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STRATIGRAPHY, GEOCHEMISTRY AND TECTONIC SIGNIFICANCE OF THE TERTIARY VOLCANIC SEQUENCES OF THE TAXCO-QUETZALAPA REGION, SOUTHERN MEXICO

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ABSTRACT

The volcanic rocks of the Taxco-Quetzalapa region, states of Guerrero and Morelos, are part of the Tertiary Volcanic Province of Southern Mexico (TVPSM) that extends from the State of Michoacán to the Isthmus of Tehuantepec region. This province is located between the Trans-Mexican Volcanic Belt (TMVB), of Miocene-Quaternary age, and the chain of Tertiary plutons that lies along the southwestern continental margin of Mexico. The volcanic sequences of the study region are distributed in three main areas: Taxco, Buenavista-Quetzalapa and Huautla.

The Taxco volcanic sequence is constituted by three units of rhyolitic composition with a maximum total thickness of about 800 m. The lower unit (Acamixtla formation) consists of ignimbrites and welded breccias and includes vitrophyric layers. This unit is overlain by rhyolitic lava flows, moderately welded ignimbrites, and vitrophyric layers (Tenería formation). The uppermost unit consists of moderately welded ignimbrites topped by a vitrophyre layer (Huizteco formation). K-Ar dates of the lower unit range from 35–38 Ma, whereas those of the upper units, from 31 to 32 Ma. The Ag, Zn and Pb sulfide hydrothermal mineralization of the Taxco mining district is mainly hosted in the underlying sedimentary and metamorphic rocks.

The Buenavista-Quetzalapa volcanic sequence is constituted by a series of dacitic lava flows and ignimbrites with a total thickness of about 900 m. The lower part of the sequence (Tilzapotla Formation) consists of a biotite-bearing ignimbrite of dacitic composition. The upper part of the sequence (Buenavista Formation) is constituted by dacitic lava flows interlayered with moderately to densely welded tuffs. These rocks are related to a caldera of about 20 km in diameter, which originated during the emission of the lower unit and underwent later resurgent activity.

The volcanic sequence of the Huautla area is represented by biotite-bearing welded tuffs, dacitic to andesitic lava flows, as well as silicic ignimbrites and breccias. This sequence is intruded by quartz-trachyte bodies.

The relationships between alkalis and SiO_2, MgO and FeO* abundance in the studied samples indicate that the volcanic sequences belong to the calc-alkaline series, with the highest SiO_2 abundance in the volcanic units of the Taxco area. REE patterns display an enrichment in light REE with respect to heavy REE, typical of magmatic arcs. The REE patterns of the Taxco area volcanic rocks show an europium anomaly (Eu/Eu*~ 0.4) probably related to crystal fractionation of plagioclase. The initial $^{87}Sr/^{86}Sr$ ratios, in conjunction with major elements and the mineralogical composition, indicate that the volcanic rocks in Taxco are highly differentiated by processes of crystal fractionation and show greater crustal contamination than the other two areas.

The age, composition and regional position of the volcanic sequences of the Taxco-Quetzalapa region indicate that they are part of a broad Oligocene magmatic arc that extended from the present coastal zone to the north of this region. The absence of Miocene volcanic rocks suggests that there was an extinction of arc activity at this time rather than a gradual migration of the magmatism to the north.

Key words: Stratigraphy, geochemistry, tectonics, volcanic rocks, Tertiary, Taxco, Quetzalapa, Mexico.

RESUMEN

Las rocas volcánicas terciarias de la región de Taxco-Quetzalapa, estados de Guerrero y Morelos, forman parte de la Provincia Volcánica Terciaria del Sur de México (PVTSM) que se extiende desde Michoacán hasta el Istmo de Tehuantepec. Esta provincia guarda una posición intermedia entre la Faja Volcánica Transmexicana (TMVB) del Mioceno-Cuaternario y el cinturón de plutones terciarios que ocupa la margen suroccidental de México. Las secuencias volcánicas de la región estudiada se distribuyen en tres áreas principales: Taxco, Buenavista-Quetzalapa y Huautla.

La secuencia de Taxco está compuesta por tres unidades de composición riolítica con un espesor total cercano a 800 m. La unidad inferior (formación Acamixtla) está constituida por ignimbritas, brechas ignimbríticas y algunas intercalaciones de vitrófidos. Esta unidad está cubierta por lavas riolíticas, ignimbritas moderadamente piroconsolidadas e intercalaciones de vitrófidos (formación Tenería). La unidad superior está

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compuesta por ignimbritas moderadamente piroconsolidadas y una capa de vitrófido en la cima (formación Huizteco). Las edades de K-Ar para la unidad inferior varían de 35 a 38 Ma, mientras que para las dos unidades superiores varían de 31 a 32 Ma y representan el último episodio de volcanismo en esta área. Esta secuencia volcánica yace sobre rocas sedimentarias y metamórficas que hospedan a la mineralización de sulfuros de Ag, Pb y Zn del Distrito Minero de Taxco.

La secuencia volcánica de Buenavista-Quetzalapa está formada por una serie de ignimbritas y derrames lávicos de composición dacítica, con un espesor máximo de 900 m. La parte inferior de la secuencia (Formación Tilzapotla) está representada por ignimbritas caracterizadas por la presencia de biotita euhedral. La parte superior de la secuencia (Formación Buenavista) está formada por derrames de dacita intercalados con ignimbritas que varían de moderada a fuertemente piroconsolidadas. Estas secuencias están asociadas a una caldera de aproximadamente 20 km de diámetro, originada durante la emisión de la unidad inferior y con una actividad resurgente posterior.

En el área de Huautla la secuencia volcánica está representada por ignimbritas que varían de moderada a fuertemente piroconsolidadas, con biotita euhedral, y derrames de dacita y andesita con un espesor máximo de 500 m. La secuencia sufre la intrusión de cuerpos subvolcánicos de traquita de cuarzo.

Las relaciones entre las abundancias de álcalis respecto al SiO_2, MgO y FeO* indican que las secuencias volcánicas estudiadas pertenecen a la serie calcialcalina, con mayores contenidos de SiO_2 para las unidades volcánicas del área de Taxco. Los patrones de tierras raras muestran, en general, un enriquecimiento de tierras raras ligeras respecto a las tierras raras pesadas, típico de arcos magmáticos. Se reconoce, para las rocas de Taxco, una anomalía de europio (Eu/Eu* ~ 0.4) relacionada probablemente con la cristalización fraccionada de una fase de plagioclasa. Las relaciones isotópicas de $^{87}Sr/^{86}Sr$, en conjunción con las abundancias de óxidos mayores y la composición mineralógica, indican que las rocas de Taxco presentan un grado de diferenciación por cristalización fraccionada mayor y una contaminación por asimilación de la corteza continental mayor, en comparación con las otras áreas estudiadas.

La edad, composición y ubicación regional de las secuencias volcánicas de la región de Taxco-Quetzalapa, indican que estas rocas se originaron como parte de la actividad de un arco volcánico amplio que se extendía desde la actual margen del Pacífico hasta esta región. La ausencia de rocas volcánicas del Mioceno sugiere que el magmatismo de arco en esta parte de México experimentó una extinción más que una migración gradual hacia el norte.

Palabras clave: Estratigrafía, geoquímica, tectónica, rocas volcánicas, Terciario, Taxco, Quetzalapa, México.

INTRODUCTION

The volcanic rocks of the Taxco-Quetzalapa region are part of an extensive Tertiary volcanic province (TVPSM) (Alba-Aldave *et al.*, 1995; Martiny *et al.*, 1996) located south of the Miocene-Quaternary Trans-Mexican Volcanic Belt (TMVB) and north of the Oligocene plutonic province of the southwestern continental margin of Mexico (Figure 1). Although some of these Tertiary volcanic sequences are located within areas covered by the classical studies on southern Mexico (Fowler *et al.*, 1948; Osborne, 1956; Fries, 1956a, b, c, 1960, 1966; de Cserna and Fries, 1981), the petrological and geochemical characteristics and the stratigraphic regional variations are poorly known.

The TVPSM predates the TMVB and originated in a time interval characterized by dramatic changes in the kinematic interactions between the Pacific and North American plates at this latitude. Among the most important plate tectonics episodes that affected the southwestern margin of Mexico since the Oligocene, are the detachment and subsequent displacement of the Chortis Block (Malfait and Dinkelman, 1972; Ross and Scotese, 1988; Ratschbacher *et al.*, 1991; Herrmann *et al.*, 1994; Schaaf *et al.*, 1995) and the gradual fragmentation of the Farallon plate (Mammerickx and Klitgord, 1982). All these episodes resulted in a change in the slab trajectory to a lower angle position and the consequent migration of the locus of the arc magmatism to the present TMVB. Interpretations of the present-day geometry of the subducted slab indicate that after an initial dip of 14–16° near the trench, the subducted slab has a low-angle trajectory reaching a depth of 100 km beneath the southern margin of the TMVB (Pardo and Suárez, 1995).

Along the TVPSM, volcanic sequences cover three distinct pre-Tertiary terranes for which different tectonic interpretations have been made regarding the nature of their basement and the Mesozoic sequences (Ortega-Gutiérrez, 1981; Campa and Coney, 1983; Sedlock *et al.*, 1993). West of Taxco, the TVPSM includes silicic ignimbrites and extensive andesitic fields covering sequences of the Guerrero Terrane. This terrane is characterized by Mesozoic volcano-sedimentary units that unconformably underlie Late Cretaceous and Paleogene continental deposits. The age of the Mesozoic sequences of the Guerrero terrane and the nature of their basement have been the subject of a heated debate (de Cserna *et al.*, 1978; Campa and Ramírez-Espinosa, 1979; de Cserna and Fries, 1981; Elías-Herrera and Sánchez-Zavala, 1990; Talavera-Mendoza *et al.*, 1995; Lang *et al.*, 1996). There is paleontological evidence indicating that most of the exposed volcano-sedimentary sequences of the Guerrero terrane range in age from Late Jurassic to Early Cretaceous (Centeno-García, García *et al.*, 1993). However, the geochronological and stratigraphic data suggest older metamorphic sequences including both oceanic affinity sequences in the Michoacán region (Centeno-García, Ruiz *et al.*, 1993) and continental affinity rocks in southern State of Mexico (Elías-Herrera and Sánchez-Zavala, 1990). The Late Jurassic-Early Cretaceous evolution of the Guerrero

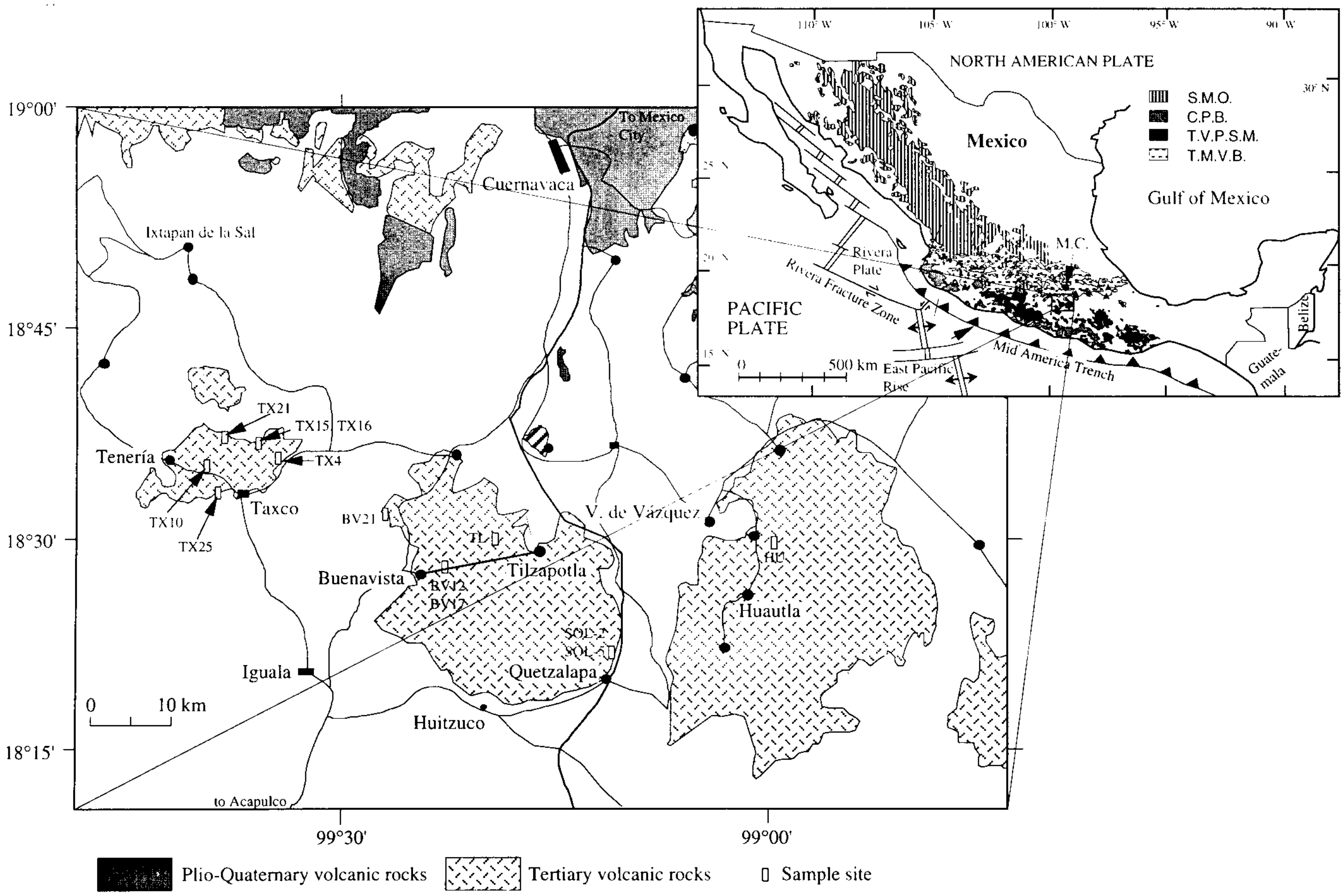

Figure 1. Geological map and location of the study area. S.M.O.= Sierra Madre Occidental, C.P.B.= Coastal Plutonic Belt, T.V.P.S.M.= Tertiary Volcanic Province of Southern Mexico, T.M.V.B.= Trans Mexican Volcanic Belt.

terrane has been interpreted in terms of a submarine volcanic arc domain affected by deformation and shearing with an eastward vergence during Late Cretaceous time (Campa and Coney, 1983; Centeno-García, García *et al.*, 1993). In the Taxco area, the basement is represented by low-grade sericite and chlorite schists with metavolcanic layers (de Cserna and Fries, 1981). The age and tectonic relationships of the basement with other terranes have remained elusive due, among other factors, to the lack of coherent isotopic dates indicating the age of the metamorphism.

East of Taxco, the TVPSM extends over the early Paleozoic Mixteca and Late Precambrian Oaxaca metamorphic basement terranes (Ortega-Gutiérrez, 1981; Campa and Coney, 1983). The basement of the former is represented by a heterogeneous metamorphic assemblage whose protoliths have deep ocean affinities. The Oaxaca metamorphic basement is characterized by granulite facies rocks including mafic and felsic ortogneiss, as well as charnockite and metasedimentary rocks (Ortega-Gutiérrez, 1993).

In the Taxco-Quetzalapa region, as well as in other localities of Morelos and eastern Guerrero states, the volcanic rocks of TVPSM are dominantly silicic (de Cserna and Fries, 1981; Alba-Aldave *et al.*, 1996). In the western Oaxaca region, the volcanic sequences are represented by extensively distributed Oligocene andesites and basaltic-andesites (Martiny *et al.*, 1996). Further to the east, in central State of Oaxaca, the TVPSM is represented by Oligocene to middle Miocene silicic and intermediate volcanic rocks (Ferrusquía-Villafranca, 1992).

The position and general petrological characteristics of the TVPSM raise the question of whether it constitutes a continuous genetically related province, or if it represents an intermediate magmatic episode in the northward migration of the locus of the arc magmatism to the Trans-Mexican Volcanic Belt. In order to have some insight on these and other problems regarding the geochemical characteristics and genesis of the Taxco-Quetzalapa region, the present authors carried out a stratigraphic and geochemical study. This study was mainly focused on the Taxco and Buenavista-Quetzalapa areas, although some stratigraphic aspects of the Huautla volcanic field are also discussed.

TECTONIC SETTING

There are no major evident Cenozoic structures to which the distribution of the studied volcanic centers could be associated. The Huautla volcanic area is limited to the north by two hypothetical, northeast trending right lateral regional faults, proposed by Fries (1966), although no field evidence has been reported in support of these structures. In the Taxco mining district, the main hydrothermal veins are associated with a well defined group of structures consisting of northwest striking normal and lateral faults affecting the Mesozoic structures, but probably older than the Oligocene volcanic sequence. The lower unit of the volcanic sequence, which has been informally named the Acamixtla formation, is pervasively disrupted by a set of north-northeast striking lateral faults without any apparent relationship to the older mineralized structures. The extensional structures affecting the volcanic sequences are of a minor scale and do not show any recognizable regional tendency. Evidence of regional grabens associated with north-south extensional faults, recognized in the Arcelia (Jansma and Lang, 1997) and Huajuapan (Martiny *et al.*, 1995) regions, are lacking in the Taxco-Quetzalapa region.

The Taxco-Quetzalapa volcanic sequences and the underlying continental beds of the Balsas Formation cover a relatively complex group of Mesozoic structures consisting of northwest to north striking folds. These structures are typical of the northern part of the Cretaceous Morelos-Guerrero platform and are characterized by open to tight folds with a curved folded axis on plan view. The Taxco region, located in the western part of this area, is occupied by a basement high, represented by outcrops of the Taxco Schist. Further to the west, the area is limited by a roughly north striking, west-dipping regional overthrust where the Morelos-Guerrero platform sequences are in contact with deformed and slightly metamorphosed volcanic-sedimentary rocks of the Guerrero terrane (Campa and Ramírez-Espinosa, 1979; Centeno-García, Ruiz *et al.*, 1993).

The Taxco volcanic sequences extend over the western limit of the Morelos-Guerrero platform, overlapping the easternmost structures of the Guerrero terrane, whereas the Buenavista-Quetzalapa and Huautla volcanic centers are located within synclinoria depressions of the Morelos-Guerrero platform province.

STRATIGRAPHY AND PETROGRAPHIC CHARACTERISTICS

The Tertiary volcanic sequences in the Taxco-Quetzalapa region extend discontinuously for about 1,000 km^2 and are distributed in three main areas: Taxco, Buenavista-Quetzalapa and Huautla (Figure 1). These sequences lie unconformably on Paleogene continental and Cretaceous marine sedimentary beds of the Morelos-Guerrero platform, represented by the Balsas, Mexcala and Morelos formations (Fries, 1960). East of the study area, the Mesozoic and Tertiary sequences lie unconformably on Paleozoic metamorphic rocks of the Acatlán Complex which outcrop more extensively to the western part in the State of Oaxaca.

The Tertiary volcanic sequences in the study area are dominantly silicic and range in composition from andesites to rhyolites. From Taxco to Huautla the volcanic sequences exhibit distinct geochemical and petrological characteristics indicating different volcanic episodes associated with more than one volcanic center.

TAXCO AREA

In the Taxco area (Figure 2) the Tertiary volcanic rocks are represented by rhyolitic ignimbrites, vitrophyres, and rhyolitic flows, forming a sequence up to 800 m thick. Although these silicic rocks display some variations, they are in general characterized by a porphyritic texture, vitreous to microcrystalline matrix and quartz, sanidine, biotite and plagioclase phenocrysts.

The base of the Taxco volcanic sequence, informally named Acamixtla formation (Figure 3), is exposed immediately east of the city of Taxco and consists of about 300 m of crystal-rich ignimbrites with fiamme, vitrophyre and welded breccia layers. Ignimbrites exhibit a porphyritic texture with phenocrysts of sanidine, plagioclase (An_{25-30}), hornblende and quartz, and lithic fragments which display the same texture and mineralogical characteristics. These lithic fragments are commonly altered to zeolites. The middle part of the sequence, named here Tenería formation, consists of flow foliated rhyolite units forming an extensive dome field covered by moderately welded ignimbrites and poorly consolidated ash fall tuffs. The rhyolite lava flows include crystalline and glassy layers with sanidine, plagioclase (An_{10-25}), quartz and biotite. Tuffs contain pumice and porphyritic crystalline fragments, as well as feldspar, quartz and biotite crystals. The uppermost part of the Taxco volcanic sequence (Huizteco formation) is exposed in the Huizteco plateau area, northeast of the city of Taxco, and is composed dominantly by moderately welded ignimbrites with some vitrophyre layers. Ignimbrites contain abundant fiamme, as well as quartz, sanidine, plagioclase (An_{10-25}), biotite and Fe-Ti oxide phenocrysts within a devitrified microcrystalline matrix.

Previous K-Ar dating of the lowest unit (Acamixtla formation) was carried out by de Cserna and Fries (1981) who obtained 35.5 ± 1.2 and 36.9 ± 1.3 Ma (feldspar and volcanic glass, respectively), and by Urrutia-Fucugauchi and Linares (1978) who obtained 49 ± 3 Ma. For the same unit, the authors obtained a K-Ar date of 38.2 ± 1 Ma in volcanic glass that is more compatible with determinations carried out by de Cserna and Fries (Alba-Aldave *et al.*, 1996). For the Tenería and Huizteco formations, four dates were obtained (Table 1), ranging from 31.6 ± 0.8 to 32.4 ± 0.9 (Alba-Aldave *et al.*, 1996). These results suggest the Taxco sequence originates from two distinct volcanic events. Since the Ag, Zn and Pb sulfide hydrothermal veins of the Taxco mining district vanish at the contact with the overlying volcanic rocks, these apparently post-date the main mineralization episodes in this region.

Table 1. K-Ar determinations for the Tertiary volcanic rocks of Taxco (TX) and Buenavista-Quetzalapa (BV-SOL) areas.

Sample no.	Area	Long. (W)	Lat. (N)	Mineral	Rock	Radiogenic ^{40}Ar (ppm)	^{40}K (ppm)	K-Ar age (Ma)	Reference
BV-12	Buenavista	99°23'35"	18°17'00"	Hornblende	Dacitic lava flow	0.000831	0.573	24.8±1.3	a
BV-17	Buenavista	99°24'05"	18°17'00"	Plagioclase	Dacitic lava flow	0.001550	0.869	30.5±1.1	a
TX-4	Taxco	99°32'45"	18°34'15"	Whole rock	Vitrophyre	0.009415	4.201	38.2±1.0	a
TX-16	Taxco	99°36'15"	18°35'50"	Whole rock	Vitrophyre	0.01081	5.686	32.4±0.9	a
TX-10	Taxco	99°38'15"	18°34'30"	Plagioclase	Rhyolite	0.001259	0.680	31.6±1.2	a
TX-21	Taxco	99°38'55"	18°37'50"	Biotite	Ignimbrite	0.01588	8.364	32.4±0.8	a
TX-25	Taxco	99°37'17"	18°33'50"	Whole rock	Vitrophyre	0.008059	4.315	31.9±0.8	a
SOL-5	Quetzalapa	99°11'15"	18°21'00"	Biotite	Dacitic ignimbrite	0.01753	9.372	31.9±0.8	a

a: Alba-Aldave and collaborators (1996).

BUENAVISTA-QUETZALAPA AREA

The volcanic sequence of the Buenavista-Quetzalapa range (Figure 4) is constituted of ignimbrites and lava flows with a maximum thickness of about 900 m. The base of the sequence (Figure 5) consists of a dacitic volcanic unit characterized by the conspicuous presence of euedral biotite. This unit was originally described by Fries (1960) in the northern part of the Buenavista-Quetzalapa range, who named it Tilzapotla Rhyolite. Outcrops of the Tilzapotla Formation are distributed discontinuously within an area of 400 km^2. It consists mainly of moderately to densely welded ignimbrites of dacitic composition with abundant biotite. In the Quetzalapa area, this unit is characterized by the presence of pumice fragments up to 10 cm in diameter and abundant limestone xenoliths ranging from a few millimeters to up to 10 m in diameter. Some quartz and sanidine phenocrysts contain inclusions of rounded limestone fragments. The matrix is constituted by a cryptocrystalline groundmass with quartz and feldspar. In one of the new freeway roadcuts to Acapulco, about 3 km south of the village of Quetzalapa, there is a small outcrop of a subvolcanic body intruding the Morelos Formation limestone. This subvolcanic body displays the same mineralogical characteristics of the Tilzapotla Formation, including the presence of euhedral biotite

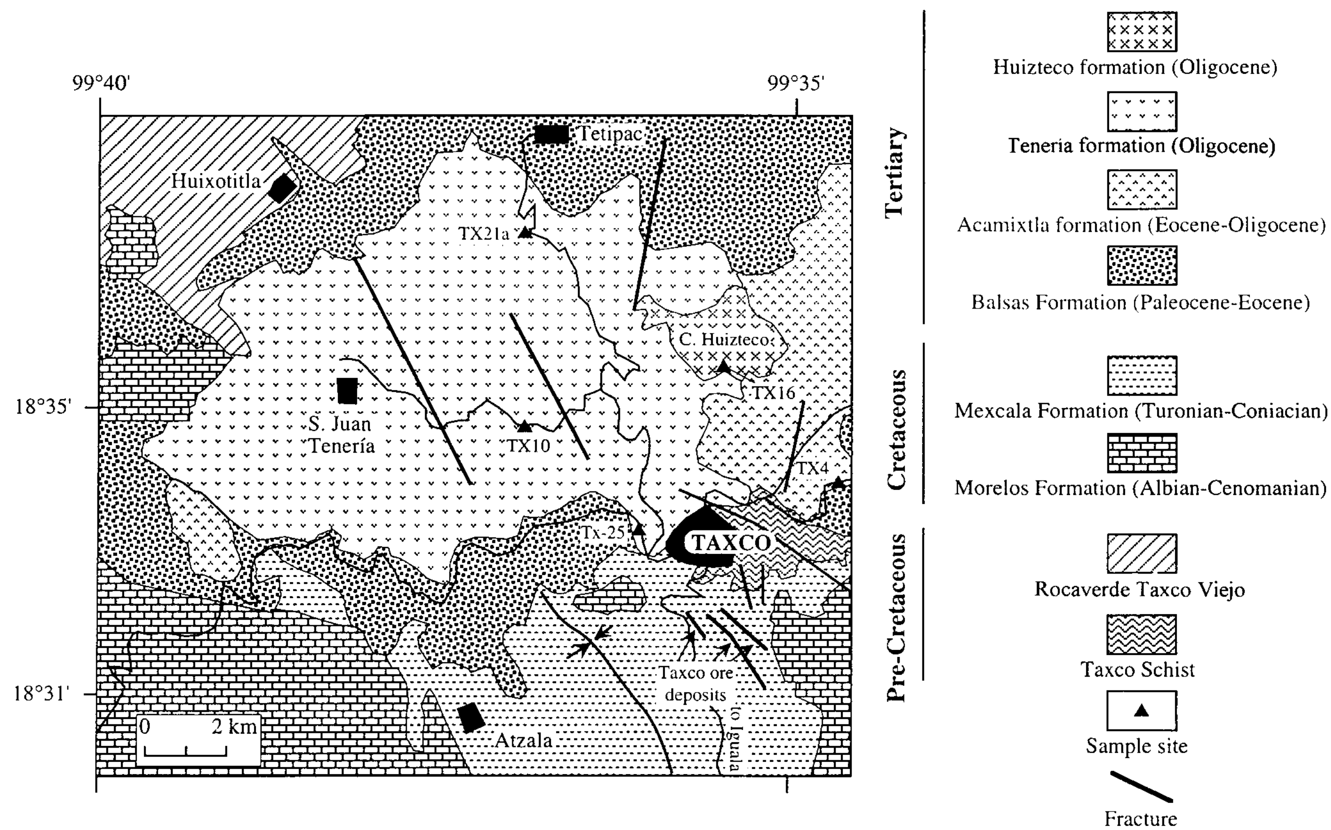

Figure 2. Geologic map of the Tertiary volcanic rocks of the Taxco area.

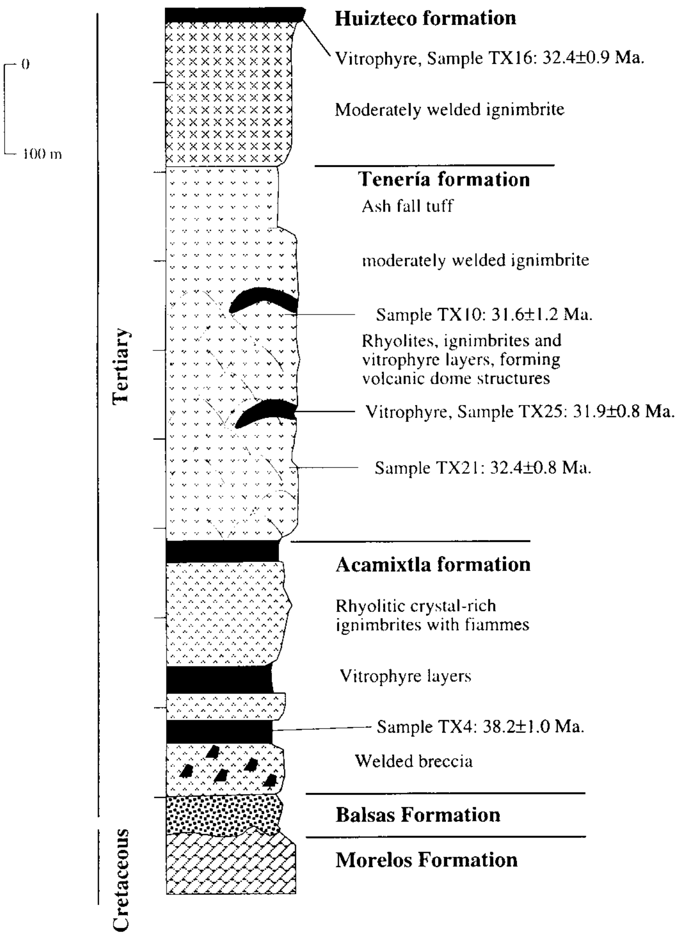

Figure 3. Stratigraphic profile of the Taxco area. Positions of the K-Ar determinations are indicated.

and limestone xenoliths, suggesting a genetical connection between them. In the Tilzapotla area, this formation is also represented by moderately welded ignimbrites with euhedral biotite containing fewer limestone xenoliths and volcanic fragments. Pumice fragments are in general smaller than in the Quetzalapa area. North of Buenavista the unit consists of slightly to moderately consolidated, fine-grained crystal- and vitroclast-bearing ignimbrites. The overall mineral composition is characterized by phenocrysts of plagioclase, K-feldspar, quartz and euhedral biotite. In the Quetzalapa and Tilzapotla areas, the matrix is constituted by a cryptocrystalline groundmass formed by sanidine and quartz. A K-Ar date for a biotite concentrate from a sample of the Tilzapotla Formation in the Quetzalapa area, yielded an age of 31.9 ± 0.8 Ma (Table 1, Figure 5).

In the Buenavista-Tilzapotla area, the Tilzapotla Formation is unconformably overlain by dacite flows and densely welded silicic ignimbrites, with a maximum thickness of 600 m. This unit was originally described by Fries (1960, 1966) and later by de Cserna and Fries (1981) as a dominantly intermediate sequence of lava flows and volcaniclastic rocks, which they named Buenavista Group and later Buenavista Andesite. According to our geochemical analyses and petrographic observations, the sequence is dominantly dacitic rather than andesitic (Figure 7). The dacitic lava flow members of the Buenavista Formation are dominant and consist of a porphyritic texture with phenocrysts of sanidine, zoned plagioclase (An_{40-60}), hornblende, biotite, quartz, as well as xenocrysts of clino- and orthopyroxene. The groundmass contains sanidine, plagioclase and quartz. In the Buenavista area the base of the sequence is constituted by a dacitic flow with abundant leucocratic xenoliths which are also present, but uncommon in the upper dacitic flows. The upper part includes some interlayered ignimbrites containing abundant pumice fragments with sanidine, quartz and biotite. Two K-Ar dates obtained for hornblende and plagioclase concentrates of different lava flow units located in the middle and upper parts of the sequence yielded 30.5 ± 1.1 and 24.8 ± 1.3 Ma, respectively (Table 1) (Alba-Aldave *et al.*, 1996). This latter date shows a large error and probably does not represent the true age of the last magmatic event of the Sierra de Buenavista.

The distribution of the Buenavista-Quetzalapa volcanic rocks and their relationships with the surrounding Mesozoic and Paleogene rocks indicate that they are associated with a collapse caldera structure of about 20 km in diameter. This structure was inferred from the semicircular boundary of the Tilzapotla outcrop area near the village of Quetzalapa and the contact relationships between the dacitic rocks and the Cretaceous limestones. By comparing the present altitudes of the volcanic rock outcrops and the limestone surrounding them, it is evident that the extrusive rocks occupy a circular depression. This is also evident by inspecting the Landsat image of the region. The paroxysmal explosive episode is represented by the ignimbrites of the Tilzapotla Formation that constitute the caldera-fill ignimbrites. North of the villages of Tilzapotla and Buenavista, the Tilzapotla Formation outcrops are suggestive of out-caldera ash flow deposits. The age and dominance of dacitic lava flow of the Buenavista Formation, overlying the Tilzapotla Formation, are suggestive of resurgent activity after the caldera formation.

HUAUTLA AREA

The silicic volcanic sequence of the Huautla area consists of about 400 m of moderately welded tuffs, dacitic flows and densely welded ignimbrites (Figure 6). In the Huautla area this sequence is intruded by a subvolcanic quartz-trachyte with coarse zoned plagioclase, xenocrysts of clinopyroxene and hornblende, and a fine grained groundmass of sanidine, plagioclase and quartz. This intrusive constitutes the host rock of hydrothermal Ag-Pb-Zn sulfide veins of the Huautla mining district. The dominantly silicic sequence of this area rests unconformably on fine porphyritic dacite with phenocrysts of hornblende and augite. This dacitic unit in turn covers red continental beds of siltstone, sandstone and conglomerate. The studied silicic sequence occupies most of the Huautla range and was originally named by Fries (1960, 1966) as the Ixtlilco Group

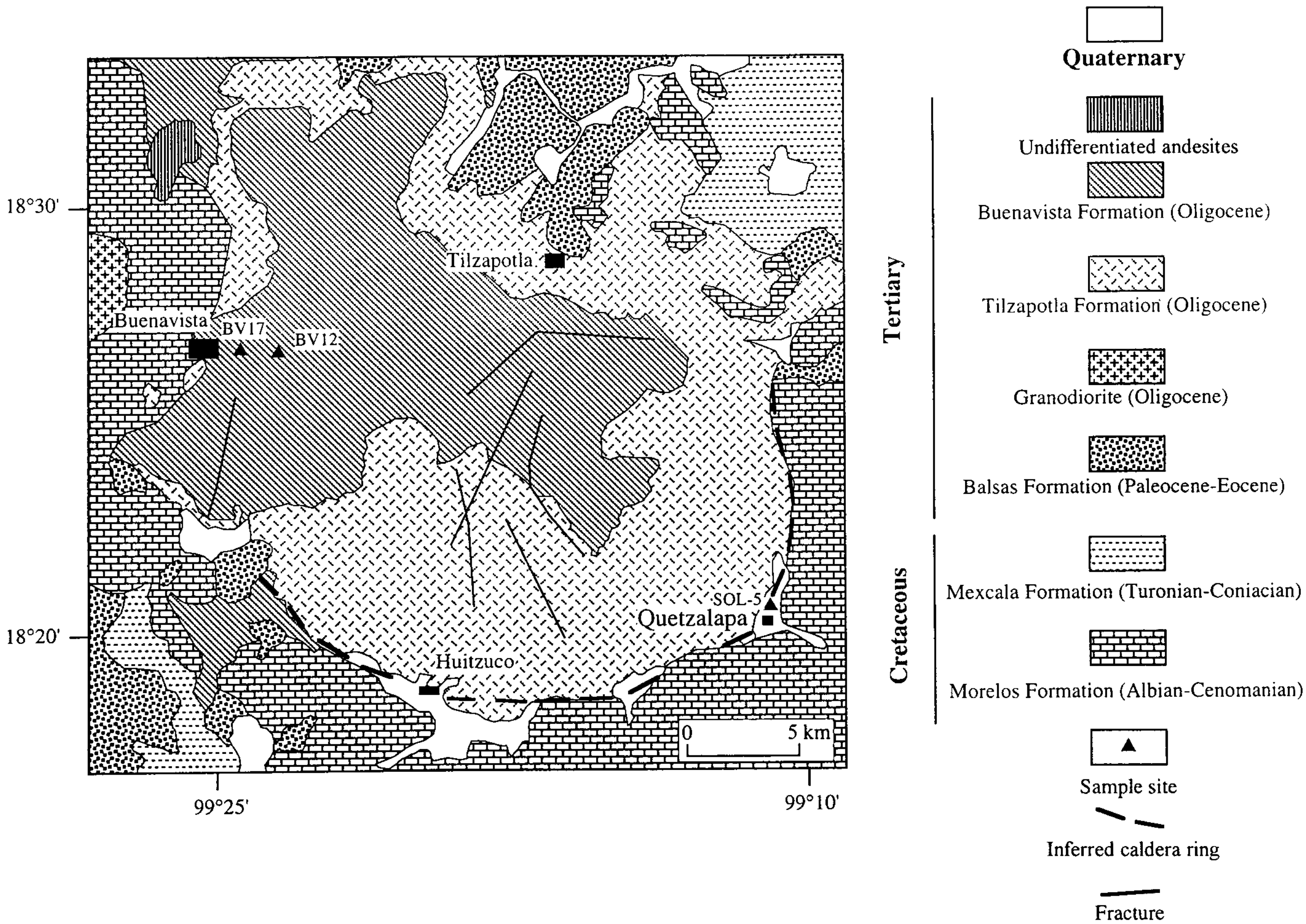

Figure 4. Geological map of the Tertiary volcanic rocks of the Buenavista-Quetzalapa area.

and described as a sequence of rhyodacitic lava flows and volcaniclastic rocks. The section that was studied in the Valle de Vázquez-Huautla area is shown in Figure 6. The lower part of the silicic sequence consists of a 100 m thick unit of white to green welded tuff containing pumiceous fragments and phenocrysts of euhedral biotite, quartz, K-feldspar, zoned plagioclase and hornblende. The groundmass is glassy and cryptocrystalline with partially devitrified shards. This unit is overlain by a thin layer of hematitic crystal rich tuff that in turn underlies a series of dacitic to andesitic lava flows with vesicular and flow laminated structures. These lava flow units contain phenocrysts of zoned plagioclase, hornblende, clinopyroxene and, in some cases, modal quartz and biotite. The upper part of the sequence consists of about 300 m of ignimbrites and breccias. Ignimbrites are porphyritic with phenocrysts of plagioclase, biotite, hornblende and quartz. The groundmass is cryptocrystalline and lithic fragments are scarce.

The lower ignimbrite unit of the Huautla area displays characteristics similar to those of the Tilzapotla Formation in the Buenavista-Quetzalapa volcanic center. We think that the paroxysmal volcanic episode that produced the collapse of the caldera in that area spread debris as far as the Huautla area.

GEOCHEMICAL RESULTS

Major element analyses of the studied samples were carried out at the Isotope Geochemistry Laboratory (LUGIS) of the UNAM using a Siemens SRS 3000 X-ray fluorescence spectrometer and trace element abundances were determined at the C.R.P.G. of Nancy, France and LUGIS by ICP-MS techniques. Sr abundances and the isotopic ratios were determined by running spiked and natural aliquots in the multicollector Finnigan 262 mass spectrometer of LUGIS using double Re filaments. Sr blanks analyses yielded 100 pg and the obtained ratios for Sr NBS 987 at the time of analysis were 0.71023 ± 0.000052. Details of sample preparation and chemical treatment are reported in Schaaf and collaborators (in preparation).

The overall SiO_2 abundances in the studied samples range from 57 to 75% (Table 2), with greater concentrations in the Taxco region, where ignimbrites and rhyolites range from 67 to 75%. Volcanic rocks in the Buenavista-Quetzalapa and Huautla areas have a broader distribution in SiO_2 abundances, ranging from 57 to 69% and from 58 to 63%, respectively, with a dominance of dacitic compositions (Figure 7). The data for the three regions plot in distinct areas of K_2O *vs.* SiO_2 dia-

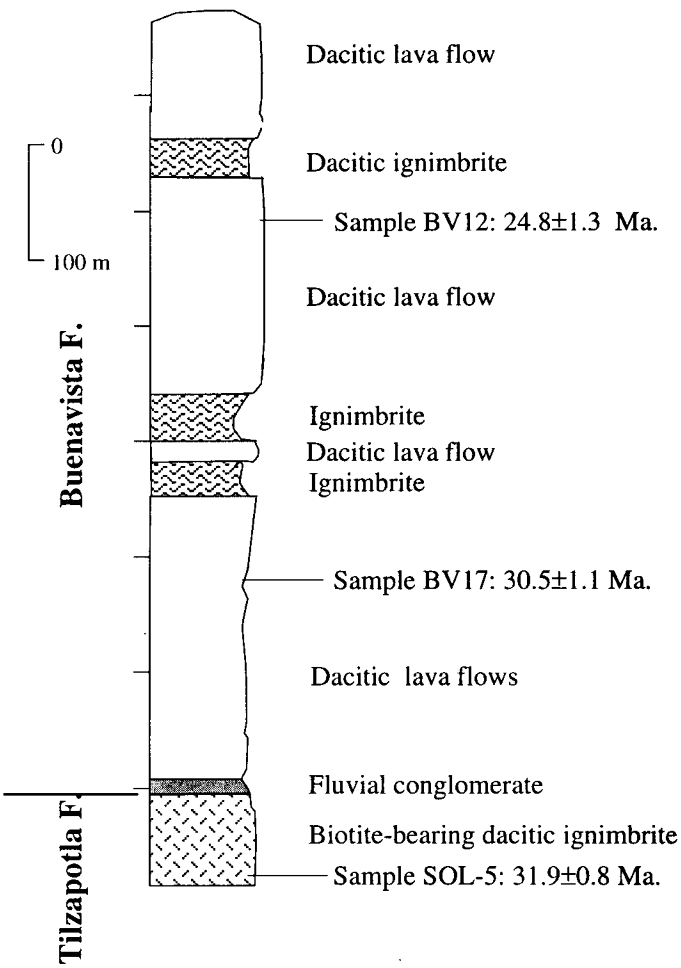

Figure 5. Stratigraphic profile of the Buenavista-Quetzalapa area. Positions of the K-Ar determinations are indicated.

gram (Figure 8), particularly the data from the Taxco and Huautla areas, supporting our position that they represent different volcanic centers. The calc-alkaline character of the studied sequences can be confirmed from the distribution of analyzed samples in an alkalis *vs.* SiO_2 diagram (Figure 7) and in the AFM diagram (Figure 9). The occurrence of igneous and limestone xenoliths as well as xenocrysts of quartz suggests that host rock contamination could contribute to some extent to the scattering of major elements.

Trace element patterns in a MORB-normalized multi- element diagram (Figure 10; Table 3) display characteristic troughs for HFSE with respect to LILE in highly differentiated magmas, and reveal a subduction component, typical of arc zones, in the original magma source. Additionally, the slight negative anomaly of Ba with respect to Rb and Th in some samples reinforces the interpretation of redistribution of the most mobile elements during and after the emplacement of pyroclastic flows. REE patterns show a typical enrichment of LREE with respect to HREE, the average being $(La/Lu)_{CN}$ = 6.93 (TX = 5.57; BV = 5.64; HU = 9.25) (Figure 11) and negative Eu anomalies in the Taxco samples (Eu/Eu*~0.4) which indicate plagioclase fractionation.

The K-Ar ages obtained by us (Alba-Aldave *et al.*, 1996) of the samples from the Taxco area range from 38.2 ± 1 to 31.9 ± 0.8 Ma (Table 2), and for the Buenavista-Quetzalapa area, from 31.9 ± 0.8 to 27.6 ± 1.3 Ma, which are similar to those of the plutons of the continental margin of the Acapulco region (except for that of Acapulco itself).

The initial Sr ratios for the Taxco area range between 0.705201 and 0.706081. The Buenavista area yielded values of 0.703800 and 0.703810, and the Tilzapotla Formation, sampled near the village of Quetzalapa, displayed a value of 0.704767 (Table 4).

REGIONAL GEOCHRONOLOGICAL RELATIONSHIPS AND TECTONIC SIGNIFICANCE

The distribution, volcanic features and geochemical characteristics of the Taxco-Quetzalapa volcanic sequences indicate that they originated from at least three Oligocene volcanic centers located in the Taxco, Buenavista-Quetzalapa and Huautla areas. The REE patterns as well as $^{87}Sr/^{86}Sr$ initial ratios of the analyzed samples suggest that the Taxco volcanic sequences are not only the most differentiated by crystal fractionation, but probably the most contaminated by crustal assimilation.

The Taxco volcanic center is characterized by two recognizable episodes of silicic volcanism. The oldest one is represented by several pyroclastic flows whose source was located somewhere west of the city of Taxco and probably was buried by younger Oligocene volcanism. There is no recognizable feature in the field or in the aerial photographs with which the source of this first episode could be associated. Its volcanic products constitute what we call the Acamixtla formation and occurred at about 38 to 35 Ma BP. An extensive rhyolitic dome field that developed between 32 and 31 Ma BP represents the second episode. The latest volcanic activity of this episode was dominated by ash fall and ash-flow deposits.

The 31.9 Ma date obtained from the Tilzapotla Formation rocks indicates that the main volcanic activity in the Quetzalapa caldera was coeval with the latest volcanic events of the Taxco area, but less differentiated. The age (30 Ma) and distribution of the overlying dacitic lava of the Buenavista Formation suggest that they are also part of the resurgent activity in the Quetzalapa caldera.

The ash flow deposits of the Tilzapotla Formation extend to the Huautla area and underlie a group of silicic units including lava flows and pyroclastic deposits that are probably related to a volcanic source different from that of the Quetzalapa caldera. The dacitic subvolcanic unit cropping out around the village of Huautla indicates the occurrence of volcanic centers in this area.

The calc-alkaline composition and trace element behavior of the Oligocene volcanic rocks of northern Guerrero and southern Morelos states suggest that they are related to the magmatic arc associated with the subduction along the south-

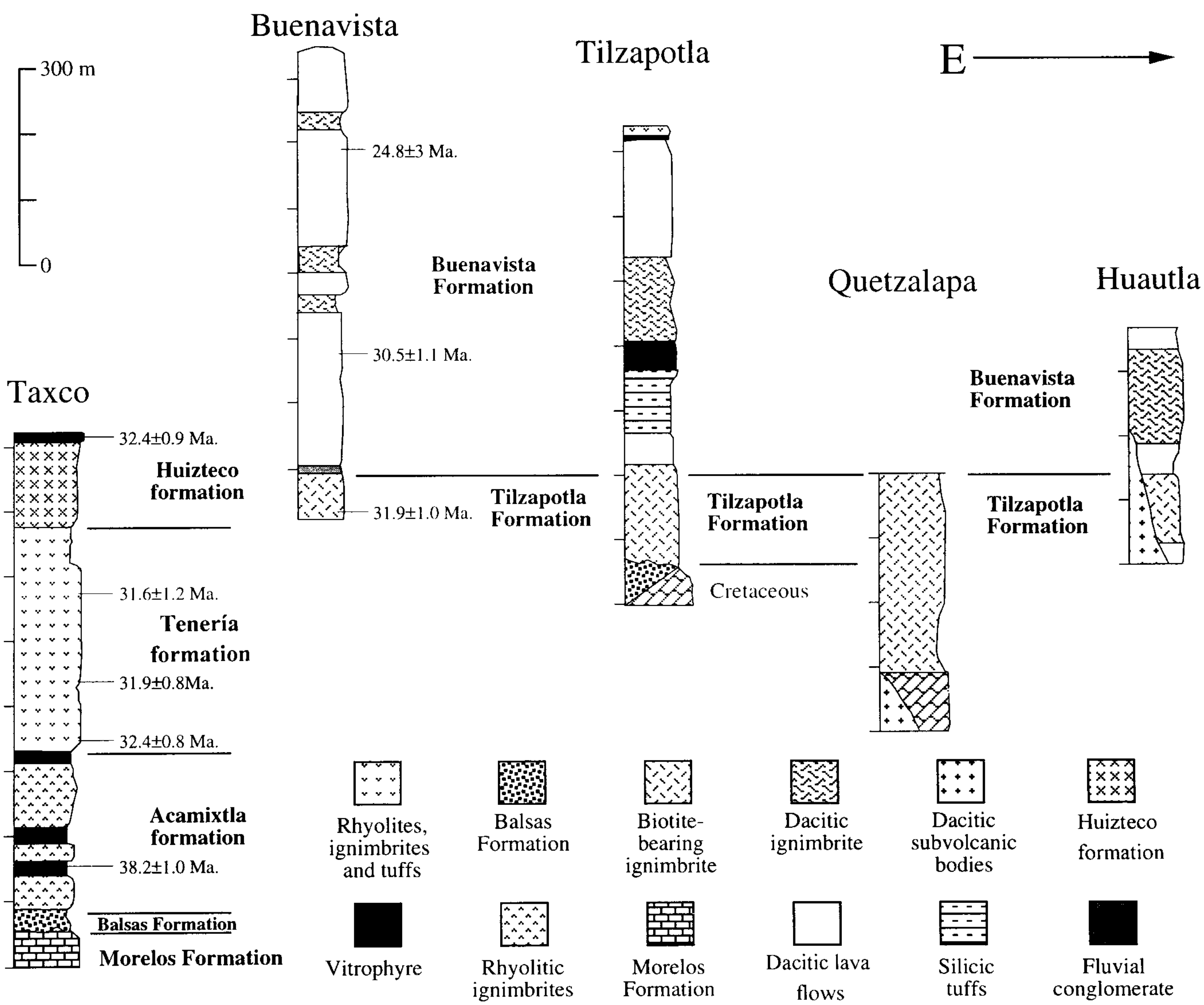

Figure 6. Schematic section with stratigraphic correlation for the study area.

western margin of Mexico. Their position indicates that they are part of the NNW trending belt of silicic magmatism of about 30 Ma in age. This belt extends from the eastern part of the Sierra Madre Occidental and the Mesa Central (Ferrari *et al.*, 1994 and references therein) (Figure 12) as far south as the Oligocene coastal plutonic belt in the Acapulco region (*i.e.*, Tierra Colorada, Xaltianguis, San Juan Reparo, San Marcos) (Schaaf *et al.*, 1995 and references therein). South of the TMVB this silicic belt is limited to the east by coeval andesite and basaltic-andesites of the western Oaxaca region (Martiny *et al.*, 1995), and to the west by intermediate to silicic Eocene to early Oligocene sequences of western Guerrero and southeastern Michoacán. The silicic volcanic rocks of northern Guerrero and southern Morelos states are located within a transition zone between two distinct tectonic domains. To the north of the TMVB, the Oligocene silicic volcanism was related to an E-W extensional domain probably associated with the plate interaction on the western margin of Mexico (Nieto-Samaniego, 1990; Henry and Aranda, 1992; Ferrari *et al.*, 1994). To the south, the distribution of the silicic plutons seems to have been controlled by a left lateral NW-SE transtensional zone originated by the displacement of the Chortis Block (Ratschbacher *et al.*, 1991).

Based on the analysis of compiled isotopic ages for Tertiary magmatic rocks in central Mexico, Ferrari and collaborators (1994) interpreted a general cessation of magmatism in late Oligocene time south of the Trans-Mexican Volcanic Belt. Our stratigraphic observations and K-Ar isotopic data confirm this interpretation and preclude Miocene ages for the Buenavista Formation as had been previously suggested. The southeastward decreasing ages of Oligocene plutons along the southwestern continental margin of Mexico (Herrmann *et al.*,

Table 2. Major element analyses of ignimbrites and lavas from Taxco (TX), Buenavista-Quetzalapa (BV, TLZ, SOL, HZ) and Huautla (HU) areas.

Sample no.	BV11	BV12	BV13	BV14	BV16	BV17	BV18	BV19	BV20	BV21	TLZ2	TLZ4B	TLZ4D
SiO_2	67.43	64.20	64.01	67.50	66.68	63.26	59.85	62.96	57.38	66.32	64.26	59.02	65.09
TiO_2	0.36	0.42	0.41	0.47	0.40	0.46	0.58	0.51	1.17	0.64	0.52	0.86	0.51
Al_2O_3	14.94	15.76	16.21	14.83	16.48	15.69	18.39	17.16	17.87	15.53	16.01	16.31	17.47
Fe_2O_3*	4.05	4.74	4.97	4.48	4.65	6.61	5.51	4.90	7.57	4.75	4.65	7.25	4.89
MnO	0.09	0.06	0.07	0.04	0.10	0.07	0.06	0.07	0.10	0.08	0.09	0.08	0.08
MgO	1.66	1.45	1.98	1.59	1.09	0.93	0.10	1.71	3.63	1.39	1.99	1.80	1.36
CaO	3.43	2.96	3.72	3.13	3.03	3.57	2.30	3.54	6.84	3.44	3.33	3.68	4.00
Na_2O	3.52	3.44	3.92	2.65	3.54	3.60	3.64	3.71	3.42	3.54	3.42	3.46	4.16
K_2O	2.69	2.89	2.78	1.59	2.80	2.72	3.83	2.53	1.38	3.37	4.09	1.75	2.47
P_2O_5	0.11	0.15	0.14	0.17	0.12	0.16	0.58	0.22	0.28	0.10	0.11	0.20	0.18
L.O.I.	1.62	3.86	1.33	3.67	1.40	2.29	3.61	1.45	1.06	1.17	0.56	5.36	0.57
Total	99.90	99.93	99.54	100.12	100.29	99.36	98.45	98.76	100.70	100.33	99.03	99.77	100.78

Sample no.	TLZ6A	TLZ6B	TLZ8	TLZ9	TLZ10	TLZ11	TLZ12	TLZ13	SOL2	SOL5	HZ1	HZ2	HZ3
SiO_2	69.87	72.49	68.2	66.09	62.14	68.36	60.93	66.93	64.09	68.32	65.56	67.74	64.79
TiO_2	0.31	0.30	0.38	0.53	0.54	0.44	0.61	0.50	0.48	0.48	0.54	0.54	0.51
Al_2O_3	15.17	14.46	15.87	16.61	16.02	15.8	17.6	14.99	14.06	14.34	14.97	14.84	14.53
Fe_2O_3*	3.19	3.23	3.97	4.88	4.68	4.04	5.81	4.17	3.47	3.58	4.61	4.28	4.70
MnO	0.07	0.01	0.05	0.10	0.08	0.07	0.08	0.02	0.04	0.02	0.05	0.11	0.06
MgO	1.19	0.36	1.25	2.14	0.59	0.80	1.89	0.92	1.04	1.40	1.71	1.55	1.70
CaO	3.71	2.17	2.36	2.83	4.72	3.55	5.65	3.35	5.83	3.67	2.35	3.03	3.00
Na_2O	3.41	3.23	4.15	4.06	3.91	3.48	3.72	3.49	3.54	1.99	2.49	3.37	2.29
K_2O	1.72	3.88	2.99	2.17	2.50	3.27	3.07	3.18	2.73	4.14	5.04	3.55	4.81
P_2O_5	0.11	0.07	0.10	0.13	0.21	0.11	0.15	0.07	0.06	0.05	0.06	0.07	0.06
L.O.I.	1.60	0.15	1.01	1.07	4.38	0.33	0.74	3.80	5.39	4.68	3.85	1.89	4.63
Total	100.35	100.35	100.33	100.61	99.77	100.25	100.25	101.42	100.73	102.67	101.23	100.97	101.08

Sample no.	TX4	TX5B	TX7	TX8	TX10	TX10B	TX11	TX13	TX16	TX21	TX25	HU1	HU4
SiO_2	71.73	73.4	67.84	69.15	72.11	70.95	72.37	73.11	75.63	72.45	70.52	66.88	59.87
TiO_2	0.28	0.23	0.30	0.34	0.25	0.25	0.25	0.27	0.10	0.01	0.25	0.50	0.87
Al_2O_3	13.77	13.49	13.21	13.84	13.51	13.20	14.37	14.04	13.67	12.86	13.39	15.74	16.52
Fe_2O_3*	4.06	3.59	4.35	4.32	3.27	3.35	3.13	3.44	1.51	1.59	3.29	4.19	6.52
MnO	0.08	0.07	0.07	0.04	0.04	0.07	0.03	0.02	0.03	0.03	0.06	0.01	0.05
MgO	0.40	0.17	0.34	0.22	0.17	0.07	0.39	0.12	0.01	0.49	0.08	1.59	1.80
CaO	1.97	1.00	2.14	1.22	1.38	1.70	1.18	1.33	1.12	2.77	1.77	3.38	5.39
Na_2O	3.77	2.95	3.83	3.80	3.69	3.52	2.78	3.53	2.16	1.94	3.51	3.19	3.32
K_2O	3.53	5.31	3.30	4.20	3.98	3.86	4.63	4.00	5.61	3.94	3.90	3.69	2.78
P_2O_5	0.05	0.003	0.06	0.34	0.08	0.004	0.03	0.01	0.003	0.002	0.03	0.07	0.21
L.O.I.	0.33	0.12	4.29	1.81	1.32	3.35	0.63	1.07	0.21	4.54	3.34	2.05	2.50
Total	99.97	100.333	99.73	99.28	99.80	100.324	99.79	100.94	100.053	100.622	100.14	101.29	99.83

Sample no.	HU5	HU6	HU8	HU9	HU10	HU12	HU13
SiO_2	62.17	63.72	60.56	59.62	60.03	58.35	62.17
TiO_2	0.95	0.98	0.59	0.55	0.88	0.92	0.98
Al_2O_3	16.09	16.75	16.60	15.63	17.21	16.66	17.00
Fe_2O_3*	5.40	5.34	5.28	4.06	6.43	6.64	6.00
MnO	0.04	0.02	0.07	0.08	0.05	0.09	0.08
MgO	1.42	1.54	1.72	1.34	2.10	2.79	2.29
CaO	4.53	4.39	3.89	6.11	6.32	6.11	5.75
Na_2O	4.03	3.79	3.68	3.15	3.33	3.33	1.10
K_2O	1.71	1.94	3.88	2.87	1.73	2.18	2.96
P_2O_5	0.27	0.20	0.20	0.18	0.26	0.21	0.13
L.O.I.	3.14	1.59	3.22	6.12	1.70	1.68	1.14
Total	99.75	100.26	99.69	99.71	100.04	98.96	99.60

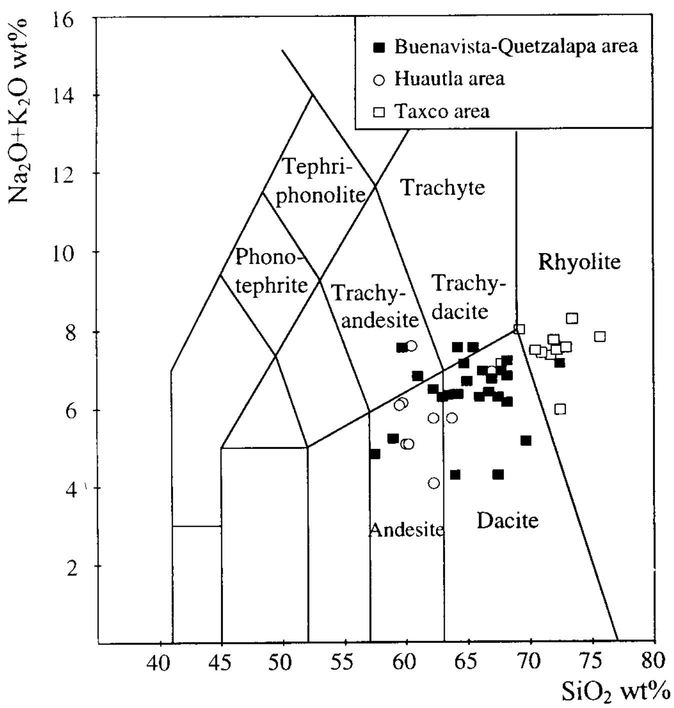

Figure 7. The total-alkalis *vs.* silica diagram (TAS) of Le Maître and collaborators (1989) for the Tertiary volcanic rocks of the study region.

1994; Schaaf *et al.*, 1995) indicate a gradual cessation related to the southeastward displacement of the Chortis Block. In the interior region represented by the northern Guerrero, southern Morelos and western Oaxaca volcanic regions, a decreasing age tendency is not evident. However, to the southeast in central Oaxaca and the Isthmus of Tehuantepec region, volcanic rocks ranging in age from 15 to 10 Ma (Ferrusquía-Villafranca,

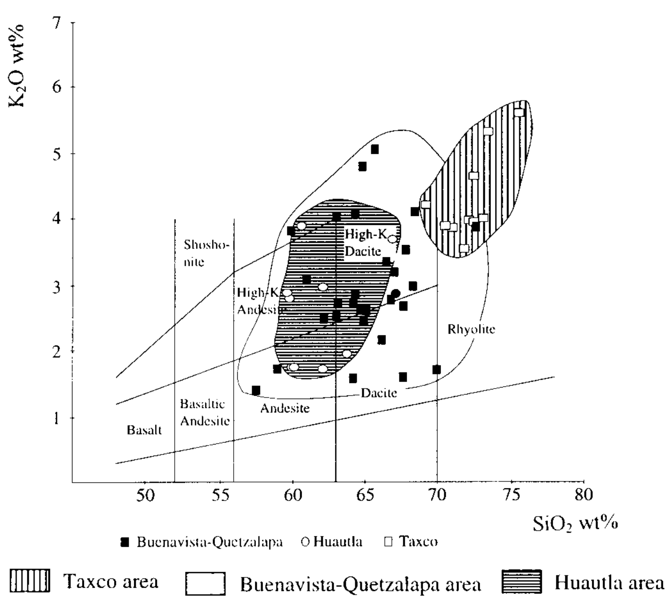

Figure 8. K_2O *vs.* SiO_2 wt %. Classification after Peccerillo and Taylor (1976) for sub-alkalic rocks. Observe that the three volcanic areas show different chemical behavior.

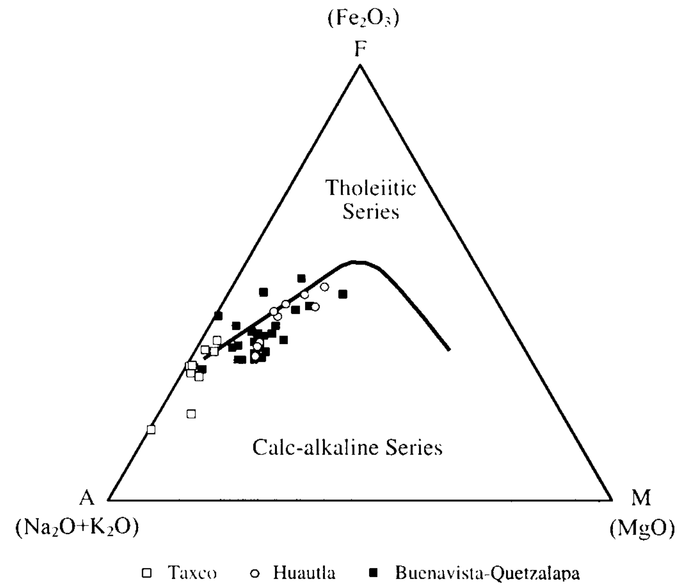

Figure 9. AFM diagram showing the behavior of the Tertiary volcanic rocks. The boundary between the calc-alkaline and tholeiitic fields is after Irvine and Baragar (1971).

1992) indicate different chronological tendencies of the magmatism related to the proximity of the trench-trench-transform triple junction.

The scarcity of magmatic rocks from the 25 to 15 Ma interval in the eastern part of the Trans-Mexican Volcanic Belt, as well as in eastern Guerrero, Morelos and western Oaxaca, indicates the occurrence of a gap in the subduction related magmatism in this region. The Oligocene ages of most of the plutons cropping out from Acapulco to Huatulco along the coast (Herrmann *et al.*, 1994; Schaaf *et al.*, 1995) and the lack of reports of younger plutonic rocks support this interpretation. In the western part of the TMVB the transition from the western SMO magmatism to the E-W trending volcanism of the TMVB occurred in a gradual way and no gap is evident (Ferrari *et al.*, 1994).

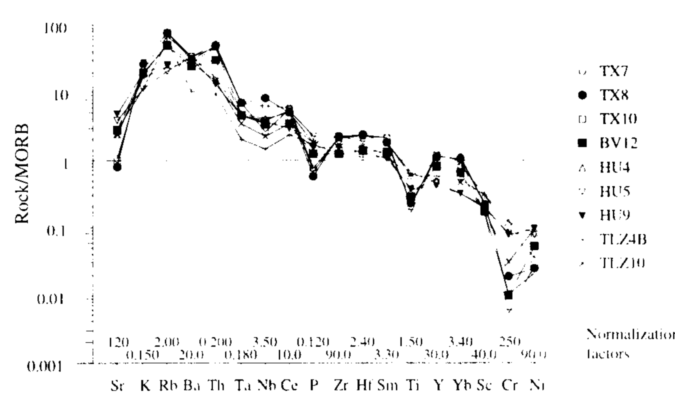

Figure 10. MORB-normalized multi-element diagram (Pearce, 1983) for the Tertiary volcanic rocks of Taxco, Buenavista-Quetzalapa and Huautla areas.

Table 3. Trace element concentrations (in ppm) for some Tertiary volcanic rocks from Taxco (TX), Buenavista-Quetzalapa (BV, TLZ) and Huautla (HU) areas.

Sample no.	BV12	TLZ4B	TLZ10	TX7	TX8	TX10	HU4	HU5	HU9
Sc	6.90	12.10	7.40	9.30	8.50	6.60	12.10	7.80	8.10
V	77.80	174.69	77.26	23.04	23.57	11.77	144.86	77.74	41.61
Cr	2.46	21.26	7.66	2.59	4.57	1.32	28.96	20.16	19.11
Co	26.82	13.94	17.75	35.95	88.38	1.31	24.22	29.78	66.80
Ni	4.87	3.21	8.58	1.93	2.24	2.52	7.49	6.85	8.46
Zn	57.54	85.19	68.08	86.86	87.98	64.03	76.69	84.49	52.76
Ga	19.13	19.03	18.52	21.87	22.20	21.65	19.96	23.33	17.08
Rb	97.80	114.87	49.77	135.59	149.46	155.22	104.10	41.19	50.69
Sr	337.94	332.29	280.54	124.24	95.15	107.72	276.07	449.45	587.68
Y	23.69	17.58	15.26	37.63	33.17	34.24	27.50	14.18	12.37
Zr	107.89	110.61	151.60	189.81	196.53	189.72	202.20	206.23	134.28
Nb	11.93	4.98	7.86	21.94	28.82	9.31	14.06	13.62	12.50
Cs	3.28	7.15	1.37	8.94	6.27	5.31	5.16	5.37	2.85
Ba	486.78	199.88	535.54	661.83	589.57	657.89	556.08	692.17	627.19
La	20.05	11.16	15.80	29.25	25.43	28.97	25.81	25.54	14.11
Ce	34.93	23.35	34.20	59.79	51.81	57.50	49.65	53.47	29.68
Pr	5.11	3.35	4.14	7.83	6.35	7.59	6.81	6.93	3.67
Nd	19.71	14.26	16.86	31.56	25.00	28.96	26.75	28.04	14.69
Sm	4.34	3.55	3.77	7.11	5.89	6.84	6.00	5.94	3.38
Eu	1.01	1.11	0.99	0.98	1.02	0.91	1.49	1.55	0.93
Gd	3.78	3.06	3.11	6.45	5.35	5.89	5.23	4.18	2.56
Tb	0.64	0.51	0.48	1.07	0.91	0.98	0.84	0.59	0.39
Dy	3.67	3.25	2.76	6.65	5.55	5.96	5.05	3.06	2.32
Ho	0.81	0.70	0.58	1.42	1.25	1.31	1.09	0.54	0.46
Er	2.00	1.80	1.52	3.46	3.25	3.23	2.60	1.34	1.15
Tm	0.30	0.26	0.20	0.56	0.52	0.51	0.44	0.17	0.18
Yb	2.16	1.74	1.55	3.79	3.50	3.40	2.83	1.07	1.08
Lu	0.31	0.30	0.24	0.56	0.50	0.51	0.44	0.18	0.19
Hf	3.27	2.69	3.77	5.50	5.77	5.62	5.52	4.64	3.15
Ta	0.82	0.37	0.62	0.00	0.00	1.24	0.87	0.00	0.00
Pb	9.91	7.53	8.01	14.86	17.85	15.37	8.84	8.37	5.33
Th	6.21	1.90	2.99	9.14	9.79	10.51	9.13	3.26	2.65
U	2.25	1.06	1.34	3.44	3.65	3.65	2.31	0.66	0.85

The present-day low-angle position of the subducted slab beneath the eastern Guerrero and western Oaxaca states (Pardo and Suárez, 1995) indicates that the time interval following the displacement of the Chortis Block was characterized by a change in the geometry of the subduction zone due to the direct interaction of the Cocos plate and the North American plate with higher convergence rates (Morán-Zenteno *et al.*, 1996). This variation in the subducted slab geometry could be favored by the changes in the rotation pole that accompanied the fragmentation of the Farallon plate and the formation of the Cocos plate. The unstable position of the subducted slab related to the change in its geometry as well as the lack of time for

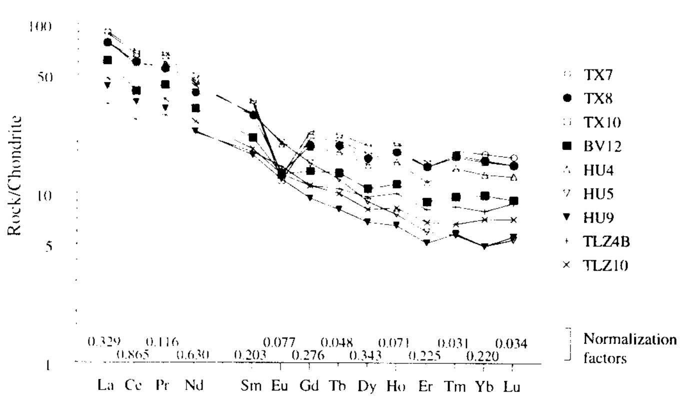

Figure 11. Rare earth elements plots (Nakamura, 1974) for the Tertiary volcanic rocks of Taxco, Buenavista-Quetzalapa and Huautla areas.

Table 4. Isotopic analyses of selected rocks from Taxco (TX) and Buenavista-Quetzalapa (BV, SOL) areas.

Sample	Rock	Rb (ppm)	Sr (ppm)	Rb/Sr	$(^{87}Sr/^{86}Sr)_m$	$(^{87}Sr/^{86}Sr)_i$
BV12	Dacitic lava flow	98	374	0.26	0.704097±51	0.703830
BV17	Dacitic lava flow	88	471	0.19	0.704044±59	0.703810
TX4	Vitrophyre	148	132	1.12	0.706961±40	0.705201
TX15	Ignimbrite	136	151	0.90	0.706255±53	0.705071
TX10b	Rhyolite	135	187	0.72	0.706966±41	0.706017
TX16	Vitrophyre	140	137	1.02	0.707442±48	0.706081
TX21	Ignimbrite	186	274	0.68	0.707190±57	0.706287
TX25	Vitrophyre	166	107	1.55	0.707449±47	0.705415
SOL-2	Dacitic ignimbrite	120	105	1.14	0.706265±56	0.704767

Sr measurements have been performed on a Finnigan MAT 262 mass spectrometer. Analytical errors for $^{87}Sr/^{86}Sr$ are expressed in 1-sigma.
$(^{87}Sr/^{86}Sr)_m$: Sr isotopic measurements
$(^{87}Sr/^{86}Sr)_i$: Sr isotopic initial ratios.

the mantle wedge to develop the metasomatic conditions for the generation of arc magmatism are probably responsible for the 25 to 15 Ma magmatic gap.

CONCLUSIONS

The stratigraphy, geochemical characteristics and distribution of the Tertiary volcanic rocks of the study region indicate the occurrence of at least three Oligocene volcanic centers. The main volcanic activity in the Buenavista-Quetzalapa area is related to a resurgent caldera developed contemporaneously with the last episodes of volcanic activity in the Taxco region. Geochemical and petrological data indicate that the Taxco volcanic rocks are the most differentiated and contaminated by crustal assimilation.

There is no evidence of major extensional features in the study region. Oligocene silicic volcanism in this region occurred in a tectonic transitional zone between E-W extension

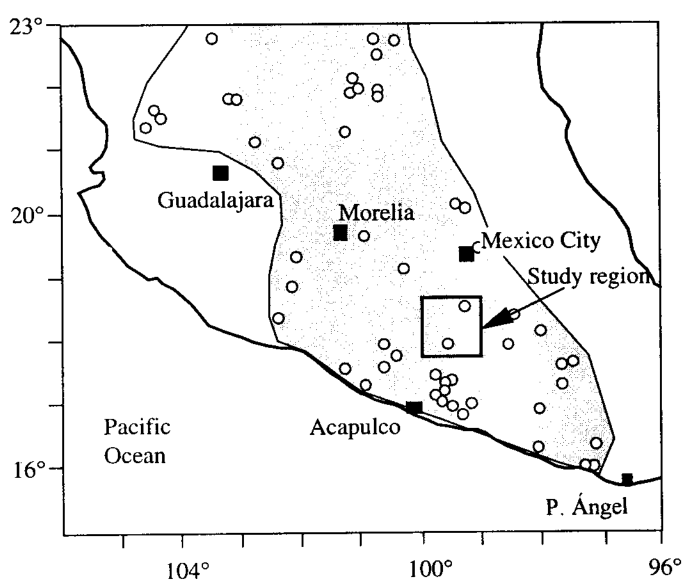

Figure 12. Areal distribution of igneous rocks for the periods 38-26 Ma (modified from Ferrari *et al.*, 1994).

north of the TMVB and the left lateral transtensional zone recognized for the SW continental margin of Mexico.

The difference in composition between rhyolitic and dacitic rocks of the studied region and the more undifferentiated coeval volcanic rocks of western Oaxaca might be caused at least in part by differences in the tectonic style of both regions. The lack of major extensional or transtensional features in the studied region contrasts with the extensional features of western Oaxaca and southern Puebla (Martiny *et al.*, 1995).

The K-Ar geochronological ages obtained by us from the studied sequences preclude the occurrence of Miocene arc related magmatic activity south of the central TMVB. This fact supports the interpretation of magmatic gap in this region which developed after the passage of the trench-trench-transform triple junction that accompanied the southeastward displacement of the Chortis Block.

The probable causes of the 25 to 15 Ma magmatic gap between the end of the Oligocene magmatism and the beginning of the TMVB are the change in the subducted slab geometry following the Chortis Block detachment and the lack of time for the mantle wedge to achieve the metasomatic conditions under which arc magmatism could be produced.

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