Pine Root-induced Petrocalcic Horizons in Volcanis Ash Soils of the Mexican Altiplano

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Abstract

Scanning electron microscope (SEM) studies of calcareous encrusting in volcanic ash soils containing active and petrified roots of pine trees revealed that the calcified material is related to the fine root mat of the pine rhizosphere and particularly to a dense network of very thin biologic filaments of about 0.1 µm in diameter. These filaments are mostly covered with a gel-like sheath that increases their diameter to 0.5 µm. The diversity in morphology of the calcitic accretions, from fibers to rods with epitaxial growth of anhedral crystals, results from different stages in the calcification. In the first stage, freshly calcified filaments are semi-rigid and coated with gel-like products composed mainly of Ca, Al and Si. In the most advanced stages, secondary anhedral calcite crystals a few microns in size develop on the biologic structures and form an open network with the accumulated debris of calcified filaments. Amorphous silica, as a cementing agent, contributes to the hardening of this porous calcitic fabric. The most advanced stages of calcification are observed in soils below 30 to 50 years old pine trees, whereas 15 years old pine plantations display only filamentous and needle-fiber calcifications.

Keywords*: Calcite Deposits - Biogenic Structures - Volcanic Soils*

INTRODUCTION

Geologists and pedologists have long time ago recognized the diversity in morphology and spatial arrangement of calcite mineralizations in soils of arid and semi-arid regions. Calcite in arid soils, however, has generally been viewed as a geochemical process involving rapid evaporation of Ca-rich solutions throughout the largest pores of the soil (Jenny, 1941; Doner and Lynn, 1989; Verges *et al.*, 1982). Geochemical processes generally relay biological processes (Klappa, 1979). Numerous evidences of calcite mineralization by microorganisms indicate that biological processes may have played an important role in carbonate accumulation in soils of semi-arid to temperate regions. These observations resulted mainly from scanning electron microscop on pedogenic calcite encrustings. Clear similarities between fungal hyphae and filamentous calcite has been evidenced in modern soils of temperate regions (Callot *et al.*, 1985a and b). In calcite encrustings in soils of the New Mexico desert, fossilized calcified structures of *Microdium* bacteria colonies were found to be involved in calcite precipitation (Monger *et al.*, 1991). In calcareous paleosoils and calcretes from South Australia, hyphae filaments and rod-shaped bacteria have been indentified (Phillips *et al.*, 1987) and needle-fiber calcite has been determined to form within mycelial strands, as a product of metabolism (Phillips *et al.*, 1985b).

The formation of calcretes is however not well understood. In regards to the specific habit of calcite microcrystals on the mucilaginous sheath of hyphae filaments or on the cell of microbial colonies, it is supposed that calcite accretion is a response of micro and mesoorganisms to their highly calcareous environment, as a detoxification mecanism. But calcite encrustings are also observed in Ca-poor materials. The present study of carbonate concentrations in rhyolitic and dacitic volcanic ash soils is a new contribution in the comprehension of the global mechanism of biological Ca-transfer and -accumulation in soils.

MATERIALS AND METHODS

Location and environment

The study area is on the western leeside of the Cofre de Perote volcano (4,250 m), a complex andesitic strato-volcano on the eastern edge of the central altiplano, Veracruz State, Mexico. The site is along the track from Perote to Escobillo, at 4 kms from Perote. Altitude is 2,700 m, corresponding to the piedmont of the volcano. Climate is temperate semi-arid, with annual precipitations of 500 mm. The dry season lasts for 6 to 7 months and the average annual temperature is 12°C.

Parent materials of soils are unconsolidated ashes of rhyolitic composition, in which SiO_2 represents more than 78% of the whole anhydrous material. The upper deposit is a dacitic ash of late Pleistocene age, discordant upon a rhyolitic pumice fall deposit of middle Pleistocene (240,000 y. B.P.). These deposits overlie a thick rhyolitic ash flow of early Pleistocene age (460,000 y. B.P.).

Soils are of loamy sand texture, rich in glass and pumice fragments and poor in clay, only 5 to 17%. Andic properties due to the existence of allophane are very weak or absent. pH is slightly acid (6.5) near the soil surface and reaches 8.3 in the calcic horizons. They are classified as Vitrandic Ustorthent (Soil Survey Staff, 1990).

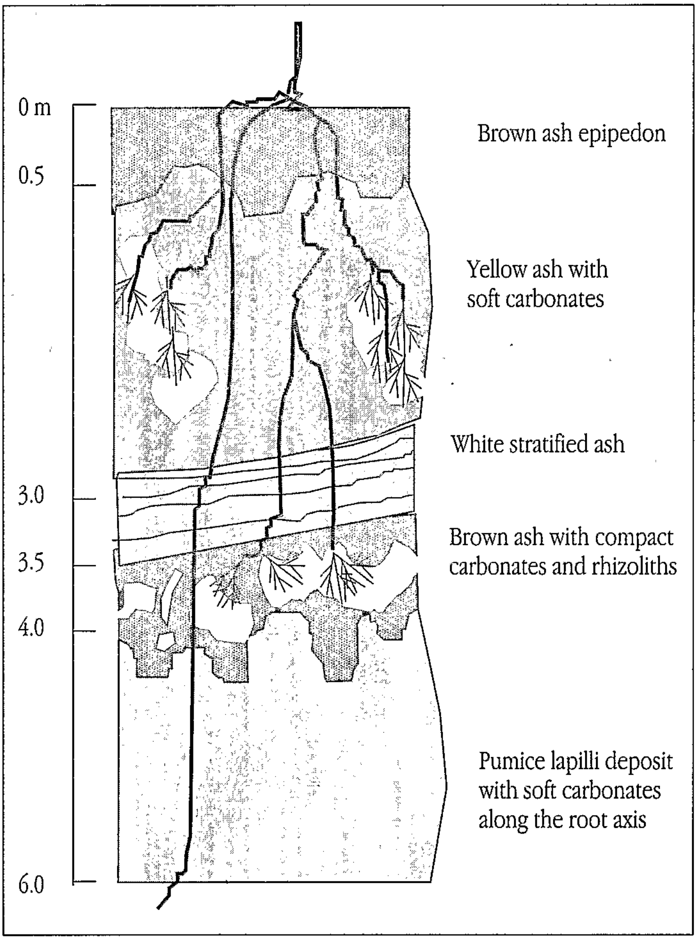
Vegetation is a small wood predominantly of pine trees. Among the 30 y. and older Pinus and Alnus trees there is a 15 y. old plantation of pure *Pinus montezumae* trees.

Soil profile and pine roots distribution

Profile description:

- 0 to 0.5 m - Pale brown, fine sand texture, reworked ash mixed with small pumice lapilli. NaF test: very weak. Clear and wavy transition.
- 0.5 to 3.0 m - Yellowish brown (10YR5/4), loamy sand texture with altered pumice lapilli, friable, whitish carbonate coatings on the walls of vertical cracks and around the fine root hairs of pine tree. Clear transition.
- 3.0 to 3.5 m - White ash of fine sand texture with beds of fine pumice lapilli. Neither secondary carbonates nor fine pine roots. Abrupt transition.
- 3.5 to 4.0 m - Brownish yellow (10YR6/6), firm when air-dried, brittle when wet. Compact ash of sandy loam texture with frequent weathered pumice lapilli. Abundant carbonate encrustings into vertical cracks and around the fine root hairs of pine trees. Several fossilized carbonated roots (rhizoliths) are visible. Clear and wavy transition.
- 4.0 to 6 m - Unconsolidated pumice fall deposit of coarse (1 to 4 cm) rounded lapilli. Soft powdery lime is deposited around the pine root axis and within the cavities of the weathered lapilli.

The profile is polygenic. The bottom layer of coarse pumice lapilli has been successively weathered into a pale brown soil and covered by a white ash containing fine pumice lapilli, itself weathered at turn into a pale yellow soil. Direct observation of the root system of pine trees in the profile shows clearly that the fine root hairs establish themselves only into the weathered soil horizons whereas unweathered ash layers or lapilli deposits are only crossed throughout by tap roots and main roots (Fig. 1). The soft powdery lime deposits are found close to the active root hairs of pine trees. Unlike pine trees, other species such as *Alnus* and *Cupressus* do not show any secondary carbonates close to their fine root system.



Sample collection and analytical methods

Taking advantage from a landslide of unconsolidated ash material due to recent erosion, sampling has been executed in vertical profiles beneath the pine trees. Undisturbed and oriented soil samples were collected (a) from the soft carbonate deposits in contact with root hairs of young pine trees in the 0.5 to 3.0 m horizon (samples COF752., COF753 and COF 756, COF 757), (b) from the soft carbonate deposits in contact with root hairs of old pine trees in the 0.5 to 3.0 m horizon (sample COF761), (c) from carbonate encrustings in contact with roots of old pine trees in the brown 3.5 to 4.0 m horizon (sample COF 762), (d) from powdery carbonate deposits on weathered pumice lapilli in the 4.0 m to 6.0 m horizon, (e) from rhizoliths in the 3.5 to 4.0 m horizon (sample COF 763). Samples were picked from fresh soil material during the end of the dry season in april of 1995 and preserved from evaporation in sealed plastic boxes until microscope observation.

Small fragments of these samples were previously mounted on aluminium plates and spray coated with gold before observation under a Cambridge Stereoscan 200 scanning electron microscope equipped with an energy dispersive X-ray (EDX) microanalyser providing spectra of the chemical composition. The spectra include the major elements except for C, H, O and N which are not reported by the microanalyser. Additional thin soil sections were cut in the samples for observation under optical microscope.

RESULTS

SEM studies provide convincing evidence on the intense biological activity in pores, fissures and channels occupied by fine pine roots. The filamentous structures observed in the neighbourhood of root hairs are organised into a network of interconnected hyphae of very small diameter about 0.1 µm each, around a central strand composed of several coaxial filamentous units with several branching divisions (photo 1). The kind of the filaments organization, the very small diameter of individual hyphae and the ornamented spores grouped in spiral-like chains (photo 2) suggest that they are not fungi but Ascomycetes (*Streptomyces sp.*) or probably various associated species including filamentous bacteria.

Photo 1
General aspect of the calcitic fabric composed of elongatred rods about 1 µm in diameter and interconnected very thin hyphae, about 0.1 µm in diameter

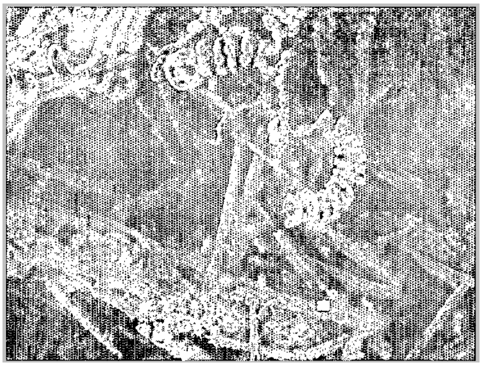


Photo 2
Some filament bear spores groupes in spiral-like chains which are characteristic of the *Streptomyces* group in Ascomycetes

1. The progressive calcification of individual filaments

Active bodies are sinuous filaments of 0.1 µm in diameter. Decaying bodies become straighter but still flexible. The filament surface is covered with a gel-like product displaying a longitudial groove that increases the filament diameter to 0.5 µm (photo 3). Except for C, H, O and N which are not determined, the chemical composition is essentially made of Ca, Si, Al with minor quantities of K and Mg (Fig. 2, microanal. S2P8). In more advanced stages of decay the filament is rigid. The mucilaginous sheath increases in diameter to about 1 µm and becomes roughly covered with small coalesent humps (photo 4). It is parted by a wide-opened longitudinal groove (photo 5). The chemical composition is predominantly Ca, with a minor quantity of Si (Fig. 2, microanal. S4P7). These observations confirm that Ca is concentrated in the mucilaginous sheath of the hypha, as an exudate. This ability of fungi, Ascomycetes, and other soil microorganisms like bacteria, to concentrate Ca on their external surface has been widely observed in soils (Klappa, 1979; Phillips and Self, 1987) and experimented in laboratory conditions (Callot, 1985; Monger *et al.*, 1991).

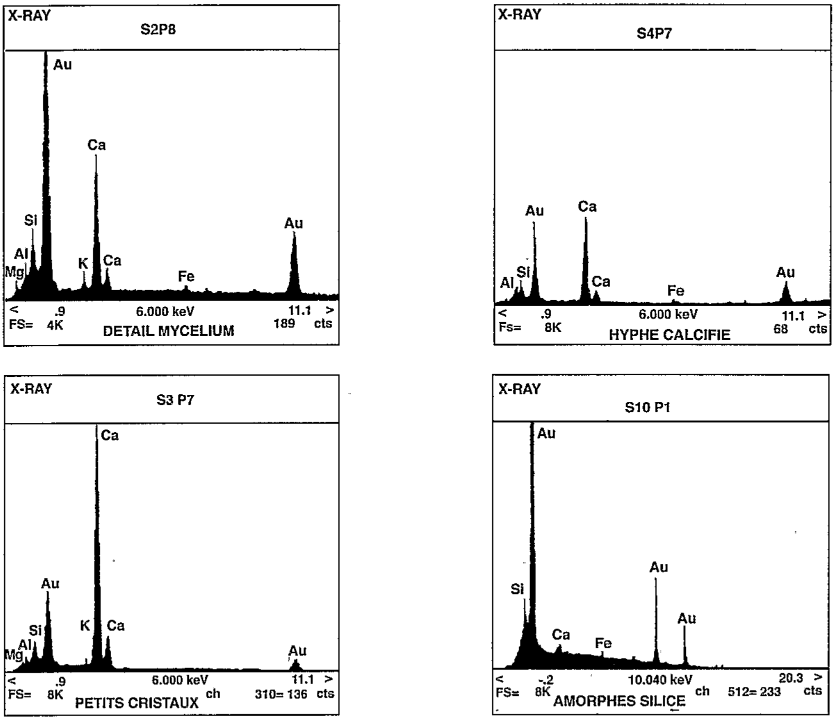


Fig. 2 - Diagrams of the chemical composition of various samples
The peak of gold results from the sputter coating on the sample
Upper left: Chemical composition of a gel-like sheath. **Upper right**: Chemical composition of a rigid sheath.
Lower left: Composition of small rhomboedric cristals. **Lower right**: Composition of an amorphous silica deposit on the calcified fragments.

2. Secondary calcite crystal growth on the biogenic calcified filaments

SEM observations on the calcitic encrusting from the buried B-horizon within soil depths of 4 to 4.5 m. show that they are almost constituted of randomly packed fragments of calcified filaments encrusted by secondary calcite rhomboedrons (photo 6). They develop on the surface of the calcified filament by epitaxial growth (photo 7). These calcite crystallizations are chemically different from the biological calcitisations. They are composed of almost pure calcium carbonate (Fig.2, microanal. S3P7). Unlike fiber calcite crystals, normal rhomboedric calcite crystals preferentially grow slowly in low concentrated solution. Rhomboedric calcite crystals are found only in the compact buried B-horizon, where solutions of low Ca concentration percolate slowly through the soil and the biogenic fragments.

Conversely, in the pumice lapilli deposit, a rapid drainage and an abundant porosity prevail, offering good conditions for evaporation and subsequent concentration of the solutions. In such material secondary needles of calcite can develop on the pore walls (photo 8) or between the calcified biologic filaments (photo 9).

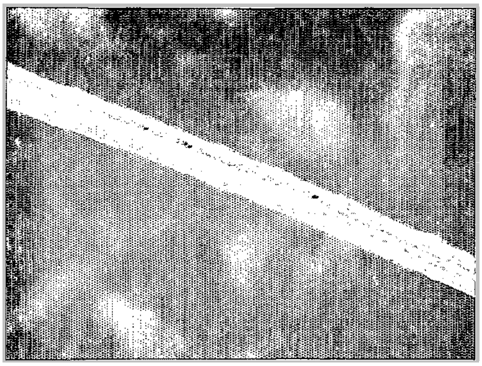


Photo 3
Detail of a still flexible filament with its gel-like sheath

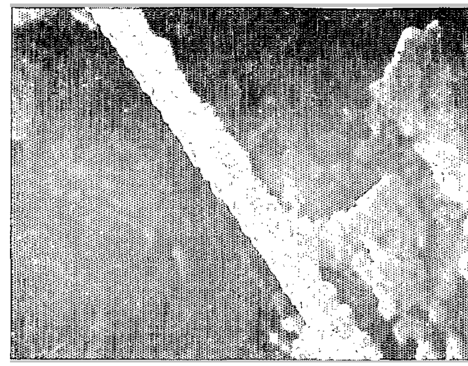


Photo 4
Detail of the rigid sheat of the filament with its rough surface and longitudinal groove

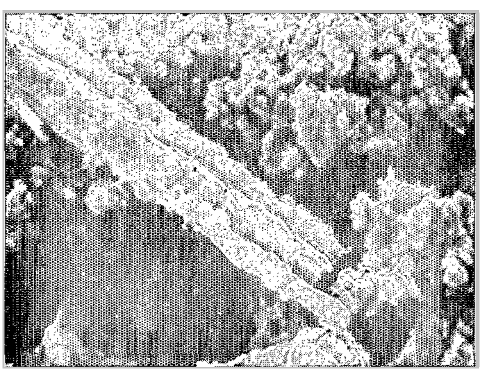


Photo 5
Detail of a petrified filament with a wide-opened longitudinal groove and a very rough surface

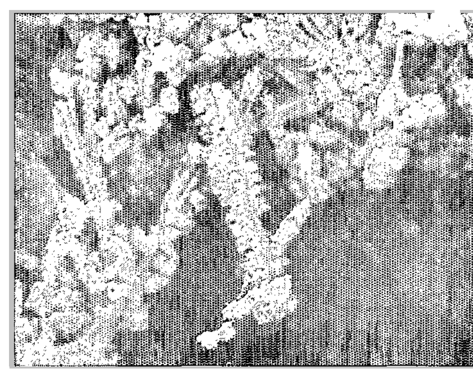


Photo 6
Secondary rhomboedric calcite crystals growing on a petrified biological fragment

3. Secondary silicification in porous biogenic calcifications

Fissures and channels in the fine ash deposits are preferential sites for fine root activity and biogenic calcitisations. Around root hairs of old pine trees, within depths of 0.5 to 3.5 m (sample COF 761), thin silica gel coatings are observed on the rod-like fragments of calcified filaments (photo 10). The shape of these products suggest a natural precipitation of Si-rich solutions. Spherules of 0.1 to 0.5 µm in diameter are visible on the surface of amorphous products, suggesting the in situ condensation of silica gels into silica lepispheres. Microanalysis spectra display a bulge of the baseline indicating abundant amorphous products and a high predominance of Si (Fig.2, microanal. S10P1). The precipitation of silica gels attests to an incipient cementation process leading, sooner or later, to the induration of the biogenic calcitic encrustings, if the actual conditions are still favourable for pine growth and rapid percolation of soil water.

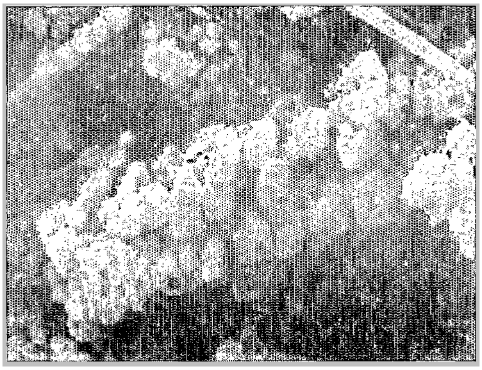


Photo 7
Detail of the rhomboedric calcite crystals growing on a petrified biological fragment

Photo 8
Detail of fine root inside a pumice fragment with secondary needle-fiber calcite growing perpendicularly to the pore wall

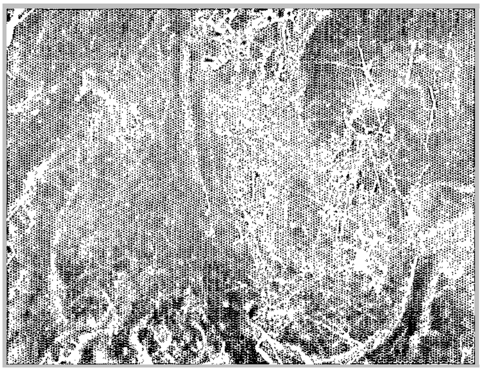


Photo 9
Aspect of biological filaments intercrossed with secondary needle fiber calcite inside a pumice lapilli

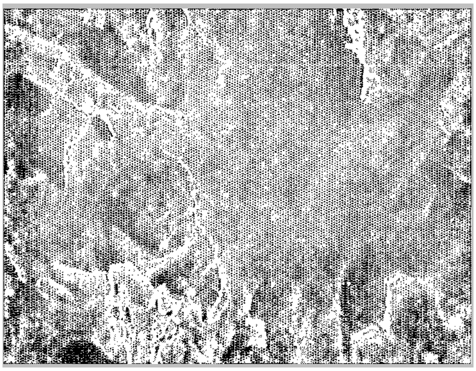


Photo 10
Detail of a silica gel coating on calcified filaments
Note the small silica spherules at the surface of the gel.

4. Secondary calcification and silicification in rhizoliths

Rhizoliths are organo-sedimentary cylindrical structures made by plant roots within permeable host sediments in regions of water deficiency (Klappa, 1980). Significance has been attached to them because they provide evidence of past vegetation and are good paleoenvironmental indicators. In the soil profile of the present study, rhizoliths are root moulds of 2 to 3 cm in diameter, which mark the position of now decayed roots. These roots probably belong to the vegetation of the paleosoil actually buried. Present and past calcitizations have fossilized the structure of the root, and they are a good example of advanced stages of pedo-biogenic induration. The internal root structure is no more discernible and the volume is occupied by a very porous material composed of residual fragments of calcified filaments cemented by a secondary micritic fabric and silica spherules

0.5 to 1 µm in size (photo 11). The shape and size of the spherules suggest that they result of the condensation of silica gels (photo 12). Nevertheless, in the internal cavities of the indurated material, many filamentous bodies are still active and grow together with few sinuous individual fungal hyphae.

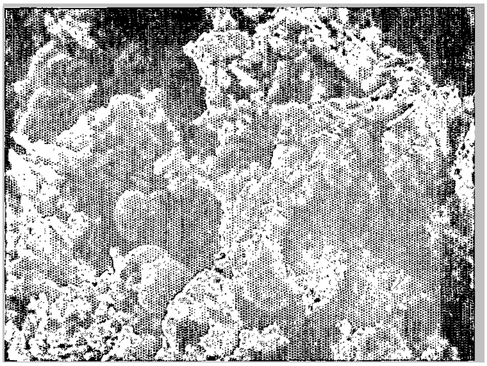


Photo 11
The silica lephispheres result from the condensation of silica gels and lead to a strong cementation of the calcified fragments

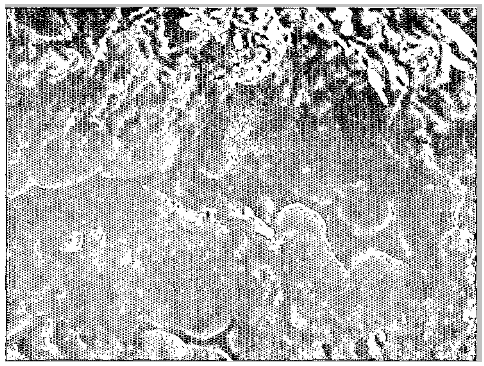


Photo 12
Detail of a silica in process of condensation into silica lepispheres

INTERPRETATION AND CONCLUSION

The fine pine roots observed in the studied soil profiles do not exhibit specific ectomycorrhyzae. The root surface is only crossed by few individual sinuous filaments about 1µm in diameter, probably of fungal origin. The thin filamentous bodies responsible for the carbonate deposits are not in close contact with the root surface. They are located in the neighbourhood of the fine pine roots, filling the macrovoids and the fissures of the soil.

Direct observation of different stages in the filament growth has shown that the mucilaginous sheath produced by the filament evolves into a calcified sheath with a longitudinal groove. The rigid sheath usually breaks down into small rods which accumulate around the central strand of the mycelium, leading to the formation, after a certain period of time, of a white deposit currently named soft powdery lime. Several observations show that enclosed individual hyphae are partially liberated when the rigid sheath is wide-opened and breaks down. But in other examples a thin filament can be observed growing from an extremity of the broken calcified sheaths. This suggests that the enclosed filament is able to endure long periods of latency and to reduce its axial growth during renewed wet conditions. Successive sheath formation and dissemination by breaking down are thus a specific aspect of the normal metabolism of the active filamentous bodies found in the pine tree rhizosphere.

The biogenic material resulting in filaments formation is a network of randomly accumulated calcitic rods and this type of fabric usually has a very abundant porosity, which facilitates a rapid water percolation and aerobiotic conditions. Secondary inorganic processes may occur in this material. The first occurre as silica gel deposits. They are observed in the soft carbonate deposits bonded on the root hairs of 15 y. old pine trees. The second products are calcitic accretions of rhomboedric crystals and anhedral micrite, in intergrowth with the calcitic rods and infillings between the rods. This secondary phase of micritization as acicular calcitic fabrics in soils of the Mexican altiplano has also been observed as responsible for the present induration of one type of *tepetate* soils (Feodoroff *et al.*, 1994). In the profile under study, secondary calcitizations are observed in more compact horizons with fine pores and around 30 y. and older pine trees roots. In such materials silica is also relatively abundant and in solid state. Silica particles have an aspect of agglomerated spherules, each one of 0.5 to 1 μm in diameter, resulting from the progressive condensation of gels. Together with the calcitic accretions they play the role of cement, increasing considerably the compactness of the biogenic material.

Pine trees are key players in the formation of carbonate-rich horizons in volcanic ash soils of rhyolitic and dacitic composition in semi-arid regions. Conspicuous accumulations are formed under 15 y. old pine plantations and the cohesion and hardening of the calcitic horizons may have occured before 30 y. old pine trees. Secondary silica precipitations and calcitic accretions are mainly responsible for the hardening of carbonate-rich horizons. The result is the formation of a semi impervious horizon retaining the vertical water percolation of the water, which is normally very rapid through ashy and pumitic materials.

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