Feature

Lötschberg—geology for tunnellers

Switzerland's Lötschberg tunnels present a long story of both failure and success. Tunnelling that began 100 years ago ended in a massive disaster—which is a classic of engineering geology—but subsequent works were very much more successful.

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In the heart of Switzerland, the Lötschberg route provides a vital transport route beneath the high mountains of the Bernese Oberland, not far to the west of the well-known peaks of the Jungfrau, Mönch and Eiger. It has never been a road route, and only a footpath crosses the high Lötschen Pass, with massive climbs on each side. But the first railway engineers spotted the potential for tunnelling beneath the mountain crest, where the Kandertal (or Kander Valley, *tal* = valley) on the north side lies close to the Lötschental on the south side (Fig. 1). Almost exactly 100 years later, the original tunnel has another being built almost directly beneath it.

The Lötschberg base tunnel

In recent years, there has been a major change in Switzerland's transport planning. The Alpine passes have become clogged with trucks going between Germany and Italy, and new road tunnels have solved only part of the problem. The famously efficient Swiss railways already have tunnels, but suffer from their long winding climbs into the mountains to reach the portals. The answer is two new tunnels, not through the mountains, but right under them. Known as base tunnels, these are designed for trains that travel at 200 km/h and can carry the bulk of the trans-Alpine freight traffic, one under the Lötschberg and one under the Gotthard (there is another base tunnel planned in Austria and another between France and Italy). Construction costs will be over a billion pounds for each tunnel.

First of the base tunnels to be built is the Lötschberg base tunnel. From the north, this starts at Frutigen at an altitude of less than 800 m, and reaches for 34.6 km beneath the Bernese Oberland, to open into the Rhône Valley at less than 700 m altitude. The tunnel lies nearly 2 km below the Lötschen Pass, and nearly 3 km beneath the shoulder of the Balmhorn. From the Rhône Valley, the old Simplon Tunnel, beneath the Pennine Alps, is already at that altitude and completes the low-level, high-speed route through to Italy.

The new base tunnel is not straight, but lies in sound rock under the mountains—notably avoiding the lower Kandertal with its alluviated floor, but staying close to the valleys so that side tunnels could create more working faces on multiple main headings. Most of the driving of the parallel pair of single-track rail tunnels was by conventional drill-and-blast techniques. Drilling jumbos drilled three holes at a time, until a round of 110 holes could be packed with liquid explosive; a heading advance of about 4 m was achieved with each round of blasting and mucking out. Following behind the excavation team, crews stabilized the tunnel with Swellex

Fig. 1. Old and new tunnels beneath the mountains and glaciers of the Bernese Oberland.

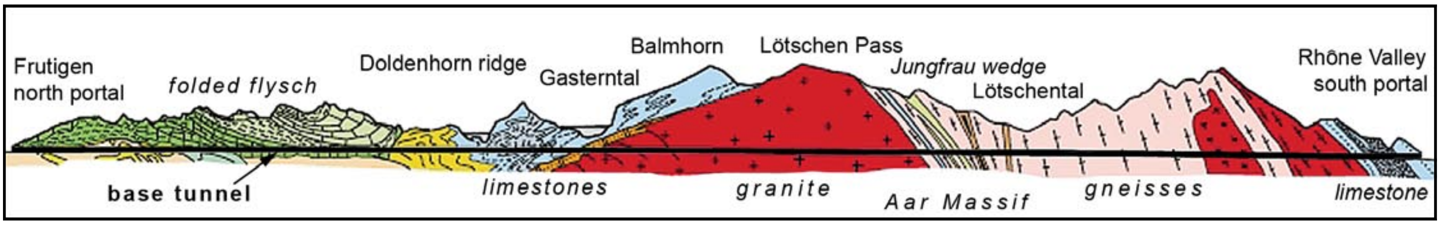


Fig. 2. Geological profile along the line of the Lötschberg base tunnel (after BLS AlpTransit AG).

rockbolts and a lining of sprayed concrete. Full-face Tunnel Boring Machines were only used for about a fifth of the tunnel length.

Not surprisingly, the base tunnel passes through a complex variety of rocks (Fig. 2). The northern section is through Alpine flysch—graded sequences of sandstone and shale that are strongly folded and lightly metamorphosed and contain some zones of very fractured and weakened rock. Near Kandersteg, the tunnel enters the overfolded Mesozoic limestones of the Doldenhorn (Fig. 3), with karstic conditions that provided some locally high flows of cold water from zones of fissures and caves. Deep beneath the Gasterntal, the tunnel enters the granite and gneiss of the Aar Massif, which extend almost all the way to the southern portal. The exceptions are two wedges of sedimentary rocks. Under the Lötschental, the Jungfrau wedge required extensive grout injection from the tunnel heading face to allow safe excavation and advance. Jurassic limestones at the southern portal were de-watered into the tunnel, and this caused a nearby spring to dry up; then some old buildings subsided over peat soils that were dewatered by the loss of the spring inflow. Overall, the geology did not create undue difficulties, and correctly selected modern working practices overcame ground conditions that were certainly variable and not always simple.

Fig. 3. Overfolded limestones of the Doldenhorn exposed in a cliff at the lower end of the Gasterntal.

On 28 April 2005, the tunnel crews linked up through the Lötschberg, 11 years after excavation began. There is still a lot more work, now under way, enlarging the advance headings, finishing the infrastructure and laying the track, but trains are due to run through in 2007. The tunnelling has been a grand success that relied on a thorough understanding of the geology. Prior to construction, 27 deep boreholes had reached as deep as 1400 m down to tunnel level, to reinforce a huge programme of geological mapping and geophysical surveys. In addition, horizontal exploratory boreholes were drilled ahead of the advancing tunnel faces in zones where difficult ground conditions were predicted

The new Lötschberg tunnel is now the world's third longest, behind Japan's Seikan Tunnel (54 km) and the Channel Tunnel (50 km), though it will slip to fourth place when the Gotthard base tunnel holes through in a few years time with a length of 57 km. By a splendid coincidence, the earlier Lötschberg tunnel was also the world's third longest (after the Simplon and the Gotthard) when it was completed in 1911.

The original Lötschberg Tunnel

Well before the Simplon rail tunnel had been opened under the Pennine Alps in early 1906, it was recognized that a Lötschberg tunnel was also needed under the Bernese Oberland to complete the route in from Bern and the north. From Spiez in the foothills, railway surveyors found the best route southwards. This headed past Frutigen up the Kandertal, with a pair of partly tunnelled spirals to climb a step in the valley profile north of Kandersteg. A second step up into the Gasterntal was too high, so the tunnel portal was opened just south of Kandersteg at an altitude of just under 1200 m, and reached for nearly 14 km through to a bend in the Lötschental (Fig. 1). The villages of this beautiful valley were some of the most isolated in the Alps, reached only by a footpath

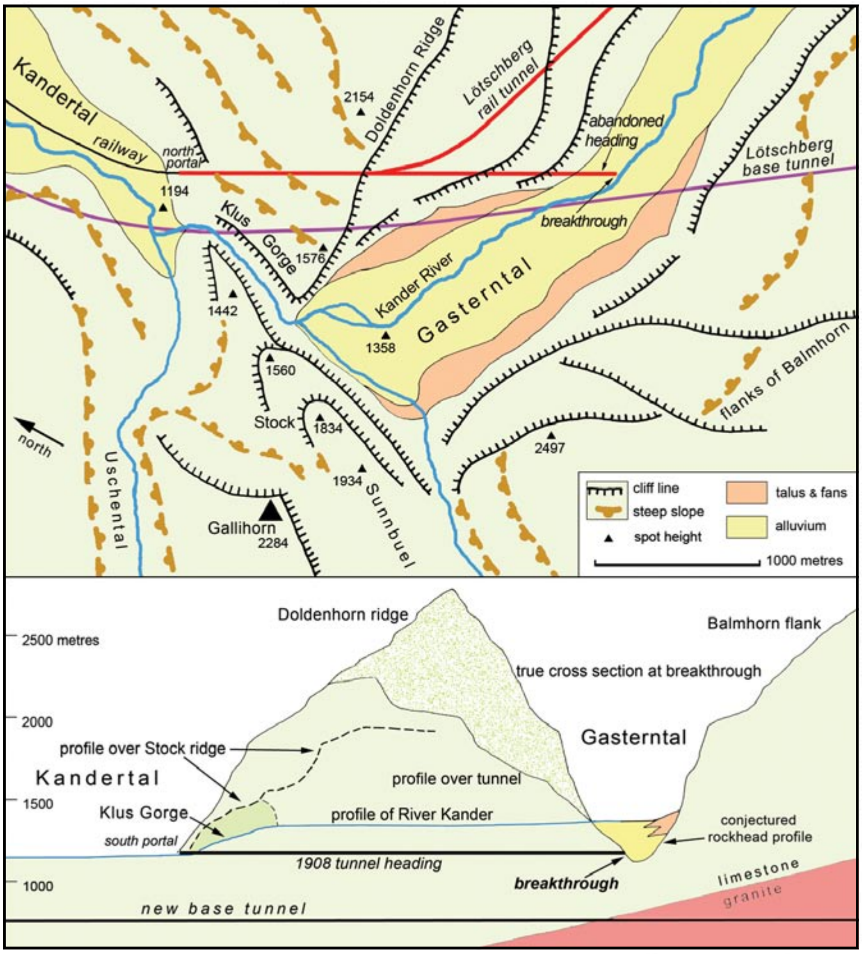


Fig. 4. Plan and profiles of the Gasterntal and Klus Gorge around the old Lötschberg tunnel site.

through the wild Lonza Gorge—and that was blocked by deep snow for many months of every winter. The railway made a new link, but it was still more than 500 m above its destination on the floor of the Rhône Valley. This was overcome by a brilliantly engineered descending traverse, first down the wall of the Lonza Gorge and then down the flanks of the Rhône's glaciated trough.

Tunnel excavation started from both ends late in 1906. There was no alternative to drill-and-blast in those days, and the smaller machines meant that only about 1.2 m of rock was removed by firing a round of holes on an undersized pilot heading. This was subsequently enlarged by breaking out the roof and both walls to achieve the full size of the single twin-track tunnel. There had been some concern about the tunnel line crossing beneath the alluvial fill of the Gasterntal (Fig. 4), but the tunnel lay a full 180 m below the flat valley floor, and in June 1908, the northern heading passed safely from beneath the shoulder of the Doldenhorn. Then in the morning of 24 July, another round of holes was fired—and disaster struck.

An avalanche of sand, gravel, silt, mud, water and rock debris burst through the tunnel face. The heading had broken through into the alluvial fill of the Gasterntal. Saturated sediment ran down the tunnel for 1300 m. The entire face team of 25 miners died; they had retreated down the tunnel for only about 100 m for the firing—as was the usual, and normally safe, practice. Up above, a sinkhole 80 m across had opened in the in the right bank of the River Kander where it wound through woodland on the Gasterntal floor. A whirlpool lake temporarily swallowed the river, but within three months it was choked with gravel and lost to sight. The whole sediment column 172 m thick had dropped when its rock floor had been blasted away from below.

Debate and recriminations raged over the details of the disaster, but the sediment-filled section of the tunnel was unusable; it was sealed off with a plug of concrete, and became the miners' tomb. Meanwhile, the tunnel project had to progress, and a re-alignment was chosen as the best option. Just behind the concrete plug, a new heading curved away to the east. The tunnel crews in the southern heading also followed a curve to the east, and the new alignment was completed with a reverse curve beneath the upper Gasterntal. At this crossing there was no danger from alluvial fills, as granite bedrock was exposed on the valley floor and there 230 m above the tunnel.

The two headings finally met on 31 March 1911, and the tunnel was opened to trains in July 1913. Most of the northern heading had been in the Doldenhorn limestones (which includes some interbedded gypsum and anhydrite), where it had met some significant inflows of cold water. In contrast, the southern heading had been largely in the much harder granite, where temperatures rose to over 34 °C and zones of heavily kaolinized rock required extra roof support.

A welcome footnote to the Lötschberg story was provided by the tunnel surveyors. With the three long curves to be set out, the tunnel survey was a real challenge, but when the headings were connected the misalignment was only 257 mm horizontally and 102 mm vertically. This was a magnificent achievement, in contrast to the rather less successful role of engineering geology in the Lötschberg project.

Disaster under the Gasterntal

Heading out of solid rock and into unconsolidated sediments is the ultimate tunnellers' nightmare. But this is exactly what happened at Lötschberg in 1908. The unsurmountable step and the sharp bend in the valley just above Kandersteg determined the position of the northern portal, and a straight tunnel would then have to pass deep beneath the Gasterntal (Fig. 5). At the earliest stage in planning, the critical

Fig. 5. The glaciated trough of the Gasterntal, looking up-valley from the Stock hill; the 1908 tunnel breakthrough sinkhole was in the woodland just beyond the large meadows.

question of the depth of the Gasterntal sediments had been raised.

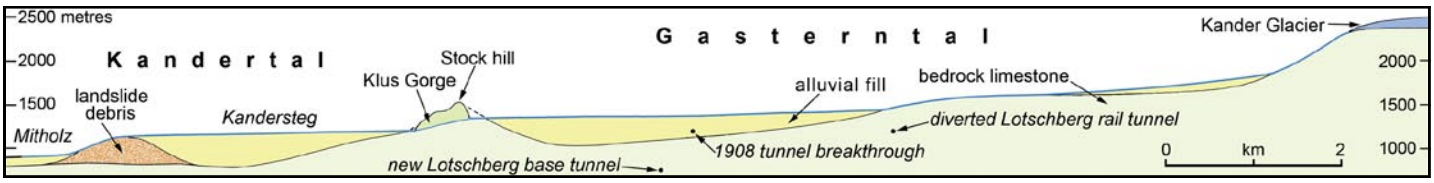
The magnificent glacial trough of the Gasterntal has precipitous walls, mainly of limestone, rising high above a narrow floor with a profile that clearly indicates the presence of a considerable sediment fill. Aprons of talus and a series of large alluvial fans line much of the valley edges. These materials must interdigitate with alluvium that forms the surface in the flat lower section and almost certainly includes various lacustrine sediments. There is, however, no indication of the depth to rockhead beneath this major fill. That question also concerned the leaders of the original Lötschberg tunnel project, who were not happy about their tunnel heading into ground that could be either rock or sediment, 172 m beneath ground level in the Gasterntal.

Others dismissed any concern, citing the bedrock limestone exposed in the Klus Gorge downstream of the tunnel crossing. They clearly did not understand the concept of glacial over-deepening, where ice was very capable of moving uphill and scouring out a deep basin when pushed ahead by a glacier flowing from a higher source. The long profile of the Kander valley system is marked by conspicuous glacial steps (Fig. 6), and it would be very reasonable to expect some degree of over-deepening on each of these steps. Eventually a commission of three geologists concluded that they anticipated at least 100 m of rock cover over the tunnel, beneath about 70 m of sediments in the Gasterntal. The background of these commission geologists is not recorded, and it may well have been political motivation and simple expediency that drove the project engineers to welcome and follow their advice. An independent geologist echoed the earlier concerns about much deeper sediments, but his warning was ignored.

A deep borehole in the Gasterntal, and close to the tunnel line, could have resolved the issue. But this was not done. Contemporary technology was a match for this, as many oil wells had already been sunk far deeper, even where they required continuous casing through weak materials, and boreholes were sunk for the investigation after the disaster. The extra cost may have been the reason; time was not critical, as the main project had to wait until tunnelling crews could be brought from the Simplon Tunnel after its completion; or maybe sediments 172 m deep were just beyond the comprehension of the engineers.

If the tunnel line was not be curved around the danger zone (so crossing under the Gasterntal further upstream where a rock floor was exposed), an alternative precaution was to drill probing boreholes in advance of the heading. Drilling horizontal holes is not as easy as sinking vertical holes, but the technology existed at that time to drill horizontal probes at least 5 m long. A single 5 m hole drilled within each round of 2 m long holes would have proven 3 m of intact rock beyond that to be blasted out. Within the small pilot heading, only 2.8 m high and 2.3 m wide, those 3 m of rock could have provided a stable barrier against any inrush. Such measures may have been needed for up to 150 m of the tunnel as it passed through the potential danger zone between sensible estimates of the steepest and gentlest buried rock profile beside and beneath the Gasterntal sediments. That would have been up to 50 over-length probes, any of which could have revealed the buried rockhead by producing a spout of high-pressure water.

Fig. 6. Long profile of the Kander valley system, with true vertical scale; except at the few points proven by boreholes, the rockhead profile is conjectured and approximate.



But such precautions were not introduced. Pressure on both time and costs may have been the reason. False security was derived from the great depth and a lack of geological understanding. Unfortunately the tunnel then broke through in clean dry rock in a buried and cleanly ice-scoured valley wall. There is no record of warning, any sign of rock weathering, or any water draining from the last round of holes. It was probably less than a metre of intact rock beyond the blasted material that failed under the pressure of sediments and water in the Gasterntal fill.

There was of course a post-event investigation. It attempted to resolve the causes of the disaster, but released almost no useful information. Late in 1908, two boreholes were sunk in the floor of Gasterntal. Close in front of the breakthrough point, one reached bedrock 39 m below the tunnel level. The second, nearer the centre of the valley was stopped only a little deeper without reaching bedrock beneath 220 m of sediment. The investigation also determined that the best remedial action was to divert the tunnel round to the east. Subsequently, all disputes were settled by arbitration, with an agreement not to publish the report, which was deemed to belong to the railway company and not be public material. The diverted tunnel went ahead, but the disaster issue was closed.

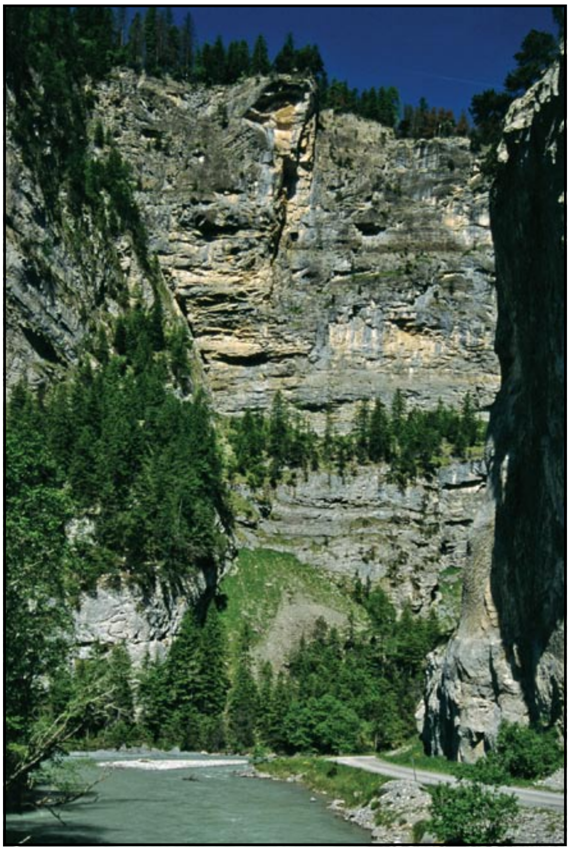


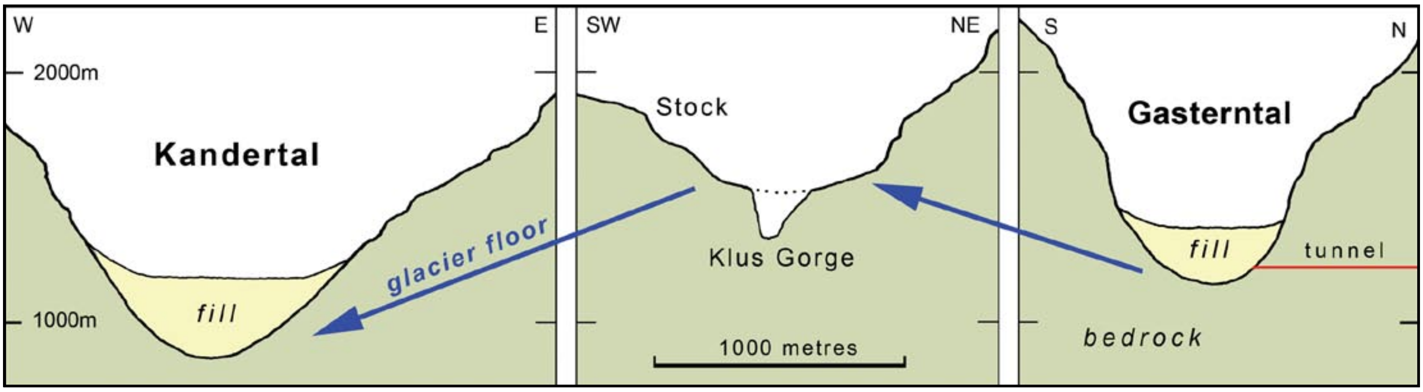
Fig. 7. The limestone cliff of the Stock hill undercut by the river as it turns right out of the Gasterntal and into the Klus Gorge.

The over-deepened Gasterntal

The great depth of the Gasterntal valley floor at the tunnel crossing is simply a result of glacial over-deepening, leaving a trough which had then been filled with sediment up to its overflow level. This did not only involve a down-valley rockhead rise of about 180 m to the mouth of the Klus Gorge where the sediment fill ended. The glacier never went though the Klus Gorge—which is a fluvial feature less than a tenth of the width of the Gasterntal trough. Its rock walls are over 100 m high (Fig. 7), and any glacier would have had to pass over the top of them. The valley over-deepening was therefore more than 300 m (Fig. 6).

The original line of the Kander Valley was determined by pre-glacial fluvial drainage on the rising Alpine mountains, and the powerful Pleistocene Kander Glacier was forced round the sharp bend from the Gasterntal into the Kandertal (Fig. 8). Furthermore, it was constricted by the rib of

Fig. 8. The top end of the Kandertal, seen from the west. A train is midway into the Lötschberg tunnel portal, hidden in the trees beyond the valley floor hotel on the far left. The power cables on the right rise across the face of the Stock ridge with its stepped profile, which lies in front of the Klus Gorge, with the higher, grey, limestone cliff on its far side. The Gasterntal lies beyond the Stock and extends round to the left, in front of the ice ridge of the Balmhorn.



strong limestone that forms the Stock spur. The ice rode up and over this, passing over a shoulder at 1560 m elevation, and also rising to a comparable level over the Doldenhorn shoulder. During the Pleistocene glacial maxima, ice sheets flowed at even higher levels, but the main stage of the valley glacier from the Gasterntal appears not to have reached as high as the Stock itself at 1834 m. The floor of the Kander Glacier appears to have risen at least 350 m (Fig. 9). The rockhead under Gasterntal has been proven at 1109 m by a borehole over the line of the new base tunnel, and this is unlikely to be its lowest point. A low point over the saddle appears to be close to the 1442 m spot height below the Stock. The glacier floor then descended into the Kandertal where another base tunnel borehole proved it at an elevation of 823 m. Glacial over–deepening of 350–400 m was therefore followed by a glacial step that dropped over 600 m where the glacier was joined by flows from Sunnbel, Uschental and other high basins both east and west of Kandertal. The cross-section area of the glacier appears to have been reduced by about 40 per cent in its passage from Gasterntal through the Stock restriction (Fig. 9), and this must have been accompanied by an acceleration of the glacier as it headed for an icefall into Kandertal.

The Klus Gorge was probably initiated by sub-glacial meltwater scouring along fractures in the limestone bedrock, and was then greatly enlarged by proglacial meltwater when the snout of the Kander Glacier stood near the lower end of Gasterntal. With further ice retreat, a proglacial lake would have accumulated until it overflowed through the Klus and thereby entrenched the gorge deeper. The lake was lost when the gravel fills in Gasterntal aggraded to meet the level of the outlet into the Klus.

Alternative concepts

Because the glacial over-deepening of Gasterntal was on a scale that almost defies belief, searches have been made for other explanations of the local geomorphology.

An early idea was that the tunnel heading broke through into a karst feature that extended well below the main rock floor of Gasterntal. This could have been either a large buried sinkhole or a part of a large, sediment-filled, descending cave system. However, the two post-disaster boreholes and three boreholes for the new base tunnel all found deep sediment in an area 300 m across, so concepts of caves or sinkholes are barely feasible. There is, however, plenty of karst development in the limestone. Just 80 m back from the tunnel's fatal breakthrough, an input of 10 litres/s of cold water was encountered and had to be sealed off; such a flow is typical of a small cave stream. A much larger stream pours from the Geltenbach cave high in the Balmhorn face of the Gasterntal (Fig. 10); the cave lies in the nose of a recumbent syncline of limestone. Its stream only flows in high summer because it is fed by meltwater from high-level karst basins; exploration has revealed only 750 m of cave passage in from the cliff face, to where the water

Fig. 9. Profiles along the line of the Pleistocene Kander Glacier, showing its rise over the rock saddle (now cut by the Klus Gorge) between Gasterntal and Kandertal; adjacent profiles are about 2 km apart.

Fig. 10. The Geltenbach cave stream resurges to feed a high waterfall down the Balmhorn flank of the Gasterntal; smaller streams emerge to the right from the same recumbent fold of karst limestone.

emerges from narrow flooded fissures.

Further alternative concepts invoke accumulation of the Gasterntal sediments behind a barrier of landslide debris. The steep floor of the Klus Gorge is a staircase of boulders that obscures any bedrock, and much of this is rockfall debris from its walls. But this would have been a detail regarding the Gasterntal sediment accumulation, and would not remove the need for a 300 m glacier rise over the gorge crest.

At first sight, the gross morphology of the Stock hill suggests that it could be a massive landslide that descended from the face of the Gallihorn (Fig. 4). Such large landslides into deglaciated valleys are increasingly recognized in the world's mountain regions, and many of those in the Himalayas are much larger than the Stock feature. Major landslides did fall from the eastern face of Kandertal, either side of Kandersteg (but long before the town was there). The debris from one ponded the basin that then filled with sediment where Kandersteg now stands (Fig. 6). Unlike the piles of broken debris in the Kandersteg landslides, the Stock is a block of intact rock, analogous to the Vaiont landslide in northern Italy, which occurred in 1963; this was a slab failure about 50 per cent larger than the Stock, and the slipped mass is still fringed by vertical cliffs of intact, bedded, Mesozoic limestone. However, both bedding and fault structures are continuous from the Stock into cliffs in all directions, and it is clearly an unmoved shoulder of bedrock. Gasterntal was not blocked by a large landslide into its steep-sided glacial trough—its depth is entirely due to glacial over–deepening.

A geological postscript

Some 32 years before the disastrous breakthrough of the Lötschberg tunnel, the Gotthard tunnel had been driven beneath Andermatt, just 70 km east of Kandersteg. There too, the tunnel had passed beneath an alluviated high-level valley, the Ursental, but no thought had been given to deep sediment fills, because the tunnel lay a full 320 m below ground level (Fig. 11). In the event the whole tunnel was in solid rock, and was excavated with no unusual difficulty. Then in the 1940s, ground investigations for a new power station in the Ursental included a deep borehole—which found unconsolidated sediments reaching to a depth of 290 m. By pure chance, the Gotthard tunnel had been driven through with less then 30 m of solid rock cover. It had been that close to breaching the rockhead—which would have had disastrous results. But if that had happened, the engineers on the Lötschberg project would (one hopes) have learned from the event. Sadly though, it does appear to require a full-blown catastrophe to induce due attention to ground conditions on engineering projects.

Fig. 11. The Ursental, with Andermatt in the foreground standing on its deep sediment fill that overlies the Gotthard tunnel.

The Ursental is a splendid glaciated trough, comparable to the Gasterntal. Its deep sediment fill may lie in an over-deepened rock basin, but may also be partly impounded by landslide debris in the outlet Schöllenen Gorge. But whether due to glacial over-deepening or landslide barriers, or both, it is clear that sediment depths can be huge in these alpine valleys – a function of the scale of the dynamic processes in young mountain chains. For geologists resident in the gentle terrain of Britain and many other lowland nations, these processes are difficult to appreciate, and yet deserve serious respect by those in the world of engineering geology. The story of the Gasterntal glaciation and the Lötschberg tunnel is a classic that should not be forgotten.

Suggestions for further reading

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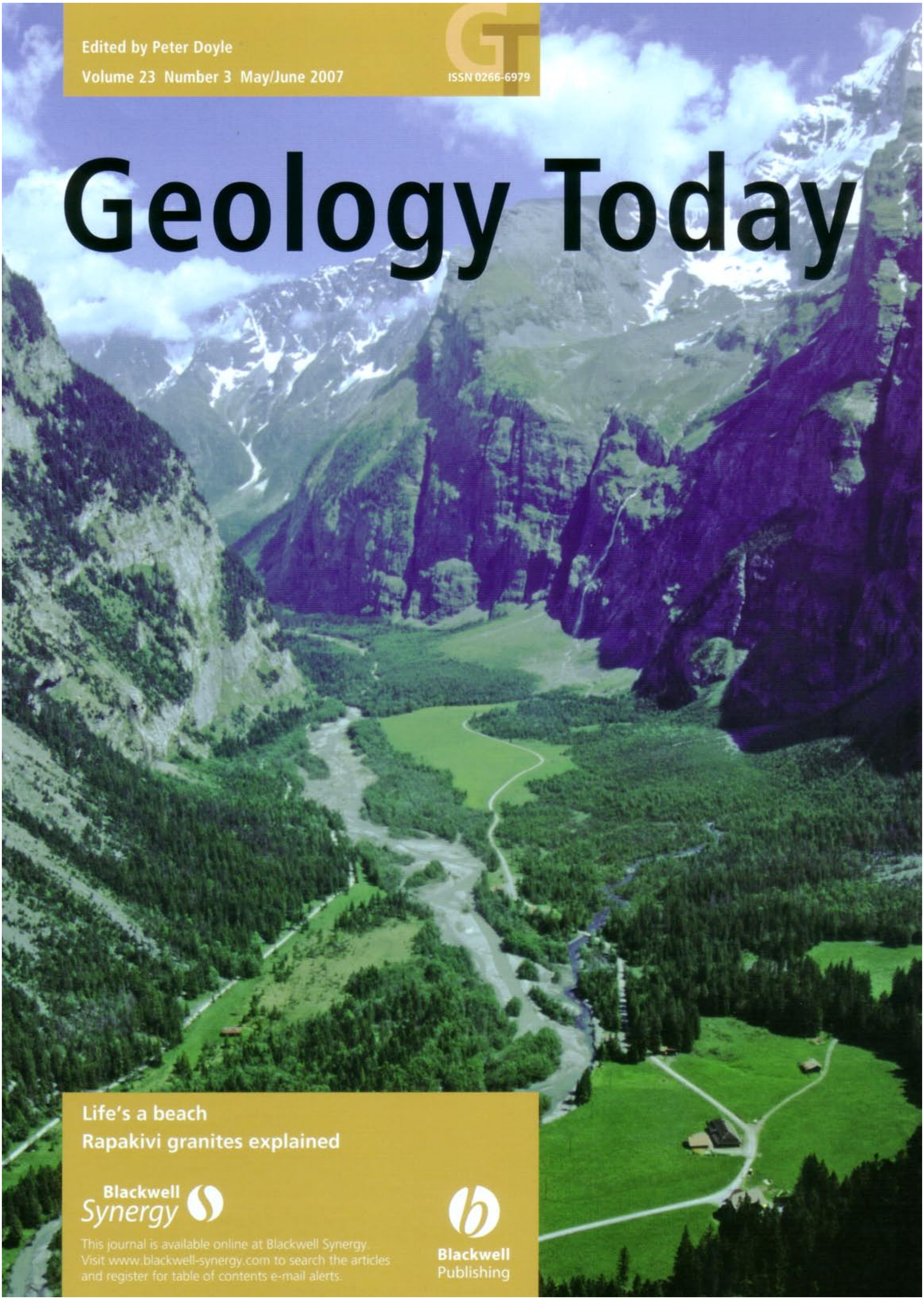

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