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**Notes**

Photographic Feature

# A field guide to the engineering geology of the French Alps, Grenoble


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**Abstract:** It is now well established in the field of engineering geology that a comprehensive ground model is critical to the success of any engineered project. This ground model must contain elements of the site geology, geomorphology and geotechnics and demonstrate the potential interactions between these elements to be of value to the engineer or geologist working on a given project. The area around Grenoble in the French Alps offers an ideal field location to exemplify and demonstrate these concepts. Here there are a number of large engineering structures that highlight the importance of sound engineering geological investigation and the establishment of detailed ground models to understand problematic ground behaviour and performance. The area demonstrates the key issues of geotechnical hazard, vulnerability and associated risks, as well as the significance of understanding both the solid and superficial ground conditions. This field guide provides details on and discusses a variety of key localities where these issues can be fully demonstrated and explored.


**Supplementary material:** Downloadable Google Earth site location file with additional photographs: *Field guide to the engineering geology of the French Alps Grenoble.kmz* is available at http://www.geolsoc.org.uk/SUP18509

Within the French Alps there are a number of large engineering structures that highlight the importance of sound engineering geological investigations and the requirement to establish a detailed geological ground model to understand and predict probable ground behaviour and performance. The area around Grenoble in the Isère presents an ideal location to examine these issues with a variety of engineering geological case studies together with sequences of problematic rocks and soils. The geological setting, both solid and superficial, presents many challenges to the engineering geologist such that failure to recognize key and significant ground conditions can lead to substantial issues with regard to the construction of any engineered structures. The area is tectonically active and has been affected by numerous glacial episodes during the Quaternary. The area is dominated by calcareous sedimentary sequences overlying metamorphic and igneous basement rocks. This geological and tectonic setting together with the glaciated landscape gives rise to major active fault systems, thrusts and shear zones, together with a variety of problematic soils. These conditions present substantial geohazards including deep-seated gravitational failures (sackung), rockfalls, debris flows, mudslides and mudflows, dissolution and karst, as well as significant seismic events. All of these phenomena need to be understood by the engineering geologist and be built into ground models in order to successfully understand the potential interactions between engineered structures and underlying geological conditions. A variety of field locations are shown in Figure 1, which highlight these conditions and allow the need for robust predictive ground models to be demonstrated on site.

## Geological setting

The area around Grenoble forms part of the outer Sub-Alpine Chains of the Alpine tectonic complex, which curves in an arc from the Mediterranean coast to Lake Geneva. The French Alps can be divided into external and internal zones. The western external zones consist of several marginal mountain chains resulting from uplift, folding and thrusting of the continental basement of the European plate together with its Mesozoic and Cenozoic cover. The internal zones to the east are more complex both structurally and stratigraphically. They are derived, in part, from successions that include continental basement not previously attached to the European plate. The External or Dauphiné Zone has basement rocks exposed in a number of crystalline massifs. These occur towards the east of the External Zone; consequently the younger cover successions crop out mainly to the west, where they form the Sub-Alpine Chains (J. S. Whalley, pers. comm.; Pomerol 1980; Debelmas 1970, 1974).

### The External Crystalline Massifs

These massifs are composed of metasediments and meta-igneous rocks, including many granites, unconformably overlain in places by Carboniferous sediments of Late Westphalian age with some Permian cover. Some of the granites intruding this basement have been dated with ages suggesting a Variscan origin (Guillot & Menot 2009).

### Sub-Alpine Chains

These external calcareous massifs can be divided on geological as well as geographical grounds into northern and southern sections.

### Northern Sub-Alpine Chains

These form a series of high plateaux or 'massifs' with a regular NNE–SSW alignment and are well separated from each other by deep transverse valleys. Their high relief is due primarily to

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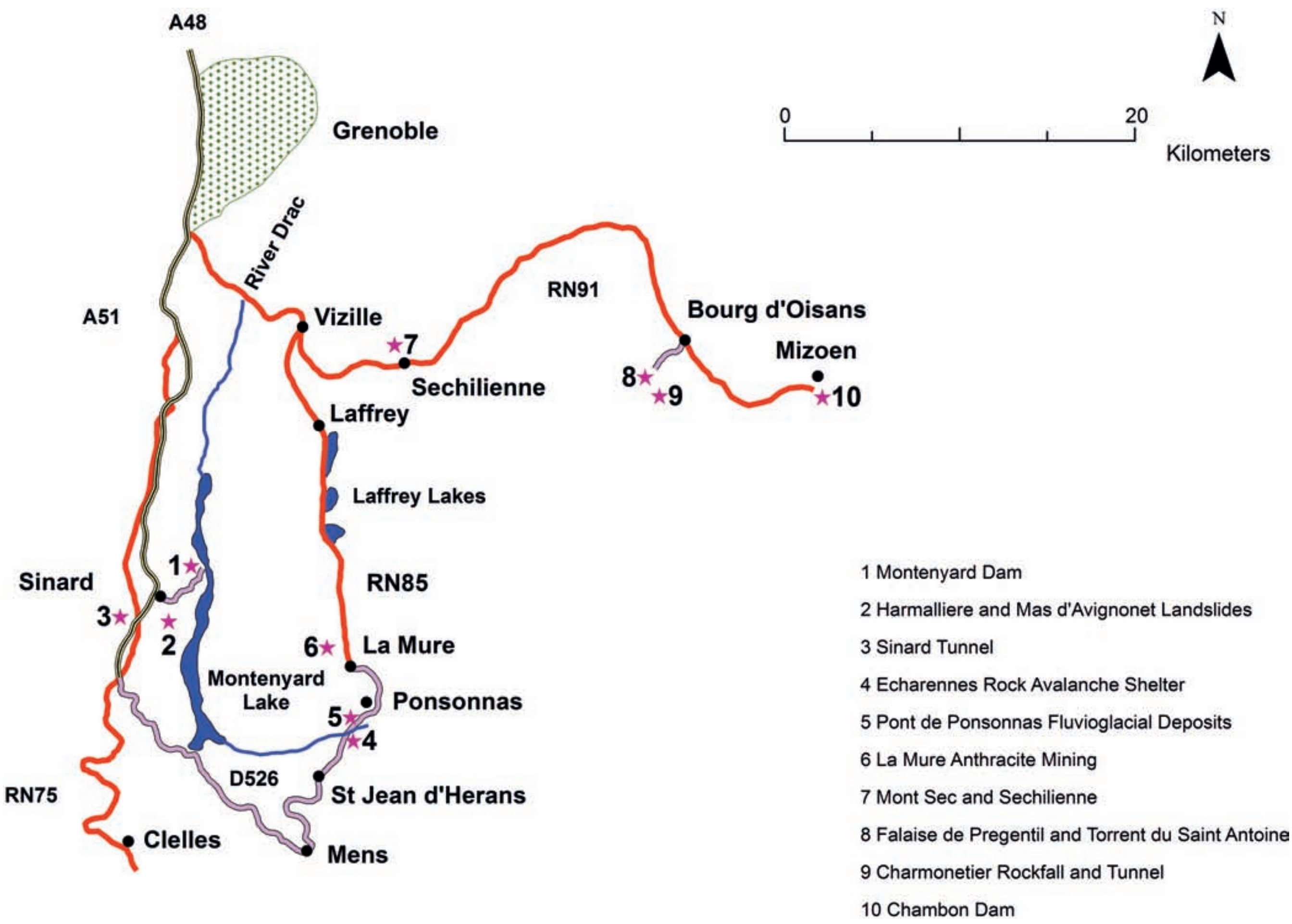


**Fig. 1.** Site localities.

thick, massive limestones of mid-Cretaceous Urgonian (Aptian) age. Structurally these chains consist of a series of folds of latest Miocene–Pliocene age trending roughly NE–SW. The Bauges, Chartreuse and Vercors Massifs are separated from the Belledonne Crystalline Massif by a great erosional trench, Le Sillon Subalpin, along which flow two major rivers, the Isère and the Drac. The valley was formed by glacial erosion exploiting the incompetent formations of Dogger–Malm age (Middle–Late Jurassic) but may also be controlled by faults associated with the en echelon folds of the massifs.

## Southern Sub-Alpine Chains

South and east of the Vercors Massif, the mountains of the Southern Sub-Alpine Chains form less regular, separable massifs. This is in part due to the disappearance of the thick, massive Urgonian limestones from the Cretaceous succession. The structure is also more complicated, with two identifiable fold trends, of different ages, trending east–west (Late Cretaceous–Eocene) and north–south (latest Miocene), which are superimposed.

## Stratigraphic history of the External Zone

The External Zone was a sedimentary basin with moderate amounts of subsidence during Triassic to Late Cretaceous times. More localized subsidence continued post-Cretaceous to allow further sediments to accumulate in restricted areas. Maximum sediment thicknesses in the main basin are of the order of 4000–5000 m. The shape of the basin was not controlled by the present-day shape of the Alpine arc until after Late Cretaceous times. In the Early and Middle Cretaceous it was elongate from east to west, reaching as far west as the Massif Central. Basin analysis techniques have demonstrated that subsidence within the basin was often fault controlled with dramatic variations in sediment thicknesses associated with listric fault blocks. These faults were primarily extensional in character but many had significant strike-slip components associated with them. Well before the major contractional tectonic events of post-Cretaceous times, some parts of the basin were affected by episodes of uplift and consequent partial erosion of the basin fill. The initial Triassic basin fill is usually clastic but is dominated in many areas by evaporitic sequences including gypsum and anhydrite. As water depth in the basin increased and evaporation ceased to be significant the fill became dominated by carbonate deposition. The whole of the Jurassic and the vast majority of the Cretaceous fill consists of varying proportions of massive limestones and calcareous shales (marls).

## Tectonic style of the External Zone

The tectonic style of the External Zone during the post-Cretaceous contractional phase is dominated by two influences: first, by early normal and strike-slip faults, which were frequently reactivated and which localized some of the deformation; second, by Triassic evaporitic units and thick, incompetent, marly

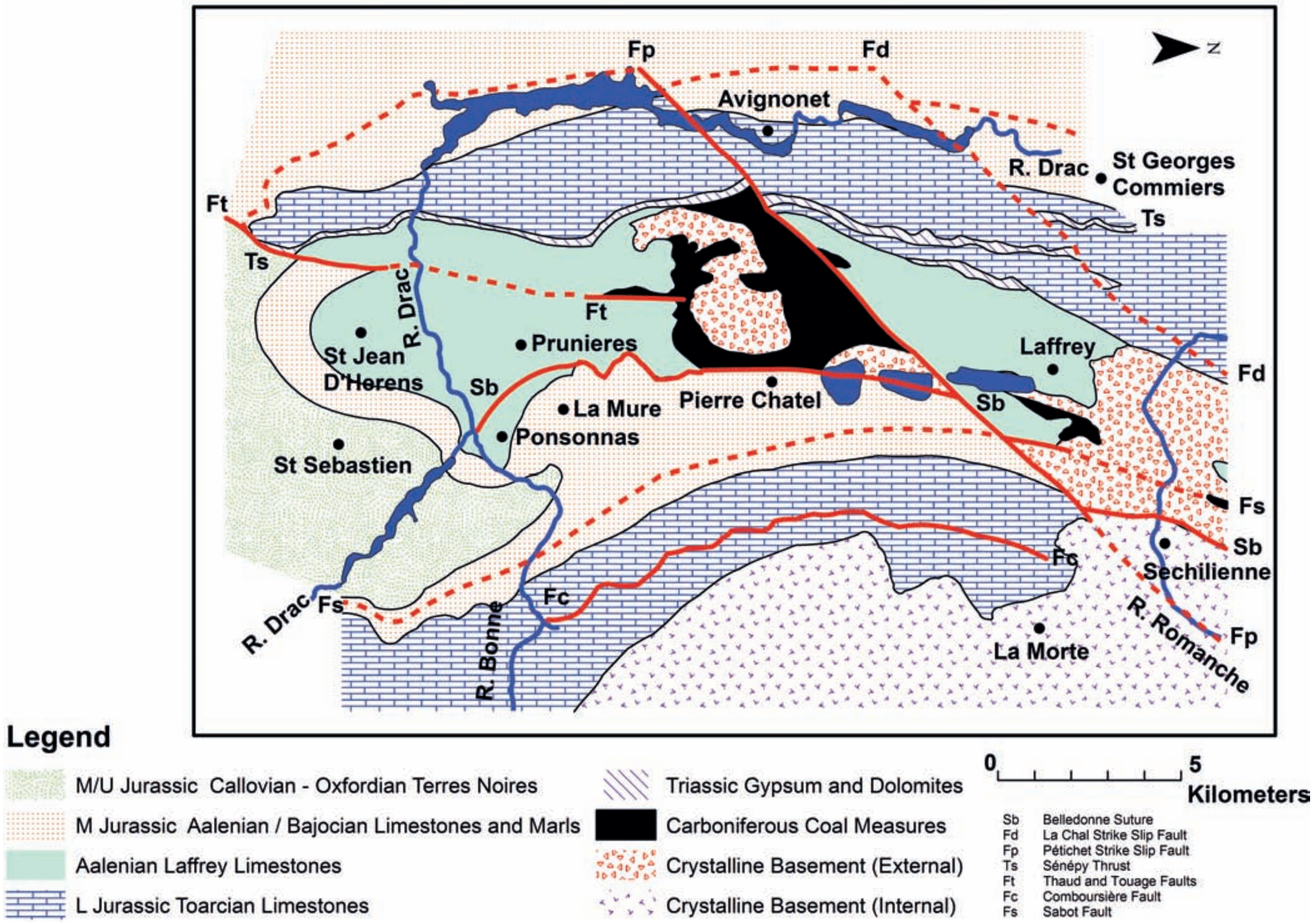


**Fig. 2.** Simplified geological map of the field area (modified from Gidon 2011).

formations within the Upper Lias and Oxfordian. These provided horizons of easy slip and detachment (décollement planes) and so prompted the initiation of thrust-dominated tectonics. Deformation within the External Zones was typically accompanied by very low grades of metamorphism.

Figure 2 presents a simplified geological map of the field area described, where the variety of sedimentary cover and crystalline basement outlined can be examined in detail.

## Quaternary history

Alpine Quaternary chronstratigraphy is classically divided into four main glacial stages with associated stadial, interstadial and interglacial periods. As with all Quaternary deposits, cross-correlation with other mainland European and British events is difficult and problematic. The oldest glacial deposits recognized date from the Günz glaciation, which occurred around 600–700 ka BP. The subsequent glacial stages of the Mindel (*c*. 410–380 ka BP), Riss (*c*. 200–125 ka BP) and Würm (*c*. 110 to 10–15 ka BP) have left a significant geomorphological imprint and associated deposits in the area under study. The younger events can be subdivided into their various stadial and interstadial stages, although again precise dating remains problematic. The Quaternary development of the Isère, Drac and Durance Basins gave rise to a variety of fluvial, glacial and periglacial processes and subsequent deposits (Monjuvent 1973; Montjuvent & Winistorfer 1980). The significant glacial events that took place in this region commenced at the end of the Mindel–Riss interglacial (*c*. 200 ka BP) with a generalized ice advance into the Drac Basin. At the onset of the Riss I stage (*c*. 200 ka BP) there was a great transfluence of the Durance and Isère glaciers into the then existing Drac valley. At the end of this period of glacial advance the great pro-glacial ice-dammed lakes of Trièves and Beaumont were initiated as the ice retreated. This deglaciation was also responsible for the higher level fluvioglacial deposits in the Drac valley. The Riss II period (*c*. 190 ka BP) was a time of periglacial conditions, with torrential melt accumulations of more high-level fans and terraces being formed. The Riss III stage (*c*. 140 ka BP) saw another glacial readvance, which did not progress as far as the Riss I ice but did travel further than the later Würm glaciations. Cataglacial alluvial material was deposited and is preserved as the first fossil river terrace. A considerable amount of morainic material was also deposited in the Drac Basin by this readvance. The Riss–Würm interglacial period saw the development of a second river network, which eroded and deepened the first. Also during this period the Greivauden Lake in the immediate vicinity of present-day Grenoble was infilling with glaciolacustrine deposits forming the Eybens Varved Clays. At the onset of the Würm I glacial stage (*c*. 80 ka BP) the second fossil river terrace was deposited into the interglacial valleys. The maximum advance of the Würmian glaciers occurred during the Würm II stage (*c*. 55 ka BP), which was a time of widespread glaciolacustrine deposition in the ice-dammed lakes of Trièves and Beaumont (Fig. 3). These pro-glacial lakes were infilled with silts and clays to give thick sequences of varves that were later overlain by high deltaic terraces. These terraces completely

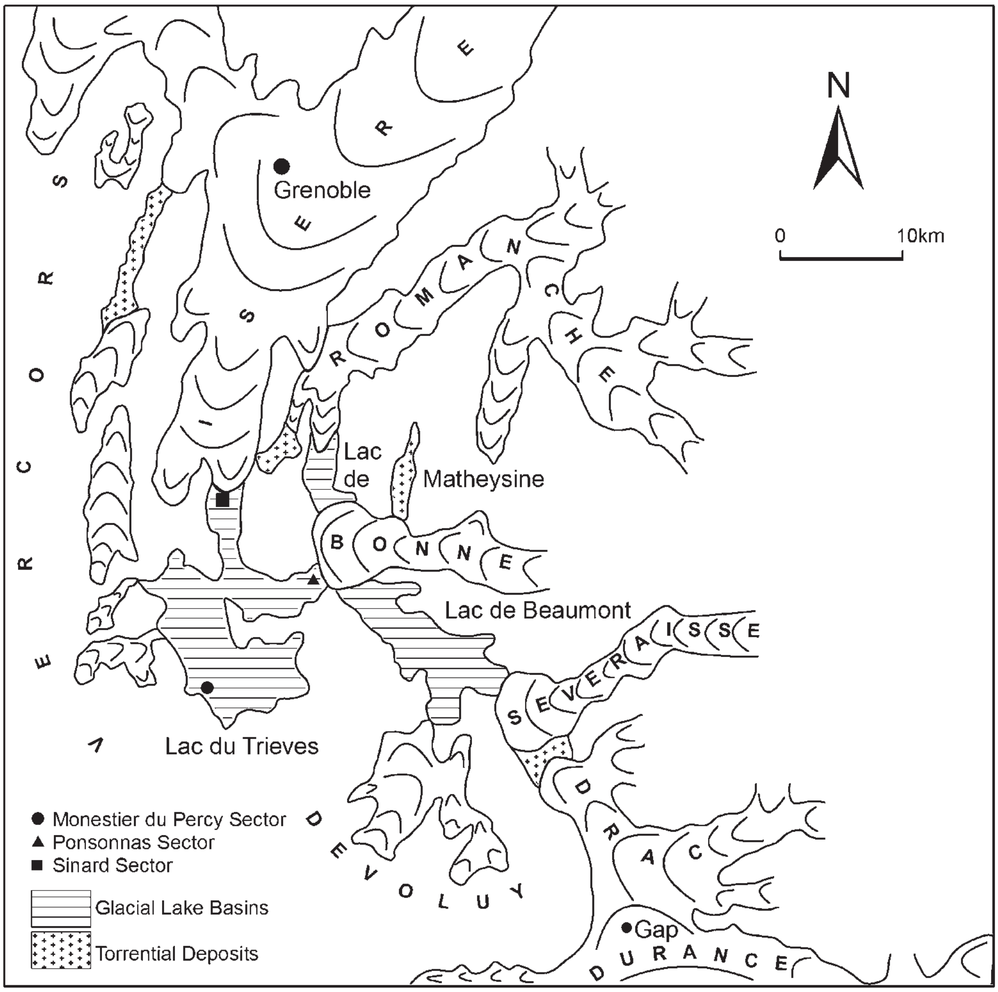


**Fig. 3.** Extent of the glaciers at the Würm Stage Maximum and location of the major proglacial lakes (after Monjuvent 1973).

covered the glaciolacustrine deposits and preserved the two ancient fossil river terraces. During this stage the great moraines of the Vercors and Devoluy were formed. During the Würm II and Würm III interstadial periods all of the glaciers retreated far upstream. There was deposition of localized cataglacial terraces. At the onset of the Würm III glacial stage (*c*. 35 ka BP) there was another major ice readvance over the Würm II glacial and Würm II–III interstadial sediments. There was only minor infilling in the Lower Drac by the Isère glacier and the deposition in the Drac Basin was generally of low-level terraces. At the end of the Würm III stage there was a complete disappearance of glaciers from the area except for a mini-readvance in the Lauritel area, sometimes referred to as Würm IV (*c*. 23 ka BP). In the post-glacial period the Greivauden Lake was finally infilled with sediment and the Drac river system continued to deepen through the glacial deposits, an erosional phase that had commenced at the end of Würm II and continued throughout the entire Würm III retreat.

**Fig. 4.** Barrage de Montenyard.

## Location 1: Montenyard Dam [GR 712020, 4982000]

The Barrage de Monteynard (Fig. 4), designed by Coyne and Bellier, is one of a complex of dams that control the River Drac and is the biggest of five hydroelectric power generating stations in the region. The dam is 150 m high with a crest length of 210 m and has a reservoir capacity of 485 × $10^6$ m$^3$, damming 21 km of lake. The useable generating capacity is 185 × $10^6$ m$^3$ via four 90 MW turbines, which have a throughput of 300 m$^3$ s$^{-1}$ with 40 m head of water. Hydroelectric power in France is used for peak load, with the base requirement being met by nuclear power. The dam's construction is of a single curvature, 20 m thick arch dam with the abutments loading 400 kPa at the top and 800 kPa at the base of the structure, abutting into limestones of Toarcian (Jurassic) age. The limestones strike north–south and dip 40° to the west. The water height in the reservoir is limited by two old glacial drainage channels of the Drac, dating from the Würm glacial stage. There is 2 $m^3$ $s^{-1}$ leakage out of these relict channels. Several almost vertical normal faults (named Berenice, Aglae, Clotide, Josephine and Julie la Rousse by the dam construction engineers), which strike across the dam, required grouting during construction. One particularly large fault (Julie la Rousse) required a network of adits and vertical shafts to replace a 1 m thick zone of fault breccia. A total of 2800 $m^3$ of concrete was used for this purpose. The faults and potential associated ground behaviour prevented a thin arch dam being adopted as the design. The dam entered service in 1962 and is designed to withstand a Mercalli Magnitude 7 earthquake. There were no movements on the foundations when the reservoir was filled but there was a tremendous increase in localized seismic activity on filling, which continued into the 1970s, including a recorded Mercalli Magnitude 5.6 event. Grenoble is an area that is prone to earthquakes, although intensities larger than VIII on the MSK (Medvedev–Sponheuer–Karnik) scale have never been observed over the last 800 years (Thouvenot *et al*. 2006).

## Location 2: Harmallière and Mas d'Avignonet landslides [GR 710700, 4979700]

During the last period of maximum glacial advance in the Trièves region (Würm II stage) a large ice-dammed glacial lake developed, which gradually infilled with a variety of glaciogenic sediments, notably glaciolacustrine silt and clay sequences (including laminated 'varved clays') with further till sequences representing ice readvances. These deposits rest on older Riss–Würm interglacial sediments and on underlying Jurassic carbonate-dominated bedrock (Jongmans *et al*. 2008). The thickness of the glaciolacustrine deposits varies between 0 m and a maximum of 200 m. These sediments (Fig. 5) are extremely prone to instability and have given rise to some large spectacular rotational mudslides and subsequent mudflows in the area. It is possible to observe the differing facies associated with the former glaciolacustrine environment (Fig. 6), with rhythmic laminated silt and clay sequences, deeper water turbidity flows and ice-rafted debris. The lake deposits are interbedded with both sub- and supra-glacial tills, demonstrating the highly dynamic nature of the former prevailing Quaternary climate. The landslides at Harmallière (Fig. 7) and Mas d'Avignonet exhibit distinctly different kinematic behaviour in terms of displacement magnitude and motion direction (Kniess *et al*. 2009), with the underlying bedrock controlling the development of the landslides. The spatial distribution and geotechnical properties of the glaciolacustrine silts and clays have been extensively investigated with respect to

**Fig. 5.** Glaciolacustrine sediments of the former Lac du Trièves.

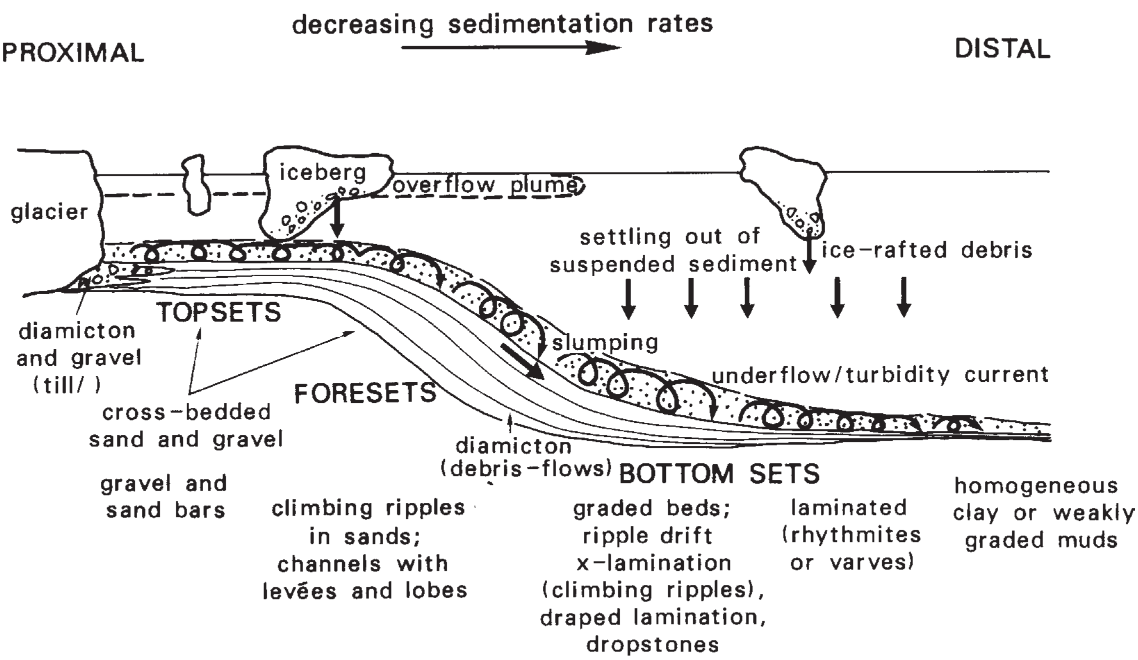


**Fig. 6.** Glaciolacustrine sediment system (Hambrey 1994).

**Fig. 7.** The landslide complex at Harmallière.

**Fig. 8.** Portal preparation works for the Sinard Tunnel (2003).

**Fig. 9.** The completed Sinard Tunnel (2008).

**Fig. 10.** The Echarennes rock avalanche shelter.

the potential alignments of the A51 autoroute passing through the region (Giraud *et al*. 1991). Their problematic nature, especially their propensity to liquefaction, has the potential to significantly affect the integrity of embankments and cuts along the road alignment.

## Location 3: Sinard Tunnel [GR 708820, 4980150]

The A51 autoroute was commissioned to provide a relief road for the A6 Rhone Corridor motorway, which connects Paris to the holiday regions of the South of France. The last remaining component of the autoroute was the section between Grenoble and Sisteron. This section was to pass through the highly problematic ground conditions of the Trièves area as observed at Location 2, and had been the subject of many investigations and research since the 1960s before a final route alignment was selected and agreed upon (Martin *et al*. 2005). Even at the construction tender stage this section remained controversial, with several initial design proposals being rejected because of the uncertainty in the ground conditions, specifically with regard to the glaciolacustrine and till sequences. This 10.5 km section between Coynelle and Col de Fau would cut through the Côte Martine massif, close to the village of Sinard, via a tunnel. The subsequently constructed Sinard Tunnel (Figs 8 and 9) is a 950 m long twin tube tunnel built between 2003 and 2006. Significantly, the tunnel was completed before the carriageway for the autoroute (Guilloud *et al*. 2005). The tunnel was excavated using drill and blast techniques cutting through a sequence of mainly calcareous quartzitic mudstones. These strata were significantly faulted, with six fault zones identified during the ground investigation. The maximum rock cover over the central zone of the tunnel was in the region of 160 m. Tunnel support varied with the rock mass conditions and was a combination of shotcrete and rock bolts, with some steel sets in the more problematic areas.

## Location 4: Echarennes rock avalanche shelter [GR 720700, 4973700]

The RD526 connects the village of Mens with the town of La Mure and traverses the tight deep ravines cut by the River Drac through the underlying Jurassic strata. At Echarennes a rock avalanche shelter was constructed to protect a vulnerable and narrow section of the road (Fig. 10). At this location the site

**Fig. 11.** The Echarennes rock avalanche shelter post failure (2004).

is flanked by a steep gorge with the cliff face rising to an altitude of 870 m a.s.l., the road level being at 620 m a.s.l. The site geology consists of three distinct lithological units, which are Jurassic in age: a heavily fractured marly limestone, a cleaved mudstone and a calcareous grey–black marl basal unit dating from the Aalenian stage (Desvarreux 2006). On 20 January 2004 a major debris flow involving several tens of thousands of cubic metres of material was initiated in the slope above the existing rock avalanche shelter and subsequently cut the unprotected section of the road at the western end of the shelter (Fig. 11; Robit *et al*. 2005). Rapid remediation works were required, which included both containment measures (netting and supplementary rock catch nets) along with further instrumentation of the 45° slope. Before this major slope failure existing protective measures were in place to safeguard the road below. These included active support systems (rock bolts, wire netting and rock catch nets) as well as the substantial rock avalanche shelter. The slope monitoring included a surveillance system linked to an alarm, which would close the road in the event of any significant slope movement. Three preferential flow paths (thalwegs), which controlled the runout of the debris flows, can be seen above the shelter, but the influence of these channels in the engineering geomorphological model had not been sufficiently delineated or understood, and consequently the original rock avalanche shelter had not been constructed long enough, leading to the road being cut by the debris flow.

## Location 5: Pont de Ponsonnas fluvioglacial deposits [GR 720760, 4973880]

The roadside section near the car park by the Pont de Ponsonnas exhibits a striking cross-section through the fluvioglacial outwash deposits from the Würm glaciations. Clasts of up to boulder size can be seen to be clearly imbricated. This orientation would suggest a high-energy outwash flow from the Bonne Glacier to the east, infilling the Trièves basin. Above the fluvioglacial deposits can be seen further basal till units overlain by the laminated glaciolacustrine sediments typical of the area. The site clearly highlights the dynamic nature of the glaciated landsystem and the typically wide variation in deposits and particle sizes that can be present in these terrains over very short distances. This site demonstrates the importance of a predictive geological ground model to fully understand the ground variability, which could potentially be missed or not accurately delineated by traditional intrusive investigation techniques.

## Location 6: La Mure anthracite mining [GR 719350, 4978290]

The Matheysine area has had a long history of coal mining owing to the high-quality anthracite deposits to be found in the region in a small Carboniferous inlier. Mining started in the early 19th century, with the mine at La Mure opening in 1808. Mining ceased in the late 1990s after a series of prolonged strikes. There were seven principal mines in the area: Mine du Majeuil, Mine de la Motte d'Aveillans, Mine du Peychegnard, Mine de la Jonche, Le Marais de la Mure, Mine de Vaulx and Les Boynes. The mines exploited four coal seams with 16 m of coal in total. One of the seams of this high-quality anthracite was 10 m thick. Several areas of former spoil tips can be observed along with areas of remediation where commercial redevelopment has taken place. The former mining activity is now commemorated by a working museum, La Mine Image, at La Motte d'Aveillans.

## Location 7: Mont Sec and Séchilienne [GR 720750, 4992880]

The Ruins de Séchilienne (Fig. 12) on the southern flank of Mont Sec in the Romanche Valley is a site of substantial slope instability initiated after the last glacial retreat around 15 ka ago. The landslide has been extensively studied owing to the extremely high impact that any large-scale failure would have on the local and wider environment and regional economy (Antoine *et al*. 1994; Rochet *et al*. 1994; Vengeon *et al*. 1999; Meric *et al*. 2005, 2006; Le Roux *et al*. 2008, 2009; Durville *et al*. 2002). The valley sides consist of predominantly mica schists, gneisses and amphibolites, rocks with a distinct metamorphic fabric, which at this locality is oriented parallel to the valley. These rocks are overlain by a Mesozoic cover, draped with various glaciogenic deposits. The area is tectonically influenced by the active Belledonne Border Fault, a major strike-slip system close by (Thouvenot *et al*. 2003). Various slope failure mechanisms can be observed, principally deep-seated gravitational failure (sackung) and more superficial rockfalls (Fig. 13). Estimates of between $25 \times 10^6$ m$^3$ for the global destabilized mass and around $3 \times 10^6$ m$^3$ for the superficial rockfalls have been calculated. Should the slope fail catastrophically a landslide dam would be formed, blocking the Romanche River. There is historical evidence that such events have occurred in the past (Bonnard 2006), with a significant damming of the river occurring in 1191. This dam subsequently failed in 1219, devastating the city of Grenoble downstream. The upper part of the slope (at elevations above 1100 m a.s.l.) displays medium levels of activity with displacement rates between 20 and 150 mm a$^{-1}$. In this upper zone vertical displacement rates give an annual subsidence of between 7 and 16 mm a$^{-1}$. In the lower slopes (between 950 and 450 m a.s.l.) the frontal mass has a displacement approaching 1 m a$^{-1}$. This frontal movement generates frequent rockfalls, which present a significant hazard to the road below. The movement rates are particularly sensitive to seasonal rainfall and snowmelt. During the 1980s rockfalls on the lower slopes reached the road below, prompting the construction between 1982 and 1983 of a small embankment to act as a rock trap wall between the slope and the road. Owing to the size, energy and frequency of the falls these initial

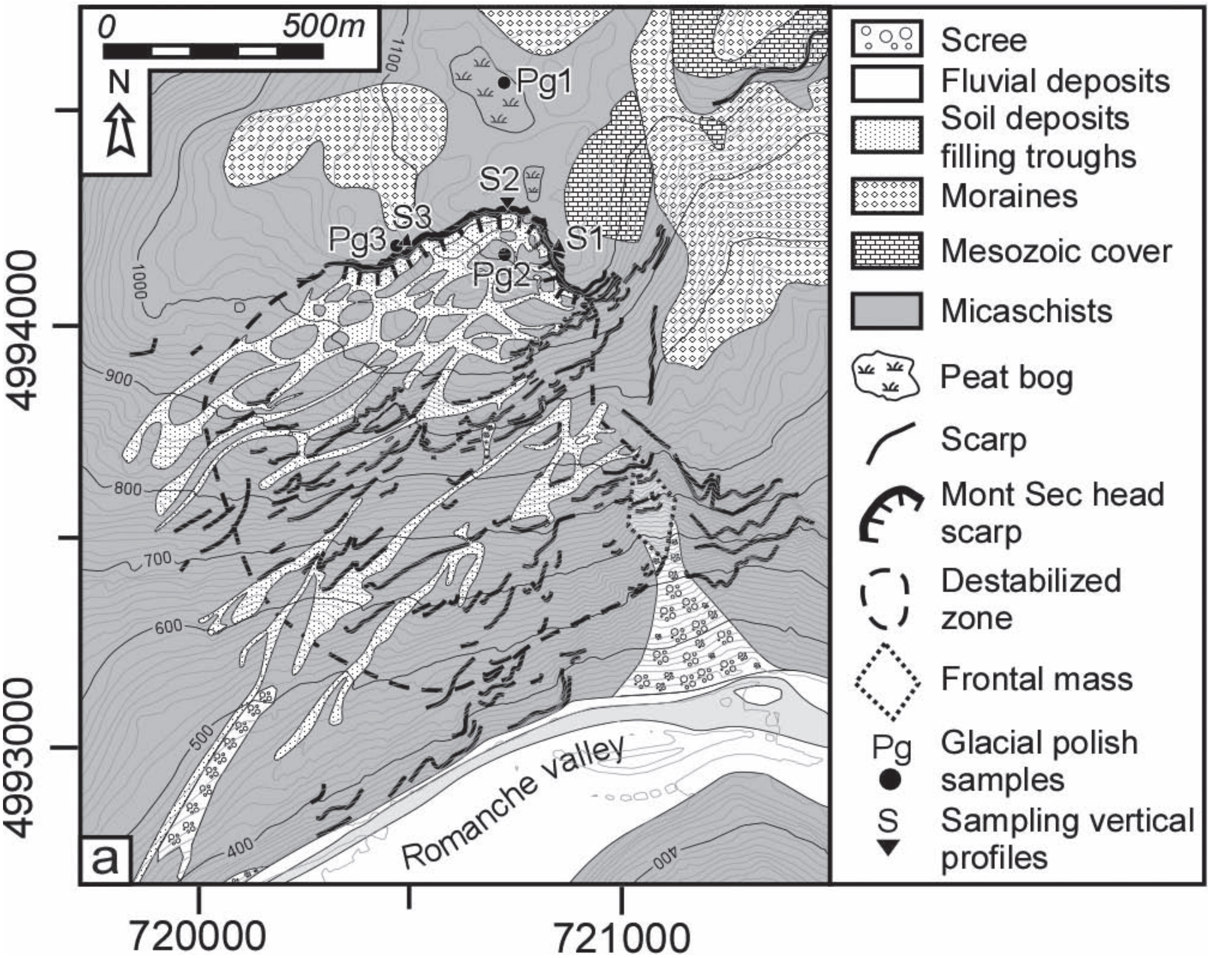


**Fig. 12.** Geological and geomorphological detailed map of the Séchilienne landslide (modified from Le Roux *et al*. 2009).

**Fig. 13.** The lower slopes of the Ruines de Séchilienne landslide (area marked as scree in Fig. 10).

protection measures were reappraised and deemed inadequate for the magnitude of the problem. This situation was further exacerated by a significant increase in rockfall events in 1985. Additional protection works were implemented, which included the excavation of a rock catch ditch at the toe of the slope together with a reinforced retaining wall. Alarm networks were also installed (Duranthon & Effendiantz 2004). These works underwent yet another reappraisal and the site risk was reassessed, which led to more significant changes, with a diversion road being constructed on the other side of the river utilizing two Bailey Bridges for the crossings. A new channel for the river was also constructed, along with a more substantial protective embankment. It was estimated that the thickness of the expected collapse mass at risk could dam the valley to a depth of 30 m or more. A further reappraisal is currently under way and is the subject of a local public consultation exercise. This site demonstrates the importance of understanding the geomechanical behaviour of the overall slope mass with respect to the potential impact of any failure on both the road and river within the valley system. Also, in terms of the risk management of this problem, the issue that the vulnerability element (in this case the city of Grenoble) may be significantly geographically removed from the hazard element (Séchilienne) should not negate the level of risk posed by the landslide system.

## Location 8: Falaise de Prégentil and Torrent du Saint-Antoine [GR 265800, 4993550]

The Falaise du Prégentil is an imposing cliff face cut by the actions of the Romanche glaciers advancing and retreating during the Quaternary. At this locality heavily folded Jurassic strata rest directly on the crystalline basement rocks that

**Fig. 14.** The Falaise de Pregentil and the Torrent du Saint Antoine above the town of Bourg d'Oisans.

underlie the Alps. The geological structure and associated rock mass properties play a significant role in the stability of this rock face. Both anticlinal and synclinal folding can be seen within the Jurassic beds. The rock mass structure is such that there is a major hazard with the potential for significant rock falls, rock flows (avalanches) and debris flows to be generated with a runout zone following the Torrent de Saint Antoine right down to the valley floor and town of Bourg d'Oisans below (Fig. 14). The sedimentary sequence present in the cliff face is especially sensitive to erosion, by rainfall, snow melt, and by freeze–thaw mechanisms during the winter months. The carbonates present are also vulnerable to dissolution, giving rise to a significant cavity system within the rock mass. The rock wall comprises interbedded marls and limestones, both of which are very prone to differential weathering. The marl units are much weaker than the limestones and therefore in-weather at a greater rate, leaving the limestone beds overhanging and liable to fail initially through rock fall. The dissolution of the limestone units compounds this problem, particularly where there is an adverse dip of the beds owing to the folding present within the mass. The instability of the cliff face is also affected by the presence of a number of vertical faults, which tend to delineate rock mass blocks and thus may lead to them failing as a single unit. Estimates of short- and medium-term risks of failure suggested that four such blocks were at risk in the short term and could potentially release between 140 × $10^3$ and 160 × $10^3$ $m^3$ of material from the face. In the medium term between 150 × $10^3$ and 200 × $10^3$ $m^3$ of rock could detach and fall. In the longer term it is thought that the supply of material that has the potential to fall should decrease as the rock mass approaches equilibrium. The lithological, geomorphological and rock mass


**Fig. 15.** Debris flow in the Torrent de Saint Antoine, 4 June 1998 (IRMa 2009).


**Fig. 16.** Rockfall of 29 June 1998 (IRMa 2009).

conditions at this site are therefore particularly conducive to a major rock fall, debris flow or even rock avalanche with no involvement of water. The significant cliff height (and hence potential energy of the rock blocks), high slope angle, large-volume supply of detachable material, significant water catchment from the rock wall face and extremely long runout track with the Torrent de Saint Antoine create a substantial problem for the town downslope. The site could therefore be considered as being a very high or extremely high hazard. This problem is compounded by two very high vulnerability elements within the landslide runout zone, notably the town of Bourg d'Oisans itself, and the Six Valleys College directly adjacent to the Torrent de Saint Antoine. Throughout documented history there have been many recorded instances of either major rockfalls from the Falaise du Prégentil, or debris flows or torrential floods running out down the Torrent de Saint Antoine, but it was the events of 1998 that led to a major re-evaluation of the risks posed by the Falaise du Prégentil (IRMa 2009). On 22 January 1998 a substantial volume of material in the region of 230 × $10^3$ $m^3$ was mobilized, which destroyed between 2 and 3 ha of forest. On 4 June 1998 a violent downpour lasting only 45 min transported about 20 × $10^3$ $m^3$ of debris downslope into the Torrent, filling the river bed with material to a depth of 4 m (Fig. 15). However, these events were to be surpassed by the rock falls of 29 and 30 June 1998. Approximately 100 × $10^3$ $m^3$ of rock fell from the cliff face, generating a dust cloud that enveloped Bourg d'Oisans (Fig. 16). From 1866 onwards a series of mitigation measures to protect the town from these geohazard events had been put in place, but the rock falls and debris flows of 1998 led to a reappraisal of their effectiveness and design. More significant protective measures were deemed to be required. A more substantial protective barrier system was constructed and a variety of monitoring and instrumentation systems were installed, directly linked to evacuation procedures for the college and town. A larger enhanced catchment basin was also excavated to deal with the diverted flows. The protective barrier walls were constructed from old tyres and compacted fill with reinforced end points. The barriers were designed to deal with debris flows of the order of 5 m high and for single falling or flowing rock blocks of between 200 and 500 $m^3$, sizes estimated from actual single blocks and flows recorded in the June 1998 event. This site is an excellent example of the importance of fully understanding the interactions of the geological structure, and lithological and geomaterial variability in the ground model, and their influence on the overall stability of the rock slope.

## Location 9: Charmonetier rockfall and tunnel [GR 265850, 4992850]

On 24 August 1987, storms and torrential rains initiated a major 'debris flow'–rock fall in the Taillefer Massif above the town of Bourg d'Oisans. Approximately $130 \times 10^3$ $m^3$ of rock ran out from the eastern flank of the Romanche valley, damaging the road connecting the two communes of Bourg d'Oisans and Villard-Notre-Dame (Couture *et al*. 1997). One year after the rock fall event a tunnel was constructed underneath the landslide zone to re-establish the road. Two check dams were also constructed to protect the village of Saint-Claude from any further flows. The rock mass mainly consists of amphibolites overlying massive granite with a Jurassic sedimentary cover and reaches a height of about 600 m above the valley floor. The initial failure zone occurred at the junction of the overlying sedimentary cover with the basement rocks and is located at an elevation of about 1250 m. The detachment zone of the failed mass extended to an elevation of about 1100 m along the natural talus slope at an angle controlled by the foliation planes within the amphibolite, which were subparallel to the valley and dipped between 25 and 40° (Desvarreux 2006). Three sets of discontinuities were observed in the original failure zone: Set 1 (Foliation), 31° ± 7°/303°; Set 2, 80°/194°; Set 3, 76°/82°. It is also possible to detect a fourth, less distinctive, set in the detachment zone (88°/332°). The joint system subdivided the amphibolite in the initial failure zone into blocks of an average dimension of 1 $m^3$. The overlying sedimentary formations have dips ranging between 20° and 40° into the slope but do not have a significant influence on the stability of this slope. The metamorphic foliation is the main controlling factor in the stability of the natural slope. The orientation and the dip of the foliation plane are conformable with the slope angle, and the dip of the foliation plane (the potential plane of weakness) is of the same order as the internal angle of friction of the amphibolite. Ancient mining activities (Mines de la Gardette) exploiting a quartz vein at the site may have also contributed to the rock fall and may also influence the stability of the slope. Laboratory shear box tests performed along foliation plane angles yielded residual friction angles of 39° and 30° under dry and wet conditions respectively (Couture *et al*. 1997). This site again demonstrates the significance of understanding the geological model both in terms of lithology and rock mass structure and in relation to the slope failure mechanisms.

**Fig. 17.** Barrage du Chambon.

## Location 10: Chambon Dam [GR 274480, 4991940]

The Barrage du Chambon (Fig. 17) is a large gravity dam high up in the Romanche Valley. The reservoir was brought into commission in 1934 but the dam is interesting as it demonstrates the potential problems that can occur with an unsatisfactory ground investigation. The dam has a reservoir capacity of $54 \times 10^6$ $m^3$. The top water level is at 1040 m a.s.l. with the dam crest at 1042 m a.s.l. The dam's catchment area covers 250 $km^2$. Chambon is a curved concrete gravity dam and has a height of *c*. 90 m above ground level (Walters 1971). The dam has been constructed on gneiss and overlying Lower Jurassic and Triassic sediments, which are predominantly cleaved calcareous mudstones (Fig. 18). Under the river bed was a significant glacial channel infilled with superficial deposits. During the ground investigation only four boreholes were sunk, and the resulting data failed to deliver a satisfactory geological ground model of the site, particularly with regard to the Quaternary modification of the valley profile. On construction the gneiss rockhead was found to be much deeper than predicted by the borehole data, and significant design modifications and substantial grouting were subsequently required.

## Concluding remarks

The area to the south of Grenoble in the French Alps offers an ideal field environment to study some of the key engineering and geological issues in the practice of engineering geology. The importance of the predictive ground model and its component parts of geological, geomorphological and geotechnical data together with visualizations of the key hazards, vulnerabilities and risks present at a site are well established. This field area exemplifies these key issues with a variety of case studies of large engineered structures and problematic ground conditions.

The sites at the Falaise du Prégentil and Charmonetier demonstrate the importance of understanding the rock mass condition and how the underlying geology can influence those conditions. At the Pont de Ponsonnas and Harmallière the variability, both vertical and lateral, in ground conditions is demonstrated in the superficial sequences, which were strongly influenced by glacial and post-glacial processes. At Chambon the inadequacy of the ground investigation and the lack of understanding of the Quaternary ground model led to significant delays and cost overruns on the

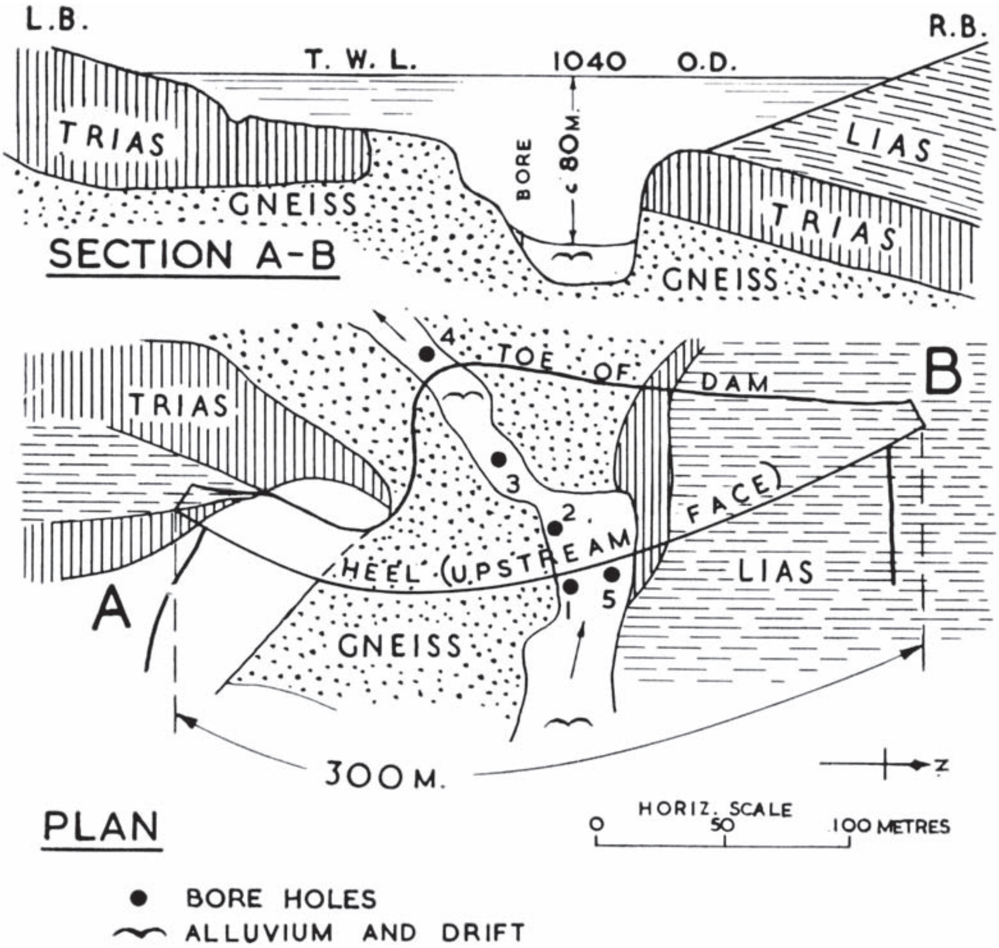


**Fig. 18.** Barrage du Chambon, plan and section view (Walters 1971).

project. At Séchilienne the key issues of operating within a risk management framework are demonstrated, as well as the wider issues of understanding the geomechanical behaviour of a very large slope, whereas at Echarennes the lack of appreciation of the geomorphological behaviour of the slope led to a major failure.

All of the sites detailed in this field guide reinforce and demonstrate the requirement of the engineering geologist to fully appreciate the geological and geotechnical ground models in a risk-based framework to allow the successful completion of any engineered structure built in those ground conditions.

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