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Restoration of degraded volcanic soils. Experience with the Tepetates and REVOLSO Projects¶

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INTRODUCTION

The surface degradation of the earth is a phenomenon that has worsened in recent times. In order to counteract this deterioration, preservation and recovery programs are developed and promoted by international organizations, government agencies, and civil society groups organized to create a healthier environment.

In this context and under the economic support of the European Union (EU), a group of scientists of various Latin American and European countries has joined efforts to study the nature of the degradation occurring in volcanic soils in the highlands and piedmonts of America and to design possible solutions to counteract its effects. Three major projects characterize these efforts. The first project, "Study of the hardened volcanic soils *tepetates* in the valleys of Mexico and Tlaxcala", focusing mainly on agricultural rehabilitation, was carried out in Mexico from 1989 to 1992. French researchers of the former ORSTOM (today Institut de Recherche pour le Développement, IRD) from France participated in this project, as well as German scientists of the Justus von Liebig University of Giessen (UG) and Mexican scientists of the Colegio de Postgraduados

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** Dr. Quantin is presently retired from the IRD and Dr. Zebrowski is deceased*

(CP) and the Autonomous University of Tlaxcala (UAT). This project allowed us to: (1) learn more about the characteristics, distribution, origin and formation of the different types of *tepetates* in Central Mexico; (2) learn about *tepetates* characteristics and their response to habilitation for agricultural purposes in the short-term, and (3) to study the agronomic and socio-economic factors related to their rehabilitation (Quantin, 1992).

The second project lasted from 1994 to 1997 and had similar objectives to the former, but two new volcanic materials one from Ecuador (*cangahua)* and other from southern Chile were incorporated for testing. The research initiated in Mexico during the first program continued, though more importance was given during this second period to the studies related to erosion control and conserving the areas with *tepetates*.

The third project is presently underway. It is named Recuperation of Volcanic Soils (REVOLSO) and operates in Mexico and Chile. In addition to scientists from latter mentioned countries, institutions from France, Germany, Italy and Spain participate in this third project. Particular mention should be made of the participation of social scientists in the latter phase of this series of studies, which are focused on the gender and sustainable management of degraded volcanic soils.

In the present paper, emphasis will be placed on the experiences and results obtained in the restoration of the fragipan type *tepetates* in the valleys of the Mexico and Tlaxcala states.

The interest to study the *tepetates* of the valleys of Mexico and Tlaxcala is related to social, economic and scientific aspects. First, there is an urgent need for new agricultural land to feed the peasants of an area with a high population density and precarious economy in order to prevent social unrest. The habilitation of certain types of *tepetates* in this area is deeply rooted in historical times well before the Spaniards conquered the continent (Hernández, 1987). However, to help in this endeavour using modern techniques it was necessary first to understand the distribution, characteristics and behavior of *tepetates* in order to set strategies tending to a sound rehabilitation for agronomic and forest use.

The term *tepetate* it is not a well defined one. *Tepetate* is a vernacular word coming from "tepetlatl" ("tetl"=stone and "petatl"=bed) in nahuatl (the native language of the aztecs), *i. e.* "bed of stone" (Williams, 1992). Currently, the term is commonly used in non-scientific language to refer to any layer of hard material present in the soil. It is not possible to apply a general definition to all types of *tepetates*. *Tepetates* come from tuffs, pyroclastic flows, cemented layers, and similar materials. If a soil layer fulfills the requirements to be classified as duripan, fragipan, calcrete, silcrete, etc., it should not be classified as *tepetate*.

A full account of the results obtained in the first and second project are found in the following works: 1st International Symposium "Hardened Volcanic Soils", Mexico, Terra 10 (special number, 1992); Terra 11 (special number, 1993); volumes 6a and 6b of "Transactions of the 15th World Congress of Soil Science" (ISSS, 1994), and the books "Suelos Volcánicos Endurecidos" (Zebrowsi et al., 1997), "Aptitud productiva en suelos volcánicos endurecidos (tepetates)" (Navarro et al., (1998), "Uso y manejo de los tepetates para el desarrollo rural" (Ruiz, 1987). Morphological and classification studies were conducted in the valley of Puebla-Tlaxcala by a group of German researchers (Miehlich, 1991; Werner, 1988; Werner, 1992).

The formation of young human resources on this particular subject is an interesting aspect resulting from all these projects. Theses and dissertations conducted in association or independently of the projects in both the Universidad Nacional Autónoma de México and the Colegio de Postgraduados have been developed. A large number of publications (many of them used as references for the preparation of the present work) were written, as well as national and international scientific events, scientific exchanges organized and particularly a true sense of the cooperation was rescued.

The Study of Hardened Volcanic Horizons and Surface Materials in Mexico Highlands

General characteristics. The hardened horizons derived from volcanic materials (they are not soils in strict terms) have different names depending on the country in which they are found. In Mexico they are called *"tepetates"* (Williams, 1992), *"talpetates"* in Nicaragua (Prat, 1991), *"cangahua"* in Ecuador (Vera and López, 1992), *"sillares"* in Perú (Nimlos and Zamora, 1992) and *"fierrillo"* in Chile (Luzio *et al.*, 1992; Luzio and Palma, 1994).

From a pure scientific point of view *tepetates* are understood today as an underground or surface horizon or whole profiles of hardened volcanic material and not as soils. Hardening is the consequence of both geological and pedological processes. The first one occurs at forming time and the latter along the years after the parent material has been deposited on the earth surface. There is no certainty on how many types of *tepetate* exist in Mexico. In the Neovolcanic Axe of mexican Highlands alone several types have been reported which are different in their nature and genesis. An inventory made by Zebrowski *et al.* (1991) points out that *tepetates*, without mentioning their type, covered by then a surface of 30 700 km^2 (27% of the surface). The area in which these *tepetates* are located is between 19°10' and 19°40' latitude North and 98°10' and 98°55' longitude West. Ortiz and Gutiérrez (1994) defined the tepetates as "C" horizons, that is, horizons which are generally mineral, little affected by pedogenetic processes, but according to Bertaux and Quantin (1993) and Hidalgo (1996), these materials will correspond to an intermediate state of alteration of a vitric rhyolitic tuff, the parent material.

Some *tepetates* are found to be hard when either dry or wet, while others are soft when wet but hard when dry. The latter is called *tepetate* of the fragipan type. Most surface exposed *tepetates* are the consequence of severe erosion and land degradation, which is the third cause of concern of the project. Erosion is a problem in most areas where the *tepetates* are dominant materials. By historical reasons, Mexican farmers also call *tepetates* those soils containing hardened horizons in the surface. The use of the term in this sense causes certain confusion. The above arguments show the agronomic, social and economic importance of studying these materials to prevent the advance of desertification in areas in which they are dominant.

The fragipan type *tepetates* appear in different positions in the physiographic environment characterized by the presence of foothills and "glacis" in the eastern and western slopes of the Sierra Nevada. Nevertheless their characteristics are different in terms of their topographic position.

One characteristic considered in naming the *tepetates* of Mexico and Tlaxcala was their stratigraphic position, which is associated to three series of volcanic material deposits (T_1, T_2, T_3) present in the area, which were studied and dated (between 10 000 to 40 000 years ago) by Miehlich (1991). The *tepetates* of the State of Mexico (Sierra Nevada) were classified by Peña and Zebrowski (1992) in accordance with two criteria:

the stratigraphic series (T_1, T_2, T_3) to which they belong and their consistency (similar to fragipans or petrocalcic horizons). For this reason, the classification developed makes reference to the fragipan type *tepetates* t_1, t_2 and t_3. Most of the *tepetates* located in foothills of the Sierra Nevada are similar to fragipans, but do not have all the characteristics included in the Soil Taxonomy (Soil Survey Staff, 1994) to be classified as such, reason for which they were called "*tepetates* of the fragipan type or with a similar behavior". In the "glacis", located further down foothills, *tepetates* show calcareous coatings and are more like petrocalcic horizons (Gutiérrez and Ortiz, 1992).

Physical properties. The most outstanding physical properties of the fragipan type *tepetates* are: an average bulk density of 1.45 Mg m^{-3}; total porosity above or equal to 40%, with a macroporosity often below 5%; a hydraulic conductivity of 0.3 to 0.5 mm $hour^{-1}$; a hardness to dry penetration below 20 kg cm^{-2} (Quantin, 1992), material that expands and gets cooler when humid and disintegrates when it is sunk in water; texture from sandy-clay-loam to silty-clay-loam (with more than 25% clay). The physical properties, especially hardness and the low values of macroporosity, are serious limitations to farming (root development, water penetration) and favor surface erosion.

Chemical properties. The fragipan type *tepetates* are rich in bases, among which calcium, magnesium and potassium prevail (in that order); these elements come from a mineral fraction rich in volcanic glasses and plagioclases highly susceptible to pedogenetic alteration. The cation exchange capacity is high, from 20 to 40 cmol kg^{-1} of fine earth, due to the abundance of 2:1 clays and has high percentages of base saturation. The pH is slightly alkaline, from 7.3 to 8.2, because of the presence of carbonates. These materials contain low percentage of organic carbon (0.2-0.7%), total nitrogen (0.04-0.07%) and phosphorus soluble in sodium bicarbonate (<3ppm), which is one of its major chemical problems. These characteristics of the fragipan type *tepetates* result in low fertility, so it is necessary to improve it before their rehabilitation for agricultural-forest use.

Mineralogical properties. The material of origin of the fragipan type *tepetates* is made up mainly of alkaline rhyolitic glasses, and of plagioclases, amphiboles and pyroxenes of different sizes. Secondary minerals correspond to a mixture of clays of the 1:1 and 2:1 types, often interstratified with a 2:1 strong component of the beidellita type. Clays are very well oriented which favors the cohesion of the fragipan type *tepetates* and strengthens the compact nature of their matrix. These materials present "free" non-crystalline silica, accumulation of iron and manganese oxides, occasionally calcite and only traces of allophane. Mineralogical properties explain the behavior and characteristics of these materials only partly.

Agronomic habilitation. Experimental plots were set up in the field to study the agronomic evolution of the fragipan type *tepetates* which had been recovered through different treatments. *Tepetates* of the stratigraphic series T_2 andT3 were used. In all the cases, the *tepetate* was broken up in small fragments to 40 cm deep with a bulldozer provided with a ripper and tilled before cultivation. The tilled *tepetate* was subjected to different types of management to measure the impact of these management practices in their agronomic rehabilitation. Previously to the amelioration samples from the plots had been subjected to a series of laboratory and greenhouse experiments to study their chemical fertility. The crop treatments assayed were different crops, associations and rotations, whose behavior was evaluated one to more years later after tillage. Different fertilizer sources and rates were evaluated, both organic (green fertilizers, manure) and minerals (inorganic fertilizers) and mixtures of both. Also biological practices were used, like the incorporation of legumes to evaluate its benefits.

The rehabilitation of the fragipan type *tepetate* begins with a deep tilling by crossed subsoiling made with a bulldozer. In Tlaxcala, the D5 and D7 models were employed, with rippers 80 cm long. The tilled layer was 40 to 50 cm deep. Subsoiling is preferably done when the *tepetate* is dry because it is then when the fracturing of hard horizons is more complete than under humid conditions (though this task is easier when it is humid) (Zebrowski and Sánchez, 1997). Later on, a size reduction of the fragments caused by subsoiling is carried out, until an optimum size of these is obtained, of 3 to 4 mm (Martínez and García, 1990) or a little bigger (Leroux and Janeau, 1997). The size control of fragments is important to prevent the smallest particles from crumbling, as they can form fine layers and favor surface hardening, surface flow and erosion (Zebrowski and Sánchez, 1997).

The agronomic rehabilitation process of the fragipan type *tepetates* is a long one because it implies the handling of a set of factors that cannot be incorporated and evaluated at the same time. First, the *tepetate* must be tilled, as pointed out before. Then it is necessary to improve its physical, chemical and biological characteristics, and therefore its fertility through tilling and by adding manure and fertilizers, as well as green fertilizers and the incorporation of microorganisms and mesofauna (Ruiz, 1987; Zebrowski, 1992; Ferrera-Cerrato, 1992; Ferrera-Cerrato *et al.*, 1997).

After 5 to 10 years of cultivation, the fragipan type *tepetate* improves its fertility level to that comparable to the soil, that is, it contains a similar amount of organic matter, total nitrogen, labile phosphorus, as well as water available for crops, but rapidly becomes productive, a process that takes only between 3 and 5 years. The pH, which is initially slightly alkaline in most cases, diminished a little. However, physical properties did not show great improvement after this period of time. On the contrary, macroporosity diminished, so sometimes it is necessary to carry out a new subsoiling after 5 years of the first tilling and first crop.

In the long-term analysis, it may be stated that a good production of maize, wheat, beans, broad beans and barley can be obtained when nitrogen and phosphorus (organic and/or mineral) are used as fertilizers, and a seedbed was prepared, with fragments of tilled *tepetate* of an optimum size of the aggregate of 3 to 5 mm..

The crop selected as the first after breaking up the *tepetate* is an important decision. It was observed that maize and beans did not have good yields the first years after amelioration. In contrast broad beans perform well, regardless of the type of fertilizer and preparation used. This behavior was attributed to biological factors. The production of maize, beans and broad beans was considered to reach a medium level only after the third year of cropping, and only in the fifth year it was rated as good.

To set up these crops (as well as others mentioned before) it was necessary to improve the chemical fertility of the *tepetates* of the fragipan type. Preliminary trials carried out in pots showed that nitrogen and phosphorus were the main factors limiting the fertility of these *tepetates*. The low content of total phosphorus was associated to low levels of this element in the material of origin. Unlike nitrogen and phosphorus, potassium reserves were high and lead to the assumption that they can provide exchangeable potassium for several years without having to make additions of this element. In contrast, the first two elements, nitrogen and phosphorus, must be added in amounts enough to reach the levels compatible with cultivation requirements (Etchevers, 1997; Etchevers *et al.*, 1992).

Field trials showed that with an application of 80 to 120 kg ha^{-1} of mineral nitrogen and 60 kg ha^{-1} of phosphorus, between 2 to 4 Mg ha^{-1} of wheat or barley can be obtained. These yields are equal to or even higher than that obtained in a regular agricultural soil. In the case of maize and beans fertilized with the same amount of fertilizers, the production obtained was of 2 to 3 Mg ha^{-1}, rated as acceptable given the conditions of the environment, but these yields were to be reached only in the second or third year after habilitation (Márquez *et al.*, 1992; Navarro and Zebrowski, 1992). The use of organic fertilization with a phosphorus fertilizer (40 Mg ha^{-1} of farm yard manure + 60 units of P) without adding inorganic nitrogen, improved the production of wheat and barley (6 Mg ha^{-1}) since the first year, but not that of maize.

The development of a good root system contributed to having an adequate crop yield in the recovered *tepetates* of the fragipan type. The root growth capacity of legumes like broad beans, ayocote beans and common beans, which form nodules with Rhizobium, depends on the depth of the tilling of the recovered horizon and of the size and abundance of the fragments resulting from it. Beans showed the lowest root density but it was the second most important crop regarding the contribution of residual root organic matter (1905 kg ha^{-1} to 40 cm deep), which was associated to the greater thickness of its roots. The maize/broad bean association produced the largest root biomass, which favored the development of larger pores. The largest contribution of root residue occurred at a depth of 0 to 10 cm (1118 kg ha^{-1}); and at 0 to 50 cm deep, which was of 2963 kg ha^{-1}. In both cases, the length of roots was not very different. Barley showed a high homogeneity in its root distribution within the profile, but a lower contribution of root biomass (1278 kg ha^{-1} at 0 to 50 cm deep). The type of tillage also had an influence in the development of roots, and these in the nutrition of crops. Minimum tillage favored the homogeneous distribution of roots within the horizons, whereas in traditional tilling, the distribution of the root mass was heterogeneous, which could have caused an inter-root competition, due to the impoverishment of soil nutrients.

Tillage practices were also related to the volume of the organic matter contribution, which is important to improve the structure and water holding capacity, as well as the physical and chemical properties of the recovered *tepetates*. Minimum tillage without a cover crop and conventional tillage differed substantially in organic matter contribution. In minimum tilling treatments, without a cover, roots were longer, but with a smaller diameter, probably because its production was limited as a result of soil compactness. In contrast, in minimum tillage with a cover crop roots contributed large amounts of organic matter, especially in the first horizons (0-10 cm).

Though the benefits of minimum tillage are recognized in the case of the recovered fragipan type *tepetates*, conventional tillage proved to be more efficient to endure the environmental stress caused by the lack of water during the period of germination and the middle summer drought, as well as strong winds. If reduced tillage wants to be introduced in maize cultivated in ameliorated *tepetates*, it is necessary to use varieties with a greater resistance to tilting (reduced height, high resistance of roots to traction forces, deep rooting).

The rehabilitation of fragipan type *tepetates* allows peasants and small farmers to have access to a larger agricultural soil surface, and also provides means of subsistence to them so that they can stay in their places of origin. This practice of rehabilitation also allows to recover desert zones, and reduce the erosion process, which is quite extended in the Mexican high plateau.

In the plots with *tepetates* of the fragipan type lying on the surface, the loss of materials amounts to 30 Mg ha^{-1}, which could be reduced if adequate tillage systems are applied. In rehabilitated *tepetate* plots managed with reduced tillage without plant cover, the soil loss registered was of 3.7 and 7.3 Mg ha^{-1}, much smaller than in bare plots with surface *tepetate*, but larger than in the *tepetate* with reduced tillage with vegetal cover or conventional tillage. These differences were due to the water height of the affluent, which was two or three times larger in reduced tillage without plant cover than in the last two cases (reduced tillage with plant cover and conventional tillage). These results show the favorable effect of keeping a plant cover in the recovered *tepetates* and the use of an adequate management practice. Under these circumstances, in the case of a plot of *tepetate* managed with reduced tillage and plant cover, the erosion rate dropped 1.5 to 3.9 Mg ha^{-1}, lower to that obtained with conventional tilling (3 to 5 Mg ha^{-1}).

The habilitation of the fragipan type *tepetates* through tillage, use of fertilizers and various cultural practices (tillage systems, addition of straw and manure, incorporation of residues, use of different crops and rotations) modified the structure of the *tepetate*. In Tlaxcala, for example, when tillage and a plant cover were combined, more stable aggregates were observed (at the first 5 cm deep) as compared to other tillage systems assayed. Aggregate stability was also affected by the years gone by since habilitation. In younger plots the stability of aggregates and fragments was higher, probably due to the fact that the numerous fragments of the hard *tepetate* preserved their stability. However, no changes were observed in water infiltration and porosity as a result of the age of rehabilitation. The *tepetate* treated with reduced tillage showed the trend of reducing its medium-sized pores, but hydraulic conductivity and apparent density did not vary after tillage.

From the experiences acquired by the researchers participating in this program and the practices conventionally used by farmers, the following agronomic management for the rehabilitation of the *tepetates* of the fragipan type is proposed:

(a) The *tepetate* layer must be ruptured at a minimum depth of 40 cm and fragments of a size between 3 and 5 mm must be left after the mechanical or manual preparation. Actions leading to a very fine fragmentation (less than 2 mm) must be avoided, as well as a frequent tillage of the *tepetate*.

(b) After tillage, organic matter must be added. An application of 40 Mg ha^{-1} of farmyard manure had a 4-year residual effect.

(c) Nitrogen and phosphorus fertilizers must be applied as a complementary practice to the addition of organic matter. Rates to be applied must be based on the crop demand and the nutrient supply capacity of the recovered *tepetates*. Nitrogen applications are recommended to be made in a fractional manner so as to improve their use and efficiency.

(d) The crops showing the best responses in the first years of the *tepetate* incorporation are small-grain cereals like wheat, barley and oats, and fodder crops like vicia, trifoliums and wild medicagos. In the case of crops, like maize, beans and broad beans, good responses are obtained only as of the second or third cropping year. For the latter crops, the recommendation is to plant them up in association. It is also advisable to use local or regional varieties and eventually to try with other resources.

(e) In the initial phase of establishing a crop, especially if small-grain cereals, it is advisable to increase up to 50% the sowing density in order to have a better plant population.

(f) The adoption of a crop rotation pattern is recommended, containing legumes and gramineae.

(g) Due to high climatic risks in the areas of habilitated *tepetates* it is necessary to study more the possible use of grasses and agroforesty systems to guarantee agroecological diversity.

The REVOLSO Project

The project "Alternative Agriculture for a Sustainable Rehabilitation of Deteriorated Volcanic Soils in Mexico and Chile" (REVOLSO) is a INCO-DEV program of the European Union (FP-5). It started on January 2002 and will end 4 years later. Nine institutions belonging to six countries participate, four European (France, Germany, Italy and Spain) and two from Latin America (Chile and Mexico. The REVOLSO project is a continuation of two previous European Union sponsored programs reported in the above sections.

The objectives of REVOLSO are to develop and implement technological packages, based of the know-how of local people, tending to get a sustainable rehabilitation of the eroded young volcanic soils (often volcanic tuffs known locally as *tepetates or tobas*) and erosion susceptible volcanic soils in Central Mexico and Southern Chile.

Several hypothesis are being tested in field and laboratory trials: (a) Soil organic carbon (SOC) improves soil physical properties, (b) Traditional or conventional agricultural system are focused to satisfy basic food and fiber needs of local communities without considering the environmental menaces and generally conduces to soil erosion; (c) Organic agriculture leads to an increase in soil organic carbon levels resulting in measurable positive effects against erosion; (d) It is possible to transform a degraded volcanic soil or a hardened volcanic materials in a fertile soil; (e) Overgrazing is one of the main causes of soil degradation; then, it is compulsory to take in account the agriculture system and the cattle, useful for obtaining needed organic manures; (f) Technological changes would be accepted by the local societies, being the women the best tool for getting the acceptation of the management changes.

Only preliminary results of this project have been obtained and they are presented in this paper

Conclusions

Several conclusions can be drawn from the documents corresponding to the above three projects. Some were discussed in this paper and some were not but the information is contained in the quoted reports of the group.

1. The fragipan type *tepetates* of the valleys of Mexico and Tlaxcala are weathered vitric rhyolitic tuffs , which form compact layers that are hard when they are dry, but fragile when they are humidified.

2. These *tepetates* are located in the foothills of the valleys of Mexico and Tlaxcala, in zones with weather conditions between subhumid and subarid (600 to 800 mm of rainfalls and a dry season of a 5 to 6-month duration).

3. Even though some physical properties (hardness, low values of macroporosity), as well as chemical ones (low content of organic carbon, total nitrogen and soluble phosphorus) and low fertility impose important restrictions to the development of crops in their natural state, these conditions may be improved through appropriate management and also to facilitate the establishment of crops for commercialization.

4. The rehabilitation of the fragipan type *tepetates* for agricultural or forest use requires the following agricultural management: (a) tilling by the subsoiling of the *tepetate*, and subsequent tasks to have an optimum size of fragments (2.4 to 3.4 mm), avoiding a very fine fractioning (less than 2 mm); (b) incorporation of organic matter and use of fertilizers based on the nutritional needs of crops, (c) use of various cultural practices (tilling systems, addition of straw and manure, incorporation of residues; different crop systems and rotations). Also a crop rotation pattern is recommended, including legumes and gramineae.

5. The cost of rehabilitation is high but it can be done with state aid. It is estiamated that the investment can be recovered in 8 years.

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