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Testing the potential of geochemical techniques for identifying hydrological systems within landslides in partly weathered marls

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Abstract

This paper's objective is to determine how useful geochemistry can be in landslide investigations. More specifically, what additional information can be gained by analysing the cation exchange capacity (CEC) and cation composition in respect to the hydrological system of a landslide area in clayey material. Two cores from the Boulc–Mondorès landslide (France) and one core from the Alvera landslide (Italy) were analysed. The NH_4Ac and $NaCl$ laboratory techniques are tested. The geochemical results are compared with the core descriptions and interpreted with respect to their usefulness. Both analysis techniques give identical results for CEC, and are plausible on the basis of the available clay content information. The determination of the exchangeable cations was more difficult, since part of the marls dissolved. With the ammonium-acetate method more of the marls are dissolved than with the sodium-chloride method. The NaCl method is preferred for the determination of the cation fractions at the complex, be it that this method has the disadvantage that the sodium fraction cannot be determined. To overcome this problem, it is recommended to try other displacement fluids. In the Boulc–Mondorès example, the subsurface information that can be extracted from CEC analyses was presented. In the Boulc–Mondorès cores deviant intervals of CEC could be identified. These are interpreted as weathered layers (and preferential flow paths) that may develop or have already developed into slip surfaces. The major problem of the CEC analyses was to explain the origin of the differences found in the core samples. Both Alvera and Boulc–Mondorès examples show transitions in cation composition with depth. It was shown that the exchangeable caution fractions can be useful in locating boundaries between water types, especially the boundary between the superficial, rain-fed hydrological system and the lower, regional groundwater system. This information may be important for landslide interventions since the hydrological system and the origin of the water need to be known in detail. It is also plausible that long-term predictions of slope stability may be improved by knowledge of the hydrogeochemical evolution of clayey landslides. From the analysis, it is concluded that geochemistry is a potentially valuable technique for landslide research, but it is recognized that a lot of work still has to be done before the technique can be applied in engineering practice.

1. Introduction

In the study of hydrological processes in landslides, little attention has been paid to techniques to determine the origin of groundwater and groundwater flow within landslides. Knowledge of the groundwa-

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ter system in landslide areas is important when (cumulative) precipitation is related to mass movement via increases in pore water pressure. Often, a black box modelling approach is adopted to relate mass movement to precipitation. However, without knowledge of the hydrological system it can be difficult to set up a model for predicting changes in landslide activity due to stabilising measures, land-use or climate change. To predict slope movement response to precipitation it is important to know the extent of the area feeding the landslide with groundwater and to have a knowledge of the internal flow system thereby enhancing the perceptual model of the appropriate process mechanisms.

For this purpose, hydrochemical research can be useful. Appelo and Postma (1993) write: "Groundwater chemistry also has a potential use for tracing the origins and history of water. Water composition changes through reactions with the environment, and water quality may yield information about the environment through which the water circulated."

In addition to hydrochemical methods, geochemical techniques can be of value, since groundwater chemistry and soil geochemistry interact. The high vertical resolution that can be obtained by geochemical analyses of soil profiles may not only reveal the broad (hydro)geological structure of a landslide, but may also provide indications for zones that are important for slope movement, such as slip surfaces or preferential flow tracks.

Furthermore, changes in exchanger composition of subsurface materials due to interactions with groundwater can induce changes in soil shear strength, and thus form another subject of geochemical investigations on landslides. The relation between catastrophic quick-clay landslides and freshening of pore water in Norwegian and Canadian marine clays was already recognized by, e.g., Bjerrum (1954) and Hutchinson (1961) and still receives a lot of attention (see Senneset, 1996). The type and concentration of salts in pore water exert a significant influence on residual shear strength of e.g., flysch clay (Michaelides, 1995) and several clay types from Italian slopes (Di Maio, 1996). This relates to local clay mineralogy.

The objective of this paper is to determine how useful geochemistry can be in landslide investigations. More specifically, what additional information can be gained by analysing the cation exchange capacity (CEC) and cation composition in respect to the hydrological system of a landslide area.

In joint research of the EU-funded HYCOSI (Leroi, 1997) and NEWTECH (Corominas et al., 1998) projects, CEC, exchanger composition and carbonate analyses were executed on samples of three cored drillings, two from the Boulc–Mondorès landslide complex in France and one from the Alvera landslide in Italy. Cation exchange capacity and exchanger composition were measured by two different laboratory techniques. The results were then compared with the geological descriptions of the drillings.

2. Drilling and laboratory methods

A rotation, double envelope, 115 mm diameter drilling technique was applied, with a cable sampler to facilitate sampling. All these drillings used local surface water as drilling fluid. Penetration of drilling fluid into the soil core is assumed to be negligible.

From the Boulc–Mondorès landslide complex samples were taken from a 'cored drilling' (core A) and a 'destructive drilling' (core B). From the former all material is lifted undisturbed and stored in wooden 'core boxes'. The latter core was taken more rapidly and stored in 2 m long PVC tubes, slightly disturbing the sample. In both cases, the total core length was saved, 21 m of core A and 25 m of core B. The upper 5–6 m were lost during drilling because the material was flushed with drilling fluid. Plasticity of material, progress of drilling and occurrences of water-bearing layers were described during drilling. In a later stage, the cores were described hydrogeologically (lamination, fractures, fissures and secondary calcite precipitation) and subsamples were taken. Twenty samples of 5–10 cm were taken from the undisturbed core A and 12 from the disturbed core B. The core descriptions give information about disturbance of the material during drilling, which may occur when the core cylinder is full, or when less coherent material is encountered resulting in twisting of the sample.

In Alvera, eight subsamples from the borehole were taken. The drilling had a total length of 24 m. The drilled core was stored in a moist state in sealed plastic bags, so some chemical alteration prior to analysis may not be excluded.

A brief description is given of the laboratory techniques for sample preparation, determination of exchanger composition, cation exchange capacity (CEC) and carbonate determinations.

The samples were air dried, crushed manually with a mortar and sieved repeatedly with a 300 μm sieve, until all material had passed the sieve. Exchanger composition and CEC were analysed with a 'displacement after washing technique' (Thomas, 1982) using two different salt solutions: ammonium acetate and sodium chloride.

In the ammonium acetate (NH_4Ac) technique, the cations at the exchange complex are displaced with 1 M NH_4Ac. The concentration of the cations in the fluid is analysed using ICP-AES. The CEC is determined by treating the sample with 1 M sodium acetate (NaAc), resulting in only exchangeable Na^+, the so-called 'index cation'. The sample is washed with 96% ethanol, removing excess Na^+. The sample is treated with NH_4Ac extracting all Na^+ from the exchange complex. Subsequently, the Na^+ is measured. The total Na^+ concentration equals the CEC.

The sodium chloride (NaCl) technique follows the same principle. The sample is treated with 1 M NaCl solution and the concentration of the Ca^{2+}, Mg^{2+} and K^+ from the exchange complex is measured using ICP-AES (Na^+ cannot be determined). Determination of the CEC was performed by washing the soil with 70% ethanol to replace the pore fluid. The Na^+ was then extracted from the sample with 1 M $MgCl_2$ solution. Sea sand, with a known CEC, was added to the sample (ratio sea sand–sample is 1:1) to bring the sample into suspension. The Na^+ concentration in the extract is then measured.

Both described techniques have Na^+ as 'index cation', but different displacement solutions (NH_4Ac and $MgCl_2$). The main drawback of the NH_4Ac technique is that NH_4Ac dissolves calcite and gypsum. This can result in an overestimation of the Ca^{2+} concentration, impeding a check of the analyses by comparing the CEC to the sum of the analysed exchanger cations. Results obtained with the NaCl technique are used to compare CEC, K^+ and Mg^{2+} determinations and to improve measurement of Ca^{2+}.

The Scheibler test (NEN5757, 1991) was used to determine the carbonate content in the sample. If a sample has relatively high $CaCO_3$ concentration, this decreases the CEC (less exchanger per 100 g dry soil).

It furthermore can point out differences in lithology within a drilling, e.g., secondary calcite deposition.

Also, unmarked double samples (duplicates) were included from each core to test the reproducibility of the analyses of both techniques.

3. Background of the test sites

3.1. Boulc–Mondorès

The Boulc–Mondorès landslide complex (Fig. 1) was one of the study sites of the HYCOSI-project, which studies the effects of hydrometeorological changes on slope stability (Leroi, 1997). It is situated in the department Drôme in the French pré-Alps. The area consists of Mesozoic limestone and marls and has a polyphase structural history from Trias to Tertiary (Bogaard et al., 2000). The main geological structure is an N–S running graben crossing the landslide. In the graben deposits from the Lower Cretaceous are found, east of the graben there is a sequence from the Upper Jurassic and west of the graben an anticline from the Upper Jurassic (Fig. 2).

The landslide can be divided into four geomorphological units (Bogaard et al., 2000): a rock sliding zone with slowly sinking huge limestone blocks ('Calcaires Tithonique') accompanied by secondary rock falls; a slumping zone with arcuated headscarps in mainly blue marls (Albian–Aptian), sliding and flowing in direction of a narrow opening towards the transition zone; a transition zone in which mudflows are channelled; and a mud flow deposition zone (Fig. 1). The slumping zone coincides approximately with the 'Terres Rouges' graben.

Phan (1992) analysed samples from the Boulc–Mondorès landslide on calcium content, percentage material < 74 and < 2 μm, and determined the various clay types and their concentration in the Albian–Aptian blue marls. Both disturbed (weathered) surface material and relatively undisturbed (less weathered) material from the Albian–Aptian marls were analysed. The analyses are summarised in Table 1.

The Aptian marls are composed of limestone, silicates and (mainly montmorillonitic) clays. Electron-microscope photographs showed abundant micro-caves of ± 2 μm in the Aptian marls and the complete absence of larger minerals (Phan, 1992).
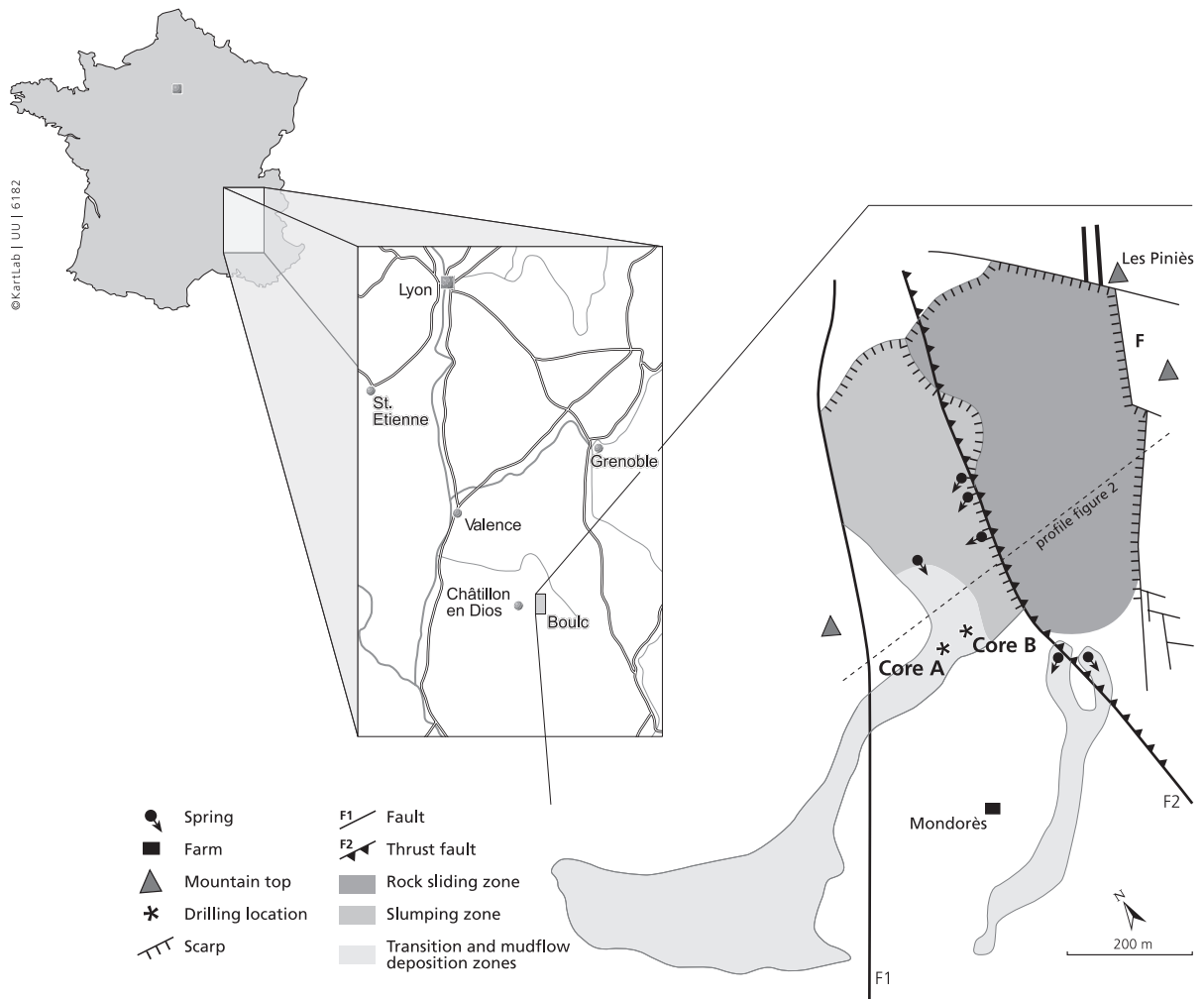
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Fig. 1. Location and geomorphological map of the Boulc–Mondorès landslide.

They also showed a mixture of coccoliths (calcareous planktonic organisms with <1% $MgCO_3$, Morse and Mackenzie, 1990), coccospheres (composed of several attached coccoliths), occasional carbonate deposition and clay. The important fine fraction with the nanofossils causes a system that is totally disorganised in structure, facilitating water circulation. Phan (1992) concluded that the Boulc–Mondorès landslide is the result of hydration–dehydration of clay and dissolution of limestone coccoliths. If CEC is assumed to be related only to the clay fraction (10%), this corresponds to an CEC of 7–13 meq/100 g (CEC for montmorillonite is 70–130 meq/100 g).

Hydrochemical samples were obtained at the Boulc–Mondorès landslide to investigate the hydrogeological system of the most active part of the landslide area: the slumping zone (Bogaard and van Asch, 1996; Bogaard et al., 2000). The samples were taken from 13 shallow piezometers that were placed in phreatic groundwater at 1.5–2.5 m depth with a filter length of 40 cm, located in the slumping, transition and mud flow deposition zones (Fig. 1). Two different water types were distinguished: low ion concentration water of around 6 meq/l in the red Oligocene marls (western part of the slumping zone, see Figs. 1 and 2) and high ion concentration water of around 20 meq/
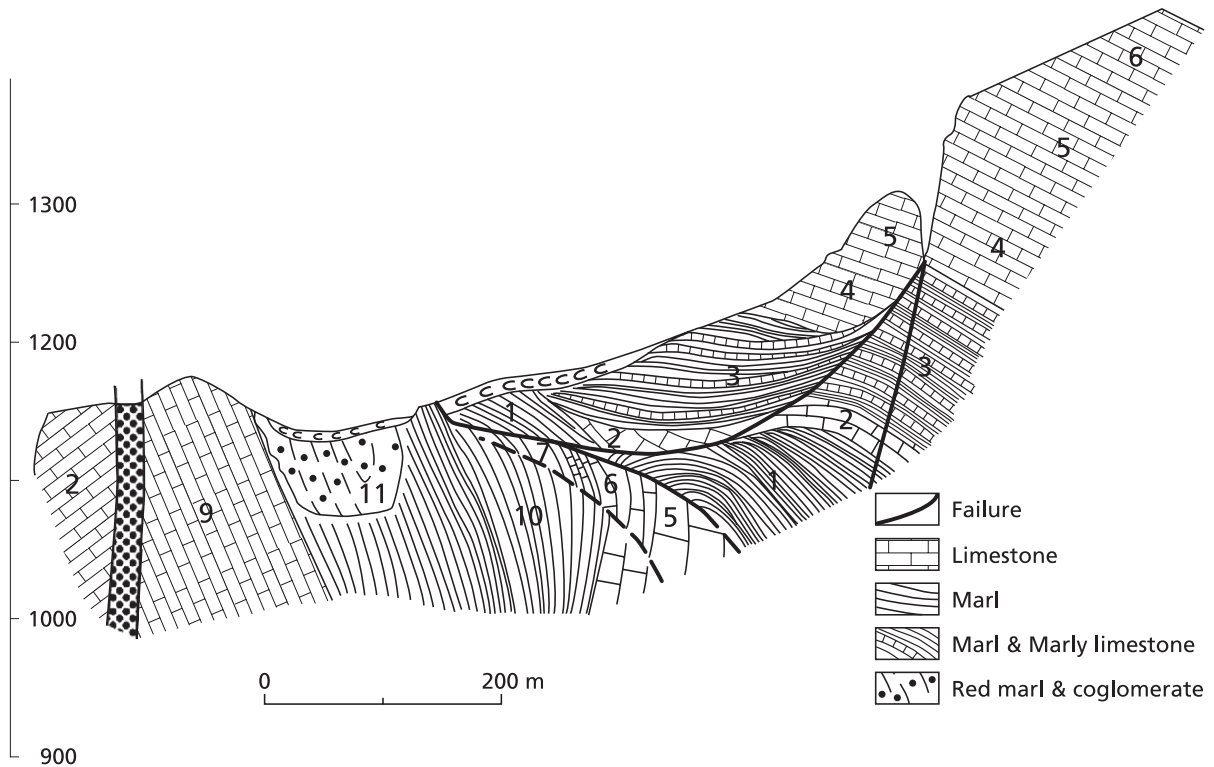
Fig. 2. Interpreted geological cross section (for location see Fig. 1). (1) Callovo-Oxfordian; (2) Sequanian; (3) Lower Kimmeridgian; (4) Upper Kimmeridgian; (5) Tithonian; (6) Berrasian; (7) Valanginian; (8) Barremo–Bedoulian; Albian–Aptian; (11) Oligocene (adapted from Bogaard et al., 2000).

l exfiltrating the Albian blue marls (eastern part of slumping zone, see Figs. 1 and 2) (Bogaard and van Asch, 1996). Both discharge in the direction of the transition zone. The red Oligocene molasse are underlain by Albian–Aptian blue marls (Fig. 2). The water chemistry indicates that the groundwater has not been in contact with the underlying deposits. The superficial hydrological system of the landslide was described by Bogaard et al. (2000) as a shallow, perched groundwater table fed by precipitation. Of

the deeper groundwater system it was suggested that it could be fed by the perched groundwater system, from the scree slope in the rock sliding zone or even by karstic supply from the eastern limestone mountains.

In Boulc–Mondorès, two cored drillings were placed (Fig. 1) at the margin of the slumping and transition zones, the most active part of the landslide area where the groundwater system was thought to converge into the transition zone (Chassagneux and Leroi, 1995). The drillings were located in the Albian–Aptian blue marls. The first drilling (core A) has three main units: 0–4.5 m remoulded unconsolidated sediment of recent mass movements, followed by Albian–Aptian marls down to 19.5 m where the Barrémo–Bédoulian limestone (see Fig. 2) was encountered. Core B consist of two units, first, to a depth of 6.5 m remoulded unconsolidated sediment of recent mass movements, followed by Albian–Aptian blue marls until the drilling was at

Table 1
Distribution of particle size and clay types of the Albian–Aptian marls (from Phan, 1992)

Particle size distribution		Clay mineralogy		
<74 μm (%)	<2 μm (%)	Illite (%)	Kaolinite (%)	Montmorillonite (%)
96	10	25	15	60

25 m where the Barrémo–Bédoulian limestone was not yet encountered.

3.2. Alvera

The Alvera landslide was a study site in the NEW-TECH-project (Corominas et al., 1998), which studies new methods for landslide monitoring and modelling. It is situated near Cortina d'Ampezzo, Eastern Dolomites in Italy (Fig. 3). It is described in detail by Angeli et al. (1992), Deganutti and Gasparetto (1992), Gasparetto et al. (1994) and Angeli et al. (1999).

The landscape of the Dolomites is dominated by very steep dolomitic plateaux (Dolomia Principale) with gentler slopes at their base, developed in the less resistant San Cassiano Formation. The Alvera landslide developed on such a gentle slope, consists of weathering products of the San Cassiano Formation: overconsolidated marine clays with calcareous, dolomitic and loamy fragments. However, due to its long

history of mass movement, the landslide body has a complex structure. It consists of badly sorted fragments of the original rock set, with thin layers of calcareous and organic material. The landslide is 1700 m long, 80 m wide and the average inclination is 7.3°. Measurements show movement totalling about 40 cm in 5 years (Gasparetto et al., 1996). The landslide is probably a reactivation of a much larger prehistoric landslide.

Gasparetto et al. (1994) and Angeli et al. (1999) examined lithological profiles from Alvera, and found that the landslide body consists almost entirely of remoulded clay with occasional calcite, dolomite and calcarenite fragments. Vertical differentiation is made up by organic layers separating zones with different degrees of consolidation. This feature indicates buried vegetation related to landslide events (Gasparetto et al., 1994). On the basis of these observations alone, no active slide surfaces could be inferred. Measurements with inclinometers and excavations revealed move-
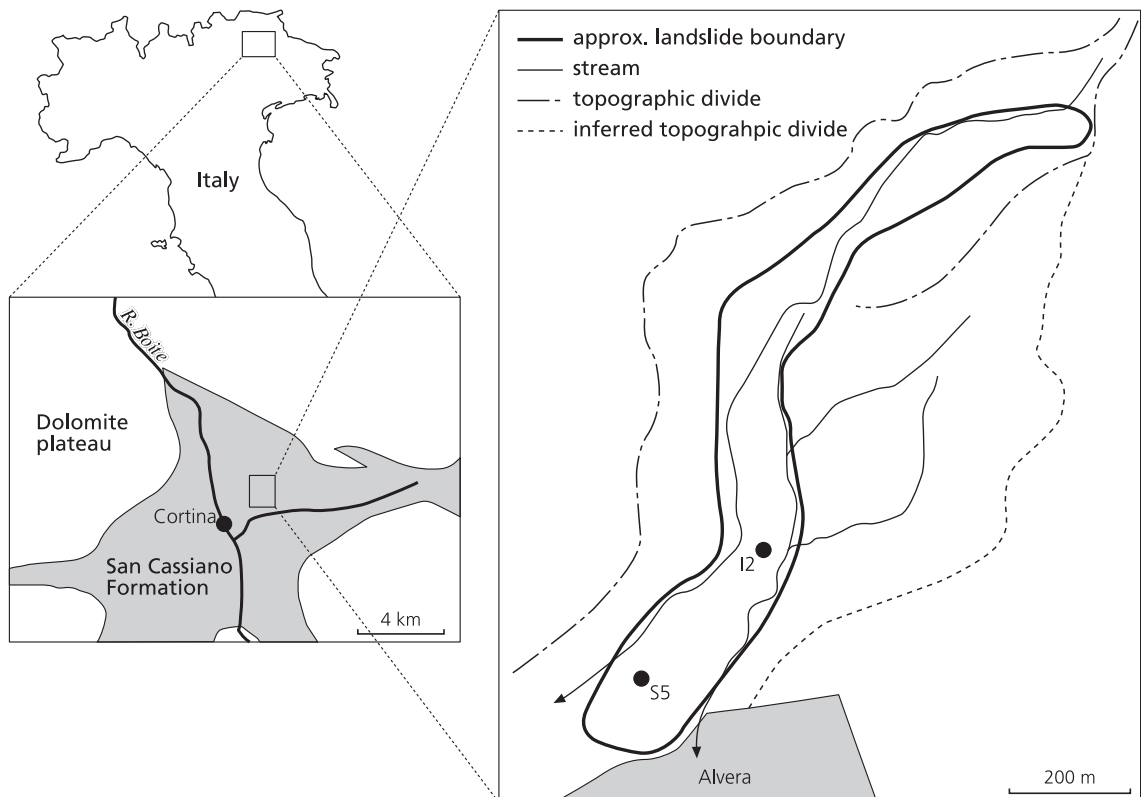

Fig. 3. Topographical setting Alvera landslide.

ment taking place mainly in zones of several millimeter thickness at depths ranging between 2.5–5 and 20–25 m depth across the landslide (Deganutti and Gasparetto, 1992; Angeli et al., 1999).

The samples for geochemical analysis were taken from borehole I2 (Fig. 3). The lithological record of this borehole displays the characteristics outlined above. A thin peat layer was found at 24.3 m, which supported the inclinometer observations of a slide surface between 20 and 25 m (Angeli et al., 1999). A clay content of 71% and a Skempton Activity Index of 0.72 were found for a sample from borehole S5 (see Fig. 3) at 5 m depth. The activity index value is intermediate to values reported by Grimm (1962) for illite and montmorillonite (0.3–0.6 and >1.2, respectively). X-ray diffraction on samples from borehole I2 at depths of 7.2, 16.5, 22.5 and 24.3 m revealed spectra that are characteristic for montmorillonitic clays (Angeli et al., 1999).

The hydrological system of Alvera is given by Angeli et al. (1998). They describe an upper zone ('root zone') of 0.5 to 2 m thickness with abundant superficial cracks, which facilitates infiltration as well as discharge. Underneath the root zone they define a clay layer of unknown thickness with some dead-end cracks facilitating deeper infiltration.

Some hydrochemical data were obtained by sampling water from streams and piezometers. Unfortunately, many of the piezometers have filters of several meters length. This induces mixing of different water qualities and thus interpretation of the measurements is difficult. The only significant trend that can be observed, is a change of Ca-HCO$_3$ type to Na-HCO$_3$ type of water with increasing depth. However, the nature and depth of the transition between these water 'types' could not be inferred.

4. Results

4.1. Evaluation of the two laboratory methods

The results for the duplicates are given in Table 2. The relative difference is 3% to 6% except for the calcium determination. Generally, the results of the duplicates show that the analyses were performed accurately and that the applied techniques give consistent results. Table 2, however, also shows that the

Table 2
Relative difference between the analyses of duplicate samples

Method	Element	A.7 (%)	A.16 (%)	B.5 (%)	B.8 (%)	S1.1 (%)	Average (%)
NH$_4$Ac	Ca	16	25	9	6	3	12
NaCl	Ca	12	1	19	20	3	11
NH$_4$Ac	K	6	12	2	4	5	6
NaCl	K	1	1	3	2	8	3
NH$_4$Ac	Mg	0	10	1	1	9	4
NaCl	Mg	3	1	3	2	7	3
NH$_4$Ac	Na	3	9	2	8	9	6
NaCl	CEC	2	1	2	3	6	3
NH$_4$Ac	CEC	1	1	4	6	5	4

In the last column, the average of the five duplicate samples is given.

laboratory analyses with NaCl are slightly better reproducible than the analyses using the NH$_4$Ac method.

The two techniques gave identical results for CEC (Fig. 4a) except for sample I2.1 (respectively 35 and 75 meq/100 g). The latter was interpreted as an unexplained laboratory error and consequently removed from the data set. The CEC values of the Boulc samples range from 15% to 35% and are in some cases a higher than would be expected on the basis of Phan's (1992) results (Section 3.1). Probably the clay content of the blue marls is higher. The amounts of exchangeable magnesium (Mg^{2+}, Fig. 4b) determined by the two techniques are in good agreement with each other for all Boulc samples, and at low values for the Alvera samples. At higher values the NH$_4$Ac technique gives higher values for the Alvera samples than the NaCl technique.

The amounts of exchangeable potassium (K$^+$, Fig. 4c) show that the NH$_4$Ac technique tends to extract more K$^+$ than the NaCl technique for the Alvera samples, but for the samples from Boulc the opposite is true. Exchangeable Na$^+$ could only be determined with the NH$_4$Ac technique. Although the Na$^+$ results could not be validated, it is assumed that these values are accurate as there are no other sources of Na$^+$ in the samples.

Fig. 4d shows the results of the concentration exchangeable Ca^{2+} determined with both methods. The NH$_4$Ac method seems to result in 15–25 meq/100 g higher fraction than using the NaCl technique. Both techniques, however, result in Ca^{2+} concentrations that are higher than the CEC, which is impossible.
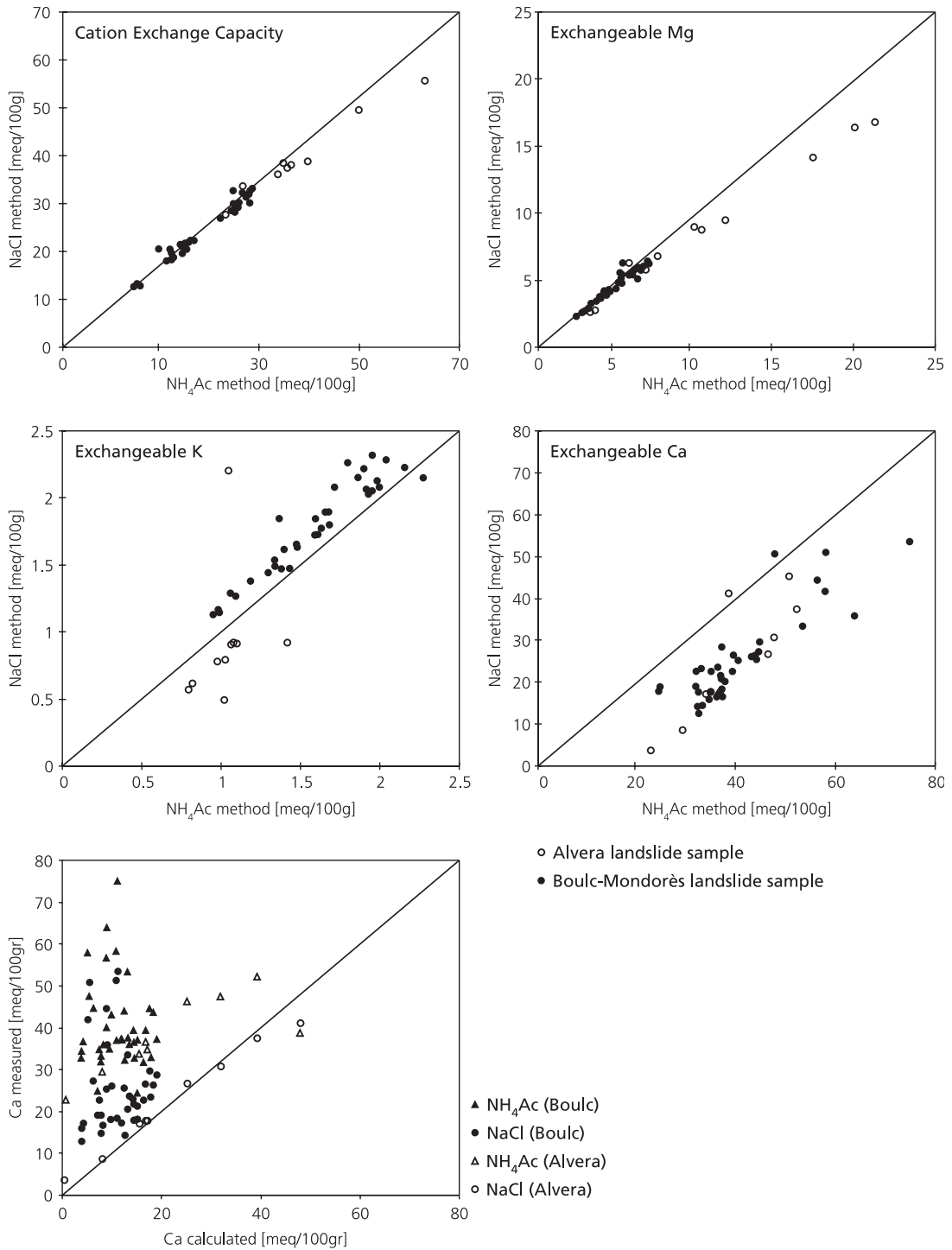
Fig. 4. Comparison of NH$_4$Ac and NaCl laboratory analyses of cation exchange capacity and cation composition for the Boulc–Mondorès (black dots) and the Alvera (open dots) landslide samples.

The amount of exchangeable calcium determined by both techniques was therefore compared with the values that would be expected if the amounts of exchangeable Mg^{2+}, K^+ and Na^+ are subtracted from the CEC (Fig. 4e). Mg^{2+}, K^+ and CEC are taken from the NaCl results and Na^+ from the NH_4Ac method. This
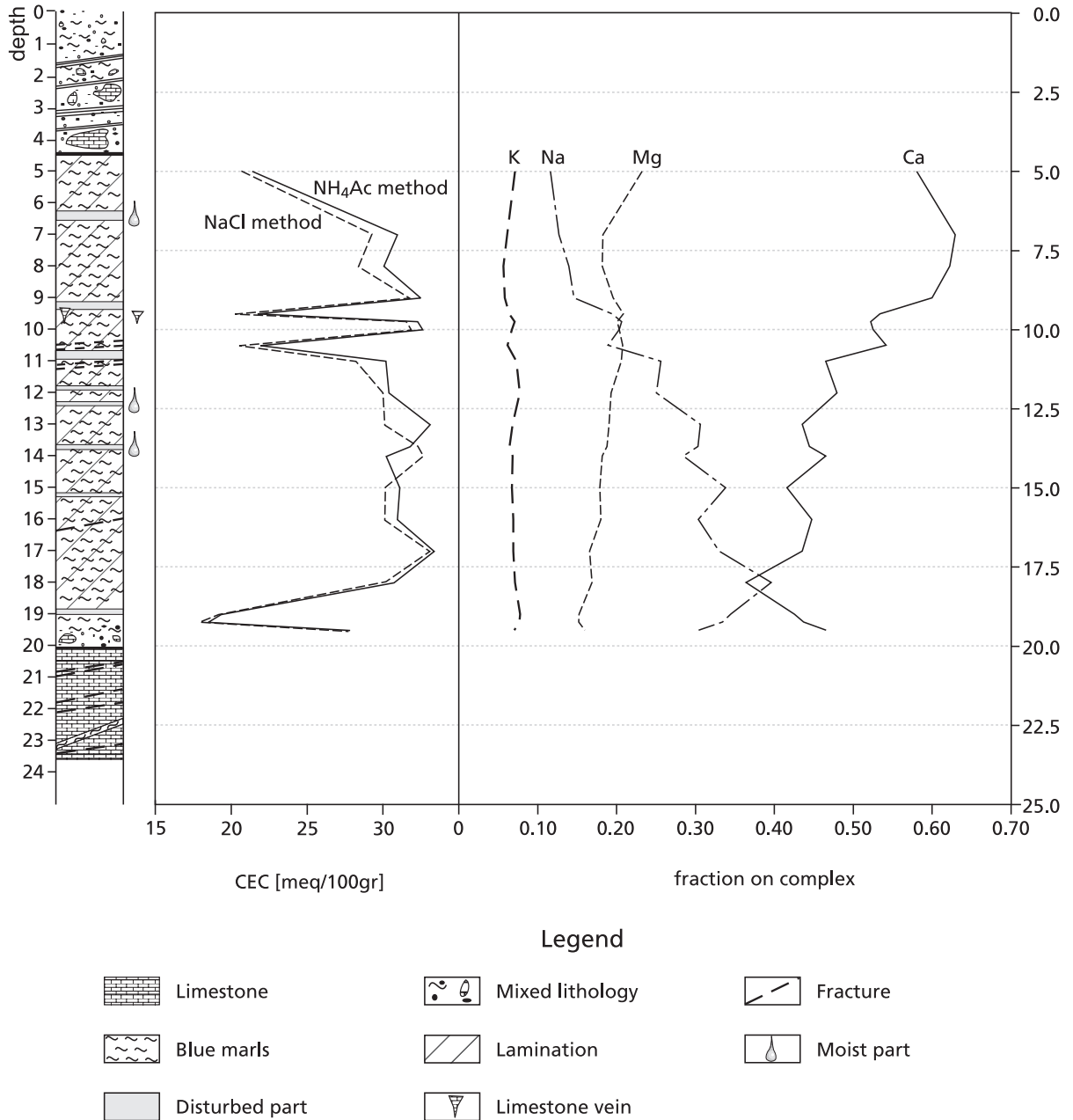

Fig. 5. Geochemical profile of core A from Boulc–Mondorès.
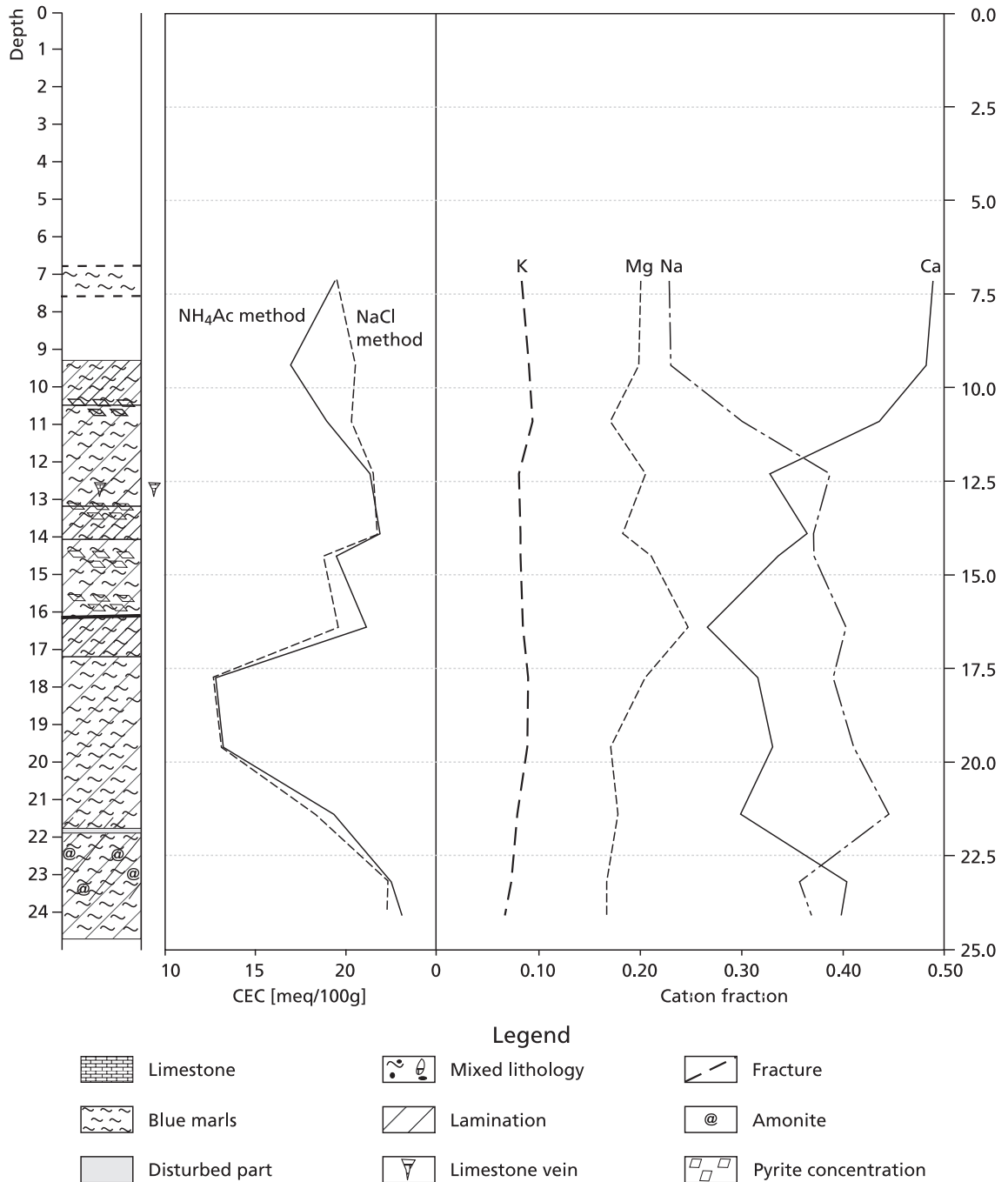
Destructive drilling

Fig. 6. Geochemical profile of core B from Boulc–Mondorès.

result also shows that the NaCl method seems to overestimate the Ca^{2+} concentration for a large number of samples. Only the Alvera samples in combination with the NaCl technique resulted in a corresponding Ca^{2+}. The overestimation of exchangeable Ca^{2+} by both techniques is more severe in the marls from the Boulc–Mondorès site than in the more clayey site of Alvera. The problem of determining exchangeable Ca^{2+} when calcite or gypsum is available in the soil is also described by Thomas (1982).

In case of determination of CEC and exchangeable cations in marly sediments, the NaCl technique appears to be more suitable than the NH_4Ac method. The determination of exchangeable Ca^{2+} remains

difficult. Furthermore, exchangeable Na^+ cannot be determined with this method and has to be measured using another laboratory method. It was therefore decided to use values of CEC, Mg^{2+} and K^+ obtained with the NaCl method. The Na^+ fraction comes from the NH_4Ac method. Lastly, the Ca^{2+} was calculated as the difference of the CEC and the sum of the analysed cations (Mg^{2+}, K^+ and Na^+).

4.2. Results of the CEC and exchanger cation measurements: I. Boulc–Mondorès

In Fig. 5, the CEC and the exchanger cations of core A are given together with a schematic geological
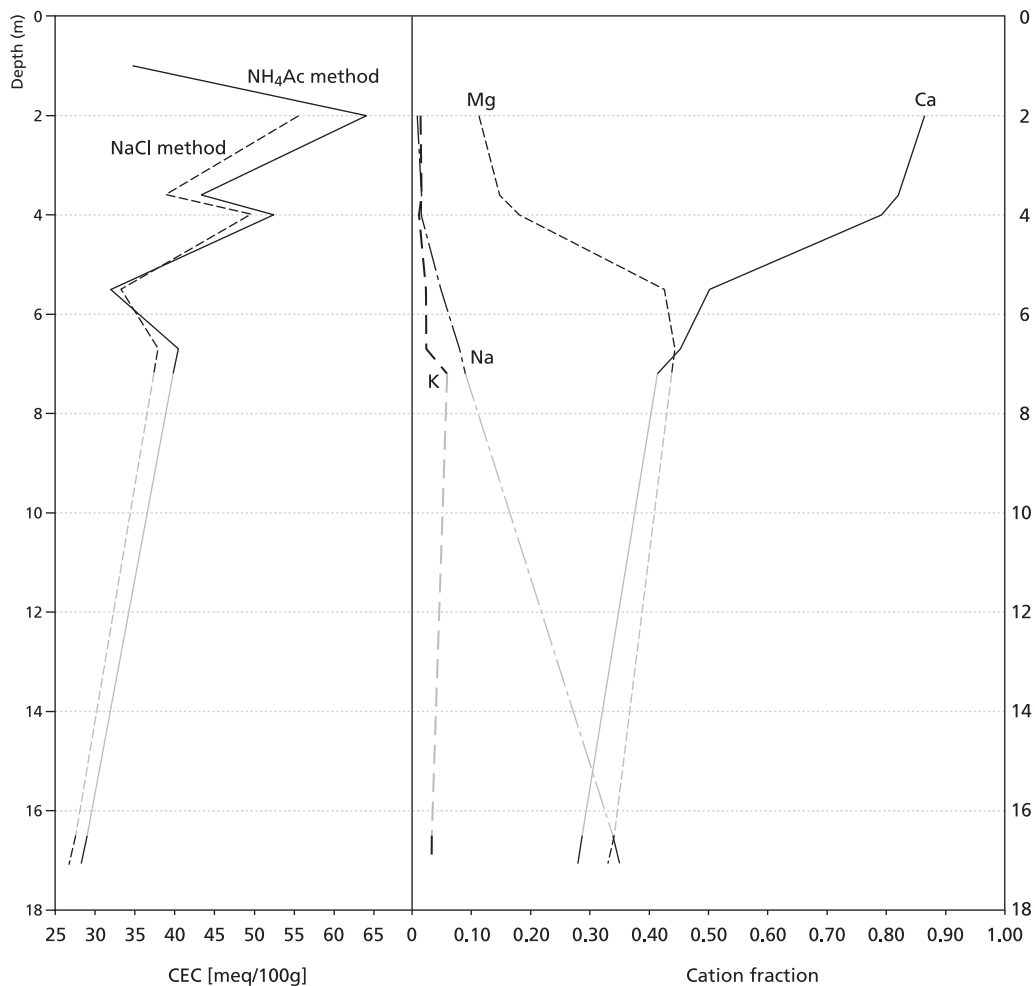

Fig. 7. Geochemical profile of core I2 from Alvera.

column. The CEC profile corresponds well with the description of the drilling. A low CEC (20 meq/100 g) is found in the marls directly underneath the remoulded deposition at 5 m depth, in the two disturbed zones at 9.5 and 10.5 m depth and at the transition of the marls formation towards the limestone formation at 19 m. Below the disturbed zone of 9.5 m depth a calcite vein was also observed. No difference in CEC was found above and below the observed fracture at 16.5 m depth with secondary calcite deposition at the fracture surface.

The exchanger cations are expressed as a fraction of the total CEC and plotted against depth. It shows a stable K^+ fraction with depth, a slowly decreasing Mg^{2+} fraction, a quickly decreasing Ca^{2+} fraction and a quickly increasing Na^+ fraction with depth. Obviously, between 19 and 19.5 m depth the Ca^{2+} fraction increases again while the sodium fraction decreases.

For core B, the CEC is lower than for core A (Fig. 6). Values are around 20 meq/100 g with a clear

minimum of 13 meq/100 g between 17 and 20 m. The exchangeable cations expressed as fractions of the CEC give a constant potassium fraction and slowly decreasing magnesium fraction with depth except for 16.5 m below surface. The sodium fraction increases rapidly down to 12 m, gradually increases until 21 m depth and decreases afterwards. The calcium fraction decreases until 16.5 m, remains constant until 21 m and increases afterwards.

4.3. Results of the CEC and exchanger cation measurements: II. Alvera

The CEC profile does not reveal any distinct intervals (Fig. 7). The CEC appears to be slightly higher in the upper 5 m and then diminishes with depth. No samples between 7.2 and 16.5 m depth could be obtained to support this observation. The analysis of exchanger cation fractions with depth shows two distinct intervals with a transition between 4 and 5.5 m depth (Fig. 7): above this transition, Ca^{2+}
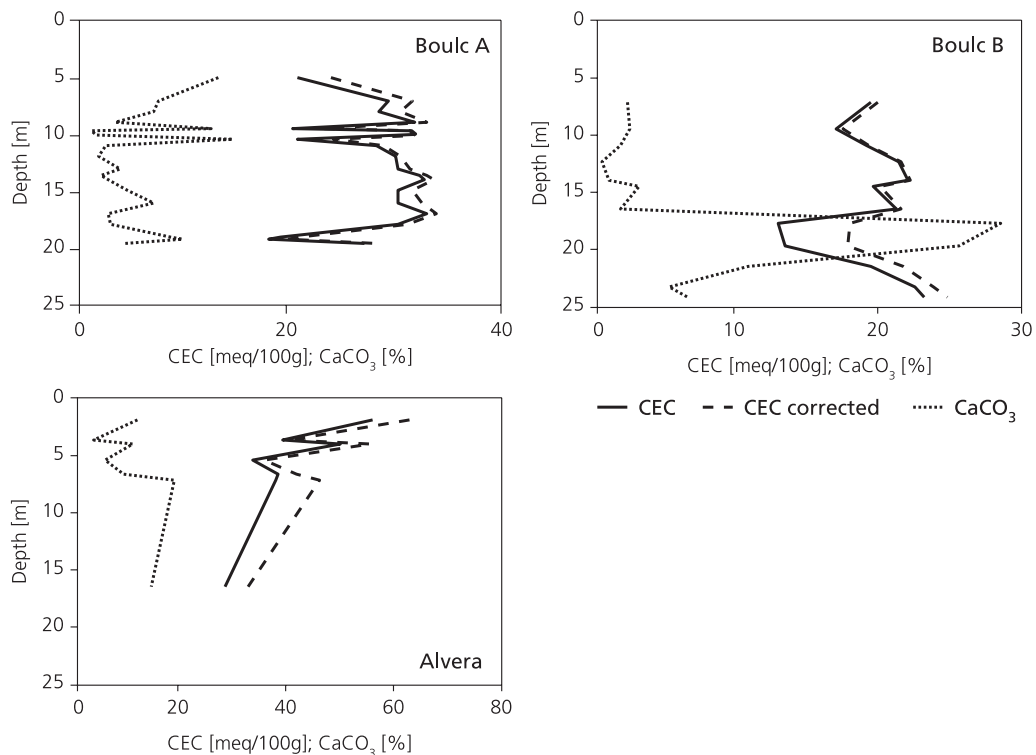

Fig. 8. CEC values and carbonate content with depth for all three cores.

is the dominant cation, while below it Ca^{2+} and Mg^{2+} dominate. Another feature is the gradual increase in exchanger Na^+ below this transition.

4.4. Results of the Scheibler carbonate test

The carbonate concentrations in the Boulc–Mondorès cores vary between 1% and 15% (average 5.7%) for core A and in core B between 0% and 28% (average 7%). The carbonate concentration in the Alvera samples range from 0% to 18% (average 9%). The Scheibler carbonate tests show strong variations with depth that correlate with the variations in CEC (Fig. 8). In the Boulc cores the negative correlation between $CaCO_3$ concentration and CEC values of a sample is very pronounced. In the Alvera core the CEC and $CaCO_3$ are positively correlated.

The CEC values as determined and described earlier should be corrected for the carbonate fraction in the samples. Carbonate does not contribute to the CEC of a sample. High percentage of carbonate would automatically result in a lower CEC. The carbonate fraction in a sample could explain the CEC variations in the core samples. The carbonate content is deducted from the dry weight of soil. Fig. 8 also shows the corrected CEC values. Only the very low CEC value in core B of Boulc–Mondorès between 17.5 and 20 m depth becomes less pronounced. Generally, the carbonate correction does not alter the CEC patterns with depth.

5. Discussion

This discussion will evaluate and analyse the chemical variations that were encountered.

In the Boulc–Mondorès core A, distinct geological and geochemical differentiations were observed. However, before attempting to link these with landslide phenomena, it needs to be determined whether the geochemical differences can be related to artificial drilling disturbances. Drilling fluid and deposition of drilling mud could be an explanation for the geochemical variation. Disturbance and twisting of the sample is either the consequence of a weaker layer, which has less coherence than the undisturbed marls, or the result of drilling with a completely full core length inhibiting further drilling progress. Fig. 5 shows that all combinations between the occurrence and absence of a drilling disturbance with both high and low CEC exist. On the basis of these observations, it is concluded that a drilling disturbance in itself does not affect the CEC values.

If the CEC variations are not artificial, the question arises what has caused these variations? The differences in CEC values could be the result of differences in material characteristics caused by weathering. The weathered intervals could result from limestone dissolution, as described by Phan (1992). Dissolution of the nanofossils will cause the collapse of the microcaves and a change in internal structure of the material in the weathered zones. The calcite oversaturation of water that flows through these preferential flow paths will result in secondary calcite deposition. This explains why the low CEC values coincide with high carbonate concentrations. So far these changes have not been measured independently with, e.g., X-ray diffraction.

An alternative check was done by comparing CEC and exchanger composition of surface (mudflow) material, with the results found in the core. If the geochemistry of the weathered surface material and that of the weathered intervals in the core are identical, it is likely that the same chemical processes are involved. The CEC of weathered surface material is around 15 meq/100 g with less than 10% sodium possession and around 50% calcium possession. The geochemistry found in the disturbed weathered layers resembles the surface sample. This suggests that the disturbed layers in the core have been subject to the same weathering process.

Core B shows less detailed information than core A. The lower CEC values for core B are most probably caused by the faster drilling and the way in which this core was stored: in a moist state and in PVC tubes. As is discussed above, weathering influences the chemical characteristics. The core is probably influenced by weathering due to exposure to oxygen in the PVC tubes.

Bogaard and van Asch (1996) suggest that the high concentration water that originates from scarps of fresh Albian–Aptian blue marls that is characterised by very high sodium and sulphate concentrations, is the result of pyrite oxidation. Pyrite is abundantly available in the Albian–Aptian blue marls. This causes an increase of acid (H^+), which is immediately

neutralised by limestone dissolution. The Ca^{2+} concentration in the water increases rapidly causing an imbalance between the water chemistry and the exchanger composition. As a consequence, sodium at the complex is replaced with calcium. While these processes need oxygen, this would lead to low sodium concentration at the cation complex near the surface and increasing sodium fraction with depth. This is in very good agreement with the measured cation fractions of both cores A and B (Figs. 5 and 6). The general decrease of the sodium fraction towards the surface in cores A and B suggests that the described weathering process takes place over a considerable depth. The pronounced dips in the sodium fraction in core A at 9.5 and 19.5 m depth can indicate that this process is more active here and would point to preferential flow paths although it is not clear whether pyrite oxidation causes these preferential flow paths, or the opposite.

Of the geochemical measurements on the Alvera core, only the results of the cation fraction could be explained, not the CEC and $CaCO_3$ analysis. On the basis of the geochemical results for the Alvera I2 borehole, two distinct intervals were identified (see Fig. 7). To 5 m depth, Ca^{2+} dominates the exchanger complex, below 5 m Ca^{2+} and Mg^{2+} prevail. These intervals point to two distinct water types with compositions related to the exchanger composition. At 16 m depth the sodium fraction has increased at the expense of Ca^{2+} and Mg^{2+}. The increase of Na^+ with depth is in agreement with the change from Ca-HCO_3 type to Na-HCO_3 type of water found in the groundwater (see Section 3.2).

Fig. 9 shows a similar development, but less distinct, of different cation composition for the Boulc–Mondorès cores. The sodium fraction is compared to the calcium and magnesium fraction in cores A and B. Both show an upper section till around 10 m
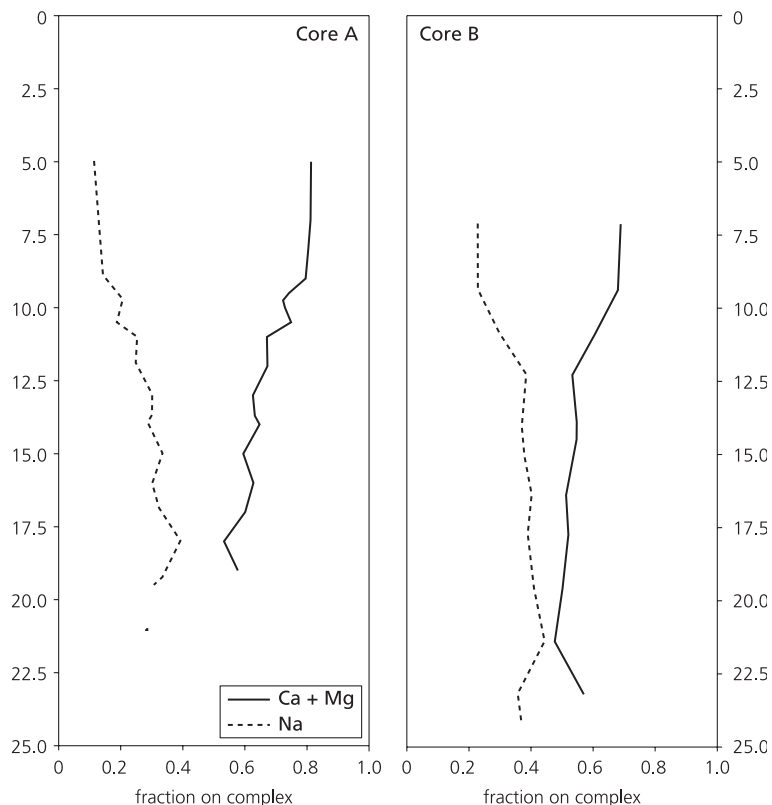

Fig. 9. Profile of cation fraction possession from cores A and B of the Boulc–Mondorès landslide: $Mg^{2+} + Ca^{2+}$ vs. Na^+.

depth with low Na^+ and high Ca^{2+}–Mg^{2+} concentrations. Below that a gradual increase in sodium concentration is perceptible. This could point to the depth of the influence of precipitation in the local water system.

6. Conclusions and further outlook

The aim of this paper is not to come up with the definitive interpretations of the hydrological systems for the two landslides presented here. For such a purpose the presented data are rather limited. However, it was shown how geochemistry can contribute to landslide investigations. Because many landslides are very difficult to unravel using standard geohydrological methods, it is proposed to add hydro- and geochemical techniques to such studies. If borehole columns are available, these techniques are relatively cheap and fast. CEC and cation fraction analyses are applicable in marls, although some caution should be taken considering carbonate dissolution.

The two laboratory techniques show that reliable geochemical results can be obtained not only for clays, but for marls as well. The tests are shown to be reproducible and consistent. Where soluble minerals like calcite are known or expected to be present in the sample, the use of NaCl as displacement fluid is preferred over NH_4Ac. The omission of sodium as exchanger cation when using the NaCl method can be prevented by applying other salt solutions like $BaCl_2$ or $SrCl_2$.

The Boulc–Mondorès example showed that distinct weathered layers were identifiable. The weathered layers may develop or may already have been developed into slip surfaces. Geotechnical analysis of the weathered material should reveal that. A slip surface of only several millimeters thick will not be found with geochemical techniques, unless it was already visible in the core and thus sampled deliberately. The proposed method works on a decimeter scale. As stated in the Introduction, chemical composition can have a very large effect on the strength parameters of the soil. The here described technique can also be used for purposive sampling for laboratory strength tests.

The hydrological system of the Boulc–Mondorès landslide was schematised as a superficial hydrological system, fed by precipitation and was quantified on the basis of the cation composition to reach a depth of 10 m (Fig. 9). Furthermore, the subsurface seems to have several important preferential flow paths. Lastly, with this geochemical information, it has been possible to improve the explanation of the water chemistry by pyrite oxidation as found in the Boulc–Mondorès landslide. In less complex settings the combination of hydro- and geochemistry could have revealed the extension of the groundwater catchment delivering water towards the landslide area.

The Alvera hydrological schematisation gave a 'root zone' of 0.5 to 2 m deep and underneath a clay zone of unknown depth. The geochemical analyses indicate an infiltration zone to a depth of 5 m below surface at I2 drilling. This enforces the idea of so-called 'dead-end' cracks where precipitation is infiltrating into the clay zone.

Both Alvera and Boulc–Mondorès examples show that geochemical techniques may be useful in locating boundaries between water types. The geochemical results obtained from boreholes can also be used in planning depth-specific hydrochemical sampling to characterise a change in water type. Knowledge of the depth of the transition between water types improves understanding of the hydrological system of a landslide. This would in particular be the case if the upper water type is representative for locally infiltrated water and the lower water type for regional groundwater.

Can this knowledge be used in slope hydrology and stability modelling efforts? Hydrogeochemical processes lead to changes in material characteristics and it is therefore plausible that knowledge of the hydrogeochemical evolution of clayey landslides improves long-term predictions of slope stability and evaluation. For the hydrological calculations, geochemical information leads to more ground truth—hydrological influence regions can better be delimited—which is worthwhile information to compare with model output. This information can also be of importance in landslide interventions for which the hydrological system and the origin of the water have to be known in detail.

From the above it is clear that geochemistry is a potentially valuable technique for, e.g., landslide research, but it is recognized that still a large amount of

work has to be done before all practical uncertainties are solved.

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