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A neotectonic–geomorphologic investigation of the prehistoric rock avalanche damming Laguna de Metztitlán (Hidalgo State, east–central Mexico)

Max Suter

Instituto de Geología, Universidad Nacional Autónoma de México, Estación Regional del Noroeste, Apartado Postal 1039, 83000 Hermosillo, Sonora, Mexico.
SuterMax@aol.com

ABSTRACT

Laguna de Metztitlán (Hidalgo State, east-central Mexico) is a natural lake dammed by an unbreached, large-scale rock avalanche (sturzstrom) deposit (area: 2.5 km²; volume: ~0.6 km³; up to ~400 m thick in the valley axis; horizontal runout distance: 2,600 m; vertical fall height: 860 m) that impounds the Metztitlán River. The natural outflow of the lake is by seepage, the difference between the lake level and the level of resurgence being ~250 m; this value also corresponds approximately to the maximum thickness of the lake deposits. Based on the earlier extent of the lake beyond the town of Metztitlán, indicated in the «Relación Geográfica de Metztitlán» (A.D. 1579), the delta progradation rate of the Metztitlán River is estimated at ~30 m/yr. Based on this rate and the maximum extent of the paleolake, the rock avalanche damming Laguna de Metztitlán must have occurred ~500–1,100 yr B.P. There are general observations that support a seismic origin of the rock avalanche.

Two regional-scale, late Cenozoic, east-west striking, and south-dipping normal faults at the northeastern margin of this rock avalanche feature pronounced scarps, up to ~250 m high. These faults have the same orientation as other normal faults with Quaternary activity farther west in the stress and deformation province of the Trans-Mexican Volcanic Belt, which is characterized by north-south oriented extension. Thick colluvium layers have been cut off and rotated along the northern fault. The southern fault forms a scarp with a height of 275–305 cm where it crosses the debris mound of the rock avalanche, which suggests the occurrence of a surface-rupturing earthquake on this fault in the past 1,100 yr.

Key words: rock avalanche, sturzstrom, seismic triggering, active normal fault, east-central Mexico, Trans-Mexican Volcanic Belt, Sierra Madre Oriental, Hidalgo State, Laguna de Metztitlán, late Holocene.

RESUMEN

La Laguna de Metztitlán, ubicada en el Estado de Hidalgo, es un lago natural, delimitado por un depósito imperturbado de una avalancha de roca (área: 2.5 km²; volumen: ~0.6 km³; espesor hasta ~400 m en el eje del valle; alcance horizontal máximo: 2,600 m; altura de caida vertical: 860 m) que obstruye el Río de Metztitlán. El drenaje natural del lago es por filtración, la diferencia de nivel entre el lago y la fuente de resurgimiento mide ~250 m. Este valor también corresponde approximadamente al espesor máximo de los depósitos lacustres. Según la «Relación Geográfica de Metztitlán» (A.D. 1579), el lago se extendió anteriormente hasta al sur del pueblo de Metztitlán, lo que permite estimar la taza de propagación del delta del Río de Metztitlán en ~30 m/yr. Basado en esta tasa y en el alcance máximo del *lago en tiempos geológicos, el derrumbe que tapa a la Laguna de Metztitlán debe haberse formado hace ~500–1,100 años. Hay observaciones generales a favor de un origen sísmico del derrumbe.*

Dos fallas normales del Cenozoico tardío, con tamaño regional, rumbo este–oeste y echado hacia al sur se ubican en la margen nororiental del derrumbe. Tienen escarpes con una altura hasta ~250 m. Estas fallas tienen la misma orientación que las fallas regionales con actividad cuaternaria que se ubican más al poniente en la Faja Volcánica Trans-Mexicana, una provincia de deformación y esfuerzos que se caracteriza por su extensión norte–sur. Capas gruesas de coluvión fueron recortadas y giradas a lo largo de la falla del norte. La falla del sur forma un escarpe con una altura de 275–305 cm donde atraviesa el depósito de la avalancha de roca, lo que sugiere que un temblor se originó sobre este falla en los últimos 1,100 años, rompiéndola hasta la superficie.

Palabras clave: avalancha de roca, derrumbe, falla normal activa, centro-oriente de México, Faja Volcánica Trans-Mexicana, Sierra Madre Oriental, Estado de Hidalgo, Laguna de Metztitlán, Holoceno tardío.

INTRODUCTION

The present study describes two regional-scale, late Cenozoic, east-west striking, and south-dipping normal faults from the vicinity of the prehistoric rock avalanche deposit damming Laguna de Metztitlán (Lake Metztitlán, Hidalgo State, east-central Mexico). These are the easternmost late Quaternary normal faults reported so far within the Trans-Mexican Volcanic Belt (Figure 1), a distinct stress and deformation province situated to the south of the Mexican Basin and Range province (Suter, 1991, fig. 7). The faults are located in the eastern extrapolation of faults documented in previous studies (Figure 2), which form the Aljibes half-graben (Suter *et al.*, 1995) and the Mezquital graben (Suter *et al.*, 1996, 2001). At the surface, the faults cut Cretaceous marine sediments of the El Abra Formation, previously deformed during the formation of the Laramide (Late Cretaceous–early Tertiary) Sierra Madre Oriental fold-thrust belt, and the Pliocene Atotonilco Formation, which is composed of volcanic rocks (pyroclastic deposits and basalt flows) interbedded with gravel layers (Segerstrom, 1962; Cantagrel and Robin, 1979; Robin, 1982).

The documentation of these previously unknown faults is part of an ongoing systematic regional study of the active intra-arc extension in the central part of the Trans-Mexican Volcanic Belt (Suter *et al.*, 2001), which includes geological mapping, the measurement of small-scale structural data, the processing and analysis of digital elevation models and satelite imagery, and the compilation of the regional seismicity. The data may serve as a basis for seismic-hazard assessments of this region.

Furthermore, I document the prehistoric rock avalanche damming Laguna de Metztitlán, which is located next to these east-west striking normal faults (Figures 3 and 4), and estimate its age. The avalanche impounded the Metztitlán River (also known as Venados River) for >20 km. As noted by Lugo-Hubp *et al.*, (1993) and García-Arizaga *et al.* (1996), the flat-bottomed river valley (Figure 3), which corresponds to the floor of the lake dammed by the rock avalanche material, is different from the generally V-shaped valleys of this region (Figure 3). The existence of Laguna de Metztitlán is unusual, since landslide barriers damming a river normally are breached shortly after their formation; only 15% of them last longer than a year (Costa and Schuster, 1988).

Based on my study of the faults and the rock avalanche, I evaluate the possible temporal and causal relations between them. Was the rock avalanche damming Laguna de Metztitlán triggered seismically or, more specifically, by an earthquake along one or both of the observed normal faults?

LATE CENOZOIC NORMAL FAULTS OF THE STUDY AREA

Excellent exposures of two east-west striking normal faults exist ~2 km to the southeast of the village of Almolón, on the eastern slope of the Almolón River valley (Figure 4). In what follows, I document the two faults, to which I refer as the northern and the southern faults.

The scarp of the northern fault (Figure 4) is formed in the Cretaceous El Abra Formation, which is here composed of well-bedded limestone belonging to the interior of the Valles–San Luis Potosí carbonate platform. The topographic relief of the scarp measures up to 200 m. Rockfall deposits can be observed at the base of the scarp (Figure 5A) where they form small debris cones that are partly devoid of vegetation. At this location (UTM coordinates 512,150/2,289,950), a large natural outcrop exists of the exhumed master fault (Figure 5A), which dips 60–70º south (Figure 6). The master fault is mantled by fault gouge, at least 2–3 m thick, the upper surface of the gouge being erosional. Large-scale wear groove striations

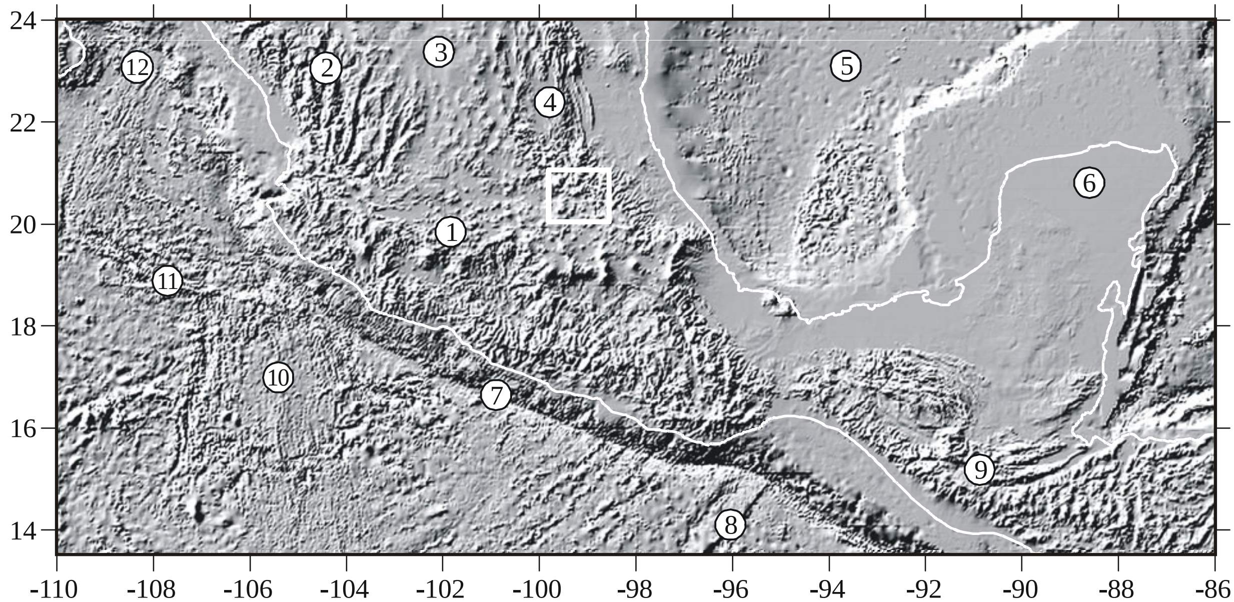

Figure 1. Shaded relief map of central and southern Mexico and western Central America, derived from a homogeneous grid of elevation values with a 2 arc-minute spacing (TOPEX model, University of California at San Diego, http://topex.ucsd.edu/marine_topo/mar_topo.html). The coastline is marked in white, and the region covered by Figure 2 is indicated by the white frame. 1: Trans-Mexican Volcanic Belt; 2: Sierra Madre Occidental; 3: Mesa Central; 4: Sierra Madre Oriental; 5: Gulf of Mexico basin; 6: Yucatan platform; 7: Middle America trench; 8: Tehuantepec ridge, 9: Motagua-Polochic fault system; 10: East Pacific rise; 11: Rivera fracture zone; 12: Tamayo fracture zone.

can be observed on the master fault plane (Figure 5, B and C); they indicate dip-slip with a minor but consistent right-lateral component (Figure 6). Thick colluvium layers form the hanging wall; they appear to be rotated and cut off along the fault (Figure 5A). However, whereas the contact between the El Abra Formation of the footwall and the colluvium is sheared at some places, it corresponds at other places to an unconformity. Striated shear fractures could also be observed within the colluvium, at ~3 m distance from the master fault (Figure 5D). Their orientations are similar to that of the master fault. The striations on the shear fractures within the colluvium, on the other hand, indicate dip-slip or a minor left-lateral component, as opposed to the right-lateral component on the master fault. In total, I measured 14 slip vectors from striations on the exhumed master fault plane (Figure 5, B and C) and on secondary faults of the hanging wall within the colluvium (Figure 5D). The slip vectors are graphed on Figure 6. Based on a striation inversion algorithm by Angelier (1990), the dynamics of this fault population are characterized by a NNW-SSE orientation of the least horizontal stress and obliquely oriented principal stress orientations (Figure 6). Alternatively, the measured striations may belong to more than one population. The striations indicating dip-slip with a minor but consistent right-lateral component (Figure 6) may have developed during the prehistoric rock avalanche damming Laguna de Metztitlán (see below). These striations are parallel to the motion of the rock avalanche, and the northern normal fault forms approximately the northern limit of the avalanche breakaway scarp (Figure 4).

The trace of the southern fault is located at a distance of 350–500 m from the trace of the northern fault (Figure 4). The southern fault also forms a scarp in the limestone of the El Abra Formation (Figure 7). It dips 65–85º south and is therefore somewhat steeper than the northern fault. The topographic relief of the southern scarp measures up to 250 m. A system of parallel, south-dipping, secondary normal faults exists in the hanging wall near the master fault (Figure 7). A major step in the mountain ridge, where it is intersected by these faults, measures 50 m, which is a minimum amount for the throw of this fault zone. The talus surface along this scarp (Figure 7) is, in general, devoid of vegetation and looks fresher than the talus surface along the northern fault scarp.

The fault forms a small scarp, with a height of ~3 m where it crosses the debris of the rock avalanche blocking Laguna de Metztitlán (Figure 4) in the vicinity of the trail that leads from Almolón to the lake. Therefore, some movement must have originated along this fault after the occurrence of the rock avalanche, within the last 1,100 years (see below).

Apparently, the two faults are not exposed either on the western side of the Almolón River valley or in the uplands. One reason is that the layering and structure of the El Abra Formation can be recognized on the steep slopes of the river valley but not in the uplands, which are covered by caliche. Another explanation is that the two fault scarps were enhanced locally by the removal of parts of their

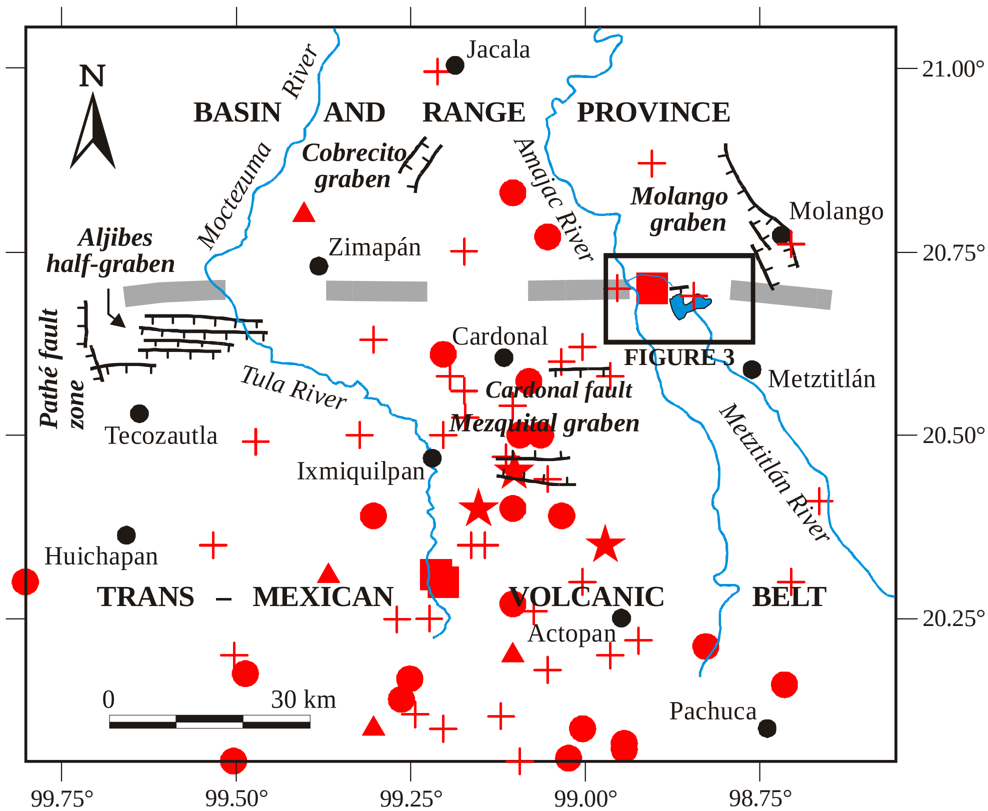

Figure 2. Seismicity and traces of late Cenozoic normal faults in the central part of Hidalgo State. The thick dashed line indicates the approximate limit between the stress and deformation provinces of the Mexican Basin and Range and the Trans-Mexican Volcanic Belt. Frame: region covered by Figure 3 and approximate location of study area. Earthquake epicenters, as listed in the composite Mexico catalog of the U.S. National Geophysical Data Center (1996), are ranked by magnitude (mostly body-wave or local magnitudes). Events with magnitude <3.0 are marked with a triangle, magnitude between 3.0 and 3.9 by a circle, magnitude between 4.0 and 4.9 with a square; and the three events with magnitude ≥5.0 by a star. Crosses represent events of unspecified magnitude. This seismicity record covers the period between 1969 and 1990 with the addition of the 11 March 1950, M_c 5.0 Ixmiquilpan earthquake (Suter *et al.*, 1996) and an event of unspecified magnitude in 1956.

hanging walls by the rock avalanche blocking Laguna de Metztitlán (see below). In the east, the faults cannot be traced farther east than the prominent limestone ridge that extends as a peninsula into the Laguna de Metztitlán (Figures 3, 4, and 7). This ridge in the middle Cretaceous El Abra Formation is the hanging wall of a major Laramide (Late Cretaceous–early Tertiary) thrust fault (Metztitlán thrust, Figures 4 and 8) that placed the El Abra Formation on top of the Upper Cretaceous Méndez Formation (Canul-Rodríguez, 1984; Martínez-Gutiérrez, 1984; Hernández-Treviño and Hernández-Bernal, 1991). The fault is part of a thrust fault system, >100 km long, that passes along the eastern edge of the Cretaceous Valles–San Luis Potosí carbonate platform (Suter, 1984, 1987; Suter *et al.*, 1997).

Approximately 3–11 km east of the limestone ridge, in the projected continuation of the normal fault exposures of the Almolón River valley, a conspicuous, east-west trending lineament, 8 km long, can be seen on the shaded relief map (Figure 3). The lineament corresponds to the Barranca Honda valley. Evidence for the existence of an east-west striking fault zone within this valley includes small faults and shear fractures in volcanic rocks where the valley is intersected by the Metztitlán-Eloxochitlán road and in alluvium and volcanic rocks farther east in the Barranca Honda valley (Figure 4). However, the prominent uneroded surface of a basalt flow (Atotonilco Formation) on either side of Barranca Honda (Figure 3) is not discernibly displaced across the valley; therefore, little or no significant vertical displacement can have occurred along the Barranca Honda fault zone after the deposit of this Pliocene (?) basalt. Locally, two linear scarps, 500–600 m long and bounded by stone walls, are very pronounced on 1:50,000 scale Instituto Nacional de Estadística, Geografía e Informática (INEGI) aerial photographs and marked on the corresponding 1:50,000 scale INEGI topographic map sheet (F14D61 Metztitlán). These scarps are located exactly in the extrapolated eastern continuation of the normal fault exposures of the Almolón River valley, to the west of the Metztitlán-Eloxochitlán road. However, a tectonic origin of these two topographic features, as earthquake rupture segments, is not evident at the surface and cannot be documented without trenching.

THE ROCK AVALANCHE DAMMING LAGUNA DE METZTITLÁN

The valley of the Metztitlán River is blocked in the study area by a rock avalanche that forms a debris mound with a well-defined rim, which in outcrop is 1,950 m wide, up to 1,900 m long across the valley, and up to ~400 m thick along the valley (Figures 3, 4, and 9–11), and covers an area of 2.5 km². These are minimum values for the dimensions of the debris mound, which must extend in the subsurface farther to the south where it is covered by lake deposits. The volume of the rock avalanche is estimated as 0.6 km^3. The debris, which is composed of limestone fragments (Cretaceous El Abra Formation), has a block size up to 20 m and a very high internal disruption (Figure 9). The original stratigraphic layering of the limestone is not recognizable. The displaced mass is not composed of internally coherent rotational slide blocks as shown on the cross section by García-Arizaga *et al.* (1996, their fig. 4). The surface of the avalanche is blocky and has a hummocky appearance (Figures 9 and 10).

In the west, the front of the rock avalanche is delimited by a linear depression formed by two small valleys draining to the Almolón River and the Laguna de Metztitlán (Figures 3 and 9); the highest point of this depression (saddle between the two valleys, windgap forming the western limit of the rock avalanche barrier) has an elevation of 1,350 m asl. In the east, a similar linear depression formed by two small valleys delimits the debris mound from colluvium of the eastern valley flank and the scarps of the two east-west striking normal faults described above (Figure 3). The highest point of this depression (saddle between the two valleys, windgap, and lowest point in the barrier blocking the Metztitlán River valley) has an altitude of 1,290 m asl.

The source slope of the rock avalanche is located on the eastern flank of the valley within the El Abra Formation. The scar is well defined on elevation models (Figures 3 and 10) and aerial photographs (Figure 9, where the top of the breakaway scarp is marked in yellow). The northern limit of the breakaway scarp coincides approximately with the northern one of the two east-west striking and south-dipping normal faults described above (Figures 4 and 9). The inclination of the source slope is 30º (locally up to 45º), and the dip of the El Abra strata ranges from 25º to 35º to the west (Figures 4 and 8); therefore, the source slope is approximately bedding-parallel (Figure 8). Colluvium

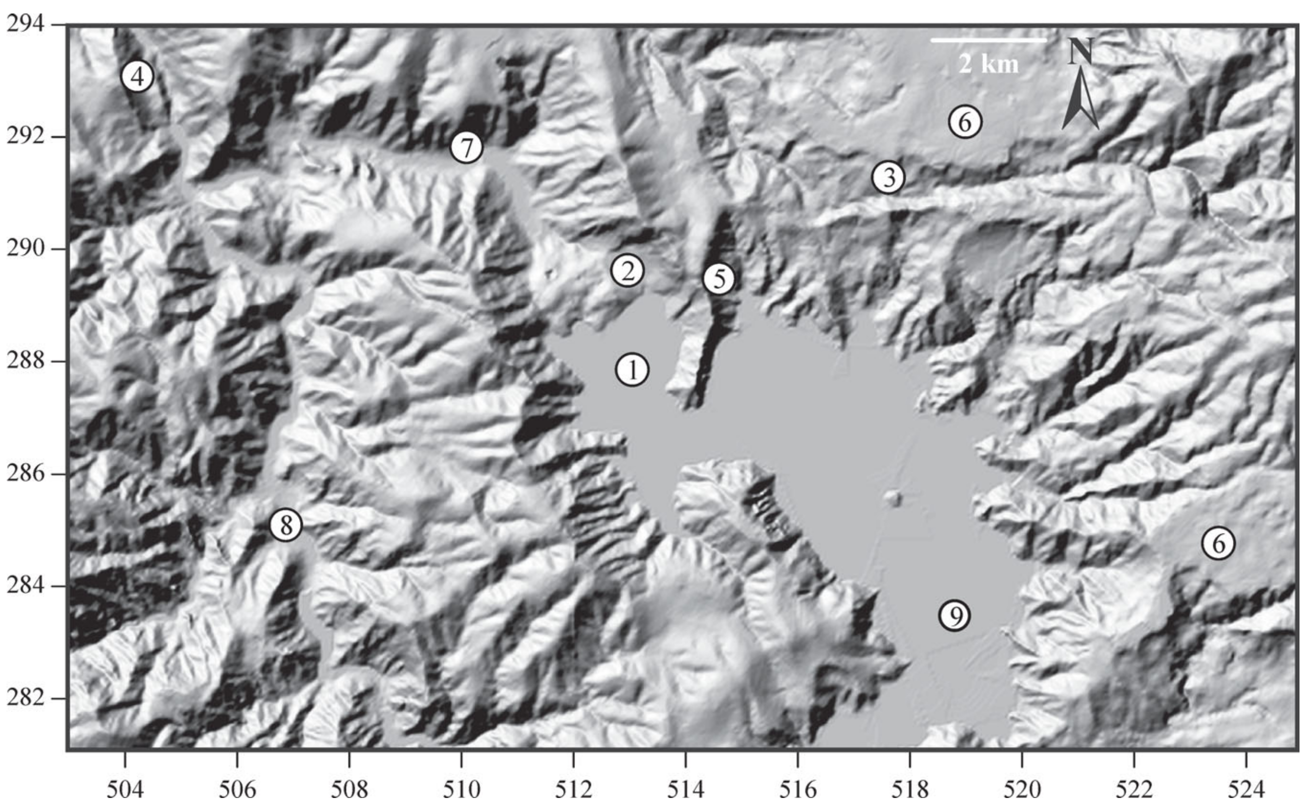

Figure 3. Shaded relief map based on INEGI elevation model (50-m resolution) of the study area. 1: Laguna de Metztitlán; 2: Rock avalanche deposit; note the two east-west striking normal fault scarps to the north of the number; 3: Major east-west lineament formed by the Barranca Honda valley, which is located in the projected eastern continuation of the two normal faults mentioned above; 4: Breached rock slide deposit in the Amajac River valley; the river flows to the right of the number, at the eastern margin of the debris mound; 5: Hanging wall (El Abra Formation) of the west-dipping Laramide Metztitlán thrust; 6: Surfaces of Pliocene basalt flows (Atotonilco Formation); 7: Almolón River valley; 8: Amajac River valley; 9: Former lake floor (La Vega de Metztitlán). Reference system: UTM (kilometer digits).

covers the source slope between the breakaway scarp and the debris mound (Figure 4), whereas the debris mound is in direct contact with bedrock on the western side of the valley (Figures 3 and 4). The height (*H*) from the top of the breakaway zone (1,860 m asl) to the base of the former valley floor (1,000 m asl) (maximum height drop of the avalanche material, vertical fall height) is estimated as 860 m, and the distance of total horizontal displacement (*L*) from the breakaway zone to the distal (western) limit of the debris mound (horizontal runout distance) measures 2,600 m. The ratio *L/H* (relative runout), which is a measure of the efficiency of rockfall movement (Dade and Huppert, 1998; Hermanns and Strecker, 1999), measures 3.02. Unconfined landslides have higher *L/H* ratios (5 to 10) than obstructed ones (2.3 to 5); the rock avalanche under study was obstructed because its path was perpendicular to the axis of the valley. The inverse of the relative runout is an empirical coefficient of friction for a cohesionless rigid mass, defined by the ratio *H/L* (Hsu, 1975; Selby, 1993); it measures 0.33 for the rock avalanche damming Laguna de Metztitlán. In fragmental flow models, on the other hand, the ratio *H/L* is interpreted as an inverse measure of the mechanical energy available for runout after collapse (Kilburn and Sørensen, 1998).

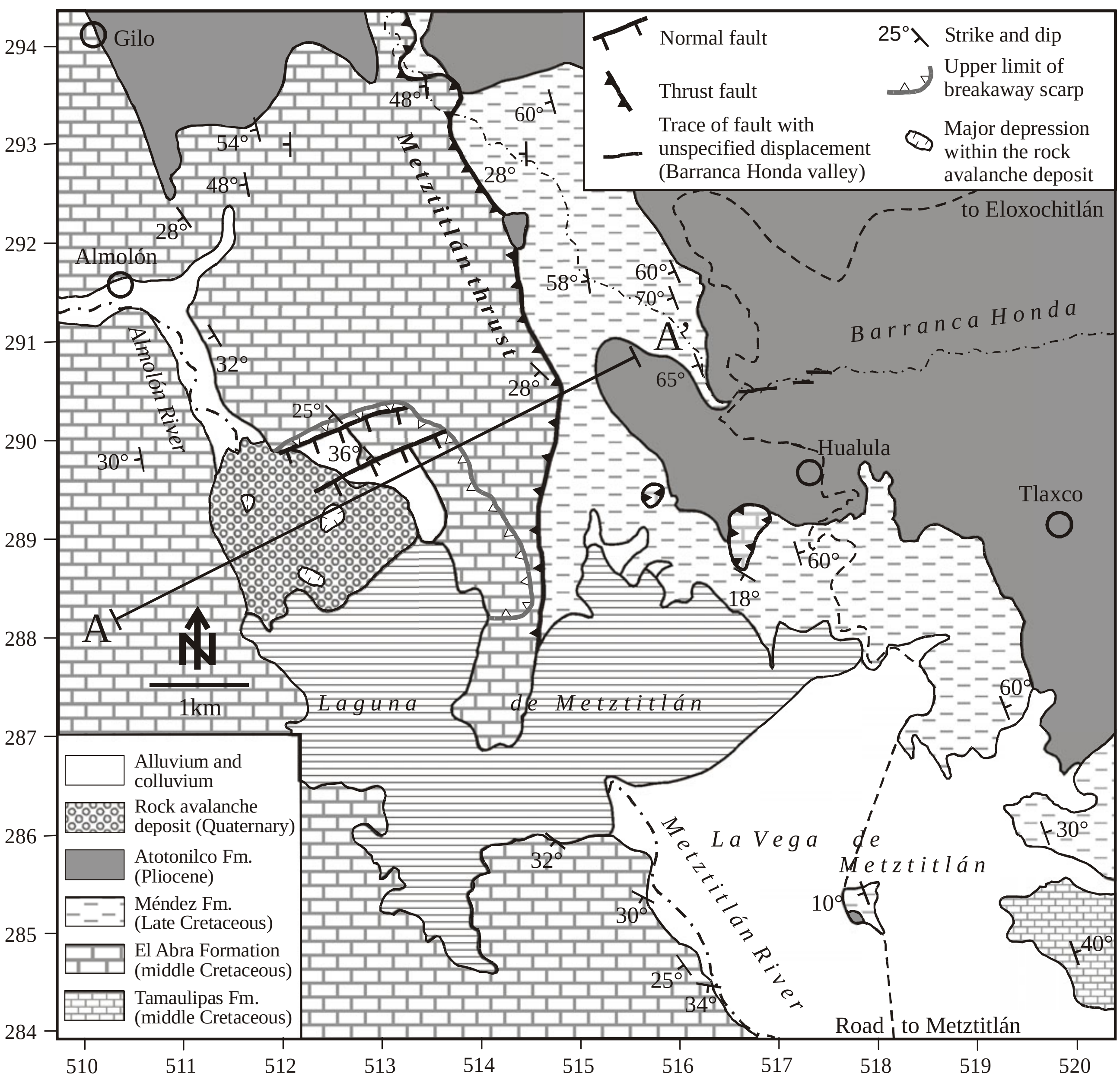

Figure 4. Geologic map of the study area; the northeastern part is based on Ochoa-Camarillo (1996). Reference system: UTM (kilometer digits). A–A': Trace of the structural cross section shown in Figure 8.

In its southern part, the breakaway scarp is located close to the trace of the Metztitlán thrust (Figure 4). However, the rocks did not slide on the tectonic contact between the El Abra and Méndez Formations; the breakaway scarp developed within the El Abra Formation (Figures 4, 8, and 9). North of the lake, the Metztitlán thrust dips ~30º in its lower part and 5–10º in its upper part (Figure 8), forming a ramp-flat structure and two klippens (Figure 4). The ramp is roughly parallel to the strata in its hanging wall and to the inclination of the rockslide source slope (Figure 8). Depending on the (undefined) locations of the Metztitlán thrust and the former river valley in the subsurface, the trace of the thrust may have turned previously around the limestone ridge that extends as a

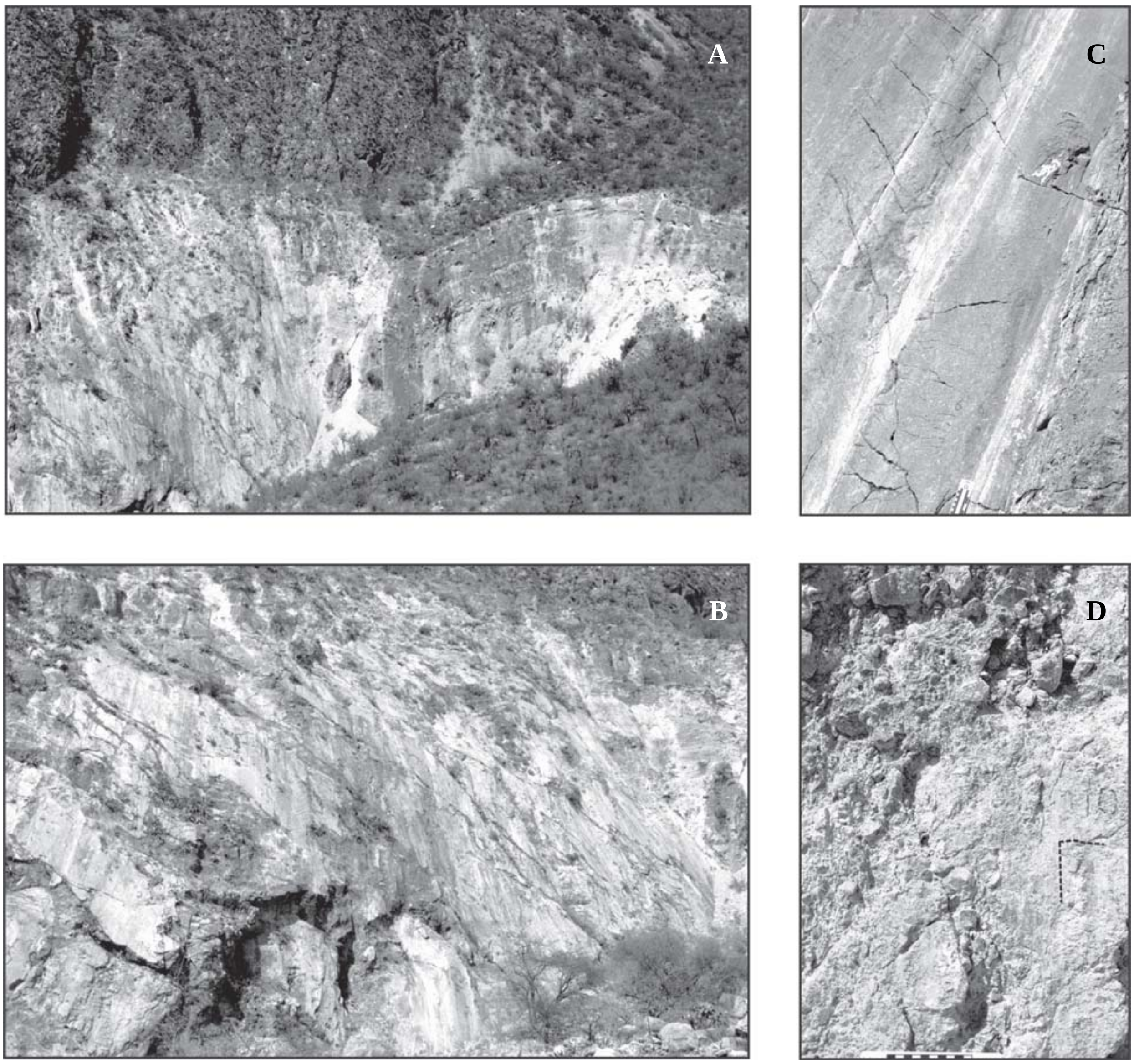

Figure 5. Outcrop views of the northern documented normal fault in the vicinity of the rock avalanche that dams Laguna de Metztitlán (Figures 3 and 4). A: The fault scarp, exposing limestone of the Cretaceous El Abra Formation, can be seen in the left and upper parts of the figure; the exhumed master fault (area in white) is shown in its lower left part (for a close-up, see Figure 5B). Thick colluvium layers are apparently rotated and cut off along the fault in the center-right part of the figure. Note the rock fall deposits at the base of the scarp (upper right part of the figure), which form small fans that are partly unvegetated, and which may have formed during seismic shaking. The figure shows an area ~150 m across; the view is from the southwest. B: Close-up of the lower left part of Figure 5A showing a natural outcrop of the grooved master fault plane, where striation data were collected (Figure 6). The trees in the lower right part of the figure are ~7 m high. C: Large-scale wear-groove striations characterize the exhumed master fault plane (Figure 5B). The scale at the base of the figure measures 10 cm. The striations indicate dip-slip with a minor, but consistent, right-lateral component. D: Secondary fault plane within colluvium, located ~3 m from the master fault within the hangingwall. Centimetric scale at the bottom of the figure. Vertical striations can be seen in the center-right part of the figure. The dashed black lines below the number 10 indicate horizontal and the orientation of the striations, respectively.

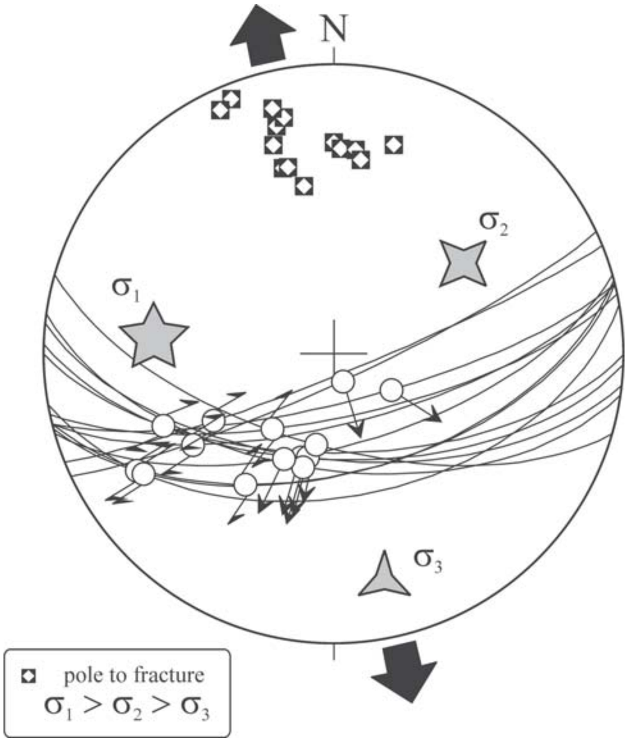

Figure 6. Stereographic equal-area lower-hemisphere plot showing 14 fault-slip striations measured along the northern normal fault. The modeled principal stress orientations are based on a striation inversion algorithm by Angelier (1990). The data are from the exhumed master fault (Figure 5, A–C) and the sheared colluvium of the hanging wall (Figure 5D). The UTM coordinates of the striation measurement site are 512,150/2,289,950.

peninsula into the Laguna de Metztitlán (Figure 4) and may have formed a half-window in the region of the subsequent rock avalanche. It can be further speculated that this former outcrop of Méndez shales on the former eastern slope of the river valley was undercut by fluvial erosion. Based on this scenario, the source region of the rock avalanche was an exceptionally unstable block delimited by discontinuities and free surfaces: two east-west striking normal faults in the north, a west-dipping thrust surface at the base, and a free surface in the south. It is likely that this block became more stable by infilling of the lake sediments, ~250 m thick.

The earliest published report of this rock avalanche was by Waitz (1947), who envisioned a scenario in which a first slide, originating on the western flank of the valley, relocated the river farther east, which undercut the eastern wall of the valley and caused a second failure originating on the eastern flank, which then dammed the valley. Waitz's scenario was promoted by García-Arizaga *et al.* (1996). Contrary to these interpretations, my observations indicate that the debris mound is the result of a one-time failure that originated on the eastern flank of the valley (red vertical hachures on Figure 8). No breakaway zone or source slope is discernible on the western flank of the valley (Figures 3 and 9). Furthermore, the limestone bedrock there dips 30º in a western direction and not into the slope of the valley (Figures 4 and 8), which hinders the development of a breakaway surface.

This slide can be considered a rock avalanche, which is a catastrophic natural granular flow of great magnitude (Friedman *et al.*, 2003). Based on the landslide classification by Keefer (1984), in a rock avalanche, the internal disruption is very high, movement is by flow as a stream of rock fragments, and the velocity is extremely rapid (>3 m/s). The rock avalanches reported by Keefer (1984) from historical earthquakes all had a volume of at least 0.5×10^6 m^3. Furthermore, data on source-slope inclination and height, available for 50 of these rock avalanches, show that the minimum inclination and height were, respectively, 25º and 150 m. The corresponding values for the slide under study are 6×10^8 m^3, 30º, and 860 m, respectively. All but one of the 50 rock avalanches reported by Keefer (1984) originated on slopes undercut by active fluvial or glacial erosion.

The rock avalanche damming Laguna de Metztitlán can also be considered a *sturzstrom*, which is a debris stream generated by rockfall and characterized by catastrophic collapse and runout within minutes (Hsu, 1975). The terms rock avalanche and sturzstrom can be regarded as synonyms. In scatter diagrams the *H/L* and *L* values and the volume of this rock avalanche are located within the systematic trends between volume and *H/L* and between volume and *L* defined for terrestrial sturzstroms (Hsu, 1975; Kilburn and Sørensen, 1998, fig. 1). Moreover, the volume of this rock avalanche (6×10^8 m^3) is larger than the threshold value on the order of 10^6–10^7 m^3 required for sturzstroms to form: beneath this critical volume, insufficient energy is available to initiate fragmental flow, and the unstable mass slumps downslope (Hsu, 1975). An additional parameter, antecedent shear of the granular mass parallel to the direction of failure, may be a requirement for the formation of sturzstroms or rock avalanches (Friedman *et al.*, 2003). As mentioned above, the orientation of the El Abra strata and the ramp of the Metztitlán thrust, resulting from Laramide shear deformation, are roughly parallel to the source slope of our sturzstrom (Figure 8), which fulfills this prerequisite.

The debris mound is crossed by the southern normal fault (Figure 4). The fault forms a small scarp (marked by a vertical arrow on Figure 9) in the vicinity of the trail that leads from Almolón to Laguna de Metztitlán. The scarp has a height of 275 cm where it is crossed by the trail and 305 cm somewhat to the west of the trail. Therefore, some movement must have originated along this fault after the occurrence of the rock avalanche, within the last 1,100 years (see below). Alternatively, this scarp could be the result of settling or small-scale movement within the rock avalanche deposit itself. However, the scarp is not oriented perpendicular to the transport direction of the rock avalanche, a typical orientation of minor scarps within rockslide deposits, but exactly in the extrapolated continuation of the multi-event scarp of the southern normal fault (Figures 4 and 9).

LAGUNA DE METZTITLÁN

On its southern side, the rock-avalanche deposit dams the Metztitlán River, impounding Laguna de Metztitlán. The lake drains underground through the barrier, and its waters emerge on the northern side of the debris mound as the Almólon River in a vauclusian spring that is located close to the northern late Cenozoic normal fault (Figures 4 and 9). The difference between the lake level and the level of re-emergence is ~250 m; this value also corresponds approximately to the maximum thickness of the lake deposits. The discharge rate of the spring ranges from less than 1 m^3/s to more than 50 m^3/s (Waitz, 1947). This natural seepage of the lake waters probably is the reason why the rock avalanche barrier was not breached soon after its formation, as is the case with most landslides (Costa and Schuster, 1988). The major drainage point is located in Bahia de los Sumideros (Figure 9) and was exposed during a drought in January 1941 (Waitz, 1947, his figs. 15-18). Several approximately circular depressions within the rock avalanche deposit (Figures 3, 4, 9, and 10) are rougly aligned between this drainage point and the vauclusian spring. These depressions, which were interpreted as karst sinkholes by García-Arizaga *et al.* (1996), are most likely the result of internal erosion from piping and seepage.

Laguna de Metztitlán is a potential source for hydroelectric power if the underground leakage points of the lake can be pinpointed and sealed (Waitz, 1947). The difference between the lake level and the level of re-emergence (~250 m) and the mean annual runoff of the Metztitlán River (1.6×10^8 m^3; Rocha-Álvarez, 1973) result in a potential gravitational energy of 3.924×10^{14} J. Based on 80% efficiency, this mechanical energy could be transformed into ~90 GWh of electrical energy per year.

The Laguna de Metztitlán is already mentioned in the *Relación Geográfica de Metztitlán* of A.D. 1579 (Acuña, 1986; Mundy, 1996) and shown on the map by Gabriel de Chávez that accompanies this historical document. Based on the local oral history recorded in the same source, the lake reached farther south in earlier times (before A.D. 1579), such that the village of Metztitlán (Figures 2 and 11) was accessed by canoe (Acuña, 1986, p. 69). On the other hand, the catastrophic occurrence of the rock avalanche damming Laguna de Metztitlán is not mentioned in the *Relación Geográfica de Metztitlán*, which suggests that this event did not form anymore part of the local oral history in A.D. 1579, and therefore is likely to have occurred before A.D. 1500. Early attempts to dewater the lake by a spillway (El Tajo) at Bahía del Embarcadero (Figure 9) were already undertaken in ~A.D. 1560 by Fray Nicolás de San Pablo (Acuña, 1986). The frequent seasonal flooding of the valley, because of the rise of the lake level, was eventually brought under control by engineering works in the nineteenth and in the first half of the twentieth centuries (Waitz, 1947). A tunnel outlet now stabilizes the maximum level of the lake at ~1,255 m asl. The overflow is directed

Figure 7. Cross-sectional panoramic view (from the southwest) of the southern documented normal fault, which crosses the rock avalanche that dams Laguna de Metztitlán (Figure 4). The scarp is formed by limestone of the Cretaceous El Abra Formation. Note the fresh rock fall, devoid of vegetation, at the base of the scarp. Also note the 50-m step in topography, where the mountain ridge is intersected by the fault, and the system of parallel, south-dipping minor normal faults within the hanging wall.

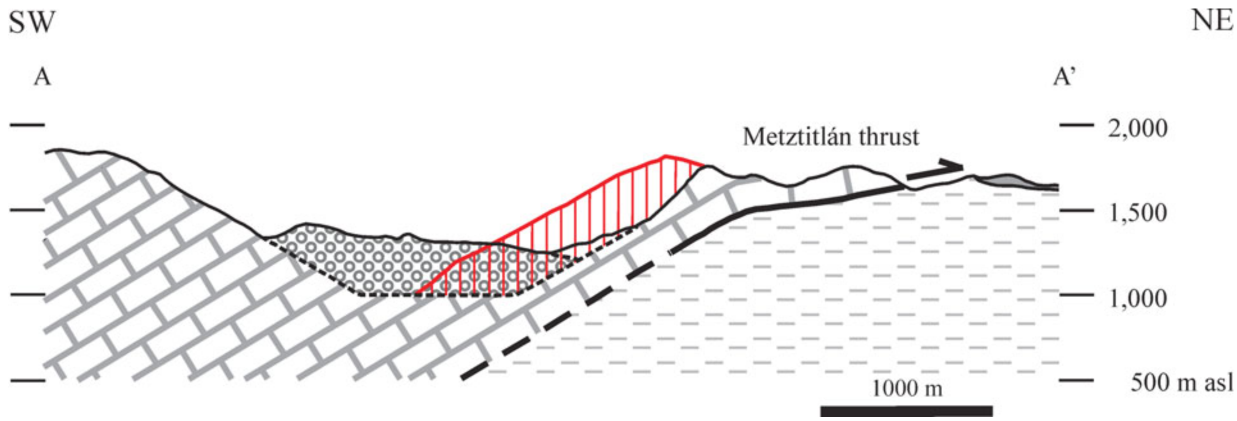

Figure 8. Section across the rock avalanche deposit and the Laramide Metztitlán thrust. The trace of the section is marked on Figure 4. The symbols for the lithostratigraphic units are the same as on Figure 4. No vertical exaggeration. The debris mound is likely to be the result of a one-time failure that originated on the eastern flank of the valley.The red vertical hachures indicate the postulated original location of the debris mound material. The source slope developed within the El Abra Formation and is parallel to the El Abra stratification and the underlying ramp of the Metztitlán thrust.

into an arroyo that flows along the eastern edge of the debris mound into the Almólon River. However, the lake's natural outflow remains by seepage; the lake overflows only occasionally through the tunnel.

Upstream of the present lake, the flat-bottomed valley floor of the Metztitlán River valley (locally known as La Vega de Metztitlán), clearly visible on the shaded relief map (Figure 3), corresponds to the former floor of the lake dammed by the rock avalanche. Most of it is used for agriculture; the irrigated surface between Puente de Venados (Figure 11) and Laguna de Metztitlán measures 48.35 km² (Rocha-Álvarez, 1973). The longitudinal profile of the Metztitlán River (solid line on Figure 11) shows two discrete knickpoints; the lower one is located at 32.3 km from its confluence with the Amajac River (1,260 m asl), the higher one at 51.1 km (1290 m asl) near Puente de Venados (Figure 11). The lower change in longitudinal river slope can be assumed to correspond to the maximum extent of the lake

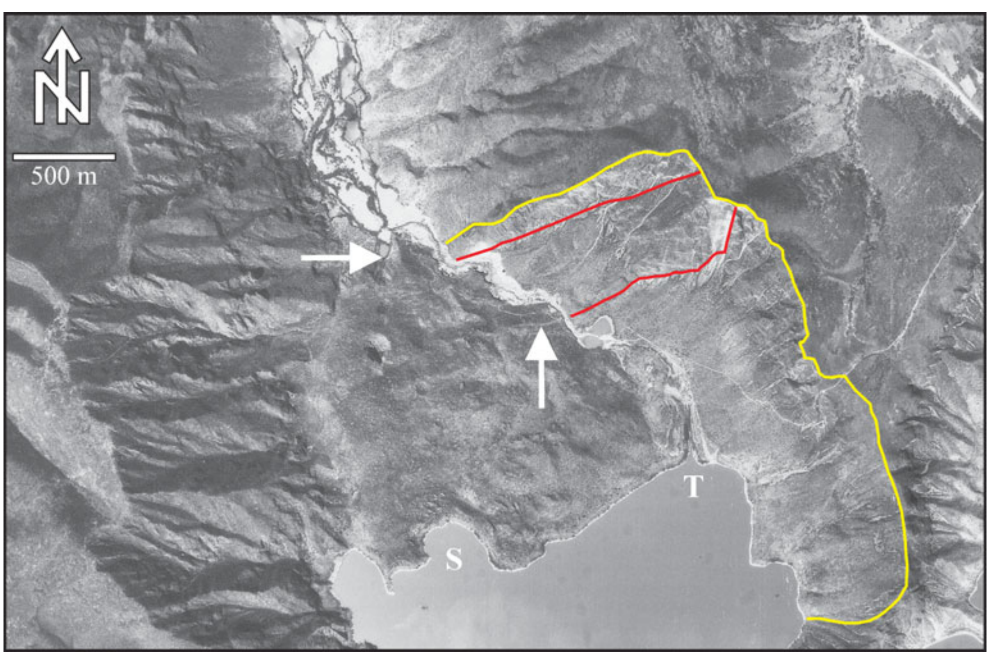

Figure 9. Vertical aerial photograph of the rock avalanche deposit with approximate dimensions of 4.8 x 3.2 km² (source: INEGI). The top of the breakaway scarp is marked in yellow and the normal fault traces in red, except on the debris mound. Vertical arrow: small scarp, with a height of 275–305 cm, where the avalanche is crossed by the southern normal fault. Horizontal arrow: vauclusian spring of the Almolón River. S: Bahia de los Sumideros; T: spillway (El Tajo) at Bahía del Embarcadero. The geology of this area is shown on Figure 4.

(21.6 km), whereas the higher one may separate the part of the formerly V-shaped river valley being filled with sediments, because of the local base level formed by La Vega de Metztitlán, from the one where stream erosion is still active. Alternatively, but less likely, the lake may have reached originally all the way to the change in longitudinal river slope near Puente de Venados at 1,290 m asl. This altitude coincides with the altitude of the lowest point in the barrier blocking Laguna de Metztitlán (see above). However, no independent evidence is available that would support the hypothesis that the lake ever flowed over the top of its barrier; also, no shorelines or lake beds exist above the present level of the alluvial plane of the Metztitlán River valley (1,255 m asl). Furthermore, overflow of the rockslide barrier probably would have led to the lake's demise.

The earlier extent of the lake beyond Metztitlán, mentioned in the *Relación Geográfica de Metztitlán* of A.D. 1579 (Acuña, 1986) (see above), can be used to estimate the growth rate of the Metztitlán River delta. If the delta has prograded in 500 years from Metztitlán to its present location (a distance of 15.7 km in the longitudinal river profile, Figure 11), then the progradation rate during this time interval has been 31.4 m/yr. This estimate is reasonable; the growth rates of river deltas worldwide range between 20 and 90 m/yr (Reineck and Singh, 1975, tab. 19).

Furthermore, the age of the paleolake, and therefore also the age of the rock avalanche damming Laguna de Metztitlán, can be inferred from the assumed delta progradation rate of 31.4 m/yr and the maximum southern extent of the paleolake. If the river delta prograded to its present location from the southern knickpoint in the longitudinal river slope, near Puente de Venados (a distance of 35.4 km in the longitudinal river profile, Figure 11), then the paleolake initiated 1,130 yr B.P. This value is probably an upper limit for two reasons: (i) The paleolake probably only reached to the northern one of the two knickpoints in the longitudinal river profile (see above); and (ii) The delta progradation rate is likely to have been higher than assumed in the southern part of the valley, which is there considerably narrower than farther north. In conclusion, the age of the rock avalanche and the paleolake can be bracketed (i) by the oral history in the *Relación Geográfica de Metztitlán*; and (ii) the estimated maximum age of the paleolake inferred from the maximum extent of the paleolake and the progradation rate of the Metztitlán River delta; the rock avalanche must have occurred ~500–1,100 yr B.P. This estimate is not much different from the age of Laguna Atezca, located in the Molango graben (Figure 2), ~18 km northeast of Laguna de Metztitlán, which formed circa A.D. 280 (Conserva and Byrne, 2002).

A radiometric age of the basal deposits of Laguna de Metztitlán would clarify the age of the lake and the rock avalanche. Furthermore, similarly to the deposits of Laguna Atezca, the deposits of Laguna de Metztitlán, which remain to be studied, are likely to contain a local paleoecology and climate history record of the late Holocene, However, the regions of these two lakes show remarkable differences in climate and vegetation, even though they are separated by a horizontal distance of <20 km. Laguna Atezca is located in a climate with a precipitation of 1,500–2,000 mm/yr (INEGI, 1992) and its deposits contain pollen of cloud forest taxa (Conserva and Byrne, 2002). Laguna de Metztitlán , on the other hand, is located in one of the driest regions of central Mexico, in the rain shadow of the Sierra Madre Oriental. This region has a precipitation of only 400–500 mm/yr (INEGI, 1992) and is characterized by cactus scrub (Puig, 1976, fig. 30).

The longitudinal profile of the Metztitlán River previous to the lake formation can be assumed to have been similar to the profile of the Amajac River (dashed line on Figure 11), which flows to the west of the Metztitlán River and nearly parallel to it (Figure 3) in a V-shaped valley eroded into limestone of the El Abra Formation. This assumption is based on the similarity of the longitudinal slopes of the two rivers downstream from the rock avalanche deposit and upstream from the former lake (Figure 11). Furthermore, this figure also provides an estimate of the thickness of the lake deposits, which can be approximated by the elevation difference between the two river profiles (shaded in grey on Figure 11), and which measures up to ~250 m.

GENERAL OBSERVATIONS SUPPORTING A SEISMIC ORIGIN OF THE ROCKSLIDE

The coincidence of the location of the rock avalanche damming Laguna de Metztitlán with the location of two faults with late Quaternary activity raises the question whether the rock avalanche was triggered seismically or, more specifically, by an earthquake along one or both of the observed normal faults. Tectonically active regions constitute by far the most common setting for rock avalanches, and the vast majority of them are believed to have begun due to ground accelerations associated with seismic events (Friedman *et al*., 2003 and references therein). In a worldwide inventory of historical rock avalanches that formed dams, 40% were triggered by earthquake shaking (Costa and Schuster, 1988, 1991), and landslides occurring in the immediate vicinity of active faults commonly are seismically triggered (Jibson, 1996). Moreover, rock-avalanche deposits are uncommon in this region. With one exception (see below), no other major rockslide is known to this author from the deep canyons that cross the Valles–San Luis Potosí carbonate platform, such as the Tancuilín, Moctezuma, Amajac, and Claro River valleys (Suter, 1990), which suggests that the slopes of these valleys are normally stable under nonseismic conditions.

Further support for a seismic origin of the rock avalanche damming Laguna de Metztitlán could be ongoing seismic activity in the region that triggered the slide. For that reason I culled the seismicity data of the study area

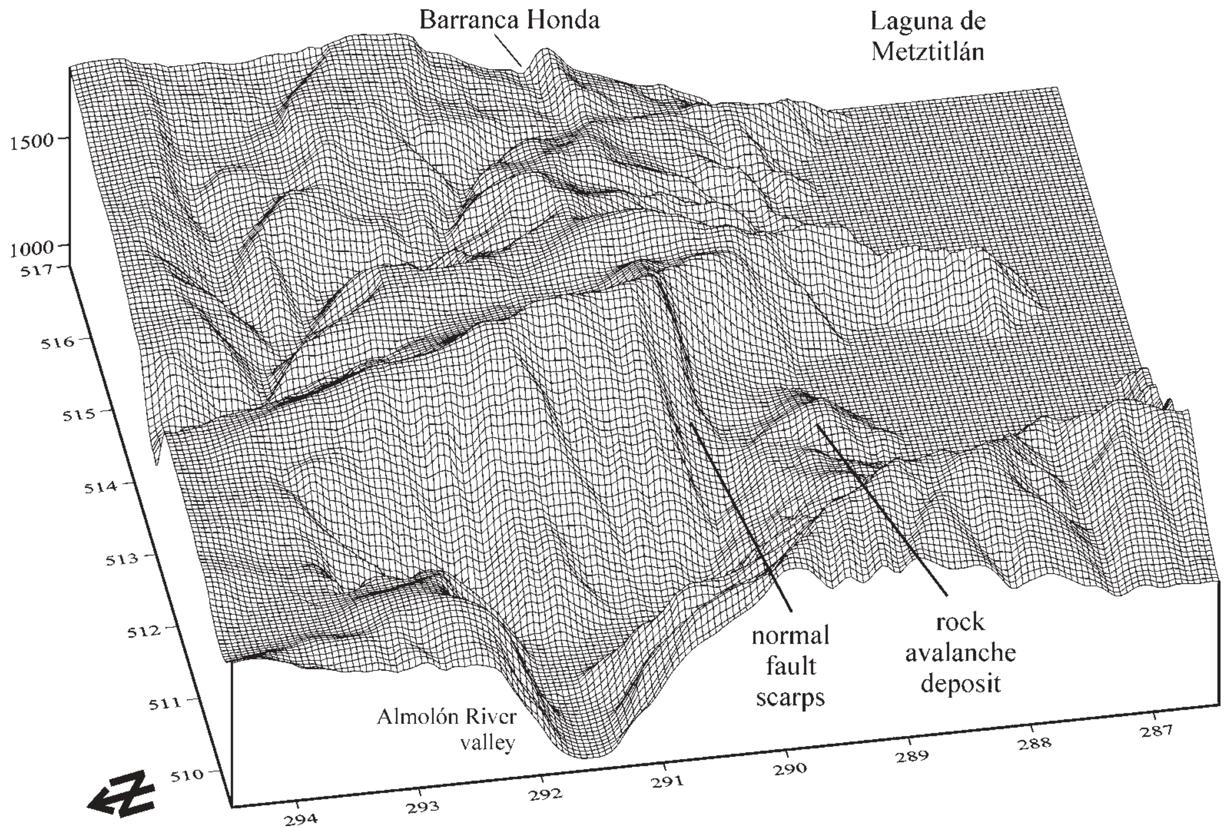

Figure 10. Terrain model (based on INEGI elevation model with a 50–m resolution) showing the debris mound of the rock avalanche damming Laguna de Metztitlán as well as the scarps of the two east-west striking normal faults described in the text. Note the hammocky surface of the avalanche deposit and the elevation difference between the lake and the Almolón River valley. The coordinates are UTM, and north is to the left. The horizontal distance between neighboring grid nodes is 50 m.

from the composite Mexico catalog of the U.S. National Geophysical Data Center (1996). I should caution, however, that this is an inhomogeneous data set with varying location quality, which has not been located with a single velocity model. The epicenter locations are graphed on Figure 2; three of them are located in close proximity to the studied normal faults. These earthquakes occurred 22 August 1970, 4 October 1976, and 8 October 1981 (M_L 4.0).

For a slide of seismic origin, the magnitude of the triggering earthquake can be approximated based on the slide characteristics; Keefer (1984) estimated the magnitude of the smallest earthquake likely to cause a rock avalanche as M_S ~6.0.

OTHER LANDSLIDES OF THIS REGION

Here I report briefly on other landslides in this region and compare them with the rock avalanche damming Laguna de Metztitlán.

A major rockslide deposit, marked as number 4 on Figure 3, is located 2 km below the confluence of the Amajac and Almolón Rivers (Hernández-Treviño and Hernández-Bernal, 1991; García-Arizaga *et al.*, 1996), between the river communities of La Garza and Otatla, approximately 10 km northwest of Laguna de Metztitlán. The debris mound has a length of 1,600 m, a height of 140 m above the river level or 1,020 m asl, and covers an area of 0.8 km² (as compared to 2.5 km² for the rock avalanche damming Laguna de Metztitlán). As in the case of the avalanche damming Laguna de Metztitlán, the surface of the debris mound is characterized by circular depressions, and the debris is composed of highly fragmented limestone of the El Abra Formation with a block size up to 20 m. The slide blocked the flow of the Amajac River; remnants of a corresponding lake basin fill can be found behind the rockslide barrier in the Almolón River valley and for a distance of ~18 km along the Amajac River valley. The rockslide scar is located most likely on the western flank of the Amajac River valley, now a vertical wall, where the dips are vertical to subvertical towards the valley. The composition and state of conservation of this rockslide suggest that it may be of similar origin and age as the rock avalanche deposit damming Laguna de Metztitlán.

A major rockslide dams Laguna Atezca, which is located in the Molango graben (Figure 2), ~18 km northeast

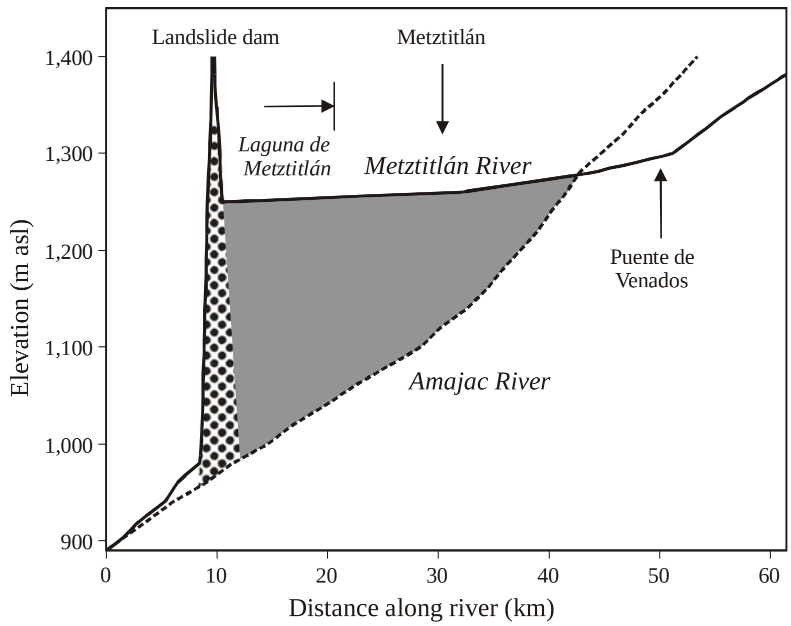

Figure 11. Longitudinal profiles of the Metztitlán River (solid line) and the Amajac River (dashed line) above their confluence at San Juan Amajac (Figure 3). The knickpoint in the profile of the Metztitlán River near Puente de Venados (arrow) indicates the maximum extent of sedimentation caused by the local base level of Laguna de Metztitlán. The present extent of Laguna de Metztitlán is indicated by a horizontal arrow. The elevation difference across the rock avalanche (marked by a dot pattern) is ~250 m. The longitudinal slopes of the two rivers downstream from the rock avalanche and upstream from the former lake are similar. The thickness of the lake deposits is approximated by the elevation difference between the two river profiles (shaded in grey); its maximum is ~250 m.

of Laguna de Metztitlán. Based on a radiocarbon date from the base of the Laguna Atezca deposits, this rockslide occurred shortly before ca. A.D. 280 (Conserva and Byrne, 2002). The Molango graben displaces the late Miocene Tlanchinol Formation by >220 m (Ochoa-Camarillo, 1997). The graben-bounding normal faults may still be active; an earthquake series occurred in the region of the Molango graben in August of 1970 (M_C 3.7; U.S. National Geophysical Data Center, 1996).

Landslides are common east of the study area, on the eastern slope of the Sierra Madre Oriental (Figure 1). Contrary to the rock avalanche damming Laguna de Metztitlán, these are shallow landslides triggered by intense rainfall related to hurricanes. They form on steep slopes in rocks and soils that are rich in clay (Capra *et al.*, 2003). Furthermore, long-term creep and fissuring, probably induced by groundwater drawdown, has caused considerable damage to buildings in Metztitlán (Figure 2; Lugo-Hubp et al., 1993).

CONCLUSIONS

The prehistoric rock avalanche (sturzstrom) damming Laguna de Metztitlán most likely formed by catastrophic collapse and runout. It is internally highly fragmented, with a block size up to 20 m, and characterized by a horizontal runout distance of 2,600 m and a vertical fall height of 860 m. The debris mound covers an area of 2.5 km², has a volume of ~0.6 km³ and is up to ~400 m thick in the valley axis. The surface of the avalanche is blocky and has a hummocky appearance. The avalanche impounded the Metztitlán River for >20 km. The source slope developed within the El Abra Formation and is bedding-parallel. Contrary to former interpretations, the debris mound is the result of a one-time failure that originated on the eastern flank of the valley. The avalanche must have occurred ~500–1,100 yr B.P. This age estimate is based on (i) the *Relación Geográfica de Metztitlán*, written in A.D. 1579, which shows on its map the Laguna de Metztitlán and mentions an earlier extent of the lake beyond the village of Metztitlán, but does not mention the occurrence of the rock avalanche damming the lake, which must have occurred in prehistoric time; (ii) the delta progradation rate of the Metztitlán River, estimated at ~30 m/yr; and (iii) the maximum possible progradation of the delta over a distance of 35.4 km.

Two regional-scale, late Cenozoic, east-west striking, and south-dipping normal faults at the northeastern margin of this rock avalanche feature pronounced multi-event scarps, up to ~250 m high. These faults are active; they displace colluvium, and the southern one of them also displaces the surface of the rock-avalanche deposit, which suggests a surface-rupturing earthquake occurred on this fault in the past 1,100 yr. Furthermore, scarps in the eastern extrapolation of the two faults may correspond to earthquake rupture segments.

General observations that support a seismic origin of the rock avalanche include the following: (i) Landslides occurring in the immediate vicinity of active faults commonly are seismically triggered; the location of the rock avalanche damming Laguna de Metztitlán coincides with the location of two faults with late Quaternary activity; (ii) landslides are uncommon in this region; with one exception, no other major landslides are known to this author from the deep canyons that cross the Valles–San Luis Potosí carbonate platform, such as the Moctezuma and Amajac River valleys, which suggests that the slopes of these valleys are normally stable under nonseismic conditions; and (iii) seismic activity is ongoing in the region that triggered the rock avalanche. However, none of the criteria mentioned above is definite; ruling out aseismic triggering of the rock avalanche damming Laguna de Metztitlán is impossible, as there is no direct evidence for a seismic origin.

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