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Normal faulting in the Pathé geothermal area, Central Mexico

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RESUMEN

El campo geotérmico de Pathé está localizado en una secuencia volcánica del Mioceno Tardío al Plioceno en una región de fallamiento normal activo. Estas fallas se agrupan en dos tendencias de dirección aproximada NS y cercana a la EW. El grupo EW es la extensión meridional de la semifosa tectónica de Aljibes cuya falla maestra es curva con un desplazamiento vertical compuesto de 480 m.

El desplazamiento somero es hasta de 70 m, y el fallamiento EW está generalmente localizado a lo largo de un área semi-elíptica de 34 km constituida por una meseta basáltica y conos ceneríticos. El fallamiento NS define la fosa tectónica de San Francisco, con desplazamientos verticales de alrededor de 30 m, incrementándose hasta 180 m en el subsuelo. Estas rocas Neógenas están intrusionadas por numerosos diques de dirección EW y troncos de rumbo NS.

Producción de vapor generalmente ocurre en la zona de intersección de la parte oriental de la fosa tectónica de San Francisco con el fallamiento EW. Fuentes hidrotermales activas están localizadas sobre una de las fallas de rumbo EW. Alteraciones hidrotermales a lo largo de segmentos de fallas y fracturas sugieren actividad hidrotermal antigua.

PALABRAS CLAVE: Campo geotérmico Pathé, geología estructural.

ABSTRACT

The Pathé geothermal area is located in Late Miocene to Pliocene volcanic rocks in a region of active normal faulting. These faults cluster in sets striking near E-W and close to N-S. The east-west fault set is the southern extension of the Aljibes half-graben whose master fault is curved and has a composite vertical offset of 480 m.

Near-surface vertical displacement is up to 70 m, while E-W faulting is generally located along a 34 km long semielliptic area of plateau basalts and cinder cones. The N-S faulting defines the San Francisco graben, with vertical offsets of around 30 m, increasing up to 180 m below the surface. Neogene rocks are intruded by numerous roughly east-west trending dikes and north-south trending stocks. Steam production occurs at the intersection of the eastern San Francisco graben with east-west faulting. Hot spring activity is located on an E-W trending fault. Hydrothermal alterations along fault and fracture segments suggest earlier geothermal activity.

KEY WORDS: Pathé geothermal field, structural geology.

INTRODUCTION

The study area for this paper (Figure 1) lies near the northern edge of the Mexican Volcanic Belt, between the states of Hidalgo and Querétaro (Segerstrom, 1962; Suter *et al.*, 1995). The area consists mainly of Miocene to Pliocene volcanic rocks with fault-bounded blocks and a regional alluvial valley. The strike of faulting is approximately E-W and N-S, from Landsat imagery (see Figure 2 of Suter *et al.*, 1995).

We map the area with emphasis on near-surface structure, because it appears that the faulting governs present and past geothermal activity (Nichols, 1970).

The lithostratigraphy consists of lower-Cretaceous carbonate platform rocks and late-Cretaceous marly and shaly rocks covered by late Miocene to lower Pliocene continental volcanic rocks. The latter include a 100 to 400 m thick basalt with ^{40}Ar and ^{39}Ar ages of 7.7 ± 0.1 M.a. and 7.1 ± 0.5 M.a. (Suter *et al.*, 1995), sandwiched between andesitic and rhyolitic lavas and tuffs (Figure 2, and 3). At three locations (Figure 3) hypabyssal dioritic, basic and porphyritic granitic igneous intrusions have been identified (Figure 4). Sanidine from a sample of the northern hill of a rhyolite dome located close to the main steam production yielded K/Ar dates of 6.6±0.1 m.y. and 6.7±0.1 m.y. (Nichols, 1970). Between Bajhi and El Salto, a swarm of aphanitic andesitic dikes and sills trend roughly E-W.

STRUCTURAL GEOLOGY

Most of the regional deformation in the study area consists of high-angle normal faults and small but widespread fractures filled by veins and dikes (Figure 3). Six shield volcanoes of the "basaltic unit" are aligned NNE. One set of faults strikes near E-W and another close to N-S (Figures 1 and 3). There is little regional faulting south of the area. Just

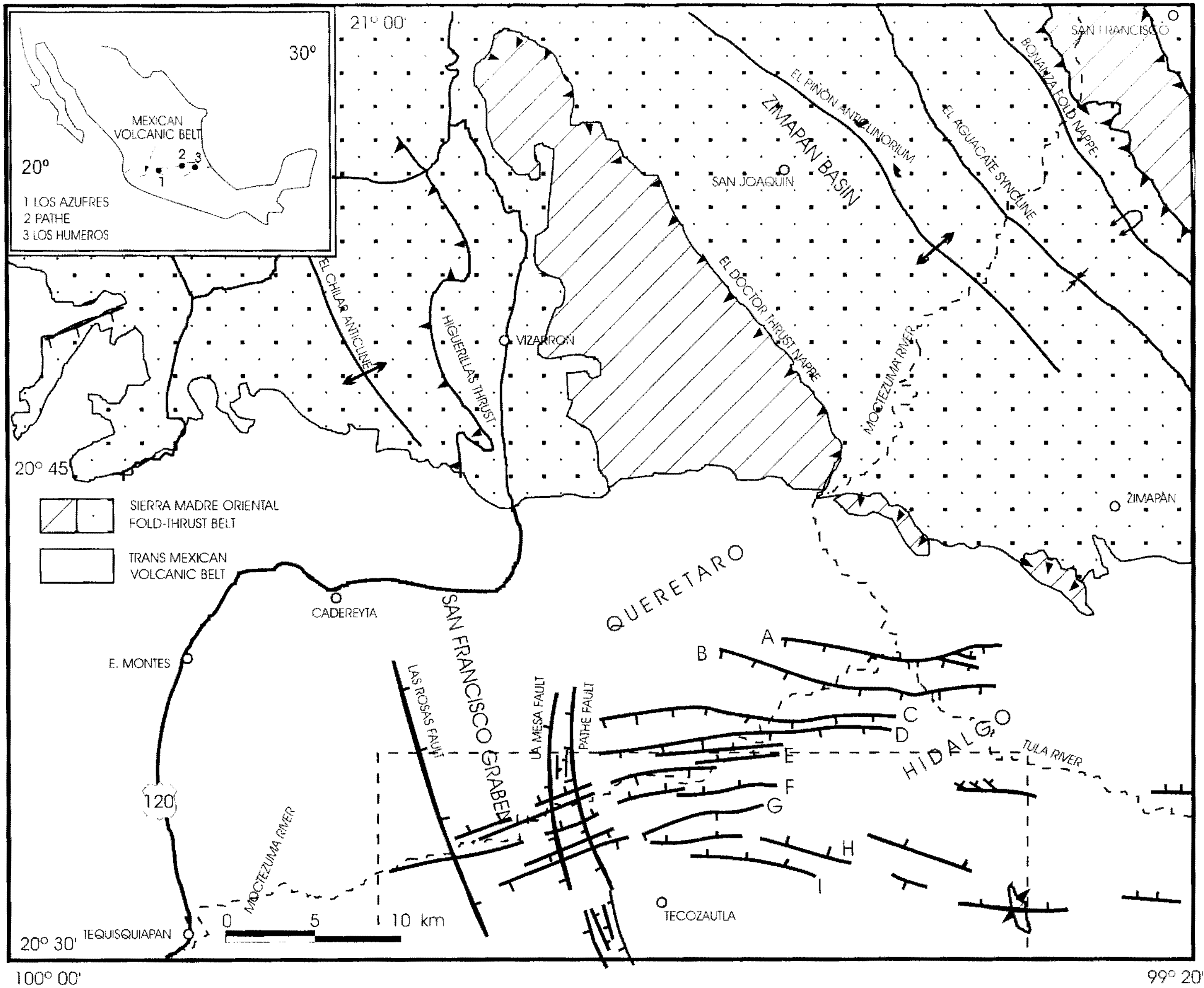

Fig. 1. Location map of the area (see inset).

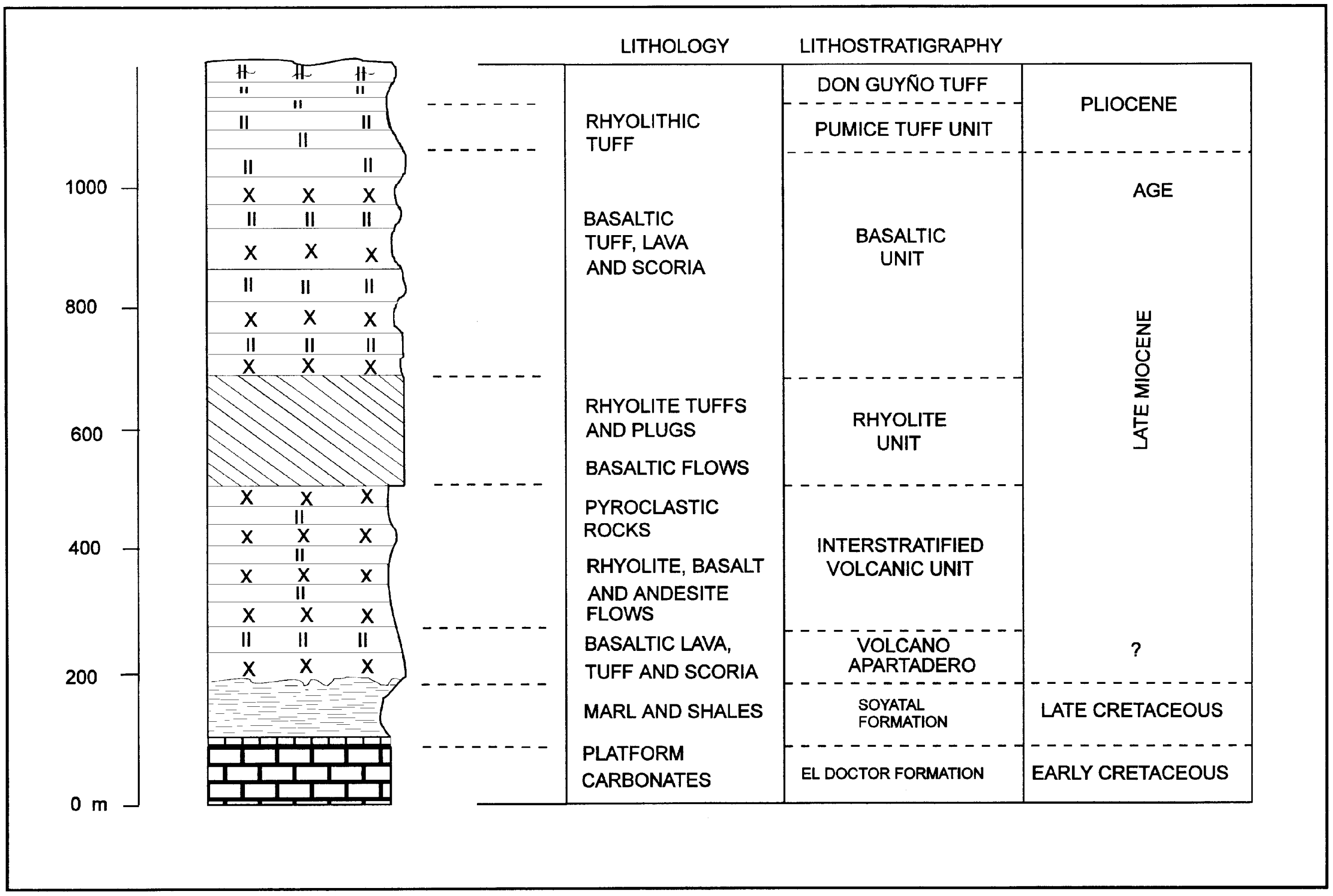

Fig. 2. Generalized lithostratigraphic section of the Pathé geothermal field and surrounding area. The units were introduced by Nichols (1970).

north and northeast there are five regional E-W normal faults in the Aljibes half-graben (Suter *et al.*, 1995). Farther to the north, in the Sierra Madre Oriental fold-thrust belt, regional normal faulting is rare (Segerstrom, 1961, 1962; Suter, 1987a; Carrillo, 1989). To the southwest, regional lineaments striking roughly E-W are observed from satellite imagery. Toward the east and southeast, normal faults with a few meters of throw exist in Huizache, La Cruz, and elsewhere beyond the area. Approximately 25 km to the east, the western fault-mapped segments of the seismically active Mezquital graben are found (Suter *et al.*, 1996).

East trending normal faults. In the northern region of the Aljibes half-graben the normal faults display a consistent down-to-the-south sense of slip (Suter *et al.*, 1995). In the studied area, however, E-W faulting is both down to the north or to the south. Sharp discontinuous escarpments are 1 to 30 m high. The four main faults are labeled F, G, H and I (Figures 1 and 3).They represent the southern continuation of the A-E faults of the Aljibes half-graben. Fault A (beyond the study area) is curved and is associated with a major rollover fold (Suter *et al.*, 1995).

Fault E. At the San Juan River near its junction with the Tecozautla River, fault E strikes roughly E-W and dips 75° to the south; it displaces the base of an upper basaltic flow by 30 m vertically (Figure 5). This fault extends to the west at least 14 km with a throw of 15 m at the Pathé cliff and across the hydrothermal sources at Taxhido, which are part of a total yield of 600 l/s (R. Riva Palacio, personal communication). On the western extension Nichols (1970) reported a major horst near the low-water ford of the San Juan River which separates the main steam-producing zone to the south from a smaller graben to the north. The top of the upper rhyolite unit is displaced 20 m downward in the northern graben and 180 m in the southern faulted block near the NS trending Pathé fault. The steam-producing master fault of the graben extends to the west beyond its intersection with the Las Rosas fault. At this locality a small horst is defined by a northern fault striking N70ºE and dipping 70º-80º to the north, and by the parallel E fault dipping 70º-80º to the south. This horst shows 30 m of throw as estimated from the contact between a thick-bedded rhyolitic tuff and the overlying andesite lavas.

Fault F. West of Banzhá a normal fault strikes N80ºE and dips 70º-80º to the north. It offsets vertically the base of a basaltic flow by about 15 m. It extends more than 17 km to

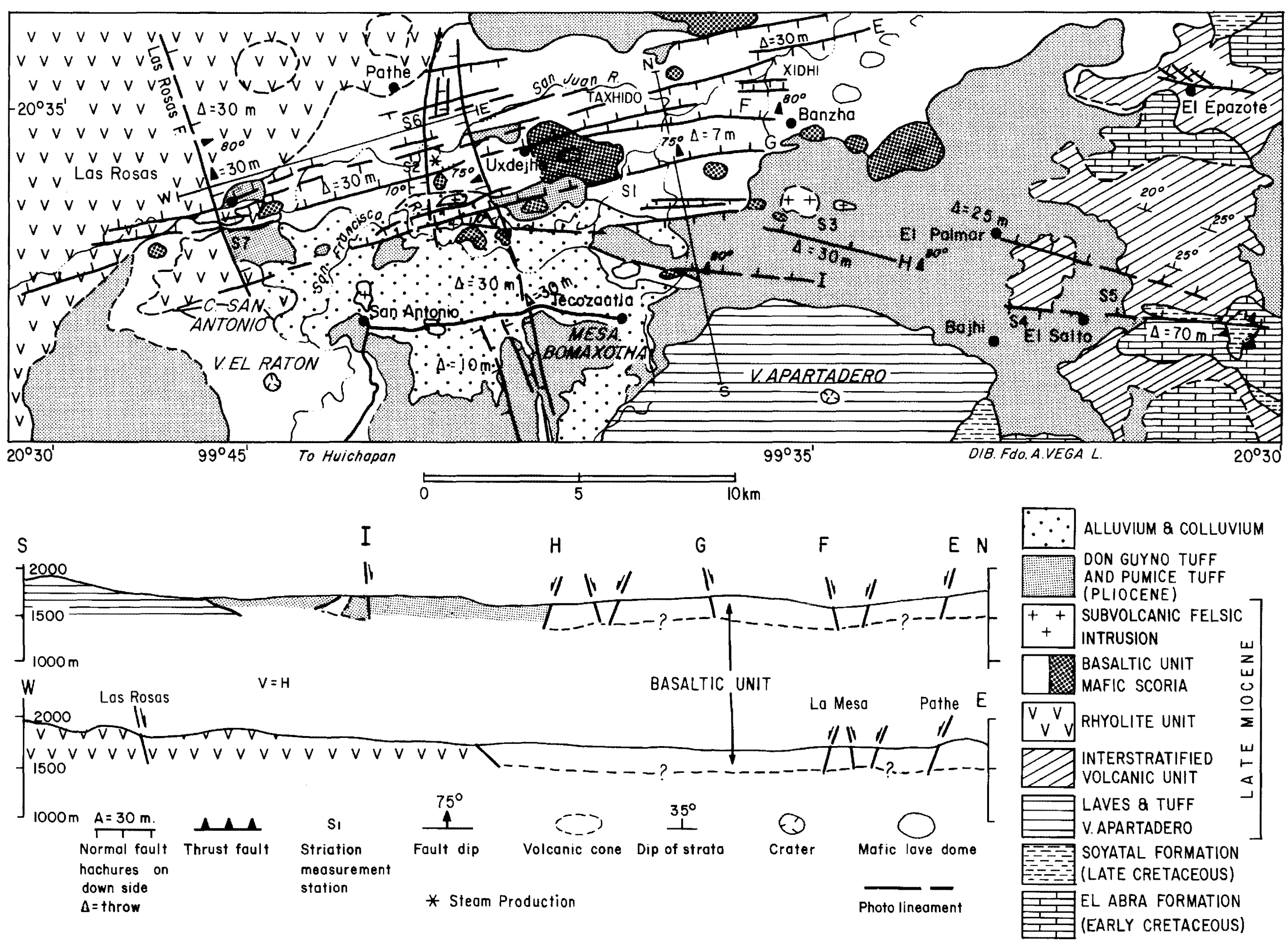

Fig. 3. Structural map of the study area and structural cross section. N-S and W-E refer to the trace of the cross section. A, B are the normal faults bordering the Aljibes half-graben.

Fig. 4. Mafic dome outcropping 2 km NE of Tecozautla. The host rocks are beds of the "pumitic unit".

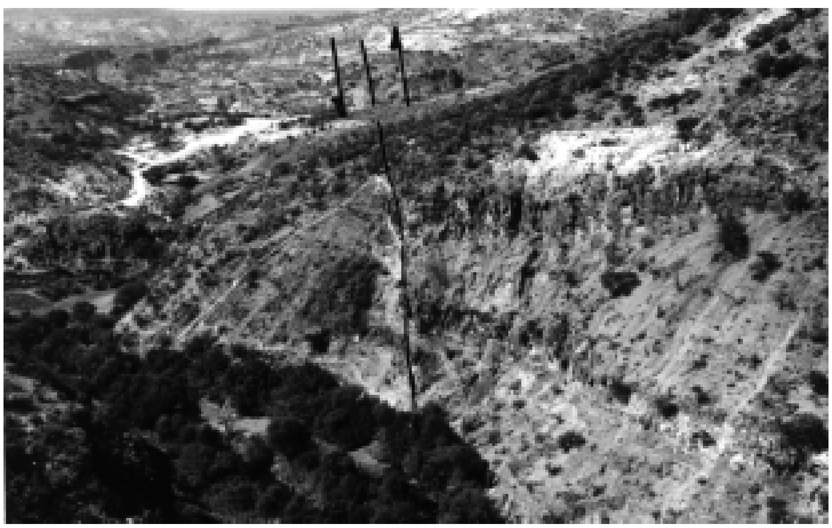

Fig. 5. Fault E across the Tziquia cliff looking to the west. The section pictured corresponds to the "basaltic unit".

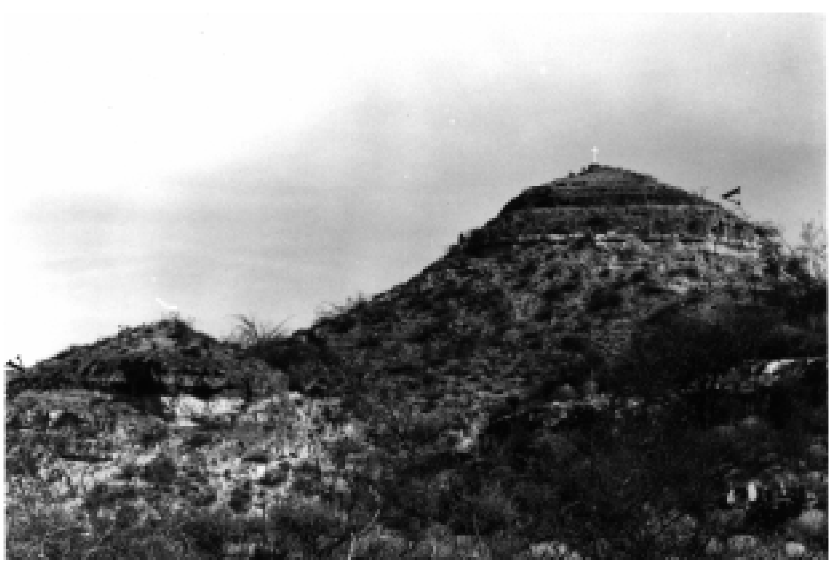

Fig. 6. Looking east at fault G, 2 to 3 km northeast of Tecozautla River. A dark-gray tuff represents the marker horizon to estimate a throw of about 30 m.

the west. In the San Juan River, near its intersection with the Las Rosas fault, a segment of the F fault shows a vertical escarpment 30 m high along the San Juan River. The escarpment height diminishes toward the west where it intersects the Las Rosas fault.

Fault G. In the cliff located west of Banzha an E-W striking fault dipping 65º-75º to the north displaces by 7 m the base of a basaltic bed which caps the pyroclastic beds of the "pumice tuff unit". The fault branches near the top of the hill. To the west the throw of this fault increases and reaches at least 25 m of vertical displacement in the valley of the Tecozautla River. Farther to the west, at the San Francisco River, this fault displaces vertically the base of a basaltic flow by 30 m.

Fault H. About 7 km to the ENE of Tecozautla the H fault crops out. At this locality the fault strikes N75ºW and dips northward 75°-80°. A black ignimbrite bed is vertically displaced by 30 m. The fault juxtaposes different beds of the pumitic unit (Figure 6). A scarp 3 m high shows well-defined striae. At Arroyo Bajhi, along the eastern extrapolation of this fault, a normal fault dips 70° toward the south. The fault offsets semiconsolidated alluvial fan deposits against pyroclastic rocks of the interstratified volcanic unit (Figure 7). Farther east of this outcrop there is a normal fault striking N80ºW and dipping 70º-80º to the north. At this locality the fault juxtaposes the limestones of the El Doctor Formation against rocks of the interstratified unit and against a narrow outcrop of the Soyatal Formation along a straight contact; well-defined striae are found in many parts of the fault. A flat of the Sierra Madre Oriental fold-thrust belt is displaced vertically about 70 m (Figure 3).

Fault I. Fault I is clearly exposed a few kilometers to the ENE of the town of Tecozautla. The fault juxtaposes the basalt unit against the pumitic unit (Figure 8). It strikes N80ºW and dips 85° to the north showing gouge, tectonic breccia and hydrothermal alteration. Intense fracturing subparallel to the fault plane exists in both blocks. These close-spaced fractures are filled with hydrothermal alteration minerals and clay deposits (illite and kaolinite), some of recent weathering. In the basaltic beds they are over 1 m wide. The minimum throw is 30 m.

San Francisco graben (north-south faults). These faults develop in the western region of the study area striking between N10ºW ± 10º and ≈ N30ºE. They corrrelate with ~ N-S normal faults in northern Mexico (Stewart, 1978; Suter, 1987b; Henry and Aranda, 1992; Aguirre and Mc Dowell, 1993). The structure of this region is dominated by the Pathé and the Las Rosas faults of kilometric length, which define a graben here called San Francisco. The eastern Pathé fault (Nichols, 1970) crops out discontinuously along its trace and features a discontinuous scarp. In the transverse valley, faulting is manifested by the abrupt truncation of bedding, tectonic breccia and, in places, slickensides. The mapped length of the trace of this fault is 14 km striking between N10ºE to N10ºW and dipping 70º-85º to the west at the surface. At the San Juan River the base of the youngest outcropping basalt flow is vertically displaced about 70 m.

La Mesa fault. West of the Pathé fault is the La Mesa fault (Nichols, 1970). The trace of this fault may be followed for 9 km from northeast of Pathé to the south of Pathé cliff where the unconsolidated clastic deposits of the San Antonio-Tecozautla valley conceal it. At the Pathé cliff, this fault strikes rouhgly N-S and dips 80º to the west. A youngest basalt flow shows about 40 m vertical displacement and about 10° tilt against the fault plane.

Las Rosas fault. This fault strikes N15ºW and dips 80º to the east, extending > 7 km northward from San Antonio hill. The trace of the fault is marked by a prominent scarp in purple andesite lavas and white tuffs of the rhyolite unit. On the surface, the fault juxtaposes thick-bedded andesite lavas and tuffs against similar rocks capped by the pumice tuff unit (Figure 9).

Faults at the Mesa of Bomaxotha. South of the valley of San Antonio-Tecozautla there is a sinuous cliff along the flows of ignimbrites and pyroclastics beds arising from the Huichapan caldera (Nichols, 1970, Silva, 1991, Milán *et al*., 1993) (Figure 3). On the surface, three straight high-angle normal faults of kilometric length offset the bedding of the pumice tuff unit. This faultin— g lies on the southward extension of the Pathé and La Mesa faults. The easternmost fault has a vertical displacement of 30 m and 8 m of heave, inferred from a characteristic 3 m thick bed of blackish welded tuff used as marker horizon. The fault plane strikes roughly N-S and dips about 75º to the west. A discontinuous scarp may be followed for at least 2 km. An about 0.70 m thick gouge, plus hydrothermal alteration, mark the fracture plane.

Just west of this fault there is another fault striking N10ºW and dipping 75° toward the east. Light gray tuff beds are displaced by about 20 m on the surface. On the top of the plateau there is a scarp with a height of about 1 m which vanishes to the south. This fault and the previous one to the east define a small graben 500 m wide and at least 5 km long.

Farther to the west, another normal fault west of the village of Bomaxotha displaces the beds of the pumice-tuff unit by 15 m. The fault plane strikes N10ºW and dips 80º toward the west. Together with the former fault they define a horst 400 m wide.

DISCUSSION

Because of their direction and age the E-W and N-S trending faults are related to those existing in the northern

Fig. 7. View from the east of a normal fault outcropping in Arroyo Bajhi, east of Rancho Bajhi.

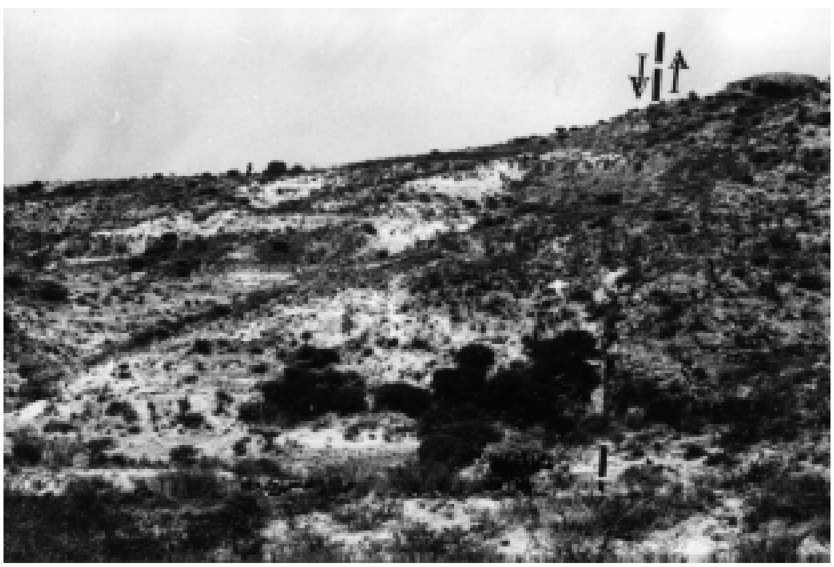

Fig. 8. View eastward of fault H at the Tecozautla River. The fault is nearly vertical and juxtaposes basaltic lavas of the basalt unit (at right) against beds of the pumitic unit.

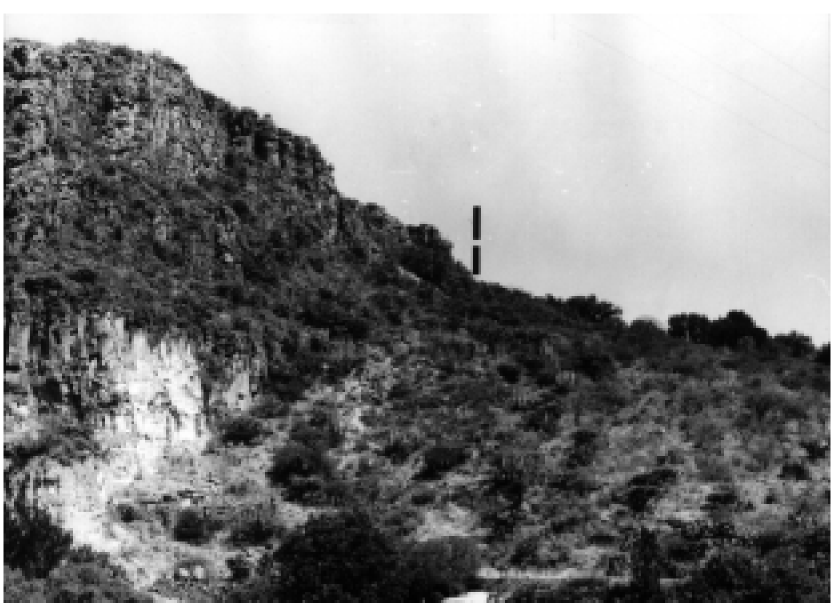

Fig. 9. Northward, slightly oblique, view of the strike of the Las Rosas fault at Rancho Las Rosas. The fault juxtaposes rocks of the rhyolitic unit against rocks of the pumitic unit capping andesite lavas and felsic tuffs.

Mexican Volcanic Belt (Suter *et al.*, 1991; Suter *et al.*, 1992), and in the Basin-and-Range province of northern Mexico (Stewart, 1978; Suter, 1987b, 1991; Stockes and Hodges, 1989; Henry and Aranda, 1992).

The Neogene normal faults are not related to the compressional structures of the Paleogene of the Sierra Madre Oriental fold-and-thrust belt. However, two balanced cross-sections across these areas suggested that the Aljibes half-graben decollement is at the same depth (~ -4 000 m bsl) than the basal decollement of the El Doctor thrust nappe (Suter, 1987a; Suter *et al*., 1995). They are related to each other because both structures are detached at the same depth.

A further consideration which might relate the Sierra Madre Oriental fold-and-thrust belt with the extension area is the origin of volcanism. The adjacent shortened section is very probably thin-skinned (Suter, 1987a) with the basal decollement leaning to the WSW, thus suggesting a "continental lithospheric subduction". Rothé (1977) believed that the crystalline basement of the detached Mesozoic cover could have been pulled down by the orogenic movements and melted at 600ºC at about 20 km depth, even after the orogeny was over. Thus the granitic magma might have erupted independently from the basaltic magma. The basalts in this area as in most of the Central Mexican Volcanic Belt are younger than the rhyolitic volcanism (Schlaepfer, 1968; Nelson and Hegree, 1989, Cserna *et al.*, 1987; Vázquez and Jaimes, 1989; Mooser *et al*., 1997).Therefore they could have risen to the surface during the deepening of the faulting. This would explain the tendency of the volcanism to become more basic in time.

CONCLUSIONS

The lithostratigraphy of the Pathé geothermal field consists of Late Miocene to Pliocene volcanic rocks. From bottom to top we find: the interstratified unit; the rhyolite unit which includes basalts, andesites and principally rhyolite lavas and tuffs; the basalt unit (6.3 ± 0.2 m.y., 6.4 ± 0.2 m.y.), the pumice unit of Pliocene age; and fluvial and colluvial deposits of Quaternary age. These rocks are deformed by many near-E-W and N-S high-angle normal faults. The roughly E-W striking faults labeled (E, F, G, H and I) are a continuation to the south of the A, B, C and D faults of the Aljibes half-graben(A, B, C, D)

The near-surface throw of most of the faults may be estimated as 20 to 30 m; but subsurface information shows that the vertical displacement increases to 180 m below the surface near the intersection of faults E and Pathé (Nichols, 1970). Thus vertical displacement is larger at the center than at either end, a feature which is also observed horizontally along the strike in the E, F, Pathé, and La Mesa faults.

The E-W set of structures consists of planar faults dipping toward the south in the range of 65° to 90°. Three of the southernmost faults face to the north and define small grabens. The overall geometry of this structure consists of 9 major faults (A to I). All the E-W faults are planar, except A which shows the appearance of a listric fault dipping 45° at the surface. The half-graben is characterized by a rollover anticline. Within the rollover, hanging-wall layers are rotated into the detachment fault, and the amount of rotation increases with the amount of extension and at depth. The synthetic and antithetic faults of the southern area are interpreted as near-surface collapse grabens formed by accommodation of the hanging-wall strain generated above the curved detachment surface.

The Aljibes half-graben forms a tectonic depression at least~ 18.5 km long and 12.5 km wide. This structure follows a roughly E-W elongated continuous basaltic outcrop.

The north-south trending Pathé, La Mesa and Las Rosas faults define the San Francisco graben. The Pathé fault is the easternmost master fault facing west, and the Las Rosas fault is the antithetic westerly one. This structure averages 12 km length and 8.5 km wide. The Pathé geothermal field lies wholly on the eastern margin of the San Francisco graben. Steam is found in the Pathé fault where it branches close to the intersection with the E fault. Along the E-W faults, especially the E fault, there are various hot springs producing over 600 l/s of water with temperatures in excess of 30ºC.

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