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A voluminous avalanche-induced lahar from Citlaltépetl volcano, Mexico: Implications for hazard assessment

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ABSTRACT

During the late Pleistocene the ancestral edifice of Citlaltépetl volcano (also known as Pico de Orizaba) collapsed to form a clay-rich deposit that extends 85 km from its source, has a volume of 1.8 km^3, and covers an area of 143 km^2 east of the volcano. The deposit has clay content ranging from 10 to 16% and contains secondary alteration minerals such as smectite and kaolinite. The deposit's features suggest that it had an origin as a sector collapse of hydrothermally altered rock that transformed from a debris avalanche to a cohesive lahar very close to its source.

The presence of glacier ice and a hydrothermal system during late Pleistocene times apparently provided a source of pore water which enhanced the hydrothermal alteration of the summit of Citlaltépetl and was the origin of most of the water for the lahar. This deposit and several others suggest that glaciated volcanoes are sites where hydrothermal alteration and resulting cohesive lahars are most likely. Although cohesive lahars and debris avalanches both have origins as sector collapses, cohesive lahars are more mobile than similar-sized debris avalanches. Thus potential hazard of edifice collapse at glaciated volcanoes, especially those with large volumes of hydrothermally altered rock, includes the possibility of large-volume cohesive lahars.

Introduction

Lahars, because they are gravity driven, are most dangerous at high-relief volcanoes like Citlaltépetl, which are surrounded by steep sided, deeply incised, high-gradient valleys. In 1985 at Nevado del Ruiz volcano, Colombia, more than 23,000 people were killed by lahars generated on an ice-capped, high-relief volcano much like Citlaltépetl. The term lahar is used in this report to mean debris flow at a volcano. A debris flow is a water-saturated mixture having a solids content of at least 80% by weight or 60% by volume and moving down slope under the influence of gravity. A cohesive debris flow has 5% or more clay relative to total sand, silt, and clay, whereas a noncohesive debris flow has less clay.

The purpose of this study is to describe the unusual character and origin of the late Pleistocene clay-rich deposit found east of Citlaltépetl volcano. A second objective is to evaluate the importance of glaciation in the genesis of clayey hydrothermally altered rock at this and other stratovolcanoes and to assess the potential hazards associated with edifice collapse of clay-rich altered volcanic rock.

Citlaltépetl, also known as Pico de Orizaba, is an ice-capped, andesitic stratovolcano that at 5675 m is Mexico's highest peak. It is located at the east end of the trans-Mexican volcanic belt (Fig. 1). On the west, Citlaltépetl is drained by ephemeral streams and has about 3000 m relief; on the east, it is drained by rivers in deep precipitous valleys and has more than 4400 m of relief. Presently only the north

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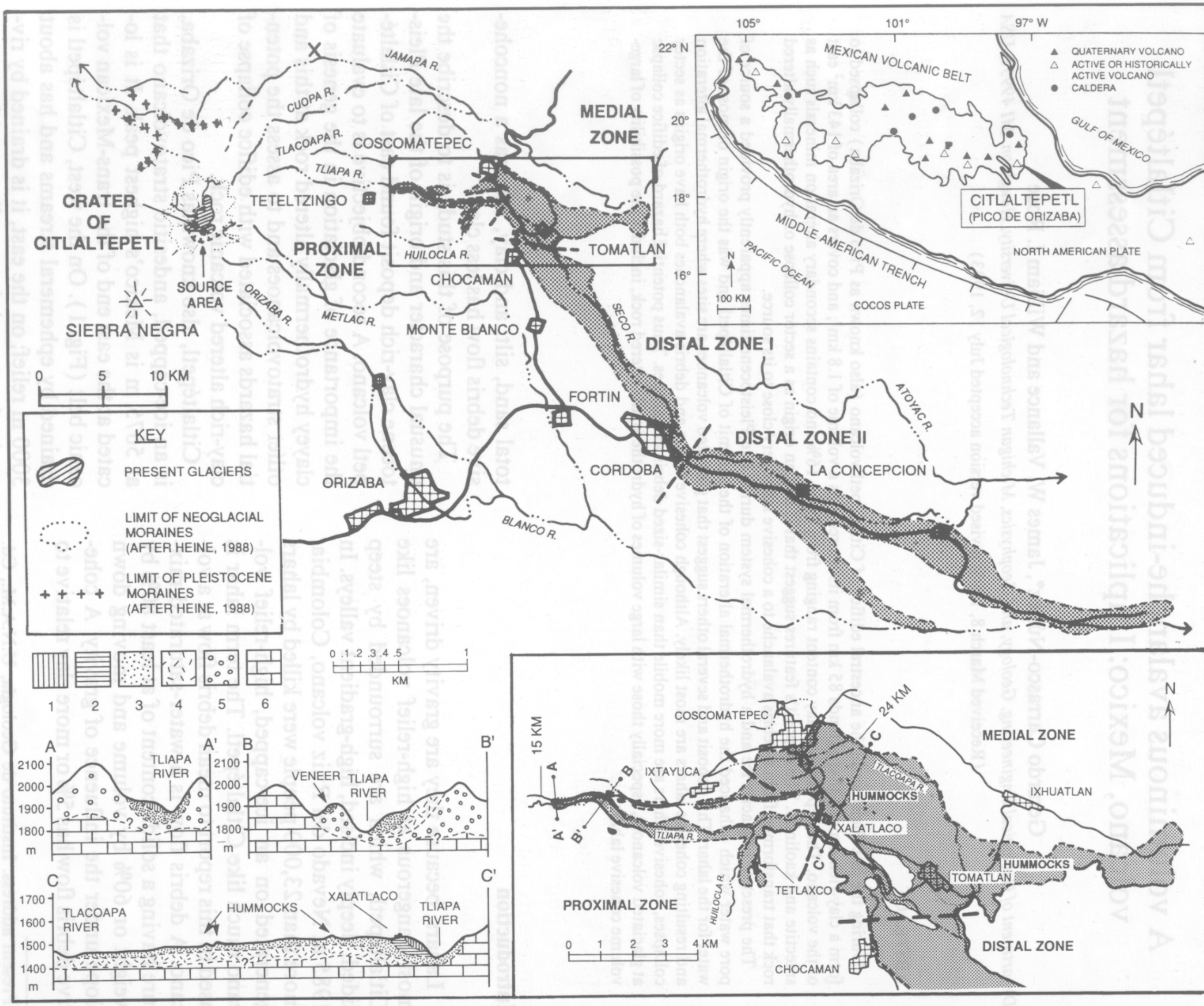

Fig. 1. Distribution of the Teteltzingo deposit with a more detailed inset of the proximal and medial zones. *X* represents location in the Jamapa river valley of cohesive-lahar deposits similar to Teteltzingo (see text). Explanations for cross sections (which have 175% vertical exaggeration) are: *1* = 8,770 years B.P. scoria pyroclastic flow; *2* = 13,270 years B.P. banded pyroclastic flow; *3* = Teteltzingo deposit; *4* = debris flows; *5* = andesite and block and ash flow; and *6* = Cretaceous limestone and shale.

side of the summit area is covered by glacier ice. During Neoglacial times, glaciers extended from 1 to 3 km in all directions from the summit area, and during the late Pleistocene, glaciers extended as far as 9 km to the north (Fig. 1; Heine, 1988), but evidence of Pleistocene glaciation in other directions has largely been destroyed by more recent volcanism.

Citlaltépetl volcano is built on dissected basement rock comprising Cretaceous limestone and shale. Robin and Cantagrel (1982) and Carrasco-Núñez and Rose (1990) recognized remnants of an older stratovolcano on which the present cone was built. Since late Quaternary times, the volcano has shed considerable volumes of volcaniclastic debris on its flanks and into the river valleys that drain it (Höskuldsson et al., 1990; this study).

Teteltzingo debris avalanche and lahar

A clay-rich debris-avalanche and lahar deposit, previously named the Teteltzingo debris avalanche (Höskuldsson et al., 1990), underlies 143 km^2 of the Tliapa–Seco drainage basin between its source at Citlaltépetl volcano and a distance of 85 km downstream (Fig. 1). Three similar clayey deposits are present in the Jamapa River valley (Fig. 1). The basal unit of this sequence is a massive clayey unit much like that in the Tliapa drainage. The degree of weathering suggests that these deposits are about the same age as those in the Tliapa valley. Inasmuch as both the Jamapa and Tliapa rivers have headwaters within the inferred amphitheater scarp, it is possible that the deposits in the two valleys are from the same event.

Distribution, size, and character of the deposit

Although the Teteltzingo deposit is typically buried or eroded away within 15 km of the summit, beyond 15 km downstream, it forms thick prominent fills in the proximal, medial, and distal depositional zones (Fig. 1; Table 1). In the proximal zone, a steep confined valley, the deposit is 20 to 100 m thick and forms terraces. In places where the valley sides are not too steep, 1- to 2-m-thick deposits form a veneer several tens of meters above the thick terrace deposits. At the Huilocla River confluence, veneers extending 60 m above 100-m-thick fill deposits suggest that the flow filled valleys to depths of up to 160 m.

In the medial zone, low-relief hills, composed of older volcaniclastic deposits and limestone, are surrounded by flat surfaced deposits of the Teteltzingo flow, which average 20 m in thickness. Although the surface of the deposit is flat, it is dotted by about 20 hummocks near Xalatlaco and Tomatlán villages. The hummocks are oval to circular in plan, have diameters ranging from 5 to 30 m, and are up to 15 m high.

In the distal zone, there are no hummocks. The deposit is up to 30 m thick, averages 20 m thick in the distal I zone (Table 1), and gradually thins over the last 40 km of the distal II zone. The deposit is divided into two lobes about 3 km downstream of La Concepción (Fig. 1).

The total volume of known deposits in the Tliapa–Seco River drainage is about 1.8 km^3 (Table 1). Additional deposits must have existed on the flanks of the volcano and possibly in the Jamapa River drainage but are now eroded or buried. Therefore, the volume of the original deposit was probably greater than 2 km^3.

Generally, the deposit appears to be a single massive, unbedded, poorly sorted mixture of pebbles, cobbles, and boulders in a very clayey, silty sand matrix. However, at a locality 27 km downstream from Citlaltépetl and 1 km north of Chocaman (Fig. 1), two separate beds are present. At another locality 60 km downstream, near La Concepción (Fig. 1), there are three beds. The contacts appear to be concordant, and there is no evidence of weathering.

The composition and texture of lithic fragments are highly variable. Most pebble- and boulder-sized clasts are porphyritic andesite,

TABLE 1

Distance from source, size, and slope of the Teteltzingo deposit

Zone	Distance (km)	Average slope (gradient)	Average thickness (m)	Area (km^2)	Volume (km^3)
Proximal	15–20	0.049	40	4	0.16
Medial	20–28	0.037	20	19	0.38
Distal I	28–48	0.024	20	31	0.62
Distal II	48–85	0.018	7	90	0.63
Total	15–85	n.d.[1]	n.d.[1]	143	1.79

[1]"n.d." means not determined.

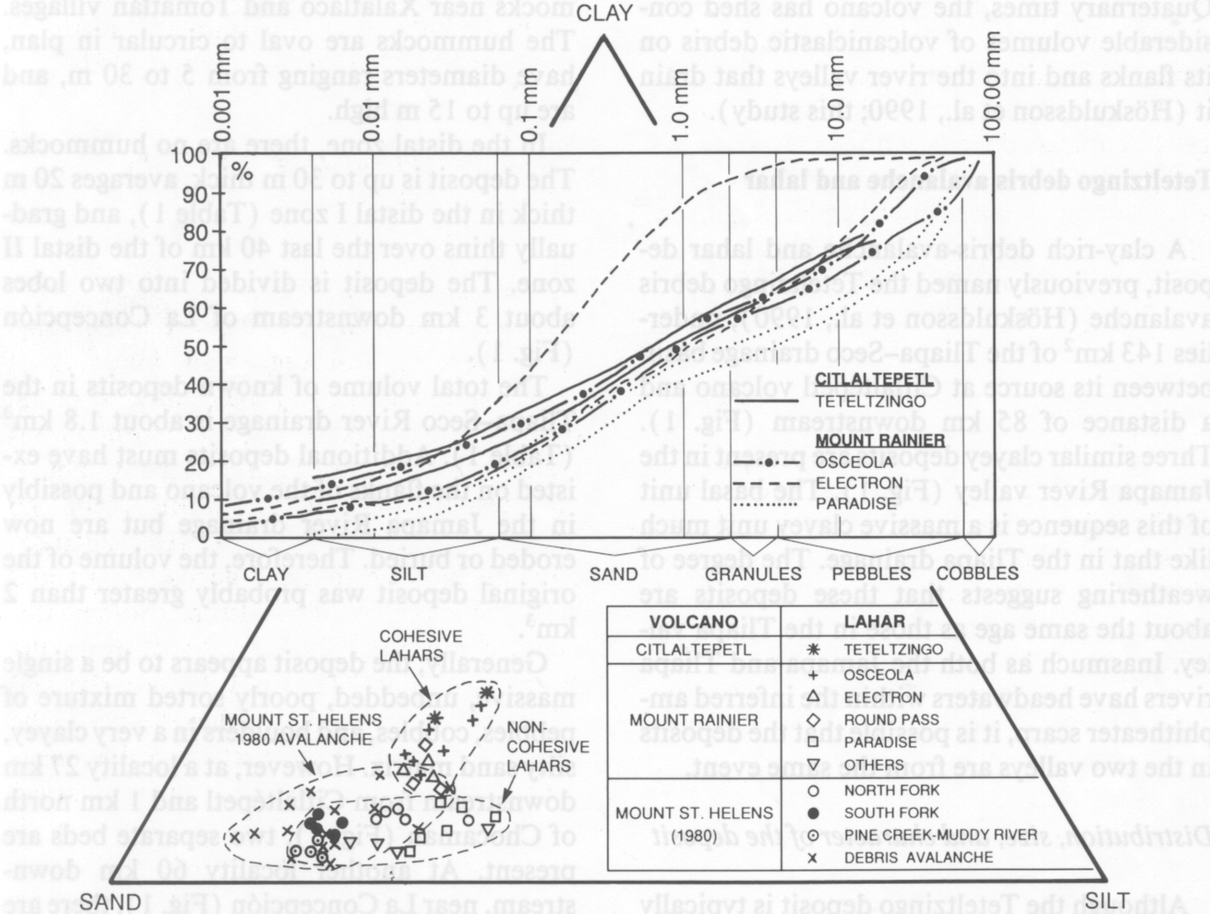

Fig. 2. Cumulative plots of grain size of the Teteltzingo deposit and selected cohesive lahars from Mount Rainier (Crandell, 1971) and ternary diagram of sand, silt, and clay for the matrix of the Teteltzingo deposit, cohesive lahars (Crandell, 1971), noncohesive lahars (Pierson, 1985; Scott, 1988), and the 1980 debris avalanche of Mount St. Helens avalanche (Voight et al., 1981).

basaltic andesite, and hornblende-bearing dacite like the rocks of the ancestral cone. Vesicular or pumiceous rocks are rare. Many of the clasts are soft because of hydrothermal alteration. All clasts are supported by a characteristic yellow-brown, clayey matrix, which contains 1- to 2-mm vesicles suggestive of air bubbles trapped in water-saturated matrix. Lahar deposits at Mount Rainier (Crandell, 1971) and Mount Adams (Vallance, in press) have similar vesicles. Larger voids are common and have shapes identical to wood fragments.

Spot samples collected from the base and top of a 15-m-thick deposit in the medial zone of the deposit are very clayey (10–16%) and are extremely poorly sorted (σ_φ, 5.7–6.1) (Fig. 2). The high clay content is a distinctive feature of the Teteltzingo deposit. Other mass flow deposits that have similarly high clay contents are lahar deposits, caused by the edifice collapse of hydrothermally altered rock, like the Osceola and Electron Mudflows at Mount Rainier (Crandell, 1971; Scott et al., 1992) (Fig. 2).

Age of the deposit

The age of the Teteltzingo deposit is bracketed by radiocarbon dates on an overlying pyroclastic flow deposit (Fig. 1) and by the extent of weathering developed on its surface. Although casts of logs are numerous, preserved logs are not. At La Concepción, carbon-rich soil material in the shape of a log 6 m below the present surface has a radiocarbon age of 1,650±60 years B.P. Because this age is not consistent with stratigraphic observations, we interpret this sample material to be the remnant of an old taproot. Charcoal from a pyroclastic flow deposit that unconformably overlies the Teteltzingo deposit has radiocarbon ages of 12,900±150 years B.P. (Robin and Cantagrel, 1982) and 13,270±90 years B.P. (this study). Soil developed on the Teteltzingo deposit is similar to, and thus suggests an age slightly greater than, that of the overlying pyroclastic flow deposit. Parts of the ancestral cone, which clearly predate the Teteltzingo deposit, are overlain by moraines of late Wisconsin age (Fig. 1). The moraines probably correspond to moraines having corrected radiocarbon ages of about 27,000 and 25,000 years B.P. at Ajusco volcano near Mexico City (White and Valastro, 1984). Thus the deposit is between 27,000 and 13,000 years B.P. in age, but on the basis of its soil development it is probably much younger than 27,000 years B.P. The deposit could have been emplaced during another glacial advance which occurred between 11,000 and 15,000 years B.P. at Ajusco and Iztaccíhuatl volcanoes (White, 1986).

Clay mineralogy and the origin of the Teteltzingo deposit

X-ray diffraction analysis of the clay-sized fraction of the Teteltzingo deposit reveals large proportions of smectite, small amounts of quartz and feldspar, and trace amounts of kaolinite and cristobalite. The rocks from the ancestral edifice that are hydrothermally altered, the alteration minerals within the Teteltzingo deposit, and the volume of the Teteltzingo deposit all indicate that the deposit originated with the collapse of weakened, water-saturated, hydrothermally altered rock from the ancestral volcano. The huge volume of clay and other secondary minerals within the avalanche deposit suggest that the portion of the ancestral edifice that collapsed must have contained of the order of 10^8 to 10^9 m^3 of intensively altered rock. Several samples from remnants of the ancestral cone, however, contain only small amounts of smectite. Apparently, therefore, most of the old hydrothermal system either avalanched down the northeast flank of the mountain or is now buried under the modern edifice.

Implications concerning behavior during flowage

Although it began as an edifice collapse, the Teteltzingo deposit has many features more typical of a debris flow than of a debris avalanche. In its proximal zone, relatively flat fill terraces are lower in valleys and thin veneer deposits coating older units are higher in valleys. The veneer deposits are relicts of the peak discharge of a very fluid flow before it drained away. Irregular hummocky topography with megablocks, closed depressions, and large transverse or lateral ridges that are indicative of a debris-avalanche deposit, are not present. The Teteltzingo deposit is exceedingly flat except for a few scattered hummocks in the medial zone.

Ui (1989) has suggested that hummocks are a definitive feature of debris-avalanche deposits; however, Scott et al. (1992) have shown that the Osceola Mudflow from Mount Rainier has nearly flat surfaces, and includes hummocks, yet behaved predominantly as a cohesive debris flow even in proximal areas. Because most large cohesive debris flows at volcanoes have origins as edifice collapses, their deposits have features of both debris avalanches and of debris flows. In fact, the results of this study, together with those of Crandell (1989), Scott et al. (1992) and Vallance (in press), suggest that a gradation in characteristics between those of cohesive lahars and those of debris avalanches exists in clayey deposits originating as edifice collapses.

The origin of water in the Teteltzingo debris flow and the importance of clay

Sources of water in the debris flow include water derived from the preexisting rocks of the volcano and water admixed with the debris. Because the Teteltzingo deposit has a volume of about 1.8 km^3, a large volume of water would be required to saturate it. The volume proportion of solids typical of debris flows is 0.6–0.78 (Pierson, 1985). Moreover, samples of the Osceola Mudflow, which is sedimentologically similar to the Teteltzingo deposit, have liquid limits that vary from 28 to 42 and average 33 (Crandell, 1971). Thus, if we assume an average water content of 33% for the Teteltzingo flow implies that at least 0.6 km^3 of water would have been needed to liquify it. There is not that much water in the rivers of this area at any time. The only possible sources for the water are glacial ice and snow, a crater lake, or pore water. Ice cannot be melted by sediment that is not hot. For example, if 10% of the potential energy of the pre-avalanche mass were converted to heat that was efficiently transferred to the ice during subsequent flowage, then frictional melting of ice and snow would have contributed less than 3% of the water needed to fluidize the avalanching debris. Although evidence of hot rock within the Teteltzingo deposit is absent, moderately hot rock from the hydrothermal system could have caused some melting of glacial ice if the hot rock and glacial ice were sufficiently well mixed. The water could also have come from a crater lake, but only if a large enough crater lake existed at 5,000+ m elevation during a glacial advance. Further, water from either a crater lake or melting of ice would have had to have been thoroughly mixed with the avalanching debris in order to saturate it uniformly. It is more likely that pore water, which would have been widely dispersed initially, was the principal source of the fluid. Clay in the hydrothermal system would have served to increase porosity but, more importantly, would have greatly reduced permeability. Continual melting of glacial ice would have provided a source of pore water. Therefore the large volume of hydrothermally altered, clay-rich rock that was present in the ancestral edifice of Citlaltépetl probably stored a large volume of water in its pore space.

The significance of ice in the development of hydrothermal systems

We checked descriptive material for North American volcanoes to examine the correlation between glaciation and evidence for hydrothermal alteration. Whereas several of the glaciated Cascades volcanoes show extensive hydrothermal alteration (Crandell, 1971, 1989; Dethier et al., 1981; Frank, 1983, 1985; Vallance, in press), no Central American (Siebert, 1988; Vallance et al., in press), and only a few ice-capped Mexican volcanoes (Citlaltépetl and Popocatépetl), are moderately altered. Mount Baker, which is presently covered by 48 km^2 of glacial ice making it one of the most extensively glaciated volcanoes in the Cascades Range, has an extensive hydrothermal system in the Sherman crater area (Frank, 1983). Frank discovered a suite of distinctive fine-grained secondary minerals including alunite, kaolinite, smectite, cristobalite, tridymite, opal, quartz, jarosite, and pyrite and speculated that, if similar alteration products were concealed within the summit edifice, a volume of up to 0.9 km^3 of hydrothermally altered rock might be present. Hyde and Crandell (1978) and Frank (1983) found that clay-rich avalanches and debris flows containing the same secondary minerals occurred at least 6 times during the past 6,000 years at Mount Baker.

Five cohesive lahars having a total volume in excess of 4 km^3 occurred at Mount Rainier in the past 5,000 years (Crandell, 1971; Scott et al., 1992). Mount Rainier is the most heavily glaciated mountain of the Cascades Range (92.1 km^2 and 4.4 km^3 of ice; Driedger and Kennard, 1986). A hydrothermal system in the summit area at the time of the Osceola Mudflow provided all of the hydrothermal clay that is present in that deposit (Crandell, 1971). Although the younger rock in the summit area is relatively fresh, a volume of about 1 km^3 of moderately to intensively altered rock is present in Sunrise Amphitheater (Frank, 1985). Vallance (in press) has estimated that Mount Adams, with 23 km^2 of ice cover, has between 1 and 3 km^3 of moderately to intensively altered rock within its edifice. Three small avalanches and two lahars with appreciable amounts of hydrothermal clay occurred during the past 6,000 years at Mount Adams.

In contrast, other less heavily glaciated volcanoes have much smaller volumes of hydrothermally altered rock. Mount Hood, whose glaciers cover 13.5 km^2, has patchy areas of moderately altered rock on its upper west and east flanks and a small area of intensively altered rock near crater rock. Mount Hood has had only one slightly cohesive, avalanche-induced lahar during Holocene times (unpublished field notes of W.E. Scott and J.W. Vallance).

The edifice of Mount Shasta collapsed about 350,000 years ago to form a 45-km^3 debris-avalanche deposit that has a clay-rich matrix facies (Crandell, 1989). Crandell (1989) infers that the matrix facies of that avalanche was water saturated during flowage and that the most likely source of the water was from the hydrothermal system of the ancestral edifice. On the basis of features of the avalanche deposit, Crandell (1989) suggests that glacier ice was present at Mount Shasta 350,000 years ago. Mount Shasta is presently covered by 6.9 km^2 of glacial ice, has exposures suggesting only a moderate amount of alteration in the summit fumarole field, and has no avalanche or debris-flow deposits of Holocene age containing appreciable amounts of hydrothermal clay (Miller, 1980).

The degree of hydrothermal alteration at 10 Cascades Range volcanoes and Citlaltépetl is assessed as to volume of altered rock and intensity of alteration and assigned discrete values of 0, 1, 2, 3, or 4 (Fig. 3). Larger numbers indicate larger areas of hydrothermal alteration, or more intensively altered rock, or a combination of both; these indicators of the degree of alteration are defined in the caption of Figure 3. This measure of hydrothermal alteration is subjective but allows comparison of

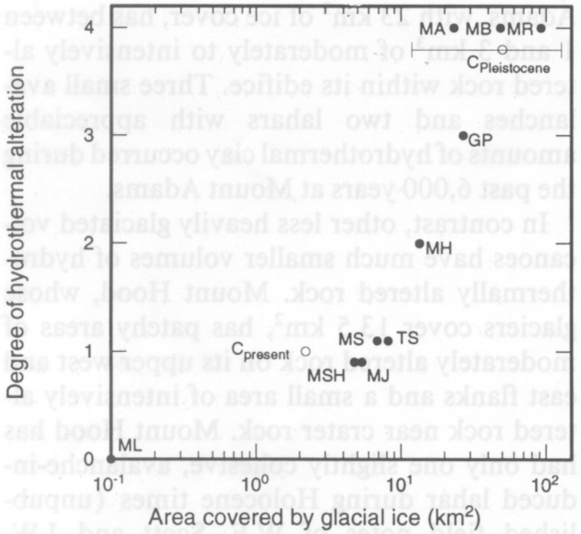

Fig. 3. Plot showing the degree of hydrothermal alteration versus area covered by glacial ice for the Cascades volcanoes and Citlaltépetl volcano. Zero indicates no appreciable alteration; 1, small areas of moderately altered rock; 2, moderate areas of moderately altered rock with possible small areas of intense alteration; 3, large areas of moderately altered rock and some intensively altered rock; and 4, large areas of intensely altered rock. Symbols for volcanoes are: *C*=Citlaltépetl; *GP*=Glacier Peak; *MA*=Mount Adams; *MB*=Mount Baker; *MH*=Mount Hood; *MJ*=Mount Jefferson; *ML*=Mount Lassen; *MR*=Mount Rainier; *MS*=Mount Shasta; *MSH*=Mount St. Helens; and *TS*=Three Sisters.

the degree of hydrothermal alteration and glacial ice cover. Although there is considerable scatter in the correlation of glacial ice and hydrothermal alteration, a trend is apparent (Fig. 3), and we conclude that an association between glaciation and extensive hydrothermal alteration is possible.

Impact of glaciation on the process of low-temperature hydrothermal alteration

The process of low-temperature hydrothermal alteration is the result of: (1) degassing and ascent of volcanic gases like H_2O, CO_2, H_2S, SO_2, and HCl; (2) combination of these gases, especially SO_2 which is highly soluble, with atmospheric oxygen and meteoric water to form sulfuric and other acids near the surface; and (3) descent and circulation of the acidic fluids (Frank, 1983). This process, known as acid-sulfate leaching, adds sulfate and removes mobile elements from the surrounding rocks to form clay, silica, and sulfate minerals. Volcanic gases, meteoric water, and atmospheric oxygen are all necessary to the process.

Obviously, hydrothermal alteration of rock can occur in areas where there are no glaciers. For example, geothermal areas at Steamboat Springs, Nevada, USA (Schoen et al., 1974) and Wairakei, New Zealand (Steiner, 1968, 1977) have highly leached zones of alteration that are dominated by acid sulfate waters derived from oxidation of sulfurous gases. Schoen and his colleagues and Steiner found the same mineral assemblage in altered rock at Steamboat Springs and at Wairakei that Frank (1983), Frank (1985), and Vallance (in press), found at Mount Baker, Mount Rainier and Mount Adams.

Hydrothermal alteration can also occur at unglaciated volcanoes. A large volume of clayey altered rock is present within the Kawah Mas massif of Papandayan volcano, Indonesia (Frank et al., 1987). Further, an eruption of Papandayan volcano in 1772 produced a clay-rich debris avalanche and debris flows that came from that area of hydrothermally altered rock (Glicken et al., 1987). Oki and Hirano (1970) describe a hydrothermal area at Hakone volcano in Japan, and Henley and Ellis (1983) describe several other examples.

Although intensively altered hydrothermal rock is exposed at some unglaciated volcanoes, there are two possible reasons that altered rock is more common and more intensively altered at glaciated volcanoes. First, glacial erosion may expose deeper potentially more altered portions of the edifice because glacial erosion more effectively incises deeply into an edifice than do normal hillslope and alluvial erosion. Thus there may be more extensive areas of hydrothermally altered rock exposed at glaciated volcanoes. Further, these areas could be more susceptible to failure because the altered rock is weak and because the slopes are apt to be overly steepened by glacial erosion.

Second, the presence of ice may actually enhance the process of alteration. Acid sulfate leaching is apt to be enhanced by a slow steady supply of water above the water table that produces small to moderate fluxes of concentrated acidic hydrothermal fluid. Large fluxes of water from infiltration during heavy rain may dilute these fluids. Except in polar climates, basal pressure melting of glaciers is ubiquitous. During periods when hot gases migrate to the surface, additional melting occurs and more meteoric water is provided to the hydrothermal system. Ablation during summer months also provides water. Thus the presence of an extensive ice cap could act as a slow-release reservoir of water to supply the hydrothermal system at depth and enhance hydrothermal alteration processes.

Obviously, unglaciated volcanoes in arid climates or in climates with long dry seasons will have a sparse or sporadic supply of water in the vadose zone; this will inhibit the alteration process. In contrast, volcanoes in wet tropical climates may have almost daily rains. Although a daily supply of groundwater from rain could enhance hydrothermal alteration, it may be less effective than melting of ice because it would come all at once, thus diluting the acid solution, especially above the water table. The water from infiltration during heavy rain could quickly be flushed through the edifice if the underlying rock is permeable pyroclastic rock or fractured lava, thus further diminishing the acid sulfate leaching process.

TABLE 2

Comparison of selected debris avalanche and cohesive lahar deposits

Name	Volcano	Age (years)	Runout (km)	H/L	Area (km^2)	Volume (km^3)	Secondary alteration minerals[1]	References[2]
Debris avalanches								
May 18, 1980	Mount St.Helens	1980 A.D.	24	0.11	64	2.8	sm, ch[3]	1, 2
Bezymianny	Bezymianny	1956 A.D.	18	0.13	60	0.8	not reported	3
Bandai	Bandai	1888 A.D.	11	0.11	34	1.5	not reported	3
Mayu-yama	Unzen	1796 A.D.	6.5	0.13	15	0.34	not reported	3
Papandayan	Papandayan	1772 A.D.	11	0.14	18	0.14	not reported[4]	3, 4, 5
Volcán Colima	Volcán Colima	4,300 B.P.	43	0.09	1,200	6–12	not reported	6, 7
Nevado de Colima	Nevado de Colima	18,500 B.P.	120	0.04	2,200	22–33	not reported	7
Popocatépetl	Popocatépetl	late Pleistocene	30	0.12	300	30	not reported	8
Mount Shasta	Mount Shasta	300 to 360 ka.	49	0.07	675	45	not reported[5]	9
Cohesive lahars								
Salt Creek	Mount Adams	200 B.P.	40	0.08	16	0.015	sm, k, a	10
Electron	Mount Rainier	600 B.P.	70	0.06	60+	~0.25	sm, ch, qz, c	11
Round Pass	Mount Rainier	2,800 B.P.	30	0.13	50+	~0.2	sm, ch, il, o, c	11
Osceola	Mount Rainier	5,700 B.P.	100	0.04	325	2.8	sm, k, il, ch, qz, c	11
Paradise	Mount Rainier	5,700 B.P.	40	0.1	34	~0.1	sm, k, o, c	11
Trout Lake	Mount Adams	6,000 B.P.	70	0.06	27	0.07	sm, k, a	10
Middle Fork	Mount Baker	6,000 B.P.	29	0.11	no data	0.05	sm, k, c, a, il	12, 13
Teteltzingo	Citlaltépetl	13,000 to 27,000 B.P.	85	0.055	140	1.8+	sm, k, qz, c	this report

[1]Secondary minerals are: sm - smectite; k - kaolinite; a - alunite; ch - chlorite; qz - quartz; c - cristobalite; il - illite; and o - opal.

[2]References are: 1 - Dethier et al. (1981); 2 - Voight et al. (1983); 3 - Siebert et al. (1987); 4 - Glicken et al. (1987); 5 - Frank et al. (1987); 6 - Luhr and Carmichael (1990); 7 - Stoopes and Sheridan (1992); 8 - Robin and Boudal (1987); 9 - Crandell (1989); 10 - Vallance (in press); 11 - Crandell (1971); 12 - Hyde and Crandell (1978); and 13 - Frank (1983).

[3]Dethier et al. (1981) report small amounts of these secondary minerals.

[4]Secondary clay minerals are common in the avalanche deposit (Glicken et al., 1987) and its scarp (Frank et al., 1987), but the minerals present are not reported.

[5]Large amounts of clay are present in a sample of the matrix facies, but the minerals present are not reported (Crandell, 1989).

Hazard implications and conclusions

There is a strong correlation between large volumes of clay-rich rock and the likelihood of edifice collapse (e.g., Crandell, 1971; Hyde and Crandell, 1978; Frank, 1983; Crandell, 1989; Scott et al., 1992; Vallance, in press). The alteration of fresh rock to form clay and other secondary minerals weakens the rock. The presence of clay increases porosity and increased pore-water content may further destabilize the altered rock, thus making it more susceptible to slope failure. Collapses of hydrothermally altered rock typically form cohesive debris flows rather than debris avalanches (Table 2). Although cohesive debris flows and debris avalanches have similar origin, cohesive lahars have longer runouts and may spread more widely than debris avalanches having similar volume (Fig. 4).

The ratio of vertical drop to travel distance (H/L) has been used in an attempt to predict the maximum runout of debris avalanches (Schuster and Crandell, 1984; Siebert et al., 1987; and Crandell, 1989). However, the method is not completely straightforward because H/L tends to decrease with increase in avalanche volume (Fig. 4). A survey of volcanic debris-avalanche deposits (Siebert et al., 1987) shows that H/L of debris-avalanche deposits having volumes greater than about 1 km^3 average 0.09 and range from 0.05 to 0.13, whereas for smaller avalanches, H/L ratios average 0.13 and range from 0.09 to 0.18. Stoopes and Sheridan (1992) document an unusually mobile avalanche from Nevado de Colima with

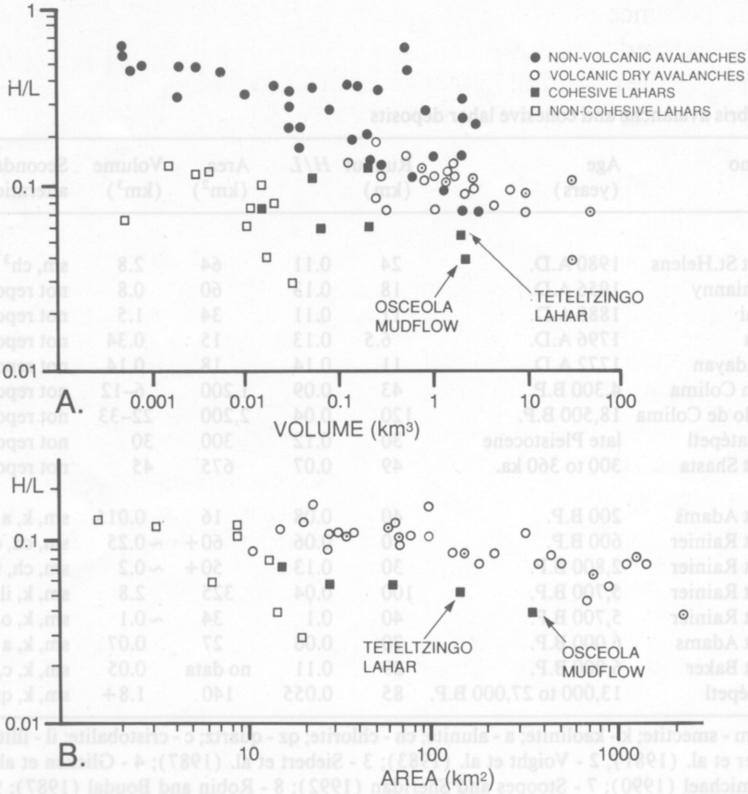

Fig. 4. Plots of height to length ratio (H/L) versus volume (V) and H/L versus area for volcanic debris avalanches, nonvolcanic avalanches, cohesive lahars, and noncohesive lahars. Sources of data are: cohesive lahars and some volcanic avalanches (circles with dots at their centers) – given in Table 2; avalanches – Ui (1983) and Siebert et al. (1987); noncohesive lahars – Pierson (1985), and Scott (1988).

H/L equal to 0.04. Schuster and Crandell (1984) propose an H/L of 0.075 for estimating the maximum runout of debris avalanches, and Siebert et al. (1987) suggest 0.05 as a worst case. The Teteltzingo lahar, with an H/L of 0.055, and the other cohesive lahars documented in Table 2 have H/L ratios that range from about 10% to more than 50% smaller than average H/Ls of comparably sized volcanic debris avalanches (Fig. 4). If the H/L method is used to estimate runouts of large avalanche-induced lahars, a value of about 0.04 should be used to encompass the examples cited in Table 2.

In attempting to assess the potential hazard of edifice collapse at a volcano, the issue of whether the avalanching debris will transform into a lahar or behave as an unsaturated debris avalanche is important because their mobilities are different. The presence of a large volume of hydrothermally altered rock within the volcano not only increases the potential for edifice collapse because the altered rock is less competent, but also increases its potential for flow as a saturated, liquified debris flow because the rock can hold more water. Thus the presence of large volumes of hydrothermally altered rock at a volcano greatly enhances the risk from cohesive lahars at that volcano.

Cohesive lahars at volcanoes generally begin with edifice collapse and avalanche of clay-rich, water-saturated debris. Their deposits may have some characteristics of debris flows and debris avalanches. This report describes such a lahar at Citlaltépetl, located in Mexico at 19°N, one of first described occurrences of a huge cohesive lahar in a tropical latitude. The presence of an active glacier appears to be an important environmental factor for the occurrence of such a lahar, because it provides a continual supply of water to enhance acid-sulfate alteration and because the glacier deeply erodes the edifice. Glaciated volcanoes anywhere in the world must therefore be considered especially susceptible to mobile, hazardous cohesive lahars.

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