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Journal of Volcanology and Geothermal Research 117 (2002) 213–235

Journal of volcanology and geothermal research

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The cohesive Naranjo debris-flow deposit (10 km^3): A dam breakout flow derived from the Pleistocene debris-avalanche deposit of Nevado de Colima Volcano (México)

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Received 15 October 2000; accepted 25 July 2001

Abstract

Mass movement processes on volcanic terrains such as landslides and debris avalanches can cause the obstruction of main drainages producing the formation of temporary dams. A good example of this occurred 18.5 ka ago when the eastern flank of the Nevado de Colima Volcano collapsed producing a debris-avalanche deposit that was previously described as one of the largest in the world. The deposit extended from the volcanic summit as far as the Pacific coast, 120 km away. New stratigraphic, sedimentological, and componentry data suggest that the volcanic collapse of Nevado de Colima resulted in a debris avalanche that traveled 20 km southeast to the Naranjo River. There it crashed against a topographic barrier consisting of Cretaceous limestones (Cerro la Carbonera) and the flow direction was diverted to the south down the Naranjo River channel for another 25 km before the avalanche came to a halt. The obstruction of the drainage produced a temporary dam that stored ca. 1 km^3 of water and deposited fluvial and slack-water sediments. Some time after the damming, the accumulated water-sediment load was able to overtop the obstructing material and to release a breakout flow with a calculated initial flow discharge of 3.5 million m^3/s. The resulting flood (cohesive debris flow) followed the channel of the Naranjo River and, due to the high erodibility of the channel and introduction of substrate material, the debris flow progressively increased its volume up to 10 km^3, six times its initial volume. This study highlights the relevance of evaluating the potential remobilization of debris-avalanche deposits to initiate large magnitude cohesive debris flows. Therefore, the hazard and risk analysis of future potential events of this nature must consider the pre-eruption conditions and the topography surrounding a volcano.

Keywords: debris avalanche; cohesive debris flow; dam breakout; Colima Volcanic Complex; Mexico

1. Introduction

The collapse of a volcanic edifice has been recognized as a common event at numerous volcanoes around the world (Ui et al., 1986; Siebert et

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0377-0273/02/$ – see front matter
PII: S0377-0273(02)00245-7

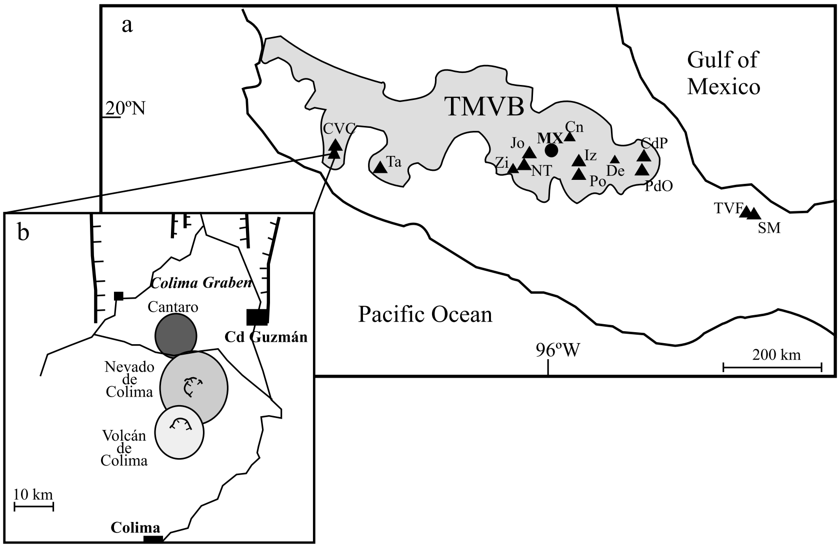

Fig. 1. (a) Sketch map of the TMVB showing the location of the volcanoes which have suffered a sector collapse (after Capra et al., 2002). Abbreviations: CVC, Colima Volcanic Complex; Ta, Tancítaro; Zi, Zirahuato; Jo, Jocotitlán; NT, Nevado de Toluca; Iz, Iztaccihuatl; Po, Popocatépetl; Cn, Cerro Las Navajas; PdO, Pico de Orizaba; De, Las Derrumbadas; CdP, Cofre del Perote; TVF, Tuxtla Volcanic Field; SM, Santa Martha. (b) Tectonic location of the Colima Volcanic Complex in the Colima Graben.

al., 1987; Vallance et al., 1995) as well as in the Trans-Mexican Volcanic Belt (TMVB) (e.g. Robin and Boudal, 1987; Siebe et al., 1992; Carrasco-Nuñez et al., 1993; Nelson and Lighthart, 1997; Rodriguez-Elizarrarás and Komorowski, 1997; Garduño-Monroy et al., 1999; Capra et al., 2002; Fig. 1a). This type of event involves the partial disruption of a volcano flank initiating a gravitational mass flow capable of moving many kilometers before coming to rest: the resulting materials are widely described as debris-avalanche deposits. These deposits are commonly associated with thick sequences of debris-flow deposits, which extend beyond the limits of the debris-avalanche deposits.

Debris flows originate from: (1) direct transformation of a debris avalanche during its transport (Scott et al., 2002a); (2) transformation of the distal portion of a water-saturated debris avalanche (Palmer and Neall, 1989); (3) post-depositional remobilization of water-saturated portions of a debris avalanche (Glicken, 1998; Pulgarin et al., 1999); and (4) rupture of natural dams formed by the obstruction of drainages during the emplacement of a debris-avalanche deposit (Costa, 1988; Costa and Shuster, 1988). Generally, the first two cases are processes that take place during the related collapse event or some hours later. In contrast, the last two cases can occur following an indeterminate lapse of time, which can range from hours to years without any premonitory sign (Costa and Shuster, 1988).

The 1980 collapse of Mount St. Helens represents the best known example of the formation of natural dams after the emplacement of a debris-avalanche deposit. Engineering work there prevented the rupture and collapse of these natural dams, which otherwise would have produced gigantic debris flows downstream (Sager and Chambers, 1986).

The emplacement of a debris avalanche generally modifies the topography of the area around the volcanic edifice resulting in the interruption and deviation of the hydrological network. Therefore, the formation of natural impoundments by blocking the drainage system and their subsequent breakout should be a common process in volcanic terrains.

In this work we present new field evidence for the generation of a huge cohesive debris flow derived from the rupture of a natural dam formed by the Pleistocene debris-avalanche deposit from the Nevado de Colima Volcano. The debris-avalanche and debris-flow deposits studied here were previously described by Stoopes and Sheridan (1992) as a single debris-avalanche deposit that extends for 120 km from the edifice. Our new stratigraphic and sedimentological data provide useful information to differentiate two types of deposits involved in this complex event. In the light of these new data we propose a new sequential model for the collapse, drainage damming, and generation of a gigantic debris flow by rupture of the dam. Finally, we discuss the importance of recognizing such types of events around volcanic areas since they can be responsible for the flooding of immense zones at even further distances from the collapse area.

2. Terminology

The terminology used in this text (Table 1) is modified mainly from the works of Palmer et al. (1991) and Glicken (1991). Common doubts are generally expressed in the literature concerning the distinction between a debris-avalanche deposit and a debris-flow deposit, which forms a key topic for this study. As stated in the following section, the textural and sedimentological characteristics of these two types of deposits can be discriminated because their sedimentological parameters, the porosity of the matrix, and the presence or absence of imbricated clasts can be used to distinguish sediment-water transport for debris flows versus granular transport for debris avalanches.

3. Previous work

The Colima Volcanic Complex (CVC) is located in the western TMVB, at the southern limit of the Colima Graben (Fig. 1a and b). It consists of three andesitic composite cones, Cantaro, Nevado de Colima, and Volcán de Colima. The last two volcanoes have been the locus of several sector collapses (Luhr and Prestegaard, 1985; Robin et al., 1987; Luhr and Prestegaard, 1988; Stoopes and Sheridan, 1992; Komorowski et al., 1994, 1997). The source area, the extension of the deposits, and the number of collapse events have been the subject of controversy among many authors during the past 15 years.

Nevado de Colima Volcano (4240 masl) began to grow ~600 ka with the youngest dated activity occurring ~8.1 ka (Robin et al., 1990). According to these authors, the volcanic activity of Nevado can be divided in three main episodes (Nevado I, II and III; Robin et al., 1987). The

Table 1
Terminology

Term	Explanation
Debris avalanche	Rapid movement of an incoherent, unsorted mass of rock and soil mobilized by gravity (Schuster and Crandell, 1984).
Block facies	Texture of a debris-avalanche deposit that mainly consists of debris-avalanche blocks (an unconsolidated piece of the old mountain transported to its place of deposition) with practically no matrix.
Mixed facies	The mixed facies (interclast matrix and clasts) defines the texture of a debris-avalanche deposit that is completely mixed. It may contain clasts of all rock types and sizes from microns to meters.
Matrix	All components of the deposit comprising material <2 mm in diameter.
Clast	Fragment with dimensions from 2 mm to 1 meter.
Megaclast	All components of the deposit >1 m that show an internal lithological homogeneity.
Debris flow	Flowing mixture of debris and water having a sediment concentration between 70 and 90% by weight (Pierson and Costa, 1987). When the content of clay fraction is >3–5% in weight, they are defined as cohesive debris flows (Scott et al., 1995).
Lahar	General term for rapidly flowing water-saturated mixture of rock debris and water from a volcano (Smith and Fritz, 1989).

Nevado I and III episodes were characterized by intense effusive activity with the extrusion of andesitic lava flows followed by extrusion of summit domes and emission of associated pyroclastic deposits. The Nevado II episode, which started at ca. ~200 ka, was also characterized by the emission of thick andesitic lava flows and a Bezymianny-type sector collapse that produced a debris-avalanche deposit probably associated with a 4-km-wide eastward horseshoe-shaped caldera (Robin et al., 1987). Stoopes and Sheridan (1992) determined the age of the deposit formed by this event to be 18 520 ± 260 yr BP, by dating a carbonized tree imbedded in the debris-avalanche deposit.

When Robin et al. (1987) first described the debris-avalanche deposit of Nevado de Colima, they considered that it extended up to 20 km southeast from the edifice, where it graded into lahars between the towns of San Marcos and Atenquique (Fig. 2a). Stoopes and Sheridan (1992) concluded that the debris-avalanche channeled into the drainage of the Naranjo and Salado Rivers and traveled more than 120 km to the Pacific coast, covering an area of 2200 km^2 with a total volume of 22–33 km^3 (Fig. 2c). According to the runout distance (L) and drop height (H), these authors obtained a H/L value of 0.04 that is the lowest value found for a debris-avalanche deposit on Earth.

Colima Volcano (3820 masl) is an active composite cone that may have started to grow at ca. ~50 ka (Robin et al., 1987) with important recent eruptions in 1913, 1961, 1975, 1981, 1991 and 1998–2000 (i.e. Thorpe et al., 1977; Rodriguez-Elizarrarás et al., 1991; Saucedo et al., 1997; Smithsonian Institution, 1999). Paleofuego, the ancestral edifice, presents a southward horseshoe-shaped caldera where the currently active cone has been built. Luhr and Prestegaard (1985) first described a debris-avalanche deposit that originated from the Paleofuego Volcano, exposed south of the volcanic edifice, covering an area of 1550 km^2. These authors dated the event at 4280 ± 110 yr BP from charcoal found in a pyroclastic-surge deposit directly overlain by the debris-avalanche deposit. In contrast, Robin et al. (1987) reported an age of 9370 ± 400 yr BP from charcoal obtained in a pyroclastic flow unit above the avalanche deposit, therefore complicating the stratigraphic framework of the deposit.

Robin et al. (1987) and Stoopes and Sheridan (1992) presented a similar distribution for the Volcán de Colima debris-avalanche deposit. They marked the southern limits of the deposit around the City of Colima covering an area of 500 km^2 but without channeling in the Naranjo and Salado Rivers (Fig. 2a and c). According to Stoopes and Sheridan (1992), the younger Colima debris-avalanche deposit overlies the 18.5-ka Nevado de Colima debris-avalanche deposit (here separated by paleosoil horizons) on the eastern portions of the deposit (Fig. 2c). In contrast, Luhr and Prestegaard (1988) proposed a more extended distribution for the 4.3-ka deposit since they reported a thick debris-avalanche deposit in the Naranjo and Salado Rivers that correlated with the Volcán de Colima collapse (Fig. 2b).

In summary, after the most recent studies it is clear that the Nevado de Colima and Colima Volcanoes collapsed at least once each, promoting at least two distinct debris-avalanche units.

More recently Komorowski et al. (1997) presented a different scenario for both volcanoes, proposing that collapse has occurred at least 12 times in the last 45 000 yr and perhaps as many as nine times from the younger edifice. Their hypothesis is based on radiocarbon dates of paleosoils and lacustrine deposits most of them in La Platanera Gully (Fig. 3), interbedded with different debris-flow units many of which were interpreted as debris-avalanche deposits. Because of the impossibility of mapping these deposits over their entire extension, these authors did not present a stratigraphic correlation between individual units and did not give any description of these units. Despite the spread of radiocarbon ages of debris-avalanche/debris-flow deposits it is not clear whether they represent a more complex collapse history of the Colima Volcanic Complex.

In this study we follow the interpretation of two main volcanic collapses, the 18.5 ka of the Nevado de Colima and the 4.3 ka of the Volcán de Colima. For the sake of simplicity, we will refer to these two debris-avalanche deposits (DAD) as the 18.5-ka DAD and the 4.3-ka DAD.

The distribution of the deposits here described is consistent with that proposed for the 18.5-ka DAD by Stoopes and Sheridan (1992). However, as described below, we divided the later deposit into two different units, which represent discrete events.

The 18.5-ka collapse, defined as a Bezymianny-type event, will be not described in this work because it has been discussed already extensively (Robin et al., 1987, 1990; Stoopes and Sheridan, 1992).

4. Morphology and hydrological conditions of the area

The CVC is located in the southern part of the Colima Rift Zone, a N–S structure that joins two

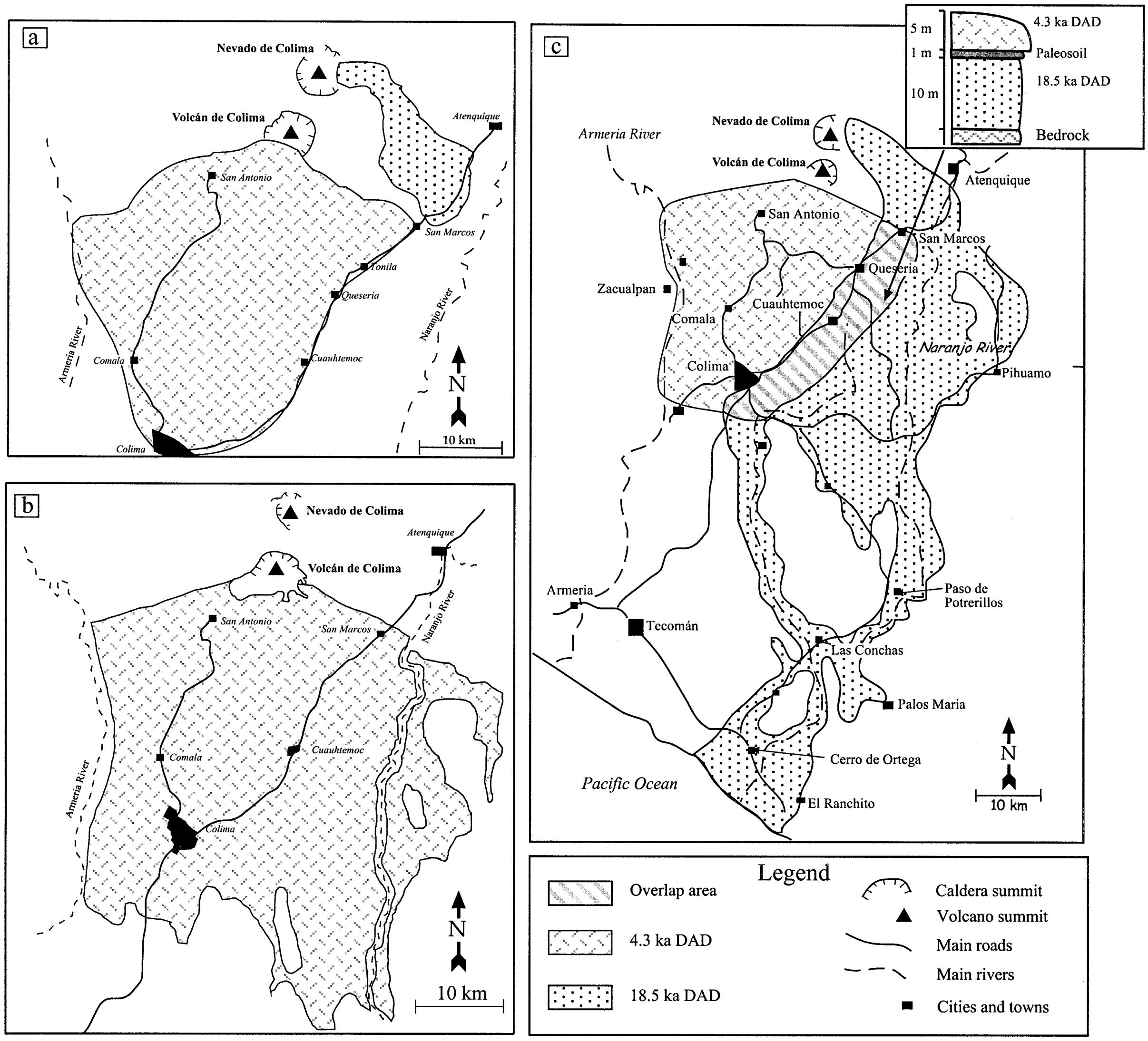

Fig. 2. Distribution of the CVC debris-avalanche deposits according to: (a) Robin et al. (1987); (b) Luhr and Prestegaard (1988); (c) Stoopes and Sheridan (1992), where the stratigraphic relation between the 4300-yr-BP and 18 500-yr-BP debris-avalanches deposits is shown.

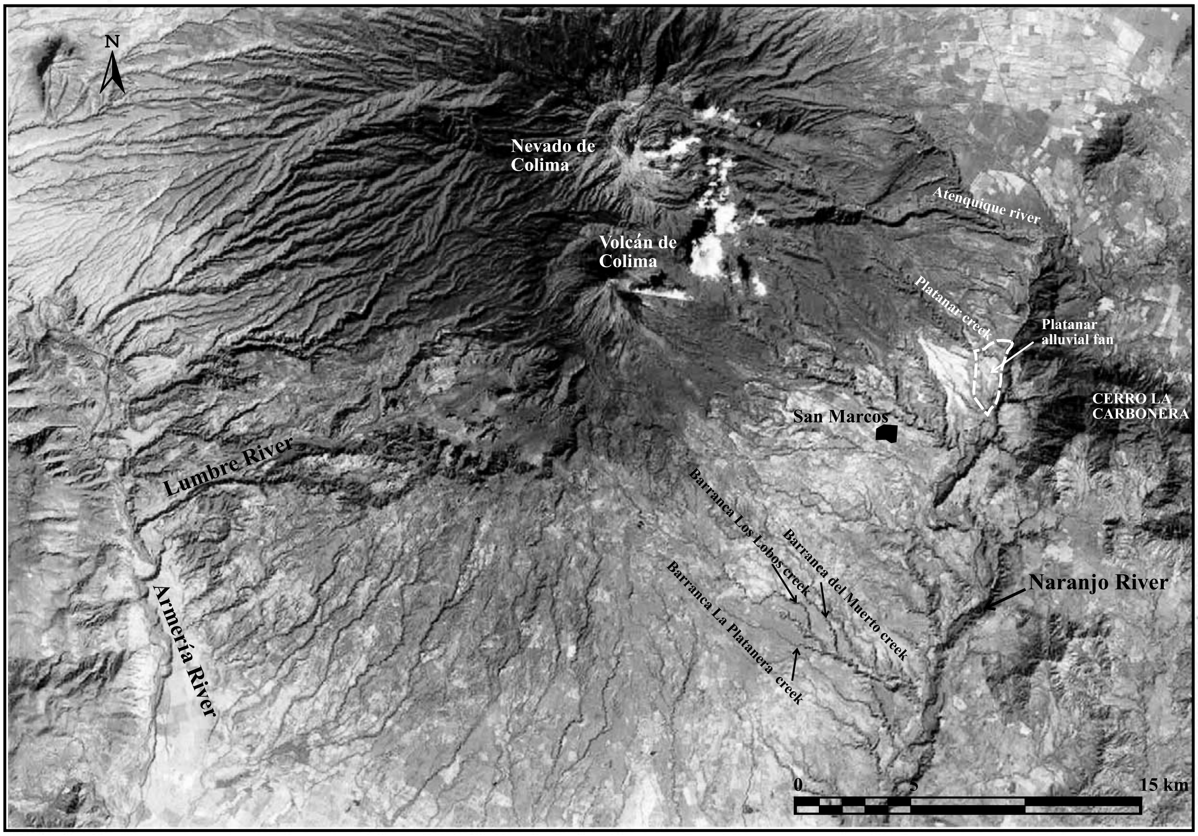

Fig. 3. Landsat image of the CVC showing the morphology of the area and the hydrographic network. Main rivers are labeled in the image.

others to the north in a tectonic triple junction (Luhr et al., 1985; Garduño and Tibaldi, 1991) and is crossed at the position of the active volcano by the proposed NE–SW Tamazula fault system (Garduno et al., 1998). The volcanic edifices of the CVC lie within these major structures, which in turn have a remarkable control on the drainage pattern of the Naranjo, Armeria, and Salado Rivers, which appear as long linear segments oriented N–S in satellite imagery (Fig. 3).

A large volcaniclastic apron flanks the CVC, on top of which many important towns are located, including San Marcos, Cuauhtemoc, and the capital city Colima. This sedimentary apron has been incised by a radial drainage (e.g. Barrancas Los Lobos, El Muerto, and Platanar) whose tributaries debouch into the main rivers. Particularly, Platanar Creek drains towards the El Naranjo River where it forms an alluvial fan that corresponds to the zone where the 18.5-ka Nevado de Colima debris-avalanche deposit obstructed the Naranjo River (Fig. 3). Cretaceous limestones and metamorphic rocks form the major escarpments in the southern portion of the Colima Rift Zone walls. Some limestone hills constitute morphological barriers on the east and west sides of the CVC including Cerro la Carbonera, located about 20 km from the eastern flank of Nevado de Colima and rising 500 m above the surrounding area (Fig. 3).

5. Deposit distribution and stratigraphic relations with younger units

In this work two main deposits are associated with the 18.5-ka edifice collapse of Nevado de Colima. The boundary of the area covered by these two deposits corresponds with the limits presented by Stoopes and Sheridan (1992) for the debris-avalanche deposit, but instead of considering this as a single unit, we distinguish a debris-avalanche deposit with secondary debris-flow deposits and a huge cohesive debris-flow deposit

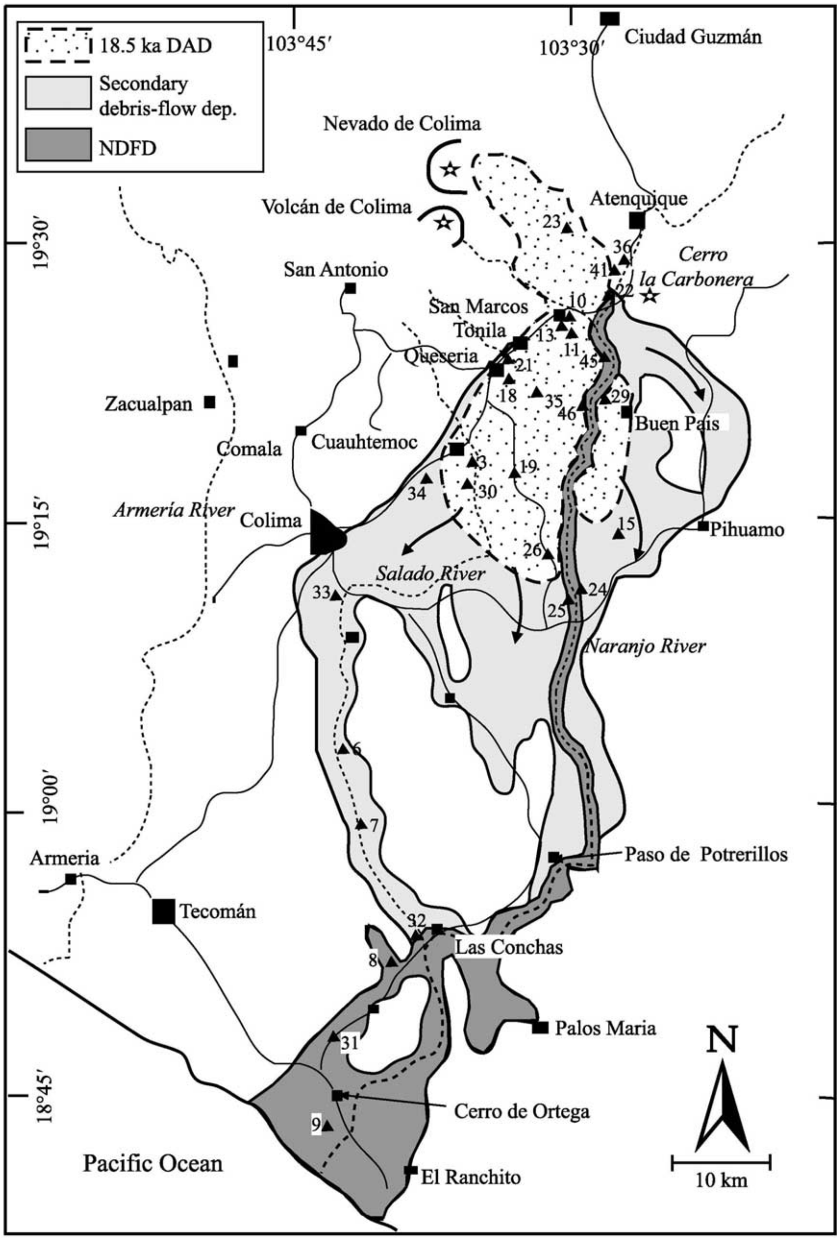

Fig. 4. Distribution of debris-avalanche and debris-flow deposits as interpreted in this study. The total distribution conforms with that presented by Stoopes and Sheridan (1992). Black arrows indicate the flow paths of secondary lahars remobilized from the debris-avalanche deposit. Numbered triangles mark the locations of studied sections.

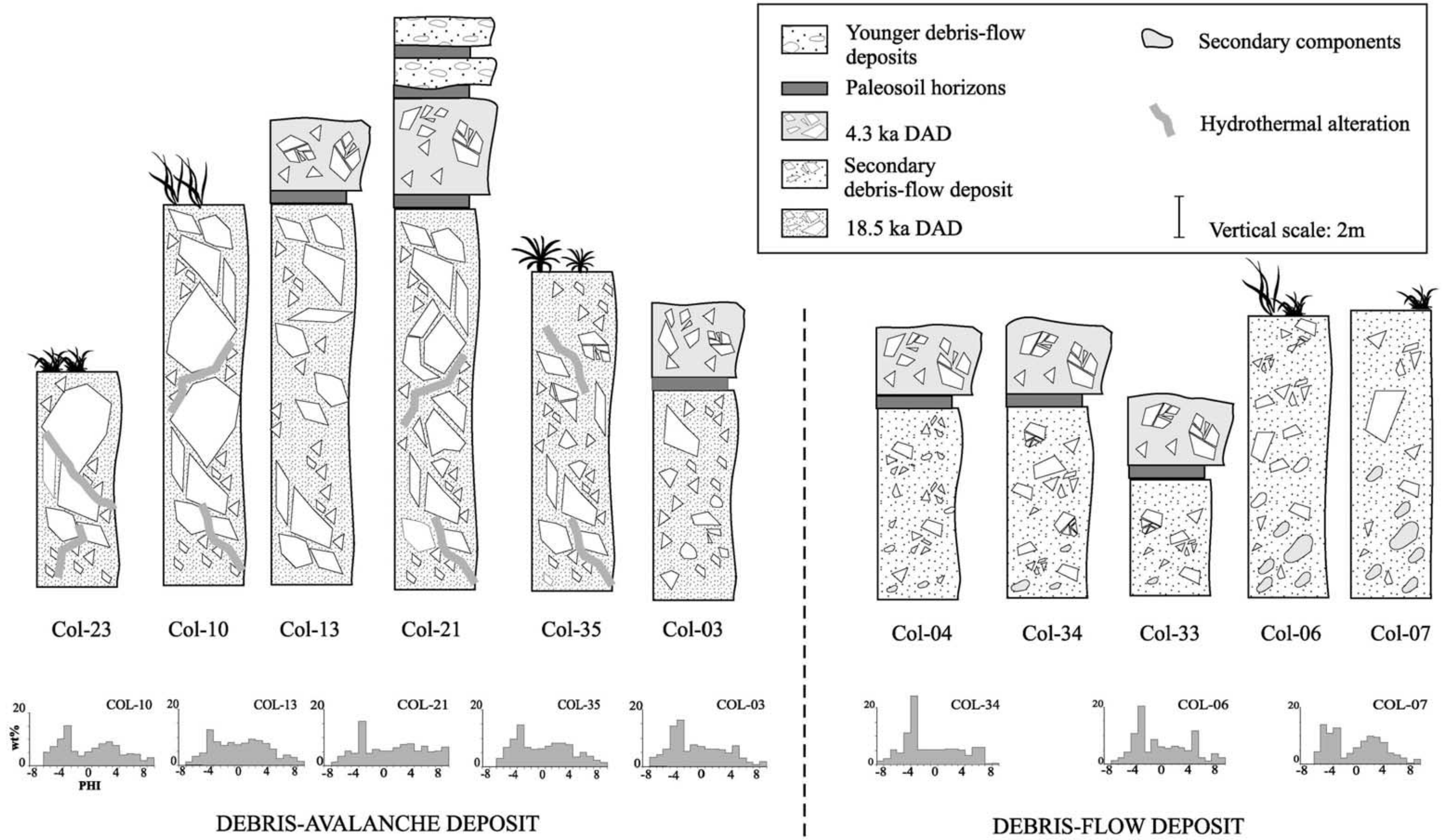

Fig. 5. Stratigraphic correlation of selected sections of the 18.5-ka DAD, its derivative debris-flow deposit along the Salado River, the 4.3-ka DAD, the younger debris-flow deposits, and interbedded paleosoils (column width represents erosive profile). The granulometric histograms refer to the 18.5-ka DAD and to the secondary debris-flow deposit along the Salado River. For section location see Fig. 4.

emplaced along the Naranjo River, here informally named the Naranjo Debris-Flow Deposit (NDFD) (Fig. 4).

5.1. 18.5-ka Debris-Avalanche Deposit

The 18.5-ka DAD crops out from the aprons of Nevado de Colima Volcano to Cerro la Carbonera (Fig. 3), some 20 km from the summit, and to the south forms the upper terraces of the Naranjo River to a distance of ∼45 km (Fig. 4). In proximal outcrops the deposit is directly overlain by co-magmatic pyroclastic-flow and -fall deposits (Robin et al., 1990). Elsewhere, it rests close to the top of the terraces along the Naranjo River, directly overlying the Atenquique Formation, a volcaniclastic sequence composed of fluvial conglomerates, massive debris-flow deposits and lacustrine horizons (total thickness of up to 200 m). The latter formation has an age range from 0.38 ± 0.10 Ma (Robin et al., 1987) to ∼40 ka (see below). Above an intervening paleosoil, the 18.5-ka DAD is capped by the 4.3-ka DAD, and up to two younger debris-flow deposits separated by paleosoils (section Col-21; Fig. 5). Between the towns of Tonila and San Marcos a 40-cm-thick paleosoil and the 4.3-ka DAD cover the 18.5-ka DAD (section Col-13; Fig. 5). The younger debris-flow deposits likely represent the products of post-depositional remobilization of the 4.3-ka DAD or a younger event of similar origin (Komorowski et al., 1997).

The exposed thickness of the 18.5-ka DAD varies from a maximum of 50 m (but probably up to 150 m thick where it obstructed the Naranjo River) to a minimum of 4 m on the left side of the Naranjo River near the town of Buen País (section Col-29; Fig. 4). It covers an approximate area of 600 km^2 and taking a mean thickness of 16 m a total volume of ca. 10 km^3 is obtained.

In summary, the 18.5-ka DAD is bracketed between the older Atenquique Formation and the 4.3-ka DAD from Colima Volcano. These stratigraphic relations were used to follow the lateral transition of the 18.5-ka deposit to a debris-flow sequence dispersed on the southern plain and farther downstream on the Salado River (Fig. 5).

In distal areas, the identification of the secondary 18.5-ka debris-flow deposits is more problematic due to the lack of the overlying 4.3-ka DAD. However, in the Salado River a debris-flow deposit lying at the same stratigraphic level has been identified and correlated with the 18.5-ka DAD. The debris-flow deposit along the Salado River consists of a single unit which forms a terrace deposited directly on top of basement conglomerates and metasediments.

The secondary debris-flow deposits may represent a single laharic event, or a series of lahars remobilized from the marginal portions of the 18.5-ka DAD that were later channeled into separated downstream drainages depositing different laterally separated units.

These secondary debris-flow deposits cover an approximate area of 800 km^2; by considering an average thickness of 3 m in the flat areas and 10 m in the channeled zones, we calculated a volume of 3.5 km^3. It is worth noting that the younger deposits are very similar in component composition and texture, and we do not exclude the possibility that the sequence described here could be confused with younger units in some sections where the stratigraphic relations are not clear.

5.2. Naranjo Debris-Flow Deposit

The NDFD forms the youngest terrace on the Naranjo River where it is inset against older terraces. The latter was dated at 41 205 yr BP ($\delta^{13}C$ −22.7, sample Col9828, lab. No. A-11103), based on a piece of wood embedded in a massive debris-flow deposit from the base of the older terrace. This terrace probably represents the youngest emplacement event of the Atenquique Formation (Figs. 6a and 7). We infer that this debris-flow deposit might be related to an older catastrophic collapse-event of the Nevado de Colima Volcano, but we do not have any evidence to support this assumption.

The NDFD has a maximum thickness of about 40 m but it never occurs beyond the margins of the channel forming overbanks deposit. The NDFD directly overlies older debris-flow deposits of the Atenquique Formation or basement rocks such as metasediments and limestones. Fig. 6a shows the relationship between the NDFD depos-

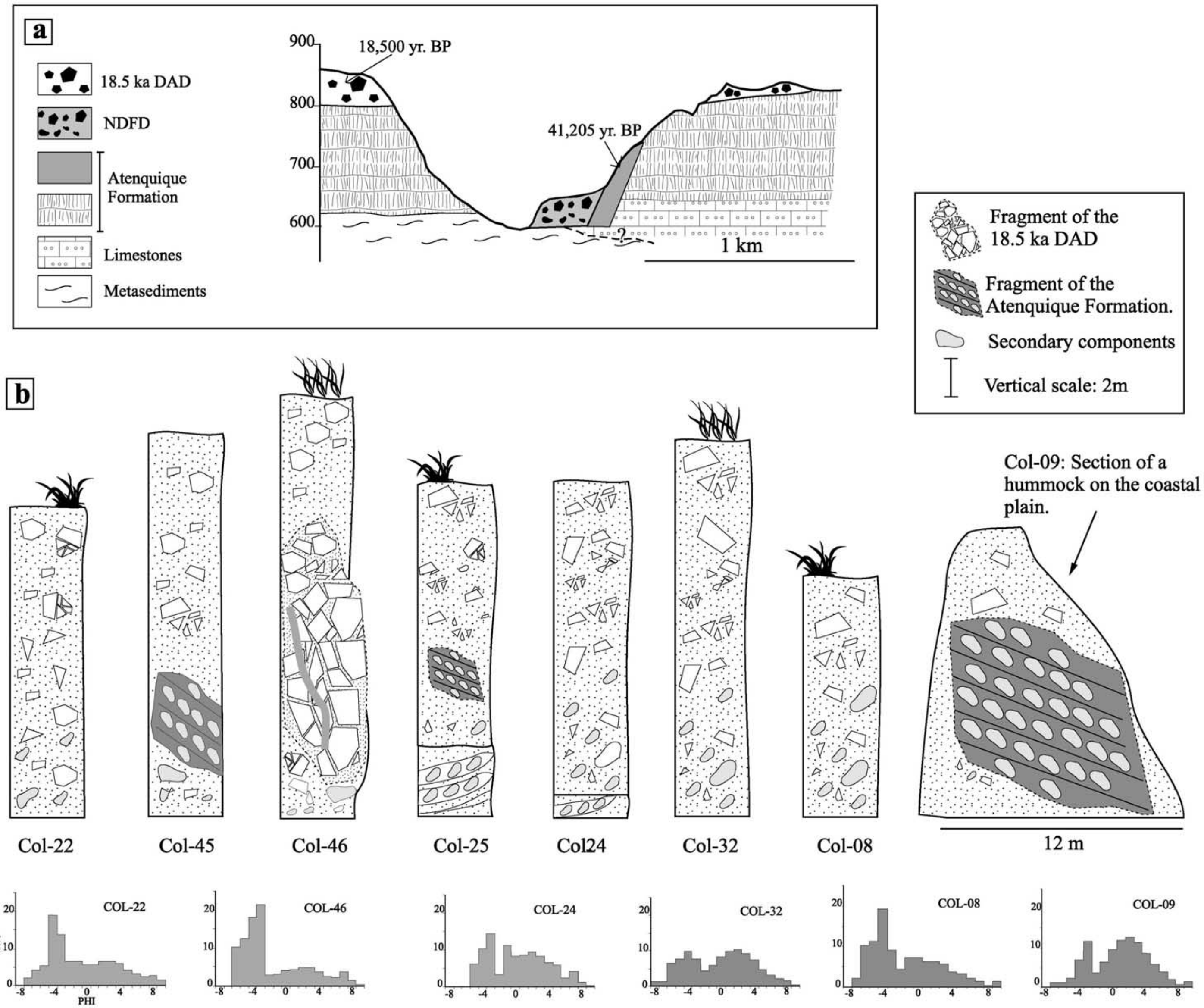

Fig. 6. (a) Section through the Naranjo River showing the general stratigraphic relationship between the 18.5-ka DAD and the NDFD. (b) Selected stratigraphic sections of the NDFD showing its textural variation downstream and relative granulometric histograms. Column width represents erosive profile.

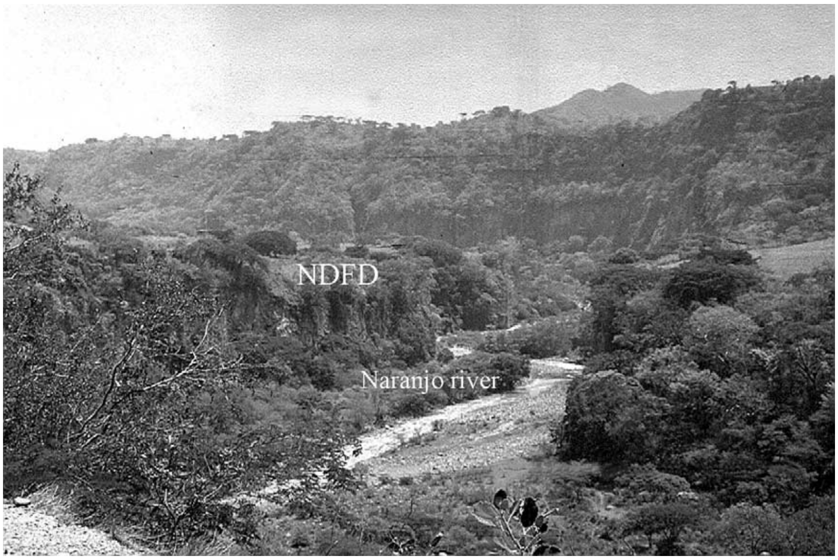

Fig. 7. Panoramic view of the Naranjo River showing the NDFD forming the younger terrace (section Col-46). View toward the northwest.

it, the associated debris-avalanche deposit, and the rocks of the basement along the Naranjo River. The NDFD deposit extends 90 km from the proximal zone close to the town of Platanar up to the Pacific coast where it constitutes a fan that forms the coastal plain (Fig. 4). It covers an area of 650 km^2 with a conservative mean thickness of 15 m. This yields a total volume of approximately 10 km^3.

6. Textural and sedimentological characteristics of the deposits

6.1. The 18.5-ka DAD and its secondary debris-flow sequence

The 18.5-ka DAD has both block and mixed facies (see Table 1 for terminology). The block facies forms a hummocky morphology and has a dominant lithology of plagioclase-porphyritic andesite megaclasts associated with fragments up 10 m in diameter of a yellow ash-flow deposit. Normal faults are common; they intersect the megablocks and cause the displacement of primary sedimentary contacts. The mixed facies consists of a massive mixture of angular to sub-angular clasts varying in diameter from a few centimeters to 1.5 m, in a silty matrix. All clasts are black plagioclase-rich porphyritic andesitic scoria and lava fragments, and gray-reddish andesite. Hydrothermal alteration affected both clasts and matrix although the deposit itself does not have a high degree of cementation.

The clasts show a well-developed jigsaw puzzle texture with open fractures filled with interclast matrix. Where the fragmentation is higher, clast domains are still recognizable. The sedimentological analyses of the mixed facies indicate a polymodal distribution, typical of debris-avalanche deposits, with modes at -4ϕ, 3ϕ, and 7ϕ. The matrix is sandy with up to 5.6% of clay fraction (Table 2 and Fig. 5).

The secondary debris-flow deposits directly associated with the 18.5-ka DAD are generally matrix supported, either massive or with a crude inverse gradation of sub-angular clasts in a sandy-silty matrix that presents a porosity with millimetric cavities. These deposits are sometimes partially cemented. The fragments vary in diameter from 60 cm down to a few cm but generally the dominant diameter is between 10 and 20 cm. Plagioclase-porphyritic andesitic scoriae and lavas are the principal components and are associated with the secondary clasts of non-volcanic origin, such as fluvial sediments and limestone fragments, mostly accumulated at the base of the deposit. Locally, the volcanic components still preserve a jigsaw texture. Sedimentological analyses show a bimodal distribution with peaks at -3ϕ and 3ϕ (Table 2 and Fig. 5).

6.2. The Naranjo Debris-Flow Deposit

The NDFD is a massive, matrix-supported heterolithologic unit. The components mainly consist of plagioclase–porphyritic andesitic scoria and lava fragments and secondary components of the basement such as limestone, igneous, and metasedimentary rocks. In general, the volcanic components are angular in shape and are most common towards the upper portion of the deposit. In contrast, the exotic components are sub-rounded and are concentrated towards the base forming imbricated clasts trains (trending down flow, with the a-axis dipping upflow) or in lenses with cross-bed stratification. At the base of section Col-25 is a 2-m-thick layer consisting of lenses of grain-supported, imbricated sub-rounded clasts (Figs. 6b and 8). The maximum diameter of the clasts reaches 5 m, although clast sizes generally range from 20 to 40 cm. In several sites, the largest clasts constitute the nucleus of hummocks typical of distal exposures of the deposit on the coastal plain. The hummocks are usually cored with fragments of conglomerates belonging to the Atenquique Formation (Section Col-09; Fig. 6b).

In the proximal zone the deposit shows a hybrid facies with characteristics between debris-flow and debris-avalanche deposits (Section Col-46; Fig. 6b). In fact, here the deposit contains

Table 2
Granulometric parameters of selected samples for the 18.5-ka DAD and secondary debris-flow deposits

Sample	Coordinates	G:S:St:C (W%)	S:St:C (W%)	Md	Mz	σ_I	σ_G	Sk_G	Sk_I	kg
18.5-ka DAD										
COL10	N 19°25′43″ W 103°29′56″	46.3:36.2:14.5:3	67.3:27.1:5.6	0.74	1.46	5.4	4.66	0.2	0.16	0.78
COL13	N 19°25′16″ W 103°31′01″	44.1:40.5:14.1:1.3	72.4:25.2:2.4	0.8	1.43	5.06	4.41	0.19	0.14	0.82
COL21	N 19°23′23″ W 103°34′03″	39.5:31.9:22.1:6.5	52.9:36.4:10.7	1.2	2.32	5.74	4.99	0.29	0.22	0.75
COL35	N 19°21′30″ W 103°32′09″	46.8:37.8:14.2:1.3	70.9:26.7:2.4	0.48	1.32	5.04	4.35	0.25	0.21	0.78
COL03	N19°18′39″ W103°36′02″	56.5:29.6:12.1:1.8	68.1:27.9:4.1	−0.9	0.37	4.8	4.22	0.4	0.32	0.8
Secondary debris-flow deposits										
COL34	N 19°18′38″ W 103°37′36″	57.9:26.7:15.3:0.2	63.3:36.4:0.3	−1.58	0.49	5.12	4.47	0.61	0.49	0.85
COL6	N 18°58′18″ W 103°41′25″	50.9:28.2:18.6:2.3	57.4:37.9:4.7	−0.1	1.09	4.84	4.34	0.37	0.34	0.78
COL7	N 18°54′21″ W 103°39′04″	47.7:41.0:9.5:1.7	78.5:18.2:3.3	0.32	0.67	4.97	4.24	0.11	0.1	0.72

Abbreviations: G, gravel; S, sand; St, silt; C, clay.
Grain-size analyses were obtained by point counting in the field using a net (1×1 m) with 100 nodes (-8ϕ (256 mm) to -3ϕ (8 mm)), by wet-sieve analyses (-2ϕ(4 mm) to 4ϕ(0.0625 mm)), and by pipette (5ϕ(0.031 mm) to 9ϕ(0.002 mm)). According to Kellerhals and Dale (1971), the results obtained from the different methodologies are equivalent and can be combined to obtain the percentage by weight of each single fraction.
The graphical statistics of grain size distribution were obtained from the cumulative frequency plotted as percentage of grains finer than each size class (Folk, 1980). $Md=\phi_{50}$; $M_Z=(\phi_{16}+\phi_{50}+\phi_{84})/3$; $\sigma_G=(\phi_{16}-\phi_{84})/2$; $\sigma_I=(\phi_{16}-\phi_{84})/4+(\phi_5-\phi_{95})/6.6$; $Sk_G=(\phi_{16}+\phi_{84}\text{-}2\phi_{50})/(\phi_{16}-\phi_{84})$; $Sk_I=(\phi_{16}+\phi_{84}-2\phi_{50})/2(\phi_{16}-\phi_{84})+(\phi_5+\phi_{95}-2\phi_{50})/2(\phi_5-\phi_{95})$; $K_G=(\phi_{95}-\phi_5)/2.44(\phi_{75}-\phi_{25})$.

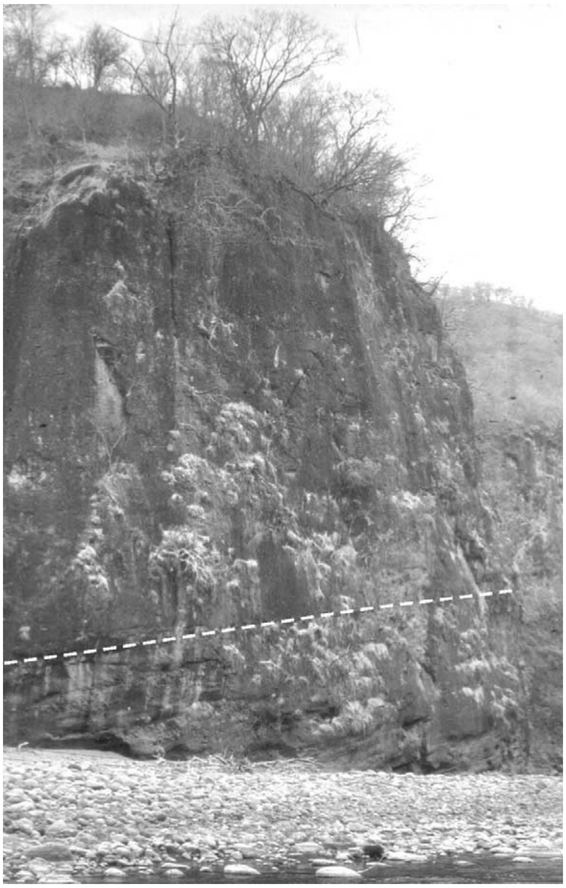

Fig. 8. Photograph of section Col-25 where NDFD show a 2-m-thick basal layer constituted by lenses of imbricated clasts covered by a 10-m-thick massive unit. White dotted line marks the contact.

large clasts ca. 10-m long of a debris-avalanche deposit (megaclast with jigsaw puzzle texture) within a massive debris-flow unit. Downstream from this place, the upper portion of the deposit locally preserves angular andesitic clasts with jigsaw textures suspended in the matrix.

Generally the deposit has a high degree of cementation but still preserves porosity with millimetric cavities. Sedimentological analyses indicate that the deposit shows an unimodal distribution with a mode at −3/−4ϕ that changes downstream to bimodal with modes at −4ϕ and 2ϕ (Fig. 6b). The matrix is sandy with up to 10% of clay. The mean clay value of 3–4%, implies that it is a cohesive debris-flow deposit (Scott, 1988). X-ray analyses performed on the clay fraction yielded a mineralogical paragenesis of kaolinite–illite–smectite with secondary cristobalite and feldspar, an association which indicates hydrothermal alteration of the rocks prior to the collapse (Frank, 1983). The sedimentological parameters show that sorting improves as the main grain size increases down-flow (Table 3).

6.2.1. *Jigsaw-puzzle texture in cohesive debris-flow deposits*

The presence of clasts with jigsaw-puzzle textures in a cohesive debris-flow deposit is compatible with the behavior of debris flows as viscoplastic flows (Johnson, 1970), where the nonlinear relation between stress and strain depends on the characteristics of the intergranular fluid (clay plus silt and water) and the particle concentration (Major, 1997). In cohesive debris flows, the sediment is mainly transported by pore-fluid pressure (Iverson, 1997; Major and Iverson, 1999), matrix strength (Rodine and Johnson, 1976), buoyant lift, and secondarily by grain interaction and structural support while turbulence is questionable (Costa, 1984). The flow moves on top of a high strain carpet. As the sediment concentration increases downward in the flow, a high density static zone forms, inducing the aggradation of particles. This depositional mechanism is termed the incremental accretion process (Vallance and Scott, 1997). Under this scenario, traction structures can develop at the base of the deposit (such as stratification with grain-support and high-angle clast imbrications as observed in section Col. 25) as well as accumulation of exotic clasts deposited from the highly erosive front of the flow. In contrast, primary structures can dominate the upper portion of the deposit that was emplaced by the tail of the flow, such as soft pyroclastic-flow fragments and jigsaw-puzzle textures. In particular, jigsaw-puzzle texture forms during the initial dilation of the rock at the time of the collapse and not by the granular collisions during flow (Glicken, 1998). Under this perspective, the presence of jigsaw-puzzle texture is not exclusive of debris-avalanche deposits but can be found in cohesive debris-flow deposits remobilized

Table 3
Sedimentological parameters of selected samples for the NDFD

Sample	Coordinates	G:S:St:C (W%)	S:St:C (W%)	Md	Mz	σ_I	σ_G	Sk_G	Sk_I	kg
COL22	N 19°27′02″ W 103°28′54″	56.7:29.7:12.13:1.3	68.8:28.1:3.1	−1.08	0.54	5.05	4.46	0.48	0.42	0.83
COL46	N 19°22′46″ W 103°33′24″	68:21.9:9.9:0.2	68.5:30.8:0.7	−2.55	−0.39	5.16	4.5	0.63	0.57	0.95
COL24	N 19°10′03″ W 103°30′06″	45.1:40.1:13.8:0.4	74.1:25.2:0.7	0.4	1.28	4.4	3.76	0.3	0.3	0.74
COL32	N 18°46′26″ W 103°44′24″	43.6:44.9:11.2:0.3	79.6:19.9:0.5	0.77	0.84	4.92	4.3	0.02	0	0.78
COL8	N 18°49′34″ W 103°42′03″	63:28.8:6.9:1.4	77.8:18.5:3.7	−2.18	−0.58	4.48	4.17	0.5	0.45	0.83
COL9	N 18°45′20″ W 103°43′32″	32.9:53.7:11.9:1.5	80.1:17.7:2.2	1.64	1.67	4.27	3.74	0.01	−0.02	0.83

See Table 2 for legend explanation.

from them, as was observed in the Pilcaya cohesive debris-flow deposit of Nevado de Toluca Volcano (Capra and Macias, 2000). These observations support the hypothesis that the NDFD formed by remobilization of a debris-avalanche deposit.

7. Discussion

7.1. River blockage: dam extension and related sediments

According to the distribution of the debris-ava-

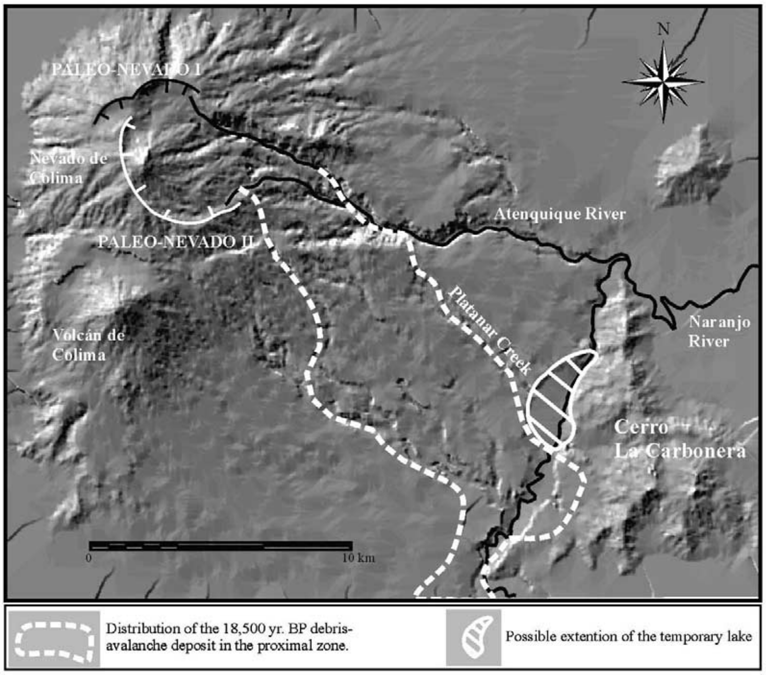

Fig. 9. The digital elevation model of the CVC shows the distribution of the DAD in the proximal area and its relationship with the Cerro la Carbonera.

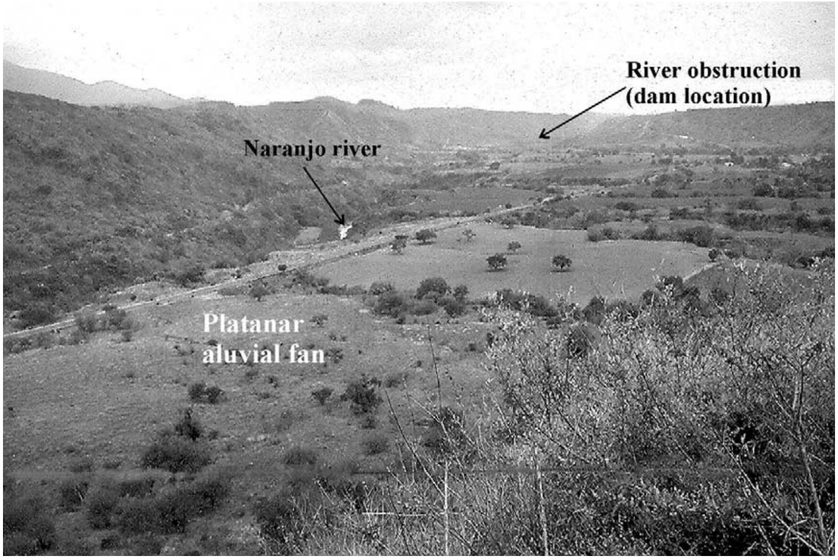

Fig. 10. Panoramic view to the SSE of the Platanar alluvial fan and the location of the dam.

lanche deposit and the particular morphology of the southeastern side of Nevado de Colima Volcano, the debris avalanche must have obstructed the Naranjo River during its emplacement. The debris avalanche flowed southeast to Cerro la Carbonera where it was diverted towards the south and followed the main channel of the Naranjo River, partially covering the river's lateral terraces (Fig. 9). We infer that the debris-avalanche deposit obstructed the water flow of the Naranjo River producing a temporary lake (at the present site of the Platanar alluvial fan) the water level of which gradually increased with time (Fig. 10). Considering the present depth of the Naranjo River channel (ca. 100 m) and the relative position of the debris-avalanche deposit, the dam had to have an approximate height of 150 m. The present morphology of the dammed area and the lake sediments associated with this process suggest that the extension of the lake would have covered an area of approximately 7 km^2, which gives an approximate volume of stored water of 1 km^3.

Fig. 11 shows two stratigraphic sections of the sequence that forms the Platanar alluvial fan. Its basal portion consists of a conglomeratic sequence up to 100 m thick of several units composed of rounded clasts and cut by channels and erosive surfaces. A 5-cm-thick layer of indurated soil separates this lower sequence from a 2-m unit composed of massive or cross-bedded centimetric horizons rich in silt–sand particles (Fig. 12). An 8-cm massive clayey layer lies on top of this fine-layered sequence. This fine-grained succession is capped by a massive debris-flow deposit that has a maximum thickness of 4 m composed of at least two units consisting of sub-angular clasts imbedded in a silty matrix (Fig. 13). This same fine-grained sequence that rests on top of the Platanar fan, occurs upstream in Platanar Canyon and at the northern edge of the terrace (sections Col-36 and Col-41; Fig. 11). The fine-laminated layers are interpreted as slack-water type sediments deposited during the inundation of the temporary lake to its maximum level. These types of sediments have been used in the literature to define the maximum inundation level during river flooding as a procedure of paleoflood analysis (Kochel and Baker, 1987). Surges of sediment-laden water move up towards tributary canyons and deposit sediments in the mouth of main streams. The basal layer is typically a coarse-grained tributary alluvium that is usually overlain by finer-grained slack-water sediments derived from the main stream (Kochel and Baker, 1982).

Based on this description, we interpret that the

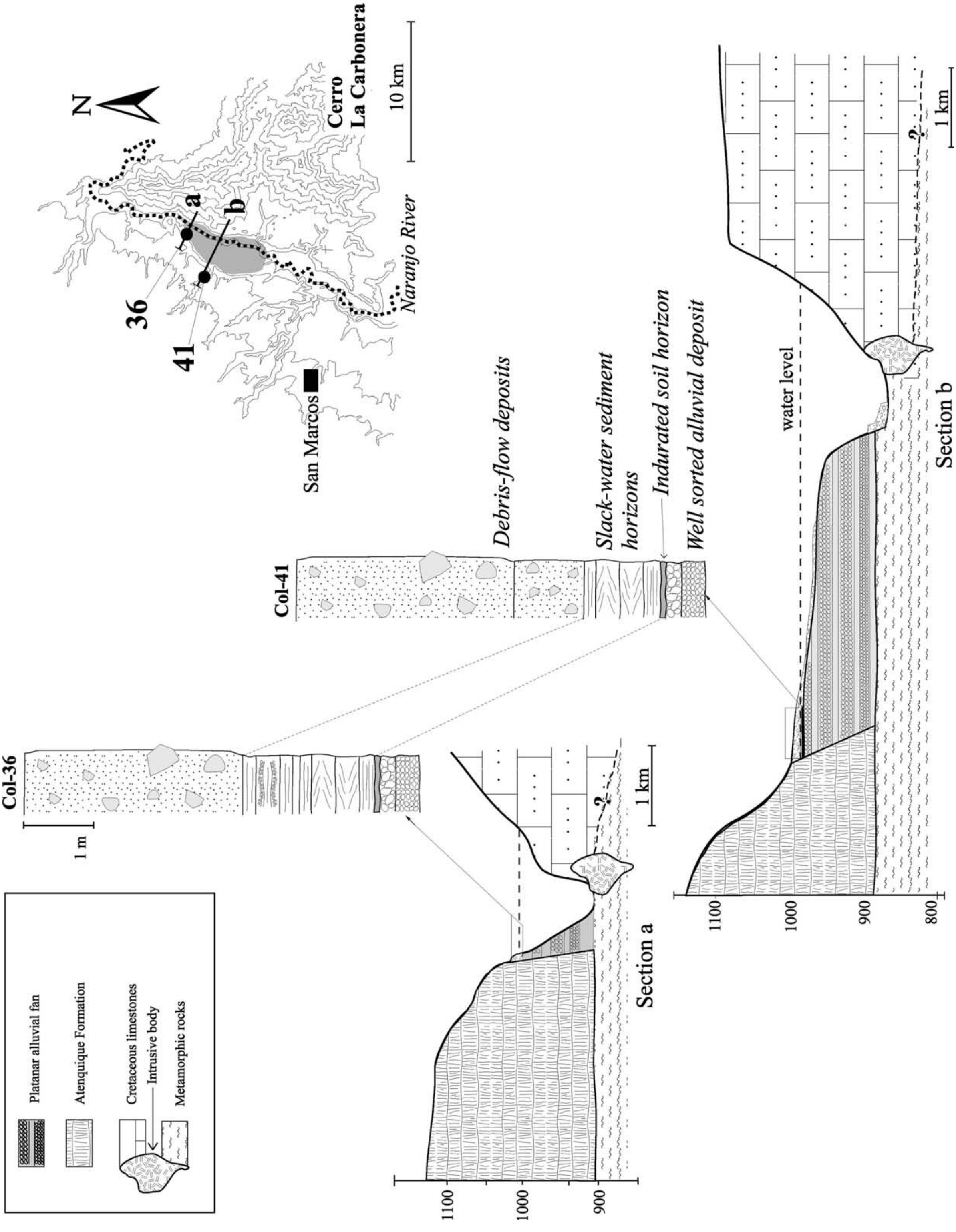

Fig. 11. Geological section of the Platanar alluvial fan and stratigraphic columns of the sedimentary sequences.

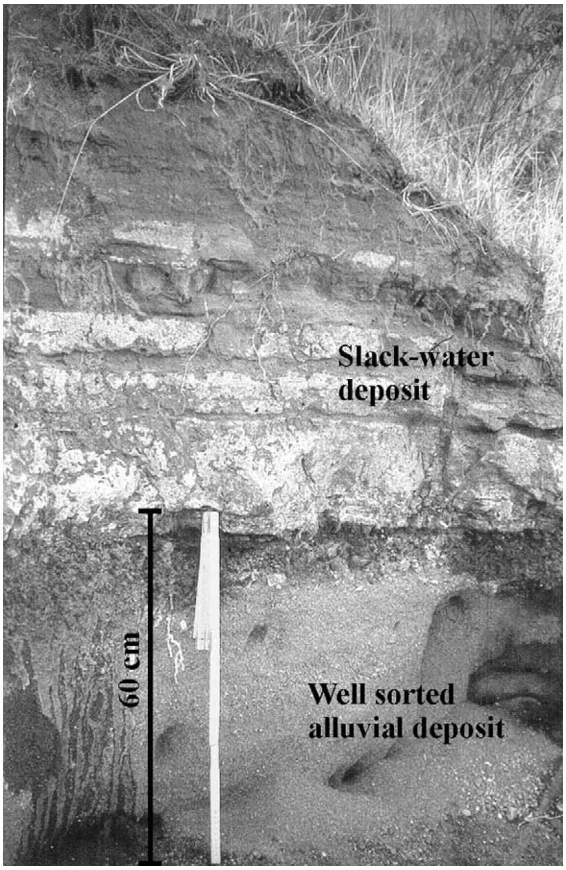

Fig. 12. Detail of the slack-water sediment deposit as it appears at section Col-36.

lower part of the Platanar alluvial fan represents sedimentation related to the Platanar drainage before the river blockage, whereas the upper portion is related to sedimentation that occurred during the existence of the temporary dam. It is clear that for our case study the latter sediments are the indicator of the maximum water level reached by the water reservoir corresponding to the present 1000-m level. If we project this elevation to the site of the proposed dammed area, we find that the tentative depth for the lake is approximately 150 m with respect to the present base of the Naranjo River, which is at 850 masl. This difference in height excludes the hypothesis that such deposits could be associated with seasonal inundations of the Naranjo River. The morphology of the area indicates that these slack-water deposits are only preserved in the most-protected zones, such as lateral drainages (e.g. Platanar Creek). Their preservation was aided by the rapid emplacement of small secondary debris-flow deposits, as observed at sections Col-36 and Col-41.

Examination of the hydrological network clearly indicates that the 18.5-ka DAD should have formed small lateral impoundments in tributary rivers (e.g. Barranca del Muerto, Los Lobos, and La Platanera Creeks; Fig. 3) that, because of their small accumulation of water, drained through the same 18.5-ka DAD and contributed to its remobilization as a sequence of secondary debris flows. A similar example is represented by the emplacement of the 1980 Mount St. Helens debris-avalanche deposit that formed at least five small lateral temporary dams related to the same number of tributaries, with elevation of the water level up to 60 m above that of the pre-existing Spirit Lake (Meyer et al., 1986). Only the latter represented a serious danger to flood breakout, whereas the smaller ones, partially drained, still exist today and are constantly monitored.

8. Rate of discharge and bulking factor

Based on the stratigraphic and morphological data we are able to estimate the discharge of the NDFD during the dam breakout and along the Naranjo River. Despite a lack of evidence to estimate the depth of the flow during its emplacement, we can make some assumptions based on flow velocity and the volume of the deposit. The NDFD along the Naranjo River originally had a volume of approximately 10 km^3. Using the model proposed by Iverson et al. (1998) where the cross section of the inundated area (A) is related to the flow volume (V) based on the relationship $A = 0.05V^{2/3}$, we determined that A is 0.23 km^2. Flow velocities were estimated in the proximity of section Col45 by using the super-elevation method (e.g. Johnson, 1984). Here the deposit formed a super-elevated lateral terrace from which we obtained an average velocity of 15 m/s. Considering the values of the cross inundation area (A) and the flow velocity, we obtained a flow discharge of 3.5 million m^3/s. This figure represents an average

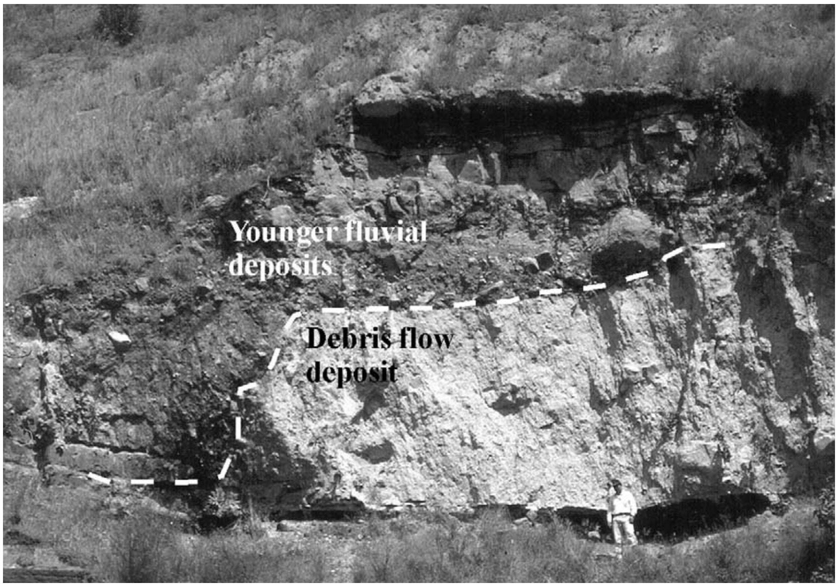

Fig. 13. Massive debris-flow deposit on top of the slack-water sediment sequence (Section Col-36).

computed value for the extension of the deposit, characteristic of extremely large flows (> 1 million m^3/s; Pierson, 1998). Such a discharge is comparable with the Osceola cohesive debris flows at Mount Rainier for which a discharge of up to 23 million m^3/s was calculated (Vallance and Scott, 1997).

If we consider the volume of the water, stored in the temporary dam, we can obtain the initial discharge, assuming that the dam broke during a single event. By using the relation proposed by Mizuyama et al. (1992), where the discharge is obtained by the relationship $Qp = 0.0188\ V^{0.790}$, where, in case of water release, V is the water volume (in this case 1 km^3) multiplied by a total bulking factor of 3 (Pierson and Costa, 1987), an approximate discharge of 0.57 million m^3/s is obtained. Comparison with the average discharge (3.5 million m^3/s) indicates a bulking factor of about 6. This means that the flow introduced an amount of sediment six times its initial volume, probably derived from water-saturated sediments in the river bed. These values are also confirmed considering that the removed volume of debris that formed the temporary dam was approximately 1.5 km^3 (calculated for the area along the Naranjo River where the 18.5-ka DAD is now absent; Fig. 4), which in effect corresponds to 1/6 of the NDFD volume. This value represents a large figure for a bulking process, which normally has been found to be 80% of the initial volume (Scott et al., 1995). The only other studied cases in which such a large bulking factor has been reported are the debris-flow deposit formed at Casita Volcano (Nicaragua) in 1998, which underwent an increase of up to 4.2 times its initial volume (Scott et al., 2002b), and the Nevado del Huila cohesive debris-flow deposit, which had a bulking factor of 3.2 (Pulgarin et al., 1999). Both the abundance of exotic materials accumulated towards the base of the deposit (bedrock or rounded sediment clasts) and the increase of the sand fraction with distance (Fig. 6b), reflect the incorporation of well-sorted sediments in accord with the large bulking factor calculated for the flow.

9. Reconstruction of the event

Some 18,500 yr ago a Bezymianny-type event occurred on the eastern flank of Nevado de Colima Volcano producing a gravity-driven debris avalanche that flowed 20 km to the Naranjo River where it smashed against Cerro la Carbonera (Figs. 4 and 9). The flow, after its collision, continued to progress downstream along the Naranjo River to a distance of 45 km from the summit where it dispersed on the plain near Cuauhtemoc town. The resulting deposit filled the Naranjo River channel for about 25 km blocking its drainage and forming a large dam impoundment on the Platanar alluvial fan. The emplacement of the 18.5-ka DAD favored the formation of small impoundments in lateral tributaries of the Naranjo River. The topography of the site with high lateral terraces within the Naranjo River and the location of the dam at an enlargement of the river where Platanar Creek had deposited an alluvial fan, facilitated the accumulation and confinement of water (Fig. 9). The water reservoir had an approximate depth of 150 m. During the existence of the dam on the Naranjo River, dewatering of the debris-avalanche deposit, superficial drainage, and water accumulated in the smaller lateral impoundments rapidly eroded the 18.5-ka DAD. Secondary lahars then started to flow onto the southwestern plain, meeting in the Salado River since the Naranjo drainage was probably still partially obstructed by the 18.5-ka DAD.

At this point two different scenarios can be hypothesized. According to the first scenario, fluvial erosion provoked headward-cutting at the front of the dam on the Naranjo River and progressively moved upstream to the lake. The erosion diminished the thickness of the temporary dam, which broke because its reduced size could not sustain the water pressure from the lake. According to the second scenario, the inflow rate of the Naranjo River was so high that the water overtopped the dam causing its erosion from the surface. Based on the present day maximum and minimum flow discharge of the Naranjo River of 1266 m^3/s and 30 m^3/s, respectively (INEGI, 1981), a 1-km^3 temporary lake would fill in a period of time between 9 days and 1 yr. The presence of slack-water sediments on the marginal portions of the dam extension supports the second hypothesis, indicating that the lake reached a maximum level during which it inundated lateral zones and overtopped the dam. In other studied cases the overtopping modality of rupture is the more frequent. This is because a debris-avalanche dam consists of large or cohesive particles that can better resist failure, allowing the high river inflow to form a lake that overtops the dam (Costa and Shuster, 1988). Independently of these two types of scenarios, we consider that even if the erosion of the deposit occurred gradually, producing small debris flows from the over-saturated zone, the main rupture of the dam took place rapidly, forming a debris flow that reincorporated previous small deposits. This seems to be the case of the NDFD since we observed a single massive unit of debris flow for more than 90 km along the Naranjo River to the Pacific coast. The observed debris-avalanche/debris-flow hybrid facies in the proximal zone and the presence of clasts with jigsaw texture all along the deposit are also evidence that the material was remobilized from a debris-avalanche deposit, confirming our reconstruction of the event.

10. Hazard assessment

Several examples of similar phenomena confirm the importance of evaluating the possible interaction of a debris avalanche with the surrounding topography. The best-known examples are the 1888 phreatic Bandai eruption where a 1.5-km^3 debris avalanche blocked river drainages forming five new lakes (Sekiya and Kikuchi, 1889) and the 1980 Mount St. Helens debris avalanche that formed five lateral impoundments (Meyer et al., 1986). Other examples are the prehistoric and modern dam formations that occurred along Rio Paez, Colombia. During Pleistocene time, a seismogenic sector collapse of the Nevado del Huila Volcano (Colombia) initiated a 5.4-km^3 debris-avalanche deposit that dammed Rio Paez (Pulgarin et al., 1999). The lake filled in approximately three days and the dam breakout formed a cohesive debris flow that traveled at least 70 km from the source and deposited a single unit with a minimum volume of 4 km^3 (with a bulking factor of 3.2). This Pleistocene event repeated in 1994 when a M6.4 tectonic earthquake, located 10 km southwest from the summit of Nevado del Huila Volcano, provoked the failure of hydrothermally altered bedrock, previously saturated by recent rainfall (Avila et al., 1995; Ingeominas, 1995). During this event, 3000 discrete slope failures coalesced along the Rio Paez, damming the river whose breakout formed a huge cohesive debris flow that traveled for 130 km from the source (Scott et al., 2002a) with 2000 deaths.

By using the model proposed by Iverson et al. (1998) for delimiting hazard inundation zones in case of lahars, we constructed a hazard map for the Naranjo River simulating the dam rupture and the formation of a 10-km^3 debris flow. Previous authors used the same methodology to estimate lahar hazard zones at Volcán de Colima (Paul and Sheridan, 1998; Sheridan et al., 1999). The method is based on the relation mentioned above, $A = 0.05\ V^{2/3}$, which permits calculation of the cross-sectional inundation area used to delimit the hazard zone. The other relation, $B = 200\ V^{2/3}$, is used to obtain the total inundated area (B) which, considering a volume of 10 km^3, resulted to be 1000 km^2. We applied this method manually by tracing 50 sections along the river and incorporated the limit into a digital elevation model of the area. Fig. 14 shows the limit of the hazard zone and several towns that might be affected by the inundation of the debris flow. In case of a similar event to that of 18.5-ka BP, a population of approximately 10 000 could be threatened. This calculation does not consider the area affected by the direct emplacement of the debris-avalanche deposit, which in the case of the 18.5-ka event inundated an area of 800 km^2, including the present location of the City of Colima (200 000 inhabitants).

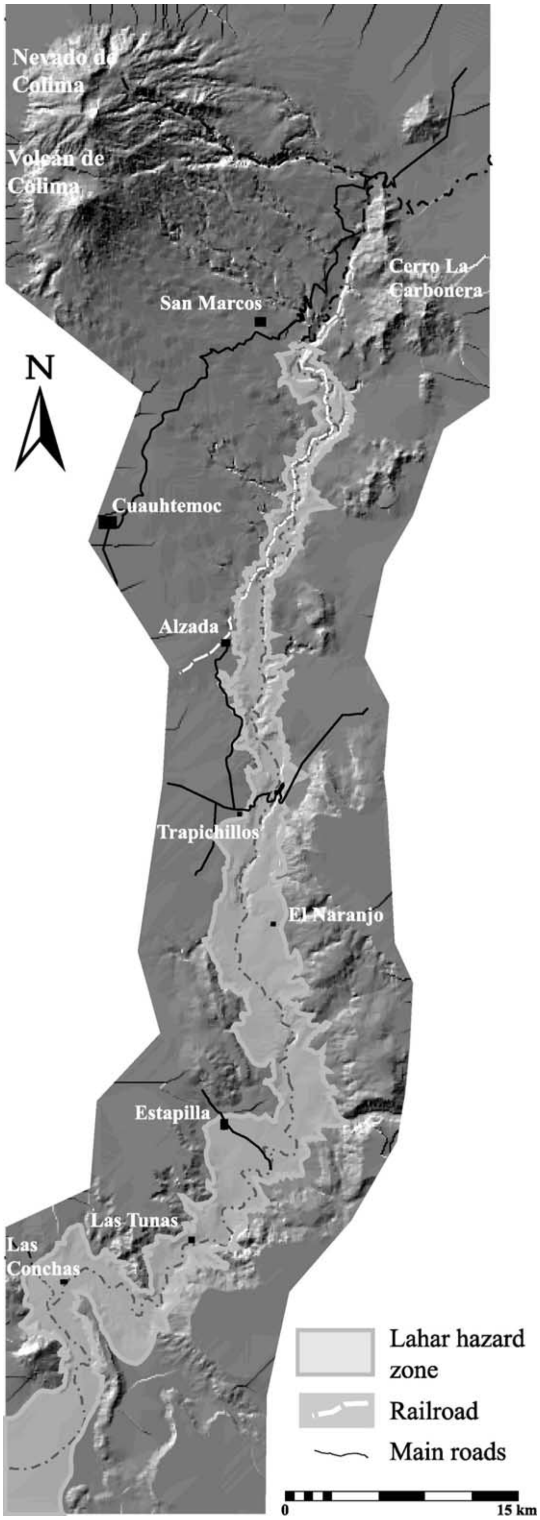

Fig. 14. Hazard zonation map for debris flows along the Naranjo River considering a scenario similar to the 18.5-ka-BP debris flow.

11. Conclusions

The volcanic collapse of the Nevado de Colima Volcano, which occurred some 18.5 ka ago, produced a 45-km long debris avalanche that completely blocked the drainage of the Naranjo River causing the formation of a natural dam and small lateral impoundments of tributaries. Initial remobilization of the 18.5-ka DAD produced a sequence of debris flows that inundated areas to the south and channelized in the Salado River, covering an area of 800 km^2 with deposits totaling 3.5 km^3 in volume. After an interval of time, between 9 days and 1 yr, the inflow of the Naranjo River filled the temporary lake causing overtopping and erosion of the dam and its subsequent breakout. A water mass of $\sim$1 km^3 eroded and remobilized approximately 1.5 km^3 of the 18.5-ka DAD by forming a 10-km^3 cohesive debris flow that traveled 90 km down the Naranjo River to the Pacific coast. The enormous increase in volume was caused by bulking of the flow and by introduction of exotic material, causing an increase of six times the original remobilized mass of the 18.5-ka DAD.

This event is an example of the interaction between topography and gravity-driven flows, in particular debris avalanches. A debris avalanche is a rapid flow that can quickly obstruct drainages where the stream water is not capable of eroding the large sudden mass blocking its passage. At Colima, the emplacement of the 10 km^3 DAD led to the formation of a sequence of debris-flow deposits, including the NDFD, for a total volume of 13.5 km^3, 30% more voluminous that the 18.5-ka DAD, and they inundated an area of at least 2.5 times the surface covered by the DAD.

On the basis of this study and examples at Bandai, Mount St. Helens, and Rio Paez (Colombia), it is clear that the interaction between debris avalanches and the topography around active volcanoes can completely modify the hazard zonation map by producing secondary events that can be more voluminous and extensive than the primary debris-avalanche deposit, and therefore completely modifying the contingency plans by civil authorities.

Acknowledgements

This work was supported by Grants DGAPA–UNAM (102297), CONACYT 27993-T to J.L.M., GSA 6199-98 to L.C. M. Abrams from the Jet Propulsion Laboratory, Caltech, provided Landsat imagery. This work benefited from several discussions with K.M. Scott, J.M. Espíndola, A. García-Palomo, J.L. Arce, and S. Hughes. C. Eastoe performed C-14 dating at the University of Arizona, Tucson. L. Siebert, M.F. Sheridan, J. Luhr and an anonymous reviewer provided useful comments that improved the manuscript.

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