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Present and Past Geocryogenic Processes in Mexico

Klaus Heine

Institut für Geographie, Universität Regensburg, 93040 Regensburg, Germany

ABSTRACT

Periglacial processes and landforms are described from the Cordillera Neovolcánica of central Mexico. Inactive rock glaciers are related to different late-glacial and Holocene phases of permafrost conditions. Active discontinuous permafrost occurs above *c*. 4600 m ASL and appears to be from the Little Ice Age. The lower limit of late-glacial rock glaciers is situated 500 and 600 m lower than during the Little Ice Age.

RESUMÉ

Les processus et les formes périglaciaires qui existent dans la Cordillère Neovolcanica du Centre du Mexique sont décrits. Des glaciers rocheux inactifs sont mis en relation avec différentes phases pendant lesquelles a existé un pergélisol au cours du Tardiglaciaire et de l'Holocène. Un pergélisol discontinu existe de nos jours au-dessus de 4.600 m d'altitude; il est apparu pendant le petit âge glaciaire. La limite inférieure des glaciers rocheux tardiglaciaires est 500 à 600 m plus basse que celle des glaciers rocheux du petit âge glaciaire.

KEY WORDS: Periglacial phenomena Permafrost Rock glaciers

INTRODUCTION

The aims of the International Geological Correlation Programme project 297 (Geocryology of the Americas) can only be achieved if the altitudinal and latitudinal changes and modifications of present-day and Quaternary periglacial processes and landforms are recognized (see Lautridou and Francou, 1992). In order to advance the correlation of geocryogenic processes and their sediments and landforms in the Americas—the present-day phenomena as well as relict features—this paper provides a brief overview for central Mexico. The object is not only to better understand the nature of the alpine periglacial regions of Mexico, but also to assist in Quaternary palaeoenvironmental reconstructions.

THE MEXICAN CORDILLERA NEOVOLCÁNICA

Geographic Setting, Altitudinal Belts

The area of investigation comprises the eastern part of the volcanic belt (Cordillera Neovolcánica) that is composed of eroded late Tertiary and Quaternary volcanic and sedimentary rocks. It extends for nearly 1000 km along the 19th parallel north (Figure 1). The huge volcanic mountain ranges constitute barriers which separate valleys or basins. The principal geographic features include five volcanic massifs, from west to east: Nevado de Toluca; Ajusco; Sierra Nevada with Popocatépetl, Iztaccíhuatl, Tláloc and Telapon; La Malinche; and Pico de Orizaba with Cofre de Perote. There are four basins: basin of Toluca,

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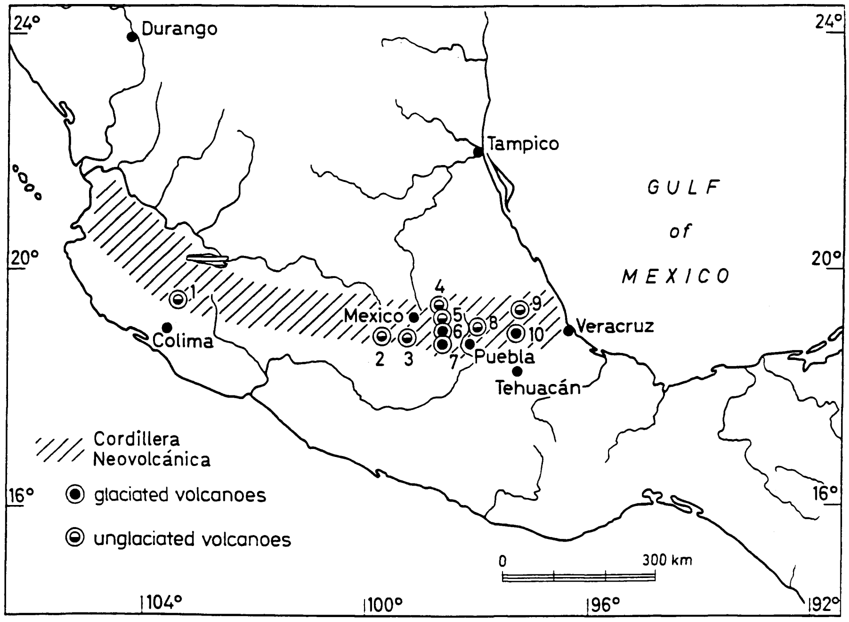

Figure 1 Location of the main volcanoes: 1 Nevado de Colima (4180 m); 2 Nevado de Toluca (4558 m); 3 Ajusco (3952 m); 4 Tláloc (4160 m); 5 Telapón (4200 m); 6 Iztaccíhuatl (5286 m); 7 Popocatépetl (5452 m); 8 La Malinche (4461 m); 9 Cofre de Perote (4282 m); 10 Pico de Orizaba (5700 m).

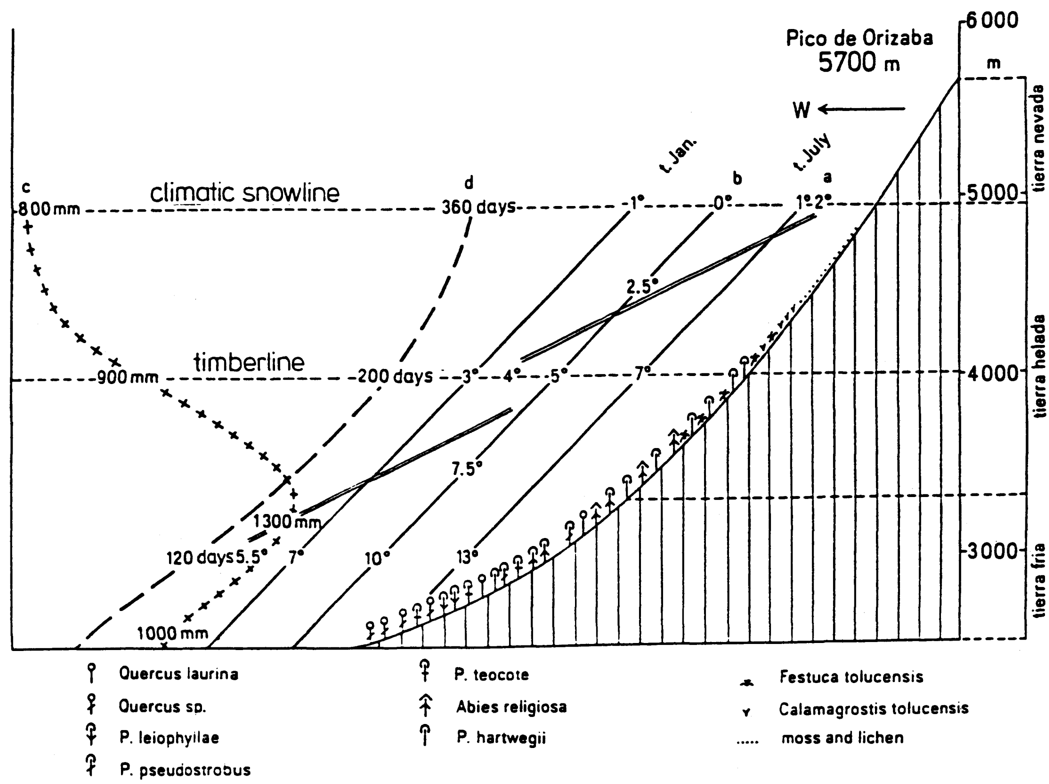

Figure 2 Approximate height dependence of selected climatic parameters in relation to the vertical distribution of vegetation on the Pico de Orizaba. (a) Mean annual temperature variation (°C); (b) mean annual temperature (°C); (c) mean annual precipitation (mm); (d) mean number of frost change days and ice days (after Lauer and Klaus, 1975).

basin of Mexico, basin of Puebla/Tlaxcala, and basin of El Seco/Oriental. The elevations of the basins range from about 2200 to 2600 m ASL, whereas the peaks of the volcanoes have heights between 3952 m (Ajusco) and 5700 m ASL (Pico de Orizaba).

The climate and altitudinal vegetation belts of the eastern part of the Cordillera Neovolcánica have been described by Klink *et al.* (1973) and Lauer (1973) (Figure 2). The limit of continuous tree growth (timberline) on the volcanic mountain slopes of central Mexico is generally found near 4000 m ASL. Up to the timberline, stands of *Pinus hartwegii* and tufted grass undergrowth (principally *Calamagrostis tolucensis, Festuca tolucensis* and *Muehlenbergia quadridenta*) predominate. Today, the timberline can be characterized as a transition zone which does not permit differentiated ecological assessment as a specific climatic zone (Lauer and Klaus, 1975).

The periglacial alpine belt of the high mountains of Mexico is located between roughly 4000 m (upper timberline) and 5000 m ASL (snowline) (Figure 2). *Festuca* grassland covers the slopes up to 4800 m ASL. Between 4800 m ASL and the perennial snow and ice, periglacial processes become dominant. According to the investigations of Lauer and Klaus (1975) the approximate height dependence of some climatic parameters in relation to the vertical distribution of vegetation on the Pico de Orizaba shows that the timberline has a mean annual temperature of 5 °C and about 200 freeze–thaw days (during which daytime temperature transgresses the freezing point) or ice days (temperature round the clock below freezing point). The snowline is in agreement with the mean annual temperature of 0 °C and 360 freeze–thaw days and ice days.

Only a few periglacial processes and features operate below timberline, namely needle-ice-induced patterned ground and small gelifluction lobes (see Figure 3).

Late Quaternary Paleoenvironmental History of Central Mexico

An outline of the development of the natural environment of the central Mexican Cordillera Neovolcánica during the late Quaternary is given in Figure 4. Periods of both normal and accelerated processes, stability, and erosion during the past 36,000 years BP are immediately recognizable. The chronostratigraphy is based on different late Quaternary stratigraphic successions of the following volcanoes: La Malinche, Pico de Orizaba, Iztaccíhuatl, Popocatépetl, Nevado de Toluca and Ajusco (Heine, 1976a, 1980, 1983a, 1983b).

An interpretation of all available palaeoclimatic and paleoenvironmental indicators suggests the following development. During the past 36,000 years BP three major periods with climatically-induced high erosion intensities and glacier advances can be distinguished: (1) 36,000 to 32,000, (2) around 12,000, and (3) 10,000 to 8500 years BP. These periods with high erosion intensities and glacier advances coincided with climatic changes from relative aridity to greater humidity. Figure 4 shows that there is no synchronous development of the temperature trend on the one hand and of the humidity trend on the other hand. The temperature curve for the last 36,000 years BP is marked in the central Mexican highland by an increase between 36,000 and 32,000, a decrease between *c.* 26,000 and 16,000 (with the last glacial temperature minimum around 17,000–16,000, and an increase with minor fluctuations from 14,000 to 8000 years BP. The postglacial climatic optimum was reached 8000 to 5000 years BP. During the Holocene the climate was slightly cooler and wetter between *c.* 3500 and 2000 years BP and in the Little Ice Age, producing minor glacier advances.

The alpine periglacial belt of central Mexico changed with regard to lower and upper limits and with regard to climatic-induced geocryogenic processes in different ways. Not only did the periglacial belt widen and narrow during the late Quaternary, but also periglacial processes were modified according to variations in temperature and humidity.

Correlation of the Late Quaternary Environmental History of Central Mexico with the Gulf of Mexico

A correlation of the Mexican palaeoclimatic reconstruction with the glacial meltwater cooling of the Gulf of Mexico and the North American and North Atlantic glacial/interglacial transition (Oglesby *et al.*, 1989; Teller, 1990a, 1990b) is given in Figure 5. Oxygen isotope data from the Gulf of Mexico deep-sea cores as well as abundant terrestrial evidence from North America clearly demonstrate that during the last glacial/interglacial transition at least two surges of glacial meltwater flowed down the Mississippi River and

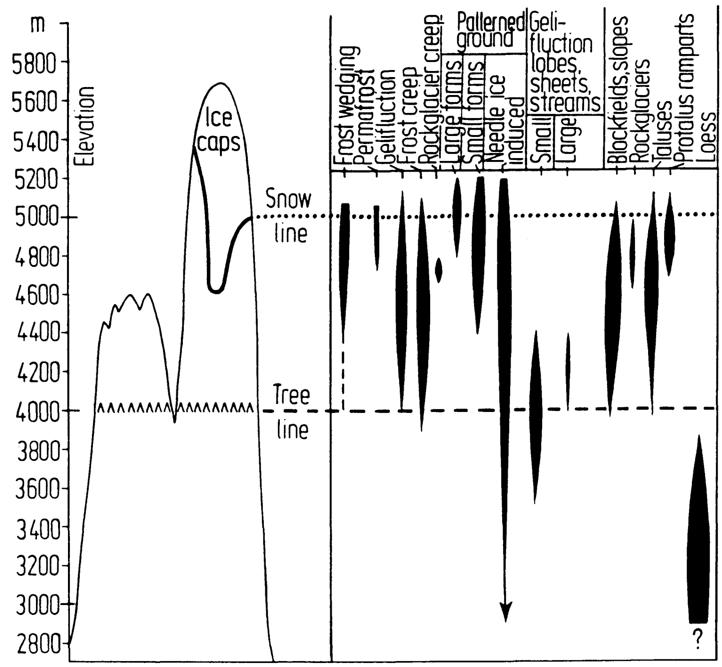

Figure 3 Distribution of periglacial processes and landforms across the Mexican Cordillera Neovolcánica.

into the Gulf of Mexico. Dates based on ^{14}C ages place these two events at roughly 16,500–11,600 (two major discharges, the largest of which lasted from 14,900 to 11,600) and 9900–9500 years BP, during which periods it is likely that a large part of the Gulf of Mexico was covered by a cap of cool, fresh water. During the period 10,800–10,000 years BP, most glacial meltwater was diverted from the Mississippi eastward into the Hudson and Saint Lawrence Rivers. This coincided precisely with the abrupt period of cooler conditions over the North Atlantic, Greenland, and much of Europe known as the Younger Dryas. While the possible climatological effects of the introduction of this meltwater on the North Atlantic and adjacent regions has been thoroughly discussed, little is understood of the meltwater effect on the Gulf of Mexico (Oglesby *et al.*, 1989; Teller, 1990a, 1990b).

The effects of such large volumes of cold, fresh meltwater on the temperature, moisture and salinity of the Gulf of Mexico are likely to have been quite significant. According to atmospheric general circulation models (Oglesby *et al.*, 1989) the possible effects are: (1) reduction of the Gulf of Mexico sea surface temperatures by approximately 6°C, (2) reduction of moisture over the Gulf of Mexico, North America and Mexico, and (3) reduction of the temperature over much of Mexico. Figure 5 shows that the late Quaternary meltwater cooling of the Gulf of Mexico and the chronostratigraphy of the glacial history of the central Mexican volcanoes are in good agreement. Therefore, we may assume that the general scheme of development of the natural environment of the central Mexican highlands has some validity and can be used to reconstruct late Quaternary periglacial processes and features.

PERIGLACIAL PROCESSES AND FEATURES

Table 1 summarizes the environmental implications of some of the periglacial processes and features of the central Mexican volcanoes. Although based on contemporary observations, the table presumably applies equally to Pleistocene and Early/Middle Holocene conditions. The distribution of periglacial processes and landforms across the Mexican Cordillera Neovolcánica is shown in Figure 3.

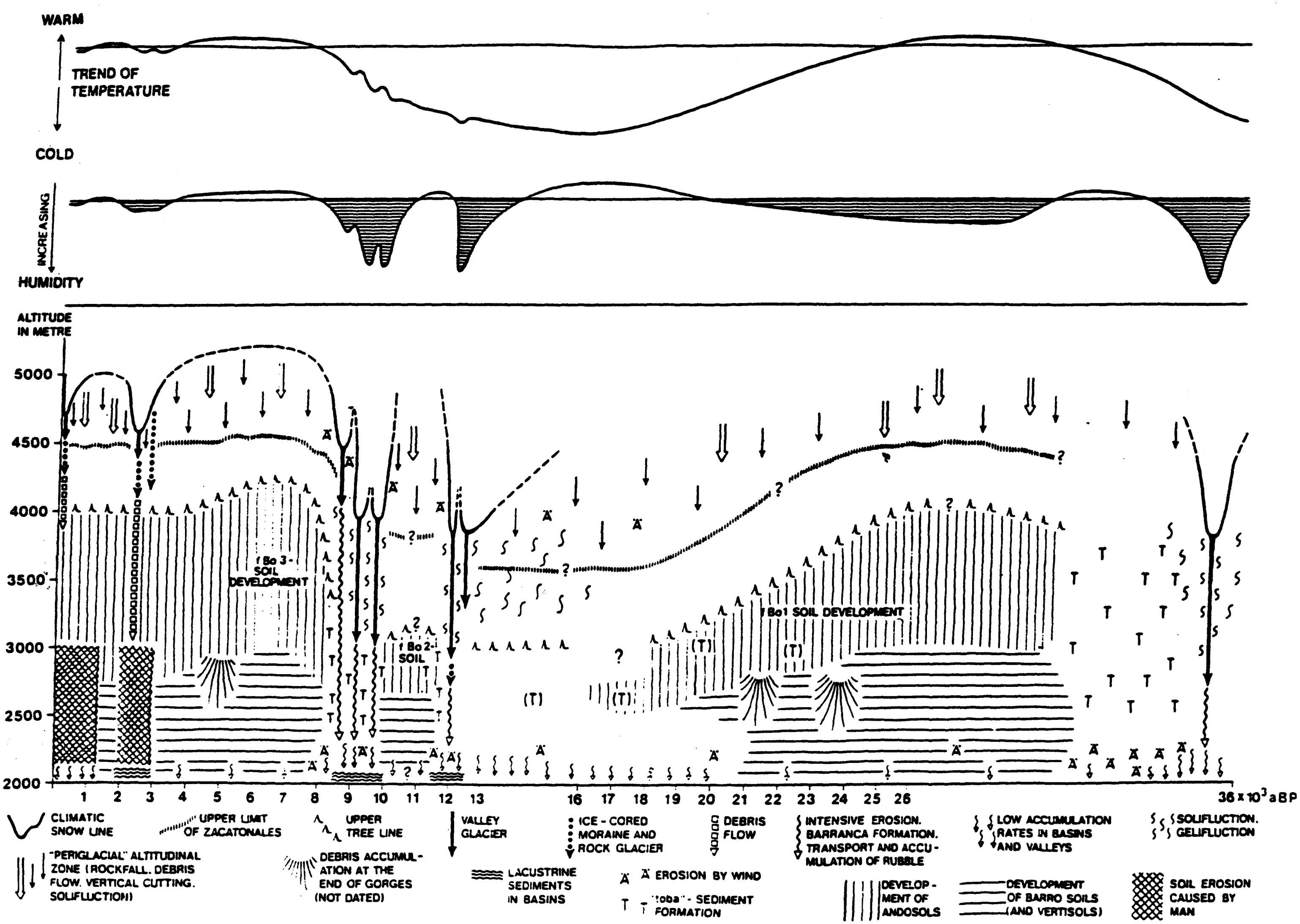

Figure 4 Paleoenvironmental reconstruction of the central Mexican highland during the late Quaternary.

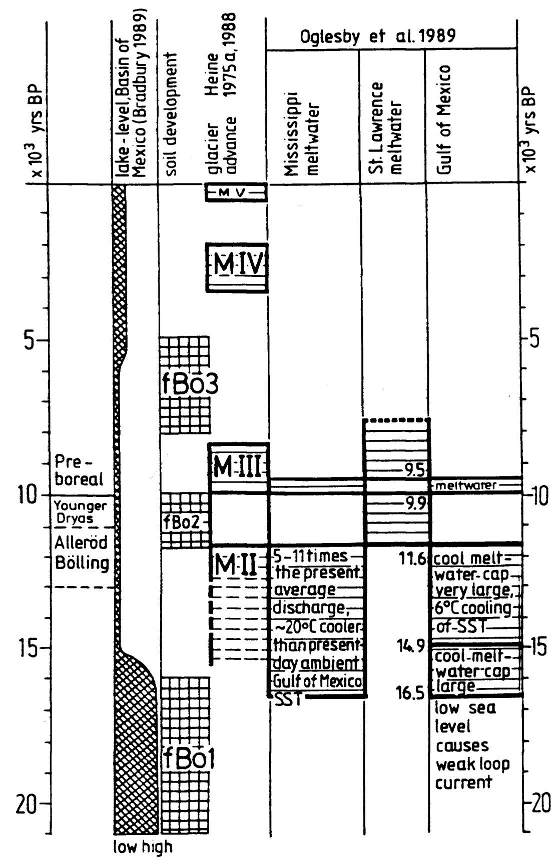

Figure 5 Correlation of lake-level fluctuations, soil development periods, glacial advances, and meltwater runoff from the southern Laurentide Ice Sheet with Central Mexican Highlands.

Permafrost

Our knowledge of the permafrost in the different Mexican mountain regions is poor. Gorbunov (1978) speaks of permafrost in Mexico above 4500 m ASL and, in addition, he refers to Lauer (personal communication, 1976) who recorded permafrost on the Iztaccíhuatl as low as 4100 m ASL. However, the lower limit of sporadic permafrost may occur under rather extreme circumstances (Cheng Guodong and Dramis, 1992).

Discontinuous permafrost was found on Popocatépetl (Delgado, 1986 after Vázquez Selem, 1989), and on Pico de Orizaba (north-eastern flanks) between 4600 m ASL and the glacier ice cap (Heine, 1975b). The author believes that the permafrost occurrences on Pico de Orizaba are mainly relict and developed during the so-called Little Ice Age glacier advances between the seventeenth and nineteenth centuries. The occurrence of relict permafrost suggests that in the Little Ice Age the mean annual ground temperature must have been at least 2°C colder than today at 4600 m ASL.

It is not yet clear where the lower limit of present-day permafrost is situated on the volcanoes. Nor is it known whether or not the relict permafrost is part of a Little Ice Age permafrost altitudinal belt that occupied the glacier-free parts of the volcanoes at heights above ± 4600 m ASL.

The evidence used so far to outline the alpine permafrost zone of today (e.g. Péwé, 1983) includes uncertain data for Mexico (about 20 °N). As a generalization, the absolute height of the recent boundary of discontinuous permafrost is near the 4600 m ASL isohyete. The lower limit of the discontinuous permafrost coincides with the + 2°C mean annual air temperature isotherm.

Rock Glaciers

Active rock glaciers are defined as lobate or tongue-shaped bodies of frozen debris, which move downslope or downvalley (Barsch, 1988). Until now no reports on active rock glaciers exist for the high Mexican volcanoes. On the other hand, many inactive rock glaciers undoubtedly

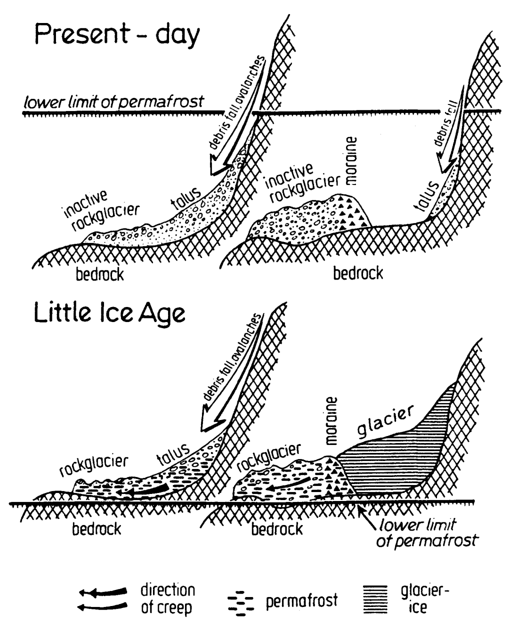

Figure 6 Formation of rock glaciers during the Little Ice Age and present-day situation on Nevado de Toluca volcano (see also Barsch, 1988; Whalley and Martin, 1992).

Table 1 Periglacial processes and features, Cordillera Neovolcánica, Mexico. Predominant ranges are suggested by numeral 1 and lesser ranges in decreasing order by 2, 3, 4; R indicates rare or absent.

Processes/features	Mexican Cordillera Neovolcánica			Highlands of low latitudes, present day (after Washburn, 1979)
	Present day	Relict	Dated	
Frost action				
Frost wedging	4	○	×	3
Frost heaving and frost thrusting	R	○		4
Mass displacement	4	○	×	R
Seasonal frost cracking	R			R
Permafrost cracking	–			R
Mass wasting				
Slushflow	–			R
Gelifluction	4	○	×	4
Frost creep	2	○	×	3
Rock glacier creep	R	○	×	4
Nivation	R			3
Wind action	2	○	×	3
Permafrost	R	○	×	4
Patterned ground				
Non-sorted circles	R			R
Sorted circles	R			R
Small non-sorted polygons and nets	2			2
Large non-sorted polygons and nets (ice wedge)	R			R
Small sorted polygons and nets	2			2
Large sorted polygons and nets	R			R
Small non-sorted and sorted stripes	2			2
Large non-sorted and sorted stripes	R			R
Involutions	–	○?	×?	R
Slushflow fans	R			R
Small gelifluction lobes, sheets, streams	4	○		3
Large gelifluction lobes, sheets, streams	R			4
Block fields, block slopes and block streams	3	○		4
Rock glaciers	R	○	×	4
Taluses	3	○		3
Protalus ramparts	3	○		3
Grèzes litées	R	○?		4
Nivation benches and hollows	–			4
Altiplanation terraces	–			R
Asymmetric valleys related to permafrost	–			R
Dells	–			R
Cold-climate varves	–	○	×	R
Loess	4	○	×	4
Dunes	R			R
Ventifacts	R	○		R

○ Relict features and processes.
× Dated relict features and processes.

exist on the high mountains. Many are located in cirques and are Holocene in age, but relatively few have been studied (Heine, 1976b; Vázquez Selem, 1989). On Nevado de Toluca volcano two different types of inactive rock glacier can be distinguished (Figure 6). The first includes rock glaciers that occur beneath talus slopes where they have been supplied with debris by avalanches and debris fall. During cooler and wetter climatic phases these rock glaciers were probably active owing to interstitial ice which resulted from the metamorphism of snow buried beneath the rock-fall debris. The second type represents (a) the debris-covered tongues of former glaciers (i.e.

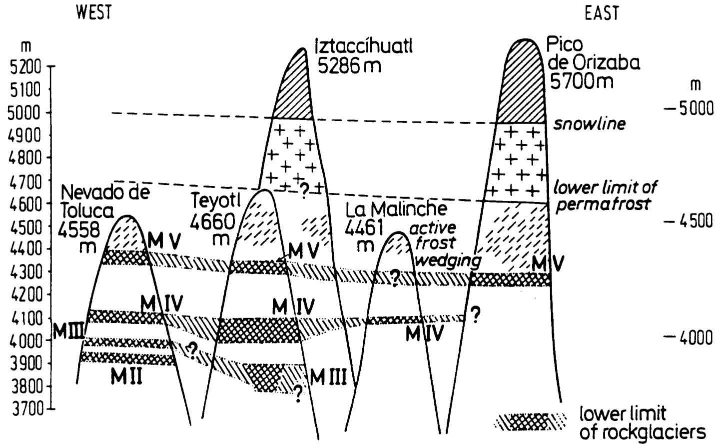

Figure 7 Lower limit of rock glaciers during different periods of the late Quaternary, present-day snowline and lower limit of present-day discontinuous permafrost. MII, late glacial; MIII, early Holocene, 10,000–9000 BP; M IV, 3500–2000 BP; M V, Little Ice Age.

ice-cored moraines) and (b) the end-moraine material which, after deposition, has been incorporated as debris into the rock glacier (rock glacier beneath glaciers: see Barsch, 1988). Four generations of rock glaciers have been observed. All are entirely stabilized. The latest generation consists of rock glaciers of the Little Ice Age. The second generation of rock glaciers was formed during the Holocene, roughly between 3500 and 2000 years BP; the third generation dates back to about 10,000–8500 years BP; and the oldest generation predates the formation of the fossil soil fBo2 (11,500–10,000 years BP).

From extrapolation of the size (length) and time of active movement, the rates of movement calculated for the rock glaciers of the Nevado de Toluca range between a few and 100 centimetres per year. The velocity was greatest on the northwestern slopes. Little Ice Age rock glaciers are known on the Nevado de Toluca volcano, the Malinche volcano, the Pico de Orizaba, and the Iztaccíhuatl. Vázquez Selem (1989) reports two generations of rock glaciers from Teyotl, the northernmost peak of the Iztaccíhuatl massif. Both types of rock glaciers were identified. A diagram (Figure 7) of the lower boundary of rock glaciers of the different volcanoes for the Little Ice Age and the periods from 3500 to 2000 years BP (MIV), the early Holocene (MIII) and the late glacial (MII) suggests the existence of perennially frozen ground during different late Quaternary climatic phases. The lower limit of discontinuous permafrost during the Little Ice Age was about 4250–4300 m ASL on Pico de Orizaba, about 4300–4350 on Teyotl and about 4350–4400 on Nevado de Toluca. The limit rose from the east (Gulf of Mexico) to the west (central Mexican highland). During the late Holocene, between 3500 and 2000 years BP, this east–west gradient was probably not obvious.

The existence of Little Ice Age rock glaciers and their altitudinal distribution on the Mexican volcanoes suggests that the permafrost patches observed on Pico de Orizaba at about 4600 m ASL relate to present climatic conditions and do not trace back to former colder climatic phases. This suggests that the mean annual temperature has risen about 1.5 to 2.0°C since the Little Ice Age.

Until now, no active rock glaciers have been observed on the Mexican high mountains. Only Vázquez Selem (1989) describes recent rock glaciers from the Teyotl (4660 m ASL); whether the rock glaciers are active or not still needs to be proven. It seems that the development of active rock glaciers is confined to certain climatic phases with cooler temperatures and higher precipitation. Active rock glaciers are fed by debris of talus slopes and moraines. It is thought that the production of debris was only possible during these cooler and wetter climatic phases. During times of glacier retreat and of low talus production, rock glaciers became inactive because of the lack of debris. This may be the reason for the non-existence of active rock glaciers even though permafrost exists in the adjacent unglaciated mountain areas.

Furthermore, the non-existence of active rock glaciers may be seen in connection with the rising temperatures since the Little Ice Age (see Lewis, 1992). The lower limit of permafrost ascended on the mountain slopes, so that the lower parts of the talus slopes became free of permafrost (Figure 6); the development of rock glaciers was no longer possible and the Little Ice Age rock glaciers became inactive or relict.

Frost Wedging

Coarse angular rock debris derived from bedrock attests to the importance of frost wedging in regions above 4300 m ASL on the Mexican volcanoes. Some slopes without cliffs or with only low cliffs at their heads are formed mainly of material much like talus rubble. Where such coarse and angular debris is derived from the underlying rock without benefit of rockfall, frost wedging must be the predominant process responsible for detaching the fragments and forming block slopes (Washburn, 1979). The distribution of the block slopes (in some cases, block streams) mainly depends on rock type.

Thawing of snow or ice adjacent to dark rocks warmed by insolation is common at subfreezing air temperatures and must be a potent factor in frost wedging when meltwater seeps into joints and refreezes. In Mexico the maximum effect of frost wedging occurs in the winter after snowfall and ice precipitation during so-called *Nortes* (northers: cold arctic air masses reaching central America).

Gelifluction, Frost Creep, Stratified Screes

Gelifluction and frost creep are characteristic processes above timberline, between approximately 4000 m ASL and the ice caps (Figure 3). Needle ice can be a significant factor in frost creep (Heine, 1977a) and in differential downslope movement of fine and coarse material. Needle-ice-induced frost creep may occur even at altitudes below 3000 m ASL on the Mexican mountains (Heine, 1977a). Gelifluction deposits (diamictons, some with crude stratification) of late Quaternary age can be observed down to *c.* 3000 m ASL. Stratified scree (Francou, 1990) occurs on different mountains above 4300 m ASL, but has not been studied in detail yet.

Patterned Ground

Large areas of patterned ground in the form of sorted stone circles and stripes have been observed on Pico de Orizaba above 4800 m ASL (Heine, 1977b). The diameter of the circles is about 1.5 m. According to investigations in Mexico, these large forms of patterned ground are confined to permafrost areas. Relict forms of patterned ground are not known. Small forms of patterned ground mainly occur at heights above 4400 m ASL. The frequent development of needle ice is responsible for the occurrence of different small forms of patterned ground all over the slopes of the mountains down to 3000 m and even below that altitude. The andosols and the fine volcanic ashes favour the development of needle ice under the specific climatic conditions (Heine, 1977a; see also Werner and Hallet, 1993).

To define the lower boundary of the periglacial belt of the mountains, the small forms of patterned ground cannot be used because of the influence of needle ice on their development in all regions where the conditions for needle ice are fulfilled (Heine, 1977a; Washburn, 1979).

Loess and Loess-Like Sediments

Loess-like sediments are widespread in central Mexico. The sedimentation of these so-called 'toba' sediments during cold late Quaternary phases was restricted to the lower slopes of the volcanoes (below 3800 m ASL). In the establishment of a late Quaternary stratigraphy, the toba deposits are very useful (Cornwall, 1970; Heine and Schönhals, 1973). Periglacial involutions (cryoturbations) and ice-wedge casts are reported from different toba layers (Lorenzo, 1969a 1969b; Heine, 1975a). These phenomena are observed in sections along the Autopista in the Río Frio pass area down to 2700 m ASL. It is doubtful whether these phenomena are of periglacial origin. The 'ice-wedge casts' seem to be refilled rills and document a phase of soil erosion with subsequent deposition. The 'periglacial involutions' in many cases do not have a periglacial origin but result from mudflow-like slumping processes and solifluction phenomena.

GEOCRYOGENIC PROCESSES IN MEXICO

The term 'geocryogenic' as used here is identical with 'periglacial' and designates primarily terres-

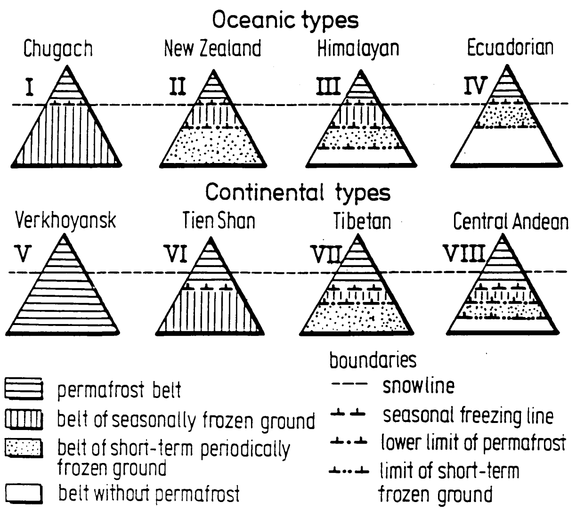

Figure 8 Schematic classification of mountain geocryological regions (after Gorbunov, 1978). The Mexican situation is represented by type III (Himalayan).

trial, non-glacial processes and features of cold climates characterized by intense frost action, regardless of age or proximity to glaciers (Washburn, 1979). Many different processes are responsible for geocryogenic effects, but for the most part these processes are not peculiar to periglacial environments. It is the combination and intensity of these processes that characterize periglacial environments. In a schematic classification of mountain geocryological regions

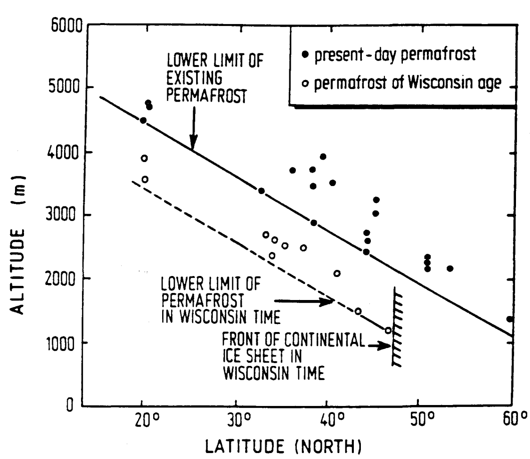

Figure 9 Relation between latitude and altitude of reported localities of existing alpine permafrost and alpine permafrost of Wisconsin age (after Péwé, 1983; supplemented by localities listed in Marker, 1990 and by the author's observations).

(Gorbunov, 1978) Mexico belongs to type III (Himalayan) with a four-belt structure: perennial; seasonal; short-term periodic freezing; and a low belt where no freezing occurs (Figure 8).

By using active periglacial processes it is not possible to define the lower boundary of the geocryogenic belt of the Mexican volcanoes. Nor is it possible to characterize the periglacial zone by using mesoforms such as rock glaciers, talus slopes or *Glatthänge*. Frost action can be found even in basins between the high volcanic mountains. Therefore, no lower altitudinal limits of the periglacial belt can be defined. The lower altitudinal limit of gelifluction and frost creep are around the treeline at *c.* 4000 m ASL, the lower limits of frost wedging are around the upper boundary of the *zacatonales* vegetation at 4400 m ASL, and the lower limits of permafrost are around 4600 m ASL (Figure 9). The combination and intensity of geocryogenic processes show more and more periglacial features as altitude increases so that one might speak of a periglacial altitudinal belt at heights of more than 4400 m ASL.

A definition of the actual altitudinal periglacial zone using mesoforms (rock glaciers etc.) is impossible, because the distribution of these mesoforms is mainly dependent on Pleistocene glacial relief. Furthermore, most mesoforms are of the Little Ice Age, of the mid Holocene or even older. Present climatic conditions are not suitable for the active development of geocryogenic mesoforms.

Figure 4 outlines the spatial and temporal distribution of geomorphic processes in the Mexican Cordillera Neovolcánica during the last 36,000 years (Heine, 1983b). It shows that (1) the geomorphic processes and hence the development and shaping of the mesoforms did not take place in the same combination and intensity; (2) during the Holocene geomorphic processes did not change markedly in areas above 5000 m and below 4000 m ASL (with the exception of the early Holocene); and (3) during the last 3000 years man has influenced geomorphic processes up to 3000 m ASL. In recent decades the influence of man on the environment even includes regions up to 4200 m ASL (as the consequence of measures against soil erosion, the construction of roads, grazing, tree cutting, burning of the *zacatonales* etc.).

It becomes obvious, therefore, that we cannot separate an actual periglacial belt by using characteristic mesoforms or characteristic geocryogenic processes. The semi-humid tropics with a rainy season in summer and a dry season in winter represent a zone of transition between the humid tropics and the arid zone. The arid zone has no actual periglacial altitudinal belt at all (Mensching, 1983).

UNSOLVED PROBLEMS

There are a number of unsolved problems. First, the relationship between the climatic snowline and the lower limit of the occurrence of continuous/discontinuous/sporadic permafrost during the relatively arid Last Glacial Maximum and during the relatively humid Late Wisconsin and Early Holocene period must be further investigated. Second, lobate rock glaciers must be differentiated from tongue-shaped rock glaciers, since lobate rock glaciers have potential for the reconstruction of past climates. Third, the loess-like toba sediments, which are eolian-redeposited volcanic ashes and pumices, must be differentiated from loess-like sediments, which are correlated with glacial and periglacial deposits. Finally, information on ice-wedge casts and periglacial involutions from Mexico must be viewed with caution.

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