag and tails). This suggests that the foliation strike might have helped the general development of landforms with a southwest-northeast orientation, as opposed to any other ice flow direction in the ice sheet’s history.

5.3 Superimposed landforms

An important observation is that the largest crag and tail in the study area, crag and tail 1 (Cnoc na Mòine), has smaller subglacial erosional landforms on top of it. These are similarly oriented as the main landform, but sometimes of differing morphologies (e.g. rôche moutonnée 15 and crag and tail 3).

This phenomenon of one type of landform piggybacking on another supports the theory that the cause of the formation of different types of landform in the study area cannot be found in spatial differences in the ice flow, but in local differences in the geology. In the case of rôche moutonnée 15 and crag and tail 1, this study shows that the gneiss of which the rôche moutonnée is formed has an abundance in mafic minerals (60 %, n=1), while the gneiss of the crag and tail on average only has 14% mafic minerals (n=5) and is mostly composed of harder felsic minerals. The rôche moutonnée appears to have been moulded out of a small section of mafic gneiss which is surrounded by gneisses that are richer in felsic minerals.

Another explanation for landforms being positioned on another landform, could be that the underlying landforms have been shaped in a different period of glaciation than the landforms on top of them. The data collected in this study cannot eliminate that possibility. Future studies could try to do this, perhaps by using cosmogenic nuclide dating.

6 Conclusions

Several bedrock properties influence the type of subglacial erosion and therefore bedform shaping. I find that one of these properties is jointing in the bedrock. Wider joint spacing appears to lead to landforms with an abraded stoss side, such as rôches moutonnées, while closer jointed bedrock can cause the formation of landforms with a plucked stoss side, such as crag and tails.

Mineralogy of the bedrock is also an important factor when looking at subglacial erosion. Softer rocks lead to more abrasion, harder rocks lead to more plucking. Abrasion and plucking shape the bedrock differently, which results in the creation of different landforms. It is important to note that soft and hard in this study relate to the relative proportions of mafic and felsic minerals in the rocks. In the study area, rôches moutonnées were formed in areas with biotite rich rocks. At locations with harder, more felsic rocks or serpentinite, no rôches moutonnées could be found, only crag and tails. Whether chemical weathering of bedrock is a control for subglacial erosion, remains unclear.

Since crag and tails as well as rôches moutonnées have been moulded out of bedrock with a similar foliation orientation, in this area the foliation does not appear to be a control of subglacial erosion.

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References

Boulton G.S., 1982. Processes and Patterns of Glacial Erosion. *In* Coates D.R., (ed.), *Glacial Geomorphology*. Springer, Dordrecht, pp. 41-87

Bradwell, T., Stoker, M.S., Golledge, N.R., Wilson, C.K., Merritt, J.W., Long, D., Everest, J.D., Hestvik, O.B., Stevenson, A.G., Hubbard, A.L., Finlayson, A.G., and Mathers, H.E., 2008. The northern sector of the last British Ice Sheet: Maximum extent and demise. *Earth-Science Reviews*, v. 88, pp. 207-226. doi:10.1016/j.earscirev.2008.01.008

Brook, M., and Rock, N.M.S., 1983. Caledonian ages for pegmatites from the Glen Urquhart serpentinite-metamorphic complex, Inverness-shire. *Scottish Journal of Geology*, v. 19 (3), pp. 327-332. doi:10.1144/sjg19030327

Clark, C.D., Hughes, A.L.C., Greenwood, S.L., Jordan, C., and Sejrup, H.P., 2012. Pattern and timing of retreat of the last British-Irish Ice Sheet. *Quaternary Science Reviews*, v. 44, pp. 112-146. doi:10.1016/j.quascirev.2010.07.019

Cleaves, E.T., Fisher, D.W., and Bricker, O.P., 1974. Chemical weathering of serpentinite in the Eastern Piedmont of Maryland. *Geological Society of America Bulletin*, v. 85, pp. 437-444.

Dühnforth, M., Anderson, R.S., Ward, D., and Stock, G.M., 2010. Bedrock fracture control of glacial erosion processes and rates. *Geology*, v. 38(5), pp. 423-426. doi:10.1130/G30576.1

Evans, D.J.A., and Hansom, J.D., 1996. The Edinburgh Castle crag-and-tail. *Scottish Geographical Magazine*, v. 112-2, pp. 129-131. doi:10.1080/14702549608554461

Fretwell, P.T., Smith, D.E., and Harrisson, S., 2008. The Last Glacial Maximum British-Irish Ice Sheet: a reconstruction using digital terrain mapping. *Journal of Quaternary Science*, v. 23(3), pp. 241-248. doi:10.1002/jqs.1143

Glasser, N.F., and Bennett, M.R., 2004. Glacial erosional landforms: origins and significance for palaeoglaciology. *Progress in Physical Geography*, v. 28(1), pp. 43-75. doi:10.1191/0309133304pp401ra

Glasser, N.F., Crawford, K.R., Hambrey, M.J., Bennett, M.R., and Huddart, D., 1998. Lithological and structural controls on the surface wear characteristics of glaciated metamorphic bedrock surfaces: Ossian Sarsfjellet, Svalbard. *The Journal of Geology*, v. 106, pp. 319-329. doi:10.1086/516025

Gordon, J.E., 1981. Ice-scoured topography and its relationships to bedrock structure and ice movement in parts of Northern Scotland and West Greenland. *Geografiska Annaler. Series A, Physical Geography*, v. 63(1), pp. 55-65. doi:10.2307/520564

Hallet, B., 1979. A theoretical model of glacial abrasion. *Journal of Glaciology*, v. 23-89, pp. 39-50. doi:10.1017/S0022143000029725

Hallet, B., 1996. Glacial quarrying: a simple theoretical model. *Annals of Glaciology*, v. 22, pp. 1-8. doi:10.3189/1996AoG22-1-1-8

Huggett, R.J., 2011. *Fundamentals of Geomorphology* (3rd edition). Routledge, London, e-book, first accessed 22-12-2016, doi: 10.4324/9780203860083

Hughes, A.L.C., Clark, C.D., and Jordan, C.J., 2014. Flow-pattern evolution of the last British Ice Sheet. *Quaternary Science Reviews*, v. 89, pp. 148-168. doi:10.1016/j.quascirev.2014.02.002

Klein, C., and Philpotts, A, 2013. *Earth materials: introduction to mineralogy and petrology*. Cambridge University Press, New York,

Krabbendam, M., and Bradwell, T., 2011. Lateral plucking as a mechanism for elongate erosional glacial bedforms: explaining megagrooves in Britain and Canada. *Earth Surface Processes and Landforms*, v. 36, pp. 1335-1349. doi:10.1002/esp.2157

Krabbendam, M., and Glasser, N.F., 2011. Glacial erosion and bedrock properties in NW Scotland: Abrasion and plucking, hardness and joint spacing. *Geomorphology*, v. 130, pp. 374-383. doi:10.1016/j.geomorph.2011.04.022

Mäkelä, J., and Illmer, K., 1992. Refraction seismic soundings on three crag and tail ridges in Central Finland. *Bulletin of the Geological Society of Finland*, v. 64(1), pp. 23-33. doi:10.17741/bgsf/64.1.003

Matthes, F.E., 1930. Geologic History of the Yosemite Valley. *In: Geological Survey Professional Paper, 160*. U.S. Geological Survey, Washington, pp. 54-103.

Matthews, J.A., and Owen, G., 2011. Holocene chemical weathering, surface lowering and rock weakening rates on glacially eroded bedrock surfaces in an alpine periglacial environment, Jotunheimen, Southern Norway. *Permafrost and Periglacial Processes*, v. 22, pp. 279-290. doi:10.1002/ppp.697

Nicholson, D.T., 2008. Rock control on microweathering of bedrock surfaces in a periglacial environment. *Geomorphology*, v. 101(4), pp. 655-665. doi:10.1016/j.geomorph.2008.03.009

Oberhuber, W., Pagitz, K., and Nicolussi, K., 1997. Subalpine tree growth on serpentine soil: a dendroecological analysis. *Plant Ecology*, v. 130, pp. 213-221. doi:10.1023/A:1009740106732

Phillips, E., Everest, J., and Diaz-Doce, D., 2010. Bedrock controls on subglacial landform distribution and geomorphological processes: Evidence from the Late Devensian Irish Sea Ice Stream. *Sedimentary Geology*, v. 232(3-4), pp. 98-118. doi:10.1016/j.sedgeo.2009.11.004

Rea, B.R., and Whalley, W.B., 1996. The role of bedrock topography, structure, ice dynamics and preglacial weathering in controlling subglacial erosion beneath a high-latitude, maritime ice field. *Annals of Glaciology*, v. 22, pp. 121-125. doi:10.3189/1996AoG22-1-121-125

Roberts, B.A., and Proctor, J., 1992. *The Ecology of Areas with Serpentinized Rocks: A World View*. Kluwer Academic Publishers, Dordrecht, e-book, first accessed on 1-4-2019.

Rock, N.M.S., Macdonald, R., Drewery, S.E., Pankhurst, R.J., and Brook, M., 1986. Pelites of the Glen Urquhart serpentinite-metamorphic complex, west of Loch Ness (Anomalous local limestone-pelite successions within the Moine outcrop: III). *Scottish Journal of Geology*, v. 22(2), pp. 179-202. doi:10.1144/sjg22020179

Röthlisberger, H., and Iken, A., 1981. Plucking as an effect of water-pressure variations at the glacier bed. *Annals of Glaciology*, v. 2, pp. 57-62. doi:10.3189/172756481794352144

Specht, A., Forth, F., and Steenbeeke, G., 2001. The effect of serpentine on vegetation structure, composition and endemism in northern New South Wales, Australia. *South African Journal of Science*, v. 97, pp. 521-529.

Turner, A.J., Woodward, J., Stokes, C.R., Ó Cofaigh, C., and Dunning, S., 2014. Glacial geomorphology of the Great Glen Region of Scotland. *Journal of Maps*, v. 10(1), pp. 159-178. doi:10.1080/17445647.2013.866369

White, A.F., Blum, A.E., Bullen, T.D., Vivit, D.V., Schulz, M., and Fitzpatrick, J., 1999. The effect of temperature on experimental and natural chemical weathering rates of granitoid rocks. *Geochimica et Cosmochimica Acta*, v. 63(19/20), pp. 3277–3291