ABUNDANCE OF HALLOYSITE NEOFORMATION IN SOILS DEVELOPED FROM CRYSTALLINE ROCKS. CONTRIBUTION OF TRANSMISSION ELECTRON MICROSCOPY

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Abstract: The soils developed from crystalline and metamorphic rocks in Galicia (NW Spain), are characterized by high concentrations of 1:1 phyllosilicates and gels. Thermal analyses, X-ray diffraction after formamide treatment, and IR spectroscopy in the OH vibration range have been performed on the clay fractions, but do not discriminate clearly between the different associated mineralogical phases. HRTEM studies linked with microdiffraction and microanalyses have led to the identification of several types of gel which transform into goethite, gibbsite, clay precursors, and/or halloysite according to their composition (Fe, Al or Si-Al). Halloysite-like minerals are the main constituents and they have a great variety of morphologies: lamellar, spheroidal, tubular, platy or poikilitic. In general, halloysite and gel formation on crystalline rocks is related to the bioclimatic conditions, involving high hydrolysis in the presence of organic matter. This halloysite seems to be a metastable mineral which would evolve into kaolinite with increasing weathering time.

Kaolinite is the most frequent and abundant mineral found during rock weathering and soil formation (Dixon, 1977; Keller, 1982). It is most abundant in tropical regions where intense drainage and hot climate induce a monosialitization process (Pédro, 1966); but the influence of different factors, past climates, weathering time or local leaching conditions can explain its presence in other climatic areas.

Halloysite has been distinguished from kaolinite since Berthier (1826), but until now reliable methods for their differentiation in mixtures such as those encountered in soils have been lacking. X-ray diffraction after formamide treatment (Churchman et al., 1984) is not precise enough in the presence of 10 Å and 14 Å phyllosilicates, and the crystallinity defined by infrared spectroscopy is not accurate when smectite, gels and/or gibbsite are present. This explains why more and more halloysitic clays are being identified by new methods of investigation such as electron microscopy. Thus halloysite is found to be a widespread 1:1 clay mineral in soils developed on volcanic rocks (Quantin, 1990; Van Oort et al., 1990). It has also been reported in other types of rocks, but usually in very small amounts.

Mineralogical studies carried out in the NW of Spain have shown that the main clay minerals found in soils developed on crystalline igneous or metamorphic rocks belong to the halloysite family. The first study using transmission electron microscopy (TEM) (Romero et al., 1992) describes different microsystems in the course of mineral weathering and

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formation of 1:1 phyllosilicates. The objective of the present paper is to evaluate both the extent and the different steps of the monosialitization process, and to discuss the conditions of genesis for the different types of halloysites and their various precursors.

MATERIAL AND METHODS

Samples

The samples have been collected from selected soils (Leptosols, Cambisols: gleic, umbric, ferralic and andic) developed from granites, granodiorites, gabbros, shales and amphibolites, as reported in the first publication (Romero et al., 1992). After collection in the field, the samples were kept in a wet state. The clay fractions were separated by sedimentation without any chemical treatment.

Methods

X-ray diffraction (XRD) was carried out on clay fractions untreated, after heating at 110°C, and after treatment with formamide in order to differentiate halloysite from kaolinite (Churchman et al., 1984). A Philips diffractometer was used with a Co anticathode and a backposition monochromator.

For differential thermoanalysis and gravimetry (DTA, TGA, DTG), aliquots of 10 mg of clay powder were used. The equipment, a Setaram symmetrical microthermoanalyser, simultaneously recorded DTA and the weight loss. The heating rate was 10°C/min. The quantitative determinations were based on the weight loss between 250 and 300°C for gibbsite (endothermic reaction, on the basis of 34.6% weight loss) and between 350 and 550°C for 1:1 minerals (endothermic reaction, on the basis of 14% weight loss). The precision was estimated at 10%.

Infrared (IR) spectroscopy was performed at room temperature on KBr pellets, with Beckman equipment, in the range of frequencies corresponding to OH vibrations (3500–4000 cm⁻¹).

Transmission electron microscopy (TEM) high-resolution TEM (HRTEM), microdiffraction and microanalysis by analytical electron microscopy (AEM) were carried out using a Philips 420 transmission microscope under the conditions detailed in Romero et al. (1992).

RESULTS

Some chemical data obtained from several soil horizons have been reported in Romero et al. (1992). They include pH, cation exchange capacity, exchangeable Al³⁺ and different forms of extractable Al₂O₃ and Fe₂O₃.

Mineralogical analyses

Thermal analyses. DTA-TGA were performed on the clay fractions from different horizons of soils from shale, gabbro, granodiorite and granite (Table 1). A high and continuous loss of water was observed with increase in temperature, there being some similarities with curves obtained on clays extracted from andosols. The total weight loss ranges from 16 to 28%.
TEM study of halloysite neoformation in soils

Table 1. Main data obtained from DTA and TGA curves for the clay fractions of different horizons of soils developed from shale, gabbro, granodiorite and granite.

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Horizon</th>
<th>W₁ (25–200°C)</th>
<th>W₂ (200–300°C)</th>
<th>W₃ (350–550°C)</th>
<th>1:1 clay content %</th>
<th>Gibbsite content %</th>
<th>ΣW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale</td>
<td>Bt2</td>
<td>3</td>
<td>4.2 (exo)</td>
<td>8.6</td>
<td>62</td>
<td>15.8</td>
<td>16.8</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>5.2</td>
<td>6.5 (exo)</td>
<td>5.1</td>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gabbro</td>
<td>AB</td>
<td>6.1</td>
<td>7.7 (endo)</td>
<td>6.2</td>
<td>44</td>
<td>22</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>5</td>
<td>1.1 (endo)</td>
<td>11.3</td>
<td>3.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td></td>
<td>1.9 (endo)</td>
<td>7.9</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Granodiorite</td>
<td>A</td>
<td>12.4</td>
<td>6.6 (endo)</td>
<td>5.4</td>
<td>39</td>
<td>19</td>
<td>27.8</td>
</tr>
<tr>
<td>Granite</td>
<td>A</td>
<td>8.8</td>
<td>(exo) continuous weight loss</td>
<td>39</td>
<td>19</td>
<td>27.8</td>
<td></td>
</tr>
</tbody>
</table>

exo: exothermic reaction. endo: endothermic reaction. W = wt. loss in %.

The 1:1 clay content ranges between 40 and 80% and is especially high in the B horizons. The 2:1 minerals are less abundant. Gibbsite is also often present but generally in minor amounts, except in the soils from granodiorite (A horizon) and gabbro (AB horizon). In the soil from granite, the continuous weight loss does not allow any quantitative estimation.

X-ray diffraction. XRD patterns (Fig. 1) obtained without treatment to remove amorphous compounds were poorly defined with a broad peak between 7 and 10 Å, except where kaolinite was present (C horizons from shale or gabbro). The broad 7 Å peak is always dominant and formamide treatment induces the shift of only one part of this peak to 10 Å. The effect was not improved by continuing the treatment. The broad 7 Å peak was

Fig. 1. XRD patterns of oriented clay fraction from soil developed from gabbro (C horizon): a: natural clay; b: clay after formamide treatment.
the most stable (no swelling with formamide treatment) in samples where precursors or primitive halloysites were abundant.

**IR spectroscopy.** IR spectra of OH vibrations have been recorded in the high-frequency range (Fig. 2) in order to attempt to discriminate between 1:1 mineral types. Unfortunately, some severe overlapping of peaks is introduced by the presence of gibbsite (AB horizons), gels (A horizons) or 2:1 clay minerals (C horizons). There is a relatively high peak intensity ratio 3620/3680 in the samples from A and AB horizons (granite, granodiorite and gabbro), indicating poor crystallinity of the 1:1 minerals (Chukhrov & Zvyagin, 1966). Spectra of C horizons (from shale and gabbro) were much closer to the spectrum of kaolinite *sensu stricto.*

**Analytical electron microscopy**

TEM analyses demonstrate that 1:1 phyllosilicates exist in all the clay fractions and bulk samples studied, but their shape and size can be very diverse. Though many of them fit varieties described in the literature, some new variations will be described.

![Fig. 2. IR spectra of clay fractions from different soil horizons developed from metamorphic and crystalline rocks; a: shale (C horizon); b: gabbro (C horizon); c: granite (A horizon); d: granite (AB horizon); e: granodiorite (AB horizon); f: gabbro (AB horizon).](image-url)
**Relict minerals.** All the relict aluminosilicates, which can be recognized by their habits, have been transformed into allophane or halloysite (Romero et al., 1992). The latter can be identified either by the existence of 1.0 nm lattice fringes as opposed to kaolinite which displays 0.7 nm lattice fringes, or by a typical tubular or spherical shape.

**Gel phases.** It is possible to distinguish other types of microsites surrounding the relicts. A gel phase forming from the dissolution of primary minerals can spread through the pores as elongated trails of polycationic-type material (Fig. 3a). Wide areas of gel mixed with paracrystalline and crystalline material also occur. The composition of these areas varies over distances of a few nanometers from silicic to aluminous or ferric (Fig. 3b). Iron-rich phases are either amorphous or crystallized and the latter can be identified as goethite by electron microdiffraction. The diffraction pattern corresponds to polycrystalline aggregates, even on very small (<0.1 µm) selected areas and is always very diffuse, attesting to the presence in the mixture of compounds of lower crystallinity. When the gel is rich in Al, some forms have a morphology typical of gibbsite, and a high sensitivity to irradiation. The less evolved forms are almost instantly rendered amorphous under the electron beam, whereas the more evolved ones are affected in a few seconds by cracking and shrinking. Xenomorphic silica-rich patches are always amorphous and contain no iron (Fig. 4).

**Clay precursors.** In other microsites different kinds of nano-organizations were observed which can be interpreted as clay precursors, including cell-textured material, fibres and lamellae.

The cell-textured material is similar to allophane, by morphology and chemical composition (Al : Si = 1), and AEM (Fig. 4) indicates a high Fe content in these allophanic-type domains which are described as feldspar pseudomorphs.

The fibres have an imogolite-like morphology with a “mohair” texture. When developed inside large trails of colloidal substance, they are 10–40 nm in length by about 2 nm in width (Fig. 3c). When developed in felspar pseudomorphs, they are contracted into polygons or circles of ~100 nm. AEM cannot be performed on individual fibres because they are intimately mixed with amorphous material. The composition of areas containing such material is complex with a severe deficiency in Si (Fig. 4). The Al:Si ratio may be very variable, (2.7–5.9), and these elements are generally associated with a number of impurities such as alkali and alkaline-earth cations, sulphur, phosphate, and sometimes a high content of Mn (Table 2). The relatively high atomic density of the fibres, due to metallic impurities, makes them look darker than imogolite sensu stricto would be under the electron beam (Fig. 3d).

Some 1 nm lattice fringes can be seen in the rolled lamellae which represent a more advanced stage of evolution of the halloysite precursor than fibres, with a circular form leading to the typical halloysitic organization (Fig. 3e). Electron microdiffraction reveals also a nascent periodic structure and confirms a slight increase in crystallinity. Elemental composition cannot be performed with precision on rolled lamellae because they are always contaminated with gel. The analyses contain a high level of impurities, especially Fe, but the Si : Al ratio is close to 1 (Fig. 4). The slight deficiency in Al may be due to irradiation effects.

**Halloysite.** Halloysite has different manifestations with spheroidal, tubular, platy and poikilitic structure. Spheroidal halloysite (Fig. 5a) and tubular halloysite, with a length of up to 0.5 µm, are also common. HRTEM confirms the 1 nm interlayer spaces (Fig. 5b). The spheroidal and tubular types commonly coexist and can form large aggregates (Fig. 5c). The spheres and the tubes have about the same composition, with a rather high content of Fe (Fig. 4).
FIG. 3. Gels, by-products and halloysite clay precursors: a: trail of polycationic gel (granite, A horizon); b: segregated Al-, Si- or Fe-rich phases aggregated with gibbsite (Gib) and goethite (Goe) (amphibolite, C horizon); c: fibres with a mohair texture mixed with polycationic gel (gabbro, AB horizon); d: contraction of fibres into polygons (granodiorite, C horizon); e: rolled lamellae (gabbro, C horizon).
In the Cambisols from granites, most of the clay is similar to the particles described as having crumpled lamellar morphology (Wada & Mizota, 1982; Quantin et al., 1984, 1988). On these samples, electron microdiffraction indicates that the crystallinity is very poor (Fig. 5d).

Large areas, several micrometers in size, with poikilitic structure, are invaded by halloysite. They contain skeletons of incompletely dissolved minerals such as feldspars and micas. Traces of K or Ca in 1:1 minerals reveal the presence of relict inclusions of parent minerals. Poikilitic structure (Fig. 5e) is more or less complete and may present voids or vugs in places. This type of halloysite is almost pure (Fig. 4).

Platy halloysite looks like 2:1 phyllosilicates with 1 nm lattice fringes, and develops epitaxially inside mica or chlorite crystals.

Kaolinite with a typical hexagonal shape is also formed. It is found in the C horizons of the oldest and deepest soils and it seems to represent the ultimate step of 1:1 mineral evolution in a soil profile.

**DISCUSSION**

It is very difficult to distinguish halloysite from kaolinite using mineralogical methods on bulk samples or clay fractions. This is in part due to the fact that 1:1 minerals are mixed with oxyhydroxides, gibbsite, gels, or organic matter and in such materials the efficiency of the formamide treatment appears very limited.

Large areas of gel have been observed in different soil horizons throughout profiles on
TABLE 2. Semiquantitative analyses of halloysite and gel in wt%.. Symbol < is used when elemental concentration is less than twice the detection limit.

**Halloysite**

<table>
<thead>
<tr>
<th></th>
<th>Spheroidal and tubular</th>
<th>Poikilitic</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>52-7 51-1 49-3 43-4 51-9 53-7 43-8 52-2 46-8 50-7 53-3</td>
<td>57-8 53-4</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>39-4 42-7 34-2 29-1 41-3 36-9 35-4 40-0 38-0 38-7 38-1</td>
<td>37-4 43-7</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>1-4 0-4 &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt;</td>
<td>&lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt;</td>
</tr>
<tr>
<td>MgO</td>
<td>&lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt;</td>
<td>&lt; &lt; 2-8 &lt; &lt;</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>&lt; 0-4 1-0 &lt; &lt; 0-5 0-8 &lt; &lt; 0-8 &lt; &lt;</td>
<td>&lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt;</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>1-5 &lt; 1-5 1-6 0-5 0-7 &lt; &lt; &lt; 1-4 &lt; &lt;</td>
<td>&lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt;</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0-9 0-2 0-5 &lt; 1-1 &lt; &lt; 0-4 5-8 &lt; &lt;</td>
<td>&lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt;</td>
</tr>
<tr>
<td>CaO</td>
<td>&lt; &lt; 0-7 0-6 &lt; 0-5 &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt;</td>
<td>&lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt;</td>
</tr>
<tr>
<td>MnO$_2$</td>
<td>&lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; 1-8 16-2</td>
<td>&lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt;</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>3-1 4-8 11-1 22-6 4-1 7-2 16-7 6-1 13-1 3-3 3-7</td>
<td>0-9 1-0</td>
</tr>
</tbody>
</table>

**Gels and by-products**

<table>
<thead>
<tr>
<th></th>
<th>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>19-2 8-8 81-7 9-4 26-5 58-6 13-9 27-4 77</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>18-2 11-8 &lt; 9-4 26-5 18-4 79-6 7-4 21-5</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0-6 1-8 &lt; 1-3 3-4 &lt; &lt; 1-8 5-1 7-7 7-3 3-3 5-8 3-0</td>
</tr>
<tr>
<td>MgO</td>
<td>&lt; 0-5 &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; 0-8 &lt; &lt; &lt; &lt; &lt; &lt;</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>2-7 1-1 &lt; 1-8 &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; 1-1 6-1 &lt; 1-1 &lt;</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>1-4 2-3 0-3 1-5 1-4 7-2 &lt; &lt; &lt;</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>&lt; 0-3 &lt; &lt; 0-5 3-6 0-8 &lt; &lt; 2-8 5-4 4-7 3-5 3-9 2-5</td>
</tr>
<tr>
<td>CaO</td>
<td>0-6 &lt; &lt; &lt; &lt; 0-9 2-4 0-7 &lt; &lt; 2-9 0-9 &lt; 2-7 &lt;</td>
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<tr>
<td>MnO$_2$</td>
<td>&lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; &lt; 1-8 16-2 28-6 34-1 47-7</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>56-1 72-7 &lt; 76-8 1-0 3-6 3-4 &lt; &lt; 39-5 6 9-5 11-9 4-0 3-9</td>
</tr>
</tbody>
</table>

Analyses of halloysite are of the spheroidal and tubular types except the last two which are of the poikilitic type. Analyses of gel and by-products: (1) allophane; (2) iron exudation from chlorite; (3) amorphous silica; (4) Fe-gel; (5) gibbsite; (6) Si-gel; (7) Al-gel; (8) exsolution lamellae Na plagioclase; (9) plagioclase exsolution domain; (11) fibres contracted into polygons; (10) xenomorphic gel; (12) polycationic gel; (13, 14, 15) fibres with a “mohair” texture. Data are reported in Fig. 4.

Various types of rocks. These provide clues to a neoformation pathway following advanced weathering of primary minerals, providing an abundant source of elements.

The following sequence of evolution is suggested: Primary mineral dissolution → gel formation + allophanes → clay precursors → incipient halloysite → different forms of halloysite (depending on parent mineral and weathering conditions) → kaolinite in some cases. Such a sequence coexists with another variant when Fe- or Al-rich gels can evolve directly into goethite or gibbsite.

The forms of gel organization are similar to the “primitive clay precursors” defined by Tazaki & Fyfe (1987). For example the fibres look like the “mohair structure” with “bundles, branches, curlings and double circular structure”. Individual fibres which develop around circular holes have very variable morphologies and chemical compositions, with Al:Si > 2 and a high level of various impurities. They strongly resemble the synthetic imogolites obtained by Henmi & Huang (1987) in presence of P impurity which inhibits the growth of imogolite.
Fig. 5. Different facies of halloysite; a: spheroidal halloysite (granite, A horizon); b: tubular halloysite displaying 1 nm lattice fringes (granodiorite, B horizon); c: halloysite aggregate with spheres and tubes (gabbro); d: crumpled lamellar precursor and microdiffraction pattern attesting the non-crystalline character of the material (granodiorite); e: poikilitic structure of halloysite (gabbro).
The next step of the proposed evolution is represented by the transition from what is called “sheet allophane-like particles and crinkly film” (Tazaki, 1982) to a spheroidal halloysite. The tubes or open cylinders can be considered as a transition to “tabular” halloysite described by Kunze & Bradley (1964), and Souza Santos et al. (1966).

Many hypotheses have been proposed to explain the great variety of halloysite forms. The first hypothesis invokes the type of genesis medium. Bates (1962), Parham (1969), Kirkman (1981), Nagasawa (1978a,b) stated that tubular and planar curved halloysites originate from feldspars, whereas spheroidal ones form from gel. Nagasawa & Miyazaki (1976) and Nagasawa & Noro (1987) made another distinction: the tabular shape is related either to a hydrothermal origin or to biogenic weathering of feldspars in sandy materials. The spheroidal morphology is related to the evolution of allophanic gels; for example, for Sudo & Yotsumoto (1977), such allophanes can aggregate into pellets giving rise to spheroidal halloysite, and then to the tubular form by transformation of the external part of the sphere.

Other hypotheses make a correlation between the shape and the chemical composition of halloysite. Long tubes (length >1 µm) have a lower SiO₂/Al₂O₃ ratio than do shorter tubes (Tazaki, 1982). The Fe content seems also to be important and Noro (1986) showed that the Fe content increases with the radius of curvature of the tube or sphere and is at a maximum in the hexagonal platy halloysite.

From the results obtained in this study, it is difficult to find a single factor to explain the halloysite morphology, because it is often impossible to know for certain whether the mineral has formed directly from a primary mineral or through a gel phase. The diversity of primary minerals and weathering micro-sites can explain the diversity of 1:1 neogeneses.

Further studies are necessary to solve the problem of the genesis of halloysite and its possible evolution to kaolinite. Paragenetic relationships between kaolinite and halloysite have been investigated by Robertson & Eggleton (1991) for examples involving the weathering of muscovite and feldspar to kaolinite and halloysite. These authors concluded that porosity was necessary to allow fluid access and freedom to curl in the process of halloysite formation.

The most determinant factor in our study seems to be the type of horizon. Thus A horizons contain spheroidal halloysites or other mineralogical forms associated with allophanic forms (allophane-like particles, crinkly films), while B and C horizons contain tubular halloysites which are always short (<0.5 µm). One explanation is the role of organic matter which is always more abundant in A horizons, and which can protect allophanes (often in aggregates) and inhibit the crystal growth of tubes. Garcia-Rodeja et al. (1987) have even observed such a formation of Andosols on acid crystalline rocks in a temperate region and have established a correlation between the presence of low crystallinity compounds and the nature and abundance of organic matter. Thus a parallel can be established between these soils developed on crystalline rocks and Andosols developed on volcanic rocks, which are always rich in gels and organic matter.

CONCLUSIONS

In the first study, it has been shown that feldspars and phyllosilicates undergo specific evolutions (Romero et al., 1992), but that the last weathering step is the formation of a gel. The non-crystalline mineral phases can be decisive for mineral neogenesis, and many clay precursors do exist and may be very abundant when bioclimatic conditions are favourable.
Such clay precursors and the first facies of halloysite formed are quite impossible to detect by XRD or other classic bulk analysis methods.

The use of electron microscopy on ultrathin sections of clay and bulk samples has enabled the distinction of two different ways of clay formation. One way occurs inside the primary crystals, and small crystalline units which are phyllosilicate layers or exsolution domains for other silicates are favourable microsites. The other way takes place in the gel phase which can occur in great abundance. This phase, which has been described previously using photonic (Delvigne & Boulange, 1973) or scanning microscopy can be studied better by TEM techniques. It can be seen that the progressive reorganization of the gel can lead to goethite, gibbsite, or through different clay precursors to different types of halloysite. Both ways lead to the formation of halloysite which has a great variety of shapes and sizes as well as degrees of crystallinity and seems to be a metastable mineral. Kaolinite apparently requires a longer weathering time to develop.

Such an abundance of gels and halloysite on representative samples of soils developed on crystalline rocks is quite unusual. The analogy is obvious with what occurs on volcanic rocks, where the source of clay is glass. Wilson & Tait (1977) have also identified an important halloysite formation on crystalline rocks in NE Scotland, but they have interpreted this 1:1 clay genesis as the result of ancient weathering in warmer conditions.

The most probable explanation for abundant halloysite neoformation is the role of the biochemical factor in weathering. The subtropical climate developed in Galicia favours high hydrolysis and gel production, and the presence of organic matter allows its conservation and slow transformation in the soil. Thus 1:1 clay can be neoformed from gels in conditions very similar to those involved in volcanic rocks.

REFERENCES