Hydrogeochemistry: an investigation tool to evaluate infiltration into large moving rock masses (case study of La Clapière and Séchilienne alpine landslides)

Y. Guglielmi · J.M. Vengeon · C. Bertrand · J. Mudry · J.P. Follacci · A. Giraud

Abstract Isotopic and hydrogeochemical methods have been used to investigate groundwater movement inside the La Clapière and Séchilienne alpine landslides in southern France. The δ^{18}O data were used to determine the infiltration altitudes of the two areas. The infiltration results indicate that the landslides are recharged from beyond the landslides' perimeters. Hydrogeochemical data on major ions were collected from springs. Numerical simulations of water–rock interactions were then undertaken. The major petrographic contrast between the limited sedimentary rocks and the more common mica-gneiss/micaschist results in a marked change between the measured and calculated groundwater contents. This contrast of 800 mg/l of SO_4 in the Triassic rocks but only 100 mg/l for the waters from the metamorphic strata at La Clapière is significant. Two different groundwaters have been identified in both landslides: (1) a perched shallow saturated zone near the slope summit; and (2) a deep saturated zone located at the foot of the slope. Chemicalmonitoring of spring waters in the two zones has allowed an assessment of the infiltration within the slope over time. There is a good correlation between the sulphate content of the perched waters and rate of slope movement, with a sulphate dilution peak corresponding to an acceleration in the movement of the landslip. However, there is no correlation between the chemistry of the deep aquifer and the speed of movement. It would appear therefore that the hydromechanical behaviour of the landslide depends on the vertical leakage from the perched aquifer down to the basal aquifer and the near-surface effects of the water movement.

Résumé Des méthodes isotopiques et hydrogéochimiques ont été utilisées pour étudier la circulation des eaux dans des glissements de terrains alpins, La Clapière et Séchilienne situés au sud de la France. Les données d'δ^{18}O ont été utilisées pour déterminer les altitudes d'infiltration de ces deux zones. L'infiltration se fait sur des zones de recharge supérieures aux périmètres des glissements. Les données hydrogéochimiques consistent à analyser les ions majeurs des eaux des sources. Des simulations numériques des interaction eaux-roche sont réalisées à partir de ces données. Les contrastes pétrographiques entre les roches sédimentaires et les roches les plus abondantes qui sont les micagneiss/micaschists impliquent des variations bien marquées entre les concentrations calculées et mesurées des eaux. Ce contraste est très net dans le cas de la Clapière car il est de 800 mg/l pour les terrains triasiques alors qu'il n'est que de 100 mg/l pour des eaux qui ont circulé sur des terrains métamorphiques. Dans les deux glissements de terrains, deux types d'eau ont pu être identifiés: a) une zone saturée, perchée peu profonde près du sommet du glissement; b) une zone profonde localisée au pied de glissement. Un suivi chimique des eaux de sources dans les deux zones permet de déterminer une estimation des infiltration dans le massif en fonction du temps. Il y a une bonne

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corrélation entre les concentrations en sulfates dans les eaux du réservoir perché et les vitesses de mouvement du glissement. Une dilution des concentrations en sulfates correspond à une accélération du mouvement du glissement. Cependant, il n'y a pas de corrélation entre la chimie des eaux du réservoir profond et la vitesse du mouvement. Cela signifie que le comportement hydromécanique du glissement dépend des pertes d'eau depuis le réservoir perché vers l'aquifère basal.

Keywords Large moving rock masses · Hydrogeology · Water chemistry · Hydromechanics

Mots clés Grands mouvements de versants rocheux · Hydrogéologie · Chimie des eaux · Hydromécanique

Introduction

One of the main factors that initiates and controls the mobilisation of rock is the infiltration of precipitation into the rock mass (Noverraz et al. 1998). Unfortunately, due to the anisotropy of the rock mass, understanding the groundwater regime beneath large landslides cannot be undertaken using classic hydrogeological methods. Further, the movement of such landslides quickly destroys instrumentation and is a danger for operators. For these reasons, it is desirable to develop an indirect method based on the study of the hydrogeochemistry of the groundwaters and any water–rock interactions in an area that includes a large landslide.

This paper presents the first hydrogeochemical data on two of the main landslides in the French Alps – at Séchilienne, bordering the Belledone massif near Grenoble, and at La Clapière in the Mercantour massif near Nice. The two objectives of the study were firstly to calibrate the hydrogeochemical water measurements on each site and secondly to show how geochemical data can be correlated with the normal monitoring of the rate of movement.

Characteristics of the hydrogeology of large moving rock masses

The observations summarised below are based on the studies of the Séchilienne and La Clapière areas (Antoine et al. 1994 ; Follacci 1999; Guglielmi et al. 2000). Comparisons are also made with other work relating to large moving rock masses and climate (Noverraz et al. 1998). Large rock mass instabilities usually occur in mountainous regions. For this reason, their hydrogeology depends on three main factors: (1) the variability of rainfall and infiltration rate; (2) the drainage anisotropy of the rock mass between a low-permeability block/matrix (primary permeability) and the fractures that readily transmit water (secondary permeability); (3) the modification of the hydraulic parameters of the rock mass reservoir related to both the change in weather (rain/snow) and the ongoing slope movement.

Variability of precipitation

Large hillside instabilities extend over considerable ranges in altitude on mountainous slopes: La Clapière extends from 1,100 to 2,000 m and the Séchilienne from 345 to 350 (Fig. 1a). In such mountainous environments, rain and snow may fall simultaneously (rain at low altitudes and snow at high altitudes), or successively, as when snow is followed by a rain event over the whole slope. Snowmelt may vary both spatially and over time; e.g. the melting of the snow cover will take place at higher altitudes later in the season. In addition, the rain and snow induce different infiltration: instantaneous rain infiltration at low altitudes while at higher elevations the infiltration is delayed until the main snowmelt. However, daily melting, partly due to the geothermal flux at the basal part of the snow cover, may result in a continuous low aquifer recharge (Jacquemin 1984). The melting of snow induces significant variations in the yield of springs; the lows of late winter are often twice as high as those of the summer months.

At La Clapière, for example, the mean yearly rainfall is some 936 mm and falls within two short periods; about 1 or 2 months long in the autumn and in June. Snow normally occurs from December to April. During the winter period, the 0 °C isotherm is at approximately 1,800 m ordnance datum (OD); hence the melting of the mean annual snow cover which is present between December and April produces an equivalent of 810 mm of water at 2,500 m OD, while at 1,100 m OD it is less than 200 mm (Programme INTERREG 1996). Typically, below 1,800 m snow melts on several occasions even in winter, but at higher altitudes it will occur as a single event in the spring. In the lower altitudes, with several periods of melting, only about 20 to 50 mm of water infiltrates into the massif at different periods. Above 1,800 m, however, there is significant infiltration at the end of the winter season and mass movements of 30 to 100 mm/day have been observed (Follacci 1987) when about 1 m of water is believed to infiltrate into the rock mass with the spring snowmelt.

Drainage anisotropy

Infiltration enters the rock mass through a complex anisotropic bedrock reservoir. This can be divided into two zones: the main landslide itself and the upslope area which tends to creep downslope due to loss of support. The movement of the landslide results in the development of open fractures in the disturbed and brecciated mass. Consequently, the disturbed mass has many voids such that it can be compared to a porous reservoir. In the less-disturbed remainder of the slope, the rock matrix behaves as a relatively impervious material with flows concentrated in the fractures. Although they undoubtedly exist, there is no obvious hydraulic connection between these two zones. When the infiltration rate is such that the full ingress cannot be transmitted through the rocks, a head of water is created as the bedrock mass becomes progressively

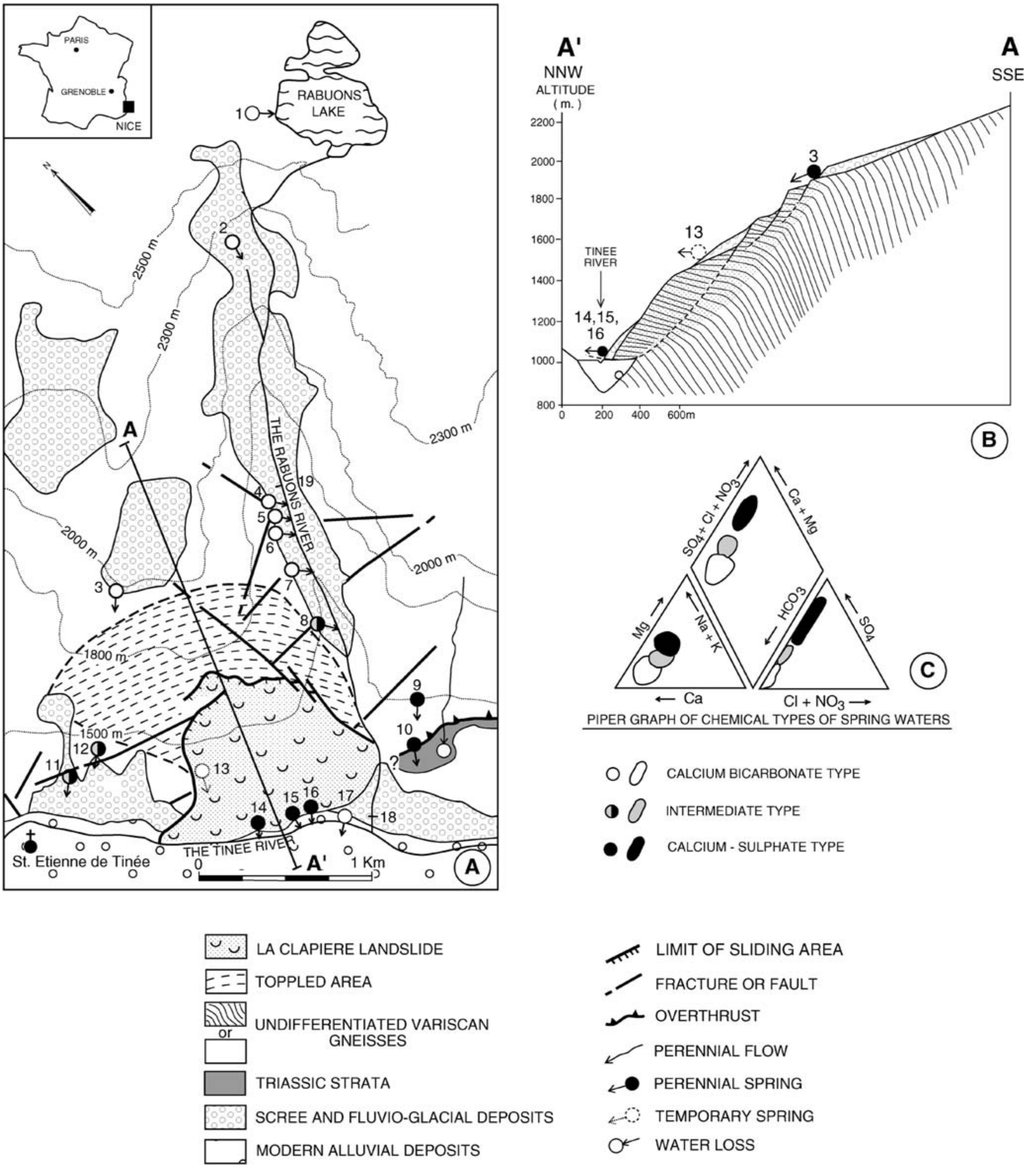


Fig. 1a–c.
Hydrogeology of the La Clapière slope. **a** Hydrogeological map; **b** geological cross section of the moving rock mass; **c** Piper diagram of chemical types of spring waters

saturated. However, on a hill slope, neither the limits of the area supplying the groundwater through a series of passageways to a landslip nor the egress points are known; some of these may be downslope of the visible landslide.

Modification of hydraulic conductivity by the movement

In a discontinuous aquifer, the flow and the consequential water pressure depend on the aperture of the fractures (Louis 1974; Neretnieks 1983; Cacas et al. 1990; Abelin et al. 1991). Laminar flow between the two sides of a fracture is approximated by a simplification of the Boussinesq equation (Krantz et al. 1979; Witherspoon et al. 1980;

Renshaw 1995). This shows that for a constant hydraulic head, the flow rate varies with the cube of the aperture of this fracture. In a system of fractures, the flow is controlled by the connectivity of the different fracture directions and by the different conductivities of the fractures (Long et al. 1985; Lee and Farmer 1990). In the case of large, rocky landslides the complex behaviour of anisotropic aquifers is complicated not only by the bedrock but also by the effects of the internal deformation of the moving mass creating and closing fractures as the movement occurs. It appears from field and laboratory studies that normal closure of a fracture can occur under low stresses and that even with a moderate closure there is a significant decrease in the rate of flow (Tsang and Witherspoon 1981; Billaux and Gentier 1990; Sibai et al. 1997). Gentier and Hoppkins (1997; Gentier et al. 1998) note that shear displacement introduces dilatancy in the plane of the fracture, resulting in an increase in the flow rate where the hydromechanical coupling is related to differences in the conductivities of the various sets of fractures (Guglielmi 1998, 1999). The internal flow is rendered more complex in the case of a fracture system and varies with time depending on the state of the deformation.

The sites

La Clapière

The La Clapière landslide is located on the left bank of the NW–SE Tinée valley, near the town of Saint-Etienne-de-Tinée (Alpes-Maritimes, France; Fig. 1a). It is monitored by the French Ministry of Equipment. It is bordered to the south-east by the Rabuons River – a major tributary flowing from a lake at an elevation of 2,500 m – while nearby the mountain peaks commonly exceed 3,000 m. The base of the La Clapière landslide is at an elevation of 1,100 m where the 1 km wide disturbed rock mass extends out over the Quaternary alluvial deposits of the River Tinée. At the top of the landslide a 120 m high scarp extends over a width of 800 m at an elevation of some 1,600 m. The base of the slip is not known over the upper 500 m of the landslide, but it can be seen at the lower elevations. It is thought the failure may reach a depth of some 100 to 200 m (Fig. 1b). The landslide itself is divided into seven segments related to pre-existing faults, each segment moving at a slightly different speed. Typically, a 200 m wide zone is present on the flanks, in which the movement is very small such that it acts as a transition between the stable area and the slide itself.

Bogdanoff and Ploquin (1980) record that the strata in this area consist of micagneisses which form the Argentera–Mercantour massif of Variscan age. The average strike of the foliation is N140°E while the north-easterly dips vary between 55 and 90°. Three sets of faults are present, trending N10–30°E, N90°E and N110–140°E (Fig. 1a). To the south-east of the Rabuons River, some 0.5 km above its confluence with the Tinée River, the gneisses have been thrust above the Triassic sedimentary sequence which here occurs as a tight overturned syncline with an inner core of gypsum and *cargneules* (cellular tectonised dolomites) enclosed by sandstone horizons. (Faure-Muret 1947; Ivaldi et al. 1991). The thrust plane between the gneisses and the underlying Triassic strata is exposed in the bed of the Cascaï where it can be seen to strike N140°E and dip north-eastwards at about 80°. Scree and fluvio-glacial deposits locally cover the gneisses, especially in the upper reaches of the Rabuons River.

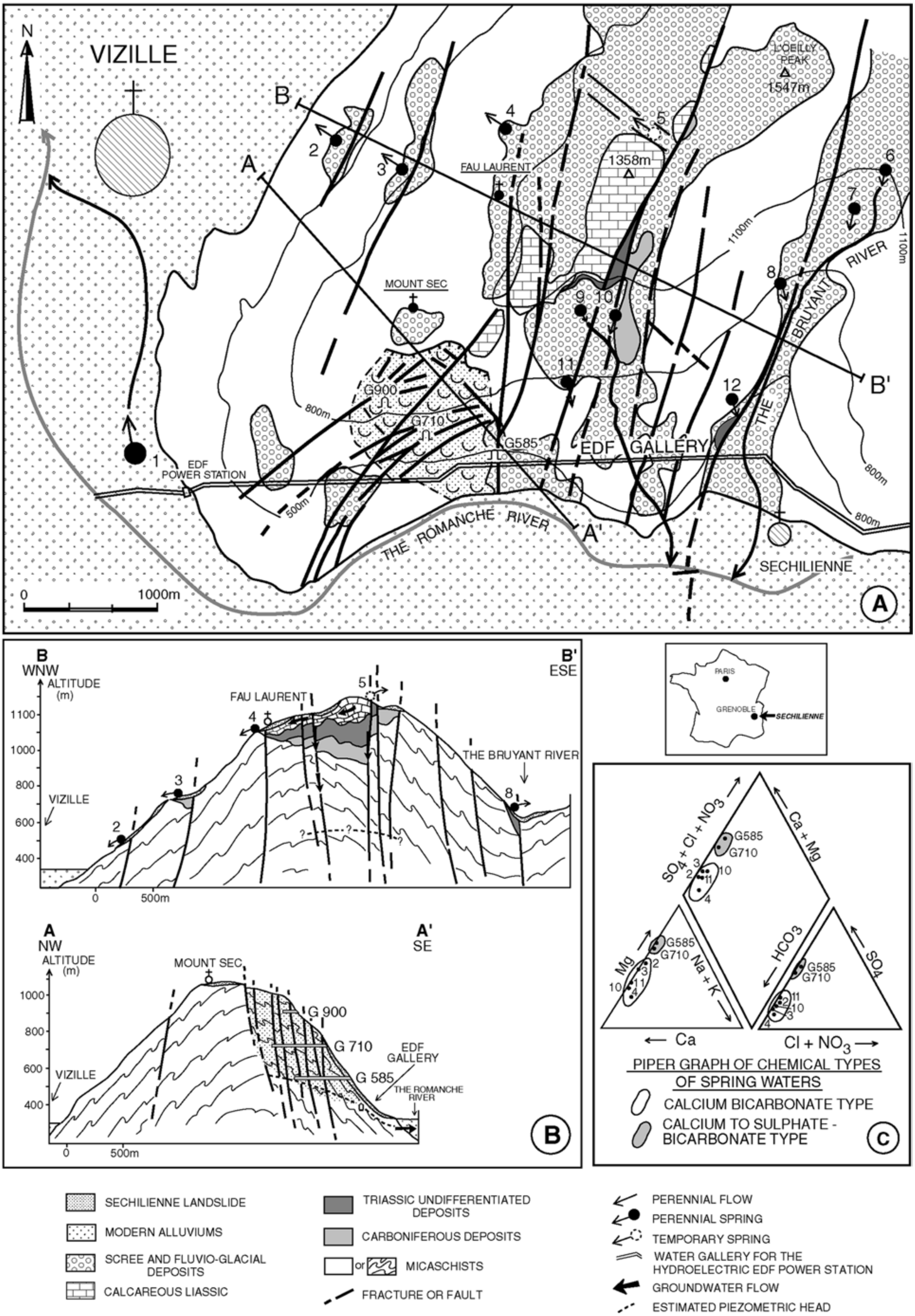
The foot of the landslide is drained by a group of perennial springs (springs 14, 15 and 16, Fig. 1a) with a total discharge estimated at 0.5 l/s. Other temporary springs occur higher up the slope, such as spring 13 (Fig. 1a), while in the adjacent areas springs can also be observed emanating from fractures in the bedrock (springs 6 and 7) or from the weathered superficial formations (e.g. spring 5). Within the Rabuons valley, other springs discharge from the glacio-fluvial and scree deposits (springs 4 and 8), while to the west springs 11 and 12 have been observed close to a mapped fracture line. The mean discharge of a single temporary spring reaches about 0.2 l/s, while the total discharge of the temporary lateral outflows is about 5 l/s. Individual flows as high as 4 to 5 l/s have been measured locally, e.g. at the overthrust (springs 9 and 10), emphasising the importance of this major feature in the drainage of the hill mass. The springs in this area are mainly egress points related to water emanating from the bedrock through the fractures. However, as would be expected, some springs drain only the screes above elevations of 2,000 m (springs 2 and 3) or the glacio-fluvial deposits where these abut the alluvium of the River Tinée (spring 17).

Séchilienne

The Séchilienne landslide is located on the right bank of the east to west flowing River Romanche, near the south-eastern side of the city of Grenoble (Isère, France). The landslide is located on the southern slope of Mount Sec, part of the L'Oeilly Peak Mountain which rises to a maximum elevation of 1,547 m (Fig. 2a). The mountain is at the south-west border of the Belledone Alpine massif. The slope is formed of micaschists, with a general northerly subvertical foliation. To the east it is bordered by a N20°E-trending major fault zone. Two conjugate subvertical strike/slip fault sets are present, trending N140°E and N50–70°E with sinistral and dextral movements respectively. The N50–70°E faults have resulted in a strip-like morphology in the slope, while other fractures present at a lower level are more parallel to the axis of the valley. The Peak of L'Oeilly is formed of sedimentary Carboniferous to Liassic deposits unconformably overlying the old strata (Fig. 2a, b), the boundary between the sedimentary and older metamorphic deposits being at approximately 1,100 m, slightly higher than the upper backscar of the disturbed zone. Locally, scree and glacio-fluvial deposits

▶

Fig. 2a–c.
Hydrogeology of the Séchilienne slope. **a** Hydrogeological map; **b** geological cross sections of the Mount Sec massif (*A–A′* cross section of the moving area; *B–B′* cross section of Fau Laurent sedimentary deposits); **c** Piper diagram of chemical types of spring waters


N
VIZILLE
B
A
2
3
4
5
FAU LAURENT
1358m
L'OEILLY PEAK
1547m
6
7
1100m
RIVER
BRUYANT
THE
8
9
10
MOUNT SEC
11
12
B'
G900
G710
G585
800m
EDF GALLERY
1
EDF POWER STATION
500m
THE ROMANCHE RIVER
A'
SECHILIENNE
800m
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A
B
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ALTITUDE (m)
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1100
1000
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VIZILLE
FAU LAURENT
THE BRUYANT RIVER
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ALTITUDE (m)
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MOUNT SEC
G 900
G 710
G 585
EDF GALLERY
THE ROMANCHE RIVER
B
PARIS
GRENOBLE
SECHILIENNE
SO4 + Cl + NO3
Ca + Mg
Mg
Na + K
HCO3
SO4
Ca
Cl + NO3
PIPER GRAPH OF CHEMICAL TYPES OF SPRING WATERS
CALCIUM BICARBONATE TYPE
CALCIUM TO SULPHATE - BICARBONATE TYPE
C
SECHILIENNE LANDSLIDE
MODERN ALLUVIUMS
SCREE AND FLUVIO-GLACIAL DEPOSITS
CALCAREOUS LIASSIC
TRIASSIC UNDIFFERENTIATED DEPOSITS
CARBONIFEROUS DEPOSITS
or MICASCHISTS
FRACTURE OR FAULT
PERENNIAL FLOW
PERENNIAL SPRING
TEMPORARY SPRING
WATER GALLERY FOR THE HYDROELECTRIC EDF POWER STATION
GROUNDWATER FLOW
ESTIMATED PIEZOMETRIC HEAD

veneer the micaschists and overlying sedimentary deposits (e.g. at Mount Sec).

The landslip is moving from the top of the dome-shaped Mount Sec (1,130 m) to the floor of the valley at 345 m (Fig. 2b, A–A′ cross section). Between 345 and 700 m there is an unstable, totally disorganised area of some 60,000 m^2 referred to as the Séchilienne Ruins, while between 700 and 1,150 m the slope has deep N50–80°E cracks in addition to some N140°E faults where the apertures may be up to several metres wide. This approximately 0.5 km^2 zone is limited to the north by a 30 to 50 m high backscarp.

The mechanical behaviour of the landslide is a consequence of loading due to collapse at the top of the slope inducing movement and hence pushing up the lower part of the slope. The deformation process has been investigated by direct observations in three horizontal galleries located at different altitudes (Vengeon 1998): a 240 m long investigation gallery at 710 m and two 60 and 240 m long old mining galleries at altitudes of 900 and 585 m respectively (see Fig. 2b). The fractures effectively divide the slope into diamond-shaped blocks such that the blocks move independently, resulting locally in differing degrees of movement. Indeed, it is these block movements that are responsible for the entire mass movement at Séchilienne where no basal shear has been identified.

Three main factors explain the hydrogeology of the massif:

1. The top sedimentary deposits contain a perched multi-layered aquifer (Fig. 2b, B–B′ cross section) drained by several perennial springs which outflow at the top and the middle of the slope at between 820 and 1,170 m (Fig. 2a; springs 4, 9, 10 and 11). During periods of high infiltration, a temporary spring appears (spring 5) at an altitude of 1,310 m, indicating that the rocks are saturated to at least 100 m above the elevation of the top of the slide. The total discharge of perennial springs is estimated at 10 to 30 l/s depending on the season. This value appears low compared to the mean annual recharge of the natural reservoir which is about 60 l/s, indicating that some 50 to 80% of the groundwater yield passes down into and through the bedrock. Some of the water rising through the springs infiltrates back into the bedrock at a lower elevation, while the remainder flows into the Romanche River.
2. An Electricité de France (EDF) water gallery is located at the bottom of the slope at 425 m (Fig. 2a, b), directly under the landslide. During the digging of this gallery, springs that were initially draining the basement aquifer at an elevation of 500 m dried up. It is clear therefore that the bedrock aquifer was drawn down and was partially released by this gallery as the water egressed through open discontinuities, particularly following rainfall on the massif (Fig. 2b). As perennial flows only occur in the lower gallery (G585), it is clear that the near-surface bedrock beneath the higher parts of the Séchilienne landslide is not saturated or that the water movement in the near-surface regolith is capable of transmitting the “diffused” outflow.
3. No spring is visible at the foot of the slope where the landslide intercepts the alluvium in the Romanche valley. Some 2 km to the west of the landslide, a spring (no. 1) rises from the alluvium in the park of Vizille Castle. This spring yields some 1,200 l/s which it is believed is partly from the Mount Sec bedrock aquifer and partly water derived from the Romanche River itself. An estimated value of 200 to 500 l/s would correspond to a recharge area of approximately 10 to 20 km^2. This would be equivalent to about 50 to 80% of the slope forming the Mount Sec and Peak of L’Oeilly on which the Séchilienne landslide occurs.

Comparison of the two sites

Although both the Séchilienne and La Clapière landslides are responsible for moving in excess of 50 million m^3 of material, in the former the main movement is in the upper part of the slope while in the latter the landslide extends over the whole hill slope. Upslope of the main landslide at La Clapière is an area where regressive slips are taking place, giving the appearance of a broken, disturbed bedrock. At La Clapière, a distinct basal slide has been located, while at Séchilienne no single sliding surface is evident, the deformation here being related to the tectonically fractured block structure.

In both cases, the geology of the slope consists of metamorphic rocks with outliers of the Mesozoic sedimentary cover. At La Clapière, the gneisses are composed of quartz, plagioclases, biotite, muscovite with minor calcite, pyrite and K-feldspar. The gneisses are highly foliated with alternating light and dark bands. At Séchilienne the foliation in the micaschists is accentuated by the biotites, phengites and chlorites alternating with granoclastic quartz and feldspar. Small layers of black schists and calcitic veins were observed in an investigation gallery. At La Clapière the Triassic deposits are present in an overthrust, while at Séchilienne the Liassic, Triassic and Carboniferous deposits unconformably lie at the top of the massif.

At La Clapière the internal drainage of the massif consists of a complex system of interconnected pathways between the fractured bedrock and the overlying screes or breccia. Most of the springs identified outflow in the higher part of the slope some distance from the landslide, hence it is difficult to assess which part of the bedrock they drain and to establish a water balance. At Séchilienne there are two main saturated zones. A perched sedimentary aquifer leaks into the underlying bedrock aquifer which could be partially drained at a spring located near the town of Vizille (Fig. 2, spring 1), although this assumption needs to be defined by tracing tests. In both landslide areas significant volumes of water can move through and/or be temporarily stored in the moving rock mass.

From classical hydrogeology to an indirect approach: methodology

Landslide hydrogeology aims firstly at evaluating the distribution of the hydraulic pressure inside the rock mass

and secondly at determining the danger thresholds. Hydrogeology is traditionally based on piezometric measurements, but these are not appropriate in the present case and would probably be quickly destroyed. Consequently, an indirect method based on the chemistry of the groundwater outlets has been developed using the water chemistry related to the interstitial fluids within the large moving rocks masses and the chemical content of the spring waters resulting from global water–rock interactions within the bedrock (Bakalowicz 1979; Mudry 1987). The sampling of spring waters was performed during different periods of the year using a typology related to the in-situ hydrogeological conditions. This typology is compared with a parametrical study on a geochemical model (Madé et al. 1990) which has been successfully tested on the La Clapière slope (Guglielmi et al. 2000). The results were compared with those obtained at the Séchilienne site in order to assess how chemical monitoring of spring waters may help elucidate the mechanical behaviour of large landslides.
The chemistry of the waters was determined by:

Atomic absorption spectrometry (accuracy ±0.05 mg l^{-1}) K^+, Na^+, Ca^{2+} and Mg^{2+}
High-pressure ionic chromatograph (accuracy ±0.02 mg l^{-1}) SO_4^{2-}, Cl^- and NO_3^-
Volumetry in the field (accuracy 1%) (acid–base titration) HCO_3^-
WTW (Wissenschaftlich-Technische-Werkstätten) (type LF30)
pH, electrical conductivity and temperature.
Measurements were modified to a standard temperature of 25 °C.

All the analyses were performed in the hydrogeology laboratory of the Department of Geosciences (University of Franche-Comté) for the La Clapière landslide and at the Grenoble Region Water Association (SIERG) for the Séchilienne landslide. The $\delta^{18}O$ measurements were made at Avignon and Thonon to an accuracy of 0.25‰.
The thermo-kinetic geochemical model KINDIS (Madé et al. 1990) was used to simulate the water composition for different water–rock interactions. This model describes the interactions between minerals and aqueous solutions, taking into account the irreversible dissolution of some reactants and the reversible precipitation of secondary products. KINDIS calculates, by incrementation, the quantity of destroyed or formed phases per kilogramme of solution, according to the reaction rate which corresponds to the mass of dissolved rock per kilogramme of weathering solution. Evolution of the chemical composition of the solution and the distribution of elements between simple and complex ions are also determined at each step of this calculation.

Results of sampling

Recharge area

$\delta^{18}O$ values of spring waters were used to establish the mean recharge altitude of both landslides (Fig. 3a, b). In the present study, both old data from La Clapière (Guglielmi and Mudry 1995; Compagnon 1996) and new data from the same springs sampled at two different periods were used, while at Séchilienne all the data were new.

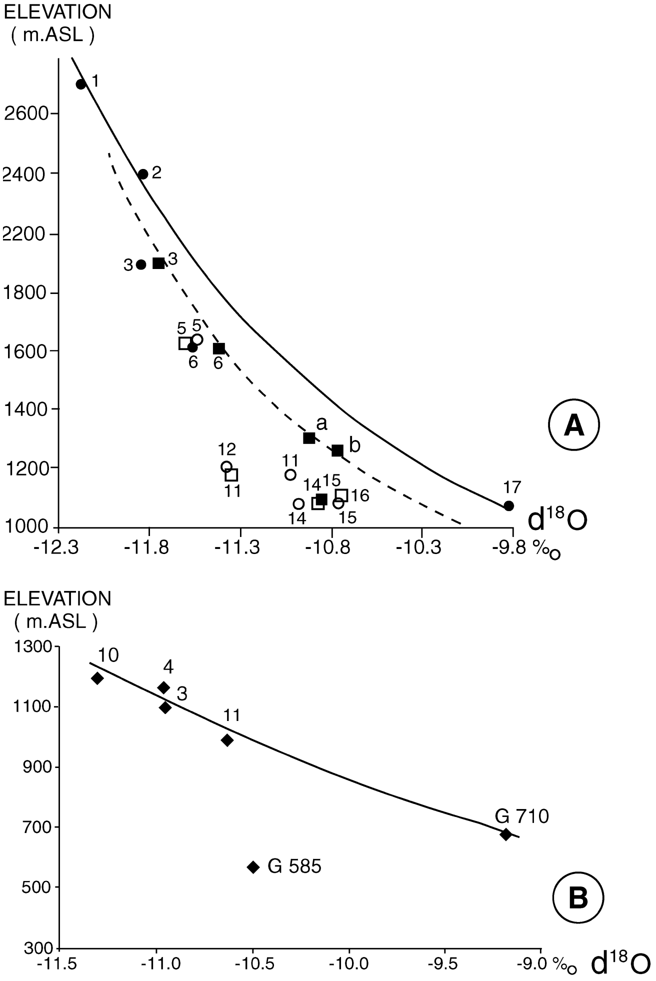


Fig. 3a,b.
Isotopic gradients (values used to calculate the gradients are plotted in *black*, values of springs in the recharge area with mean elevation are plotted with *open circles* and *squares*). *Squares a* and *b* correspond to $\delta^{18}O$ values of springs located about 2 km from the landslide and are not shown on the hydrogeological map in Fig. 1. **a** La Clapière massif (June gradient *dashed line* with $\delta^{18}O$ values in *squares*; December gradient *continuous line* with $\delta^{18}O$ values plotted in *circles*); **b** Séchilienne massif

^{18}O is a thermo-dependent tracer. This means that a spatial and temporal tracing exists: winter and/or high-elevation waters are more negative than summer and/or low-elevation ones. In order to take into account the effect of relief on the variations of the isotopic ratios, the local gradient on the slope was calibrated. Local springs were used where the catchment area could be clearly bounded (e.g. springs related to limited scree areas). The average elevation of the springs recharge area was estimated and the $\delta^{18}O$ plotted to allow comparison with the recharge altitude. The variation of $\delta^{18}O$ versus season was evaluated at La Clapière by measuring δ ^{18}O at different elevations during the winter, low-water period and early summer – snow-melt flood period – while at Séchilienne the measurements were taken only at the end of the spring infiltration period. Similar variations have been documented by Razafindrakoto (1988).

On these calibration curves (lines in Fig. 3a,b), a general decrease of $\delta^{18}O$ versus altitude is observed, although, as with other Mediterranean mountain areas (Mudry et al. 1994; Guglielmi et al. 1998), this relationship is represented by a flex curve because of the non-linear distribution of effective rainfall versus elevation (Blavoux et al. 1992). On the $\delta^{18}O$ versus altitude scattergram, each point for which the altitude of the intake area is unknown was plotted with its $\delta^{18}O$ and the altitude of the spring itself. Projecting the $\delta^{18}O$ value in parallel to the vertical axis, the average elevation of the recharge areas could then be estimated.

At La Clapière, both winter and summer gradients were calculated from springs at 1,100 and 2,500 m with a known average recharge elevation (Compagnon 1996; Fig. 3a):

$$\delta^{18}O = -2.10 \ln(\text{elevation}) + 4.18 \text{ with } r = 0.989 \qquad (1)$$

$$\delta^{18}O = -2.92 \ln(\text{elevation}) + 10.69 \text{ with } r = 0.988 \qquad (2)$$

The data on which Eq. (1) are based were collected in December 1995 and the data for Eq. (2) in June 1996. By plotting ^{18}O contents of the spring waters on the gradients already established, the mean elevation of infiltration area was determined. The lateral springs of the landslide have an infiltration area that ranges from 1,600 to 1,800±150 m. This corresponds to the transitional area which surrounds the landslide. The recharge area of waters outflowing from the foot of the landslide have an average altitude ranging from 1,570±150 m at the end of the low-water period to 1,780±150 m during the snow-melt flood period. This would indicate that the area of water infiltration for all the springs outflowing from the basement aquifer is approximately the same, larger and higher than the landslide area itself and varying according to the seasons.

At Séchilienne, the gradient is calculated from springs located between 1,000 and 1,200 m and from water that temporarily flows in the investigation gallery from a local recharge area at a mean altitude of 710 m (Vengeon 1998; Fig. 3b). The gradient $\delta^{18}O=-3.86\times\ln(\text{elevation})+16.1$ with $r=0.991$ was established on 29 August 1996 after a 100 mm local rainfall on the massif. Only the sample from the perennial flow observed in the gallery at 585 m was used to plot this gradient. Recharge comes from an altitude of 980 m which corresponds to an infiltration area that includes the top of the landslide and a large part of the summit of the Mount Sec massif, including the sedimentary deposits.

Discussion

The data show that at La Clapière the elevation of the recharge into the landslide varies according to the season, the type of precipitation and the temperature (Compagnon et al. 1997). Direct infiltration of the autumn rainfall is spread over the whole recharge area. Very little delayed infiltration occurs after winter rainfall and only at low altitudes. During the spring period, snowmelt is responsible for substantial infiltration at progressively higher altitudes (Follacci 1999). At La Clapière the surface recharge area was assessed to be about 4 km^2 and at Séchilienne 5 to 10 km^2, indicating that the hydrogeological resource boundaries are much larger than the landslide surface (less than 1 km^2 in both cases). At La Clapière the recharge area includes the moving zone, the zone above and part of the bedrock. At Séchilienne, it includes the calcareous and gypsiferous marls at the top of the Peak of L'Oeilly, a part of the Mount Sec metamorphic bedrock and the landslide area. Taking into account the local mean annual precipitation (mathematically corrected for the assumed evapotranspiration), the infiltration yields onto these surfaces are about 40 l/s at La Clapière and 60 to 80 l/s at Séchilienne. Comparison with the outflow of the springs of the two massifs (5 l/s at La Clapière, 2 l/s at the perennial outlet in the gallery G585 at Séchilienne) shows an important loss of 35 and 70 l/s, indicating that the majority of the water flowing into the hill slope moves in the rock mass, flowing directly into the alluvial deposits of the valley in the case of La Clapière or through outlets situated at some distance from the landslide in the case of Séchilienne.

The variation of the recharge areas as determined by the change in ^{18}O implies a seasonal as well as an elevation effect. Only where the limits of the recharge area are well known can the ^{18}O gradients be calculated. With this information, the mean infiltration altitude can be established within approximately 50 to 100 m. The study has indicated that the gradients at Séchilienne (Vengeon 1998) and at La Clapière (Compagnon et al. 1997) have notable differences, probably due to local morphological factors and to the proximity of the seashore. In fact, the lowest intercept which is observed at La Clapière is due to the Mediterranean and mountainous climate of the Mercantour massif, whilst the Séchilienne area is subject to oceanic air masses.

Infiltration flow paths deduced from mineral content of the waters

In-situ measurements of water chemical contents at La Clapière

The chemistry of the waters flowing from the foot of the landslide can be clearly distinguished from spring waters egressing from higher up the slope. The SO_4^{2-} content at the landslide foot is some 800 mg/l compared with 50 mg/l at higher altitudes. Plotting the chemical types previously defined on the Piper diagram on the hydrogeological map, three distinct water chemistries are noted (Compagnon 1996; Guglielmi and Mudry 1996; Compagnon et al. 1997): (1) calcium-bicarbonate-rich waters from the more stable upper slopes (Fig. 1c, springs 4 to 7); (2) magnesium-sulphate-rich waters occur in the springs at the foot of the landslide and along the thrust fault between the gneisses and Triassic rocks (Fig. 1c, springs 9, 10, 14, 15, 16); and (3) water with intermediate chemistry – between (1) and (3) – from springs situated on the central part of the slope (Fig. 1c, springs 11 and 12).

Examination of Fig. 4b shows three distinct zones: (1) an upper zone relating to spring 4 at approximately 1,000 m, where the SO_4 and HCO_3^- contents are low; (2) a zone from springs 2 (400 m), 3 (800 m), 10 (1,000 m) and 11 (800 m), where the HCO_3^- content is high but the SO_4 content is still relatively low; and (3) a spread of points with higher HCO_3^- and SO_4 values from waters taken from fractures in the bedrock tunnel at G585 and G710.

Figure 4a shows the relationship between the SO_4^{2-} and HCO_3^- for the waters sampled from both the foot and upper part of the landslide at La Clapière. It can be seen that the points cluster in two groups with positive slopes: (1) a line through the data points related to the springs at the top and middle of the slope (r=0.71; n=161) intersects the origin; and (2) the springs at the foot of the landslide (r=0.96; n=38) intercept the SO_4^{2-} axis at values of between 580 and 700 mg/l, indicating a large increase in the sulphate and calcium bicarbonate contents in the waters issuing at lower altitudes.

The similarity between the gradient of the lines indicates that much of the sulphate in the waters sampled is associated with an enrichment of HCO_3^-, probably due to leaching as the waters percolated through the unsaturated zone of the massif (Bakalowicz 1979). Such a situation is probably related to the dissolution of calcite mixing with the sulphuric acid from weathered pyrites in the aerated zone and the minerals in solution being leached from this zone and appearing at the foot of the landslide.

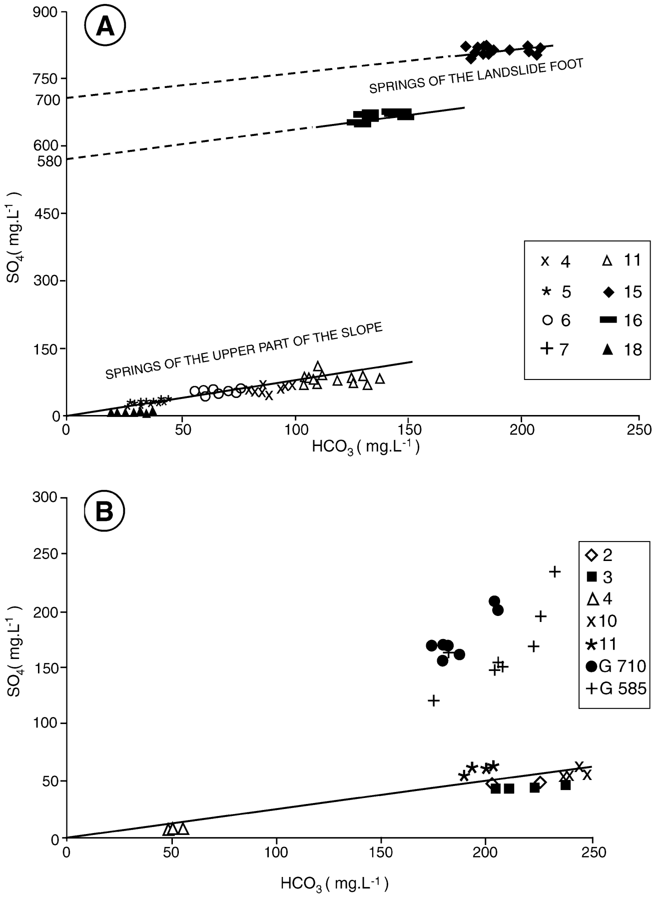


Fig. 4a,b.
Plot of the springs on an SO_4^{2-} versus HCO_3^- diagram. *Numbers on right* correspond to springs shown in Fig. 1a (graph **a**, La Clapière) and Fig. 2a (graph **b**, Séchilienne)

In-situ measurements of water chemical contents at Séchilienne

At this site, the chemical composition of waters has less variation, the SO_4^{2-} contents varying from 10 mg/l (Fig. 2c, spring 4) to 60 mg/l (springs 2, 3, 10 and 11), with a maximum of 250 mg/l at G710 and G585. Figure 4b indicates that the calcium-bicarbonate-rich waters are due to dissolution from the sedimentary perched aquifer as all the water from the sedimentary rocks clusters in one group.

Theoretical calculation of water chemical contents: geochemical modelling

The minerals taken into account at both landslips are those described by Bogdanoff and Ploquin (1980) and Vengeon (1998); see Table 1. In both landslides the major rock-forming minerals are quartz, albite, biotite and muscovite, while phengite is present at Séchilienne. The minor minerals include pyrite, calcite and K-feldspars, while chlorite is also present at La Clapière. Table 1 also provides the geochemistry of the snowmelt waters.

As the system is open to atmospheric gases, the partial pressure of CO_2 is 3.14×10^{-4} atm. However, the partial pressure of O_2 is fixed at a value of 10^{-30} atm, considerably lower than found in the atmosphere (about 0.21 atm), in order to take into account the fact that the redox equilibrium cannot be attained in natural solutions (Michard 1989). The 10^{-30} atm partial pressure of oxygen and pH determine the initial redox potential of the solution at 560 mV (oxidising medium). During the modelling, only calcite could precipitate as a primary mineral, although siderite and gibbsite occurred as secondary minerals. The other minerals could not precipitate at these temperatures due to their slow precipitation kinetics.

Theoretical curves of sulphate incorporation obtained using the weathering rate of the La Clapière gneisses or the Séchilienne micaschists by snow-melt waters displayed the same general shape (Fig. 5). The sulphate contents (solid line) progressively increase following an approximately linear trend for reaction rates over 0.01 g/l. During the simulation, the sulphate contents are controlled only by the oxidation of pyrite. As described by Deutsch (1997), the more aerated the soils, the more the pyrite will be affected and sulphates produced.

During the simulation, the pH displayed very different variations (dashed line). This is due to the different mineralogy of the La Clapière gneisses and the Séchilienne micaschists (Fig. 5a, b). In the case of the gneisses, the pH decreased in two steps. Firstly, pH increased to between 0.0001 and 0.001 until water was saturated with albite at approximately 7.5. It then decreased slowly until water reached saturation with respect to anorthite. At a reaction rate of 100 g/l, the pH fell to values below 5. In the case of the Séchilienne area, in the micaschists there is no

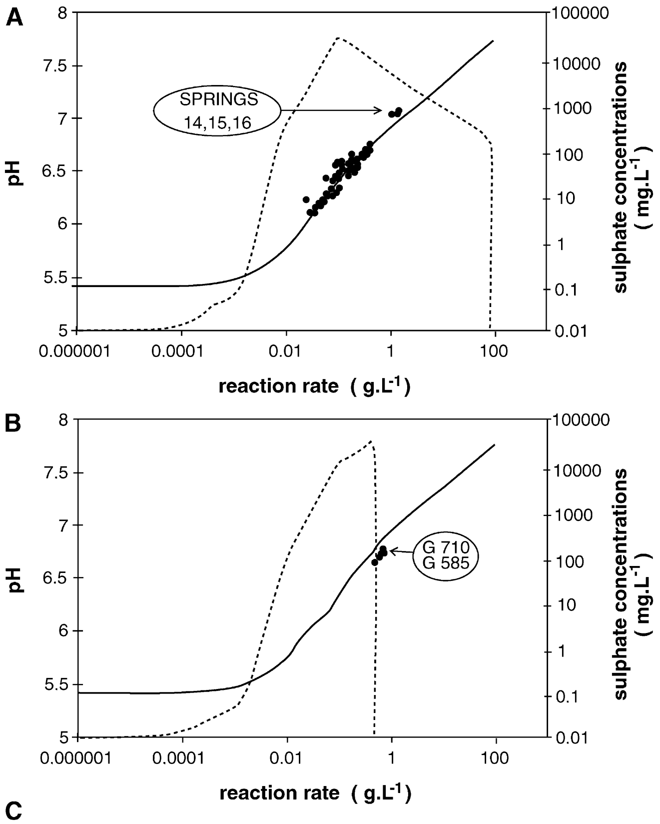
Table 1.
Relative amounts of rock minerals (molar %) taken into account in the geochemical model and snow-melt water chemical content (mg/l). Alkalinity recalculated from values of pCO_2 and pH

	Majors				Minors			
Rock minerals	Quartz	Albite	Muscovite	Biotite	Pyrite	Calcite	K-feldspar	Chlorite
La Clapière	65.67	12.37	9.5	6.42	3.98	1.34	0.46	0.23
	Majors					Minors		
Rock minerals	Quartz	Albite	Biotite	Muscovite	Phengite	Pyrite	Calcite	K-feldspar
Séchilienne	66.07	11.69	6.42	4.75	4.75	3.98	1.346	1.00
Snowmelt water, pH 5		K^+	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	H_4SiO_4
		0.039	0.023	0.04	0.024	0.0478	0.096	0.096

anorthite, hence the pH decreased markedly immediately after the water was saturated with albite. The increased pH is due to silicate mineral dissolution which incorporates the protons of the solution and those related to pyrite dissolution. Only the pH ranges from 5 to 8 were plotted as the upper values fit the pH measured in the field, which ranged between 7.0 and 7.6 at La Clapière and 7.35 and 7.5 at Séchilienne (Fig. 5c).

At La Clapière, the springs at the foot of the landslide (Fig. 5a) clearly do not correspond with the modelled curves. Solutions with the same order of magnitude of pH (between 7.0 and 7.6) show a difference in sulphate concentration of about 100 mg/l (Fig. 5c). This indicates that the sulphates are provided not only by the dissolution of pyrite but also by the evaporites within the massif bedrock. The springs at the top and middle part of the slope fit with the theoretical curves for a low reaction rate (about 0.03 to 0.3 g/l of dissolved rock) and with the modelled sulphate contents related to the dissolution of the pyrites in the bedrocks of 17 to 126 mg/l (Fig. 5c).

At Séchilienne, data were only plotted from the waters of galleries G585 and G710 which drain the basement aquifer (Fig. 5b). These waters did not fit the modelled curve and there was an important difference between the calculated and the measured pH values (2.8 and 7.5 respectively; Fig. 5c). This is probably related to the fact that the simulation was carried out using the composition of snow-melt waters. In the field, however, much of the infiltration comes from the perched sedimentary aquifer. The numerical simulation suggests that sulphate values of 100 to 200 mg/l can be obtained from the dissolution of pyrites inside the micaschists by snow melt for a neutral pH. In conclusion, the sulphate content of the Séchilienne waters sampled in the galleries indicates that about 30% of the minerals within the water are from the sedimentary deposits and 70% are from the micaschist bedrock.



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SIMULATED VALUES	*LA CLAPIERE*				*SECHILIENNE*	
	LANDSLIDE FOOT		TOP + CENTRAL PART			
	MAX	MIN	MAX	MIN	MAX	MIN
pH	7.3	7.4	7.6	7.6	2.8	3.1
[SO_4^{2-}] mg. L^{-1}	900	520	150	10	280	150

MEASURED VALUES	MAX	MIN	MAX	MIN	MAX	MIN
pH	7.5	7.0	7.6	7.5	7.5	7.3
[SO_4^{2-}] mg. L^{-1}	823	650	140	12	250	150

Fig. 5a–c.
Plot of measured/simulated data for pH and sulphate versus reaction rate. *Dashed line* simulated pH; *solid line* simulated sulphate; *black points* measured sulphate concentrations. **a** La Clapière; **b** Séchilienne; **c** comparison of measured and calculated mean values

Correlation of spring water chemistry and landslide speeds

At the La Clapière site, three springs were monitored from December 1995: spring 4 at an elevation of 1,650 m (Fig. 1), spring 11 at 1,185 m and spring 15 at 1,100 m. Springs 4 and 11 collect perched waters from the superficial zone and spring 15 from the deep basal saturated zone. The spring waters were sampled at least once a month and as often as every 2 days, depending on the flow. The results of the sampling between 17 February and 24 October 1996 are shown in Fig. 6.

Precipitation was monitored using a rain gauge located at the village of Saint-Étienne-de-Tinée (elevation 1,150 m) and two snow gauges at elevations 1,800 and 2,500 m. The main purpose was to compare the variation in sulphate content of the spring waters during periods of infiltration and to compare the chemical variations with landslide speed measurements as reported by the Centre d'Etude Technique de l'Equipment (CETE) (Follacci et al. 1988). For the latter, two points were selected at the top and bottom of the moving zone. The first point (Fig. 6, number 35) was taken to represent the speed of the displacement between 1,500 and 2,000 m, while the second (number 10) represents the speed of the displacement between 1,100 and 1,500 m.

The monitoring included three infiltration periods: (1) from 23 April 1995 to 4 June 1995 – snow melt infiltrates at elevations higher than 1,800 m and rainfall occurs below 1,800 m; (2) from 10 November 1995 to 4 February 1996 – significant rainfall occurred in the valley and on the slopes to quite high elevations. This induced snow melting between 1,800 and 2,500 m such that the infiltration

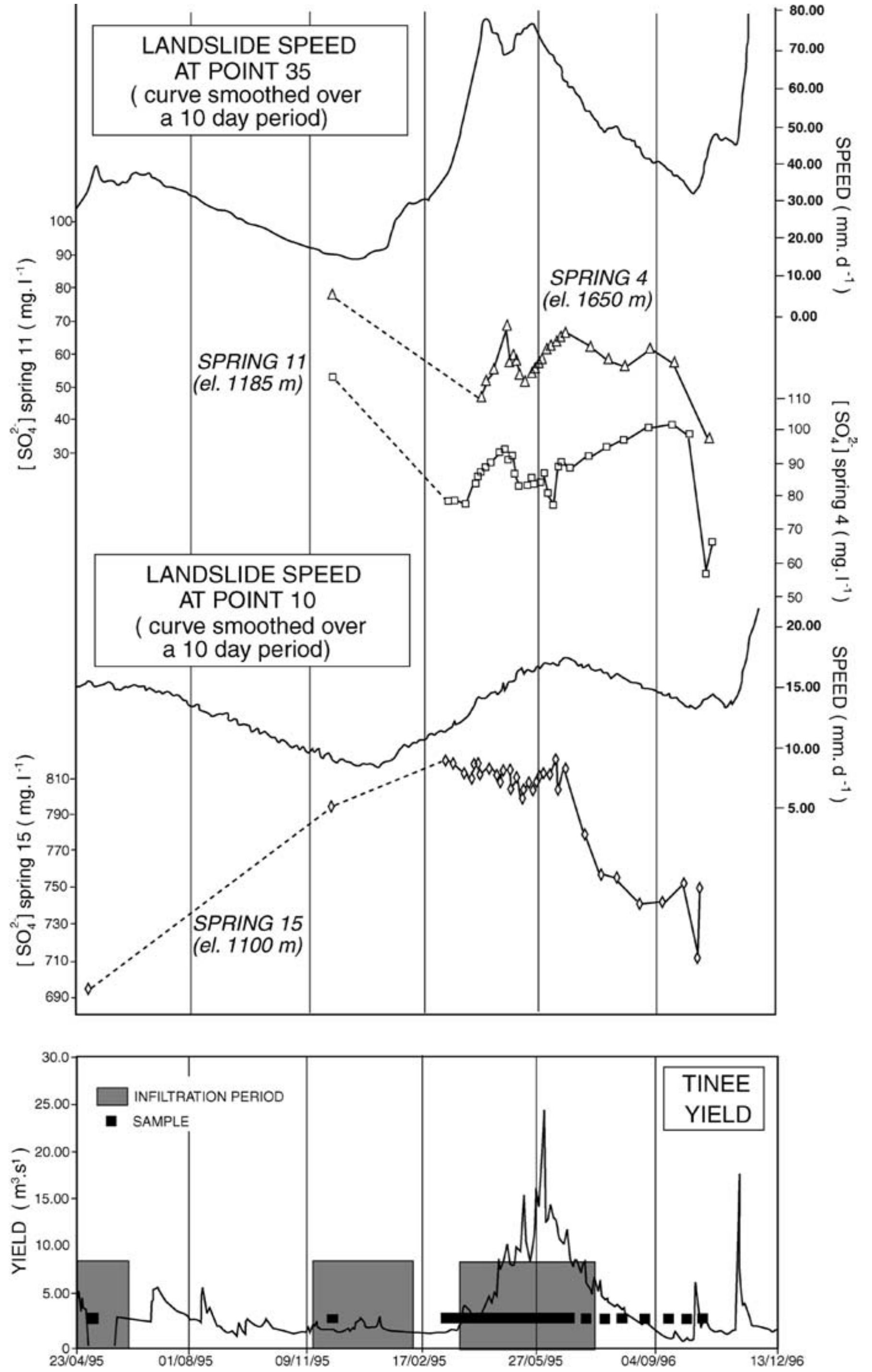

Fig. 6.
Comparison between SO_4^{2-} content of spring waters and speed variations for two representative points of the moving zone at the La Clapière site

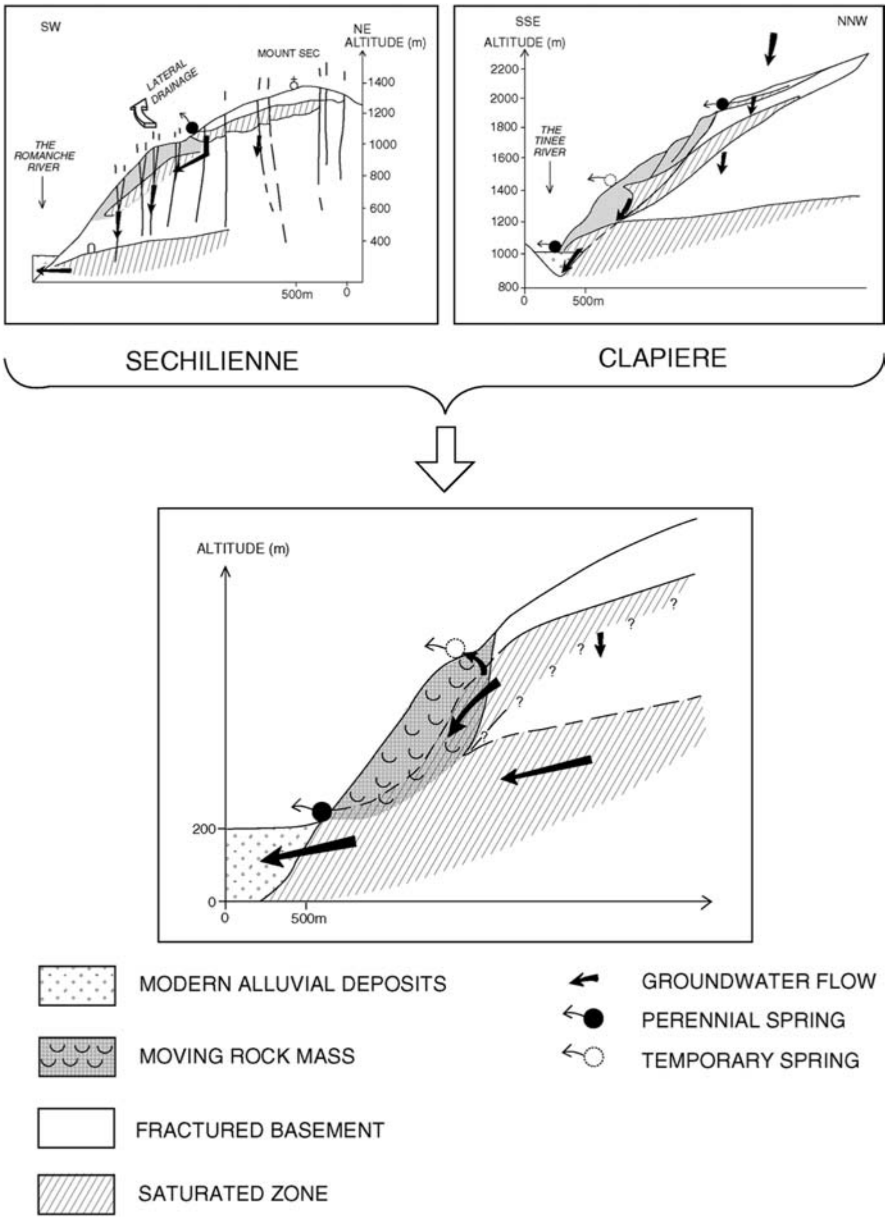

Fig. 7.
Schematic hydrogeological cross section of a large moving rock mass

consisted of a mixture of rain and snow melt; and (3) from 22 March 1996 to 7 July 1996 – snow melting began at a low altitude (about 1,800 m) and was taking place at 2,500 m by 11 June 1996.

The sulphate content of the water varied over time and two very different patterns can be seen (Fig. 6). Springs 4 and 11, to the north and west of the landslide, had sulphate contents under 100 mg/l, the two springs having similar variations with two troughs recorded between 17 February and 30 March 1996 and from 25 April to 4 June 1996, associated with two snow-melt infiltration periods (from 10 November 1995 to 4 February 1996 and from 21 March 1996 to 7 July 1996 respectively). The lowest sulphate concentrations were found some 40 to 50 days after the beginning of infiltration, an increase in sulphate concentrations being noted with the return to low water levels and a decrease in the outflow of the Tinée River with the end of the snow melting on the Argentera–Mercantour massif.

Spring 15, at the foot of the landslide, had a sulphate content of over 700 mg/l, in contrast to those noted for springs 4 and 11. In the case of spring 15, there was only one dilution period which occurred from 17 June to 1 September 1996. This cannot be correlated with the two snow-melt periods or the flows in the River Tinée. As the mean altitude of the recharge area of spring 15 is the same as that of springs 4 and 11, it is concluded that the transit time of the infiltration to this spring is much longer, with a delay from the beginning of the infiltration period to the minimum sulphate concentration of about 80 to 90 days.

The speed variations at the top of the landslide (Fig. 6, point 35) indicate two acceleration peaks exceeding 70 mm/day coincident with troughs in sulphate concentration at springs 4 and 11. Between the peaks, a deceleration period occurs in parallel with an increase in the sulphate content of the springs. At the foot of the landslide there is only one continuous acceleration from 10 January to 23 June 1996, followed by a slowing down. Acceleration begins when there is no notable chemical variation at the spring, i.e. presumably before the percolating waters reach the spring.

The chemical monitoring of spring waters with time shows a notable difference in the speed of water passage through the regolith/bedrock between the top and the foot of the La Clapière slope. This affects both the time and intensity of flow at the springs and the movement of the landslide. Movement of the foot of the landslide is induced by gravity loading from above; the upper part (point 35), with infiltration rates of 17 to 33 mm/day, moving at three times the rate measured at point 10.

Conclusions

There is a clear difference between the sulphate contents acquired by laboratory analysis and those used in a model simulation. Concentrations up to 800 mg/l were measured for waters emanating from the Triassic strata, while the bedrock waters at La Clapière produced only 150 mg/l. This is in stark contrast to the established pyrite content of some 5% in the bedrock which gives a calculated sulphate water content of 10 mg/l.

At La Clapière, the variation in sulphate from 10 mg/l at the top of the landslide to 800 mg/l at the foot may be related to dissolution from the Triassic gypsum where it is overthrust over the microgneisses. At Séchilienne there is downslope enrichment of sulphate ions from 60 to 250 mg/l. Again, it is considered that this is related to percolating water from the Triassic syncline through the micaschist bedrock.

The study has shown that the monitoring of water chemistry over time gives a sensitive indication of infiltration flows into the landslide. At La Clapière the chemical variation of the spring waters coincides with the rate of movement of the slide; 10 mm/day acceleration is associated with a 15 to 20 mg/l drop in the sulphate concentration in the groundwater.

The hydrochemistry implies that there are two water passages within the slope (Fig. 7): (1) at La Clapière there is a perched water level in the scree and the upslope zone of regressive slips and a further zone above the overthrust. At Séchilienne the groundwater is at the top of the sedimentary deposits; and (2) a deep saturated zone which extends into the fractured metamorphic bedrock with a probable unsaturated zone above.

Isotopic results indicate that the main recharge of the landslide is from the perched saturated zone. As this water passes downslope and possibly into the slope, in order to establish a hydrogeological balance it is necessary for the waters to migrate for some distance from the area of the instability. It is believed that the groundwater flows mainly through a network of widely dilated fractures and through the breccia, becoming enriched with HCO_3 as it passes through this aerated zone. During snow melt, waters already enriched in Ca^{2+} or SO_4^2 are leached from the perched aquifer into the fracture network within the bedrock.

The hydromechanical behaviour of the moving rock mass depends on the passage of water between the two saturated zones: the upper perched condition and the lower saturated zone towards the base of the slope. As anticipated, in both areas the maximum speed of sliding is coincident with periods of increased underground flow and a consequential rise in water pressures in the massif: (1) an increased head of water – possibly between 200 and 400 m; (2) a raising of the general groundwater level in the perched zone with water passing into the landslide. At La Clapière temporary springs occur at about 1,500 m, indicating temporary drainage of the saturated zone above the landslide where heads of up to 100 m may develop.

The study indicates that hydrogeochemistry could be a useful additional tool in the study of large landslides. However, more work is required to confirm the validity of the method, which can only be substantiated with very careful monitoring of not only the groundwater chemistry and precipitation as rainfall and snow but also the periods over which snow melt occurs, both in the lower parts of the valley and higher on the hill slopes.

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