

FORMS OF SILICA IN INDURATED VOLCANIC SOILS OF THE MEXICO VALLEY

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Abstract

A study of forms of free silica has been made on 'tepetate' horizons of the Mexico Valley. These indurated horizons have a fragipan consistency and they are observed in soil profiles derived from several pyroclastic deposits. We have made successive observations using optical microscopy, and SEM coupled with EDS in situ micro-analysis on thin sections, or on smear slides in order to better distinguish the fine particles of the matrix. The focus of this study is the matrix, micro-laminated clay infillings and bright yellow cutans in voids or fissures. HRTM observations coupled with element microanalysis have been made on ultra thin sections of infillings and cutans. The clay mineral analysis has been made by XRD on the $<2\mu\text{m}$ fraction and fine clay; and a chemical analysis of $<2\mu\text{m}$. A selective dissolution of Si and Al elements by NaOH has been done on the fine earth. We then made observations using TEM, and micro-analysis of isolated particles. Forms of free silica have been observed at every scale ranging from milli to nanometer. There occur phytoliths, nanometric opal and perhaps micrometric cristobalite. Phytoliths are present in the matrix and infillings. Opal-A has been seen only by HRTM in fillings and cutans, but its location remains to be precisely determined as does that of cristobalite.

Keywords: silica, indurated soils, volcanic, tepetate horizons, phytoliths, opal, cristobalite, Mexico

INTRODUCTION

Indurated horizons, called 'tepetates', are common in volcanic soils of the Central Mexican High Plateau, particularly in the Mexico Valley, on the western piedmont of the Sierra Nevada. We studied three fragipan horizons where the induration seems to result from slight silicification (Hidalgo, 1991). These fragipans have been observed in a soil profile located at the middle of a climotoposequence on the piedmont, at an altitude of

2555 m, under a 'ustic' climate regime with 6 dry months. The fragipans occur between the less consolidated formations on the wetter upland and the harder and lime encrusted ones of the drier downslopes (Fig. 1). The aim of this study following previous studies of Miehlisch (1991), Hidalgo (1991) and Hessmann (1992) to determine the forms of silica and their distribution in the soil profile. Miehlisch considered the cementing agent to be a mixture of halloysite and silica which hardens under air drying (after soil erosion). Hessmann has shown phytoliths and silica



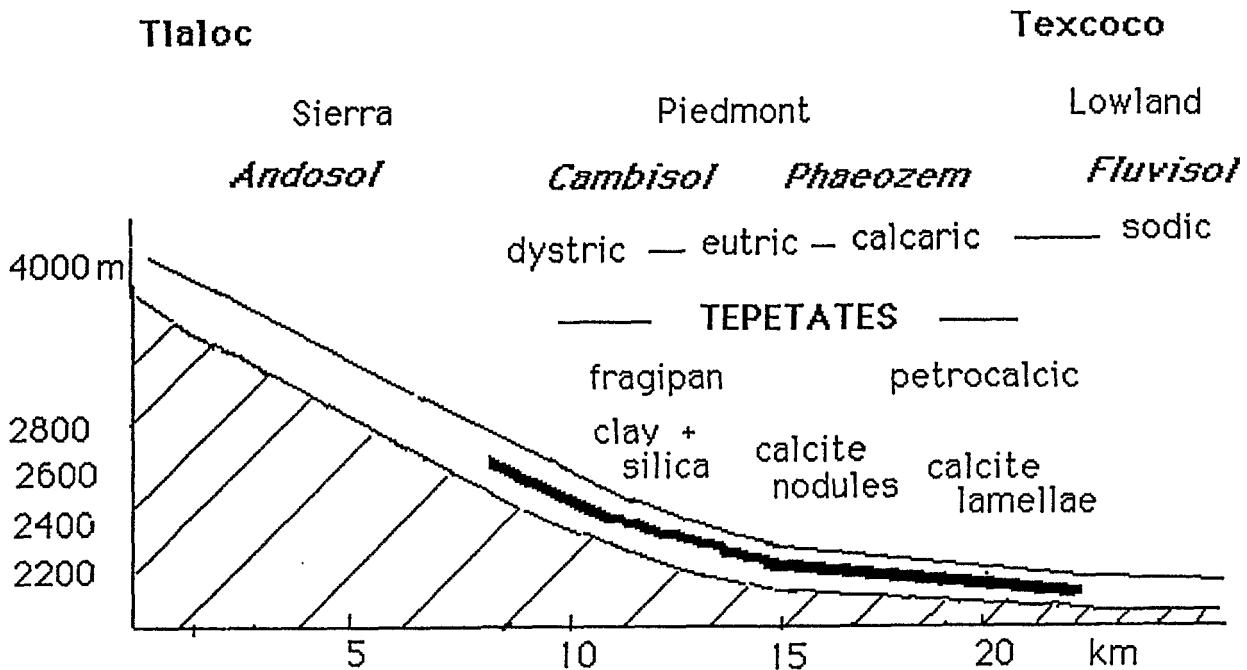


Fig. 1 Climotoposequence of soils and 'tepetates'

intercalations in clay infillings. Our study aims to complement these previous observations.

MATERIAL

Parent material

The parent material is composed of pyroclastic deposits, locally termed 'tobas' (T). The oldest deposit (T_3) is well characterised by its reddish colour and this formation is between 20 000 and 35 000 years old. It was covered by a newer one (T_2) 10 000–20 000 years old, of white to grey colour. The uppermost deposit (T_1) is composed of a dark Vertisol formed from Holocene volcanic ash and covered by the present topsoil.

Soils

The soil profile used in this study (Fig. 2) shows three indurated horizons, of a fragipan consistency, called 'tepetates'. They underly paleosols and are designated t_{2a} , t_{2b} and t_3 , according to the series of pyroclastic deposits. The 'tepetates' t_{2a} and t_{2b} are of white or pale grey colour; sometimes they are overlying lenses of a white and unaltered fine pyroclastic tuff, but t_3 is reddish and looks harder and more massive. These tepetates, especially t_3 , are often exposed at the soil surface by erosion. The lower part of each tepetate has a massive or prismatic structure but becomes more dissected by cracks, tubes and fissures towards the top.

METHODS

Microscopy and microanalysis (EDS)

We have successively used optical microscopy (OM), and scanning electron microscopy (SEM) coupled with microprobe (EDS) on thin sections, or smear slides, then transmission electron microscopy (TEM) with microanalysis of fine clay deposits;

and finally high resolution TEM (HRTM) with microanalysis of microsamples of selected objects from thin sections.

OM and SEM were carried out first on thin sections of Nos 4, 5, 7, 8, 10 and 11 of the respective horizons B_t and B/C_{tx} of T_{2a} ; B_t and B/C_{tx} of T_{2b} ; B/A , B_{t2} and B/C_{tx} of T_3 deposits, then on smear slides of the same horizons in order to observe the finest particles of the matrix. We have separately analysed the clayey plasma of matrix and glasses, feldspars and phytoliths, as well as the plasma of laminated clay infillings or bright yellow cutans.

TEM and microanalysis of fine clay particles, from the extracts of Nos 4, 5, 6 and 7 horizons (obtained by clay dispersion, centrifugation and filtration) were used to ascertain morphology, elemental analysis and microdiffraction.

HRTM was used on microsamples of a microlaminated clay infilling (No 11 horizon) and of a bright yellow cutan (No 8 horizon) in a fissure; observations on ultra thin sections of microsamples included in a resin of undisturbed objects, viz structure, composition, microanalysis and microdiffraction at the scale of a clay particle.

Mineralogy by XRD

We have determined first the composition of primary and secondary minerals on whole soil powders; secondly the clay minerals on the $<2 \mu\text{m}$ fraction and then on the 'fine clay' fraction (without microlites), in powder, oriented clay before and after 4 treatments (glycolated, heated successively at 100°, 300° and 500°C).

Chemical Analysis

We have analysed the 'triacid' extractable major elements (Brétémieux, 1948) of the $<2 \mu\text{m}$ fraction, which belong mostly to secondary minerals (clays, iron oxides). The results are normalised after deduction of loss on ignition and insoluble (primary minerals) residue. Then we have determined the chemical

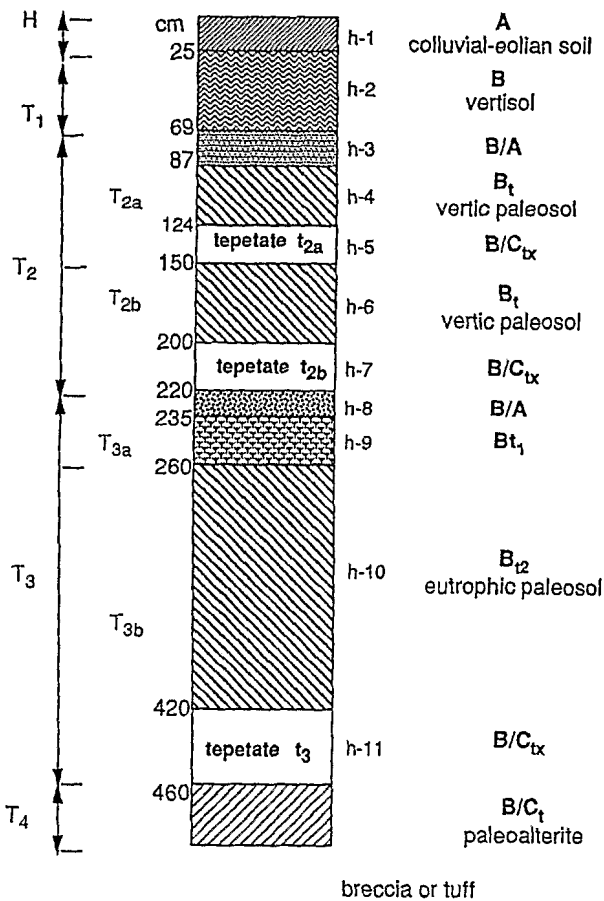


Fig. 2 Soil profile. Pyroclastic deposits (T₁, T_{2a}, T_{2b}, T_{3a}, T_{3b}) and 'tepetates' (t_{2a}, t_{2b}, t₃). Numbered horizons (h₁, h₂, h₃, h₄, h₅, h₆, h₇, h₈, h₉, h₁₀, h₁₁).

elemental composition of the residue after dissolution by a fluoro-perchloric acid digestion. We also made a sequential selective dissolution of Al and Si elements by 0.5 N NaOH consecutive 5 min extractions, at 20° or at 50°C, 8 successive extractions (Quantin et Bouleau, 1983), in order to estimate successively the very soluble (non crystalline), moderately soluble (paracrystalline) and slowly soluble (well crystalline) forms of clay and silica.

RESULTS

Optical microscopy allows us to define the main features of this study, namely the matrix (skeleton and plasma), microlaminated clay infillings and bright yellow cutans, where we have looked for different forms of silica.

Matrix

In thin section, the groundmass of t_{2a} and t₃ 'tepetates' looks continuous and a little cracked. The skeleton assemblage is porphyric, without sedimentary features, as is the case of a pyroclastic tuff; it is made of angular pyroclasts of lava, glass and phenocrystals. Plagioclases are predominant. There are few or traces of K feldspars, quartz, hornblende, hypersthene, augite and magnetite; these very small sized minerals may be also blended into the plasma. The phenocrysts appear unweathered or weakly altered, due to the recent age of the parent material.

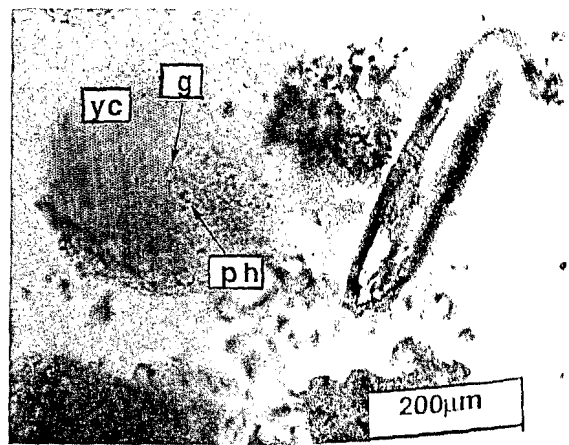


Fig. 3 Small fragment of yellow cutan (yc). Inclusion of micrograins of phytolith (ph) and glass (g) (OM on smear slides)

The pedogenic features in the t_{2a} and t₃ 'tepetates' are shuffling fissures, due to alternation of wet and dry seasons, as well as biological voids and channels, and cutans and clay infillings in voids or fissures. However the t_{2b} 'tepetate' shows a pedoplasma according to angular aggregates with reticulated striations, which characterise a vertic soil structure; the t₃ 'tepetate' has a reddish brown plasma dotted by ferruginous micronodules which resembles ferallitic or ferruginous tropical soils; but in the t₃ we only have a redistribution of iron oxides.

The smear slides show individual grains of phenocrystals, clay aggregates (infillings and cutans), phytoliths and plasmers. Among silica forms, quartz is scarce (only the coarse fraction); but phytoliths are abundant in the fine sand (100-200 µm); they occur as rods, tubes or fragments; other forms or fragments of phytoliths are present in the fine silt, but not in every horizon.

Infillings and cutans

In thin section, we can distinguish microlaminated clay and iron infillings and bright yellow cutans. The microlaminated infillings are frequent in the t_{2a}, scarce in the t_{2b}, abundant and typical in the t₃ 'tepetate'. In cross polarised light, we can see an extinction band, orthogonal to clay lamellae. Sometimes, clay sheets are mixed with siltans, organic matter and excrement pellets. The bright yellow cutans in the voids can show a diffuse extinction fringe parallel to fissures, 'rolling' or in black cross in voids, which suggests the presence of chalcedony or other neoformed mineral. These cutans are scarce in the upper horizons, but frequent at the bottom in the T₃ series horizons, namely number 10 overlying the t₃ 'tepetate'.

The smear slides show small fragments of yellow cutans, namely in the t_{2a} and t₃ 'tepetates' (Fig. 3). The limpid part of them can show some micrograins of phytolith and glass; on the margin of the matrix the inclusion of microlites becomes more abundant. Sometimes the cutan is dark red coloured by an organic or ferruginous product.

SEM and in situ micro-analysis

Matrix

In thin section, we have separately analysed (at the smallest size) the plasma of groundmass (Table 1), as well as phenocrystals.

Table 1 Microanalysis of thin sections of soils and 'tepetates'

Material	Horizon	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O (%)	K ₂ O	CaO	TiO ₂	ki
Matrix	4	63	25	5	0.8	1-7	0.5	1-7	1.0	4.3
Infilling		59	28	9	1.1	0.8	0.6	0.7	1.3	3.7
Coating		59-82	13-29	7-3	1.0	1.0	1.0	1.0	1.0	5-9
Matrix	5 (t _{2a})	65	24	7	0.8	1-4	0.5	≈1	1.0	4.7
Infilling		60	27	9	0.9	0.5	0.5	0.8	1.0	3.8
Coating		57-68	21-29	7-10	1.0	0.3	<1	<1.0	1.0	3-6
Matrix	7 (t _{2b})	60	27	8	1.5	0.4	0.7	0.8	0.9	3.9
Infilling		62	26	7	2.1	1.0	0.7	0.9	1.0	4.1
Matrix	8	63-67	20-23	4-7	1.0	0.5-2	0.4-3	1.0	1.0	≈ 5.0
Infilling		47-59	21-28	7.5	15	0.3	0.7	1.0	1.5	3.6
Coating		62	23	8-9	1.5	0.3-2	1.0	0.7-2.3	1.0	≈5.0
Matrix	10	67-76	15-23	5.2	0.6	1.0	0.7	1.0	0.6	≈ 7.0
Coating		91-82	24-12	3-6	0.8	0.4	0.5	0.7	0.5	10-53
Matrix	11 (t ₃)	61	25	10	1.0	1.0	0.8	0.8	1.0	4.3
Infilling		57-75	12-29	3-10	1.0	2	0.7	1-4	1.0	4.0
Coating		63	20	7	1.2	1.1	1.3	3.3	1.0	≈ 5.0

ki, Mol SiO₂/Al₂O₃ ratio; t_{2a}, t_{2b}, t₃, tepetates

and their alteration products. The whole plasma of t_{2a} and t₃ 'tepetates' and Nos 4, 8 and 10 horizons is rich in silica (61-81%) and in Ca, Mg, K and Na oxides; the range of ki (mol SiO₂/Al₂O₃) ratio is between 3.9 and 7. That means a partial alteration of volcanic glass and other microlites to clay and iron oxide minerals, with a little loss of silica and base elements (Hidalgo 1991). The plasma ki values are generally too high in comparison with the clay mineral composition, except in the t_{2b} 'tepetate' where a value of 3.9 fits with smectite clay minerals. The abundance of phytoliths seems to be insufficient to explain this result. At this scale of observation, in a mixture of clays, microlites, glasses and phytoliths, we cannot say if there is an unobtrusive form of free silica.

On the smear slides of the 2-20 μm fraction, of Nos 4 and 6 horizons and t_{2a} 'tepetate' (No 5), micro-analysis gave the following results (Table 2): the phytoliths contain 80-98% of SiO₂, 1-7% of Al₂O₃ (ki: 20-40), 1% of Fe₂O₃ and traces of other elements. These results are close to those of Wada (1982), but a little higher than those obtained by Bartoli and Wilding (1980). The plasma clays are aggregates of clay platelets mixed with micrograins of feldspars, phytoliths and probably altered glasses (Fig. 4). At this scale we could not identify other forms of free silica. In most studied horizons, the plasma ki values between 3.2 and 4.5 (Table 2) are higher than would be expected for the clay mineral composition obtained by XRD, namely halloysite with some smectite and Hr-Sm interstratified. Only in No 6 horizon does the 3.6 ki value fit well with an abundance of smectite.

Microlaminated infillings

Analyses have been made only on thin sections of Nos 4, 8 and 10 soil horizons of t_{2a}, t_{2b} and t₃ 'tepetates', respectively. The ki values of every horizon, except t_{2b}, are between 3.6 and 4; though lower than in the groundmass, these values are still too high in comparison with the clay composition where halloysite is the predominant clay mineral. Indeed, there is a mixture of clay with other more siliceous forms, namely phytoliths and

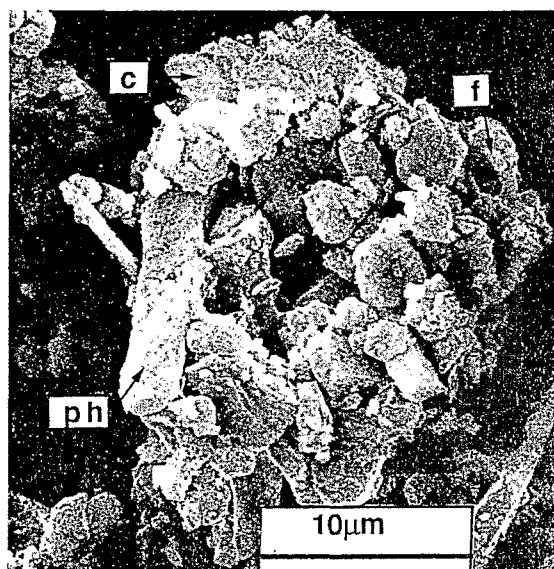


Fig. 4 The plasma: clay platelets (c), micrograins of feldspars (f), phytoliths (ph) and probably altered glass (SEM on smear slides).

Table 2 Microanalysis of soils and 'tepetates'

Mineral	Horizon	SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	MgO (%)	CaO (%)	Na ₂ O (%)	K ₂ O (%)	TiO ₂ (%)	ki
Scanning electron microscopy										
Feldspars(+Fe)	4/6	60	25	2.0	0.7	7.0	4.2	0.5	0.2	—
Altered Material	5	86–76	10–16	2.5–5	≤1	0.5	<1	0.5	≤1	8–15
Phytoliths	4/5/6	90–98	1–7	0.3–1	≤0.1	<0.5	<0.5	<0.1	<0.5	22–40
Layers of clay	4/5/6	57–62	25–30	6–9	1–3	0.7	0.2	0.5	0.8	3–5
Transmission electron microscopy										
Ovoidal	4/5	50	43	3.5	≤1	≤1	≤1	0.4	0.2	2.0
Halloysites										
Platy	5/6	51	39	4.5	≤1	0.3	2–3	21	0.7	2.3
Halloysites										
Rolled	5	48	37	7.0	0.5	0.7	0.9	0.4	0.5	2.2
Halloysites										
Spherical	4/5/7	54	36	3–8	0.9	0.5	1.4	0.8	0.3	2.6
Halloysites										
Smectites	6/7	56	25	8.0	≈1.5	0.8	4–8	2.6	—	4.0
High resolution transmission electron microscopy										
Volcanic Glass	11	76	15	1–4	0.04	0.30	2.7	5.0	0.1	7.6
Anorthoclase	11	64	21	0.1	—	0.15	3.2	12	—	—
Albite	11	64	24	0.4	0.11	2.8	7.3	1.9	—	—
And.-Lab.	11	54	29	0.9	0.08	8.0	7.4	0.4	—	—
Phytoliths	11	97	<0.1	<0.5	0.03	0.4	≈1	0.5	—	—
Clays	11	54	32	9.0	0.7	0.6	1.4	2.2	—	2.9
Clays (+Fe)	11	34	10	50	0.7	1.0	2.3	1.7	—	—

ki, Mol SiO₂/Al₂O₃ ratio; And.-Lab., Andesine-Labrador;

plagioclase. However, in the t_{2b} 'tepetate' the ki of 4.1 is close to the values of groundmass and of smectite clay minerals.

Bright yellow cutans

Analyses have been made only on thin sections from soil horizons Nos 4, 8 and 10 respective of t_{2a}, t_{2b} and t₃ 'tepetates'. The ki values near 5 or more (Table 1), suggest an alteration product which is enriched in silica in proportion to microlaminar clay infillings; while the content of base cations and iron remains similar. We note also an abundance of K₂O, about 1% of these features.

HRTM observation of infillings and cutans

The microlaminated clay infillings in the t₃ 'tepetate' have a ki value of 2.9 meaning a more siliceous composition than that of halloysite rich clay. Indeed, there are some inclusions of very small pieces of plagioclase and K feldspars, of which some fragments remain at the margin of crystals removed in the manufactured ultra thin sections. There are also some fragments of phytoliths and iron oxides (Table 2). But the excess in silica seems to be due mainly to the intercalation of minute grains of non crystalline opal (Fig 5) between clay laminae or infilling very narrow fissures which cut clay sheets.

A bright yellow cutan in a fissure of No 8 horizon matrix shows a coating of non crystalline silica, as well as an organic deposit enriched in nitrogen, iron and titanium.

XRD mineralogy

The <2 μm fraction is a mixture of clay and minor plagioclase microlites and traces of cristobalite, quartz, pyroxenes and iron oxides. The residue of 'triacid' dissolution of No 10 horizon clay fraction is mainly composed of plagioclases (andesine-labrador) and αcristobalite (XRD at 4.05 and 2.49 Å). The clay is made up 7 Å-halloysite, smectite and an interstratified mineral. Halloysite is predominant in most horizons, namely the t_{2a} and t₃ 'tepetates'; but smectite is abundant in the t_{2b} 'tepetate'.

The fine clay fraction gives a better X-ray diffraction, due to the loss of microlites and phytoliths (after centrifugation). The strong intensity of 7.35 and 3.55 Å peaks in proportion to 4.45 Å shows an ordered stacking of halloysite platelets, rather than curved or hydrated sheets. Smectite is well characterised and abundant only in the t_{2b} horizon (No 7). In the other horizons, the presence of a swelling 2:1 clay is always noticeable as a band around 15 Å, which moves close to 18 Å after swelling by glycerol treatment, or collapses almost to 10 Å after heating at 500°C; but it is badly defined and does not allow any estimation of its content.

TEM observation on fine clay

The halloysite rich clays of Nos 4 and 5 (t_{2a}) horizons mainly appear as fine and irregular platelets; some present a curved border, others, more rarely, are spherical. The platelets have a ki value between 2 and 2.3 and contain 3.5–4.5% of Fe₂O₃ (Table 2). The rolled forms have ki near 2.2 and 7% Fe₂O₃. The spherical shapes have ki between 2.6 and 3.0 and 3–8% Fe₂O₃. Iron

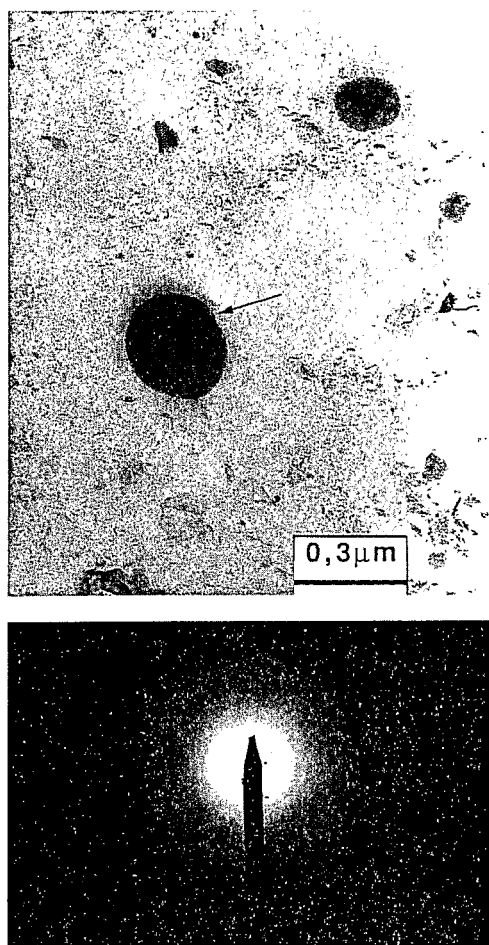


Fig. 5 Grain of non crystalline opal in ultra thin section of t_3 'tepetate' (a) electron micrograph $\times 51\,000$, (b) an electron-diffraction pattern from a grain.

can be derived from minute particles of iron oxides on the clay sheets. K_i values from 2 to 2.3 are often given for halloysite clay minerals in the literature.

The smectites of No 7 horizon appear as fine irregular and crumpled platelets. They have k_i of 4, 8% Fe_2O_3 and a rather high content of alkaline elements. Except for some fine particles of iron oxides, there are no other minerals within the clay sheets because fine grains of feldspars or phytoliths are rare and obvious in TEM.

Chemical composition

'Triacid' extract of $<2\mu m$ fraction

There remains an important insoluble residue, essentially of plagioclases and cristobalite, between 7 and 11% of $<2\mu m$ fraction of every soil horizon. But this value increases to 16 and 19% in the t_{2a} and t_3 horizons, probably due to an increase of cristobalite. Indeed, in both these 'tepetates' the k_i values of 3.74 and 3.79 are higher than the values of 3.4–3.5 for other soil horizons. The soluble clay fraction is thus more siliceous in a 'tepetate' than in the overlying soil horizon. In every case the k_i value is too high for a predominantly halloysitic clay. Only in Nos 6 and 7 does the k_i around 3.6 fit well with a predominantly smectitic composition. We have to postulate that in the

$<2\mu m$ fraction there is a mixture not only of 1:1 and 2:1 clay minerals, but also of minute particles of very soluble non crystalline silica. We note also the high content of MgO (1–2%) and K_2O (0.5–0.6%) in the clay fraction, which could selectively retain these elements. The Fe_2O_3 content is around 9–12%; it does not significantly increase in the 'tepetates'.

Sequential selective dissolution of Si and Al removed from fine earth ($<2 mm$) by NaOH

There is an initial phase of silica which is very soluble in NaOH at 20°C, with little or no alumina (k_i 3.4–12) that indicates a non crystalline form of gel or minute particles (~ 10 nm); the amount is ~ 0.2 –0.5% (Hidalgo, 1991). This form is also dissolved in the first stage by NaOH at 50°C, but mixed with some Si and Al from a little allophane or a very fine clay mineral; however, high k_i values between 6 and 12 testify again to free silica dissolution. Then, in the second stage, Si dissolution decreases as well as the k_i value to between 6 and 2; it involves a mixture of fine clay and slowly soluble silica, which could be opal from phytoliths. In the third stage k_i values increase again to between 6 and 12; that means slow dissolution of a more stable silica form (opal, fine cristobalite) after extraction of the fine clay. But it is difficult to estimate accurately the various forms of free silica for lack of a differential mineralogical analysis after each step of dissolution and also of knowledge of the dissolved clay formula. It is only certain we have at least two forms of free silica, a first very soluble (gel, fine opal), a second slowly soluble which comes from phytoliths and eventually fine cristobalite particles.

DISCUSSION

Silica is abundant in every soil horizon and 'tepetate'. However, from the analysis of fine earth and $<2\mu m$ fraction, its amount increases slightly in relation to Al content (Hidalgo, 1991) in the more consolidated t_{2a} and t_3 'tepetates', in comparison with the overlying loose soil; this fact may suggest a secondary silicification. Silica is located firstly in the primary silicates, namely alkaline glasses and plagioclases (with a little hornblende and pyroxene); secondly in the secondary clay minerals as halloysite, smectite and interstratified material; thirdly under several forms of free silica such as: abundant phytoliths in the matrix as well as in microlaminated infillings and some very fine opal in microlaminated infillings, but only traces of quartz or cristobalite.

The abundance of alkaline glass and phytoliths is subject to a quick alteration, producing a high silica concentration within solutions. This phenomenon can explain, under a climate with two alternate wet and dry seasons, the formation of minute particles of opal-A and perhaps α -cristobalite. The α -cristobalite could either appear during ash deposition, after initial dissolution of very fine glass particles, without loss of solutions, or it may result from pedogenesis. A model to explain the formation of opaline silica and its chemical interaction with other soil components was not investigated in the present work; these aspects will be studied later.

In order to locate the forms of free silica, microanalysis was made at the micrometer scale (SEM). It showed a high excess of free silica in the clay plasma of matrix and in microlaminated infillings and bright yellow cutans, in comparison with the clay

mineral composition. We have found that the <2 μm fraction contains, in addition to clay minerals, some plagioclase and cristobalite micrograins (XRD analysis), as well as rare phytolith fragments (from TEM). These minerals ($\leq 1\%$ of fine clay) are mostly eliminated, but not completely, from the fine clay by centrifugation. The chemical composition of fine clay (triacid extraction) indicates a high silica content and fairly high mol. $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio, ranging from 2.9 to 3.4. XRD shows a mixture of smectite and halloysite clay minerals. Indeed, direct TEM chemical analysis of clay particles gives a chemical formula close to either halloysite or smectite minerals. At this stage of the investigation we cannot ascertain with certainty if there is free silica in the fine clay.

Finally, some detailed observations by HRTM, as well as microanalysis of the matrix, the microlaminated clay infillings and the bright yellow cutans showed that there are some nanometric grains of a non crystalline silica form inside microfissures or intercalated between the illuviated clay layers. Silica gel occurs too in the bright yellow cutans and some microlaminated clay infillings as a 'plasma' embedding clays and other minerals. However, we have no evidence that silica gel is adsorbed onto clay mineral surfaces as in the case described by Singh and Gilkes (1993), concerning kaolinite.

At macro and microscopic scales, this matrix looks continuous and microporous, but *in situ* altered and cut by fissures and biological tubes, thus maintaining the original structure of consolidated ash. Hessmann (1992) suggested the simultaneous formation of a soil during a long period of ash fall or 'volcanic loess', then the hardening of some horizons by a pedogenetic silicification as was also postulated by Miehllich (1991). This question is not completely answered; we will have to analyse in greater detail the tuffs at the bottom of 'tepetate' horizons as well as the matrix of these 'tepetates'. We have not considered the mechanism for the formation of Si-Al and FeIII complexes proposed by Taylor (1988) because 'tepetates' are not forming in acid conditions. The model of silica deposition in duric soils postulated by Chadwick *et al.* (1987) is more consistent with our conditions (pH 7–8). Finally, we did not demonstrate the role of silica gel as a cementing agent.

CONCLUSION

In conclusion, several forms of free silica are observed at every scale from millimeter to nanometer. There are abundant phytoliths, as well as fine opal (nm) and eventually fine cristobalite (μm). The very siliceous composition in the clay plasma of the matrix and in the infillings or cutans can be explained firstly by a

mixture of 1:1 and 2:1 clay minerals, secondly by intercalation of fine particles of opal and eventually cristobalite (at micro and nanometric scale) between the clay illuviated layers, and thirdly by precipitated silica gel. Just how the phytoliths observed in the indurated matrix got there requires further investigation. The forms of free silica observed in the soil horizons and 'tepetates' suggest a secondary silicification. But, we are not sure that silica is the cause of the induration of 'tepetates'. We have to explain the role of the different forms of silica in unconsolidated and consolidated soil horizons. Other investigations are to be carried out.

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10TH INTERNATIONAL CLAYS CONFERENCE

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