Tepetates of Mexico

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INTRODUCTION

Tepetate is a vernacular Mexican term referring to a hardened land with various degrees of infertility. Tepetates are derived from volcanic material, mainly tuff. The scientific definition reserves the term *tepetate* for a hardened layer in soils formed from pyroclastic materials. In the Central Valley of Mexico these indurate layers are among the most striking pedological features. Two types have been recognized: the fragipan and the duripan type. The first one can be converted into soil after proper management to alleviate the social pressure for agricultural land.

TEPETATES: HARDENED VOLCANIC SOIL LAYERS

Tepetate is a vernacular Mexican term referring to a soil or hardened material with various degrees of infertility.[1] Etymologically, *tepetate* derives from the Nahuatl term "tepetlatl" ("tetl"=stone and "petatl"=bed) which means "bed of stone."[2] However, in both folk and technical senses *tepetate* has a wide semantic range of meanings.[2,3] In the 16th century, the Nahuatl classification of earth materials included the *tepetate* as both a deductive class defined by slightly friable consistence "rock-like materials" and an inductive class of "arable soil."[2] It is speculated that the term *tepetate* was adopted to enclose two Nahuatl words: "tepetatl" and "tepetatlali," used to differentiate between "bed of stone" nonapt for agriculture and ameliorated "bed stone," respectively. This explanation makes it easier to understand today the ambiguity of the term. Recent studies on peasant soil classification make these terms equivalent to nonworkable and workable land, respectively.[4] Although the folk definition is widely used, a more modern scientific definition reserves the term *tepetate* for a hardened layer found in soils formed from pyroclastic materials.[5,6] The main attribute of *tepetates* is their hardness when dry.

Hardened soil layers are not exclusive from Mexico. Similar formations can be found in Nicaragua, Salvador and Honduras,[5,7,8] Ecuador,[9] Chile,[10] Peru,[11] and Colombia[12] under different names "talpetate," "cangahua," "tobas and ñadis," and "sillares" (Table 1).

Pedologically, *tepetates* are surface or subsurface hardened layers derived from tuff,[13] pyroclastic flows,[5] or old volcanic ashes.[14] *Tepetates* have been described as mineral "C" horizons little affected by pedogenetic processes, which correspond to an intermediate state of alteration of a vitric rhyolitic tuff.[13,15] The main attribute of *tepetates* is its hardness, although there are big differences among different types. They vary in color from gray over yellow to reddish brown, as well as, in thickness and structure.

The best known *tepetates* in Mexico are located in the Valleys of Mexico and Tlaxcala, in the eastern and western slopes of the Sierra Nevada between 19°10′ and 19°40′ LN and 98°10′ and 98°55′ LW[16–18] (Fig. 1).

Up to 10 layers of superimposed *tepetates* have been described in Central Mexico.[18]

The first three series of these volcanic deposits (named T_1, T_2, T_3) were dated between 10,000 to 40,000 years old.[18] Peña and Zebrowski[19] classified the *tepetates* of Central Mexico in accordance with two criteria: the stratigraphic series of origin and their consistency (similar to a fragipan or petrocalcic horizon). The fragipan-type *tepetates*, which are the ones that can be ameliorated for agricultural and forestry uses, were classified as *tepetates* types t_1, t_2, and t_3 with or without calcium carbonate.[19]

This type of *tepetates* appears in different positions in the landscape, mainly in foothills and glacis, in the eastern and western slopes of the Sierra Nevada. Their characteristics differ in terms of the topographic position. Most of the *tepetates* located in foothills are of the fragipan type but do not have all the characteristics required by the Soil Taxonomy to be classified as such, the reason for which they were called fragipan type (Table 2). In the "glacis,"

Encyclopedia of Soil Science
DOI: 10.1081/E-ESS 120017323

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Table 1 Areas reported to have hardened layers of volcanic origin in different countries of Latin America

Country	Name of the layer	Area (km^2)
Mexico[a]	tepetate	30,700
Nicaragua[b]	talpetate	2500
El Salvador y Honduras[c]	talpetate	Not reported
Ecuador[d]	cangahua	3000
Chile[e]	ñadis y tobas	4750 and not reported
Perú[f]	sillares	10,000
Colombia[g]	hardened volcanic formations	12,000 to 15,000

[a]Ref. [16].
[b]Refs. [8,26].
[c]Information not available.
[d]Ref. [27].
[e]Ref. [28].
[f]Ref. [11].
[g]Ref. [12].

located further down foothills, *tepetates* show calcareous coatings and are more like petrocalcic horizons.[20]

The most outstanding physical properties of the fragipan-type *tepetates* are an average bulk density of 1.45 Mg m^{-3}; total porosity near 40%, with a macroporosity often below 5%; a hydraulic conductivity of 0.3 to 0.5 mm hr^{-1}; a hardness to dry penetration below 20 kg cm^{-2}; texture from sandy-clayey-loam to silty-clayey-loam (with more than 25% clay).[5,6,18] This kind of *tepetates* expands and gets friable when moist and disintegrates when it is sunk in water. The physical properties, especially hardness and the low values of macroporosity in natural conditions, are serious limitations to farming (root development, water penetration) and favor surface erosion.[21] Loss due to erosion amounts to 30 Mg ha^{-1}.

The fragipan-type *tepetates* are rich in bases, among which calcium, magnesium, and potassium prevail; they come from a mineral fraction rich in volcanic glasses and

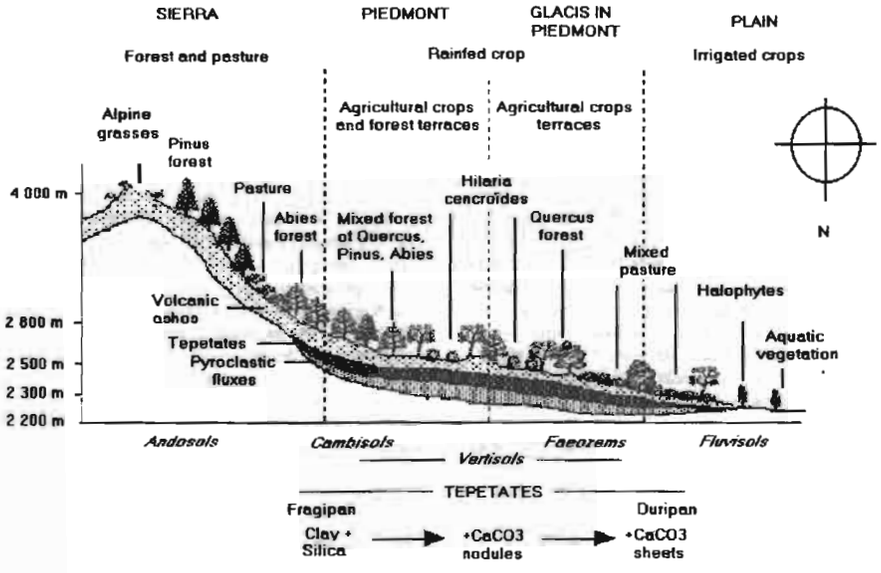

Fig. 1 Localization of the *Tepetates* in the landscape in Central Mexico.

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Table 2 Similarities and differences between fragipan and *tepetates*

Characteristic	Fragipan[a]	*Tepetate*
Layer thick	15 cm or more	6 cm or more
Pedogenesis	Evidence within the horizon or, at minimum, on the faces of structural units	Evidence within the horizon
Layer structure	Very coarse prismatic, columnar, or blocky structure of any grade; weak structure of any size; massive	Massive structure predominant and virtually no structural units, blocky structure of any grade in the t_3 *tepetate*
Separations between structural units	Separations allow roots to enter, have an average spacing of 10 cm or more on the horizontal dimensions	Virtually no separations in the massive structure, but the spacing in the t_3 *tepetate* can be around 10 cm
Diameter of air-dry fragments of the natural soil fabric	5 to 10 cm	Virtually no fragments when dry
Water behavior	More than 50% of the horizon slake when they are submerged in water; slowly or very slowly permeable to water	The *tepetate* slakes when submerged in water, slowly or very slowly permeable to water
Layer resistance	A firm or firmer rupture-resistance class in 60% or more of the volume, a brittle manner of failure at or near field capacity	Hard and very hard when dry and friable to very friable when moist
Roots	Virtually no roots	Virtually no roots
Organic matter content	Relatively low	Very low
Bulk density	High, relative to the horizons above it	Very high, relative to the horizons of the profile
Translocation of clay	Some evidences	Very frequent

[a]NRCS. Keys to Soil Taxonomy (7th edition 1996 and 8th edition 1998).

plagioclase highly susceptible to pedogenetic alteration. The cation exchange capacity ranges from 20 to 40 cmol kg^{-1} of fine earth, due to the abundance of 2:1 clays; the percentage of base saturation is high. Reaction is slightly alkaline, pH 7.3–8.2, because of the presence of carbonates. These materials contain only traces of organic carbon (0.2–0.7%), nitrogen (0.04–0.07%), and soluble phosphorus (<3 ppm), which is one of its major chemical problems. These characteristics of this type of *tepetates* result in low fertility, so it is necessary to improve it before their rehabilitation for agricultural or forest use.[21,22]

The material of origin of the fragipan-type *tepetates* is made up mainly of alkaline rhyolitic glasses, plagioclases, amphiboles, and pyroxenes of different sizes.[15,18] Secondary minerals are a mixture of 1:1 and 2:1 clays, often interstratified with a 2:1 strong component of the beidellite type. Clays are very well oriented, which favors the cohesion of the fragipan-type *tepetates* and strengthens the compact nature of their matrix. This *tepetate* type presents "free" noncrystalline silica, accumulation of iron and manganese oxides, and occasionally calcite and only traces of allophane. Mineralogical properties explain only partly the behavior and characteristics of these materials.[5,14,15]

The fragipan-type *tepetates* can be converted into soil after mechanically breaking up the hardened material[21] to improve their physical conditions (pore space, water retention capacity). Chemical and organic fertilizers must also be added to increase the available nitrogen and phosphorus, as well as the organic matter content.[23] *Tepetates* are very poor in the first two; however, their content of the other essential nutrients and clay, as well as their cation exchange capacity, is similar to that shown by productive soils.[23]

Manual incorporation of the fragipan-type *tepetates* to agricultural or forest activity began centuries ago. Nearly 40 years ago, mechanized methods were introduced. The ripped-up layer is 40 to 50 cm deep. Deep plowing is done when the *tepetate* is dry because fracturing of hard horizons is more complete than under moist conditions.[24,25]

Ancient experiences gathered by local farmers and recent modern research experiences allow to propose a series of management practices for the rehabilitation of the *tepetates* of the fragipan type: 1) The *tepetate* layer must be broken 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*). 2) After tillage, organic matter must be added (an application of 40 Mg ha^{-1} of farmyard manure had a 4-year residual effect). 3) 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. 4) The crops showing the best responses in the first years of the *tepetate* incorporation are small-grain cereals such as wheat, barley, and oats, and fodder crops such as vicia, trifoliums, and wild medicagos; good responses are obtained only as of the second or third cropping year for maize, beans, and broad beans, mainly planted in association. 5) 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. 6) The adoption of a crop rotation pattern containing legumes and gramineae is recommended.

CONCLUSION

Tepetates are layers of hardened material that develop in profiles of lands formed from volcanic material in Mexico and other countries with volcanic influence, and are object of particular scientific interest. Amelioration of the fragipan-type *tepetates* allows small farmers to have access to agricultural land and to obtain a means of support, reducing their migration toward populated areas, and at the same time slowing down erosion and desertification.

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Etchevers J.D., Hidalgo C., Prat Christian, Quantin Paul. (2004)

Tepetates of Mexico

In : Lal R. (ed.) Encyclopedia of soil science

New-York : M. Dekker, 1745-1748. ISBN 978-0-8247-0634-0