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Hydrogeochemistry in landslide research: a review

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Key words. – Landslide, Hydrochemistry, Geochemistry, Hydrology

Abstract. – This review aims to give an overview of the potential hydrogeochemical information can have for landslide research and analyses the use of hydrogeochemical information to unravel the hydrological processes in landslide triggering. Landslides are well known for their data shortage; especially in case the hydrogeology is heterogeneous and difficult to measure. In this article we analyse the impact hydrogeochemical processes has on physical properties of the soil material and rock slopes, i.e. the relation with deformation rate and the relation of pore fluid composition and residual shear strength of soil material. Furthermore, the paper looks at the subsurface information that can be gained, i.e. the geological information of subsurface architecture and the hydrological information on origin of water, flow paths and travel times (using isotope analyses). Hydrochemical information used in both hard and soft rocks enables the display of clusters of water types, which is useful to identify contribution of different aquifers to the landslide area. Moreover, it can demonstrate the existence of lithologies and structures that are not visible with surface based geological investigations. Kinetic-based modelling is shown to be very useful in the interpretation of hydrogeochemical information. Lastly, it is shown that chemical information such as cation exchange properties coming from cored drilling is worthwhile for hydrological interpretations of landslides.

Utilisation de l'hydrogéochimie pour l'étude des mouvements gravitaires de versants

Mots clés. – Glissement de terrain, Chimie des eaux, Géochimie, Hydrologie

Résumé. – Cet article a pour objectif d'établir une revue de l'utilisation de l'hydrogéochimie pour l'étude des mouvements gravitaires de versants et de démontrer son intérêt pour la compréhension des processus hydrologiques impliqués dans leur déclenchement. En raison de l'hétérogénéité des milieux étudiés et des difficultés métrologiques et expérimentales associées, les mouvements de versant souffrent généralement d'un déficit d'information. Dans cet article, nous analysons d'abord les effets de l'hydrogéochimie sur les caractéristiques physiques des matériaux, c'est-à-dire la relation entre le taux de déformation ou la contrainte résiduelle de cisaillement et la composition chimique des eaux. Ensuite, l'hydrogéochimie est abordée comme outil d'investigation géologique de l'architecture du réservoir hydrologique souterrain et comme outil d'analyse hydrologique destiné à déterminer l'origine, les chemins et le temps de résidence des eaux (notamment grâce aux données isotopiques). Par exemple, l'hydrochimie, utilisée avec succès aussi bien dans les massifs rocheux que marneux, permet de définir des familles d'eaux et d'identifier la participation des différents réservoirs à l'écoulement dans les versants en mouvement. D'autre part, ces méthodes peuvent également mettre en évidence l'existence de variations lithologiques ou de structures géologiques qui ne sont pas visibles à partir d'investigations géologiques classiques. Compte tenu de la complexité de ces milieux, l'étude des processus de minéralisation fondée sur des modèles géochimiques apparaît comme un complément indispensable à l'interprétation des informations hydrogéochimiques. Finalement, il est démontré que les informations telles que les mesures géochimiques d'indice d'échange cationique, issues de forages carottés sont elles aussi importantes pour la compréhension de l'hydrologie des mouvements de versants.

INTRODUCTION

Improved knowledge of processes inducing natural hazards is required to cope with the growing risk of natural hazards for society. The increasing population and economic pressure on land induces progressively more risk associated with hazards like landslides. Prevention, mitigation and warning systems become more and more important aspects of engineering practice. To meet those societal demands, research in natural hazards is focusing on developing new technologies, or developing new methodologies with existing technologies, for example, for monitoring purposes. Chemical information is one of the new sources of information gaining increasing attention. This review aims to catalogue and elucidate the current state of applying hydrogeochemistry to landslide research.

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In slope stability research, groundwater level increase is often the critical factor for slope failure. High groundwater levels and hence high pore water pressures reduce the internal strength of slopes. Knowledge of groundwater behaviour in undulating or mountainous terrain typically suffers from a lack of data. The hydrogeological setting of large landslide systems is often quite complex [Lindenmaier *et al.,* 2005; Malet, 2003; Tullen *et al.,* 2002; Bogaard *et al.,* 2000] with very variable water flow paths. Frequently, in mass movement analysis the landslide activity is directly related to precipitation records. In fewer cases, opportunities exist to include the spatial distribution of pore water pressure, which is very important to explain local variation in mass movement behaviour [Anson and Hawkins, 2002]. In a limited number of studies, verification of the water origin, age and the flow processes within the landslide body is possible [de Montety *et al.*, 2007]. This is relevant to understand the landslide processes and to propose mitigation measures.

Several studies showed the importance of water contributions to landslide areas other than the local precipitation directly feeding the landslide area. Lindenmaier *et al.* [2005], for example, used combined field techniques and 2D modelling to show that an infiltration area exists in which water pressure propagates to an adjacent unstable area: a clear example of the differences between hydrological catchment area and the ‘affected’ unstable area. Mikoš *et al.* [2004] give another example of tracing to identify the triggering factor of a debris flow. Here 18-oxygen and tritium have been used successfully to point out local artesian pressures due to the exfiltration of 2 years old groundwater in the slope of the landslide. Water chemistry can also contain information on the subsurface architecture and can be used to get insights on the subsurface lithology and structure [Guglielmi *et al.,* 2000, 2002; Binet *et al.,* 2007]. However, it is the delicate mutual dependency of water flow, subsurface architecture and hydrogeochemical processes that make interpretations quite difficult.

Another aspect in this matter is the relation between soil chemical composition and pore water composition, and the physical properties of a soil. Anson and Hawkins [2002] postulated in their research on the *Soper’s Wood* Landslide near Bath in the United Kingdom that hydrogeochemical processes changed the clay minerals from illite to illite-montmorillonite due to leaching of potassium exchanged by calcium. Furthermore, they suggested that shear strength changed seasonally due to seasonal change in the dissolution and precipitation of minerals along the failure plane. Also Moore and Brunsden [1996] described the influence of physio-chemical processes on the *Worbarrow* coastal mudslide. It is known that the composition of the pore water influences the strength in the so-called sensitive clays [Torrance, 1996 for overview of sensitive clays in different sediments]. Also the difference between salt and fresh pore water fluids has been subject to detailed studies [Anson and Hawkins, 1998 for review of pore water chemistry on residual shear strength]. Related to this are the effects of weathering and the availability of potential sliding material. Why does a slope remain stable for decades and then suddenly lose its stability during a rather normal rain event with a recurrence interval of, for example, 10 years? In other words: what is the cause of a movement triggered by this average rain event? Can this be subscribed to changing physical properties?

This paper aims to give an overview and summarizes the different applications of hydrogeochemistry in landslide research. It tries to answer the question: “What can hydrogeochemistry do for landslide research?” This ranges from mudslides to rock fall and from hydrological delimitation of the source areas to the influence of pore fluid composition on residual shear strength of the material. In that, the review hopes to encourage the application of hydrogeochemistry in landslide studies. The review uses two thoroughly studied landslide: the *La Clapière* landslide and *Super-Sauze* mudslide, where abundant use has been made of hydrogeochemistry. In the next sections we will draw a general outline of hydrogeochemical information that can be interesting in landslide work. The relationship between pore fluid composition and soil strength is discussed. We elaborate on the relation between hydrochemistry, hydrogeology and deformation of unstable hard rock slopes and give the example of the *La Clapière*, France research of the last 10 years. The paper continues with the specific use of hydrogeochemical investigation and geochemical modelling on extracting subsurface information in landslides that occur in soft sediments. Here we elaborate on the *Super-Sauze* research site. Furthermore, the use of cation exchange properties is demonstrated. A separate section describes the use of isotopes tritium and 18-oxygen (^{18}O) for landslide research. The review finally will give a summary and discuss shortcomings, inherent difficulties and possible future research lines.

WHAT CAN HYDROGEOCHEMISTRY DO FOR LANDSLIDE RESEARCH?

Hydrogeochemistry is defined as ‘The study of the chemical characteristics of ground and surface waters as related to areal and regional geology’ [Dictionary of Earth Science, 2002]. This definition is also suitable for engineering geology practice, as one relates the hydrochemical fingerprint to local lithology. Basically, information from hydrogeochemical studies is just another variable, which can be measured and taken into account in landslide research. Both water chemistry and geochemical measurements contain information about the subsurface reservoir properties and about subsurface flow processes. Moreover, chemical reactions can influence the physical properties of the subsurface, such as its permeability and its (residual) shear strength.

Clearly, hydrogeochemistry is not a new field in the earth science. Many earth science disciplines have preceded the landslide researchers. A well-known example is the application of various hydrochemical techniques in catchment hydrology [Kendall and McDonnell, 2003]. In catchment hydrology, tracer information was needed to better understand the process of discharge generation: from a lumped empirical approach towards a more distributed and deterministic approach. This demand for increasingly detailed, process knowledge is also the motivation for performing hydrogeochemical research in landslide studies.

However, some differences exist between the application of tracer studies in catchment hydrological and the application in landslide studies. The latter focuses mainly on groundwater reaction at a specific location, often only a part of a slope, and not in the overall catchment scale discharge generation. Also, the dynamic character of an unstable hillslope can make application and interpretation of hydrogeochemical investigations difficult. Lastly, in landslide research one is also interested in the strength properties of the soil material. Soil and rock properties can change because of hydrogeochemical processes.

The earth science information that can be gained on the subsurface, i.e. the geological information of subsurface architecture and the hydrological information on origin of water, flow paths and travel times. The chemical information that is used, can be divided into information coming from water chemistry determined from standard water analyses, from isotope measurements or from information of geochemical measurements.

THE INFLUENCE OF PORE FLUID COMPOSITION ON STRENGTH PROPERTIES

Probably the most spectacular example of the influence of water chemistry on the physical properties of a soil is the sensitive (“quick”) clays. Quick clays are defined as soils that lose their shear strength after being disturbed [Dictionary of Earth Science, 2002]. Soils change from normal firm ground to a liquid mass when it is set in motion. This results in large soil (debris) spreads of tens of hectares even on very low gradient slopes [Dikau *et al.*, 1996].

The definition for clay sensitivity is the ratio between undrained shear strength in undisturbed and remoulded clay 30 or 50 and the remoulded shear strength 0.4 or 0.5 kPa. The sensitive clays, derived from crystalline metamorphic rock flour deposited in marine and brackish environment, show a house-of-cards open structure and high porosity. Disturbance of the delicate structure results in collapse of the house-of-cards structure. However, the strength reduction is also caused by inter-particle repulsion, related to the electrical potential in the double layer, caused by leaching of salt pore water [Bjerrum, 1955; Eide and Bjerrum, 1955]. In fresh water sediments, the post-depositional introduction of organic dispersing agents causes high sensitivity [Soderblöm, 1966].

There is a strong correlation between the pore water composition of sensitive clays and its geotechnical behaviour: high salinity results in high shear strength, low salinity in very low shear strength. However, leaching of salinity is not the only cause for an increase in sensitivity. Other factors influence the sensitivity of the clays, such as the mineral composition, weathering and total pore fluid concentration. Only a few percent of expandable clay (smectite) produced by in situ weathering increases the shear strength of a soil [Berry and Torrance, 1998]. Weathering of the near surface clays often results in higher strength and lower sensitivities. This is probably related to oxidation of the near surface layer. The weathering processes and dissolution of Mg, Ca and K counterbalances the de-salinisation of pore waters [Andersson-Sköld *et al.*, 2005; Berry and Torrance, 1998; Torrance, 1990].

The effects of Na, K, Mg and Ca and their ratios on the sensitivity of clays depend on the total concentration and on the mineralogy. Karvounis [1997 cited in Andersson-Sköld *et al*, 2005] showed that the yield stress/water content relationship was the same for 1 $g.l^{-1}$ KCl saturated clay and a 20 $g.l^{-1}$ NaCl saturated clay, suggesting the maximum pore water concentration having high sensitivity is much lower for K than for Na. Andersson-Sköld *et al.* [2005] report also that Na to K, Mg and Ca ratios and the relative amounts of Na and K in the pore water are correlated to the sensitivity only when the total ion concentration is relatively high.

The strength decreases caused by dilution, is mainly coupled with rainwater infiltration. Percolation does not only take place through the soil matrix from the surface downward. Surface discontinuities are known to favour rapid transfer of dilute waters. Detailed analysis on cored borings sometimes shows the lowest pore water salinity at the lowest depth, indicating the flow of fresh water laterally and upwards from the underlying bedrock [Torrance, 1979; Andersson-Sköld *et al.*, 2005]. Quick clay conditions at the bottom of the deposits have a large impact locally on landslide.

Pore water chemistry is not only influencing the geotechnical properties of sensitive clays. Anson and Hawkins [1998] showed a raise in residual shear strength of sodium montmorillonite with increasing Ca concentration in the pore water. The same article shows that kaolinite is less sensitive to Ca concentration in pore water. Moore and Brunsden [1996] showed the influence of physico-chemical processes on a shallow coastal mudslide on the south coast of England. They reported that fluctuations in groundwater chemistry coincided with temporal movement patterns. The aluminium concentrations increased in pore water following mudslide movement. Also they found that low pore water ion concentrations result in lower residual shear strength. Lefebvre [1984, cited in Di Maio, 1996] showed that low pore water salinity is required for very low remoulded shear strength.

Di Maio *et al.* [2004] systematically analyse geotechnical properties of several Italian clays in relation to mineralogy, pore water composition and stress state. As an example of their results, figure 1 shows the residual shear strength as function of pore fluid composition. They hypothesized that the strength increase related to pore fluid composition depends on the lower void ratio of the clays prepared. Under the considered stress level, the void ratio of the clays, either dry or in cyclohexane (low dielectric fluid), is equal to or higher than that in the saturated salt solution. Di Maio *et al.* [2004] concluded that the increase in shear strength “reasonably depends on a particular particle aggregation or on shear resistance increase at the particles contact”. Furthermore, Di Maio *et al.* [2004] found that smectite fraction in the soil strongly influences the geotechnical behaviour of the soil as Berry and Torrance [1998], but on the other hand that increasing stress reduces the influence of smectite fraction on compression and swelling.

The interaction between mineralogy, pore water chemistry and stress state should be considered more often in geotechnical research. As a result, laboratory testing on strength parameters should take care in the choice for pore fluid composition as stated by Moore and Brunsden [1996] and Di Maio *et al.* [2004]. Generally, distilled water seems to cause a reduction of shear strength [see for example the results of Di Maio *et al.,* 2004; fig. 1]. Furthermore, Moore and Brunsden [1996] conclude that ‘residual strength should be regarded as a dynamic property which can vary seasonally with environmental conditions and in feedback response to ground movement’. Overall, evidence mounts

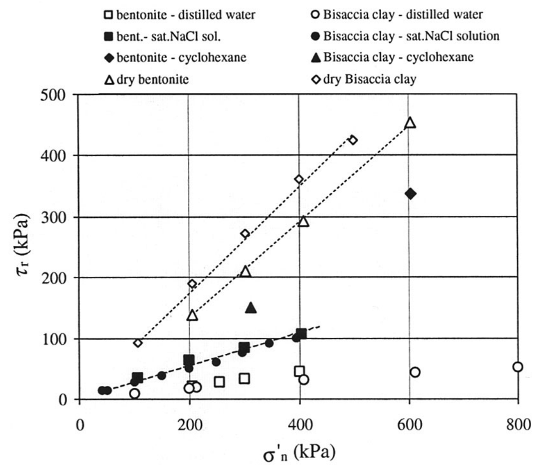

FIG. 1 – Residual shear strength of the Bisaccia clay and the Ponza bentonite dry and reconstituted with various fluids [modified from Di Maio *et al.*, 2004]

FIG. 1 – *Résistance résiduelle au cisaillement de l'argile de Bisacia et de la bentonite de Ponza, en conditions sèches et humides pour plusieurs compositions de fluides.*

showing the significant influence that pore water chemistry has on the geotechnical behaviour of soils.

THE USE OF HYDROCHEMICAL INFORMATION IN LANDSLIDE STUDIES: HARD ROCK SLOPES

This review looks at the hydrogeology of hard rock slope in the narrow sense of bedrock flow, typically through fractures and fissures but also influenced by the unconsolidated topsoil or slope debris layer. Landslides or more specific rock slides and rock fall in these environments are characterised by local water flow patterns, which are to a large extent determined by the secondary porosity of mountain slopes. Indeed, the hydrogeology of a rock slope depends on land surface topography, internal highly heterogeneous hydrogeological and mechanical properties and infiltration of rainfall and melting snow.

Heterogeneity of hydraulic properties

The hydrological response of a fractured rock slope depends on the geometry and hydraulic connectivity of the network of discontinuities, individual discontinuity properties and on the intact rock properties [Tsang, 1999; Bonzanigo *et al.*, 2001]. At the slope scale, a decrease in hydraulic permeability is commonly observed with depth because the increase of the state of stresses induces a closing of rock fractures. Close to the land surface, there is a low-stress decompression zone that can be 600 m thick where permeability may vary between 10^{-4} and 10^{-8} m.s^{-1}. Deeper in the high-stress zones of the massif, the permeability is comprised between 10^{-9} and 10^{-11} m.s^{-1} [Marechal, 1998; Marechal *et al.*, 1999]. This permeability contrast between the two zones induces two types of groundwater flows, a shallow one parallel to the land surface and a deeper one in the slope [Leca *et al.*, 1993]. At the discontinuities network scale, contrasts of a factor 10^2 to 10^7 can be observed respectively between different discontinuities and between discontinuities and intact rock matrix [Cappa *et al.*, 2005; Guglielmi *et al.*, 2006]. At the single discontinuity scale, a 50% variability of the permeability and stiffness values is commonly observed [Rutqvist and Stephansson, 2003; Guglielmi *et al.*, 2006]. Such heterogeneous hydraulic properties in a slope induce a drainage concentration in 1 to 10% of the fractures [Black *et al.*, 1991; Olsson *et al.*, 1998; Bour, 1997; François and Massonnat, 1981]. As a result, it appears that landslides can be triggered by the presence of one open fissure diverting water towards a landslide region. Abundant observations of the local character of bedrock flow are available in literature. For example, Johnson and Sitar [1990] observed during their study to debris flow initiation by pore pressure built-up that 'scars with exposed bedrock continue to emit significant amounts of water from the bedrock for days or weeks following failure'. Therefore, Johnson and Sitar also conclude that the flow through bedrock should not be neglected as an important flowpath for pore pressure built-up at the soil-bedrock interface, which could lead to debris flow initiation. Wilson and Dietrich [1987] showed as well the importance of water circulation through bedrock and the heterogeneities in bedrock permeability for the stability of shallow landslides. Ewert [1990] gave numerous examples of observations of the heterogeneity of ground water flow in hard rock engineering practice, especially in tunnelling. He stated: 'I have got the impression that we still lack basic information which would enable us to better predict the behaviour of rock masses in view of their groundwater flow'. From the above it follows that in hydrogeological setting detailed knowledge of local water flow paths is a prerequisite to understand the landslide dynamics in hard rock slopes.

Characterization of coupled effects between groundwater infiltration and slope movements

Couplings between hydrogeology and deformation of rock slopes correspond to complex mechanisms. 'Direct' couplings occur through deformation and pore-fluid interactions and 'indirect' couplings imply changes in material properties. Interstitial waters linked to the infiltration of seasonal precipitation induce a localized seasonal deformation inside fracture voids. Interstitial pressure elevations act to reduce effective stress in the discontinuities [Biot, 1941; Terzaghi, 1923; Tang *et al.*, 2002]. A reduction of effective stress state leads to a traction opening of discontinuities in zones close to the surface and in the upper part of the slope. Furthermore, deeper in the slope and at the foot, normal opening of discontinuities leads to the reduction of the available shear strength of discontinuities or of the failure surface [Tsao *et al.*, 2005]. In both cases, coupling between groundwater pressure and deformation is a major factor in the elastic and non-elastic deformation of a slope. When the discontinuities of the slope are being deformed, their hydraulic properties are modified and thus the hydrogeology of the slope can change.

Adding to those seasonal hydromechanical effects, long period underground hydrochemical and erosional effects can take place in the slope [Clow *et al.*, 1996; Furuya *et al.*, 1999; Gardner *et al.*, 1996]. Water can dissolve or transform minerals in the fillings of some discontinuities thus reducing the material strength and modifying material hydraulic properties [Girod, 1999]. When the deformation of the slope becomes very active (deformation rate of a few millimeters per day), rock is crushed and dilatancy occurs on deep discontinuities around the failure surface. Highly conductive flowpaths can then be generated and particle erosion can take place [Wen *et al.*, 2004]. In these situations hydrochemical information can be meaningful.

Indirect methods based on the study of water-rock interactions [Compagnon *et al.*, 1997; Guglielmi *et al.*, 2000] and on artificial tracing experiments [Bonnard *et al.*, 1987] were developed in order to locate water flow paths through the rock mass and to estimate pore pressures at the scale of the large moving rock mass. Methods were based on the one hand on chemical and stable-isotopes analyses of spring waters and, on the other hand, on modelling different interface water-rock exchanges observed on the field. Chemical analysis of waters originating from springs outflowing from the slope aquifer was performed during different periods of the year. We defined a typology of existing water-types depending on in situ hydrological conditions. This typology was then compared to a parametrical study on a geochemical model [Madé *et al.*, 1990]. These methods were tested on French, Swiss and Italian large moving fractured rock masses, and confirm that they are worthwhile to improve knowledge of landslides' water infiltration areas and groundwater flow paths. Furthermore, they give estimates of the amounts of water drainage and renewal times and they give insights of long term slope properties modifications linked to damage [Guglielmi *et al.*, 2002; Binet *et al.*, 2007].

Results from 10 years of hydrogeochemical monitoring of the *La Clapière* landslide

The *La Clapière* landslide complex is a typical example of a large moving landslide occurring in highly fractured and altered gneissic rocks (fig. 2). The 60 x 10^6 m^3 moving rock mass body displays a high internal brittle-ductile deformation and it is bounded by a multi-planar failure surface located at a 100-200 m depth. For a quarter century, the *La Clapière* landslide has been monitored for slope deformation and hydrometeorological conditions. Follacci [1987, 1999] showed the correlation of local precipitation with the deformation rates. Indeed, seasonal accelerations of the landslide of 30 to 200 $mm.day^{-1}$ are clearly correlated to snowmelt and rainfall events on the slope. Unfortunately, the correlation was obviously highly non linear (because it did not take into consideration slope properties) and resulted in a poor estimate of hydrologic risk to trigger a catastrophic slope collapse.

Since 1995, a multi-scale field hydrogeological study was combined with a hydrogeochemical approach to improve knowledge of water flow through unstable hard rock slopes, taking the *La Clapière* site as a reference site. Repeated sampling was performed of spring water chemistry in high and low water periods, both at the foot of the active landslide area and along the slope. $\delta^{18}O$ isotopes were also used to characterize the landslide recharge area. We first elaborate on the water chemistry and the thermodynamic modelling. The isotopic information is described in a separate section further below.

Spatial chemical variations of spring chemistry was explored by plotting the water composition in a Piper diagram to distinguish water types of the springs mapped on the hillslope [Compagnon *et al.*, 1997; fig. 2a, 2b]. A Ca-Mg-HCO_3 type of water exists at the higher located springs, whereas the springs at the foot of the slope showed a Mg-Ca-SO_4 water type. The upslope springs show low-mineralised water types whereas the springs at the toe of the landslide area show very high mineralised water. The latter concentrations could not be explained by normal water-rock interaction of infiltrating upslope water and Triassic gypsum dissolution hidden under the foot of the slope was invoked [Guglielmi *et al.*, 2000]. Indeed, some structural data can support the location of a major thrust plane separating Triassic strata and gneisses at the foot of the slope [Ivaldi *et al.*, 1991; fig. 2c].

In order to explain the source of the high SO_4 concentrations, a hydrogeochemical modelling approach was followed by Guglielmi *et al.* [2000]. The idea behind this methodology is that the calculation of the dissolution and precipitation of minerals because of water-rock interactions helps to interpret water chemistry information or at least constraints the possible explanations for the sampled water chemistry. The thermodynamic- and kinetic-based model KINDIS [Madé *et al.*, 1990] can be used to simulate the

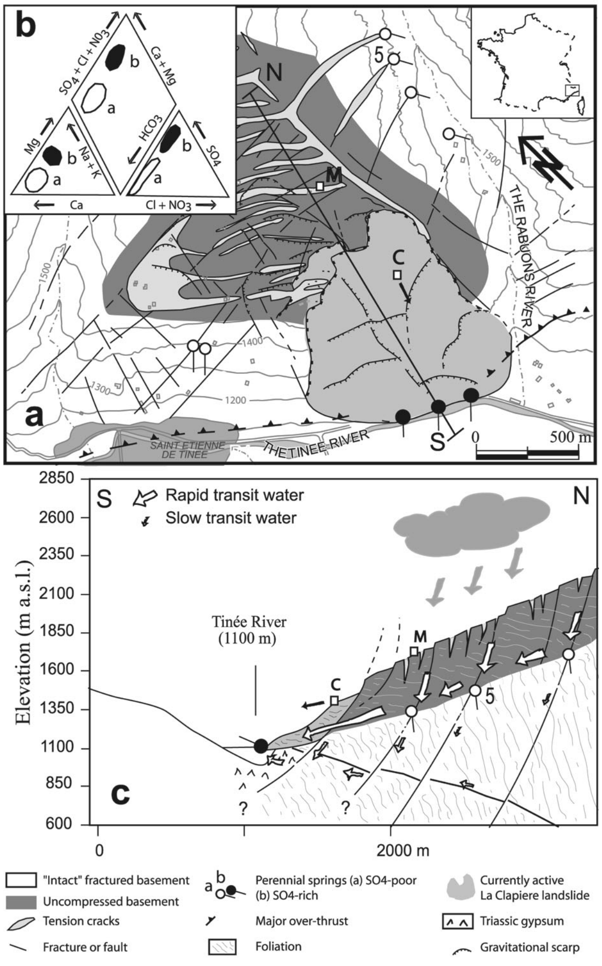

FIG. 2 – Hydrogeological model of La Clapière slope as inferred from hydrogeochemical data. Hydrogeological map (2a). Piper diagram of spring water chemical contents (2b). Conceptual hydrogeological cross-section of groundwater flow (2c).

FIG. 2 – *Modèle hydrogéologique du versant instable de La Clapière dérivé de données hydrogéochimiques. Carte hydrogéologique (2a) ; diagramme de Piper de la chimie des eaux de source (2b) ; profil conceptuel hydrogologique (2c).*

observed water concentrations according to different water-rock interactions. This model describes the interactions between minerals and aqueous solutions and takes into account the irreversible dissolution of reactants and the reversible precipitation of secondary products. The model can be used to assess the chemical saturation level of the different minerals by performing iterative computations until the system has reached equilibrium between the mineral phases and the water.

In case of the *La Clapière* study (fig. 3), acquisition of spring water chemistry was tested according to the chemical composition of the different expected input waters (snow-melt-type and rainfall-type waters) and the abundance of some minerals (quartz, plagioclase, muscovite, biotite and accessory minerals which are feldspar, calcite, chlorite and pyrite). On the gneissic slope of *La Clapière*, geochemical modelling explains sulphate concentration of waters from 0 to 130 mg.l^{-1} by dissolution of sulphurous minerals, which exist in the basement as observed in the springs at the upper part of the slope (fig. 2a). The high concentrations (600 to 800 mg.l^{-1}) cannot be explained by results from simulations (fig. 3, group b). At the top of the slope, groundwater directly flows through the uncompressed fissured basement with different flowpaths mainly guided by the high permeable gravitational features that correspond to interconnected tension cracks widely opened and more or less filled with colluvium that characterizes the structure of this part of the slope. A perched aquifer nested in those features is drained by the perennial springs located at the top of the slope. A basal aquifer is drained by springs at the lower part of the slope and at the landslide foot. The method strongly suggests existence of non-exposed rocks hidden under the studied slope (fig. 2c). In the local geological context, these rocks can only be Triassic gypsum likely to be trapped under a major thrust fault located at the foot of the slope.

Time evolution of spring water chemistry was characterized by SO_4^{2-} concentration decreases that occurred after precipitation events (fig. 4). When there is no precipitation (for example in August; fig. 4), the SO_4^{2-} concentration remains high and the variation is low. SO_4^{2-} transient variations appeared the opposite of NO_3^- transient variations. After a precipitation event, there is an increase of NO_3^- that is synchronous to a decrease in SO_4^{2-} content. The NO_3^- peak in spring waters corresponds to the transit of the infiltrated meteoric waters to the reservoir outlet. The sulphate peak results from the dissolution of pyrite within the slope gneisses and from the dissolution of Triassic gypsum likely to be trapped at the foot of the slope. Thermodynamic calculations showed previously that the more sulphate-rich the waters are, the longer they have stayed inside the slope. The significant decrease in SO_4^{2-} means that, during precipitation periods, there are rapid infiltration fluxes through the reservoir corresponding to shallow waters, chemically far from equilibrium with the reservoir rock chemistry. Transient signals are in such cases interpreted as dilution inflows, linked to low concentration precipitation inflows, which mix with pre-event groundwater from the saturated zone that is chemically near equilibrium with the rock matrix primary minerals. Such hydrochemical variations with time can be well explained by a dual-permeability model. During periods of infiltration, a quick transit of fresh infiltrated water essentially flows through the very conductive fractures and a very delayed transit of those waters flows through the poorly conductive zones.

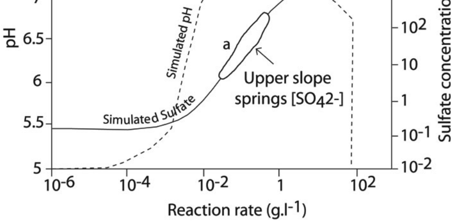

FIG. 3 – Simulation of water-rock interactions in the gneissic La Clapière slope. Plot of measured data on the simulating pH and sulphate versus reaction rate diagram (a and b groups refer to chemical facies measured in the field and plotted in the Piper diagram in fig. 2b).

FIG. 3 – *Simulation des interactions eau-roche dans le gneiss de La Clapière.*

The monitoring of springs allowed to propose a model of spatial transient infiltration in the slope. The springs are located at various elevations at the slope and represent drainage of perched and basal aquifers that were nested in the active landslide, stable uncompressed and “intact” zones. An estimate of flow yields and transit times was conducted based on a simplified analytical application of the equations of conservation of fluxes using measured spring $S0_4^{2-}$ contents and flow rate variations [Cappa *et al.*, 2004]. When infiltration occurs in the upper part of the slope, for example snow melting above 1800 m a.s.l., it takes approximately 20 days to go through the landslide and flow out of the foot of the slope. Infiltration rates range between 0.4 l.s^{-1} and 0.8 l.s^{-1}. It clearly appears that such quick infiltration transit occurs through the currently active landslide that is hydraulically connecting the upper perched aquifer to the basal aquifer. Rapid transit waters that do not reach chemical equilibrium with the reservoir rock are waters characterized by low ion concentrations (their concentration is close to that of meteoric water).

Landslide velocities of *La Clapière* are characterized by very slow periods with velocities of 1 to 5 mm.day^{-1} and periods of acceleration of 0.02 and 0.25 m.day^{-1}. These periods of acceleration are roughly synchronous and have the same duration as dilution periods of springs (fig. 4). Acceleration curves display an asymmetric shape with a rapid rise synchronous with the decreasing part of the spring water chemical content (dilution linked to main groundwater flood infiltration) and a slow decrease synchronous with the slow return to spring initial chemical content (slope drying up). Even if the correlation between estimated infiltration rate and landslide acceleration is far from being simple and linear, the main result is that a relatively small amount of water infiltrated (small infiltration rate over a short time period) triggers a general acceleration of the 60 x 10^6 m^3 sliding volume. This means that the predominant effects of water in fractured hard rock are linked to the interstitial pressure increase located in a limited number of discontinuities within the slope, as was analyzed using various numerical codes by Guglielmi *et al.* [2006].

This combined geochemical–hydrogeological approach showed two main water flowpaths in the *La Clapière* landslide and could link the high spatial variability of groundwater

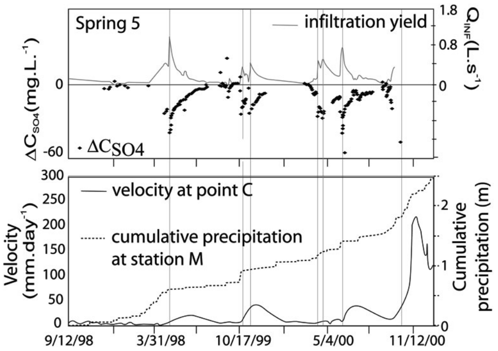

FIG. 4 – Typical comparison of chemical variations of spring 5 draining the upper part of the La Clapière slope and La Clapière landslide acceleration at Point C for 1999-2000 hydrologic period (Spring 5, Point C and Point M are located on the map of fig. 2a).

FIG. 4 – *Comparaison des variations chimiques de 5 sources drainant la partie amont du versant de La Clapière et accélération du glissement au Point C pour la période hydrologique 1999-2000 (Source 5, Point C et Point M sont localisés sur la carte de la fig. 2a).*

chemistry to major heterogeneities (Triassic gypsum) of the slope that could likely be responsible for stress and strength heterogeneities of the slope. Similar results were obtained on the unstable *Séchilienne* rock slope near Grenoble where sedimentary layers located at the top of slope were responsible for a characteristic chemical content of infiltration waters in the landslide. This allowed Guglielmi *et al.* [2002] to perform a natural tracing of those waters through the landslide. The time variability of groundwater chemistry appeared closely correlated to slope movements. Indeed, the measured chemical variations are typical surficial waters, rapidly flowing into a limited number of highly permeable and deformable discontinuities responsible for the destabilization of large fractured hard rock slopes destabilization. This approach is based on three types of data; hydrogeological context that can be deduced from spring occurrence in the slope, rock petrography and spring water chemistry and yield that are easily sampled within the field. Then the hydromechanical behaviour of the slope can be analyzed using coupled numerical modelling of hydromechanical and chemical processes both in the saturated and unsaturated parts of the slope.

THE USE OF HYDROGEOCHEMICAL INFORMATION IN LANDSLIDE STUDIES: SOFT SEDIMENT SLOPES

Landslides often occur in non-consolidated, weathered materials like marls. The high clay content and the specific geomechanical characteristics of weathered marls make them prone to failure. The low permeability of the clayey matrix make hydrological analyses of the landslides difficult [Bogaard, 2001]. Several pioneering studies have been performed on landslides using hydrochemical tracing in order to better understand the hydrological system [for example, Bogaard *et al.*, 1996; Sakai *et al.*, 1996; Bogaard *et al.*, 2000; Anson and Hawkins, 2002; Mikoš *et al.*, 2004; de Montety *et al.*, 2007]. To elucidate the potential of hydrogeochemistry in landslide research, the well documented *Super-Sauze* example is described here in detail.

The example described here, the *Super-Sauze* mudslide, is one of the best studied landslides in weathered marls using hydrochemistry as a source of information for the hydrological behaviour of the site. The *Super-Sauze* landslide is a mudslide and was triggered in the 1970's at the interface between moraine and autochthonous black marls [Malet, 2003; Weber and Herrmann, 2000] It has been studied since 1996 and a spatio-temporal database on rainfall, temperature, capillary pressure head, soil moisture content, groundwater level and displacement is available [Malet, 2003; Malet *et al.*, 2005]. The groundwater system has been described from a set of about twenty open standpipe piezometers evenly distributed over the landslide body. Montety (de) *et al.* [2007] have studied how relevant the hydrochemical approach could be to improve our knowledge of a shallow slow-moving mudslide, sampling the borehole and spring around and at the landslide. The objectives were to provide insights on the origin of the water, to define the hydrological limits of the landslide system and, eventually, to specify the hydrological short– and long-term processes. Accordingly, water chemistry has been surveyed at different strategic periods in 2003 and 2004 (end of winter and the snowmelt impact, spring, the low flow period of summer, autumn and the soil re-wetting), so that the hydrochemistry areal variations have been investigated according to the seasons. Continuous sampling over shorter periods has also been undertaken to examine the infiltration and recharge processes.

Water chemistry variation over space and time: Super-Sauze mudslide

The characteristics and organisation of water chemistry over the *Super-Sauze* mudslide turned out to be stable throughout the year [de Montety *et al.*, 2007]. There was a systematic increase of the water mineralization downwards while the proportion of Na decreased (30% to 5%) to the benefit of Ca and Mg (30% to 50% and 35% to 60% respectively) (see figure 5). These evolutions have been readily explained by combined geochemical processes such as dilution (mixing of the landslide groundwater with the low mineralised moraine waters or meteoric waters), dissolution-precipitation of carbonate minerals, cation exchange and pyrite dissolution. This consistent areal distribution of the water chemistry is also an argument for the continuity of the groundwater system.

Locally, unexpected high concentrations of SO_4, Mg and Na were observed. Typically, these chemical anomalies were shown to relate to topographical peculiarities and were explained as a contribution of deep waters moving along major discontinuities (faults, bedding and schistosity planes).

Long- and short-term variations of the hydrochemistry were surveyed to investigate further the conditions of subsurface water infiltration. Comparison between chemical variations and hydrologic observations enabled the authors to provide hypotheses about the distribution of rapid preferential vertical flows.

For example, the short-term chemical variations were investigated at the beginning of the snow-melt period. All the ions except NO_3 were characterised by the same temporal variation (fig. 6). The first part of increasing concentrations is explained by the contribution of the pre-event soil water, which attained the groundwater via a piston flow mechanism. As soon as the low-mineralised new water has

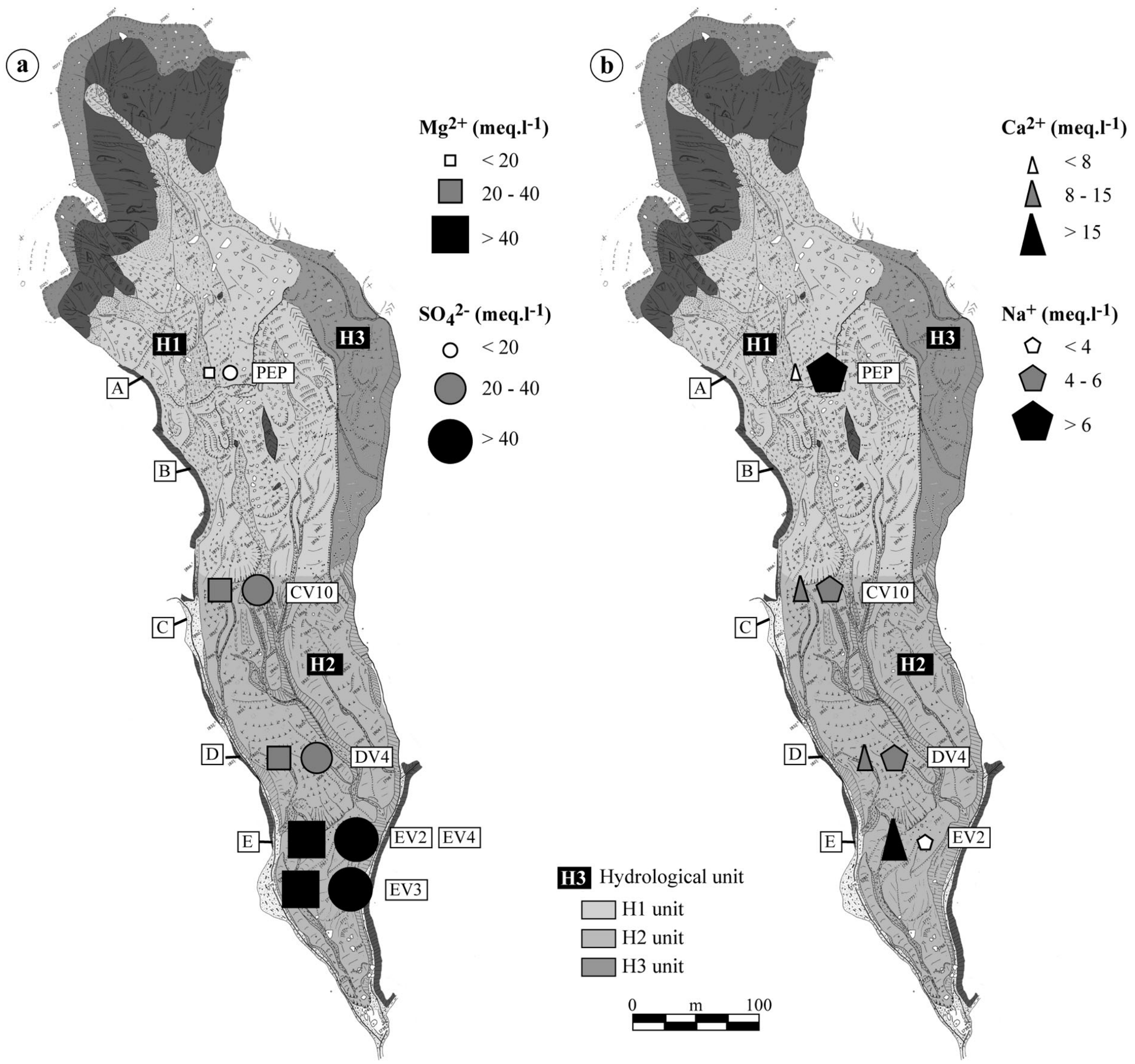

FIG. 5 – Spatial distribution of the major cations and anions in the groundwater at the Super-Sauze landslide. Water flows from the top of the figure downwards [modified from de Montety *et al.*, 2007].

FIG. 5 – Distribution spatiale des cations et anions majeurs dans les eaux de nappes du glissement-coulée de Super-Sauze. Les eaux de nappes s'écoulement du haut vers le bas de la figure [modifié de Montety de et al.*, 2007].*

reached the water table, the concentrations decreased as a consequence of the dilution effect. The new water is enriched in nitrate compared with the pre-event water in keeping with the cattle defecations or other animals faeces lying on the ground surface. As melting and water sampling started at the same time, it was possible to assess the mean transit time of water infiltrating through the unsaturated zone: it took 7-8 days for the new water to reach the water table (beginning of the dilution process and NO_3 rising), proving the importance of the preferential vertical flows on the local recharge of the groundwater body.

Use of geochemical modelling

The general hydrochemical features showed a very high ionic strength in keeping with the hydrochemical data from other landslides in marls of the South French Alps. But the water chemistry at *Super-Sauze* has its own peculiarity. The concentration in SO_4 was found to be up to twice that observed in the other studies while, unlike most landslides situated in black marls where Ca is usually the dominant cation, Mg has proved to be the major cation. Also, the specific character of the *Super-Sauze* mudslide lies in the very high Na concentrations (up to 35 $meq.l^{-1}$). Further analyses have revealed unusually high concentrations in strontium. As suggested by Meybeck [1984], strontium anomalies may be a consequence of celestite dissolution, which is usually associated to gypsum. Yet, gypsum was not found in the mineralogical composition of the material.

To tackle this problem, a geochemical modelling exercise has been undertaken as already applied with success at the *La Clapière* landslide [Guglielmi *et al*, 2000]. The

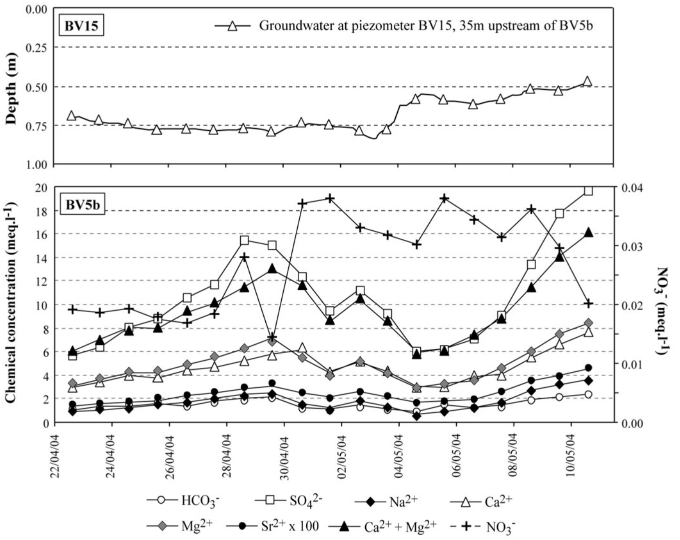

FIG. 6 – Example of short-term chemical variations compared with the water level variations [modified from de Montety *et al.*, 2007].
FIG. 6 – *Example de variations chimiques à court-terme et comparées avec des variations piézométriques [modifié de de Montety et al., 2007].*

thermodynamic- and kinetic-based model KINDIS [Madé *et al.*, 1990] has been used to simulate the observed water concentrations according to different water-rock interaction. The results of the simulations have shown that the mudslide water chemistry could not be explained by the dissolution of the constituent material. The groundwater is clearly not originated from direct rainfall or snow-melt with subsequent enrichment or from any other sources detected in the field. Evaporites, which are not present in the mudslide material, have been proved by de Montety *et al.* [2007] to be the main origin of the observed water chemistry. These results have pointed out the major impact of the gypsum and dolomite layer of the overthrust contact above the *Super-Sauze* mudslide. This is the only identified source of evaporite at a regional scale and accordingly they have identified a remote origin for the water. Finally, this hydrochemical investigation has contributed to the refinement of the conceptual hydrological model of the mudslide as proposed by Malet *et al.* [2005] (fig. 7).

THE USE OF ISOTOPIC ANALYSIS IN LANDSLIDE STUDIES

Environmental isotopes are natural and anthropogenic isotopes whose wide distribution in the hydrosphere can assist in the solution of hydrogeochemical problems [Kendall and McDonnell, 2003]. Tritium (^3H) analysis provides information on water transit times and the dynamics of deep-water percolation. The use of tritium to calculate recharge rate requires assessment of the temporal and spatial variation of the tritium content. If initial atmospheric concentrations are unknown, an alternative dating method is to use both ^3H and ^3He. The former decays into ^3He, which can be used as a quantitative tracer of the age of the water since precipitation [Kendall and Doctor, 2004].

Mikoš *et al.* [2004] studied the debris disaster in November 2000 at the *Stoze* landslide in Log pod Mangartom, Slovenia, that occurred after an extreme rain event. A hydrological analysis showed a significant increase in runoff coefficients (the percentage of precipitation that appears as runoff [Dictionary of Earth Science, 2002]) in the preceding autumn 2000. They used tritium tracer to assess the travel time of sampled spring water and oxygen-18 to assess the recharge area of the groundwater (see also below). The age of the groundwater was determined to be around 2 years. Interestingly, the authors cautiously link the groundwater

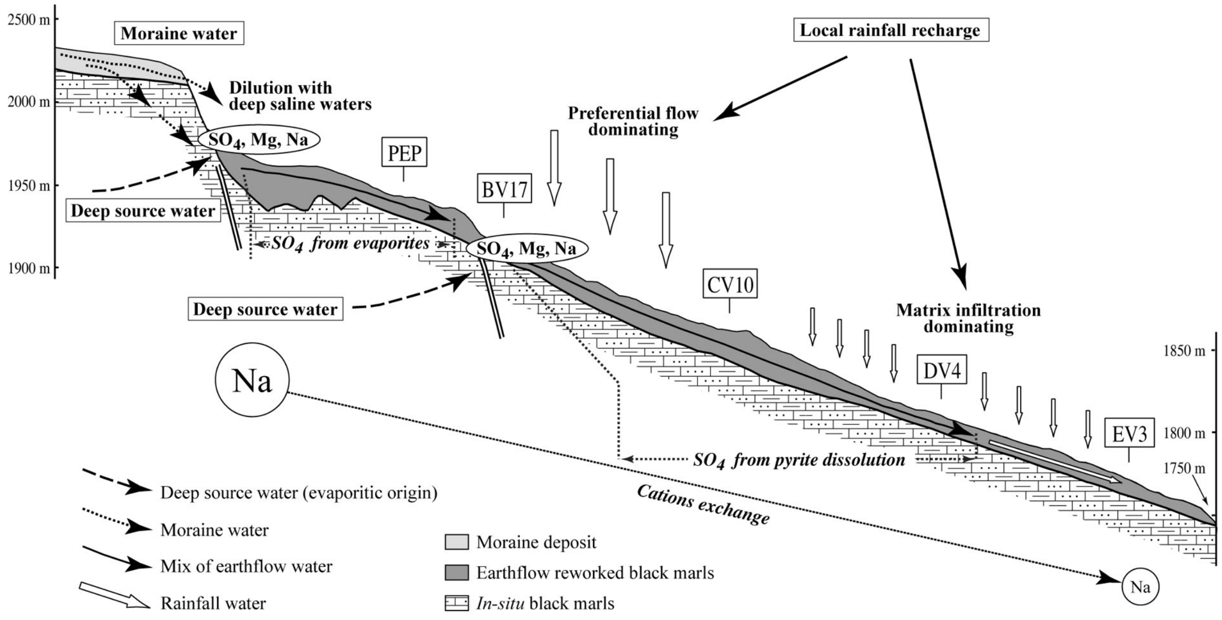

FIG. 7 – Synthetic cross section representing the hydrological concept of the Super-Sauze mudslide as interpreted from hydrochemical analyses, with indication of the mudslide velocities [modified from de Montety *et al.*, 2007].
FIG. 7 – *Profil en long interpretative représentant le concept hydrologique du glissement-coulée de Super-Sauze interprété d'analyses hydrochimiques, et indications des vitesses de glissement observées [modifié de Montety de* et al.*, 2007].*

age with a major earthquake in April 1998, hypothesizing that this event might have generated new groundwater pathways through the fractured subsurface. This also explains the unusual wet initial conditions of the landslide area preceding the triggering event in November 2000. Although very cautiously stated, Mikoš *et al.* [2004] show the possibility dating has for the analysis of hydrologically triggered landslides.

The $\delta^{18}O$ composition (and δ^2H but that one is not considered here as $\delta^{18}O$ and δ^2H are strongly correlated) in precipitation depends on the temperature of the condensation of the precipitation and the rain out characteristics of an air mass. $\delta^{18}O$ is influenced by altitude (decrease in temperature) and distance from the sea and other local environmental conditions (e.g. humidity) [Kendall and Doctor, 2004]. The isotopic altitude effect means that the isotopic composition of precipitation changes with the altitude of the terrain and becomes more and more depleted in ^{18}O and ^2H at higher elevations. Other fractionation processes that play a role are the effect of decreasing pressure with increasing altitude, which implies that a larger temperature decrease is required to reach the saturated water vapour pressure than for isobaric condensation. Furthermore, evaporation enriches ^{18}O and ^2H in raindrops during their fall beneath the cloud base, which is larger at low altitudes where the cloud base is typically high above ground level. Consequently, one may find more enriched values at low altitudes.

It is therefore of interest to know an interannual weighted average of the isotopic composition of the rainwater as a function of altitude. Ideally, this gradient is obtained in the field from raingauges set up at different altitudes and requires a long-term isotopic database. If such a network is not available, spring water from local, limited, altitude-ranged aquifers, is sampled. The main drawback is the need to have a perfect knowledge of the aquifer system to get the correct mean altitude of recharge. Evaporation processes may also alter the initial rainwater signal. Furthermore, a methodological problem originates in the time factor. During a sampling campaign, the $\delta^{18}O$ gradient is plotted by means of values of the local small springs. Despite the precise knowledge of their recharge area, their response to rainfall episodes are real-time variations and their low discharge is due to small recharge areas and reservoirs. This means that their water has a short residence time in the aquifer. Conversely, springs at the landslide toe generally drain a bigger reservoir, with longer residence times. Thus, during an instantaneous sampling campaign, water is not that of the last rainfall episode. So, the gradient of the standardisation springs is not perfectly representative of the gradient within the slope aquifers. The best way to avoid this difference of residence times is to repeat these monitoring campaigns, according to seasons.

Using this altitude-isotopic composition relationship, oxygen-18 information can contribute to understanding the origin and flow paths of water within a slope. Compagnon *et al.* [1997] used this $\delta^{18}O$ characteristic of springs on the *La Clapière* landslide complex to determine the altitude of the recharge. Guglielmi *et al.* [2002] also used $\delta^{18}O$ data for the *Séchilienne* landslide. Local isotopic $\delta^{18}O$ gradients were determined in the summer (*Séchilienne*) or both in the summer and winter (*La Clapière*) from springs of which the elevation of the source area is known.

Using this information the recharge areas of landslide springs could be deduced (fig. 8). The figure shows that most water samples (e.g. 11 through the 16 in A) have isotopic concentration, which is depleted in $\delta^{18}O$ to a level normally found at higher altitudes than the sample location. This has important consequences for the hydrological analysis of a landslide area as the hydrological 'catchment' of the landslide reaches outside the landslide limits.

Concerning the *La Clapière* slope (fig. 8A), for instance spring 12 (toe) displays an average recharge altitude of 1780 m in June. This elevation equals the highest altitude of the moving area. This showed that a significant part of the recharge area is situated in the tilted area of the slope, where the hydraulic conductivity is higher than that of the solid gneiss underneath. In the *Séchilienne* slope (fig. 8b), the same phenomenon could be observed. The recharge area includes Liassic limestones outside the landslide area. In both cases, these aquifers situated upgradient of the unstable slopes can delay and buffer the groundwater seepage, negatively influencing the correlation of motion with rainfall episodes.

Another example is the aforementioned analysis using natural isotopes of $\delta^{18}O$ and tritium of water samples from the *Stoze* landslide [Mikoš *et al.*, 2004]. The tritium dating

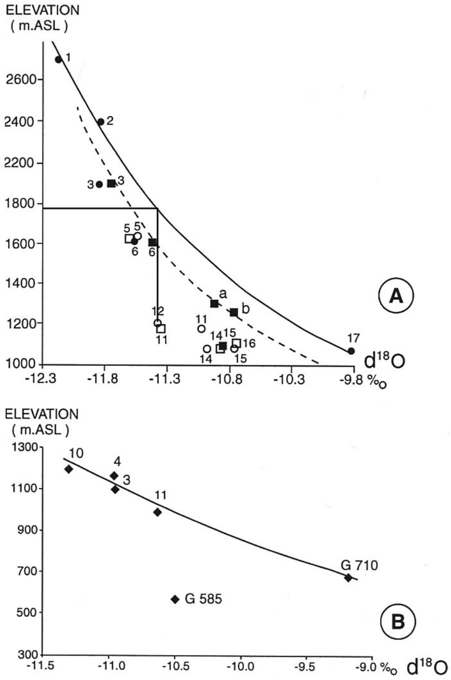

FIG. 8 – Isotopic gradients (values used to calculate the gradients are plotted in black, values of springs in the recharge area with mean elevation are plotted with open circles and squares). Squares a and b correspond to $\delta^{18}O$ values of springs located about 2 km from the La Clapière slope (June gradient dashed line with $\delta^{18}O$ values in squares; December gradient continuous line with $\delta^{18}O$ values plotted in circles, fig. 8a); B Séchilienne massif (fig. 8b) [modified from Guglielmi *et al.*, 2002].

FIG. 8 – *Gradients isotopiques (les valeurs utilisées pour le calcul des gradients sont indiquées en noir; les valeurs des sources dans la zone de recharge ainsi que leur altitude sont indiquées par des cercles et des carrés). Les carrés a et b correspondent à des valeurs $\delta^{18}O$ des sources localisées à environ 2 km du site de La Clapière (gradient identifié en juin en ligne tireté avec les valeurs de $\delta^{18}O$ indiquées en carré; gradients identifiés en décembre en ligne continue avec les valeurs de $\delta^{18}O$ indiquées en cercle) (fig. 8a); Même légende pour le site de Séchilienne (fig. 8b) [modifié de Guglielmi et al., 2002].*

showed an age of about 2 years. The recharge area was estimated using the stable δ^{18}O. The article concludes that the landslide area has permanent but slow exfiltration of groundwater from a reservoir in the slope. The volume of this reservoir was estimated to be of the order of 0.1 million m^3. Lastly, Tullen *et al.* [2006] used δ^{18}O time series of two springs to determine the hydrogeological system of the translational *Hohberg* landslide in Switzerland. The rapid response of springs on snowmelt and rain events could be explained by water flow through the high permeable morainic deposits.

THE USE OF GEOCHEMICAL INFORMATION IN LANDSLIDE STUDIES: SOFT SEDIMENT SLOPES

Hydrogeological information not only has to come from water chemistry alone. The chemical fingerprint of the solid material can be used as well [Moore and Brunsden 1996; Bogaard et al., 2004]. The former concentrated especially on the relation with geotechnical properties of the soil (see section: The influence of pore fluid composition on strength properties). The latter tested which additional information could be gained from cation exchange capacity (CEC) and exchangeable cations in landslide investigations and for the hydrological system of a landslide area in marly-clayey material. This research was conducted using two 20 m long cores from the Boulc-Mondorès landslide in department Drôme, France [Bogaard et al., 2000] and one 17 m deep core from the Alvèra landslide in northern Italy [Angeli *et al.,* 1999]. The work showed that is was possible to perform reproducible cation exchange measurements on (partly) weathered marls and in addition discussed the information coming from these cation exchange measurements.

Two distinct results were achieved in this study. First of all, clear intervals of CEC and exchanger composition were identified with depth that compare well with the geological core description from the *Boulc-Mondorès* landslide (fig. 9). The research could not prove the origin of the CEC differences found in the core samples. However, they were interpreted as more weathered layers as the exchanger composition of the weathered superficial mudslide material compared well with the low CEC-values found in the core. The more weathered layers could act as preferential flow paths and may develop or have already developed into slip surfaces.

Secondly, the study of Bogaard *et al.* [2004] revealed how useful information can be gained from cation composition measurements with depth. Figure 10 shows the cation exchanger composition of the *Alvèra* core. The first 5 m has calcium dominated complexes whereas magnesium and calcium prevail below. This observation fitted perfectly with the conceptual model of the so-called dead-end cracks: fissures storing rainwater and facilitate water infiltration in the clayey soil. Both figures 9 and 10 show an increase of sodium concentration. Sodium is the most important exchanger cation from the original deposition of the material. In *Alvèra*, the latter could be explained with the change from $Ca\text{-}HCO_3$ type to $Na\text{-}HCO_3$ type of water found in the groundwater.

SUMMARY AND DISCUSSION ON APPLYING HYDROGEOCHEMISTRY IN LANDSLIDE STUDIES

This review aims to give an overview of the potential hydrogeochemistry has for landslide research. Hydrogeochemical data have not been used regularly in landslide research, with the exception of the physio-chemical analyses related to soil strength characteristics like in quick clay studies. This paper shows that applying hydrogeochemistry is valuable but that it also is a specialised research field. Therefore, multidisciplinary collaboration is necessary. As stated in the introduction, it is the delicate mutual dependency of water flow, subsurface architecture and hydrogeochemical processes which should be kept in mind when using water composition and geochemical information.

The relationship between pore fluid composition and soil strength is important and studied in a limited number of cases. As most landslide research struggles with a paucity of data, underdetermination of the complex system behaviour is quite common. The influence of pore fluid composition on the mobilised (residual) shear strength can easily be unnoticed. The changes in residual shear strength could be an explanation for changing rates in landslide movement. Therefore, the systematic analysis of pore fluid composition and the chemical composition of a soil and its physical properties [di Maio *et al*., 2004] is an interesting field of study.

When used as a tracing technique, both in hard and soft rocks, the hydrochemical approach is one of the only methods that allow a spatial integration of the processes. This means that the input-output analysis is carried out at the scale of the studied system. It is typically the case when water is sampled at a spring, which represents the outlet of the

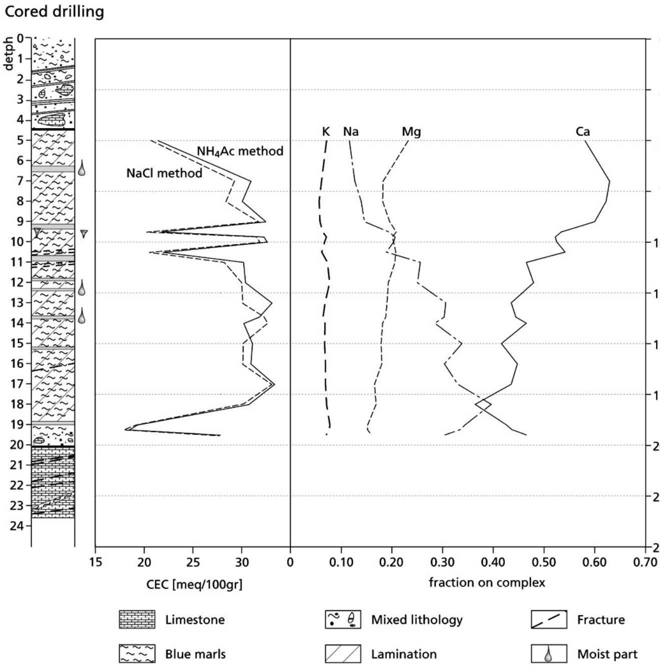

FIG. 9 – Cation exchange capacity and exchanger cation profiles from the Boulc-Mondorès landslide together with a core description [modified from Bogaard *et al*., 2004].

FIG. 9 – *Capacité d'échange cationique et profiles associés pour le glissement-coulé de Boulc-Mondorès [modifié de Bogaard* et al., *2004].*

entire hydrosystem. Even with sampling in piezometers, the water chemistry is expected to depend on the upstream features. Combined with more local (but essential) investigations (mineralogical analyses, rock chemistry, laboratory tests, etc.), these techniques may help to overcome the so-called scale transfer problem.

In addition, hydrochemistry used in hard and soft rocks enables the display of clusters of water types. In fractured hard rocks, a high variability of hydrochemistry can be observed versus time. This variability enables the identification of the contributions of different aquifers to the landslide hydrology, if a sufficient geochemical contrast is available. There it can demonstrate the existence of lithologies and structures hidden by the mobile area. It allows also for validation of conceptual water flow schemes. Using a kinetic-based model, the observed concentration can be simulated, and hypotheses of weathering can be validated (e.g. gypsum dissolution versus pyrite oxidization). In unstable soft sediments, the range of seasonal variations is narrower, due to the less heterogeneous hydraulic conditions. The spatial chemical variations can reveal water inflow from depth or distance. Ion exchange and precipitation of minerals through these clayey minerals can also be displayed.

In both the *La Clapière* and *Super-Sauze* case studies that we have described, the spatial and temporal hydrochemical survey helped to refine the hydrological limits of the landslide bodies. Along with hydrogeochemical modelling, the hydrochemical data provided useful insight into the main hydrogeochemical processes involved in the water mineralization. This is a first step towards a complete knowledge on the mechanical impact of water flow processes and water-soil interaction. Preliminary results from short term tracing experiments at the *Super-Sauze* landslide showed evidence of rapid vertical infiltration through discontinuities in the marls. Large amounts of water possibly driven down to the shear surface may be one of the major mechanisms in the triggering of landslides.

Analysing cation exchange capacity and exchanger cation profiles showed important information on hydrology. In particular, the hydrological separation in the profile in infiltration water and regional water was worthwhile. Furthermore, the possible flowpaths and slip surfaces that were identified in the *Boulc-Mondorès* cores were encouraging. Lastly, the increased sodium content at the exchanger complex indicates weathering processes of the marly substratum. All these data helped to better understand and interpret the behaviour of the complex hydrological landslides.

The main advantage of isotopic analysis is its non-reactive character. Oxygen-18 has proven itself extensively in tracing flowpaths. For landslide research, it is especially useful for delimiting catchment area. Together with travel time distribution determined with, for example, tritium analyses, this can give essential insight into the hydrology of landslides.

Of course several drawbacks can be identified for the application of hydrogeochemistry in landslide recognition. To delineate the hydrological area influencing a landslide area implies having knowledge of the lithological built-up of the slope. As it is not unusual that landslides occur in geological active areas (or used to be active) the geological structure with all their fissures and faults is quite complex which hinders the interpretation.

Chemical analysis is delicate. Sampling needs special equipment, training and logistic in order to obtain reliable results. Storage is an important source of error in chemical analyses, as chemical reactions will change the concentrations in the solution. Furthermore, chemical information can show quite large temporal and spatial variability. This needs attention in landslide research. Trends of chemical information are in that sense more reliable than the absolute value at a certain point.

Future work could, in our opinion, focus on the relation of residual strength and pore water composition, in the field of coupling hydrogeochemistry with permeability changes, the relation of permeability and reaction rate, and more specific the relation of fissures dynamics (alternation opening-closure) and chemical processes (reaction rate, kinetics, phase behaviour, etc.). In fine-grained soils (loam-clay), the influence of salt concentration on saturated permeability is very strong for some soil types whereas limited for other soils [see for example Kutilek and Nielsen, 1994]. Lastly, it would be interesting to apply a coupling of hydrogeochemistry with geophysics. For example, hydrogeological characterisation may be improved by adding radar tomographic data to tracer test information [Linde *et al.*, 2006] or the combination of radiomagnetotelluric survey, numerical groundwater modelling and 18-oxygen isotopic data [Tullen *et al,* 2006].

In addition, the study to quantify the effect of preferential flow on landslide triggering could benefit from hydrogeochemical research. Preferential flows have been identified as major processes in landslide environment where discontinuities are so obvious. There is no reliable hydrometric technique that can measure such processes. Few attempts have been made with geophysics. However, tracers have been the first and often the best tools to get

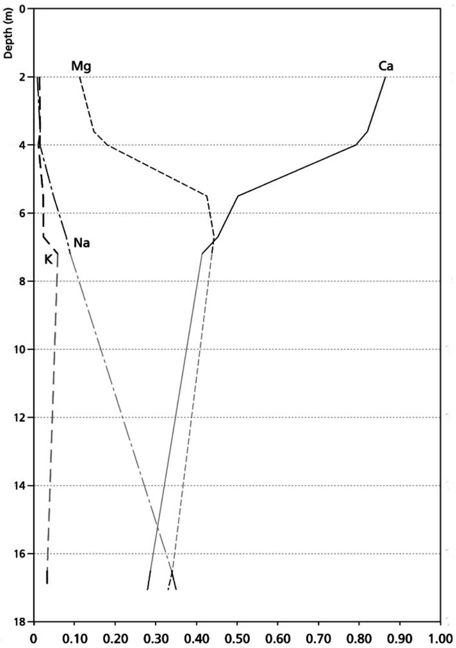

FIG. 10 – Exchange cation profile of Alvèra landslide [modified from Bogaard *et al.*, 2004].
FIG. 10 – *Profil d'échange cationique du glissement d'Alvèra [modifié de Bogaard* et al.*, 2004].*

quantitative information on these processes. For example, our knowledge in landslide triggering could be improved from in situ artificial water tracing.

This paper aimed to give an overview of the different applications of hydrogeochemistry in landslide research. It tried to answer the question: 'What can hydrogeochemistry do for landslide research?' It is aimed for that the above review encourages colleagues to apply hydrochemistry in their own landslide research. Although the results of isotopic and hydrogeochemical analyses are very promising and useful in landslide research, they should not be used alone. The surplus value is that it adds new insight to our standard information in geology, geomorphology, hydrology and engineering geology.

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