

Stratigraphy of the Balsas Group in the Amacuzac area, southern Mexico: relationship with Eocene volcanism and deformation of the Tilzapotla-Taxco sector

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ABSTRACT

The Zapalco-Amacuzac area in the Morelos and Guerrero states, southern Mexico, constitutes one of the classic sectors where Paleogene continental beds of the Balsas Group were originally described. The exposed succession has an apparent thickness of ~2,500 m and it is constituted by two distinct sedimentary units separated by a slightly angular unconformity and by two intercalated ignimbrites (35.1 ± 0.4 and 38.5 ± 0.7 Ma, sanidine, K-Ar). The basal beds of the lower sedimentary unit (Tepetlapa Formation) are constituted by matrix-supported conglomerates that grade upwards to sandstone with a poorly defined planar parallel stratification and some intercalated andesitic and mafic lava flows. One of the andesites yielded a whole rock K-Ar date of 44.5 ± 0.7 Ma. Intercalations of conglomerate beds increase again toward the top of this unit. The upper sedimentary unit (Huajintlán Formation) is constituted by a ~300 m thick succession of matrix-supported conglomerate with some lenses of conglomeratic sandstone. This unit unconformably underlies the Tilzapotla ignimbrite whose best age estimate is 34.3 Ma (sanidine Ar-Ar). The beds of the two sedimentary formations dip east to northeast with higher dips for the lower unit (50–30°). Recognized facies in both units are indicative of an alluvial fan environment with more proximal facies for the Huajintlán Formation.

The studied succession is located immediately northwest of a large elliptical (50×30 km) dome structure that resulted from the tumescence stage, in the early evolution of the Tilzapotla caldera, previous to the collapse. The northwestern termination of the dome merges and interferes with the NNE-trending Laramide fold and thrust front of the Iguala Cacahuamilpa highs, near Taxco. In the study area, the dome contours display a local inflection defined by a change in the dip direction of the Morelos and basal beds of the Tepetlapa Formation from north to east. The slight angular unconformity between the Tepetlapa Formation and the overlying units indicates a first stage of eastward tilting related to an uplift episode in the Taxco area, probably originated by the emplacement of silicic magmas (ca. 38 Ma). The proximal facies of the overlying Huajintlán Formation and the age (35.1 ± 0.4 Ma) of the Piedras Altas Tuff, indicate that this formation resulted from the rejuvenation of the source area triggered by the tumescence and the initiation of the volcanic activity in the nearby Tilzapotla caldera area. This is confirmed by the higher dips (~50°) of the Tepetlapa Formation near the dome structure and the decreasing dips toward the northeast. The age of one andesite lava flow (44.5 Ma) intercalated in the lower unit is indicative of an Eocene age for the beginning of the Balsas Group accumulation in this area.

Key words: terrestrial sedimentation, Southern Mexico, Balsas Group, Tilzapotla caldera, Eocene.

RESUMEN

El área de Amacuzac-Zacapalco, estados de Morelos y Guerrero, constituye una de las áreas clásicas en donde el grupo Balsas fue descrito originalmente. La sucesión expuesta en esta zona tiene un espesor aparente de ~2,500 m y está formada por dos unidades separadas por una ligera discordancia angular y por dos ignimbritas intercaladas (35.1 ± 0.4 y 38.5 ± 0.7 Ma, K-Ar en sanidino). La unidad inferior (Formación Tepetlapa) presenta en su base conglomerados matriz-soportados que gradúan hacia la parte media y superior a capas de arenisca con estratificación imperfecta e intercalaciones de lentes de conglomerado matriz-soportado con algunos derrames intercalados de andesita y basalto. Para una de las andesitas se obtuvo una edad de K-Ar en roca entera de 44.5 ± 0.7 Ma. La unidad superior (Formación Huajintlán) presenta una granulometría notablemente más gruesa representada por conglomerados matriz-soportados con algunos lentes de arenisca conglomerática. Esta unidad subyace en discordancia a la ignimbrita Tilzapotla, para la cual se ha obtenido una edad Ar-Ar en sanidino de 34.3 ± 0.09 Ma. Las capas de ambas unidades tienen buzamientos al oriente y nororiente con echados mayores para la unidad inferior ($50\text{--}30^\circ$). Las facies observadas para ambas unidades revelan que se trata de depósitos de abanico aluvial con facies proximales para la Formación Huajintlán.

La sucesión estudiada se localiza inmediatamente al noroeste de una gran estructura dómica-elíptica (50×30 km) que se originó en la etapa de tumefacción, durante la evolución temprana de la caldera Tilzapotla, previa al colapso. La terminación noroccidental del domo converge e interfiere con el cinturón de pliegues y cabalgaduras que forma los altos del sector Iguala-Cacahuamilpa cerca de Taxco. En el área de estudio, el contorno del domo presenta una inflexión local definida por un cambio en la dirección del echado de las capas de la formación Morelos y la base de la Formación Tepetlapa de norte a este. La ligera discordancia angular entre la Formación Tepetlapa y las unidades subyacente indican una primera etapa de inclinación hacia el noreste probablemente originada por el levantamiento en el área de Taxco que acompañó el emplazamiento de magmas silícicos (ca. 38 Ma). Las facies proximales de la Formación Huanjintlán y la edad (35.1 ± 0.4 Ma) de la Toba Piedras Altas indican que esta formación resultó de un rejuvenecimiento del área fuente provocado por la tumefacción en el área más cercana de la caldera Tilzapotla. Esto se confirma por los echados mayores de la Formación Tepetlapa ($\sim 50^\circ$) en las capas próximas a la estructura dómica. La edad de una de las andesitas intercaladas (44.5 Ma) en la unidad inferior es indicativa de una edad eocénica para el inicio de la acumulación del Grupo Balsas en esta área.

Palabras clave: sedimentación continental, Sur de México, Grupo Balsas, caldera Tilzapotla, Eoceno.

INTRODUCTION

The Balsas Group was originally described by Fries (1960) as a succession of terrestrial deposits made up of conglomerate, sandstone, siltstone and lacustrine limestone as well as pyroclastic and lava flows. Fries (1960) included within the Balsas Group successions that crop out in five different areas distributed within the Morelos and northern Guerrero states. Subsequently, de Cserna and Fries (1981) and de Cserna (1982) applied the name of Balsas Formation to successions equivalent to the Balsas Group distributed in northwestern Guerrero State, southern Estado de México and western Michoacán State. However, in neither case was this unit formally defined.

In general, the main criterion used to allocate terrestrial rocks as part of the Balsas Group in central Guerrero and Morelos states has been its stratigraphic position. All conglomeratic units that unconformably overlie deformed Cretaceous marine beds and underlie Eocene-Early Oligocene volcanic rocks (*i.e.*, “Tilzapotla Rhyolite” in its broad sense) (Fries, 1960) have been considered part of the Balsas Group. Therefore, a diverse range of Tertiary terrestrial continental sedimentary successions

widespread from western Michoacán State to western Guerrero State have been described as part of the Balsas Group (*i.e.*, Fries, 1960; 1966; de Cserna and Fries, 1981, de Cserna, 1982). Given the scarcity of paleontological and geochronological data, inferences on the age range and regional chronological variations of the Balsas Group are still vague. However, in a few localities, more precise inferences based on geochronological data have been made. For example, near Tetelcingo (Figure 1), by the Balsas river, Ortega-Gutiérrez (1980) and Cerca *et al.* (in press) reported intermediate and silicic volcanic rocks, with K-Ar and Ar-Ar dates ranging from 60 to 68 Ma, that underlie terrestrial rocks assigned to the Balsas Group. Cerca *et al.* (in press) provided geochronological data and stratigraphic observations that indicate that the lower beds of the Balsas Group are intercalated with Paleocene volcanic rocks. These authors also reported and compiled geochronologic data from late Eocene-early Oligocene volcanic rocks that overlie the Balsas Group in a broad area around the high Balsas river. Molina-Garza and Ortega-Rivera (2006) obtained an Ar-Ar age of 33.1 Ma for an ignimbrite intercalated in a succession attributed to the Balsas Group, southeast from the Tilzapotla caldera, between Tuzantlán and the

Balsas river. Based on a magnetostratigraphic analysis, the authors suggested that the whole succession belongs to the Eocene.

In the Taxco area, Alaniz-Álvarez *et al.* (2002) recognized different sedimentary units (previously included within the Balsas Group by Fries), separated by andesites and ignimbrites ranging in age from 33 to 38 Ma. These authors also described a “red conglomerate” previously mentioned by Edwards (1955) and Fries (1960) in the Acamixtla-Taxco sector. The succession of reddish conglomerate underlies the earliest late Eocene volcanic rocks in the area and do not display any folding effects.

De Cserna (1983) suggested that parts of the Balsas Group in southern Estado de México and westernmost Michoacán may be Late Cretaceous in age. This is coincident with inferences by Campa and Ramírez (1979) who interpreted continental beds as Late Cretaceous in age (Cutzamala Formation), based on the occurrence of marine limestone intercalations and the folding deformation. More recently, Benammi *et al.* (2005) reported in the Tiquicheo region, eastern Michoacán, the finding of dinosaur rests, confirming that continental deposits resembling those of the Balsas Group in this region are, at least partially, Late Cretaceous in age.

Available up-to-date data suggest that not all the terrestrial successions that were deposited previously to

the widespread late Eocene to early Oligocene volcanism belong to the Balsas Group in the original meaning given by Fries (1960). Therefore more detailed stratigraphic and geochronologic studies are required to differentiate the units that have been wrongfully considered as one single depositional event, under the name of Balsas Group.

There are also different interpretations on the origin of the basin-fills that have been grouped under the Balsas Group. According to Cerca *et al.* (in press), Balsas Group rocks in the Balsas river region accumulated in intermontane basins originated as a consequence of the Late Cretaceous Laramide deformation. In contrast, Alaniz-Álvarez *et al.* (2002) interpreted that Balsas Group units (Chontalcuatlán and Atzala formations) in the Taxco area and to the north were accumulated in a pull-apart basin associated with NW and N-trending strike-slip faults. Preliminary evidence indicates that several independent sedimentary basins in Guerrero and Morelos states, with similar depositional environments, developed at different times, but all were covered by late Eocene-early Oligocene volcanic rocks (Cerca *et al.*, in press) (Figure 1).

Beyond the problem of applying the same lithostratigraphic denomination to a diversity of terrestrial deposits distributed in several basins, there are uncertainties regarding the age range, sedimentary environment and tectonic conditions during their accumulation. In order to set some constraints on the stratigraphy, depositional environments and age of what is described as the Balsas Group by Fries (1960), we have undertaken detailed studies in some selected areas of Morelos and northern Guerrero States. In this paper we present the results of a stratigraphic and geochronological study of the Amacuzac-Zacapalco area, which is located southwest of Cuernavaca city, and is traversed by the highway and roads to Taxco and Iguala (Figure 2). The Amacuzac-Zacapalco area contains extensive exposures of the Balsas Group rocks that allowed us to carry out detailed field observations.

STRATIGRAPHY

The Balsas Group in the Amacuzac-Zacapalco area unconformably overlies deformed beds of the Morelos and Mezcala formations. The Morelos Formation consists of over 1,000 m of platform limestone successions, while the Mezcala Formation is constituted by alternated marine beds of sandstone, siltstone and shale. The Balsas Group is made up of conglomerate, sandstone and siltstone, including intercalations of silicic ignimbrites and andesitic lava flows (Fries 1960, Monter-Ramírez, 2004). On the basis of differences in the dominant lithologies and the occurrence of a minor angular unconformity, the Balsas Group is divided in this study into two sedimentary and two pyroclastic units. The basal unit, defined here as the Tepetlapa Formation, is dominated by sandstone beds with subordinated intercalations of siltstone and matrix-supported

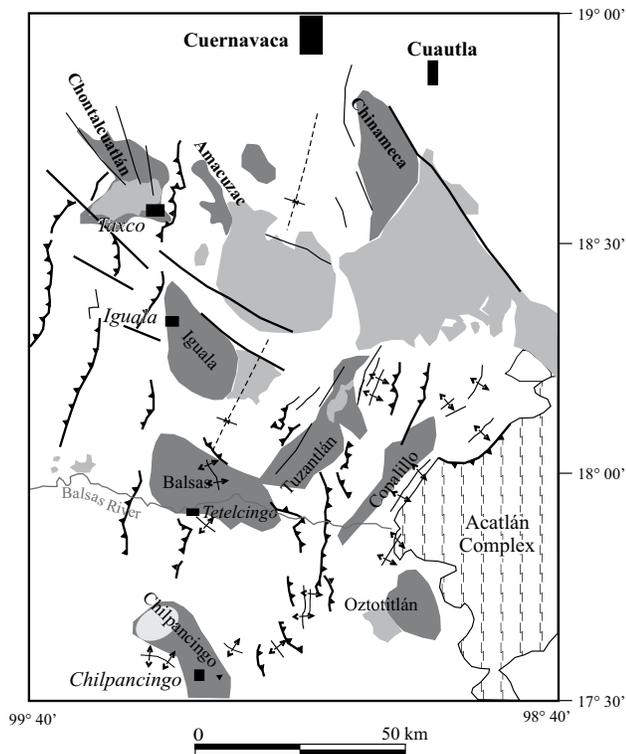


Figure 1. Distribution of the main Paleogene continental sedimentary basins in the Morelos and northern Guerrero states (dark gray). Main Cenozoic volcanic zones are also indicated (light gray). Configurations of basins on the southern part of the map from Cerca (2004).

conglomerate. The Tepetlapa Formation is unconformably overlain by the two pyroclastic units, which from base to top are the Teacalco Tuff and the Piedras Altas Tuff. To the south, these volcanic units pinch out entirely and leave in direct contact the Tepetlapa and Huajintlán formations. The uppermost unit, also sedimentary, is named here as the Huajintlán Formation. This formation is made up of coarse matrix-supported conglomerate, unconformably covered by the late Eocene (34 Ma) Tilzapotla ignimbrite (Morán-Zenteno *et al.*, 2004). These units are also unconformably covered by post Eocene andesite flows (Zacapalco Andesite) and by Pliocene volcanic debris-flow deposits (Cuernavaca

Formation) (Figures 3, 4a, 4b) (Fries, 1960; Morán Zenteno *et al.*, 2004).

Tepetlapa Formation

The Tepetlapa Formation is here defined as a succession of intercalated siltstone, sandstone and matrix-supported conglomerate with an apparent thickness of ~2000 m. It shows lateral and vertical variations in grain size as well as in bed thickness. The best exposures of the Tepetlapa Formation are located along highway 90, near Santa Fe

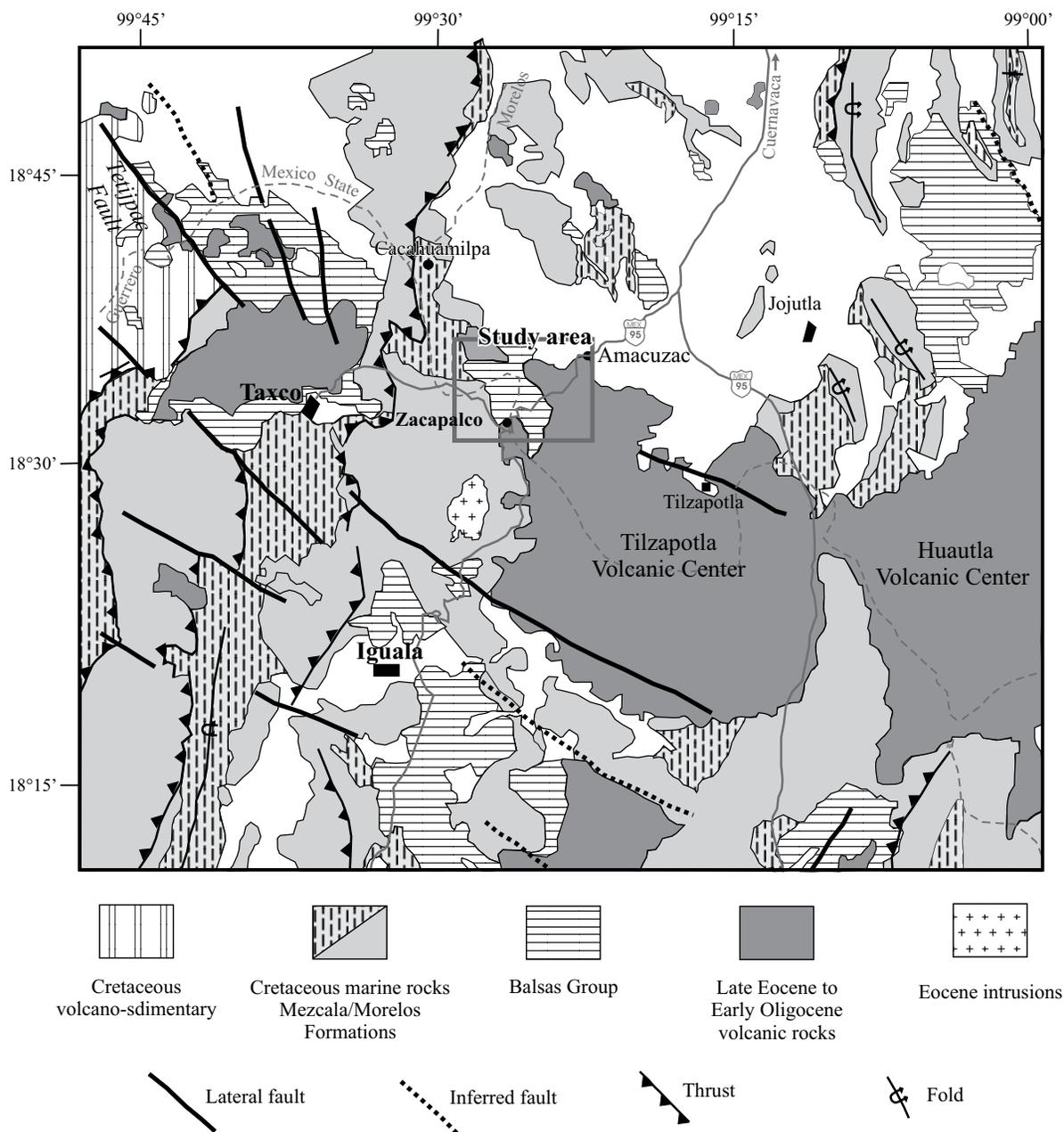


Figure 2. Location and geologic setting of the studied area indicating the distribution of Paleogene volcanic and continental deposits and major tectonic structures (modified from Rivera-Carranza *et al.*, 1998).

de Tepetlapa village (Km. 19–22, from 99° 24'30" to 99°46'00" longitude) (Figure 4a), forming a succession that we consider here as the type section. The contact with the underlying Mezcala and Morelos formations is an angular unconformity, but it was locally overprinted by NW trending left lateral faults, which can be observed in outcrops at the highway cuts near Zacapalco.

The succession was divided into three members (Figure 3). The basal member is ~150 m thick, and is made up of matrix-supported, poorly sorted conglomerate, interbedded with pebbly sandstone and poorly sorted medium to fine-grained sandstone. Conglomerate and sandstone beds

range in thickness from 1 to 5 m, and show remarkable lateral variations from sheet-like to lenticular geometries, laterally extending for several tens of meters. The conglomerate is mainly composed of subangular fragments of sandstone and limestone resembling the dominant lithologies of the Mezcala and Morelos formations respectively. According to the facies classification of Miall (1996), this member is formed by matrix-supported pebbly conglomerate with weak grading (Gmm), massive sandstone (coarse to fine) (Sm), and horizontally laminated fine to coarse sandstone (Sh). Gmm facies is dominant in the lower 70 m of this member, and Sm and Sh facies are dominant in the upper

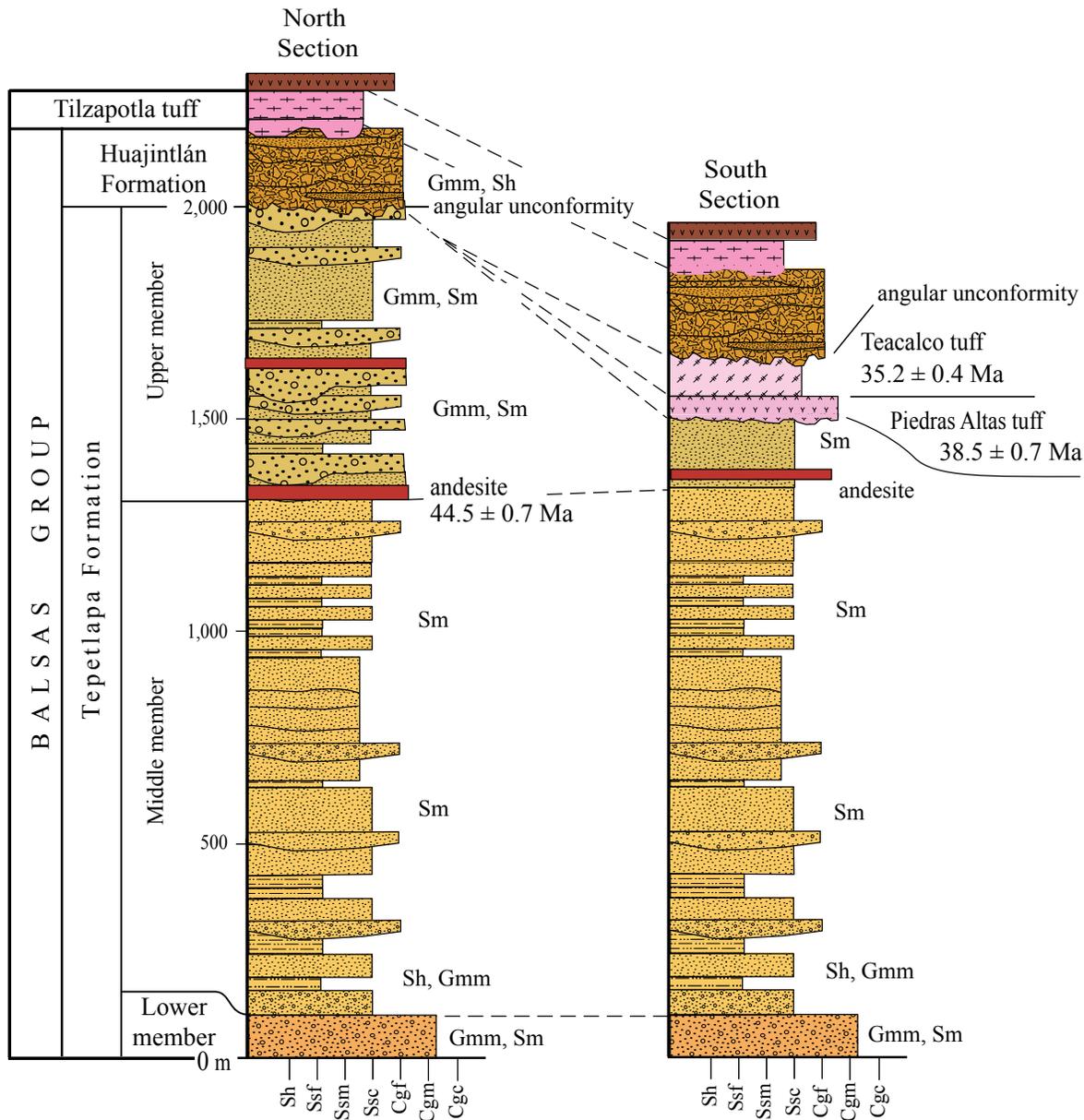


Figure 3. Stratigraphic sections of the Balsas Group and associated volcanic units of the northern and southern segments of the studied area. Gmm: matrix-supported pebbly conglomerate with weak grading; Sm: coarse to fine massive sandstone; Sh: horizontally laminated fine to coarse sandstone. The grain size is indicated at bottom of the columns; Sh: shale; Ssf: fine sandstone; Ssm: medium grained sandstone; Ssc: coarse sandstone; Cgf: fine conglomerate; Cgm: medium grained conglomerate; Cgc: coarse conglomerate.

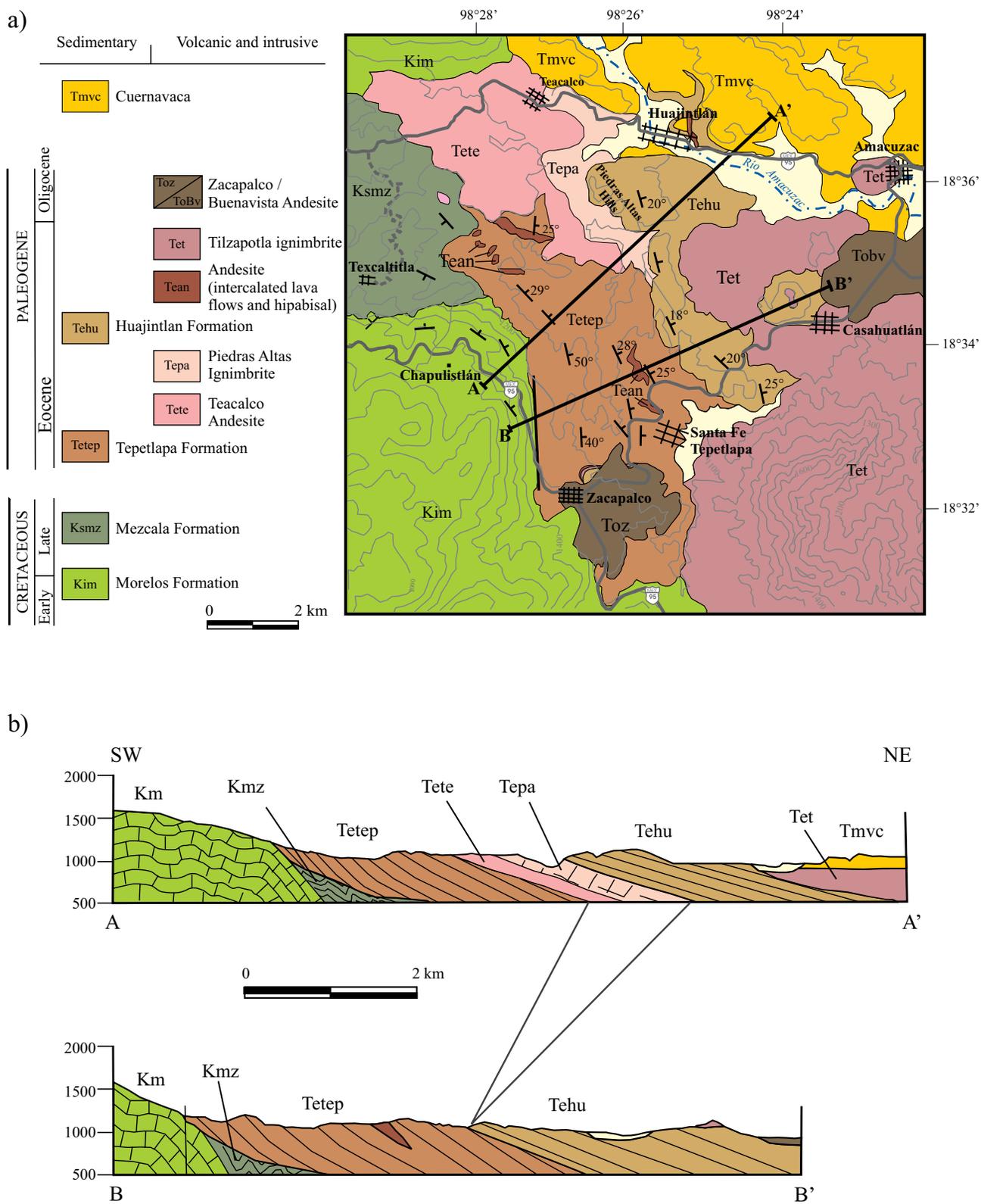


Figure 4. a) Geologic map of the Amacuzac-Zacapalco area. b) Geologic sections; traces are indicated on the map.

80 m. A 20 cm thick bed of felsic ash-fall tuff was identified about 50 meters up section from the base.

The second member is ~1200 m thick and is formed by coarse, poorly sorted sandstone, interbedded with siltstone, to fine-grained sandstone. Coarse sandstone beds are 10 cm to 2 m thick. The base of the sandstone shows irregular, concave-up, erosional bounding surfaces, and upper boundaries are mostly flat. It is well sorted, but contains some isolated pebbles up to 5 cm in diameter. The coarse sandstone is a litharenite, formed mainly by limestone and fine-grained sandstone grains, showing subordinate amounts of volcanic grains, mostly andesitic in composition. Siltstone and fine-grained sandstone intervals are massive and vary in thickness from 2 to 7 m. They have some thin intercalations of matrix-supported pebbly conglomerate, lenticular in cross section. Conglomerate is constituted by subrounded and subangular clasts, made up of limestone and sandstone. The recognized facies, in order of abundance, are Sm, Fm (mud, silt) and Gmm.

The upper member is represented by a 700 m-thick succession of massive to poorly stratified lithic sandstone interbedded with conglomerate. Conglomerate beds range in thickness from 40 cm to 30 m. Sandstone is poorly sorted and is formed by limestone and sandstone/siltstone grains in different proportions, with subordinated quartz, feldspar, biotite and hornblende grains, as well as some volcanic lithics. Conglomerate is mostly made up of limestone clasts with some sandstone and mafic volcanic clasts. Massive to weakly laminated sand (Sm) is the dominant facies, with Gmm bedforms defining sometimes fourth-order erosive surfaces over sand intervals. It also contains some beds of tuff and greenish epiclastic sandstone. This member is exposed in the southern section along the road to Zacapalco and seems to have been removed by erosion to the north.

At least three interbedded andesitic and basaltic lava flows and one dike were found within the upper member. Andesitic lava flows display plagioclase and hornblende phenocrysts in a groundmass of plagioclase laths and or-

thopyroxene, defining an intergranular to intersertal texture. Basaltic lava flows contain iddingsitized olivine phenocrysts, glomerocrysts of clinopyroxene in an intergranular groundmass with plagioclase, clinopyroxene and orthopyroxene. The mafic dike was found 3 km east of Texcaltitla town, and is basaltic in composition with abundant (~40%) olivine phenocrysts. One andesitic lava flow intercalated in the upper part of this succession yielded a whole rock K-Ar age of 44.5 ± 0.7 Ma (Table 1).

The Tepetlapa Formation is distributed from the Tepetlapa-Zacapalco sector to the north-northwest, defining a continuous band of E and NE dipping beds (Figures 4a and 4b). Bed dips range from 50° for lowest beds exposed east the highlands of the Zacapalco-Chapulistlán to ~30° in the eastern zone of the outcrop area. There are some minor NNW-trending, SW-dipping normal faults exposed in the easternmost outcrops with up to 1 m of displacement. The small displacements of these rather scarce faults can not account for the tilting of the studied successions.

The Tepetlapa Formation is Eocene in age, as suggested by the K-Ar ages obtained from the upper member. It is unconformably overlain by the Teacalco Tuff in the north-central part of the study area, and by the Huajintlán Formation in the southern part of the area. Facies associations are indicative of distal alluvial-fan depositional environment and its coarsening-upward sedimentation suggests progradation of the fan. Given the general geometry of the fan body, the total measured stratigraphic thickness of 2,000 m is greater than the real thickness in a vertical section.

Teacalco Tuff

We define the Teacalco Tuff as a vitric crystalline massive welded tuff (Figure 3) whose type area is located on the road cuts near Teacalco village (from 99°27'00" to 99°28'50" longitude) (Figure 4a). It has a variable thickness,

Table 1. K-Ar dates obtained from different volcanic units in the study area. All analyses were carried out in the Laboratorio Universitario de Geoquímica Isotópica (LUGIS) at the Universidad Nacional Autónoma de México (UNAM). K was obtained following the method of Solé and Enrique (2001). Argon was measured by isotope dilution (³⁸Ar tracer) with a VG1200B noble gas mass spectrometer. Variation coefficients for ⁴⁰Ar and ³⁸Ar are generally below 0.1%. Date of sample TZ 145 was first reported by Morán-Zenteno *et al.* (2004).

Sample	Longitude	Latitude	Mineral	Rock	⁴⁰ Ar *moles/g	K %	K-Ar age
TZ145 (Tilzapotla)	99° 24.53'	18° 33.79'	biotite	ignimbrite	3.12E-10	6.4	34.3 ± 1.5 Ma
A0-54 (Piedras Altas)	99° 27.35'	18° 36.09'	sanidine	ignimbrite	5.87E-10	9.52	35.1 ± 0.4 Ma
TZ 100 (Teacalo)	99° 28.17'	18° 36.86'	biotite	ignimbrite	3.99E-10	5.9	38.5 ± 1 Ma
TZ 100 (Teacalo)	99° 28.17'	18° 36.86'	sanidine	ignimbrite	5.49E-10	8.14	38.5 ± 0.7 Ma
A1 26 (Tepetlapa, andesite)	99° 25.69'	18° 33.01'	whole rock	andesite	1.17E-10	1.49	44.5 ± 0.7 Ma

with a maximum of 60 m in the northern exposure area, vanishing to the south where the Huajintlán Formation directly overlies the Tepetlapa Formation. The tuff is constituted by quartz, abundant sanidine, biotite and plagioclase in a groundmass of glass with relicts of shards displaying variable degrees of devitrification. It also includes fragments of fiamme-like pumice and lithics of siltstone. This member has a characteristic pink color when weathered. K-Ar dating from concentrates of sanidine and biotite obtained from a sample collected from the middle part of the section yielded ages of 38.5 ± 0.7 and 38.5 ± 1.0 Ma respectively, indicating an Eocene (Bartonian) age.

The Teacalco Tuff overlies the Tepetlapa Formation with a slight angular unconformity, and also overlies the Mezcala and Morelos formations in the northern part of the area. It dips about 15° to the northeast and is distributed from northwest of Teacalco to the southern flank of the Piedras Altas hills (Figure 4a).

Piedras Altas Tuff

The Piedras Altas Tuff is here defined as a slightly to non-welded ignimbrite that comprises at least two different ash-flow units, with a total thickness of ~120 m. The type area is located at the western flank of the Piedras Altas hills, 2 km southeast of Teacalco Village ($18^\circ 36' 102$ latitude, $99^\circ 26' 45''$ longitude). The lower flow is made up of slightly welded pink ignimbrite, containing pumice fragments up to 5 cm in size, quartz, plagioclase, biotite and scarce sanidine in a pumicitic matrix. The upper flow is constituted by a white, non-welded ignimbrite richer in pumice, with fragments up to 10 cm in size. It contains some red lithic volcanic clasts, as well as crystals of quartz, plagioclase and scarce biotite. A concentrate of sanidine from a sample collected at the base of the lower flow yielded a K-Ar age of 35.2 ± 1 Ma (Priabonian) (Table 1).

The Piedras Altas Tuff unconformably overlies the Teacalco ignimbrite and the upper contact with the Huajintlán Formation is a disconformity. The best exposures of this ignimbrite are distributed along the highway between Teacalco and Huajintlán and at the western flank of Piedras Altas hills (Figure 4a). There are some isolated bodies of ignimbrite attributed to the Piedras Altas Tuff, located north of Zacapalco and in the La Escondida locality, at km 22.7 of highway 90 to Taxco ($99^\circ 26' 00''$, $18^\circ 32' 30''$).

Huajintlán Formation

The Huajintlán Formation is defined as an up to 300 m thick succession of poorly sorted conglomerate dominated by limestone fragments (>90%) with minor content of sandstone and volcanic fragments (Figure 3). Limestone clasts range from subangular to subrounded and reach up to 50 cm in diameter. The matrix is made up of sandstone,

formed by limestone grains with subordinated amount of siltstone, volcanic lithics, as well as quartz and plagioclase. According to the facies classification of Miall (Miall, 1996), the Huajintlán Formation is dominated by Gmm (massive matrix-supported gravel) and, in lower extent, by Gmg (matrix-supported conglomerate with some grading) and Gh (crudely bedded gravel). The succession displays fourth and fifth order surfaces bounding minor and intermediate paleochannels as well as minor lenses of coarse and pebbly horizontally stratified sand.

The type section is in Huajintlán village and some of the best exposures are also located along highway 95 and along the Amacuzac River near Huajintlán (from $99^\circ 25' 00''$ to $99^\circ 26' 00''$ longitude). There are also good exposures along the highway between Casahuatlán and Zacapalco (from km 17 to km 19; $99^\circ 24' 30''$ to $99^\circ 25' 00''$ longitude).

In the northern part of the study area, the Huajintlán Formation unconformably overlies the Piedras Altas Tuff, whereas in the southern part it directly lies over the Tepetlapa Formation with a slight angular unconformity ($\sim 10^\circ$) (Figures 4a and 4b). The Huajintlán Formation is unconformably overlain by the 34–35 Ma Tilzapotla ignimbrite. Its exposure area define a NNW-trending belt extending from the northwest of Huajintlán to the northeast of Tepetlapa, with beds dipping from 20 to 10° to the northeast. In the Huajintlán locality the unit is cut by a 10 meters thick, north-trending andesitic dike.

Tilzapotla ignimbrite

The Tilzapotla ignimbrite unconformably overlies the Huajintlán Formation. It was formed during a major volcanic episode related to the collapse of the Tilzapotla caldera (Morán-Zenteno *et al.*, 2004), and is the most widespread pyroclastic unit in the region. It displays contrasting thickness depending on its intracaldera or extracaldera character. In the Amacuzac area, the Tilzapotla ignimbrite is represented by proximal extracaldera facies; it has a maximum thickness of 50 m and gradually thins toward the north. It is constituted by a massive crystal-rich ignimbrite with characteristic euhedral biotite phenocrysts, rounded quartz, broken plagioclase, as well as minor sanidine in a micro-cryptocrystalline groundmass. Some intervals contain altered, up to 10 cm pumice fragments with biotite phenocrysts. A biotite concentrate from this area yielded a K-Ar date of 34.3 ± 1.5 Ma, which is undistinguishable from other ages obtained for the same unit in different areas around and within the caldera (Morán-Zenteno *et al.*, 2004).

Zacapalco andesite

This unit is constituted by an up to 20 m-thick succession of andesitic lava flows, overlying in angular un-

conformity the tilted beds of the Tepetlapa Formation and Teacalco Tuff. It is distributed immediately northwest of the inferred northwestern segment of the Tilzapotla caldera ring. In many aspects, it is similar to the andesitic rocks distributed within and near the caldera ring (*i.e.*, Buenavista Formation) (33–32 Ma) that were interpreted by Morán-Zenteno *et al.* (2004) as volcanic rocks related to the post-collapse caldera resurgence. Lavas have a porphyritic texture with plagioclase phenocrysts in a groundmass of orthopyroxene, plagioclase laths and brown glass, forming an intersertal to intergranular texture. They also include plagioclase xenocrysts displaying disequilibrium features (sieve texture), as well as amphiboles with opacite rims.

TECTONIC SETTING AND VOLCANO-TECTONIC EVOLUTION OF THE TILZAPOTLA CALDERA

The Balsas-related beds of the Amacuzac-Zacapalco area are distributed northeast from the intersection of two

structural highs: the NNE-trending Laramide thrust and fold belt of the Iguala-Cacahuamilpa sector and the NW-trending elliptical dome associated with the Tilzapotla caldera (Figures 2, 5).

The Laramide sector of the Iguala-Cacahuamilpa region is formed by a tectonic stack of overturned folds and thrust sheets with a general east vergence (Figure 2) (de Cserna y Fries, 1981; Rivera-Carranza *et al.*, 1998). This forms a range dominated by extensive exposures of the Morelos Formation that thrust over the Mezcala Formation and the Morelos Formation itself. Deeper erosion of the Mezcala Formation east of the Iguala-Cacahuamilpa front produced an elongated topographic low, approximately 20 km wide, partly filled with the Balsas-related sediments in Paleogene time. The NNE-trending topographic low was broken up by the Eocene-early Oligocene Tilzapotla volcanic edifice and associated NW-trending elliptical dome structure. The dome is 50 km long, and extends from Quetzalapa to the Taxco area where it merges with the Iguala-Cacahuamilpa highs (Figures 2, 5). The structural dome interfered with the older Laramide NNE-trending structures. This is indicated

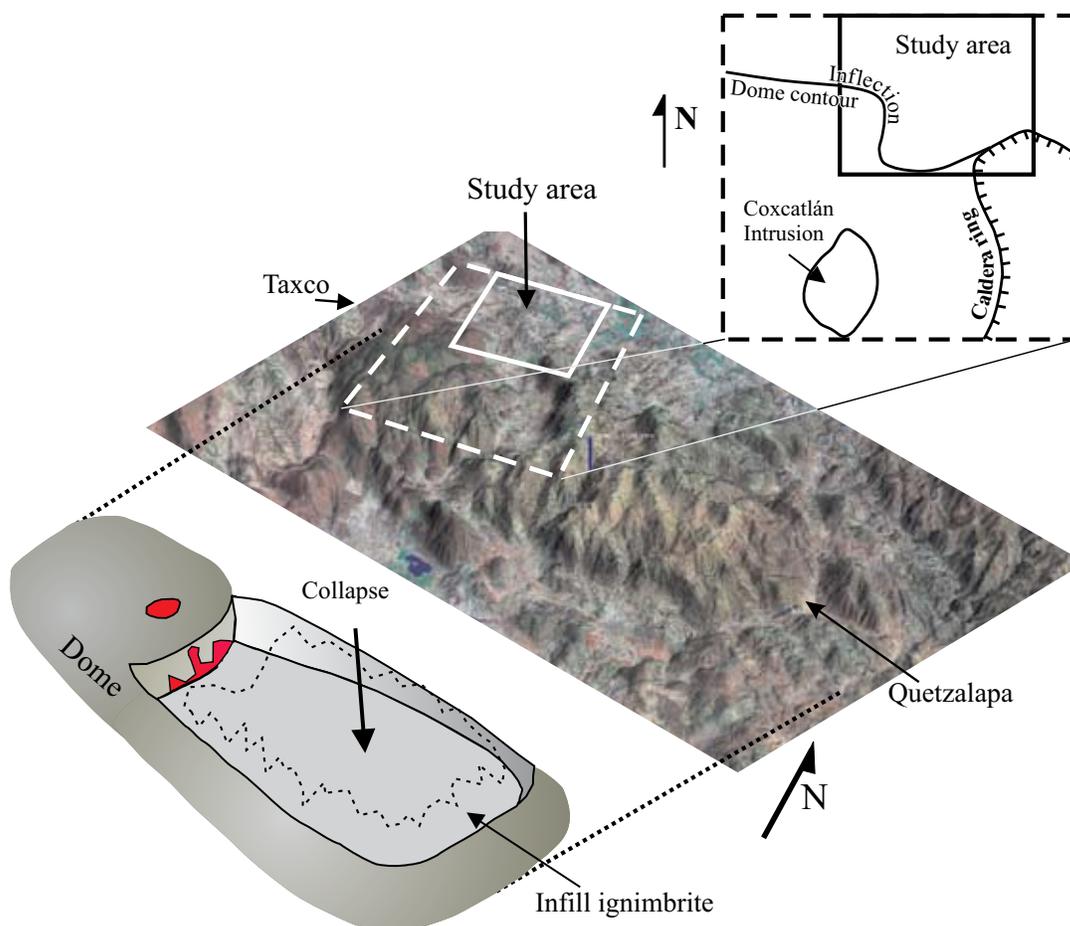


Figure 5. 3D Landsat image of the dome structure and the Tilzapotla collapse caldera indicating the location of the studied area. The interpretation of the partial collapse of the dome structure associated with the emplacement of the Tilzapotla ignimbrite is also shown. A detail of the inflection in the dome contour within the study area is shown in the upper right corner.

by the attitude of Late Cretaceous fold axes, which plunge to the north and to the south at north and south flanks of the structure respectively (Morán-Zenteno *et al.*, 2004). Based on stratigraphic and structural observations around the Tilzapotla caldera, Morán-Zenteno *et al.* (2004) considered this dome as a structure developed in the early stages of the caldera evolution, and a result of the tumescence associated with the overpressure in the magma chamber. The elongated shape of the dome is partly controlled by the tectonic lineaments at its northeast and southwest flanks (Figure 2). The deformation and volcanic events related to the caldera evolution, as well as their chronological relationships, have been previously documented by Morán-Zenteno *et al.* (2004). The Tilzapotla ignimbrite (34–35 Ma) is the major volcanic product of caldera collapse. The studied area, where the Balsas-related rocks are exposed, is located at the northwestern margin of the dome structure near the northwestern limit of the caldera ring. In this area, the dome margin displays a local inflection in the form of a curvature, convex to the northeast, defined by a change in the dip direction of the Morelos Formation and basal Tepetlapa beds from north to east (Figures 4a, 5).

One remarkable feature in the studied area is the relatively high northeast and east dip of the Balsas-related beds, without recognizable shortening at outcrop scale (Figures 4a, 4b, 6). Dip angles become lower eastwards, being up to 50° in the basal beds exposed in the southwestern sector contiguous to the Tilzapotla dome structure, but less than 10° near the top, in the northeastern sector. The basal unconformity with the middle Cretaceous Morelos Formation is tilted as well, and rocks of the Morelos Formation form a steep topographic slope (Figure 4b). The decrease in angle of the Balsas Group toward the east and upsection was previously interpreted by Fries (1960) as the result of syn-sedimentary tilting produced by faulting or large amplitude folding. However, our data suggest that the wide folding



Figure 6. Outcrop of tilted (dip ~35°) sandstone and conglomerate beds of the Balsas Group (Tepetlapa Formation) at the highway between Amacuzac and Zacapalco.

and change in dips might be related to the evolution of the Tilzapotla caldera, as it is discussed below.

DISCUSSION AND CONCLUSIONS

The angular unconformity separating the basal Tepetlapa beds and the underlying folded beds of Mezcala and Morelos formations (Figure 4b) indicate a time interval between the cessation of the Laramide deformation and the accumulation of the terrestrial deposits. The alluvial fan that originated the Tepetlapa Formation probably originated from an outlet of the topographic front formed by the thrust anticline. This is also suggested by the general eastward decrease in the clast size of the Tepetlapa Formation. The location and origin of the eastern limit of the sedimentary basin is unknown because it is covered by Pliocene epiclastic and alluvial deposits that unconformably overlie the Balsas Group and the Mezcala Formation.

The sedimentary facies recognized in the Tepetlapa Formation are indicative of an alluvial fan environment dominated by debris flow and sheet flow deposits. The lower and middle members show distal fan and/or flood plain facies (Figure 7a). The upper member shows a coarsening-upward tendency, which might be related to the rejuvenation of the landscape. This probably was due to a first uplift stage related to the emplacement of silicic magmas in the Taxco volcanic center located at the northwestern side of the Tilzapotla dome structure. This is also suggested by an increment in the percentage of volcanic clasts in conglomerate beds of the same upper member. The slight angular unconformity between the Tepetlapa formation and the overlying units records a break in the sedimentation and is probably related to the eastward tilting produced by this uplift episode. Regional geochronology of silicic magmatism suggest that the doming process began near the Taxco volcanic center at around 38 Ma and was progressing toward the SE until 34 Ma, when the collapse of the Tilzapotla caldera occurred.

There is no evidence of normal or lateral faulting at the piedmont that could have produced a slope break between the accumulation area and highlands to the west. Therefore we suggest that the deposition of the Tepetlapa Formation occurred at the flank of an intermontane basin.

The age range of the Tepetlapa Formation is less well constrained than the ages of the overlying units. The age obtained for an andesitic flow comes from the upper member (44.5 ± 0.7 Ma), and indicates a minimum Eocene (Lutetian) age for the sedimentation. Therefore the Tepetlapa Formation was not related to the evolution of the Tilzapotla caldera, but to a previous stage in the evolution of the sedimentary basin.

Remarkably coarser textures of the Huajintlán Formation indicate a significant change in the depositional environments. The relatively high abundance of sandstone and siltstone lithic fragments in the Tepetlapa beds, re-

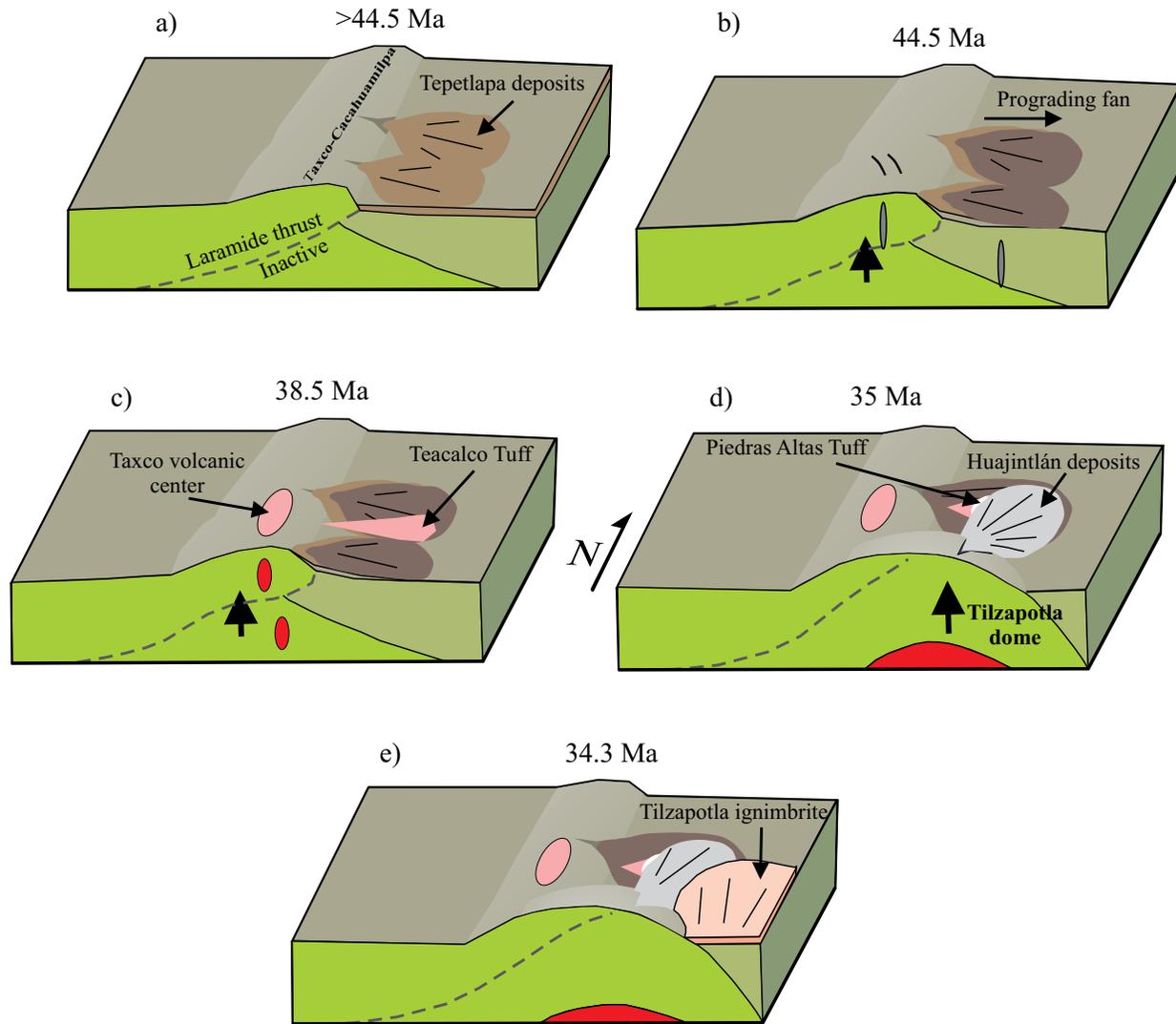


Figure 7. Proposed model for the evolution of the sedimentation and sediment sources for the Balsas Group in the studied area (see text).

sembling the lithology of the Upper Cretaceous Mezcala Formation, is not found in the Huajintlán Formation. In contrast, the Huajintlán Formation is dominated by limestone clasts derived from the Morelos Formation. This change in composition of the lithic components is indicative of a change in the dominant lithology exposed in the source area. In addition to the change in clast composition, there is a major change in the facies and depositional environments in the Huajintlán Formation, compared to those observed in the Tepetlapa Formation. The coarse matrix-supported conglomerate texture and the sedimentary features of rocks of the Huajintlán Formation are typical of proximal alluvial fan deposits (Figure 7d).

The change in clast composition and depositional environments recorded in the Huajintlán Formation suggests an uplift of the source area, which occurred in a more proximal position to the studied area. The best candidate for the rejuvenation of the landscape and the change in

the sedimentary system observed in the area is the late Eocene doming produced by magma emplacement in the early stages of the evolution of the Tilzapotla volcanic center (Figures 5 and 7d). This is supported by the age of the ignimbrites underlying (Piedras Altas) and overlying (Tilzapotla) the Huajintlán Formation. The best age estimate for the caldera collapse is the 34.29 ± 0.09 Ma Ar-Ar date obtained for the Tilzapotla ignimbrite (Morán-Zenteno *et al.*, 2004) at the eastern margin of the caldera. These results, compared to the K-Ar date of 35.2 ± 0.4 Ma of the Piedras Altas Ignimbrite, left a time interval of at least 0.5 Ma for the volcanic center evolution since the first pre-collapse ignimbrite emplacement, which is a reasonable time for this kind and size of volcanic center (Smith and Bailey, 1968).

The northeastward and eastward relative high dip of the westernmost Tepetlapa beds at the dome border ($\sim 50^\circ$) and their strike following the inflection in the contours of this structure indicate a tilting episode related to the tumes-

cence in the Tilzapotla caldera (Figure 4a). The relatively slight angular relationship with the syn- and post- doming Huajintlán Formation farther to the northeast, indicates that the tilting effect produced by the tumescence decreased in a short distance from the dome boundary.

The K-Ar ages obtained from intercalated volcanic rocks (35.2, 38.5 and 44 Ma) in the studied succession (Figure 3, Table 1) indicate that the main episodes of deposition occurred during the Eocene. The age estimates for the Balsas Group in the study area are in part similar to those obtained in other areas within the Guerrero-Morelos region. In the nearby Taxco area, Alaniz-Álvarez *et al.* (2002) documented Eocene volcanic rocks intercalated with continental deposits, similar to those of the study area. There are no indications that the basal beds of the studied succession could be contemporary with the Paleocene beds exposed along the Balsas river in central Guerrero State (Cerca, 2004). Even assuming low rates of sedimentation for the beds underlying the oldest dated andesite (44 Ma) in the studied area, it could hardly be interpreted that the basal beds reach a Paleocene age, unless significant interruptions of sedimentation of the Tepetlapa Formation occurred, which is not evident in the studied sections. This indicates that the evolution of the Paleogene continental basins began diachronously in the region.

There are no signs of accumulation in a coeval, fault-bounded, subsidence basin as it has been documented in the neighboring Taxco region. Inclination of Balsas beds in the area are clearly related to doming processes and no listric faults seem to have been involved in the tilting process. Besides the evidence of tilting related to the doming process in the Tilzapotla caldera area, the structural attitude does not support listric or lateral faulting associated with the main slope break, separating the accumulation area from the highlands to the west. There is no evidence of the prolongation in this area of the tectonic lineament that defines the northeastern boundary of the Tilzapotla caldera (Figures 2, 4a).

Sedimentary and volcanic facies identified in this work suggest that five successive paleoenvironmental settings characterized the sedimentation of the Balsas Group throughout time in the Amacuzac region (Figure 7a-e): 1) distal alluvial fan or flood-plain sedimentation of the lower and middle member of the Tepetlapa Formation; 2) progradation of the fan lobe at the time of the andesitic volcanism, recorded in the upper member of the Tepetlapa Formation; 3) tilting of the Tepetlapa Formation related to the first stage of uplift originated by doming near the Taxco area and emplacement of the Teacalco Tuff; 4) initial stages of volcanic activity in the Tilzapotla volcanic center (Piedras Altas Tuff) and development of a new fan lobe (Huajintlán Formation), originated by the pre-caldera tumescence; 5) post-Balsas volcanism related to the caldera formation (Tilzapotla ignimbrite) and later initiation of intermediate magmatism (Zacapalco Andesite).

Regarding the concept of using the name Balsas

Group, it should be considered that this name was proposed but not formally defined as a lithostratigraphic unit by Fries (1960). In addition, the name has been used for relatively diverse deposits accumulated in different basins and with different lithostratigraphic rank (*i.e.*, Balsas Formation, de Cserna, 1982). We think that, in order to avoid further confusions, it should remain as an informal group, as originally described by Fries, until lateral relationships among sedimentary units distributed in these basins can be documented in more detail.

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