3 TESTING THE POTENTIAL OF GEOCHEMICAL TECHNIQUES IN IDENTIFYING HYDROLOGICAL SYSTEMS WITHIN LANDSLIDES IN PARTLY WEATHERED MARLS

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3.1 Introduction

In the study of hydrological processes in landslides, little attention is paid to techniques to determine the origin of ground water and flowing system within landslides. Knowledge of the ground water system in landslide areas is important when (cumulative) precipitation is related to mass movement via pore water pressure increase. 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 concept for predicting changes in landslide activity due to stabilising measures, land use or climate change. To predict slope movement as a reaction to precipitation it is important to know the extent of the area feeding the landslide with ground water and to have knowledge of the internal flow system.

For this purpose hydrochemical research can be useful. Appelo and Postma (1993) write: "Ground water 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 ground water 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 ground water 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.

This chapter objectives are twofold: first to test the potential of cation exchange capacity (CEC) analysis for refinement of the knowledge of the hydrological system in landslide areas, secondly to examine two laboratory CEC analysis techniques for their applicability to partly weathered marls. In other words, what additional information can be gained by CEC analysis in respect to the hydrological system of a landslide area and are these tests feasible for marls.

In a joint research of the EU-funded HYCOSI (Leroi, 1997) and NEWTECH (Corominas et al, 1998) projects, CEC analyses were executed on samples of 3 cored
drillings, 2 from the Boule-Mondorès landslide complex in France and 1 from the Alvera landslide in Italy. Cation exchange capacity and exchanger composition were measured with two different laboratory techniques. The results were then compared with the geological descriptions of the drillings.

3.2 Physiography of the test locations

Boule-Mondorès

Figure 3.1 Geomorphological map of the Boule-Mondorès landslide (adapted from Bogaard et al., 2000).
The Boulc-Mondorès landslide complex (figure 3.1) 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 polyphasic structural history from Trias to Tertiary (Bogaard et al., 2000). The main geological structure is a N-S running graben crossing the landslide. In the graben depositions from lower Cretaceous are found, east of the graben a sequence from upper Jurassic and west of the graben an anticlinal from upper Jurassic is located (figure 3.2).

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 headscarsps 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 (figure 3.1). The slumping zone approximately coincides with the 'Terres Rouges' graben.
The Alvera landslide was a study site in the NEWTECH-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 (figure 3.3). It is described in detail by Angeli et al. (1992), Deganutti & 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 at their base gentler slopes, 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.
3.3 Previous research

*Boucle-Mondorès*

Phan (1992) analysed samples from the Boucle-Mondorès landslide on a.o. calcium content, percentage material < 74 µm, < 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 3.1:

Table 3.1 Distribution of particle size and clay types of the Albian-Aptian marls (from Phan, 1992).

<table>
<thead>
<tr>
<th>Particle size distribution</th>
<th>Clay mineralogy</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;74 µm [%]</td>
<td>Illite [%]</td>
</tr>
<tr>
<td>&lt;2 µm [%]</td>
<td>Kaolinite [%]</td>
</tr>
<tr>
<td>96</td>
<td>10</td>
</tr>
<tr>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>60</td>
<td>10</td>
</tr>
</tbody>
</table>

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). It also showed a mixture of coccoliths (calcareaous planktonic organisms with <1 % MgCO₃, 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 Boucle-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 a CEC of 7-13 meq/100g (CEC for montmorillonite is 70-130 meq/100g).

Hydrochemical samples were obtained at the Boucle-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 thirteen shallow piezometers that were placed in phreatic ground water at 1.5-2.5 m depth with a filter length of 40 cm, located in the slumping, transition and mud flow deposition zones (figure 3.1). 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 figure 3.1-3.2) and high ion concentration water of around 20 meq/l exfiltrating the Albian blue marls (eastern part of slumping zone, see figures 3.1-3.2) (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 (figure 3.2). The water chemistry indicates that the ground water 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 ground water table fed by precipitation. Of the deeper ground water system it was suggested that it could be fed by the perched ground water system, from the scree slope in the rock sliding zone or even by karstic supply from the eastern limestone mountains.
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. Inclinometric measurements and from excavations revealed movement taking place mainly in zones of several mm thickness at depths ranging between 2.5-5 m 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 (figure 3.3). The lithological record of this borehole displays the characteristics outlined above. A thin peat layer was found at 24.3 m, which supported the inclinometric 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 figure 3.3) 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).

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 CaHCO$_3$-water to NaHCO$_3$-water with increasing depth. However, the nature and depth of the transition between these water 'types' could not be inferred.

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.

### 3.4 Description of drilling method and cores

Both in Boulc-Mondorès and in Alvera, a rotation, double envelop, 115 mm diameter drilling technique was applied, with a cable sampler to facilitate sampling. In both cases, local surface water was used as drilling fluid. Penetration of drilling fluid into the soil core is assumed negligible.

In Boulc-Mondorès, two cored drillings were placed (figure 3.1) at the margin of the slumping and transition zones, the most active part of the landslide area where the ground water system was thought to converge into the transition zone (Chassagneux and Leroi, 1995). Core A is a 'cored drilling': all material is lifted undisturbed and stored in wooden 'core boxes'. Core B is 'destructive': the cores were 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 incoherent material was flushed with drilling fluid. Plasticity of material, progress of drilling and occurrences of waterbearing 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. 20 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.

The drillings were located in the Albian-Aptian blue marls. The first drilling (core A) has three main units: until 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 figure 3.2) was encountered. Core B consist of two units, first until a depth of 6.5 m remoulded unconsolidated sediment of recent mass movements, followed by Albian-Aptian blue marls until the voluntary stop of the drilling at 25 m where the Barrémo-Bédoulian limestone was not yet encountered (see also figure 3.5).

In Alvera, the CEC measurements were carried out on 8 subsamples from borehole I2 (figure 3.3). The drilling had a total length of 24 m, but so far CEC measurements have been carried out to a maximum depth of 16.5 m only. The drilled core was stored in a moist state in sealed plastic bags, so some chemical alteration prior to analysis may not be excluded.

3.5 Description of laboratory analyses

A brief description of the laboratory techniques for determination of exchanger composition and cation exchange capacity (CEC) is given. Furthermore, unmarked double samples (duplicates) were included from each core to test the reproducibility of the analyses of both techniques (part of the second objective). Lastly, carbonate determinations were performed to adjust CEC determinations for carbonate content.

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 (NH₄Ac) technique, the cations at the adsorption complex are displaced with 1M NH₄Ac. The concentration of the cations in the fluid is analysed using ICP-AES. The CEC is determined by flushing the sample with 1M Sodium Acetate (NaAc), resulting in only exchangeable Na⁺, the called 'index cation'. The sample is washed with 96 % ethanol, removing excess Na⁺. The sample is again flushed with NH₄Ac extracting all Na⁺ from the adsorption complex. Subsequently, the Na⁺ is measured by flame photometry. The total Na⁺ concentration equals the CEC.

The Sodium Chloride (NaCl) technique follows the same principle. The sample is flushed with 1M NaCl solution and the concentration of the Ca²⁺, Mg²⁺ and K⁺ from the adsorption 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 porefluid. The Na⁺ sample was then flushed with 1M MgCl₂ solution. Seasand, with a known CEC, was added to the sample (ratio seasand-sample is 1:1) to bring the sample into suspension. The Na⁺ concentration in the extract is then determined by flame photometry.
Both described techniques have Na\(^+\) as 'index cation', but different displacement solutions (NH\(_4\)Ac and MgCl\(_2\)). The main drawback of the NH\(_4\)Ac technique is that NH\(_4\)Ac (carried out at pH=7) 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 (carried out at pH=8.2) 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 100g dry soil). It furthermore can point out differences in lithology within one drilling, e.g. secondary calcite deposition.

3.6 Results

Evaluation and comparison of the two laboratory methods

The results for the duplicates are given in table 3.2. 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 3.2, however, also shows that the 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 (figure 3.4a) except for sample I2.1 (resp. 35 and 75 meq/100g). The latter was interpreted as an unexplained laboratory error and consequently removed from the data set. The CEC values of the Boule samples range from 15 to 35 % and are in some cases a higher than would be expected on the basis of Phan's results (§ 3.3). Probably the clay content of the blue marls is higher. The amounts of exchangeable magnesium (Mg\(^{2+}\), figure 3.4b) determined by the two techniques are in good agreement with each other for all Boule 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.

Table 3.2 Relative difference between the analyses of duplicate samples. In the last column the average of the 5 duplicate samples is given.

<table>
<thead>
<tr>
<th>Method</th>
<th>Element</th>
<th>A.7</th>
<th>A.16</th>
<th>B.5</th>
<th>B.8</th>
<th>S1.1</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>25</td>
<td>9</td>
<td>6</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>NH(_4)Ac</td>
<td>Ca</td>
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<td>1</td>
<td>19</td>
<td>20</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>NaCl</td>
<td>Ca</td>
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<td>12</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>NH(_4)Ac</td>
<td>K</td>
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<td>1</td>
<td>3</td>
<td>2</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>NaCl</td>
<td>K</td>
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<td>10</td>
<td>1</td>
<td>1</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>NH(_4)Ac</td>
<td>Mg</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>NaCl</td>
<td>Mg</td>
<td>3</td>
<td>9</td>
<td>2</td>
<td>8</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
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<td>Na</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
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<td>3</td>
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<td>CEC</td>
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<td>1</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>NH(_4)Ac</td>
<td>CEC</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

44
Figure 3.4  Comparison NH₄Ac and NaCl laboratory analyses of cation exchange capacity and cation composition for the Boule-Mondorès (black dots) and the Alvera (open dots) landslide samples.
The amounts of exchangeable potassium (K\(^+\), figure 3.4c) show that the NH\(_4\)Ac technique tends to analyse 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 due to the conservative nature of Na\(^+\).

Figure 3.4d 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/100g higher fraction than using the NaCl technique. Both techniques, however, result in Ca\(^{2+}\) concentrations that are higher than the CEC, which is impossible. 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 (figure 3.4e). Mg\(^{2+}\), K\(^+\) and CEC are taken from the NaCl results and Na\(^+\) from the NH\(_4\)Ac method. This result shows that also 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. Stronger overestimation of exchangeable Ca\(^{2+}\) by NH\(_4\)Ac may be related to the slightly acid character of the displacement fluid. 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 then the NH\(_4\)Ac 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\(_4\)Ac 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\(^+\)).

Results of the CEC and exchanger cation measurements I: Boulc-Mondorès

In figure 3.5 the CEC and the exchanger cations of core A are given together with a schematic geological column. The CEC profile corresponds well with the description of the drilling. A low CEC (20 meq/100g) 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 also a calcite vein was 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 (figure 3.6). Values are around 20 meq/100g with a clear minimum of 13 meq/100g between 17-20 m. The exchanger 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.
Destructive drilling

Figure 3.6 Geochemical profile of core B from Boule-Mondorès.
Results of the CEC and exchanger cation measurements II: Alvera

The CEC profile does not reveal any distinct intervals (figure 3.7). 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 (figure 3.7): above this transition, $\text{Ca}^{2+}$ is the dominant cation, while below it $\text{Ca}^{2+}$ and $\text{Mg}^{2+}$ dominate. Another feature is the gradual increase in exchanger $\text{Na}^+$ below this transition.

Figure 3.7 Geochemical profile of core I2 from Alvera.
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 (figure 3.8). In the Boulc cores the negative correlation between CaCO₃ concentration and CEC values of a sample is very pronounced. In the Alvera core the CEC and CaCO₃ 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. Figure 3.8 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.

Figure 3.8 CEC values and carbonate content with depth for all three cores.
3.7 Discussion

This discussion will first deal with the presented laboratory methods and then the measurement results will be discussed (CEC, CaCO$_3$, cation fraction) for each core. Here, the measurements are evaluated and explained and placed into their local context.

The two laboratory techniques show that reliable geochemical results can be obtained not only for clays, but for marls as well. The tests showed 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 the slightly acid NH$_4$Ac. The omission of sodium as exchanger cation when using the NaCl method can be prevented by applying other salt solutions like SrCl$_2$.

Of the Boulc-Mondorès drillings, core A was an undisturbed drilling for sampling and geological description purposes. Core B was a so-called ‘destructive’ drilling, i.e. it was not meant for sampling. It used the same drilling technique but was executed faster. Therefore, core A shows more detailed information. The lower CEC values for core B are most probably caused by the way in which this core was stored: in a moist state and in PVC tubes. The core is probably influenced by weathering due to exposure to oxygen in the PVC tubes. On the other hand it shows that in the case of possible oxidation of soil samples, geotechnical tests should be carried out as soon as possible after sampling to exclude a change in chemistry and mineralogy that may have a large influence on shear strength.

In Boulc-Mondorès core A, distinct geological and geochemical differentiations were observed. However, before attempting to link these with e.g. landslide phenomena, it needs to be examined 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. Figure 3.5 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 can be assumed 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 micro-caves 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 could then result in secondary calcite deposition. This could explain 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/100g with less than 10 % sodium possession and around 50 % calcium possession. The geochemistry found in the disturbed weathered layers resembles
the surface sample. This indicates that the disturbed layers in the core could have been subject to the same weathering process.

Bogaard and Van Asch (1996) suggest that the high concentration water that originates from scarps of fresh Albian-Aptian blue marls and 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 (figures 3.5 and 3.6). 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 large 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 flowpaths. Although it is not clear whether pyrite oxidation causes these preferential flowpaths, 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 figure 3.7). Till 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 CaHCO\(_3\) to NaHCO\(_3\) found in the ground water (see § 3.3).

Figure 3.9 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 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.

The hydrological system of the Boulc-Mondorès landslide was schematised as a superficial hydrological system, fed by precipitation. On basis of the cation composition, this ‘infiltration’ system seems to reach as deep as 10 m (figure 3.9). Furthermore, the subsurface seem to have several important preferential flowpaths. Lastly, some additional arguments for pyrite oxidation were come across, but no decisive answer about the origin of the water quality can be given. 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 infiltrating the clay zone.
Knowledge of the depth of the transition between water types can improve understanding of the hydrological system of a landslide significantly, if the origins of these water types are known. 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 ground water. However, it is too early to make statements with respect to this without more spatial geochemical information to support the findings, and some more detailed hydrochemical measurements to better characterise the water types.

### 3.8 Conclusions / further outlook

The aim of this chapter 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 in what respect geochemistry can be used in 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. It is furthermore recommended to try SrCl$_2$ as displacement fluid.

The Boulc-Mondorès example showed that a large amount of information on the subsurface can be extracted from geochemical analyses. In the Boulc-Mondorès cores distinct weathered layers could be identified. The weathered layers could develop or may
already have been developed into slipsurfaces. Geotechnical analysis of the weathered material should reveal that.

With this geochemical information it has also been possible to explain the water chemistry found in the Boulc-Mondorès landslide. In less complex settings the combination of hydro- and geochemistry could reveal the extension of the ground water catchment delivering water towards the landslide area. Both Alvera and Boulc-Mondorès examples show that geochemical techniques may be useful in locating boundaries between water types where this is not possible with lithological data. The geochemical results obtained from boreholes can be used in planning depth-specific hydrochemical sampling to characterise a change in water type. The above-mentioned information can be of great importance in landslide interventions for which the hydrological system and the origin of the water have to be known in detail. It is also plausible that knowledge of the hydrogeochemical evolution of clayey landslides may improve long-term predictions of slope stability.

A slipsurface of only several millimetres thick will not be found with geochemical techniques, unless it was already visible in the core and thus sampled deliberately. The proposed methods work on a decimetre scale, not smaller. As the CEC analyses may reveal ‘internal differences’ that could have severe influence on the slope stability. 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.

From the above it is clear that geochemistry is a potentially valuable technique for e.g. landslide research, but it is recognised that still a large amount of work has to be done before all practical uncertainties are solved.