Unstable rock slope hydrogeology: insights from the large-scale study of western Argentera-Mercantour hillslopes (South-East France)

STÉPHANE BINET[1], YVES GUGLIELMI[2], CATHERINE BERTRAND[1] et JACQUES MUDRY[1]

Key words. – Large rocky landslide, Hydrogeology, Groundwater chemistry, Hydro-mechanics

Abstract. – Inventory of unstable hillslopes, hydrogeological mapping and hydrochemical characteristics of natural spring waters were used to determine the long-term relationships between groundwater and gravitational instabilities in the Upper Tinée Valley (South-East French Alps). Water chemistry and flow records allow to propose a conceptual model of water flow within unstable rocky slopes and to back-calculate the volume of infiltrated water and the flow velocity in the aquifers for different deformation states of the slopes. An increase in infiltrated yield, flow velocity and porosity is observed and linked to collapsed and toppled structures in the upper parts of the hillslopes. In these areas, perched aquifers take place in the reworked media. When a large landslide occurs, it modifies the geometry of the slope and bypasses the perched flows down to the foot of the slope. With long-term continuous slope deformation, the associated effect between water flows and slope destabilization changes. In the fractured rock, the coupled effect corresponds to rising water pressures with limited volumes of infiltrated water; in the more fractured and permeable collapsed and toppled areas, the volumes of infiltrated water increase with a lower variation of water pressures.

Hydrogéologie de versants rocheux instables : apport d'une étude à grande échelle dans l'Ouest du massif de l'Argentera-Mercantour (Sud-Est des Alpes françaises)

Mots clés. – Grands mouvements de versant rocheux, Hydrogéologie, Chimie des eaux souterraines, Hydromécanique

Résumé. – Une cartographie des instabilités gravitaires et de l'hydrogéologie des versants à l'échelle d'une vallée, ainsi que les caractéristiques hydrochimiques des sources, permettent de déterminer les relations à long-terme entre les écoulements souterrains et les structures des instabilités gravitaires dans la Haute Vallée de la Tinée (Alpes françaises). La chimie de l'eau et le suivi temporel des écoulements permettent de proposer un modèle conceptuel des écoulements en milieu fracturé instable et d'estimer l'évolution des volumes d'eau infiltrée et des vitesses d'écoulements pour différents états de déformation du versant. Dans les parties amont des versants, le basculement de certaines structures crée une augmentation de la porosité, des vitesses d'écoulements et des volumes d'eau infiltrés et des aquifères perchés se développent. Quand un grand glissement de terrain se déclenche, il modifie la géométrie du versant et court-circuite les écoulements perchés vers le pied du versant. Sur le long-terme, l'effet associé des infiltrations d'eau dans le versant et sa déformation sont modifiés : dans les zones fracturées, une augmentation des pressions d'eau est observée pour de faibles variations de volumes d'eau infiltrés ; dans les zones basculées les plus fracturées et les plus perméables, de faibles variations de pression d'eau sont observées pour de larges variations de volumes d'eau infiltrés.

INTRODUCTION

In mountainous environments, fractured rock slopes are often affected by decompression since the last glaciation period as can be clearly observed in the field through geomorphological structures like counterscarps or trenches [Julian and Anthony, 1996]. This decompression is followed by the formation of new failure surfaces and generates deep-seated deformation (DSD) and landslides [Cruden and Varnes, 1996], like for the "Valfurna" landslide [Agliardi *et al.*, 2001] or for the "Rosone" unstable hillslope [Forlati *et al.*, 2001]. Several geomechanical studies showed that the main controlling factors of these deformations are the geological structure, the strong toe slope-gradient and the water seepage conditions. The coupling between water pressures and landslide kinematics has been demonstrated on large landslides [Vengeon, 1998; Bonzanigo *et al.*, 2001; Forlati *et al.*, 2001; Cappa *et al.*, 2004].

In the fractured rocks, flow anisotropy combined with regional topographic effects can produce a important increase in water pressure with a strong hydro-mechanical coupling [Bonzanigo *et al.*, 2001]. The seasonal variations of water saturation can progressively load the hillslopes and potentially conduct to destabilization [Tullen, 2002].

The location and rate of water infiltration play a significant role in the hydro-mechanical behaviour [Cappa *et al.*, 2004]. However, the DSDs evolve very slowly and add a temporal evolution to the geometry and hydrogeological characteristics of the aquifer that can modify groundwater

1. 'Geosciences Besançon', EA 2632 UFC, 16 Route de Gray, F-25030 Besançon, France. Tel. +33 (0)381 666 431 / Fax. +33 (0)381 666 558 / E-mail: stephane.binet@univ-fcomte.fr
2. 'Géosciences Azur', UMR 6526 CNRS-UNSA-IRD, 250 Rue Albert Einstein, F-06560, Valbonne Sophia-Antipolis, France.

flows. The water pressure distribution in the hillslope is therefore in constant evolution.

The water has a long-term and indirect effect on destabilization that creates a complex coupling between water and deformation. For instance at "Zentoku" landslide, the movement induces underground erosion and the groundwater transports the destructured rocks that increase the brittleness of the slope and hence control the kinematics [Furuya *et al.*, 1999] In the "Shek Kip Mei" landslides, geochemical investigations reveal that the slip surfaces have signatures distinct from their parent materials due in part to chemical water alterations [Wen *et al.*, 2004].

These interactions between deformation, rock and water induce long-term hydro-mechanical interactions superimposed to the seasonal water pressures fluctuations. To approach this long-term effect between groundwater flows and slope destabilization at several spatial and temporal scales, a multi-scale flows analysis was carried out in representative unstable areas of the South-East French Alps.

METHODOLOGY USED TO ANALYSE UNSTABLE HILLSLOPE HYDROGEOLOGY

Geomorphologic, geologic and hydrogeological context of the study area

The study area reaches 3030 m at the Ténibre Mount which is the highest summit of the Mercantour massif cut by the narrow valley of the Tinée River, with inclinations larger than 30° [Julian and Anthony, 1996]. Many unstable areas are located on these abrupt slopes (fig. 1a). One of these landslides is the noticeable "La Clapière" landslide on the left bank of the valley; this landslide presents a 1 km wide disturbed rock mass extending from 1100 m to 1850 m in elevation (fig. 1a).

The Tinée valley was dug since the lower Pliocene [Bigot-Cormier *et al.*, 2000]. Then, the glaciers covered the valley with a maximum thickness estimated to 600 m until 18 000 years ago [Dubar and Stephan, 2001]. The Mercantour massif consists of granitic and gneissic rocks, covered by Jurassic limestones. Permian sandstones and slates, Triassic quartzites and evaporitic rocks crop out in the valley. Fractures have affected both the basement and the overlying sediment cover [Faure-Muret, 1955]. Faults and joints of various types and related to several tectonic phases have resulted in highly fragmented rock masses [Julian and Anthony, 1996]. At the valley scale, the two main directions of fractures are N020^o and N080^o [Delteil *et al.*, 2003].

These fractured rock slopes are submitted to a pronounced spatial and temporal variation of precipitations. Rock glaciers, observed over 2500 m [Julian and Anthony, 1996], may increase superficial water storage and delay the infiltration [Dysli, 1998]. Thus, the local variation of meteorological parameters induces a complex spatial distribution of infiltrating zones and a delayed infiltration in the aquifer system [Guglielmi *et al.*, 2002].

Slope aquifers can cover considerable ranges of elevation that induce (i) a high rainfall gradient versus elevation during the rain events (Summer storms and Autumn rainfalls), (ii) a quick evolution of the 0°C isotherm position and the snow front during Winter [Verbunt *et al.*, 2003] and, (iii) a shallow storage in Winter. In fractured gneissic

hillslopes, the hydraulic conductivity is very low and ranges from about 10^{-7} to 10^{-11} m.$^{-1}$ [Maréchal, 1998] and the water flows into discontinuities of the rock. The inter-connections of the fractures originate mainly from polyphased tectonics. Averaged hydraulic conductivity of the rock is increasing with the decrease of the compression stress [Maréchal, 1998]. Closer to the surface [Maréchal, 1998; Jiao and Malone, 2000] a perched saturated zone is often nested in highly weathered gneisses.

Methodology

This study will compare several unstable areas located in the Upper Tinée Valley (South-East French Alps) where many landslides are currently active and submitted to the same climatic conditions [Julian and Anthony, 1996]. In the entire Tinée valley, the rock is mainly composed of gneiss, the slope of the valley bottom reaches 45° and the fracturation is controlled by N020^{o}E and N100^{o}E directions. The geomorphological map (fig. 1a) indicates a generalized decompressed area bounded by large landslides. Actually, the hillslope cross-sections can be interpreted as the result of a long-term evolution caused by DSDs and weathering that allow to discuss the long term hydro-mechanical interactions.

Location of springs, water reservoirs and main geomorphological forms

A detailed geomorphological and hydrogeological mapping of the Tinée Valley was realised. First, the gravitational movements and the geomorphic forms were mapped at a 1:50,000 scale. Second, a hydrogeological map was realised after an inventory of the springs and was correlated to the geomorphological map.

Origin of infiltrated water

Hydro-geochemistry is a method [Vengeon, 1998; Guglielmi *et al.*, 2002; Tullen, 2002] that allows to build conceptual model of underground water flows [Meijer, 2002] in anisotropic and heterogeneous systems because it records global contrast within the system [Blavoux and Mudry, 1983; Mudry, 1987]. On the "La Clapière" landslide, the chemical approach has improved the knowledge of the relationship between infiltrated water and the landslide kinematics [Cappa *et al.*, 2004; Guglielmi *et al.*, 2005].

To study groundwater flows, an instantaneous physical and chemical analysis of several springs has been performed during the 2003 low groundwater period. Ten profiles were sampled from the bottom of the valley to the mountain top in order to get a representative sampling of the water chemistry variation. 248 springs were localized and 92 of them were sampled. Analysis of some unstable zones compared to observations of the total valley gives a multi-scale approach from 10 m to 70 km.

Estimation of infiltration characteristics in different geomorphological contexts

The infiltration characteristics of the aquifers are estimated from yield and chemical content of several springs monitored over time: the flow from a fracture to a gallery under 100 m of overburden gneiss ("Valabres" hillslope) was
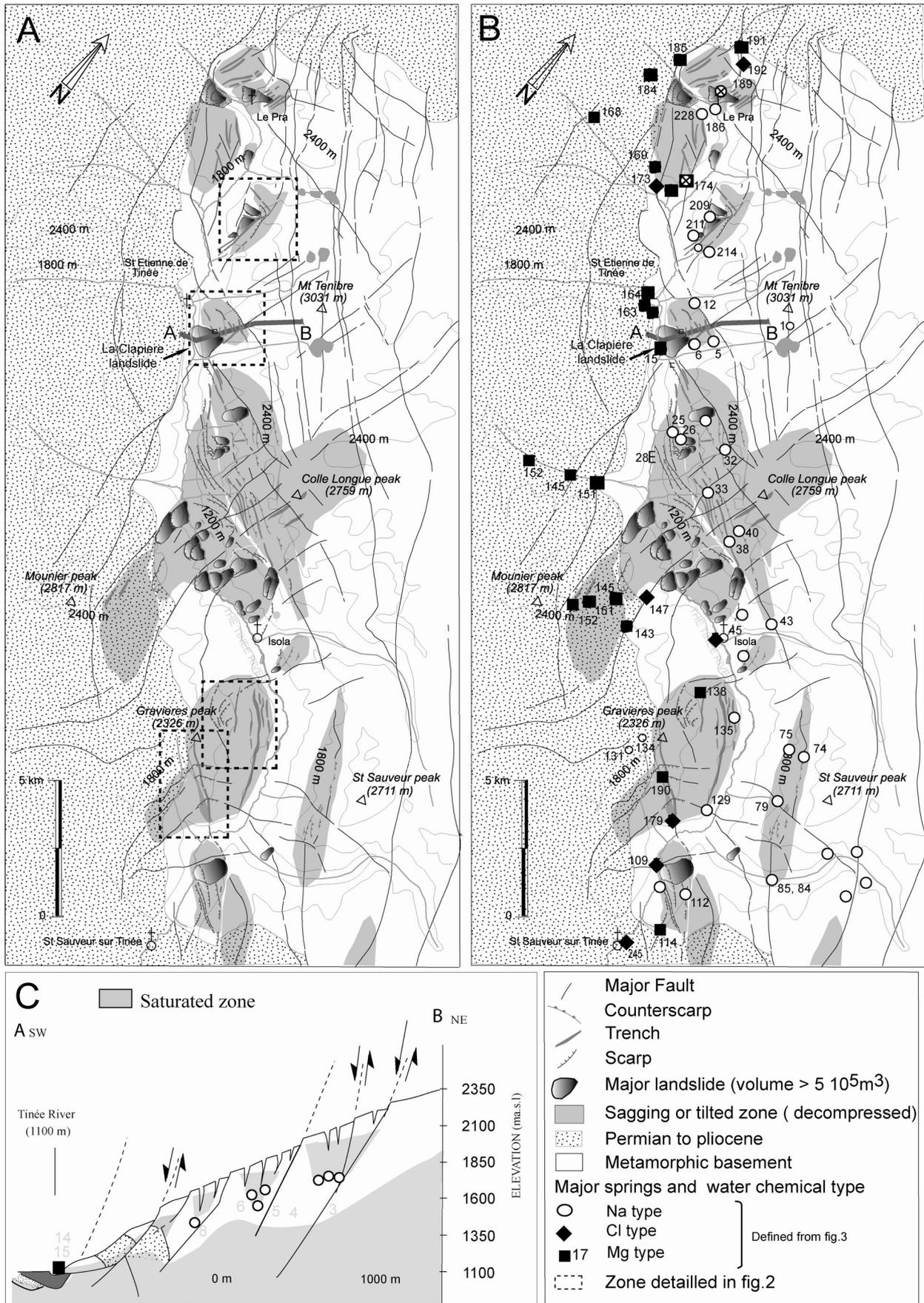
FIG. 1. – Schematic map of the Upper Tinée Valley. a) Geomorpholocical map. b) Hydrogeological map. c) Hydrogeological cross-section of the "La Clapière" unstable slope.

FIG. 1. – *La Haute Vallée de la Tinée. a) Carte géomorphologique. b) Carte hydrogéologique. c) Coupe longitudinale du versant instable de "La Clapière".*

taken as representative of flows in unweathered fractured gneiss. Two springs draining a decompressed area (fig. 1b, spring n° 43 and n° 179) and two springs located at the foot of "La Clapière" landslide (fig. 2b; spring n°14 and n°15) are monitored to estimate the hydraulic reactions to rainfall events in an active large landslide.

The specific yield is the ratio between low water period yield and the estimated surface of the infiltration area; it gives an idea of the amount of water infiltrated in the hillslope. Dilution curves, linked to fresh water flows in the slope, allow to estimate the volume of water drained by the spring during a flood and the average flow velocity [Mudry *et al.*, 1994].

With the flux conservation equations, neglecting the volume variations inside the reservoir, the spring yield (Q_S) and the spring water content (C_S) can be described for two water periods:

– for low water periods $Q_S = Q_R + Q_I$ (Eq. 1)

– for high water periods $Q_S C_S = Q_R\ C_R + Q_I\ C_I$ (Eq. 2)

with Q_R, the yield of the spring in the period of low water table, C_R the water content at the spring during a period of low water table, Q_I, the infiltration yield and C_I, the water content of rainfall. By integrating Eq. 2 over time, for $C_I = 0$, we can assess the water volume that provokes a dilution observed at the spring during a rain event (Equation 3):

$$V_{\text{infiltrated}} = \sum_{t}^{0} \frac{(C_R - C_S)}{C_S} Q_R\ dt \qquad \text{(Eq. 3)}$$

with t, the end time of the flood.

For each spring the percentage of infiltrated water is determined with the infiltrated volume (Eq. 3) and compared to rainfall measurements and to the infiltration areas. The rain heights are measured at the "La Clapière" meteorological station multiplied by the infiltration area estimated with mapping result in a rainfall volume for a flood. The ratio between the infiltrated volume and rainfall gives information on
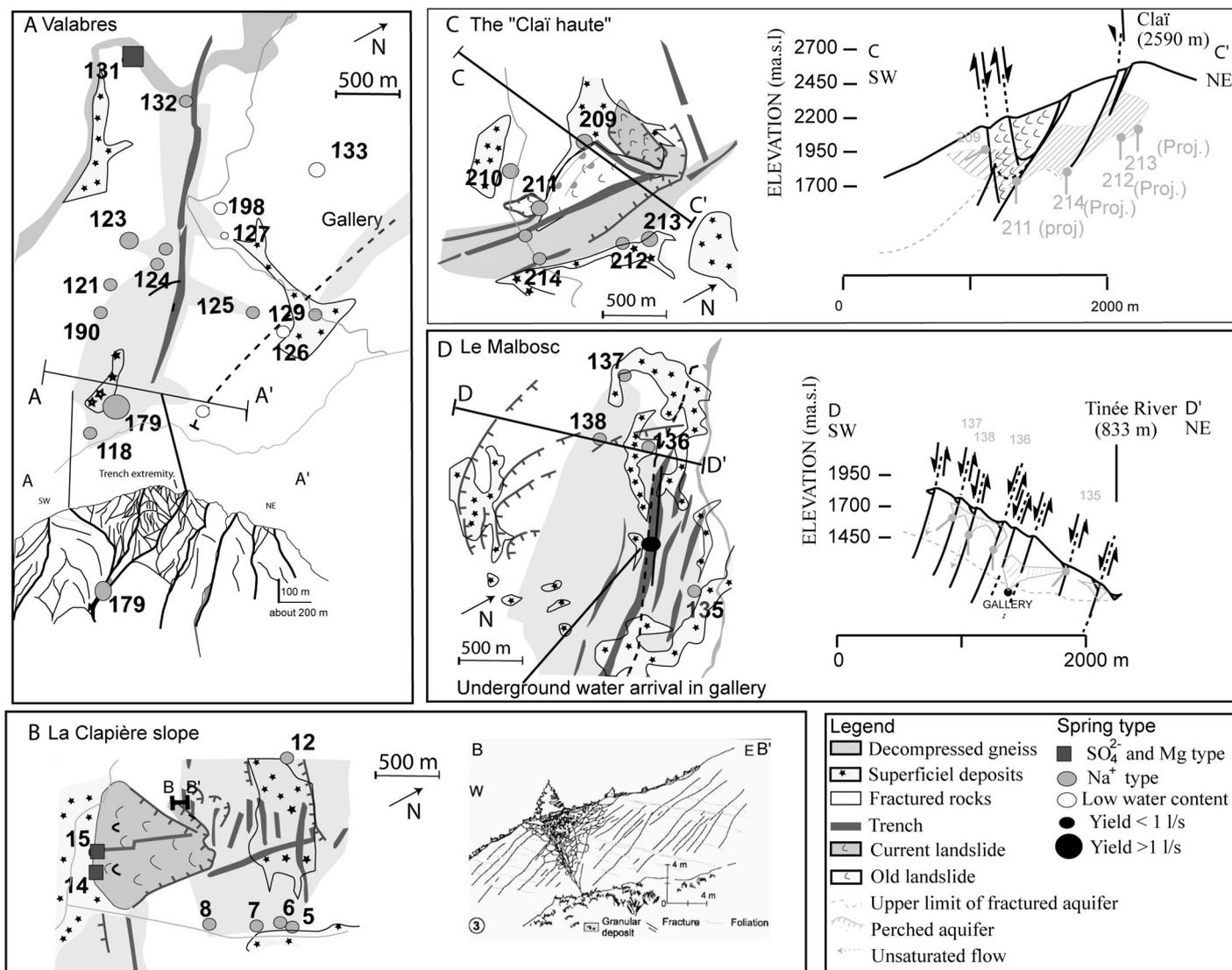

FIG. 2. – Hydrogeological details of representative unstable areas. a) "Valabres" hillslope. b) "La Clapière" hillslope. c) "Claï Haute" hillslope; d). "Malbosc" hillslope.
FIG. 2. – *Hydrogéologie détaillée de versants instables représentatifs. a) Versant de "Valabres". b) Versant de "La Clapière". c) Versant de "Claï Haute". d) Versant de "Malbosc".*

the percentage of water that arrived to the spring after a flood. As the sulfates in water have a pyrite or evaporite origin, sulfate content can be neglected in the rain water which is therefore a relevant marker of infiltration [Cappa *et al.*, 2004].

RESULTS: CORRELATION BETWEEN GRAVITATIONAL STRUCTURES AND SLOPE HYDROGEOLOGY

Geometry and geological characteristics of the water reservoirs

The geographical relation between spring location and geology defines three principal types of aquifer (fig. 1a). The glacial deposits and the screes are superficial aquifers of reduced size. The Jurassic and the Triassic rocks constitute a second type of aquifer, where the permeability contrast between sedimentary rocks and metamorphic rocks explains the location of the springs outflowing around this contrast zone. The third type of aquifer is the gneissic rock, which springs are located near fractures or faults.

If we focus on the geometry of the gneiss aquifers, most of the springs are located at the middle of the hillslope close to the unstable structures. The decompressed areas (scarps and trenches; fig. 1 and fig. 2) influence the draining system and may explain the location of springs under the trenches, such as for the Malbosc trenches (fig. 2d). The areas of decompressed gneiss correspond to recharge area of springs.

The characteristics of the aquifers geometry can be detailed at various scales. The cliffs of "Valabres" are an interesting zone too, because the Tinée River crosses the geological regional structures. It is possible to observe a deep cross section of the structures. The bottom of the main double ridge is drained by one of the most important spring of the country (fig. 2a, spring n° 179) with a minimum yield of 5 l.s^{-1}. A schematic view of the gorge shows the N180° double ridge which extends about 2 km in the massif. The zone around the trench is highly fractured. A decompressed area is observed between a vertical tectonic fracture towards the north-west and a fracture dipping about 45° towards the south-east. The spring is located at the convergence of the main fractures, which is the boundary between a collapsed zone and the fractured gneiss.

Some trenches (fig. 2b) are cut in the "La Clapière" main scarp and show cracks filled with colluviums, sands and blocks of various sizes. The bedding is warped, showing that sedimentation occurred while gravitational movement was active and these trenches extend under the slope because of the gravitational reactivation of a tectonic fault. Tilted rocks open the fractures in the upper part of the trenches.

These perched waters, observed over 800 m are perennial, flow in unstable structures, parallel to the valley axis and perpendicular to the gravitational toppling directions (fig. 2). These water reservoirs, structured by gravitary features are interconnected via the tension crack network. The toppled zone is a highly fractured area where tension cracks create linear drains that induce a permeability contrast.

An intermediate aquifer is also clearly identifiable on the hillslopes. The sliding mass takes place on the border of the decompressed area and creates a new water pathway near the valley. The movement increases the gneiss weathering, observable for example in the "La Clapière" landslide (fig. 2b, spring n° 14, spring n° 15) or in a dormant landslide located in the "Claï Haute" area (fig. 2c, spring n°209, spring n° 211). In these two areas, the cross sections (fig. 1c, fig. 2c) indicate that destructured sliding rocks bypass the flow of the perched water in the trench network. The bypassing waters outflows at the foot of the moving masses.

Finally, in the Malbosc hillslope (fig. 2d) a gallery was drilled and an important water inflow was observed 100 m down to the trenches. These observations prove that these aquifers have a continuity with depth around the fractures.

All these observations can be reported on a hydrogeological cross-section (fig. 1c). The represented faults are only the faults with a major gravitational reactivation. Throughout the valley, the structures reveal an extensional movement that explains the decompression of the upper part of the hillslope bounding the perched flows.

Analysis of origin of infiltration waters deduced from spatial variations of water chemistry

To discuss the flows origin, water chemistry of springs is compared to the hydrogeological map (fig. 1b). The spatial variability of the water content is presented with a
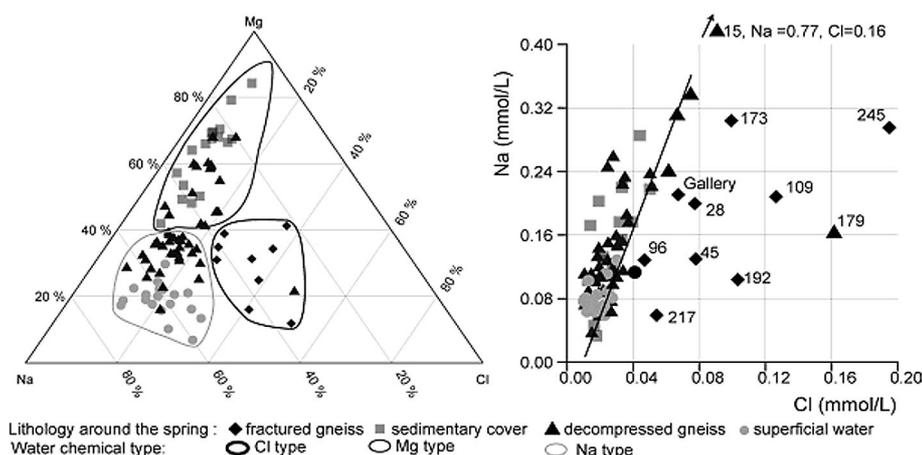

Lithology around the spring : ◆ fractured gneiss ■ sedimentary cover ▲ decompressed gneiss ● superficial water
Water chemical type: ◯ Cl type   ◯ Mg type   ◯ Na type

FIG. 3 – Water quality of the springs sampled in the Upper Tinée Valley (August 2003). a) Hydrochemistry ternary plot; b) Na-Cl graph.
FIG. 3 – *Composition chimique des sources échantillonnées dans la Haute Vallée de la Tinée (Août 2003). a) Diagramme ternaire. b) Diagramme Na-Cl.*

ternary (Mg – Na – Cl) plot. The close correlation between magnesium water type and springs sampled in the Triassic and Jurrasic covers proves that magnesium is a marker of the Triassic-Jurassic aquifer, originating from dolomite mineral dissolution (fig. 3a). The magnesium content is higher than 0.2 mmol.L^{-1}; at the opposite, the springs sampled in gneiss never exceed a magnesium content of 0.15 mmol.L^{-1}.

Relatively to magnesium, the sodium (Na) content is more present in the superficial water and in the decompressed aquifer; this feature may be explained by the plagioclase weathering.

Some springs located in the decompressed gneiss have a magnesium water type that demonstrates a connection of the gneiss decompressed aquifers with the Triassic-Jurassic aquifer.

Finally, chlorides ions (Cl) are more present in the springs of the fractured aquifer located in the bottom of the valley (fig. 3a, fig. 3b), which is apparently not connected to the instability features (fig. 1b). A close correlation between sodium and chloride in water from the decompressed aquifer can be linked to weathering dynamics in the decompressed gneisses. The springs sampled in the fractured aquifer have higher chloride concentrations and reveal a different chloride weathering dynamic in gneiss or a different origin. Thus, chlorides enable to prove connection of a spring with the fractured aquifer or with flows within decompressed areas.

According to chemistry measurements, a cross-section (fig. 1c) can be drawn; this cross-section differentiates a fractured aquifer at the bottom of the valley and perched structures in the upper hillslopes driven by unstable structures. The two water types suggest two different aquifers within the same rock mineralogy. The hydrochemical contrast, during low water table periods, argues the presence of two disconnected behaviours because low chlorides contents are observed in the perched waters.

Destabilization effect on infiltrated water

The specific yield is estimated by hydrochemistry (tabl. I) for the springs classified as draining a fratured aquifer and for the springs classified as draining a decompressed aquifer. Figure 3 shows an increase of 2 order of magnitude of the specific yield for the decompressed areas compared to the fractured areas. These specific yields indicate that the collapsed structures increase strongly the infiltrated water volume compared to the stable fractured slopes with high potential runoff and lower water infiltrated volumes.

The percentage of water drained by the springs during a flood (calculated with Eq. 3) is applied to the "Valabres" hillslope and the "La Clapière" landslide. Applied to the Luicetta spring (fig. 2a; n° 179) which drains a large double ridge of the "Valabres" hillslope (tabl. II), ~ 40% of the water fallen in the ridge passes through the aquifer during the flood. At the opposite, in the recharge area of the "La Clapière" hillslope, a maximum of 10% of rainfall passes through the perched aquifer during the flood. The uncertainty on these percentages is estimated at ±15% related to the hypothesis on the type of infiltration, the seasonal evolution of evapotranspiration, and for "La Clapière" hillslope to a part of water flowing directly into the alluvium deposits. This analysis reveals that 10 to 50% of rainwater can be drained by the geomophological structures.

Destabilization effect on the water flows

The response of the fractured aquifer ("Valabres" gallery) to the 2003, 01/11 flood indicates a dilution phenomena and flow velocities of 1.10^{-5} m.s^{-1} (fig. 4; tabl. III). The dilution curves monitored at spring n° 43 and spring n° 179 in the toppling and decompressed aquifer present high flow velocities from 5.10^{-4} to 5.10^{-3} m.s^{-1} (tabl. III) and a piston flow-type (fig. 4).

In the "La Clapière" landslide, the dilution curves have different shapes related to these locations. Spring n° 15 presents a high velocity of 10^{-3} m.s^{-1} and a piston flow-type; the water drains a highly destructured trench. Spring n° 14 shows an immediate response with a residence time of 5.10^{-4} m.s^{-1} and a low dilution that displays a homogeneization caused by a large density of fractures within this part of the landslide.

These four springs (fig. 4), representative of different geomorphological contexts, demonstrate that water flows evolve with slope deformation, with a decrease of residence time and an evolution of the flow types from a dilution phenomena in the fractured hillslopes to piston flows in the decompressed hillslopes.

TABLE I. – Specific yield estimated for fractured and decompressed aquifers.
TABL. I. – Débit spécifique estimé pour les aquifères fracturés et décomprimés.

Aquifer type	Spring	Yield (l.s^{-1})	Recharge area (km^2)	Specific yield (l.s^{-1}.km^{-2})
Fractured	n° 245	1.10^{-3}	0.9	0.001
Fractured	n° 192	3.10^{-3}	0.5	0.007
Fractured	n° 96	3.10^{-3}	0.4	0.010
Decompressed	n° 5	0.20	0.5	0.40
Decompressed	n° 11	0.11	0.3	0.40
Decompressed	n° 129	0.12	1.5	0.10
Decompressed	n° 211	1.50	1.3	1.20

TABLE II. – Water balance for two decomprimed aquifers.
TABL. II. – *Bilan hydrogéologique estimé pour deux aquifères décomprimés.*

	P (mm)	V_{IN} (m^3)	V_{OUT} (m^3)	I (mm)	Water drained by fracture (%)
Luicetta, spring n° 179					
01/11/2003	118	11800	4539	45	38 %
23/02/2004	55	5500	2460	25	45 %
03/12/2003	65	6500	2399	24	37 %
La Clapière, springs n° 5, 6, 7, 8, 12, 15 (Infiltration area = 3,500 000 m^2)					
29/04/1996	50	150000	15457	5	10 %
07/09/2000	8	28000	1659	0.5	6 %

TABLE III. – Hydrogeological characteristics of three springs representative of a draining trench, of a decompressed area and of a fractured aquifer.
TABL. III. – *Caractéristiques hydrogéologiques de trois sources représentatives d'une crevasse drainante, d'une zone décomprimée et d'un aquifère fracturé.*

Characteristics	Draining trench	Decompressed zone	Fractured aquifer
Spring name	La Clapière n° 5	Luicetta n° 179	Galerie EDF
Number of events analysed	n = 15	n = 3	n = 3
Recharge area (m^2)	50000 + – 5000	100000 + – 10000	
Sulfate concentration during periods of low water table (mg.L^{-1})	39	20	57
Estimated mean transit time (days)	from 1 to 8	from 1 to 4	from 10 to 20
Estimated transit speed (m.s^{-1})	from 5.10^{-3} to 5.10^{-4}	from 2.10^{-2} to 8.10^{-3}	from 1.10^{-5} to 1.10^{-4}

DISCUSSION: A CONCEPTUAL MODEL OF GROUNDWATER FLOWS IN UNSTABLE HILLSLOPES

Conceptual model

Figure 5 proposes a synthesis of water flows within the hillsope and indicates the complex relationship between water infiltration and geomorphological context. With the toppling and opening of the fractured rocks, the draining role of the trenches increases. The correlation between the hydrogeological map and the geomorphological map (fig. 1 and fig. 2) proves that water is drained by fractures and counterscarps which are opened by deformation and allow flows perpendicular to the topographic slope. The trenches and the counterscarps tend to limit runoff and facilitate groundwater infiltration. Water is drained in these structures and outflows in the middle of the slope, at the bottom of the gravitational structures, where decompression does not occur.

The landslides occur mainly at the border of the decompressed areas. Water in the landslide can originate from upper parts of the hillslope (fig. 1c); the three groups of springs (toe of the landslide, fractured rocks and decompressed areas) are draining most of the infiltrated water (fig. 5).

In a stable fractured gneiss the average permeability may range from 1.10^{-9} to 1.10^{-4} m.s^{-1} and the maximum porosity is less than 1% [Guimera and Carrera, 2000]. In the upper part of the unstable slope of the study site, the porosity increases with the filling of the trenches by weathered materials (fig. 2b) and can reach the porosity of a sand (around 20%). Maréchal [1998] had computed hydraulic conductivity of Alpine gneisses ranging between $2.7.10^{-8}$ m.s^{-1} (for fractured gneiss) to $1.6.10^{-4}$ m.s^{-1} (for decompressed areas)

and assumes the presence of perched water in a more permeable decompressed rock. The observed contrasted hydrochemical behaviour (fig. 3) indicates that the perched flows are not influenced by water from the fractured rock. Moreover, referred to the variability of spring elevations in
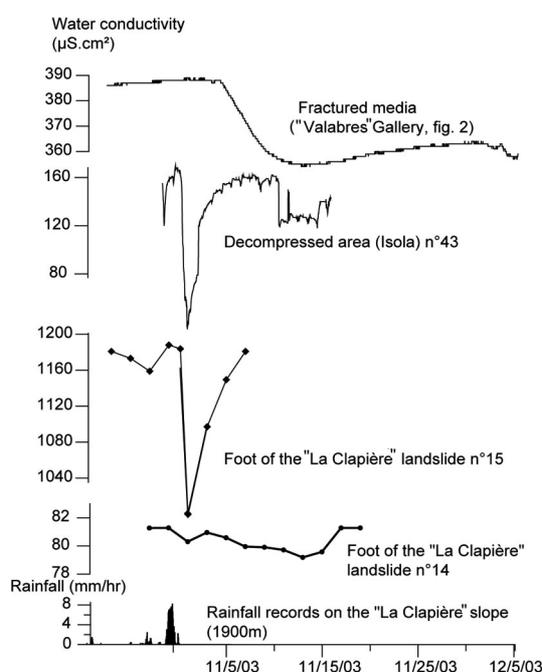
FIG. 4 – Records of conductivity measurements for 4 springs after the 2003, 11/01 flood.
FIG. 4 – *Evolution temporelle de la conductivité de quatre sources suite à l'épisode de crue du 01/11/2003.*
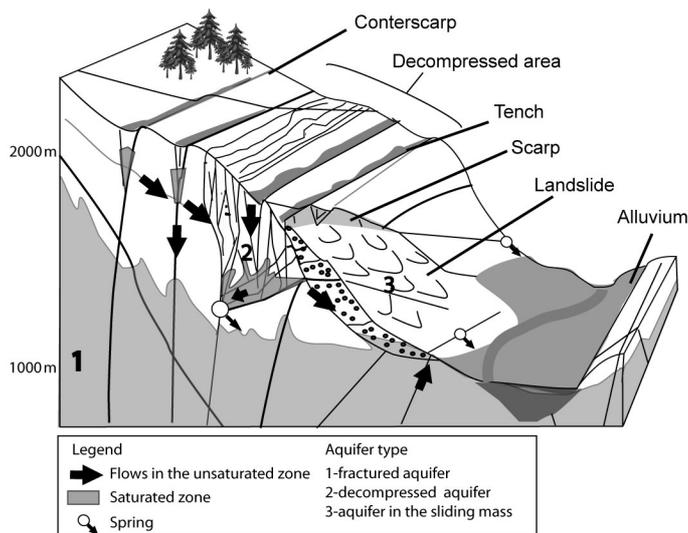
FIG. 5. – Conceptual model of groundwater flows in unstable rock slopes, derived from the analysis of hillslopes in the Upper Tinée Valley (South-East French Alps).
FIG. 5. – *Modèle conceptuel des écoulements d'eau dans les versants rocheux instables, constuit selon les informations acquises pour les versants de la Haute Vallée de la Tinée (Sud-Est des Alpes Françaises).*

the slope, the hypothesis of a single saturated perched zone implies a hydraulic gradient of 50% that is difficult to argue in a highly diffusive context. Thus a conceptual model with perched saturated zones disconnected from the fractured aquifer seems more appropriate.

In large rock slope failures such as the Hope slide (British Columbia, Canada; Brideau *et al.* [2005]), such type of flows were observed with seepages zones (up 800 m above the valley floor) draining the slip surfaces. Examples of outflows of lateral flows in the middle part of hillslope and of a disconnexion between the local aquifer and the regional water tables have also been identified in the Hubei Province in

the Three Gorge dam weathered granite [Zhang *et al.*, 2000] or in the Highlands of Scotland where slope deformation creates fracture facets, allowing lateral groundwater percolation and progressive creep [Jarman, 2006].

Evolution of water flow paths in the slope

During the glacial period, the hillslope is considered without failure (fig. 6a). For similar deep-seated deformation observed in metamorphic rocks in the Alps, long-term evolution begins after glacier melting. Glacier melting unloads the slope which consequence is the formation of failure surfaces [Agliardi *et al.,* 2001] such as hypothesised at the "Valfurna" or the "Rosone" landslides [Forlati *et al.*, 2001]. The decompression linked to glacier melting enables a decompression in the upper part of the slope. In some places, the deformation can be accommodated by toppling, that opens the tensile cracks and decompresses some zones, creating trenches (fig. 6b). This stage is similar to the "Sechilienne" landslide [Vengeon, 1998]. Toppling creates trenches progressively filled with a granular matrix (fig. 6c). In the "La Clapière" landslide, the landslide recuts the trenches (fig. 2b) and toppling evolves towards the landslide in the border of the decompressed areas. This relation between landslides and decompressed areas is confirmed for all the landslides observed in the valley (fig. 1; fig. 2).

The hydrogeological observations in the Upper Tinée Valley indicate that the evolution of deformation modifies the groundwater flows (fig. 4). The more the toppling is developped, the more important is the drained water volume in the perched aquifer (tabl. I; tabl. II). When the yearly cyclic hydromechanical effect had damaged sufficiently the material within the perched aquifer, a landslide may occur that bypasses the water flow parallel to the slope (fig. 1c) and decreases the water pressure in the trenches. After failure, the infiltration periods occurring upper in the landslide can create significant hydromechanical effects in the moving-mass.
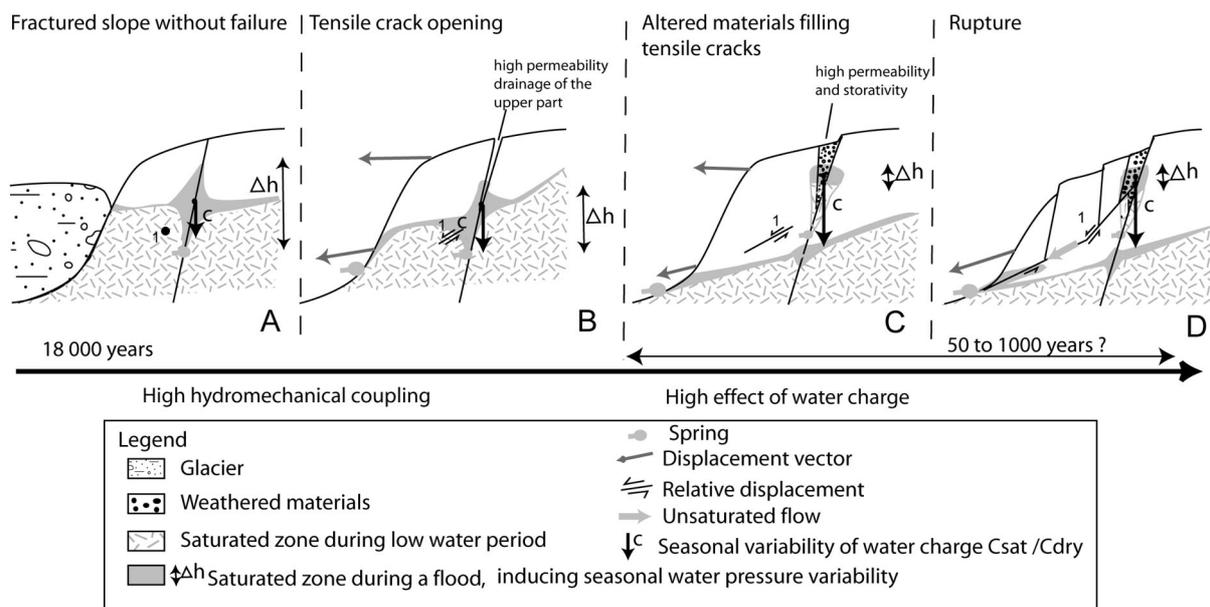

FIG. 6. – Long-term effect of the coupling between water flows, hillslope deformation and landslides.
FIG. 6. – *Effets à long-terme des interactions entre les écoulements d'eau, la deformation du versant et les ruptures gravitaires.*

Evolution of water diffusivity in the slope

The hydraulic properties of the gneiss evolve with deformation (fig. 4): (i) the transit time decreases; (ii) the flow type changes from a dilution-type flow to a piston-type flow; (iii) the seasonal variation of the hydraulic head decreases because fractures fillings have a stronger storage capacity (fig. 2a, fig. 2b, fig. 2c; cross-sections). In fractured hillslopes or in slopes with tensile cracks, the storage capacity in the middle part of the slope is low. The seasonal variability of water infiltration may create strong water pressures with low water volumes; the slope is therefore subjected to a high hydromechanical coupling (fig. 6a; fig. 6b) as in stable fractured rock [Rutqvist and Stephansson, 2003]. For example, the failure observed at point 1 at "La Clapière" landslide (fig. 6b) is affected by changes in water pressures in the saturated zone.

In the "Séchilienne" landslide [Vengeon, 1998] or in the "Campo Vallemaggia" landslide [Bonzanigo, 1999], numerical calculations link effective strain in the landslide with seasonal variability of water pressures. With toppling, weathered materials fill tensile cracks that create a storage zone. The saturated zones of the slope become disconnected from the saturated zones of the perched aquifer (fig. 1c; fig. 3) and the water pressure distribution is modified. The variability of the seasonal hydrostatic pressure decreases relatively to the fractured slopes, but is applied higher in the slope (fig. 6c). Point 1 (fig. 6c) is not submitted to hydrostatic water pressures because it is located in the unsaturated zone. The rupture propagation at this point is influenced by water loads and pressure in the tensile cracks located upper in the slope. The seasonal variability of water infiltrated in the perched aquifer can influence the slope stability, loading the middle part of the slope; these conditions may increase the possibilities of failures by the tilt of large rock volumes from the bottom of the perched aquifers to the foot of the hillslope [Guglielmi *et al.*, 2005] (fig. 6c).

CONCLUSION

In unstable hillslopes, groundwater flows are continuously modified because long-term slope deformation and toppling continuously changes the geometry of the aquifer. Growing fractures create new drains that may increase the hydraulic properties of the decompressed volumes. The main part of the infiltrated water in the hillslope is drained by these decompressed volumes in a perched zone that outflows at the middle of the slope. When a landslide occurs, it may cut these drains and bypass the groundwater flowing in the trenches. It is therefore necessary to study the entire hillslope to understand the water transfers from the upper part of the slope to the slip surface, to take into account the effect of the perched water on the landslide kinematics, and to understand the hydromechanical interactions within the landslide.

Toppling may create voids filled progressively with colluviums that create a high hydraulic conductivity gradient between the trenches and the gneissic rock. The saturated zone of the hillslope is therefore disconnected from the saturated zone of the perched aquifer, and the water pressure distribution is modified. With the progressive destabilization of the slope, the hydromechanical coupling evolves from high water pressures in the low storage capacity fractures to a potential high water loading in the high storage capacity zones in the upper parts of the hillslope.

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