

Forms and dynamics of silica gel in a tuff-dominated soil complex: Results of micromorphological studies in the Central Highlands of Mexico

Thomas Poetsch

Universität Hamburg, Institut für Geographie, Bundesstr.55, D-20146 Hamburg, Germany
Poetsch@geowiss.uni-hamburg.de

ABSTRACT

Within the basins of Mexico and Tlaxcala in the Central Highlands of Mexico, thick pyroclastics–paleosol sequences, grouped into units T_1 to T_7 , can be found. Unit T_2 at the site Tlalpan was chosen for a mineralogical-microscopical study. The unit consists of four late Pleistocene strata of pyroclastics (toba) with associated clayey soil horizons. Apart from magmatic particles, the pyroclastics contain many opal particles, especially diatom fragments and other bio-opals. In the basal stratum of pyroclastics 'i', the opals are orientated within the layers and, therefore, must have been deposited together with the other components. They were not, consequently, admixed later through soil formation or bioturbation. The very well-preserved microlamination and the orientation of the individual particles render a significant loss of pore volume (compaction) after sedimentation unlikely. According to the microscopic findings, in-situ weathering is the dominating process in this stratum, as it is, probably, in the other pyroclastic strata ('c', 'e' and 'g') as well. The clayey soils—as the tobas—are characterized not only by weathering of volcanic glass, but also by weathering of opal particles. Colloidal silica gel is the result of weathering of opal and volcanic glass, in addition to which clay minerals are formed from the glass. Microscopic silica gel crusts and clay cutans are the characteristic forms found, the latter described more precisely as clay-mineral / silica gel compounds. Laterally adjacent to the studied profile, characteristic indurated layers, so-called 'Tepetates' in the pyroclastic strata 'e' and 'i' can be observed. They develop out of the respective pyroclastics after their exposure following erosion. The following reasons for their formation are proposed: A comparatively dense packing of the parent material, a subsequent compaction, an intense re-location of silica gel within the matrix, its loss of water, and, probably, its partial crystallization. These results only refer to the stratigraphic unit T_2 and may not be applied to other stratigraphic units.

Key words: pyroclastics, paleosols, opal, silica gel, tepetate, micromorphology, late Pleistocene, Mexico.

RESUMEN

Dentro de las cuencas de México y Tlaxcala, en el centro de México, se encontraron secuencias gruesas de depósitos de piroclásticos–paleosuelos, agrupadas en unidades T_1 a T_7 . La unidad T_2 del sitio Tlalpan se escogió para un estudio microscópico-mineralógico. Esta unidad consiste en cuatro estratos de depósitos piroclásticos (toba) del Pleistoceno tardío con horizontes de suelo arcilloso asociados. Además de partículas magmáticas, los piroclásticos contienen muchas partículas de ópalo, especialmente fragmentos de diatomeas y otros bio-ópalos. En el estrato basal de piroclásticos 'i', los ópalos están orientados dentro de sus capas y, por lo tanto, deben haber sido depositados junto con los otros componentes. Consecuentemente, no fueron mezclados después por pedogénesis o bioturbación. La muy bien preservada micro-laminación y la orientación de las partículas individuales, hacen improbable una significativa pérdida de volumen de poro (compactación) después de la sedimentación. De acuerdo a los resultados microscópicos, el intemperismo in situ es el proceso dominante en este

estrato, como lo es también, probablemente, en los otros estratos piroclásticos ('c', 'e' y 'g'). Los suelos arcillosos —así como las tobas— están caracterizados no sólo por el intemperismo del vidrio volcánico, sino también por el de partículas de ópalo. El gel de sílice coloidal es el resultado del intemperismo del ópalo y del vidrio volcánico, además de que a partir del mismo vidrio se forman minerales arcillosos. Las formas características que se encontraron son cortezas de gel de sílice microscópico y los cutanes arcillosos, siendo las últimas más precisamente descritas como compuestos de minerales arcillosos / gel de sílice. Adyacentes lateralmente al perfil estudiado, pueden observarse capas endurecidas características, llamadas Tepetates, en los estratos piroclásticos 'i' y 'e'. Estas capas se desarrollan a partir de los respectivos depósitos piroclásticos, después de su exposición por erosión. Se propusieron las siguientes razones para su formación: empaquetamiento comparativamente denso del material parental, una compactación subsecuente, una intensa redistribución del gel de sílice dentro de la matriz, su pérdida de agua y, probablemente, su parcial cristalización. Estos resultados se refieren sólo a la unidad estratigráfica T₂ y no pueden ser aplicadas a otras unidades.

Palabras clave: piroclásticos, paleosuelos, ópalo, gel de sílice, tepetate, micromorfología, Pleistoceno tardío, México.

INTRODUCTION

In the Central Highlands of Mexico, a peritropical climatic area, Quaternary pyroclastics interposed with paleosols are fairly common. The stratigraphic structure of these formations in the basins of Puebla and Tlaxcala is presented schematically in Figure 1. The sequence here consists of seven pyroclastics-paleosol sequences (T₁ to T₇).

The results of studies carried out by Aeppli (1973), Miehlich (1984) and others showed that the weathering of the pyroclastics is characterized by very marked silica gel dynamics. According to these authors, the silica is released

by pedogenic weathering of the volcanic glasses. One part of the silica is integrated into newly formed clay minerals and the remaining part is eluviated from the topsoil and later precipitated as silica gel in the subsoil. So, the horizon with silica gel accumulation can be considered a subsoil of a quite thick soil profile. Exposure due to erosion leads to an induration of the layer with silica accumulation, transforming it into a hard crust, the so-called 'Tepetate'.

Hidalgo (1995), on the other hand, considers the characteristic dense packing of tepetates as a feature inherited from the parent material, *i.e.*, volcanic tuff. This question has practical significance, since the problems of soil erosion and Tepetates play a decisive role for the land-use patterns (Werner, 1988).

Aeppli (1973), Miehlich (1984), and Oleschko *et al.* (1994) stress that in spite of chemically proven silica gel dynamics, any silica crusts could be found, neither macroscopically nor microscopically. Hessmann (1992), on the other hand, was able to demonstrate the possibility of detecting silica (*i.e.*, silica gel, opal) by means of special microscopic techniques in thin sections from undisturbed soil samples. Poetsch and Arikas (1997) followed up on Hessmann's results and the study is continued in this paper.

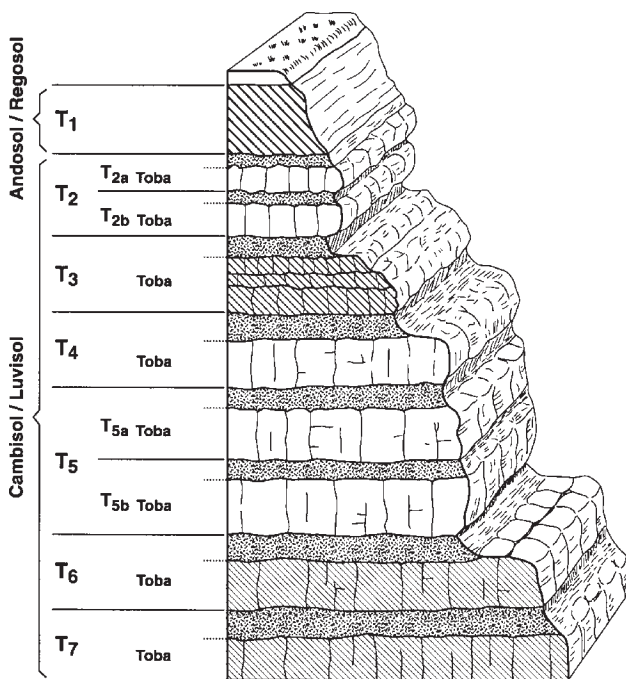


Figure 1. Stratigraphy of paleosols in the basins of Mexico and Tlaxcala (compiled from different sites); modified after R. Hessman (1992). T₂: Investigated stratigraphic unit.

MATERIAL AND METHODS

For this study, a site situated south of the village of Tlalpan (northwest of Apizaco) was chosen (Figure 2). Here, at the proximal part of a barranca (large gully) at 2,600 m above sea level, the stratigraphic units T₂ to T₇ are exposed. This study investigates a soil profile formed in the late Pleistocene unit T₂, having a thickness of 2.5 m here.

The T₂ unit was chosen especially because it contains only traces of pedogenic iron oxides (~2–5 mass %). These pedogenic iron oxides have the property of optically masking other components, so higher content of iron oxides would impair examination of silica forms.



Figure 2. Location of the site researched.

The T_2 unit consists of a dark-gray covering strata 'a' and underlying four bright yellow-gray, sandy-silty toba layers 'c', 'e', 'g', and 'i', alternating with another four dark gray clayey soil horizons 'b', 'd', 'f', and 'h'.

The term 'toba' originally was a local designation for volcanic tuff. Here, following Miehlich (1984), this term is used both for primary volcanic sediments, and also for materials of volcanic origin redeposited later, providing they both surpass 10,000 years of age. The toba layers are roughly prismatic, the clayey horizons are polyhedral, except for 'd'. The studied part of the site, unit T_2 (Figure 3), has the following sequence (simplified):

In reality, the boundary between a toba and the respecting overlying clayey horizon usually is not quite sharp. Clay cutans, characteristic of the clayey horizons, are found in the underlying toba layers as well, albeit with abated frequency. Underlying the lowest toba layer 'i' of the T_2 unit, T_3 is found (Figures 1 and 3), which is not considered in this paper. T_1 , overlying T_2 at other locations, is already eroded in the study profile. Consequently, the uppermost T_2 soil horizon 'b', together with the covering stratum 'a', forms the surface soil profile.

From the studied profile, undisturbed samples were taken at close intervals and thin sections produced from them. To get a general overview and to confirm the

representative nature of the thin sections, ten thin sections sized 47 by 47 mm were made. Additionally, 16 sections were prepared for detailed research, using the standard size of 28 by 32 mm but with an especially low thickness of 5 to 10 μm , intended for use with medium to high magnification. These latter thin sections allowed for an exceptionally detailed impression and for visualization of the refracting properties of the respective components. The theoretical basis for phase-contrast microscopy of thin sections and examples of its implementation is covered extensively in Altemüller (1997). This technique is especially helpful for the depiction of achromatic, optically isotropic, low-refractive objects like volcanic glass and opal.

THE TOBA 'i' AT THE BASIS OF T_2 UNIT

The bottom part of the toba 'i' is densely packed and contains only very few coarse pores with clay cutans. It is apparently only minimally influenced by illuviation. It is, therefore, well suited as reference for other comparative observations. Microscopically, with low magnification, the

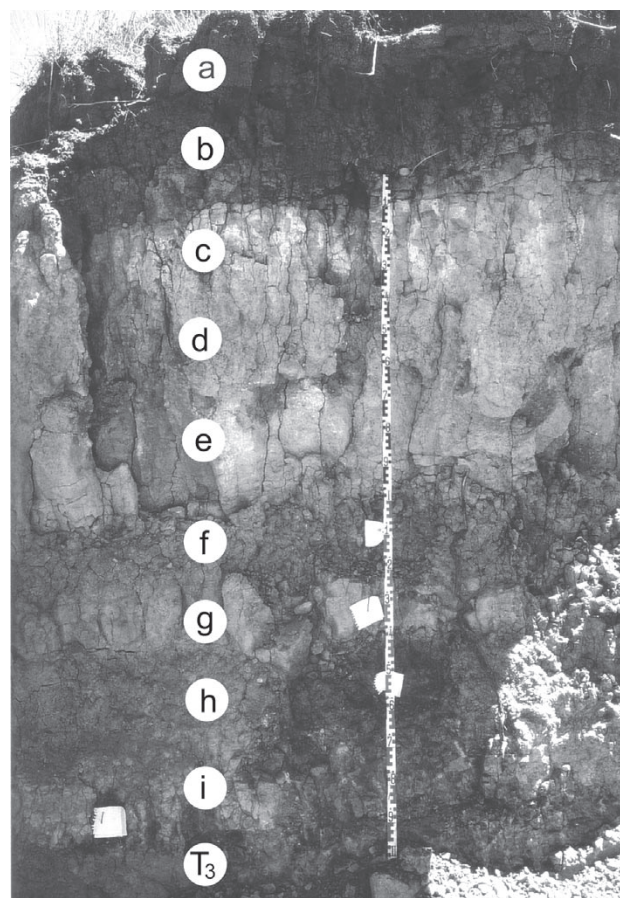


Figure 3. The researched profile. T_2 -unit: a: Covering stratum; b: clayey soil horizon; c: toba; d: low-clayey soil horizon (paleosol); e: toba; f: clayey soil horizon (paleosol); g: toba; h: clayey soil horizon (paleosol); i: toba. T_3 -unit: clayey soil horizon (paleosol).

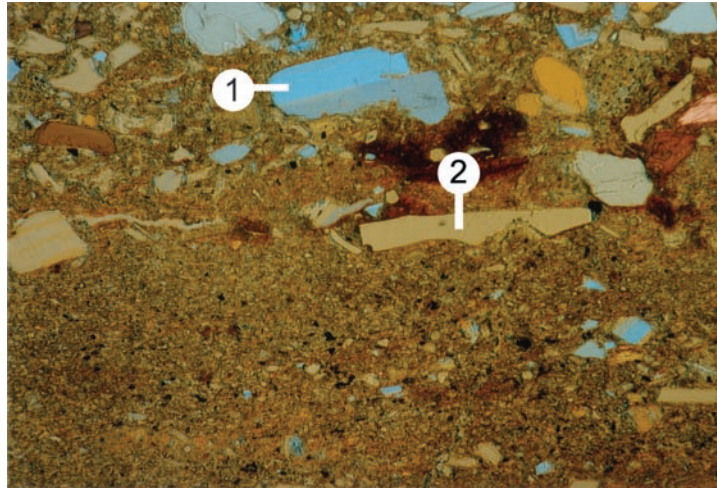


Figure 4. Clearly stratified toba at the foot of the profile (layer 'i'). 1: Plagioclase; 2: glass fragment. Natural size 0.9 x 1.34 mm, parallel polarizers + compensator.

dense packing of the fabric elements –visible even macroscopically– is obvious. The fabric elements mostly show uniform orientation and microlamination (Figure 4).

Because of this very good preservation of the microlamination, substantial compaction of the material is unlikely. So, the sediment must have been comparatively more densely packed from the outset, being in agreement here with the results of Hidalgo (1995).

The center of Figure 4 shows the microscopic borderline between two layers with different grain size and grading of the sediments. The sample is dominated, nevertheless, by coarse, weakly sorted sediment with sand-sized fragments of crystals, volcanic rock and glass in a silt-sized matrix (visible in the upper half of the photo). The internal structure of this matrix becomes visible with

phase-contrast and medium magnification (Figure 5). A high content of opal of different grain size, from coarse to fine silt, is characteristic. Glass fragments occur as well. Among the coarse and medium (partially) silt-sized particles, opals and glasses are easy to distinguish. They not only show different forms, even more important is their characteristic respective coloring under phase-contrast, resulting from their respective refractive index (Pichler and Schmidt-Riegraf, 1993). Comparing this detritus with the clearly visible, well-preserved diatom reveals that the detritus is composed predominantly of fragments of diatoms and other opals. The high content in diatoms indicates the aquatic nature of the sediment. The presence of silicoflagellates (not visible in the photo) only found in marine environment (Schallreuter, 1998, oral communication), would point to a

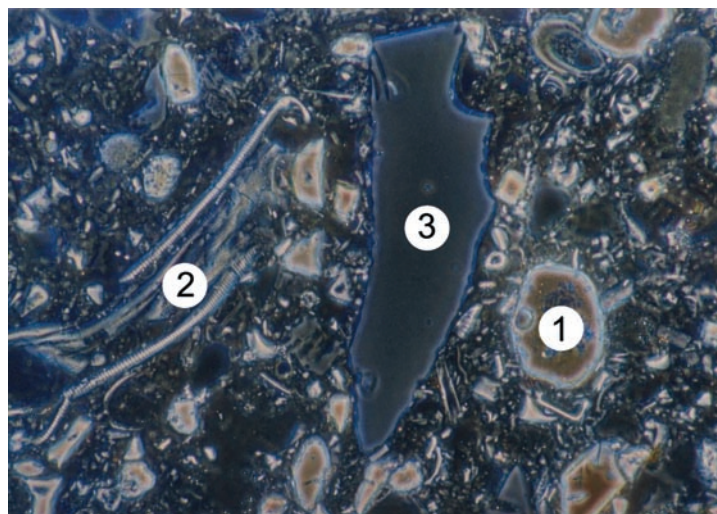


Figure 5. Toba at the foot of the profile (layer 'i'). 1: Phytoopal; 2: diatom shell; 3: volcanic glass. Natural size 0.14 x 0.2 mm, phase-contrast.

marine sedimentation, but tuffs sedimented under marine conditions are impossible at the given stratigraphical position in the late Pleistocene. One possible explanation would be, that the volcanic explosion blasted through older marine sediments containing silicoflagellates and hurled them out. They were then redeposited and mixed together with magmatic materials. It would be possible as well, that these sediments were redeposited in a non-marine environment and were in this way intermixed with other materials. This question may not be stressed here further, as it is more important here that the toba is a sediment very rich in opal from the outset. The primary opal content in the sediment can be microscopically estimated at 10 area % in the thin section.

The aforesaid refers to the toba at the base of T₂ unit; the younger tobas of this unit display much higher opal content. To verify the microscopic estimation of the opal content, chemical analyses with a microprobe were carried out on a similar sample, albeit with higher opal content (reference profile 'Canoa' near Puebla), the results are given in Table 1. The table shows that of 17 points identified as opal in the thin sections, 13 contain more than 99 mass % Si, thus verifying the microscopic results. The remaining four points show Si contents of 95.8 to 98.1 mass %, probably indicating an additional low content of clay minerals and iron oxides.

MORE RECENT TOBA LAYERS OF THE T₂ UNIT

The more recent toba layers 'c', 'e', and 'g' in the sample profile frequently show clay cutans and deposition of silica on fissure surfaces and in other substantial cavities. Figure 6 shows under polarized light that at the wall of a fissure, clay minerals (primarily) were deposited first (blue and yellow), later to be followed by a 0.1–0.2 mm thick layer of quite pure precipitated silica gel. The cover consisting mainly of clay minerals shows birefringence, the silica gel is isotropic. The silica gel layer contains traces of very small clay cutan fragments, probably detached from adjoining contiguous clay cutans.

The next photo (Figure 7) from another sample was taken with medium to high magnification and the phase-contrast technique. It gives a much different impression. In the upper right, silica gel, shining bright in the photo, can be seen, followed by a 30–40 μm packet composed predominantly of orientated clay minerals. This packet, attached to the wall of a cavity, is in part interspersed with bright, laminated silica deposits. At some spots, these colloidal silica gel deposits change into grains and fragments of silica gel. Apparently, some of these layers do contain particles surpassing 2 μm size, among them many opal grains and fragments. Embedded in the clay laminae as they are, they weather over the years into colloidal silica gel. Below this microscopically laminated zone, the adjacent ground mass is characterized by heavily corroded opal

Table 1. Chemical composition of selected points in thin section (EDAX measurements).

Nr.	Al (g/100g)	Si (g/100g)	Other (g/100g)
1	0.39	99.61	
2	0.60	99.40	
3	0.69	99.31	
4	0.36	99.64	
5	0.14	99.86	
6	0.56	99.44	
7	0.55	99.45	
8	0.68	99.32	
9	0.25	99.75	
10	0.11	99.89	
11	0.12	99.88	
12	0.63	99.37	
13	0.13	99.87	
14	1.91	98.09	
15	1.97	97.02	Fe 1.01
16	2.90	95.42	Fe 1.51; Mg 0.17
17	2.81	95.83	Fe 1.37

particles. In this area, close to a fissure and therefore heavily weathered, opals of only fine to medium silt size down to colloidal size dominate. They show markedly diffuse contours. This becomes especially apparent when comparing them with the coarse-silt-sized opals in the less weathered inner part of the matrix.

Obviously, this sample shows that a redistribution of silica has taken place. The decisive process is, apparently, that the smallest opal fragments, with their especially high specific surface (apart from volcanic glass), most importantly weather to a colloidal silica gel, although the more sizeable opal particles are dissolved and so reduced in size as well. The dissolved silica is partially eluviated, partially relocated on a small scale, and deposited again. An especially good example of this process is the silica gel lamella in the upper right of Figure 7. It can be assumed, therefore, that a decisive part of the redeposited silica gel is not illuviated from overlying materials, but stems from rather adjacent opal and glass particles.

CLAYEY SOILS

The relatively high clay content of these horizons is marked even in the field. In thin sections, observed with plain polarized light, the clay appears as a bright yellow-brown mass. With crossed polarizers, birefringent streaks within the matrix and fringes around the grain surfaces as well as along shrinkage breaks stand out. These areas of orientated clay are most likely results of soil swelling and contraction, and the gliding and shearing movements caused thereby. Laminated clay cutans of illuviated clay were observed in the horizons 'd', 'f', and, most prominently, in

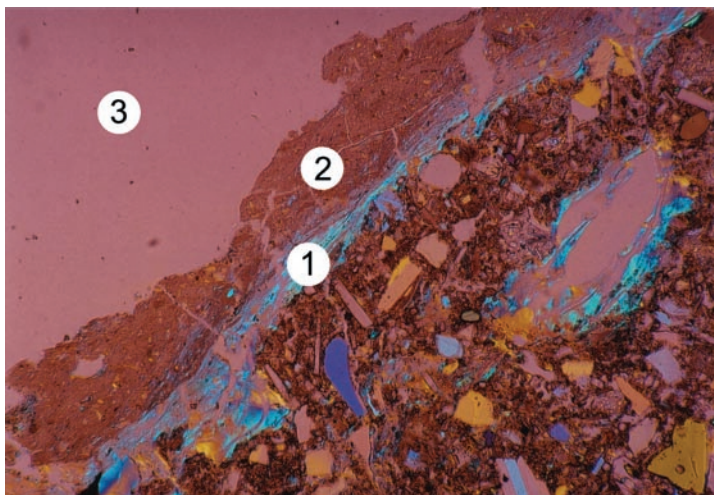


Figure 6. Toba with silica gel cover (layer 'g'). 1: Clay cutan; 2: precipitated silica gel; 3: fissure. Natural size 1.14 x 1.71 mm, crossed polarized light (XPL) + compensator.

'h', but not in the surface soil 'b'. Most likely, the current shrink–swell dynamics destroyed any possible clay cutans in 'b'. Microscopic comparison of more and less weathered spots in these clayey soils with toba sediments reveals that weathering affects not only the volcanic glass, but the opal particles as well. Although intense silica illuviation is present in the clayey soils (Miehlich, 1984; Poetsch and Arikas, 1997), on the other hand, microzones where clay is undoubtedly newly formed *in situ* and where almost all glass and opal particles have weathered away are also present. Additionally and among other minerals, microscopical silica gel crusts are formed, as well as submicroscopical clay–mineral/silica gel compounds, which closely resemble the described clay cutans chemically. Poetsch and Arikas (1997), in another context, point to the characteristically

wide $\text{SiO}_2/\text{Al}_2\text{O}_3$ molar ratio in clay cutans with submicroscopically admixed silica gel. One chosen example even features a molar ratio of 10.9. For a detailed description of thin sections of similar submicroscopical clay mineral/silica gel-compounds and their interpretation, see Altemüller (1997).

TEPETATE

Laterally adjacent to the profile described, several toba layers and soils have been eroded. Here, two Tepetates are extant, one in toba layer 'e', one in toba layer 'i' (see scheme in Figures 1 and 3). Compared to the tobas, they are much more indurated, whereas the microscopical impression given

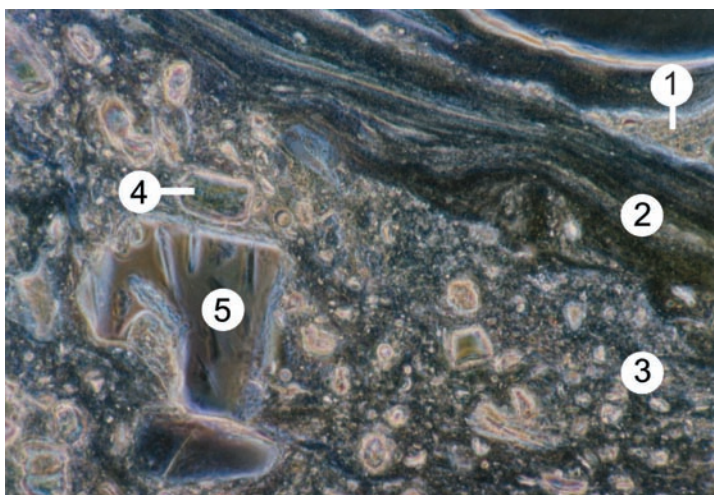


Figure 7. Toba with a laminated mix of clay cutans and silica gel (layer 'c'). 1: Precipitated silica gel; 2: clay cutans with interspersed silica gel; 3: zone with heavily weathered opals; 4: phytoopal; 5: volcanic glass. Natural size 0.14 x 0.2 mm phase-contrast.

by these Tepetates closely resembles the toba layers in the profile (Figure 7). As in the tobas, there are many fine to medium silt-sized opal fragments, clay cutans showing microlamination, pure silica lamellae, and mixed clay–silica compounds. Even the direct transition between the opal fragments and silica gel particles in the process of dissolving into the clay matrix can be found.

The exact conditions of Tepetate formation still require further research. It takes place close to the soil surface and is linked to the warm and dry local climatic conditions on the foot of a slope (Miehlich, 1984, p. 318). Further important preconditions for Tepetate formation are, most probably, an already high opal content in the parent material and the above mentioned relocation of silica, together with a pervasive distribution in the matrix. My observations show that the silica gel deposits, rather porous at first, compact into more stable masses. This process is probably linked to the combined processes of loss of water and beginning crystallization of the initially amorphous masses. In an extremely hard Tepetate from T₄ or T₅, Poetsch and Arikas (1997) were able to ascertain a very pure, compact, slightly birefracting silica gel cutan by means of a microprobe. Its anisotropic properties can be interpreted as a hint of beginning crystallization. The transformation from an amorphous to a crystalline state is reflected by increased induration.

CONCLUSIONS

In the toba layer T₂ of the thick pyroclastics-paleosol sequences in the Central Highlands of Mexico, silica is set free from opal and volcanic glass. In the deeper parts of the profile, silica is only partially washed out because of the lack of percolation. Another sizeable proportion of the dissolved silica is re-integrated into newly formed clay minerals, and, more important, silica gel formations. Only a small part of this silica originates from illuviation from overlying soil horizons; a more sizeable part is the result of *in-situ* weathering. It should be stressed that these results refer only to the stratigraphic unit T₂ and may not be applied to other stratigraphic units.

ACKNOWLEDGEMENTS

I am indebted to Dr. H.-J. Altemüller for his invaluable introduction into phase-contrast microscopy and for many academic discussions, to Priv.-Doz. R. Schallreuter for his help in identifying the silicoflagellates, and to Dr. W. Hachmann for the measurements with the microprobe.

REFERENCES

- Aeppli, H., 1973, Barroböden und Tepetate, Untersuchungen zur Bodenbildung in vulkanischen Aschen unter wechselfeuchtem, gemäßigttem Klima im zentralen Hochland von Mexiko: Giessen, Universität Giessen, Doctoral Thesis.
- Altemüller, H.-J., 1997, Polarisations- und Phasenkontrastmikroskopie mit dünnen Bodenschliffen: Stuttgart, Universität Hohenheim, Institut für Bodenkunde und Standortlehre, Hohenheimer Bodenkundliche Hefte, 40, 21–88.
- Hessmann, R., 1992, Untersuchungen verhärteter Vulkanaschböden (Tepetate) in den Becken von Mexico und Tlaxcala (Mexico): Paris, Giessen, Bericht für die Kommission der Europäischen Gemeinschaft.
- Hidalgo, C., 1995, Étude d'horizons indurés à comportement de fragipan, appelés «tepetates», dans les sols volcaniques de la vallée de Mexico: Nancy, Université Henri Poincaré, Unité de Formation et de Recherche en Sciences et Techniques de la Matière et des Procédés, Thèse de Doctorat en Pedologie.
- Miehlich, G., 1984, Chronosequenzen und anthropogene Veränderungen andesitischer Vulkanaschböden in drei Klimastufen eines randtropischen Gebirges (Sierra Nevada de Mexico): Hamburg, Universität Hamburg, Habilitationsschrift.
- Oleschko, K., Zebrowski, C., Quantin, P., Fedoroff, N., Osoro, E., 1994, Hardened volcanic soils (Tepetate) in Mexico; their geological, pedological or anthropological origin, in Transactions of the 15th World Congress of Soil Science, Acapulco, Mexico: Nairobi, Kenya, International Centre for Research in Agroforestry and International Society of Soil Science, Nairobi, Kenya, International Centre for Research in Agroforestry and International Society of Soil Science, 6a, 229–249.
- Pichler, H., Schmidt-Riegraf, C., 1993, Gesteinsbildende Minerale im Dünnschliff: Germany, Stuttgart, Enke.
- Poetsch, T., Arikas, K., 1997, The Micromorphological Appearance of Free Silica in some Soils of Volcanic Origin in Central Mexico, in Zebrowski, C., Quantin P., Trujillo G., (eds.), Suelos Volcánicos Endurecidos, III Simposio Internacional, Quito, diciembre 1996: Ecuador, Quito, Impresora Polar.
- Werner, G., 1988, Die Böden des Staates Tlaxcala im Zentralen Hochland von Mexico: Germany, Wiesbaden, Das Mexico-Projekt der Deutschen Forschungsgemeinschaft, F. Steiner.

Manuscript received: April 3, 2002

Corrected manuscript received: June 16, 2003

Manuscript accepted: June 23, 2003