Unloading joints and rockfalls in Norway's fiordlands

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When overburden is removed by erosion, rock relaxes towards the surface and develops new fractures. These are then the focus of slope failures that are common and sometimes disastrous in Norway's mountain regions.

Unloading joints could well qualify as the geological structures that are least known in proportion to their true importance. They are often lost behind a welter of alternative names – dilatation joints, stress relief fractures, relaxation joints, exfoliation or sheeting – and rarely win more than a couple of short sentences in a textbook of geology or geomorphology. Yet in Norway there are large multilanguage roadside boards explaining them to passing tourists.

When rock is buried deeply within the ground, it is subjected to enormous compressive stresses. It is squeezed tight; fractures, joints and fissures cannot open up, and the rock itself is very slightly reduced in volume (even granite can be compressed if enough stress is applied). Horizontal compression derives from plate movements, and these tectonic stresses change very slowly. But vertical stress is largely due to overburden – the sheer weight of other rocks above – and this burial stress is reduced by erosion and denudation. When surface lowering exposes a rock at the surface, it is no longer confined on that side; it expands towards its unconfined face. Relieved of stress, the rock relaxes (the analogy to human behaviour is not unreal), and it dilates in response to the unloading (hence the multiple terminology). A soft, plastic clay simply expands and swells, but a strong, brittle rock also develops cracks that open into fissures, broadly parallel to the unconfined face. These are the unloading joints that are so significant to the strength or weakness of near-surface rock

Fig. 1. A borehole core (40 mm diameter) of highly stressed gneiss extracted from great depth in Namibia. It has deformed from its original perfect cylinder as a result of uneven relaxation since being unloaded by being brought to the surface.

Unloading processes

Rock relaxation is a measurable process. When information is needed for tunnel design, engineers can cut slots into rock and physically measure the rate of closure as the destressed rock deforms towards the slot. Core from deep boreholes may be seen to expand and deform when it is brought to the surface (Fig. 1). New fractures develop in a rock when stresses reach about half the rock strength, but this is difficult to relate to the balance between confining horizontal stresses and the nil stress offered by the exposed surface. The effect is best seen in the natural weathering profile, where fracture densities increase towards the surface. At depths of more than about 25 m, confining pressures exceed the stresses of elastic expansion, and unloading joints cannot develop.

Many of the fractures in the weathering profile are initiated as unloading joints, although the dominant process is their subsequent enlargement by water pressure, frost action and root action. Perhaps even more important is the opening of pre-existing joints and bedding planes in response to the stress relief, so that water can reach in and continue the weathering process.

These weathering processes are all very slow, as time-scales are set by the rates of erosion. More rapid unloading is created by man's activities – engineering, quarrying and mining. A quarry face leaves rock unconfined in one horizontal direction, so the rock relaxes towards it. This creates or enlarges roughly vertical fractures that then become potential failure surfaces, and requires that faces above working areas are regularly cleaned. The process is most acute in vertically bedded rocks that splay and peel outwards into the quarry, in a process often known as springing. A greywacke quarry in the Yorkshire Dales has exposed walls in vertical slates (the unusable rock adjacent to the greywacke). Over a period of nearly 40 years, these slates have been seen to steadily peel away like the pages of a book, rotating from the vertical so that they now rest in a pile of nearly horizontal slabs (Fig. 2). Horizontal unloading joints have even been seen to develop in the floors of deep open excavations for the foundations of large dams, creating new fractures in rock that was sound when it was first exposed.

The excavation of a mine gallery creates instant

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stress reduction in one direction in the wall rocks, with maximum relaxation in the deeper mines where initial stresses are greatest. Clays and soft rocks squeeze in; so unsupported mine tunnels progressively close up. But stronger rocks develop unloading joints, followed by the spalling of slabs from mine walls. A morning routine in the potash mine 1000 m beneath the North Yorkshire Moors at Boulby is a check for any blocks of rock in the walls and roof that have broken loose overnight; these are then heaved down with long crow-bars before men start working beneath them. A rock burst is the same process on a grander scale in very strong rocks in very deep mines. The South African gold mines are 3000 m deep, where the rocks have such enormous in-built stress that they relax explosively. Pieces of rock can burst away from a mine wall with no warning, and have on occasions killed miners working beside an exposed face.

Fig. 2. An old face of a Yorkshire greywacke quarry, where unloaded slate has sprung outwards since horizontal stress was released. Slabs have further peeled away from the vertical by the combined action of water pressure, ice expansion and then gravity.

Fig. 3. Curved sheets of granite separated by unloading joints on the exfoliation dome of Half Dome in Yosemite Park, California. Scale is given by people on the cable ladder on the extreme left.

Unloading of slopes

While the relaxation of flat ground merely creates fractured and more easily weathered rock, the denudation of sloping ground creates unloading joints roughly parallel to the sloping surface, with significant consequences for the stability and evolution of the slope.

Perhaps the best-known effects of rock relaxation are the massive curved sheet joints of exfoliation that develop in exposed granite. Stress patterns are smoothed across initial surface irregularities, so that successive generations of unloading joints tend towards the rounded profiles seen in the huge exfoliation domes that are particularly famous in California's Yosemite Park. The domes are exposed as the unloaded sheets fall away, and the curved joints of the next failures are clearly seen at some sites (Fig. 3). Although this sheeting is a conspicuous feature of homogeneous granite, the process also occurs in other rocks but is masked by the patterns of existing structural weaknesses. It is, however, totally different from spheroidal weathering (which is a much smaller scale of chemical degradation where shells peel away in an onion-style owing to hydrolosis expansion of feldspars to clays, and not due to unloading).

In steeply sloping ground, any inclined fractures become potential slip surfaces for both small rockfalls and large landslides. Instability is greatest where denudation and unloading has been most rapid. Far more effective than steady, progressive denudation by rivers is glacial erosion followed by removal of the ice. The glaciation of a valley creates the characteristic U-shaped profile, where the sides are over-steepened beyond angles that are sustainable in a fluvial environment. The end of an ice age sees the loss of the ice, and hence the loss of the support that the glacier gave to its marginal rock walls. Furthermore, the newly unsupported walls are also de-stressed, so that steep unloading joints develop parallel to them. Glaciation is among the most rapid of natural processes that can create a steep slope, which consequently is likely to be unstable. Deglaciation landslides are a feature of many glaciated troughs in the basalt plateaux of Iceland, and unloading is contributory to the abundance of landslides in many of the deep Himalayan valleys. It is also very significant in the glaciated fiordlands of Norway – hence the roadside information boards.

Norway's rockfalls

Not only do the steep-sided valleys make the Norwegian landscapes so very spectacular, but they are also perfect sites for rockfalls. Over the past few centuries, an average of two or three people have died every

Fig. 4. A small rockfall on the Lofoten Islands, defined by unloading joints and contributing to the talus slope below.

year in Norway's rockfalls (and this does not include the 176 people who drowned in the waves created by the three largest falls). In recent times, the death rate has declined in the face of much careful and inspired engineered preventive measures, but it is still very difficult to predict the failure of a mountainside that does not have a record of previous failures.

It has to be admitted that any rock face in Norway's deglaciated valleys is a site of potential failure. This applies until it has degraded to an angle of less than about 40° or has become covered with a veneer of scree (at about the same angle). With typical slope

Fig. 5. The Skjelfjord rockfall on the Lofoten Islands, with the later road curving round the end of the debris flow run-out on the valley floor.

angles of 60° or more in the fiordlands and on the northern mountains, continuing slope degradation is the natural process, and the dominant mechanism is a succession of rockfalls. Most events are small, so that the fallen debris merely lands on the talus ramp at the foot of the face (Fig. 4). But larger events (involving over 250 000 tonnes, or 100 000 cubic metres, of falling rock) produce debris run-outs onto the valley floors (Fig. 5), and are fatal to anyone who happens to be in the wrong place at the wrong time.

There are recognizable rockfall seasons in Norway, where two-thirds of recorded events occur in March/April/May and October/November These are the two periods when freeze/thaw cycles occur daily, as opposed to almost continuous freezing or thaw in the winter and summer, respectively. This shows the importance of ice expansion by the freezing of joint water in finally triggering the rockfall event. The March to May season is also when meltwater from the winter snow raises joint water pressures to an annual maximum, and water pressure alone triggers many rockfalls. However both water pressure and ice expansion require pre-existing fractures in the rock, and these owe much of their initial opening to the stress relief of unloading in the exposed cliffs and slopes.

A very fine example of a larger rockfall can be seen at the head of Skjelfjord in the Lofoten Islands (Fig. 5), even though the event dates back a few hundred years and the debris is now partly covered by shrubs and bushes. The top of the head scar of the fall stands 600 m above the valley floor, and the debris run-out reaches 1400 m from the head. The rock is a relatively massive granite, and its fracturing by stress relief since the Pleistocene glacial unloading was a major factor in the failure of a shallow slice off the slope surface. This rockfall landed on dry ground on a watershed, but others have landed in valleys where the debris dams the river and creates a new lake. Such landslide-dammed lakes are common in Norway; Langstoylvatn was formed after a rockfall in the lovely Norangsdal (Fig. 6) in May 1905, and the remains of stone houses drowned by the new lake can

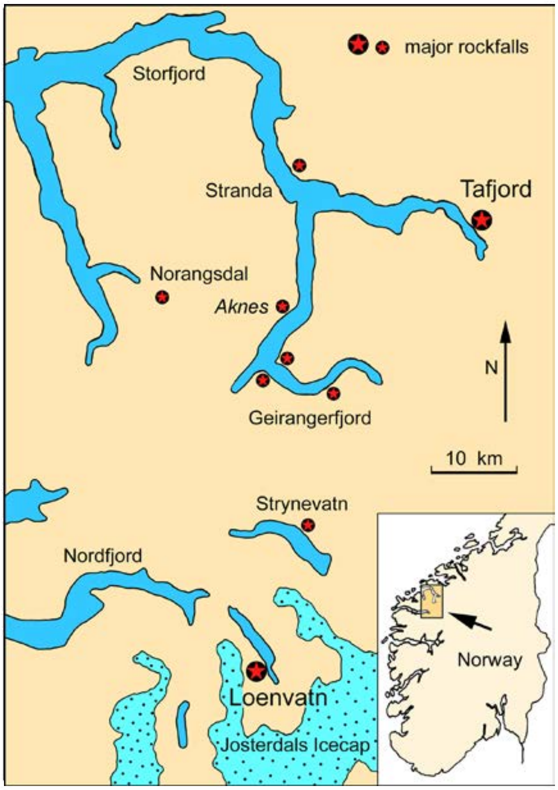

Fig. 6. Location map of some notable rockfalls in the Norwegian fiordlands around Geiranger.

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still be seen beneath the clear waters.

The most destructive rockfalls are those that land in the fiords and create massive waves. These waves carry along and across the fiords and run up any opposing slopes, especially the gentle ones, where farms and villages are sited, so that many more people are drowned than are buried by the initial rockfalls on steep, uninhabited slopes. A small area in the north of the western fiordlands, between Nordfjord and Storfjord (Fig. 6), has seen a series of catastrophic rockfalls in historical times. These include the rockfalls of Lovatn and Tafjord, where the features are still clearly visible to the geologically minded visitor. Three more rockfalls have fallen into the famous Geirangerfjord (Fig. 7 and front cover), but each involved less than 100 000 tonnes of rock and no lives were lost, although various fiord-side boathouses were washed away. Another into Storford in 1731 drowned 17 people when its wave hit Stranda on the opposite shore.

The most recent rockfall was a smaller event, also at Tafjord. About 30 000 tonnes of rock broke away and fell 300 m, fortunately landing harmlessly on a basal scree slope, and it demonstrated the roles of the critical structures in the failure of the cliff face (Fig. 8). Very steep unloading joints had developed within the outermost 10 m of the cliff; these do emerge to daylight towards the left, and appear to have followed pre-existing tectonic weaknesses. In plan view, the failure surface steps *en echelon* across these critical fractures. These joints also came to light in the receding crest of the cliff, so surface water could easily drain into them; the increasing water pressures (and perhaps ice expansion) then heaved the face slabs outwards. Minor cross-joints provided a break on the right-hand side of the failing slabs; the weathered faces show that these were already open. Foliation within the biotite gneiss dips across the face at about 30°, and provided some weaknesses that helped define the left-hand margin of the failed slabs. Fresh breaks across the unloaded slabs were the last sections to fail, releasing the complete rockfall. It was

Fig. 7. The precipitous walls of Geirangerfjord, with the scars of ancient rockfalls largely defined by unloading joints.

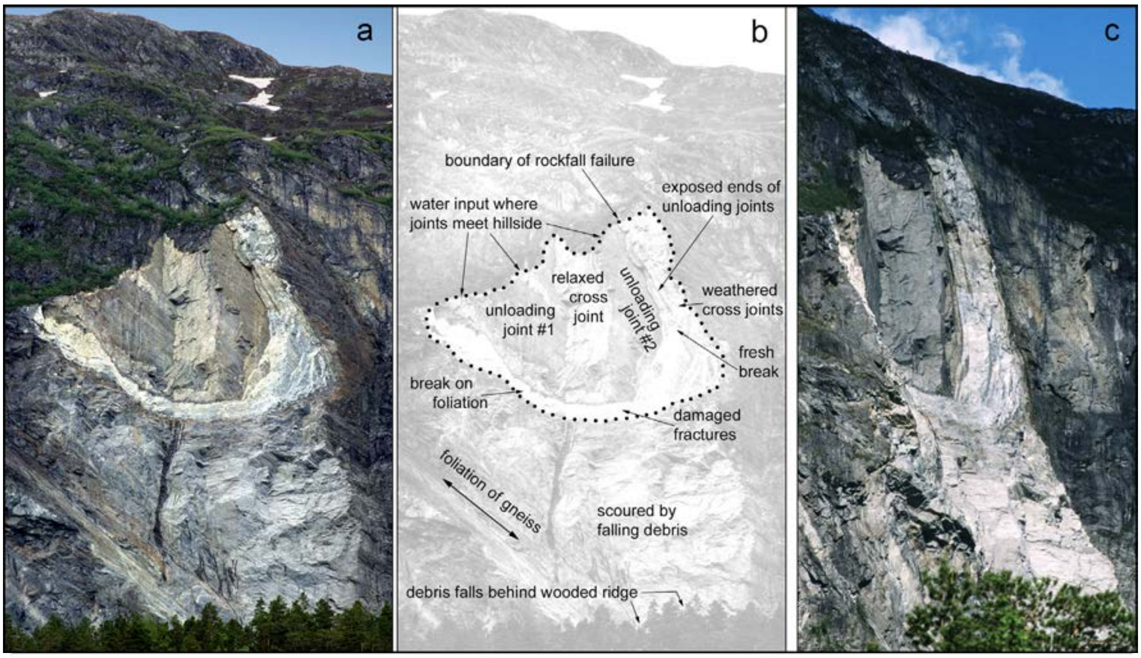

Fig. 8. The recent rockfall at the south end of Tafjord. The section of failed rock (a) is about 50 m high and wide at its maxima, and the rock structures are identified in (b); the oblique view (c) of the same failure shows the unloading joints in the adjacent rock that remains on the face.

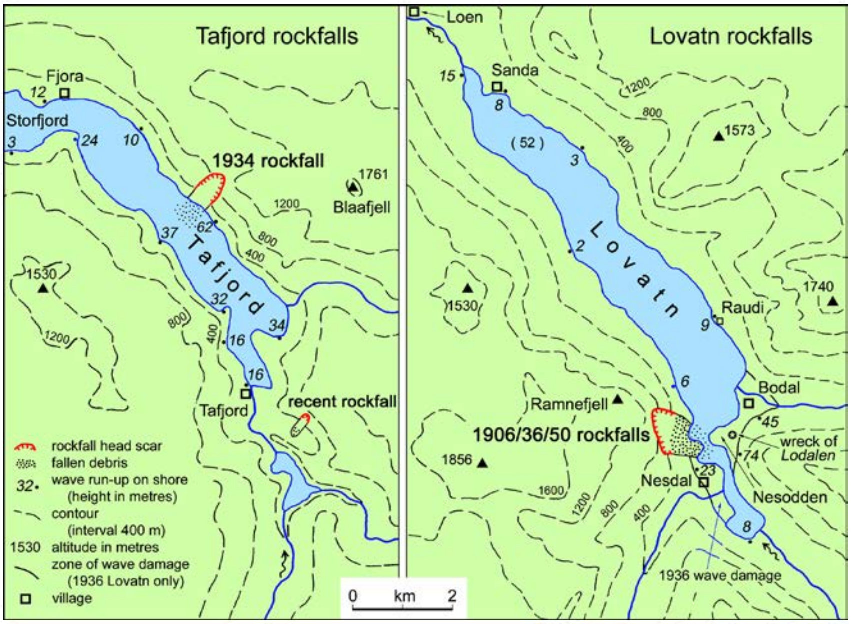

Fig. 9. Maps at the same scale of the rockfall sites at Tafjord and Lovatn, also showing the heights reached by the resultant waves when they ran up the shorelines.

only a small rockfall, but it was a classic demonstration of the role of unloading joints.

Rockfalls into Lovatn

Often known as Lake Loen, Lovatn lies just beyond the end of Nordfjord, with its surface 52 m above sea level (Fig. 6). The mountain of Ramnefjell rises to 1493 m on its western side (Fig. 9), with a truncated spur at its eastern end standing 1200 m above the lake (Fig. 10). This spur has produced a series of catastrophic rockfalls The main damage was caused when these landed in the lake, and waves destroyed buildings far from the failing cliff.

A rockfall in 1753 buried the Heiset farm at the foot of the face. Another, in 1885, one of a number in that century, created a wave that destroyed the Raudi farm on the far side of the lake. But these were followed by a succession of three giant rockfalls.

In January 1905, about 800 000 tonnes of rock fell from the face of Ramnefjell. The failed slab was about 100 m high, 50 m wide and 10 m thick, and came away 500 m above the lake (Fig. 11). The rock is Archean gneiss with a foliation dipping at about 50° across the face, and the failure developed on massive unloading joints that lay across this foliation. The debris landed in the lake to create a wave that wrecked the farm villages of Bodal and Nesdal, drowning 61 people. Waves also carried the lake steamer *Lodalen* 30 m high onto the low rock peninsula of Nesodden, leaving it stranded 250 m from the shore. A few very minor rockfalls followed, and the survivors rebuilt their farms. This was unfortunate, as Bodal was at a particularly bad site on an alluvial fan that gave the maximum scope for destructive wave run-up.

In September 1936, another fall occurred. This time, over two million tonnes of rock came away from the face about 700–800 m above lake level. It, too, landed in the lake, pushing forward a wave that achieved a run-up 74 m high on the slope above the Nesodden peninsula (and also hurled the wreck of the *Lodalen* another 150 m inland). This massive wave spread across the lake, washing up every inlet, and reaching 15 m high at the far end of the lake (Fig. 9). It totally destroyed the rebuilt villages of Bodal and Nesdal, drowning another 73 people. There had been an increase in minor rockfalls just before the main event, but the warning signs were not recognized; and there were the usual minor falls afterwards as hanging blocks fell away.

A third rockfall occurred in June 1950 (right at the end of the Spring rockfall season). About 500 000 tonnes of rock fell away from the top of the face, nearly 900 m above the lake. The fallen rock landed on the apron of debris from the earlier falls (which now meets the Nesodden peninsula except for an excavated channel). So there was no destructive wave. However, Bodal and Nesdal had already been abandoned, and few people now live in the upper valley.

The three Lovatn rockfalls were effectively parts of the same event, played out very slowly, as the initial failure was followed by two phases of very steep head-scar retreat. The first two failures each undermined and left unsupported the higher parts of the face, and

Fig. 10. Profile of the failed slope above Lovatn, with bare-head scar standing above the tree-covered rockfall debris.

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made subsequent rockfalls almost inevitable. The top of the cliff came away in the third rockfall, so the face is now rather more stable – for the present. Unloading joints allowed the whole trio of failures to occur, and now that the rock can relax towards the newly exposed face, a new set of unloading joints will develop. Some time in the future, new rockfalls will occur when water and ice opens those joints into fissures and again heaves the face rock outwards.

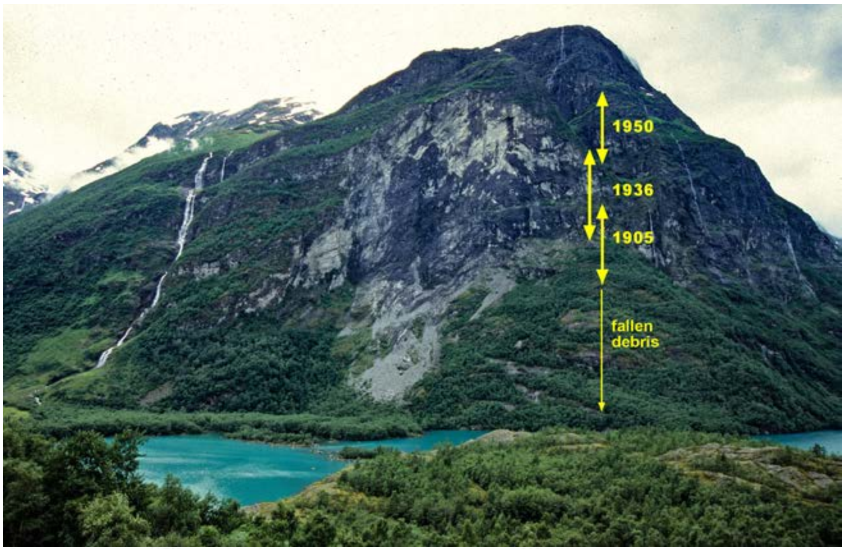

Fig. 11. The scar of the Lovatn rockfalls, with the bar on the right showing the approximate heights of the three major falls. Most of the debris is now covered by trees, as is the Nesodden peninsula in the right foreground.

Rockfall into Tafjord

Forming the farthest tip of Storfjord, Tafjord is very similar in proportions to Lovatn, but is just a little smaller (Fig. 9). It, too, occupies a glaciated trough cut into biotite gneisses, and its northern wall drops over 900 m on a slope of more than 60° straight into the deep fiord waters (Fig. 12). In April 1934 over four million tonnes (1500 000 m^3) of rock broke away from high on the face, and fell into the fiord. The wave was 62 m high beside the fall, reached 37 m high on the opposite bank, and killed 41 people in the villages at each end of the fiord, most of them in the fishing village of Fjora (Fig. 9).

This rockfall was essentially a massive wedge failure. One side of it was bounded by foliation planes dipping at 60° obliquely across the slope and towards the face, while the other side was along a fault dipping at 80° in nearly the opposite direction. Unloading of the face, by Pleistocene glacial excavation of the trough, allowed the initial fractures to enlarge, and water and ice then continued the work. Opening of the fault fissure had been observed over the three years prior to the 1934 event, in which time the main break had enlarged from about 20 cm to over a metre. The observed fissure then became the head scar of a rockfall that was very much larger than had been anticipated. Yet again, the dangers of predicting landslide behaviour were demonstrated. Significantly, it had been a cold winter in 1934, and the rockfall occurred on the third day of the first major thaw.

Like so many other rockfalls, in Norway and elsewhere, water and ice were the power behind the failure, but they followed in the wake of unloading, that ubiquitous process that lies at the root of so many geohazards.

Fig. 12. The view along Tafjord from the south-east. The scar of the 1934 rockfall is the zone of lighter rock below the distant snowfield. In the foreground, the houses of Tafjord village stand higher above the shore than those that were destroyed by the rockfall wave.

Postcript: the Aknes landslide

Above the approach to Geirangerfjord, a moving slab of gneiss, 30m thick, is known as the Aknes landslide, looming over Sunnylvsfjord. Some 30M m^3 of gneiss are sliding on dipping foliation that has been weakened by unloading. Since 2005, it has been continuously monitored, with links to warning systems in Hellesylt and Geiranger, which would both be impacted by tsunamis if the slide failed as a single unit.