Geochemical and Sr-Nd isotopic characterization of the Miocene volcanic events in the Sierra Madre del Sur, central and southeastern Oaxaca, Mexico

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ABSTRACT

The Etla, Mitla-Tlacolula and Nejapa volcanic regions in central and southeastern Oaxaca comprise the southeastern part of a wide Cenozoic magmatic arc in the Sierra Madre del Sur. Most volcanic events in these regions ocurred between 22 to 15 Ma, almost contemporaneously with the initial volcanic events of the Trans-Mexican Volcanic Belt. Petrographic, geochemical, and isotopic characteristics were determined for representative volcanic samples from the three regions, where ignimbrites, volcaniclastic and epiclastic deposits, lava flows and minor lacustrine deposits are found. In a SiO_2 vs. alkalis diagram, chemical classification of volcanic products for the study area indicate variations from basaltic andesites to rhyolites, following a subalkaline trend, but with a bimodal pattern. Components with SiO_2 concentrations between 58 to 67 wt. % are absent. The trace-element patterns for andesites and rhyolites are similar, with enrichment in the large-ion lithophile elements relative to the high-field-strength elements. Chondrite-normalized REE patterns display light rare earth element enrichment (La-Sm) with respect to the heavy rare earth elements (Eu-Lu), which show flat patterns. These chemical characteristics are typical of volcanic arc rocks. Initial Sr and Nd isotopic data show certain differences between samples from the Etla and Mitla-Tlacolula regions ($^{87}Sr/^{86}Sr$: 0.7047 to 0.7066 and εNd: -1.15 to 1.75) and the Nejapa region ($^{87}Sr/^{86}Sr$: 0.7035 to 0.7048 and εNd: +0.52 to +1.42). These data and those reported for the basement rocks suggest greater involvement of continental crust for the magmas of the two first regions in comparison to magmas of the Nejapa region. The isotopic compositions are similar to those observed in other volcanic regions of the Sierra Madre del Sur. Early to middle Miocene volcanic events in central and southeastern Oaxaca, together with the contemporaneous initial magmatic events in the Trans-Mexican Volcanic Belt, could conform a magmatic arc with an anomalous orientation before attaining its present position.

Keywords: geochemistry, Sr-Nd isotopic ratios, volcanic rocks, Miocene, Sierra Madre del Sur, Mexico.

RESUMEN

Las regiones volcánicas de Etla, Mitla-Tlacolula y Nejapa, en la parte central y sureste de Oaxaca, conforman la porción oriental de un amplio arco magmático cenozoico dentro de la Sierra Madre del Sur. La mayoría de los eventos volcánicos ocurrieron entre los 22 y 15 Ma, casi de manera contemporánea con los primeros eventos volcánicos de la Faja Volcánica Transmexicana. Se determinaron las características petrográficas, geoquímicas e isotópicas de muestras volcánicas obtenidas de las tres *regiones, donde existen ignimbritas, depósitos volcaniclásticos y epiclásticos, flujos de lava, y algunos depósitos lacustres. La clasificación química de las rocas en un diagrama SiO_2 vs. álcalis varía entre andesitas y riolitas, siguiendo un patrón subalcalino bimodal. Al parecer no existen rocas con contenidos de SiO_2 de entre 58 y 67 % en peso. Los patrones de comportamiento de elementos traza de las andesitas y riolitas son muy similares, con un enriquecimiento en los elementos litófilos respecto a los elementos de alto potencial iónico, mientras que los patrones de los elementos de tierras raras, normalizados con respecto a condrita, muestran un enriquecimiento de las tierras raras ligeras (La-Sm) respecto a las tierras raras pesadas, con un comportamiento casi plano para estas últimas (Eu-Lu). Este tipo de patrones se ha asociado con rocas de arco volcánico. Las relaciones isotópicas iniciales de Sr y Nd muestran ciertas diferencias entre las regiones de Etla, Mitla-Tlacolula ($^{87}Sr/^{86}Sr$: 0.7047 a 0.7066 y εNd: -1.15 a 1.75) y Nejapa ($^{87}Sr/^{86}Sr$: 0.7035 a 0.7048 y εNd: +0.52 a +1.42). Con base en estos datos isotópicos, más los existentes para rocas del basamento de estas regiones, se sugiere que los magmas de las dos primeras regiones sufrieron una mayor interacción con la corteza continental en comparación con los magmas de la región de Nejapa. Las composiciones isotópicas de las rocas del área de estudio son similares a las observadas en otras regiones volcánicas cenozoicas de la Sierra Madre del Sur. Los eventos volcánicos del Mioceno temprano a medio de la parte central y sureste de Oaxaca, junto con los primeros eventos magmáticos de la Faja Volcánica Transmexicana podrían conformar un arco magmático continuo con una orientación anómala, antes de alcanzar su posición actual.*

Palabras claves: geoquímica, isotopía de Sr y Nd, rocas volcánicas, Mioceno, Sierra Madre del Sur, México.

INTRODUCTION

The Paleocene-Miocene magmatic rocks of the Sierra Madre del Sur (SMS), southern Mexico (Figure 1) have been identified as two broad belts approximately parallel to the Pacific coast. These rocks are part of a widespread magmatic arc that include an almost continuous WNW-trending plutonic belt made of granitic to tonalitic batholiths emplaced along the present-day coast of southern Mexico and a second volcanic belt discontinuously distributed inland, up to the northern part of the SMS. The volcanic belt shows compositional variations from basaltic andesites to rhyolites (Morán-Zenteno *et al.*, 1999; Martiny *et al.*, 2000a). The plutonic and volcanic rocks of this arc extend for about 600 km, from the southern part of Jalisco to the Isthmus of Tehuantepec, displaying a decreasing age trend from Paleocene in Colima to early Miocene in southeastern Oaxaca (Figure 1) (Morán-Zenteno *et al.*, 1999). These arc-related magmas were originated during subduction episodes along the Pacific margin previously or contemporaneously to the truncation of the continental margin by the displacement of the Chortis block (Ross and Scotese, 1988; Pindell *et al.*, 1988; Ratschbacher *et al.*, 1991; Herrmann *et al.*, 1994; Schaaf *et al.*, 1995; Morán-Zenteno *et al.*, 1999) or by subduction erosion processes (Keppie and Morán-Zenteno, 2005; Keppie *et al.*, 2007).

Several stratigraphic, geochemical and isotopic studies have been carried out in some cenozoic volcanic fields of the SMS in the last fifteen years (*e.g.*, Ferrusquía-Villafranca, 1992; 2001; Martínez-Serrano *et al.*, 1997; 1999; Morán-Zenteno *et al.*, 1998; 1999; 2004; 2007; Martiny *et al.*, 2000a; Alaniz-Álvarez *et al.*, 2002). These studies showed that volcanic rocks display a decreasing formation age, from 46 Ma in the NW part of the state of Guerrero to 15 Ma in the SE part of the state of Oaxaca. Geochemical and isotopic results of these rocks, from several regions, suggest a mantle source in the subcontinetal lithosphere that has been enriched by subduction components. Crystal fractionation magma processes associated with a moderate degree of old crustal involvement probably produced these magmatic rocks (Martiny *et al.* 2000a; Morán-Zenteno *et al.* 1998, 1999).

Several volcanic successions located in the southeastern SMS, in the regions of Etla, Mitla–Tlacolula and Nejapa (central and southeastern parts of the state of Oaxaca; Figure 1), display K-Ar ages that range from 22 to 15 Ma (Ferrusquía-Villafranca and McDowell, 1991; Iriondo *et al.*, 2004). However, their geochemical and isotopic characteristics, and their tectonic context are not well known. These volcanic sequences may represent the final magmatic events in the Sierra Madre del Sur before reappearing in the Trans-Mexican Volcanic Belt.

In this contribution, new petrographic, geochemical and isotopic data are provided for volcanic rocks of the Etla, Mitla–Tlacolula, and Nejapa regions, state of Oaxaca, in order to gain insight into the significance of these rocks in the tectonic evolution of southern Mexico during Miocene time.

GEOLOGICAL SETTING

Basement rocks and tectonic setting

The Cenozoic volcanic sequences in the central and southeastern parts of the state of Oaxaca cover two

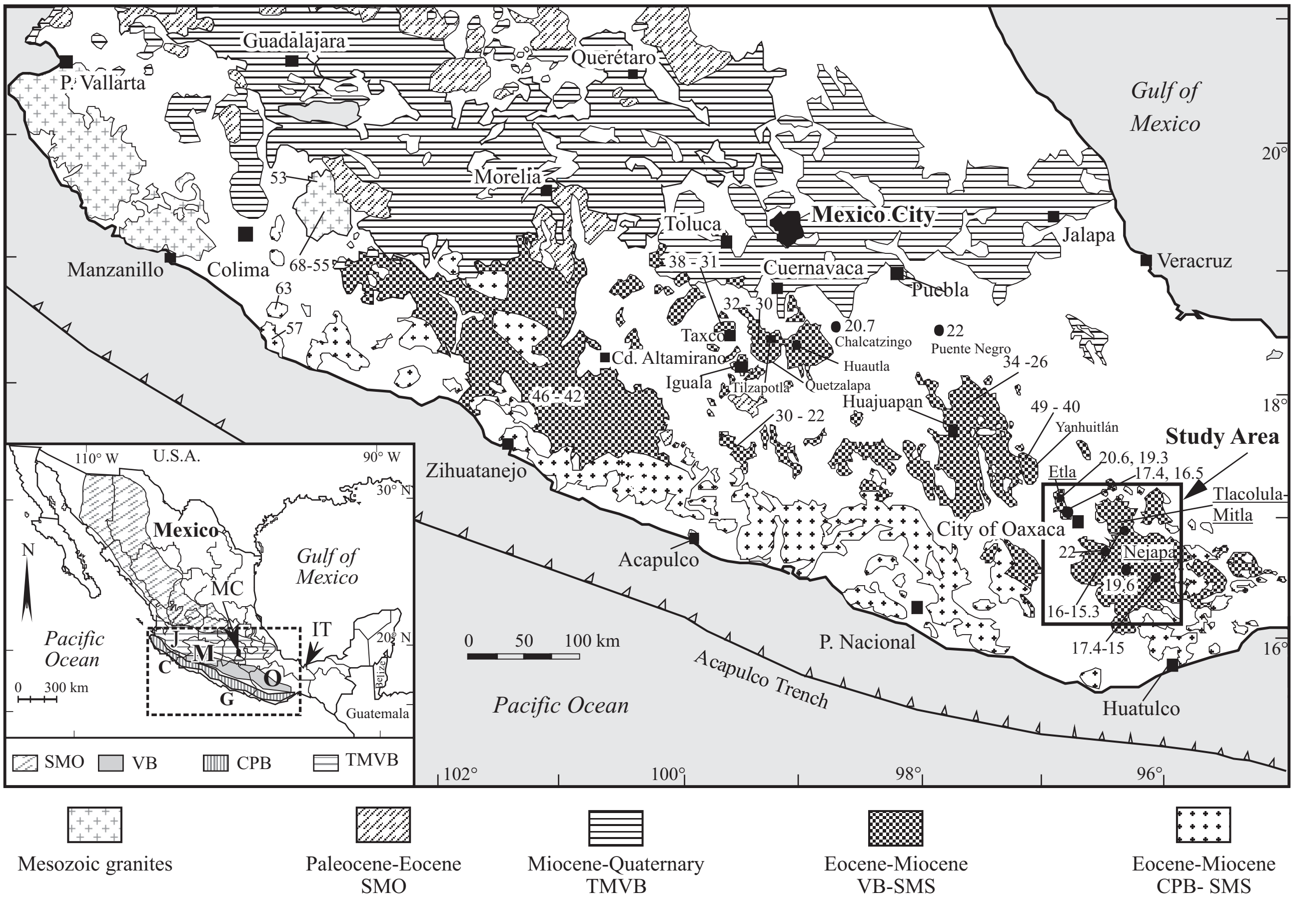

Figure 1. Cenozoic magmatic rocks of southern Mexico with some selected dates or age ranges in Ma. The study area is marked with a square. The inset displays the distribution of the main magmatic provinces in Mexico (SMO: Sierra Madre Occidental, VB: Volcanic Belt of the Sierra Madre del Sur (SMS), CPB: Coastal Plutonic Belt of the SMS, TMVB: Trans-Mexican Volcanic Belt). States: J: Jalisco, C: Colima, M: Michoacán, G: Guerrero, O: Oaxaca; MC: Mexico City, IT: Isthmus of Tehuantepec). Modified from Morán-Zenteno *et al.* (1999) with some additional ages from Iriondo *et al.* (2004), Martiny *et al.* (2004) and Rincón-Herrera *et al.* (2007).

major tectonostratigraphic terranes (Figure 2): the Oaxaca or Zapoteco terrane and the Cuicateco or Juárez terrane (Campa and Coney, 1983; Sedlock *et al.*, 1993). The oldest unit of the Oaxaca terrane is characterized by a granulite-facies metamorphic basement of Grenvillian age (900–1100 to 1300 Ma) (Ortega-Gutiérrez, 1981; Solari *et al.*, 2003) overlain by Paleozoic and Mesozoic sedimentary sequences, and Cenozoic sedimentary and volcanic rocks (Pantoja-Alor, 1970; Schlaepfer, 1970; López-Ticha, 1985; Ferrusquía-Villafranca, 1992; Morán-Zenteno *et al.*, 1999; Urrutia-Fucugauchi and Ferrusquía-Villafranca, 2001). The present-day ^{87}Sr/^{86}Sr and εNd isotopic values of the metamorphic Oaxaca complex generally range from close to those of bulk earth to 0.717 (although one paragneiss has a reported ^{87}Sr/^{86}Sr ratio of 0.750) and from -9 to -12, respectively (Patchett and Ruiz, 1987; Ruiz *et al.*, 1988a, 1988b).

The Juárez terrane (Ortega-Gutiérrez *et al.*, 1990; Sedlock *et al.*, 1993) is a west-dipping fault-bounded prism of strongly deformed Jurassic and Cretaceous oceanic and arc volcanic rocks that structurally overlies the Maya terrane and underlies the Oaxaca terrane. Many aspects of the geology and geochronology of this terrane are unresolved. It is composed of Mesozoic marine and continental sedimentary sequences, and intensively deformed volcanogenic strata thrusted to the east (Carfantan, 1986; Barboza, 1994, Nieto-Samaniego *et al.*, 2006). In the western margin of the Juárez terrane, the Etla area (north of the City of Oaxaca) is defined by a west-dipping NNW trending polygenic mylonitic shear zone, which was reactivated in Middle Jurassic and Cenozoic times (Alaniz-Álvarez *et al.*, 1996). No geochemical and isotopic data are available for rocks from this terrane. The Miocene volcanic rocks of the Etla and Mitla–Tlacolula regions cover part of the stratigraphic sequences from the Oaxaca and Juárez terranes whereas the volcanic products of the Nejapa region were probably emplaced over Grenvillian rocks of the Oaxaca terrane (Figure 2). The influence of theses old continental rocks in magma composition might be observed in neogenic volcanic rocks.

According to Nieto-Samaniego *et al.* (2006) the major cenozoic structures in central-southern Mexico (Figure 2)

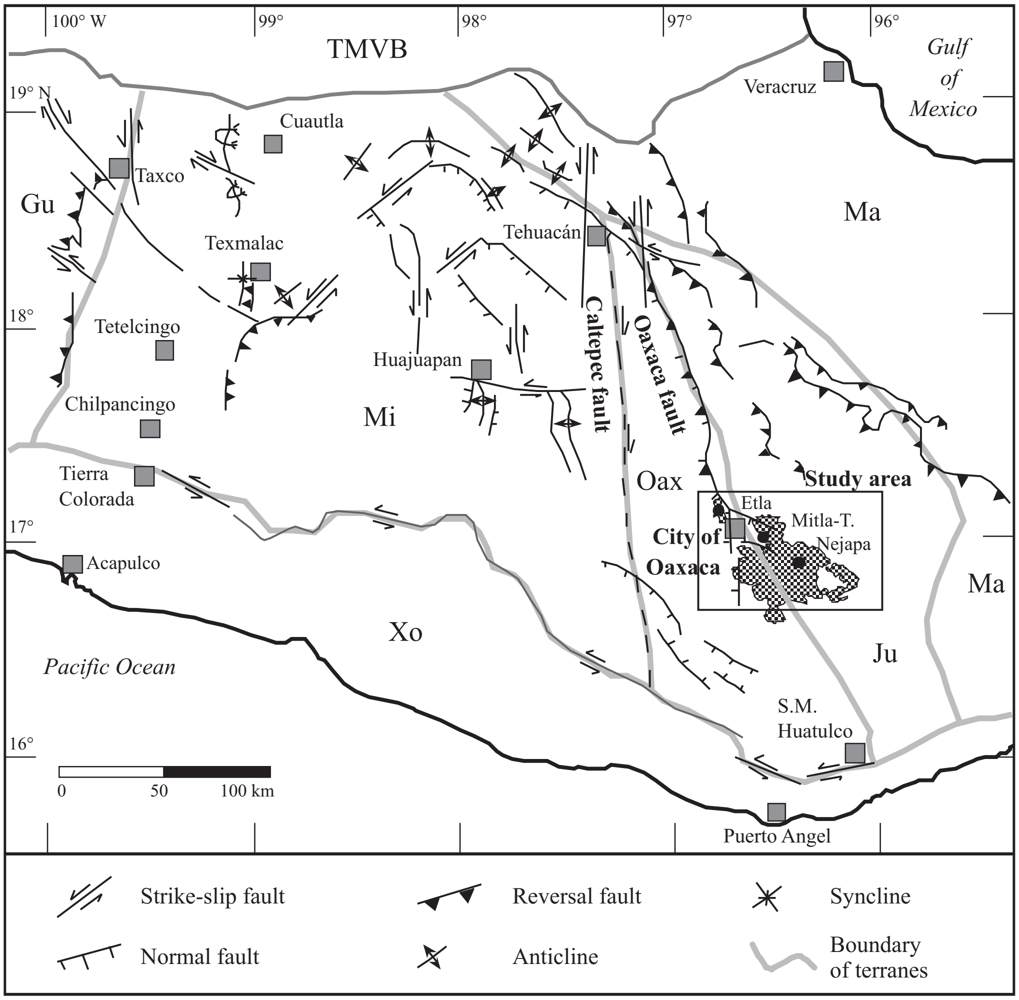

Figure 2. Schematic map of southern Mexico showing major Mesozoic-Cenozoic deformation domains. Main structures in the study area are also displayed. Gray lines indicate the distribution of tectonostratigraphic terranes after Campa and Coney (1983). Gu: Guerrero terrane, Mi: Mixteca terrane, Xo: Xolapa terrane, Oax: Oaxaca terrane, Ju: Juárez terrane, Ma: Maya terrane, and TMVB: Trans-Mexican Volcanic Belt (Modified from Nieto-Samaniego *et al.*, 2006).

were produced in three main successive tectonic events: the first event, in the late Cretaceous – middle Eocene, corresponds to the Laramide orogeny during which deformation migrated from west to east. The Oaxaca fault system, which bounds the Oaxaca and Juárez terranes, displayed significant activity during this orogeny. The second event produced strike-slip faulting during NE-SW horizontal shortening from Eocene to Oligocene time. The third event produced normal and strike-slip faults, indicating NE-SW horizontal extension during Oligocene-Miocene time. The major structures are roughly distributed along the borders of the main tectonostratigraphic terranes, but others are distributed within the terranes (Figure 2). In the Etla region, the NW-trending Oaxaca fault (Figure 2) exhibits a complex history of displacement beginning in the Paleozoic and followed by lateral motion in the Jurassic, although the sense of shear remains unknown (Alaniz-Álvarez *et al.*, 1996). Its most recent activity has been described as normal fault motion with the down-thrown block to the west. The Oaxaca fault shows normal displacement as recently as the late Cenozoic (Alaniz-Álvarez *et al.*, 1996). To the southeast of the Oaxaca fault, several E-W oriented graben structures were recognized by Morán-Zenteno *et al.* (1999), for which an early to middle Miocene age can be inferred on the basis of K-Ar dates of pyroclastic materials from the basin fill (Ferrusquía-Villafranca, 1992). The Mitla–Tlacolula region is found in one of these E-W grabens. Although structural and tectonic studies are lacking in the Nejapa region, Ferrusquía-Villafranca (2001) described the presence of NW-SE trending horst and graben structures.

The Cenozoic plate tectonic setting of southern Mexico is characterized by a predominantly convergent plate boundary, with several periods of oblique subduction and continental transform boundaries. Several authors proposed that the Paleocene-Miocene magmatic arc of the SMS was originated during subduction episodes along the Pacific margin previous to, and in part contemporary with, margin truncation attributed to the displacement of the Chortis block

(Mailfait and Dinkelman, 1972; Ross and Scotese, 1988; Herrmann *et al.*, 1994; Schaaf *et al.*, 1995, Meschede *et al.*, 1997). However, Keppie and Morán-Zenteno (2005) and Keppie *et al.* (2007) recently proposed a new model for the tectonic arrangement between the Chortis block and the Pacific margin of southern Mexico, in which Chortis was located southwest of its present position rather than off southwestern Mexico. These authors also suggested that the collision of the Chumbia Seamont Ridge with the Acapulco trench led to flattening of the subducting slab, inducing subduction erosion and exhumation of the southern Mexican margin.

Cenozoic stratigraphy

The Cenozoic volcanic rocks in the study area are distributed in isolated outcrops and in this work these rocks have been grouped in three regions: Etla, Mitla–Tlacolula and Nejapa. Figures 3 and 4 show a schematic geological map and composite stratigraphic columns for each region.

The Etla region

The Neogene volcanic sequences in the Etla region are exposed in discontinuous outcrops of lava flows, epiclastic-volcaniclastic deposits, lacustrine, and pyroclastic deposits emplaced in an elongated valley located to northwest of the city of Oaxaca (area A in Figure 3). This valley displays a NW-SE orientation and is bordered to the SW by metamorphic rocks of the Oaxaca complex (Grenvillian age) and to the NE by folded Mesozoic sedimentary rocks of the Juárez terrane. The limit of these two terranes is represented by the Oaxaca fault system that is over 150 km in length, and whose most spectacular expression is represented by a mylonitic belt in the Sierra de Juárez. Figure 4a summarizes the stratigraphic features of this region, where metamorphic rocks of the Oaxaca complex and sedimentary sequences of the Juárez terrane form the basement.

The Cenozoic sequences that have been dated are Miocene in age and lie unconformably on basement rocks,

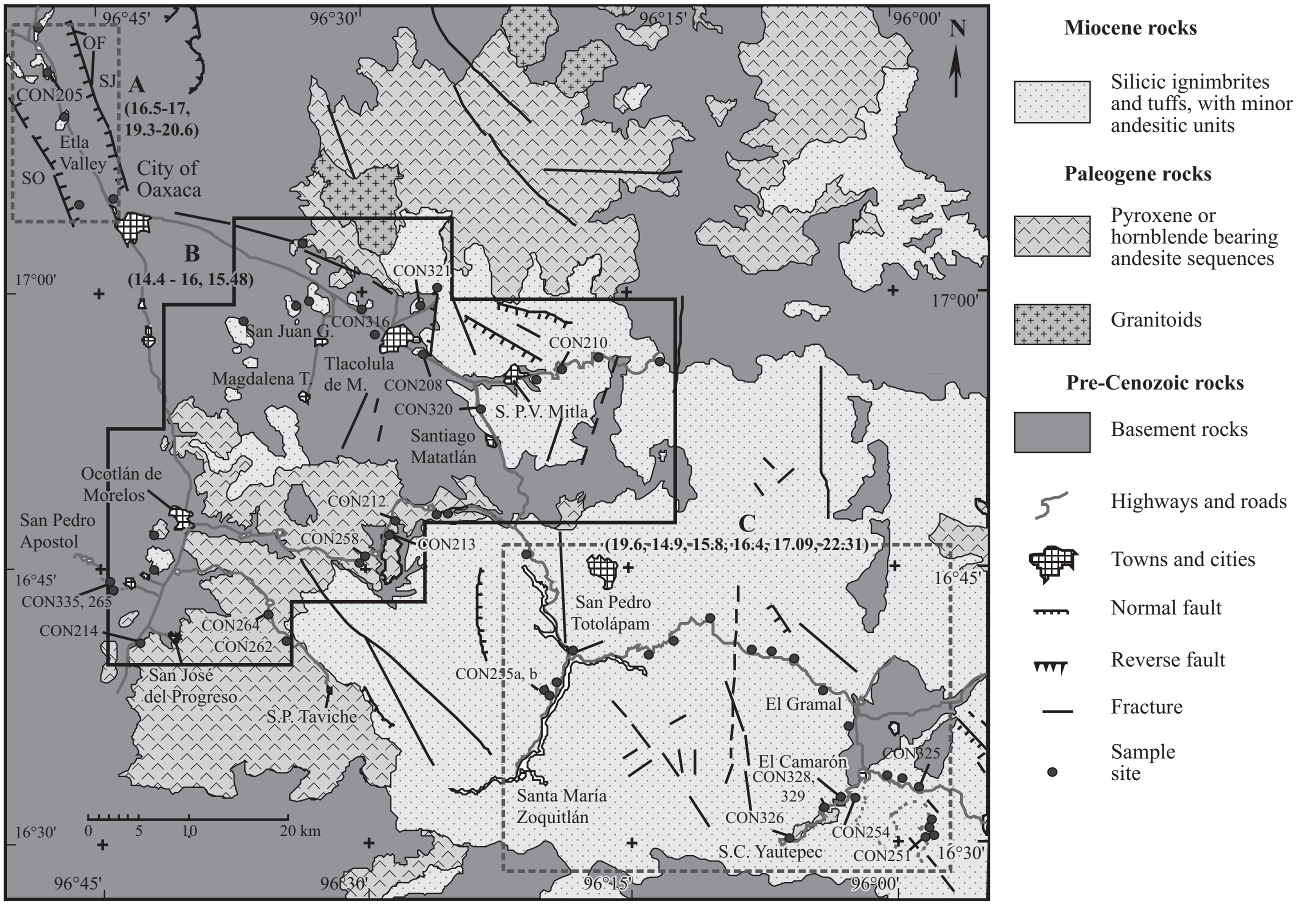

Figure 3. Schematic geological map of the study area in central and southeast Oaxaca showing Paleogene-Neogene volcanic sequences, general structural features and location of analyzed rocks (sample number indicated). A: Etla region, B: Mitla-Tlacolula region and C: Nejapa region, OF: Oaxaca Fault, SJ: Sierra de Juárez and SO: Sierra de Oaxaca. Numbers in parentheses refer to K-Ar ages (Ma) of volcanic sequences reported by: Ferrusquía-Villafranca *et al.* (1974), Urrutia-Fucugauchi and Ferrusquía-Villafranca (2001), Ferrusquía-Villafranca (1990), Ferrusquía-Villafranca (2001), Iriondo *et al.* (2004) and this work. Geology modified from Ferrusquía-Villafranca (1990) and (2001).

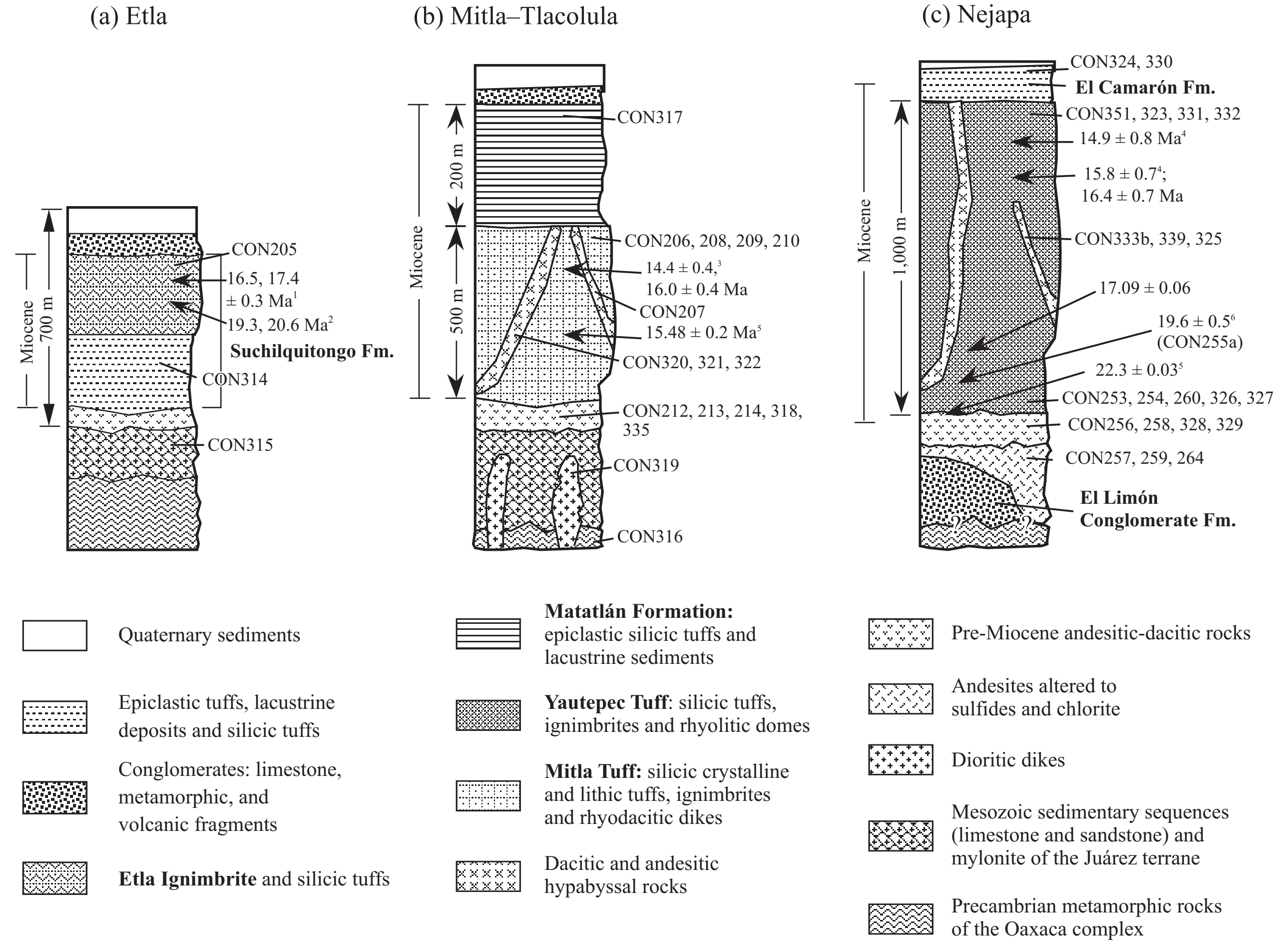

Figure 4. Composite stratigraphic columns for the volcanic sequences in central and southeast Oaxaca. K-Ar ages (Ma) of volcanic sequences are from (1): Ferrusquía-Villafranca *et al.* (1974), (2): Urrutia-Fucugauchi and Ferrusquía-Villafranca (2001), (3): Ferrusquía-Villafranca (1990), (4): Ferrusquía-Villafranca (2001), (5): Iriondo *et al.* (2004) and (6): this study.

having a mean thickness of 700 m (Ferrusquía-Villafranca, 1992 and Flores-Márquez *et al.*, 2001). Most Cenozoic sequences in the region are observed as tilted blocks in various directions (12º to 15º). It is possible that a main NW – SE 45º fault system produced this structural pattern (Flores-Márquez *et al.*, 2001). A first volcanic event in the region is composed of several isolated outcrops of pyroxene andesites that are highly altered to chlorite and clay minerals. The age and thickness of this unit are unknown but Ferrusquía-Villafranca (1990) proposed a Paleogene age based on its stratigraphic position. The Suchilquitongo Formation (Wilson and Clabaugh, 1970), composed of epiclastic tuffs, silicified lacustrine limestones and thick ignimbritic deposits, lies over the previously mentioned pyroxene andesites or directly over rocks from the metamorphic and sedimentary basement. This formation, with an estimated thickness of 300 m, is exposed as NW – SE elongated hills within the valley (Ferrusquía-Villafranca, 1990). It consists of two members. The first member is composed of intercalated thin layers (5–20 cm) of epiclastic tuffs, pyroclastic products and lacustrine deposits with angular to subangular detritic fragments (~1.5 mm in size) of quartz, feldspar, pumice, volcanic fragments, and iron oxides in a cryptocrystalline matrix. Some layers of silicic lacustrine limestones are present in the sequences. Ages of middle to late Miocene have been assigned on the basis of abundant vertebrate fossils found in the sedimentary sequence (Ferrusquía-Villafranca *et al.*, 1974). An important well-indurated ignimbritic succession, designated as the Etla Ignimbrite by Wilson and Clabaugh (1970), overlies the lacustrine and volcaniclastic deposits. This second member is composed of silicic pumice, volcanic fragments, quartz, feldspar and abundant biotite included in an altered glassy matrix. The thickness of the ignimbrite was estimated at 30 m and in some outcrops it is covered by ash-fall deposits. The source of the volcanic products is not known, but judging from the small thickness of deposits and their textures, it might be located outside of the Etla region. Ferrusquía-Villafranca *et al.* (1974) determined two K-Ar dates for the Etla Ignimbrite (16.5±0.5 and 17.4±0.3 Ma, although the material dated is not indicated). Subsequently, Urrutia-Fucugauchi and Ferrusquía-Villafranca (2001) reported three K-Ar biotite and plagioclase ages (from 19.2±0.5 to 20.5±0.3 Ma). A polymictic conglomerate about 70 m thick unconformably overlies the Suchilquitongo Formation. Even though its age is unknown, Urrutia-Fucugauchi and Ferrusquía-Villafranca (2001) proposed a Pliocene age. Important Quaternary alluvial deposits and soil (some tens of meters of thick) fill the Etla Valley covering the majority of the older rocks.

The Mitla–Tlacolula region

The Cenozoic volcanic rocks in the Mitla–Tlacolula region show a wider distribution in a valley with an almost E-W orientation (area B in Figure 3). This valley is bordered to the south by rocks of the Oaxaca complex and to the north by Mesozoic sequences. Figure 4b summarizes the stratigraphic features. Mesozoic and Cenozoic sedimentary and volcanic sequences cover most of the basement rocks in the region. However, some outcrops of gneiss and other metamorphic rocks, probably associated with the Oaxaca complex, have been observed near the town of Tlacolula (Sample CON316, Figure 4b). A thick sedimentary sequence (400 m) composed of fossil-bearing micritic marine limestones and intercalated shales overlies disconformably the metamorphic basement rocks. Ferrusquía-Villafranca (1990) proposed an Aptian-Cenomanian(?) age for this sequence. These rocks display different patterns of fractures and folds, and some silicic hypabyssal bodies are emplaced in the limestones, producing contact metamorphism with garnet, quartz, calcite, and sulfide mineralization.

Some isolated andesitic-dacitic lava flows and dikes lie on Mesozoic sedimentary rocks in the northern part of the Mitla–Tlacolula valley, but a larger volume of andesitic lava flows are observed to the south covering the Oaxaca terrane basement. In this area, the andesitic rocks are strongly altered to chlorite and clay minerals, and in some regions hydrothermal Cu, Fe and Pb sulfide mineralization is observed. Although the age of these volcanic products is not known because of their advanced alteration, a Paleogene age is proposed on the basis of their stratigraphic position.

Several ignimbritic and tuffaceous deposits were emplaced in discordance over Mesozoic sedimentary rocks and Paleogene volcanic rocks. These ignimbrites and tuffs were designated as the Mitla Tuff Formation (Ferrusquía-Villafranca, 1990), composed of two members. However, in the present study it is considered that the formation consists of several rhyolitic to rhyodacitic vitro-crystalline indurated tuffs, ignimbrites and also ash-fall deposits. The thickness of this volcanic sequence was estimated at 500 m. The ignimbrites display several horizontal plateaus in the Mitla–Tlacolula valley. Ferrusquía-Villafranca (1990) reported three K-Ar ages for this sequence that range from 14.4 ± 0.4 to 16 ± 0.4 Ma, although in his work it is not indicated the type of material dated nor its location. Iriondo *et al.* (2004) reported an ^{40}Ar/^{39}Ar age of 15.48 ± 0.2 for biotite in a rhyolitic tuff located in San Pedro Quiatoni. The Miocene volcanic sequence is affected by normal fault systems producing several tilted blocks. The source of volcanic rocks in this region is not known but it is considered to be near the valley given their great thickness. Some hypabyssal dikes or eroded volcanic necks 0.5 to 2 km in diameter were observed and sampled in the area.

The Matatlán Formation unconformably covers the Mitla Tuff Formation and other older sequences. It is composed of epiclastic deposits and some ash-fall deposits emplaced in the Mitla–Tlacolula Valley and can attain a thickness of 200 m. Mammal fossils were identified in this formation by Ferrusquía-Villafranca *et al.* (1974) suggesting early to middle Miocene ages. These paleontological ages are in disagreement with the K-Ar ages previously indicated. A Pliocene conglomerate covers some parts of the valley, and alluvial deposits and soil fill the region.

The Nejapa region

The Cenozoic volcanic and continental sedimentary sequences are broadly distributed in this region (Figure 3c) and in some areas reach a total thickness of almost 1,500 m. The stratigraphic characteristics of this region are summarized in Figure 4c. Some rocks from the basement were identified in discontinuous and rare outcrops southwest of the town of El Camarón (Figure 3c). Granulites containing pyroxene, plagioclase and biotite are the main rocks of these outcrops and could be associated with metamorphic sequences of the Oaxaca complex. Ferrusquía-Villafranca (2001) described the El Limón Conglomerate Formation, with coarse-grained metamorphic and limestone fragments included in a fine-grained matrix of silt and sand cemented by calcium carbonate. The estimated thickness of this formation is about 900 m and it overlies unconformably the metamorphic basement of the region. This formation has been observed as elongated hills in the central part of the region. These hills actually represent tilted blocks of conglomerates affected by NW-SE fault systems. The age of this formation is not known but Ferrusquía-Villafranca (2001) considered it as Paleogene because of the presence of Late Cretaceous lithic limestones in the conglomerate. Pyroxene-hornblende andesitic lava flows with moderate hydrothermal alteration to clay minerals, chlorites and some sulfides were identified in some outcrops from the SW part of the region (Santa Maria Zoquitlán, Figure 3c). These altered volcanic rocks lie directly on the metamorphic basement in some areas, but in others they cover the El Limón Conglomerate Formation. Their ages are unknown but the stratigraphic position suggests a Paleogene age. A basaltic-andesite to andesite sequence, composed of some lava flows, cinder cone breccias, and hypabyssal bodies, has been observed in some outcrops overlying the hydrothermal altered volcanic rocks. Plagioclase, pyroxene and olivine phenocrysts included in a glassy matrix are the main components of these rocks. The total thickness of the sequence is not established but in some areas near the town of Yautepec, it can attain 15 m. Its age is probably early Miocene because it underlies in concordance the Yautepec Tuff Formation. An ^{40}Ar/^{39}Ar age of 22.31 ± 0.03 (volcanic matrix) was determined by Iriondo *et al.* (2004) for an andesite next to the Totolapan area (east of the region).

The most voluminous and widespread stratigraphic unit observed in the region is made up of silicic ignimbrites, several pyroclastic deposits and rhyolitic-rhyodacitic domes. This sequence was denominated by Ferrusquía-Villafranca (2001) as the Yautepec Tuff Formation and it can attain more than 1,000 m in thickness. These volcanic rocks and pyroclastic deposits conform most mountains and plateaus in the region, overlying in discordance the oldest formations (Figure 4c). The Yautepec Tuff is composed of at least three tabular bodies (Ferrusquía-Villafranca, 2001) that display different morphological expressions. The first and oldest body is represented by limited exposures of moderately welded ignimbritic deposits with pumice and lithic fragments included in volcanic ash. The intermediate body has the greatest thickness in the area (~600 m) and is composed of ignimbrites and other pyroclastic deposits displaying cross stratification. The main components are abundant pumice and lithic fragments, and broken quartz, feldspar and biotite crystals in volcanic ash. These deposits form most plateaus and mountains in the area. Finally, the third body is lesser known and is composed of thin pyroclastic deposits overlying the ignimbrites. The composition of these bodies is predominantly rhyolitic with abundant subhedral to anhedral crystals of plagioclase (oligoclase-andesine), quartz, sanidine, biotite, and some pyroxenes, which are associated with pumice and lithic fragments in a silicic glassy matrix. The volcanic sequence has inclinations in several directions ranging from 15 to 40º as a result of at least two main fault systems with orientations of NW-SE 65º and SW-NE 25º. These structures have produced blocks tilted in different directions forming several horst and grabens. The sources of the volcanic deposits have not been identified yet because the block tilting has destroyed original volcanic structures. However, the textures and structures of the deposits suggest the idea that these sources were relatively nearby. The emplacement ages of the pyroclastic rocks were assigned to the middle Miocene by means of mammal fossils found in the lower body of the formation (Ferrusquía-Villafranca 1990). K-Ar determinations indicate ages of 15.82 ± 0.70 to 16.47 ± 0.7 Ma for the basal units and 14.96 ± 0.85 Ma for plagioclase and biotite in an upper silicic tuff (Ferrusquía-Villafranca, 2001). More recently, ^{40}Ar/^{39}Ar age determinations of 17.09 ± 0.06 (plagioclase) and 17.51 ± 0.05 (volcanic matrix) were obtained by Iriondo *et al.* (2004) for a porphyric andesite, next to the Totolapan area. In this work, a K-Ar age of 19.6 ± 0.5 Ma was obtained for a rhyolitic vitrophyre (whole rock) at the base of the volcanic unit (sample CON255A: 96º19'10.8"W, 16º38'13"N, K = 3.673%, ^{40}Ar = 0.005015). These values confirm the early to middle Miocene ages of emplacement for the silicic and some andesitic rocks, but more isotopic ages are required to define the age range of the volcanic events in the region. In several outcrops, dikes and hypabyssal bodies of andesitic to dacitic composition intrude the Yautepec Tuff Formation. These intrusive bodies were also sampled and they display porphyritic to aphanitic textures with plagioclase and pyroxene phenocrysts included in a glassy matrix. Even though the age of emplacement of these magmatic bodies is unknown, their position with respect to the Yautepec Tuff and the upper units (the El Camarón Formation) might suggest a middle Miocene age.

The El Camarón Formation (Ferrusquía-Villafranca, 2001), composed of epiclastic, fluvial and lacustrine deposits, covers in discordance the Yautepec Tuff in basins and valleys in the central portion of Nejapa region. The main deposits attain 200 m in thickness and are composed of volcaniclastic sandstones, although the grain size of the fragments varies from boulders to sand and silt, with predominance of quartz, feldspar, biotite and iron oxides, and minor volcanic lithics. The variable dips displayed by these deposits give evidence of the existence of regional fault systems. The abundant presence of terrestrial mammal fossils in the lower levels of this formation suggests a middle Miocene emplacement age (Ferrusquía-Villafranca, 2001). Finally, Quaternary alluvial and soil deposits cover the older rocks in the valleys.

SAMPLE SELECTION AND ANALYTICAL METHODS

The Neogene volcanic sequence and basement rocks were sampled during several fieldwork campaigns in the Etla, Mitla–Tlacolula and Nejapa regions. In order to determine the petrographic and geochemical variations of the stratigraphic sequences, lava flows, ignimbrites, pyroclastic deposits and hypabyssal intrusions were sampled in each region. Thin sections of more than 45 sampled rocks were studied to determine the mineralogy and petrography, and fresh samples were selected for bulk chemical analyses and Sr and Nd isotopic determinations. Major-elements and Sc abundances of 12 representative samples were determined by inductively couple plasma emission, and all other trace elements, including the rare earth elements, by inductively coupled plasma mass spectrometry (ICP-MS) in the analytical laboratories of the Centre de Recherches Pétrographiques et Géochimiques (CRPG), Centre National de Recherches Scientifiques (CNRS), in Nancy, France (SARM, 2004). The following errors are reported: <3% for major elements and <10% for trace elements. ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd isotopic ratios of 12 whole rock samples were measured using a Finnigan MAT-262 thermal ion mass spectrometer at LUGIS (Laboratorio Universitario de Geoquímica Isotópica), UNAM. The spectrometer is equipped with a variable multicollector system (eight faraday cups) and all measurements were made in static mode. Sr and Nd samples were loaded as chlorides on double rhenium filaments and measured as metallic ions. Sixty isotopic ratios were determined for Sr and Nd on each sample. Elements were separated using standard ion-exchange methods. Total procedure blanks during analysis of these samples were less than 10 ng Sr and 20 ng Nd.

A volcanic rhyolitic glass sample (CON255a) was prepared for K-Ar measurements and analyzed by Geochron Laboratory Division of Krueger Enterprises, Inc. Data results were indicated in a previous section (Nejapa region).

GEOCHEMICAL RESULTS

Petrographic characteristics

Table 1 shows the modal mineralogical analyses and petrography of the majority of the samples. The first Cenozoic volcanic sequence in the study area shows a predominantly andesitic composition, although basaltic andesites have also been observed. Aphanitic to porphyritic textures are present, with phenocrysts (~1mm) of plagioclase, orthopyroxene and clinopyroxene, hornblende with oxide reaction rims, and some olivine. The groundmass is composed of microlitic plagioclase, clinopyroxene, olivine in trace amounts, Fe-Ti oxides and andesitic glass. Most andesitic rocks are strongly altered (20 to 55 vol. %) to clay minerals, chlorite and in some cases to sulfides.

The early to middle Miocene pyroclastic sequences in the three regions display a predominantly rhyolitic-rhyodacitic composition with broken crystals (1-2 mm) of plagioclase (oligoclase-andesine), K-feldspar, quartz and some biotite included in a glassy matrix (Table 1). However, ignimbritic deposits in the Nejapa region are more voluminous than in the Mitla-Tlacolula region, where crystal-vitric tuffs with at least 50 to 60 vol. % of crystals predominate. The groundmass is composed of silicic glass (>27 vol. %) with a low to moderate degree of alteration to clay minerals, chlorite and quartz (from 1 to 10 vol. %). Quartz and feldspar are intergrown in spherulitic structures in these silicic rocks. Hypabyssal intrusions emplaced in the pyroclastic sequences display andesite to basaltic andesite composition, with porphyritic to microlitic textural variations. The degree of alteration to clay minerals of these intrusive rocks is relatively low (<10 vol. %).

Major and trace element geochemistry

Table 2 shows major and trace element concentrations determined in Neogene volcanic rocks for the three

Table 1. Modal mineral assemblages (vol. %) of selected lava, dike and pyroclastic samples.

Sample	Phenocrysts								Groundmass				Alteration	Total	Rock type
	Pl (An_{32-54})	Kfs	Hbl	Opx	Cpx	Bt	Ol	Qtz	Plg (Ab_{32-54})	Kfs	Ox	Glass			
Etla and Mitla–Tlacolula regions															
CON205	2	1	0	0	0	4	0	1	T	T	T	83 (Silicic)	9 (clay+Chl)	100	Rhyolitic ignimbrite
CON210	40	3	0	0	0	6	0	10	5	4	1	30 (Silicic)	1 (clay)	100	Rhyolitic tuff
CON208b	35	2	0	0	0	4	0	12	3	2	1	40 (Silicic)	1 (clay)	100	Rhyolitic tuff
CON213	25	0	0	3	7	0	0	0	40	0	3	16 (And)	6 (clay+Chl)	100	Andesite
CON214	20	0	5	2	2	0	0	0	41	0	5	0	25 (clay+Chl)	100	Andesite
CON265	25	0	5	5	3	1	0	0	44	0	4	8 (And)	5 (clay+Cc)	100	Andesite
CON320	7	0	0	0	0	0	0	0	43	~10	5	0	35 (clay+Qtz)	100	Dacitte
CON321	30	0	0	0	7	0	0	0	40	0	6	7 (And)	10 (Cc+Chl)	100	Andesite
CON335B	15	0	1	5	0	0	0	0	52	10	5	8 (And)	4 (Qtz+clay)	100	Dacite
Nejapa region															
CON251	20	5	0	T	T	5	0	7	15	10	1	27 (Dev)	10 (clay)	100	Rhyolitic ignimbrite
CON254	15	3	0	0	0	4	0	5	15	10	1	37 (Dev)	10 (clay)	100	Rhyolitic ignimbrite
CON255b	30	0	0	7	4	0	T	0	40	0	4	8 (And)	7 (clay)	100	Andesite
CON258	10	0	0	0	4	0	0	0	10	0	6	15 (Dev)	55 (clay+Cc+Chl)	100	Andesite
CON262	8	0	0	0	0	0	0	0	16	0	8	18 (Dev)	50 (Cc)	100	Andesite
CON264	15	0	4	0	0	0	0	0	35	0	6	20 (Dev)	20 (Cc+Chl+clay)	100	Andesite
CON323	2	1	0	0	0	2	0	3	2	1	2	83 (Silicic)	4 (Cc)	100	Rhyolitic tuff
CON326	10	5	1	0	0	4	0	10	0	0	0	70 (Silicic)	T (clay)	100	Rhyolitic vitrophyre
CON328	10	0	0	5	7	0	7	0	50	0	6	10 (Dev)	5 (clay+Cc)	100	Basaltic andesite
CON329	25	0	0	4	5	0	0	0	40	0	5	20 (Interm)	1 (clay)	100	Andesite

Pl: Plagioclase, Kfs: K-feldspar, Hbl - hornblende, Opx: orthopyroxene (hypersthene), Cpx: clinopyroxene (augite-diopside), Bt: biotite, Ol: olivine, Qtz: quartz, Ox: Fe-Ti oxides; And: andesitic; Dev: devitrification; clay: clay minerals, Chl: chlorite, Cc: calcite, T: traces, . The modal mineral assemblages were obtained with around 1,000 count points in thin section.

Table 2. Major oxide and trace element abundances of volcanic rocks from central and eastern Oaxaca (A: andesite, B-A: basaltic andesite, D: dacite, R-I: rhyolitic ignimbrite, R-T: rhyolitic tuff, R-V: rhyolitic vitrophyre, t = trace).

	Etla and Mitla–Tlacolula regions						**Nejapa region**		
Sample	CON205	CON208b	CON210	CON212B	CON213	CON320	CON335b	CON255	CON325
Rock	R-I	R-T	R-T	B-A	A	D	D	R-V	A
Long. W	96º48’27”	96º27’29”	96º18’56”	96º28’27”	96º28’44”	96º22’51”	96˚43’53”	96˚20’03”	96˚05’53”
Lat. N	17º14’02”	16º56’54”	16º55’49”	16º47’26”	16º46’54”	16º52’19”	16˚43’39”	16˚38’06”	16˚29’59”
(wt. %)									
SiO_2	66.92	67.98	66.75	54.93	57.16	68.90	65.33	68.86	53.71
TiO_2	0.14	0.37	0.41	1.12	1.05	0.40	0.73	0.22	1.37
Al_2O_3	12.37	14.94	15.34	16.06	16.88	16.01	14.86	13.81	17.72
Fe_2O_3	1.22	2.19	2.59	7.59	7.03	3.03	5.08	2.77	8.84
MnO	t	t	t	0.09	0.11	0.05	0.06	0.05	0.11
MgO	0.79	0.61	0.68	6.11	4.18	0.28	1.36	0.26	3.94
CaO	1.45	3.33	3.14	7.31	6.71	2.19	4.10	1.18	7.79
Na_2O	2.85	3.36	3.16	3.52	3.61	4.63	3.16	3.53	3.51
K_2O	2.09	2.17	2.77	1.26	1.92	3.32	2.61	4.37	1.26
P_2O_5	t	0.12	0.11	0.25	0.21	0.11	0.16	0.06	0.31
L.O.I.	12.06	4.81	4.93	1.72	1.07	1.00	2.66	5.23	1.38
Total	99.90	99.89	99.89	99.96	99.93	99.92	100.11	100.34	99.94
Trace elements (ppm)									
V	14.98	22.31	27.11	167.32	159.29	10.37	69.97	2.17	186.12
Cr	4.78	3.33	1.57	307.37	99.93	0.20	76.77	2.69	125.04
Co	0.72	2.37	3.10	29.49	20.07	1.59	11.94	1.12	23.99
Ni	2.50	2.64	4.46	97.03	22.50	1.72	15.85	1.78	39.81
Cu	2.83	3.63	5.12	30.99	18.44	3.10	16.31	4.65	13.66
Zn	33.47	47.24	65.90	107.82	106.58	72.45	61.25	76.12	120.01
Rb	103.99	98.84	86.34	27.51	58.74	103.22	83.40	208.40	30.67
Sr	364.47	556.69	483.29	499.97	450.45	327.99	464.22	126.20	578.92
Y	18.10	8.37	10.47	19.43	23.79	22.41	18.06	23.18	17.21
Zr	118.65	148.55	172.52	165.23	183.90	297.04	170.89	295.07	171.00
Nb	7.32	4.98	5.69	7.00	7.21	11.17	6.61	10.04	7.10
Ba	901.17	667.02	694.52	418.59	490.01	855.17	570.35	833.69	450.71
La	32.18	25.08	23.79	15.93	19.36	35.47	22.72	32.57	18.53
Ce	67.22	47.75	44.58	38.25	43.88	72.25	50.89	66.41	41.37
Pr	7.76	5.33	4.98	4.65	5.32	8.36	6.07	7.61	5.64
Nd	27.93	18.85	18.30	21.12	22.05	29.39	23.49	27.75	25.46
Sm	5.07	3.14	3.20	4.94	5.39	5.16	4.74	5.47	5.12
Eu	0.84	0.95	0.97	1.36	1.35	1.23	1.11	0.91	1.66
Gd	3.79	2.16	2.40	4.17	4.18	4.16	3.79	4.44	4.25
Tb	0.57	0.29	0.33	0.61	0.70	0.59	0.56	0.71	0.58
Dy	3.16	1.54	1.80	3.54	3.92	3.09	3.22	3.84	3.11
Ho	0.57	0.28	0.32	0.65	0.77	0.63	0.63	0.74	0.62
Er	1.50	0.77	0.93	1.81	2.11	1.81	1.76	2.23	1.47
Tm	0.25	0.10	0.14	0.28	0.33	0.27	0.24	0.31	0.18
Yb	1.89	0.76	0.89	1.76	2.09	1.81	1.59	2.20	1.22
Lu	0.25	0.11	0.12	0.28	0.30	0.27	0.22	0.31	0.17
Hf	4.09	3.71	4.14	4.09	4.57	6.43	4.44	7.11	3.77
Ta	0.87	0.43	0.50	0.58	0.64	0.99	0.65	1.03	0.50
Th	14.36	6.29	6.77	2.78	5.29	10.35	11.26	12.29	2.94
U	3.20	0.96	0.71	0.72	1.55	2.85	2.07	3.83	0.74
Pb	7.38	9.98	11.60	8.62	20.06	20.65	12.53	25.58	7.99
Ga	17.12	19.25	20.54	21.81	20.89	20.17	18.23	19.03	22.30

Table 2 (continued).

	Nejapa region		
Sample	CON326	CON328	CON329
Rock	R-T	B-A	A
Long. W	96°06’02”	96°03’22”	96°04’12”
Lat. N	16°29’52”	16°32’10”	16°43’39”
(wt. %)			
SiO_2	73.92	52.87	53.06
TiO_2	0.12	1.18	1.13
Al_2O_3	12.55	18.12	17.96
Fe_2O_3	1.32	9.04	8.82
MnO	0.03	0.22	0.14
MgO	0.18	3.87	5.41
CaO	0.90	8.66	8.58
Na_2O	2.78	3.21	3.10
K_2O	5.00	1.40	1.37
P_2O_5	0.02	0.21	0.23
L.O.I.	3.16	1.57	0.70
Total	99.98	100.35	100.50
Trace elements (ppm)			
V	6.79	220.18	204.41
Cr	1.64	103.59	70.28
Co	1.18	29.71	24.69
Ni	1.37	23.40	21.82
Cu	2.55	15.19	17.13
Zn	32.41	108.20	103.91
Rb	217.21	36.80	41.68
Sr	71.60	590.75	566.34
Y	12.05	24.03	23.38
Zr	92.38	134.54	125.48
Nb	6.80	6.47	6.33
Ba	466.97	602.48	380.15
La	28.01	14.61	16.06
Ce	54.31	36.11	34.12
Pr	5.08	4.73	4.53
Nd	15.22	19.56	19.79
Sm	2.39	4.91	4.41
Eu	0.37	1.45	1.33
Gd	2.02	4.52	4.26
Tb	0.30	0.67	0.66
Dy	1.78	4.39	3.96
Ho	0.37	0.90	0.81
Er	1.12	2.21	2.21
Tm	0.17	0.35	0.34
Yb	1.48	2.32	2.38
Lu	0.23	0.37	0.36
Hf	3.16	3.54	3.38
Ta	1.18	0.56	0.56
Th	25.11	4.72	4.63
U	6.28	1.55	1.52
Pb	24.07	12.89	15.24
Ga	15.18	21.50	20.91

regions: Etla, Mitla–Tlacolula and Nejapa. Because no previous chemical data exist for these rocks, some comparisons have been made with chemical results from volcanic rocks of nearby areas in the Sierra Madre del Sur such as western Oaxaca (Martiny *et al.*, 2000a) and NE Guerrero (Morán-Zenteno *et al.*, 1998). Chemical classification of the rocks is given in the SiO_2 *vs.* alkalis diagram in Figure 5a (Le Maitre *et al.*, 1989). All volcanic rocks analyzed were classified on an anhydrous basis. The volcanic products of the three regions vary from basaltic andesites to rhyolites, but a bimodal pattern is observed for these rocks. A first group of rocks ranges from 53.17 to 57.82 wt. % SiO_2 (basaltic-andesite to low SiO_2 andesite), whereas the second group varies from 67.04 to 76.35 wt. % (silicic dacite to rhyolite). No SiO_2 concentrations between 58 and 67 wt. % were observed in the samples from the study area. Although the small number of chemical analyses could bias this bimodal pattern, the petrographic descriptions of more than 45 samples indicate a predominance of basaltic-andesites, andesites and rhyolites with a remarkable absence of dacites. All volcanic rocks are subalkaline (Figure 5a) as defined by Irvine and Baragar (1971), lack iron enrichment, and display a typical calc-alkaline trend in the AFM diagram of Figure 5b. This is equivalent to the low- to medium-Fe suite proposed by Arculus (2003). Chemical data of volcanic rocks from Martiny *et al.* (2000a) and Morán-Zenteno *et al.* (1998) display patterns similar to those of our data (Figure 5a) although without the bimodal distribution in SiO_2. Oligocene volcanic rocks from the NE Guerrero area have rhyolitic, andesitic and dacitic compositions [from 57 to 76 wt. % SiO_2 with a wide dispersion in alkalis (Na_2O+K_2O)] while no basaltic-andesites were observed. The volcanic rocks of western Oaxaca (Oligocene age) range in composition from basaltic andesites to dacites (53 to 67 wt. % SiO_2), and rhyolitic tuffs were described at the base of the succession.

Negative correlations have been observed between SiO_2 (wt. %) and TiO_2, CaO and MgO (wt. %) in rock samples from the study area (Figure 6), although a certain amount of dispersion is present. Samples from NE Guerrero and western Oaxaca are also reported in various diagrams for comparison. Some samples from the Nejapa region (CON325, 328) and others from the western Oaxaca display relatively high (1.19, 1.39 wt. %) TiO_2 concentrations, which is not common in calc-alkaline magmas. The K_2O contents of the magmatic rocks in the study area are typical of calc-alkaline series, with a positive correlation with respect to SiO_2 (Figure 6), and with Nb contents smaller than 12 ppm.

A multielement diagram for trace elements is shown in Figure 7. Trace-element patterns for andesites and rhyolites are similar, with enrichment in large-ion lithophile elements (LILE) relative to high-field-strength elements (HFSE). This enrichment is typical of calc-alkaline volcanic arcs. All rocks display negative Nb, Ta, P and Ti anomalies that are also characteristic of subduction-related magmas (*e.g.*,

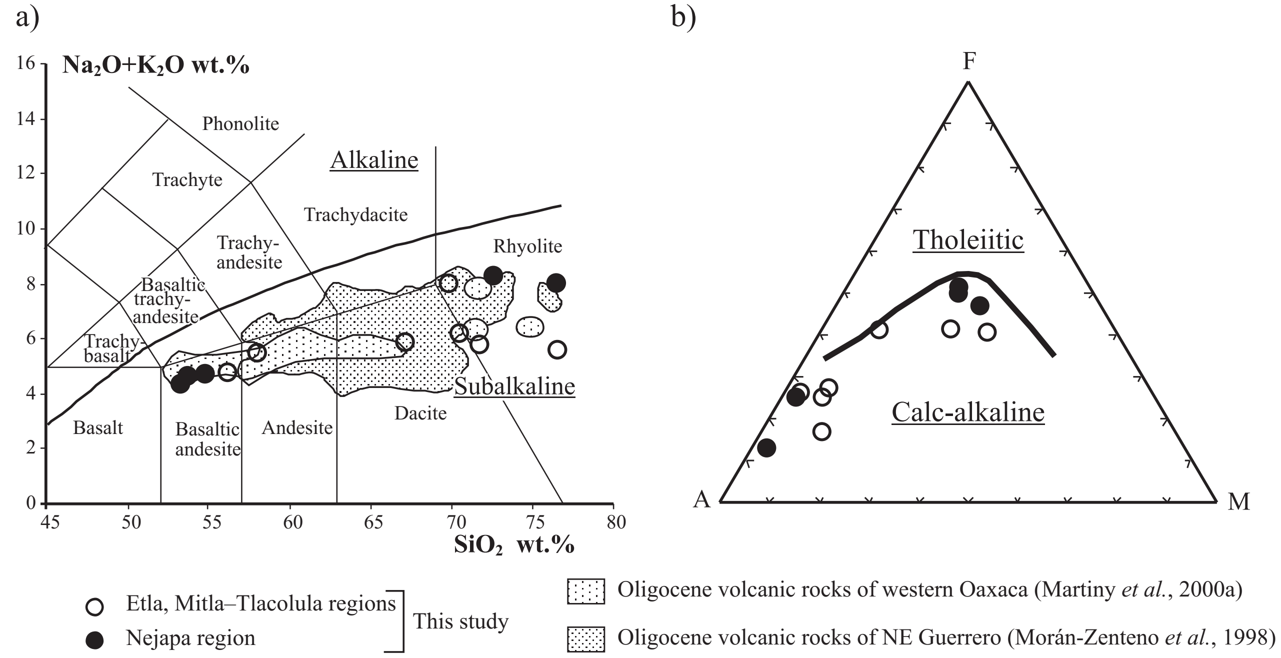

Figure 5. a: SiO_2 *vs.* total alkalis (Na_2O+K_2O) diagram (Le Maitre *et al.*, 1989) for Cenozoic volcanic rocks of central and southeastern Oaxaca. Division between alkaline and subalkaline fields is from Irvine and Baragar (1971). b: Analyzed samples plot in the calc-alkaline field of the AFM diagram, A: Na_2O+K_2O, F: $Fe_2O_{3\,T}$ and M: MgO.

Gill, 1981; Walker *et al.*, 2001). In Figure 7, trace element patterns are variable for each sample because each analyzed sample represents a different volcanic unit in the study area, and thus a different magmatic process. The patterns of the immobile elements (Nb, Hf, Zr, Ti, Y and Yb) in the variation diagram and the enrichment in LILE suggest a depleted mantle source in the subcontinental lithosphere modified by subduction fluids, which have added the more mobile elements (Rb, Ba, K, and Pb) (Pearce, 1983; Wilson, 1989). The volcanic sequences in the study area have Ba/Nb ratios that range from 17 to 28 and La/Nb from 2.3 to 5. These ratios are similar to those found in volcanic rocks from western Oaxaca and are typical of calc-alkaline lavas from other convergent plate boundaries (Gill, 1981).

The rare earth element (REE) abundances of the andesites and rhyolites from the study area show similar trends. Chondrite-normalized REE patterns display light rare earth element enrichment (LREE: La-Sm) and relatively flat patterns for the heavy rare earth elements (HREE: Tb-Lu) (Figure 8). All rhyolitic samples and one andesite (CON335b) exhibit moderate to slight negative Eu anomalies indicating some degree of plagioclase fractionation, where the plagioclase probably crystallized first and was substantially removed from magmas before their ascent to the surface. This is consistent with Na_2O and Al_2O_3 concentrations that are almost constant or display a slight decrease with SiO_2 contents (diagrams SiO_2 *vs.* Na_2O and Al_2O_3 not shown). Andesites show slightly lower REE concentrations in comparison to rhyolites. This is commonly observed in continental volcanic arcs, in which abundances of incompatible trace elements (HFSE and REE) typically increase with SiO_2. However, assimilation and crystallization processes (AFC; DePaolo, 1981) can not be discarded. Similar trace element patterns are observed for volcanic rocks from western Oaxaca (Martiny *et al.*, 2000a) and NE Guerrero (Morán-Zenteno *et al.*, 1998).

ISOTOPIC RESULTS

Isotopic analyses of Sr and Nd are given in Table 3 for several volcanic samples from the study area. Initial $^{87}Sr/^{86}Sr$ ratios of the Etla and Mitla–Tlacolula samples are relatively high (0.70472 – 0.70659) compared to those of the Nejapa region (0.70352 – 0.70482). Initial εNd values obtained for the volcanic rocks of the Etla and Mitla–Tlacolula regions range from -1.84 to +1.75 and in the Nejapa region from +0.52 to +1.42 (Table 3). Figure 9 shows the initial Sr – Nd isotopic ratios for rock samples from the study area and other volcanic regions of the Sierra Madre del Sur (SMS): western Oaxaca and northeastern Guerrero (Martiny *et al.*, 2000a and Morán-Zenteno *et al.*, 1998, respectively). Considering the isotopic heterogeneity of the crust in central and southeastern Oaxaca, the narrow ranges (without considering sample CON 326) and generally low $^{87}Sr/^{86}Sr_i$ ratios and εNd_i values near and mostly above that of bulk earth, suggest a relatively low degree of crustal contamination for volcanic rocks of the Nejapa region. In contrast, the initial Sr and Nd isotopic values for the Etla and Tlacolula sites are more variable and lower than those of bulk earth, possibly indicating more

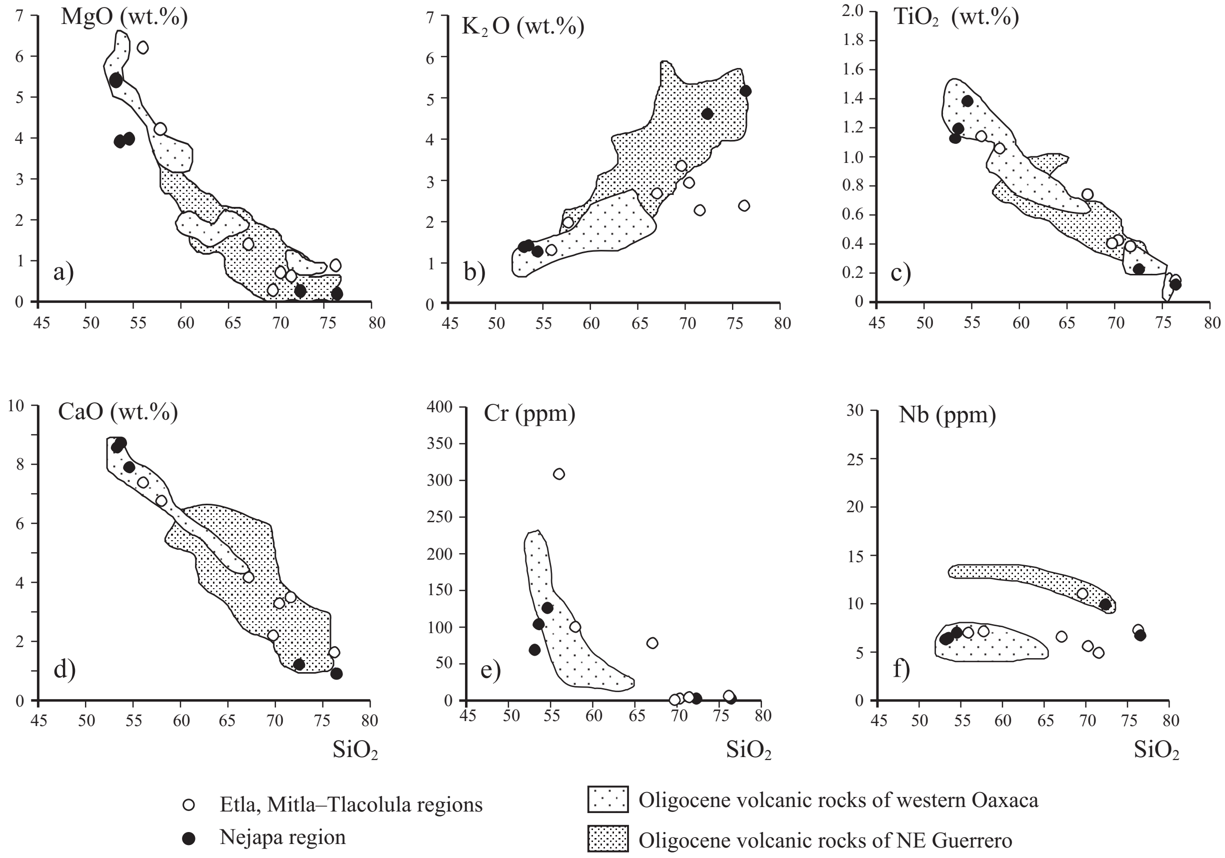

Figure 6. Variation diagrams for SiO_2 (wt.%) *vs.* (a) MgO (wt.%), (b) K_2O (wt.%), (c) TiO_2 (wt.%), (d) CaO (wt.%), Cr (ppm), and (e) Nb (ppm). Data from western Oaxaca and NE Guerrero are from Martiny *et al.* (2000a) and Morán-Zenteno *et al.* (1998), respectively.

crustal contamination or a more evolved crustal component (see isotopic composition of Oaxaca complex in Figure 9). An example of extreme involvement of continental crust in magma genesis is the andesitic intrusion of Puente Negro, where the presence of abundant xenoliths from the Acatlán complex has strongly modified the original isotopic compositions (Figure 9) (Martiny *et al.*, 2004). The majority of andesites and dacites from western Oaxaca display isotopic ratios similar to those of the Nejapa region (Figure 9). On the other hand, andesites and rhyolites from the Etla and Mitla–Tlacolula regions have higher initial $^{87}Sr/^{86}Sr$ and negative εNd_i values, as was observed in volcanic samples from NE Guerrero. For Taxco, Guerrero, Morán-Zenteno *et al.* (1998) indicated that initial $^{87}Sr/^{86}Sr$ ratios, in conjunction with chemical and mineralogical composition of volcanic rocks could be explained by moderate crustal contamination of magmas.

DISCUSSION AND CONCLUDING REMARKS

Regional stratigraphy and geochemical patterns

Cenozoic volcanic rock types found in the study area are, in order of decreasing abundance, rhyolites, basaltic andesites, dacites ($SiO_2 > 66$ wt. %) and andesites (< 59 wt. % SiO_2). Andesite-dacite with SiO_2 concentrations between 59 – 66 wt. % were not identified (Figure 5a). The first volcanic event in all these regions is represented by basaltic andesites and some andesitic lava flows that most of the time are highly altered and eroded. The age of emplacement of these rocks is not known, but Ferrusquía-Villafranca (1990) considered it as Paleogene. Overlying these sequences, thick rhyolitic-rhyodacitic rocks observed in all regions are composed of ignimbrites, lava flows, epiclastic and pyroclastic deposits emplaced in different intermontane basins, associated with some andesitic lava flows. K-Ar dates for these sequences indicate that the main magmatic event occurred in the early - middle Miocene (22 to 15 Ma). However, a migration pattern has not been fully determined, since rocks with similar ages were found in the three regions. Andesitic to basaltic andesite dikes cut the silicic sequences in Mitla–Tlacolula and Nejapa regions. Volcanic structures or vents were not observed to date, probably because of the presence of fault and fracture systems that dramatically cut these rocks. The emplacement of these andesitic to basaltic andesite dikes could represent the final magmatic events in the regions. In this work, they are considered of middle Miocene age on the basis of their stratigraphic position and lower degree of alteration.

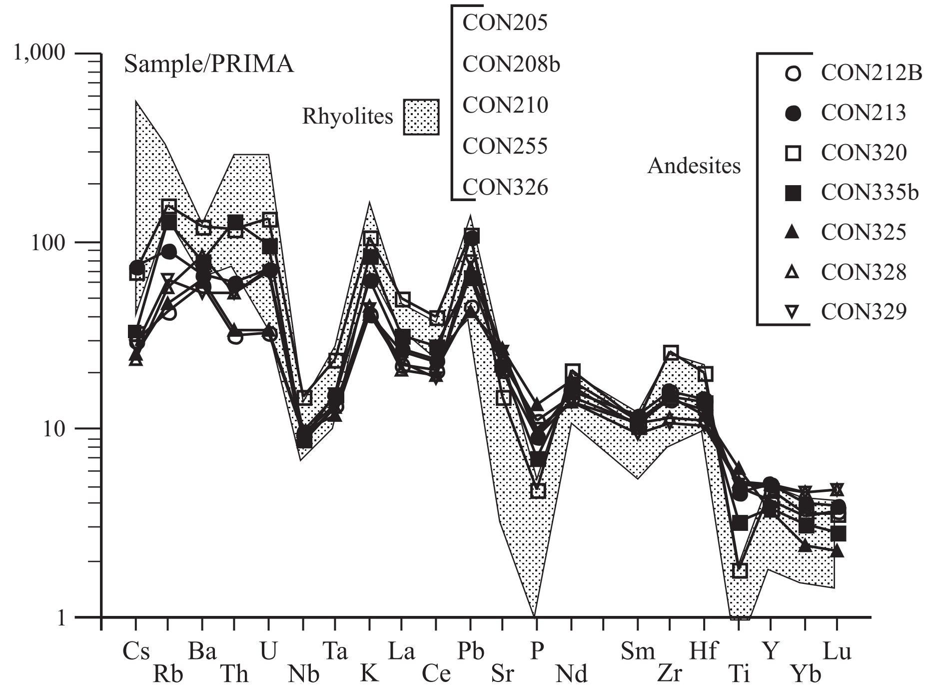

Figure 7. Trace-element diagram for Cenozoic volcanic rocks of the study area. Primitive mantle (PRIMA) normalized using the values of Sun and McDonough (1989).

The stratigraphic and certain petrographic features of the volcanic sequences in the study area show some differences in comparison to nearby regions in the Sierra Madre del Sur: western Oaxaca and northeastern Guerrero. In western Oaxaca (Huajuapan area), Martiny *et al.* (2000a) reported a thick volcanic pile composed principally of basaltic andesites to andesitic-dacitic lava flows overlying minor silicic to intermediate volcaniclastic rocks. Some intermediate to silicic pyroclastic and epiclastic deposits were reported to the south in the Tlaxiaco area. Numerous andesitic-dacitic hypabyssal intrusions are emplaced at different levels in the sequence. All volcanic rocks in westernmost

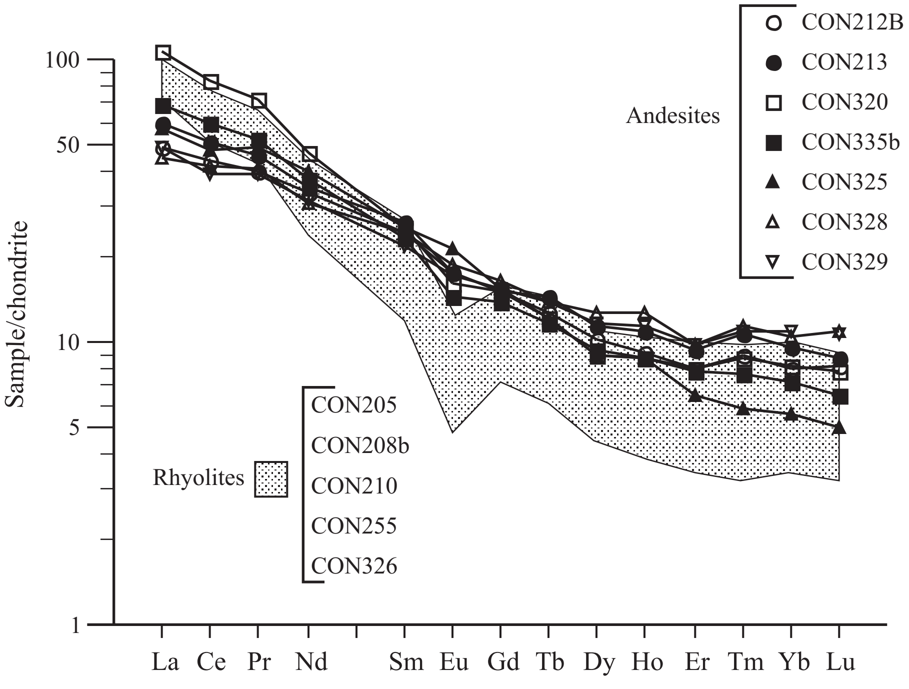

Figure 8. Chondrite-normalized rare earth element data for Cenozoic volcanic rocks of the study area, using the values of Nakamura (1974).

Table 3. Sr and Nd isotopic and chemical data of Cenozoic volcanic rocks from central and eastern Oaxaca.

Sample	Rock	Rb (ppm)	Sr (ppm)	Sm (ppm)	Nd (ppm)	(^{87}Sr/^{86}Sr)m	± 1s	(^{87}Sr/^{86}Sr)i	(^{143}Nd/^{144}Nd)m	± 1s	(^{143}Nd/^{144}Nd)i	(εNd)i
Etla												
CON205	R-I	104	364	5	28	0.706825	42	0.70659	0.512568	22	0.512554	-1.15
Mitla–Tlacolula												
CON208b	R-T	99	557	3	19	0.705781	28	0.70564	0.512577	30	0.512565	-0.94
CON210	R-T	86	483	3	18	0.705802	41	0.70566	0.512532	17	0.512518	-1.84
CON212b	B-A	27	500	5	21	0.705162	43	0.70512	0.512627	24	0.512608	-0.09
CON213	A	59	450	5	22	0.705259	55	0.70515	0.512636	18	0.512617	0.08
CON320	D	103	328	5	29	0.704973	38	0.70472	0.512716	21	0.512702	1.75
CON335b	D	83	464	5	23	0.704934	43	0.70479	0.512599	23	0.512583	-0.58
Nejapa												
CON255	R-V	208	126	5	28	0.706174	53	0.70482	0.512681	18	0.512665	1.03
CON325	A	31	579	5	26	0.704756	41	0.70471	0.512684	18	0.512659	0.91
CON326	R-T	217	72	3	15	0.705997	34	0.70352	0.512655	21	0.512639	0.52
CON328	B-A	37	591	5	20	0.704818	38	0.70476	0.512705	17	0.512685	1.42
CON329	A	42	566	4	20	0.704778	48	0.70472	0.512683	33	0.512665	1.03

Element concentrations obtained by ICP-MS. Measurements for the La Jolla Nd standard are ^{143}Nd/^{144}Nd = 0.511882±27 (1 s.d., n = 29) and for the SRM-987 standard are ^{87}Sr/^{86}Sr = 0.710233±16 (1 s.d., n=179). Initial εNd values and ^{87}Sr/S^{86}Sr ratios were calculated at 20 Ma for the volcanic rocks, assuming a present-day ^{143}Nd/^{144}Nd (CHUR) = 0.512638 and ^{87}Sr/^{86}Sr = 0.7045.

Oaxaca rest on Paleozoic metamorphic rocks (Mixteca terrane; Ortega-Gutiérrez, 1981), Mesozoic sedimentary units or Paleogene conglomerates. K-Ar ages for these sequences range from 29 to 34 Ma and some volcanic vents or central structures were identified at NE of Huajuapan (Martiny *et al.*, 2000b). In northeastern Guerrero, the Cenozoic volcanic sequences are distributed in two main areas, Taxco and Tilzapotla. In both areas predominate thick sequences of rhyolites and minor andesites and dacites, which are represented by pyroclastic deposits, lava flows and hypabyssal dikes. The most important structure in this area is represented by a major resurgent caldera in the Tilzapotla area (Morán-Zenteno *et al.*, 2004). All volcanic sequences display ages from *ca.* 38 to 32 Ma and are mainly deposited over Cretaceous marine rocks.

The Y and Yb concentrations for some rocks of the study area are relatively low (Y< 23 ppm and Yb<1.8 ppm) whereas the Sr concentrations are moderately high (328 to 591 ppm) (Table 2 and Figure 10), with HREE depletions, suggesting that a possible slab-melt component has participated in the subduction process. Relatively high Sr/Y ratios and low Y contents have also been observed in some Oligocene volcanic rocks from western Oaxaca (Figure 10) (Martiny, personal communication), and central-southeastern Oaxaca, indicating the existence of a geochemical adakitic signature. Positive anomalies of Ba and Pb, together with the high values of some element ratios (*e.g.*, Ba/Zr and K/Nb) shown by certain volcanic rocks from the study area confirms that fluids and/or melts from the subducted slab contributed to magma genesis. This feature has not only been observed in volcanic arcs where young and hot slabs are being subducted (Defant and Drummond, 1990; Martin, 1999), but also when a flat subduction phenomenon produces the temperature and pressure conditions necessary for the fusion of a cold oceanic crust (Gutscher *et al.*, 2000). Although more integrated investigations are required about geochemistry and tectonic patterns in the southeastern SMS, on the basis of the geochemical data it is proposed that melts of the subducted oceanic crust could had contributed to the magmas erupted in the Etla, Tlacolula–Mitla and Nejapa regions. This is not a rare feature in the Miocene to Quaternary volcanism linked to the subduction processes in southern Mexico, as has been recently reported for several volcanic sites of the Trans-Mexican Volcanic Belt that show geochemical adakitic signatures (Martinez-Serrano *et al.*, 2004, Gómez-Tuena *et al.*, 2005, Rincón-Herrera *et al.*, 2007), associated to flat-slab subduction of the oceanic plate under the continental crust.

The initial ^{87}Sr/^{86}Sr and epsilon-Nd values for volcanic rocks in western Oaxaca (0.7042 to 0.7046 and 0 to +2.6) suggest a relatively low degree of old crust involvement (Martiny *et al.*, 2000a). Whereas in NE Guerrero, initial isotopic compositions were explained by a greater crustal contribution to rhyolitic rocks from the Taxco region (0.7063 to 0.7075) (Morán-Zenteno *et al.*, 1998), in the Tilzapotla caldera, the initial isotopic variations (^{87}Sr/^{86}Sr$_i$: 0.7034 to 0.7066; epsilon-Nd$_i$: -1.07 to +5.41) are related to input of more primitive magmas into the magma chamber and the contamination of magmas with Cretaceous carbonates (Morán-Zenteno *et al.*, 2004). In the study area, although most samples represent volcanic products derived from different events and struc-

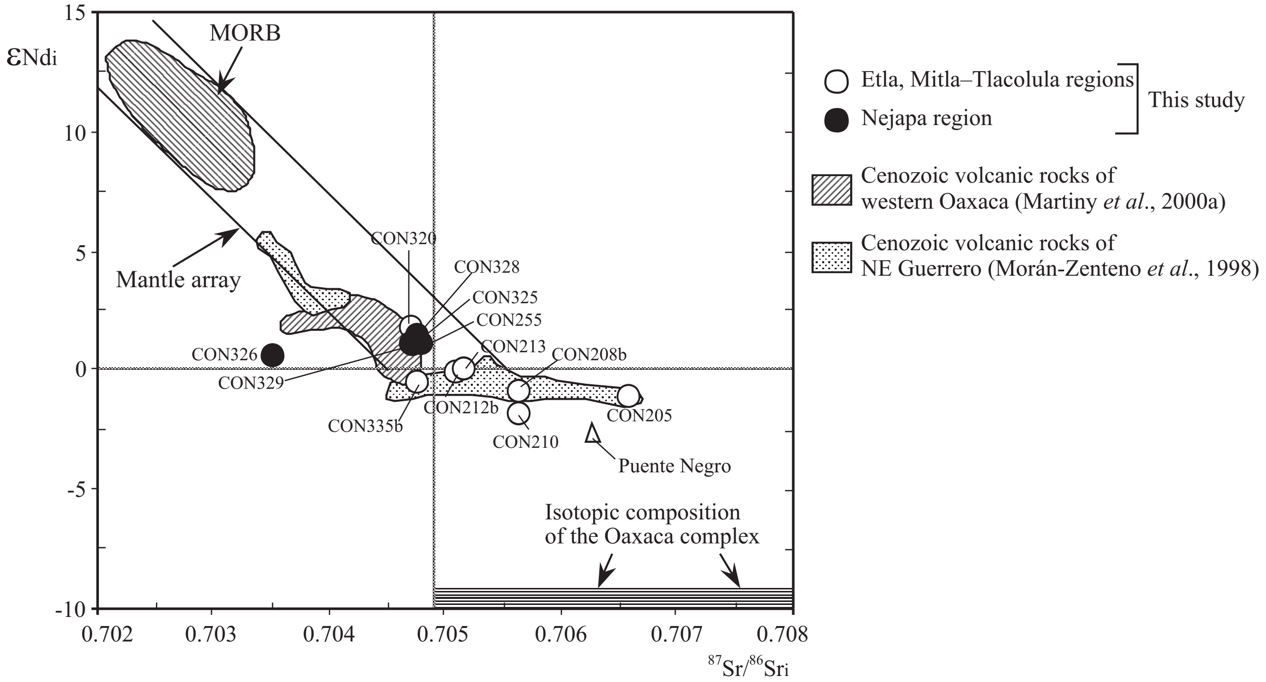

Figure 9. Sr-Nd isotopic initial ratios of early Miocene volcanic rocks in the central and southeastern parts of the state of Oaxaca. Initial isotopic results for other magmatic regions in the Sierra Madre del Sur are also indicated. A partial field for the present-day Sr and Nd isotopic values for the Oaxaca complex is shown (after Patchett and Ruiz, 1987; Ruiz *et al.*, 1988a, 1988b). Puente Negro is an andesitic volcanic body with an apparent age of 22 Ma (Martiny *et al.*, 2004).

tures, in general, the major and trace elements display coherent chemical patterns (low dispersion) suggesting crystal fractionation as the main magmatic process. However, certain differences in the isotopic and geochemical behavior are observed between the Etla, Mitla–Tlacolula and Nejapa regions. In Figure 11, initial epsilon-Nd isotopic compositions seem to change with increasing SiO_2 contents for the Etla, Mitla–Tlacolula regions, whereas the isotopic compositions of samples from the Nejapa region are almost constant with respect to SiO_2. The isotopic variations in the first regions could be due to a major interaction of magmas with an old continental crust, in addition to crystal fractionation processes. For the Nejapa region, the existence of more evolved rocks is probably associated with crystal fractionation processes with minor interaction between magmas and continental crust. In central and southeastern Oaxaca, most Cenozoic volcanic rocks are emplaced in the Oaxaca terrane (Grenvillian age), where present-day isotopic compositions show large variations ($^{87}Sr/^{86}Sr_i$ = 0.705 – 0.717 and εNd_i = -12 – -9; Patchett and Ruiz, 1987; Ruiz *et al.*, 1988a, 1988b). In spite of these radiogenic isotopic compositions, the volcanic products in the study area do not evidence a large interaction of parental magmas with crustal rocks, especially for volcanic rocks from the Nejapa region. It is not the case for the Miocene andesitic dike from Puente Negro, Puebla, where the assimilation of an old continental crust produced dramatic changes in the isotopic compositions (Martiny *et al.*, 2004). Although at present we do not have sufficient structural evidence, the minor interaction of magmas with older continental crust could be explained by the presence of large NW -SE fault systems (Ferrusquía-Villafranca, 2001), through which the magmas could ascend more easily without a significant degree of interaction with the crust.

Space-time magmatic evolution in the SMS

Taking into account the geochronological database for the SMS magmatic rocks and the initial volcanic events of the Trans-Mexican Volcanic Belt (data from Schaaf *et al.*, 1995; Morán-Zenteno *et al.*, 1999; 2005; Martiny *et al.*, 2004; Gómez-Tuena *et al.*, 2005, and references therein, Rincón-Herrera, 2007), it is observed that arc-magmatism was active from Paleocene to early - middle Miocene. Figure 12 schematically displays the distribution of the magmatic arc rocks at different times, conforming NW-SE belts with an orientation similar to that of the volcanic sequences of the Sierra Madre Occidental. The location of the radiometric ages indicates a migration of arc-magmatism from west to east (Eocene in Michoacán to early-middle Miocene in the southeastern Oaxaca study area). This NW – SE migration could explain the age variations observed in the two main magmatic belts present in the SMS. One interesting point observed in the distribution of age data is the presence of early to middle Miocene (23.7 to 15.48 Ma) volcanic events in the central and southeastern parts of the state of Oaxaca (study area), and in the central and eastern parts of

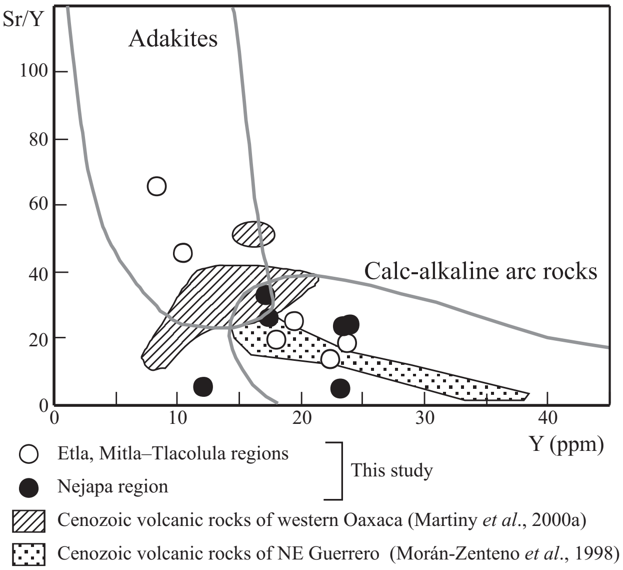

Figure 10. Y *vs*. Sr/Y discrimination diagram between adakites and typical arc calc-alkaline compositions (after Drummond and Defant, 1990), for rocks from central and eastern Oaxaca study area.

the Trans-Mexican Volcanic Belt (TMVB) (Figure 12d). In the TMVB, these ages represent the first volcanic events in this province (ages reported by Gómez-Tuena *et al*., 2005 and reference therein). The TMVB is considered to be a continental magmatic arc that transects central Mexico with an almost E – W orientation, from the Pacific Ocean to the Gulf of Mexico (Figure 1). Although no continuous volcanic outcrops are registered between these two magmatic provinces (SMS and TMVB), in this work is proposed that a continuous early Miocene magmatic arc, with a relatively anomalous orientation, could have existed before the present-day position on the TMVB was attained. Today, several stratigraphic and geochemical studies have provided important evidence of the existence of this magmatic arc; for example, the andesitic subvolcanic body of Puente Negro, Puebla, with an apparent age of 22 Ma (Martiny *et al.*, 2004); the Chalcatzingo rhyolitic domes with an age of 20.7 Ma and adakitic signature (Rincón-Herrera *et al.*, 2007), and a silicic tuff in the valley of Tehuacán, Puebla where a K-Ar determination yielded an age of 16.4 ± 0.5 Ma in biotite (Dávalos-Álvarez *et al.*, 2007). The change from SMS magmatism to the E –W trending volcanism of the TMVB in Miocene time probably reflects the tectonic evolution of southern Mexico during several episodes of plate tectonic rearrangement. At present, different tectonic models try to explain the Cenozoic magmatic migration in the Sierra Madre del Sur and its transition to the Trans-Mexican Volcanic Belt. These models include the existence of the Chortis block and its displacement along the Pacific margin (Ross and Scotese, 1988; Pindell *et al.*, 1988; Ratschbacher *et al.*, 1991; Herrman *et al.*, 1994; Schaaf *et al.*, 1995; Morán-Zenteno *et al.*, 1999) or the existence of subduction erosion (Morán-Zenteno *et al.*, 2007) and a Miocene collision of the Tehuantepec ridge with the Acapulco trench (Keppie and Morán-Zenteno, 2005). If an adakitic geochemical signature is demonstrated for some early-middle Miocene igneous rocks in southern Puebla (Chalcatzingo domes, Rincón-Herrera *et al.*, 2007) and central-southeastern Oaxaca (this work), then a flat-slab subduction process could have produced these geochemical characteristics. Some recent geodynamic models of subduction systems in southern Mexico (Manea and Manea, 2007) proposed the following evolution of the subducting slab: between 25 and 17 Ma the volcanic arc formed an approximately continuous belt in central and southeast Mexico, then the volcanic arc migrated to the north, suggesting that the subducting slab became sub-horizontal at this time. These authors also proposed, in their geodynamic model, that the Chortis block migration along the Middle-American-trench might have created the conditions for cooling the mantle wedge and ceasing the existence of the Miocene volcanic arc in southeastern Mexico. However, future tectonic and geochemical studies in southern Mexico can contribute to the understanding of the magmatic evolution during the Miocene.

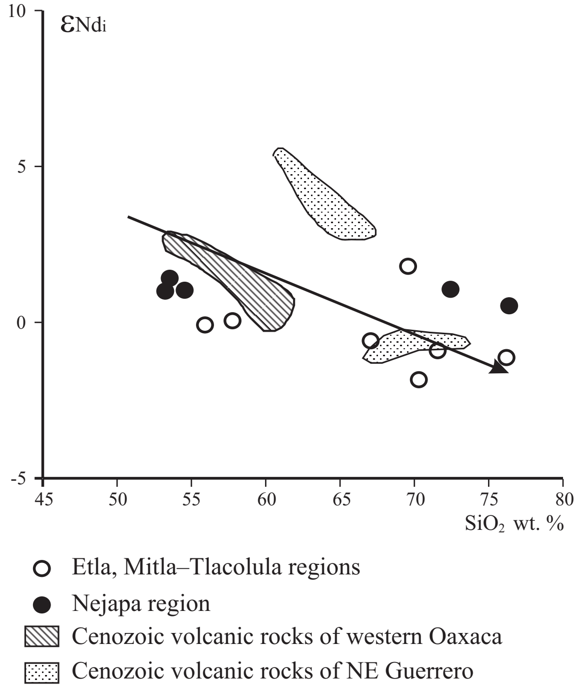

Figure 11. Nd isotopic variations *vs*. differentiation index (SiO_2) for volcanic rocks of the study area. Isotopic data from western Oaxaca and northeastern Guerrero are from Martiny *et al.* (2000a) and Morán-Zenteno *et al.* (1999), respectively.

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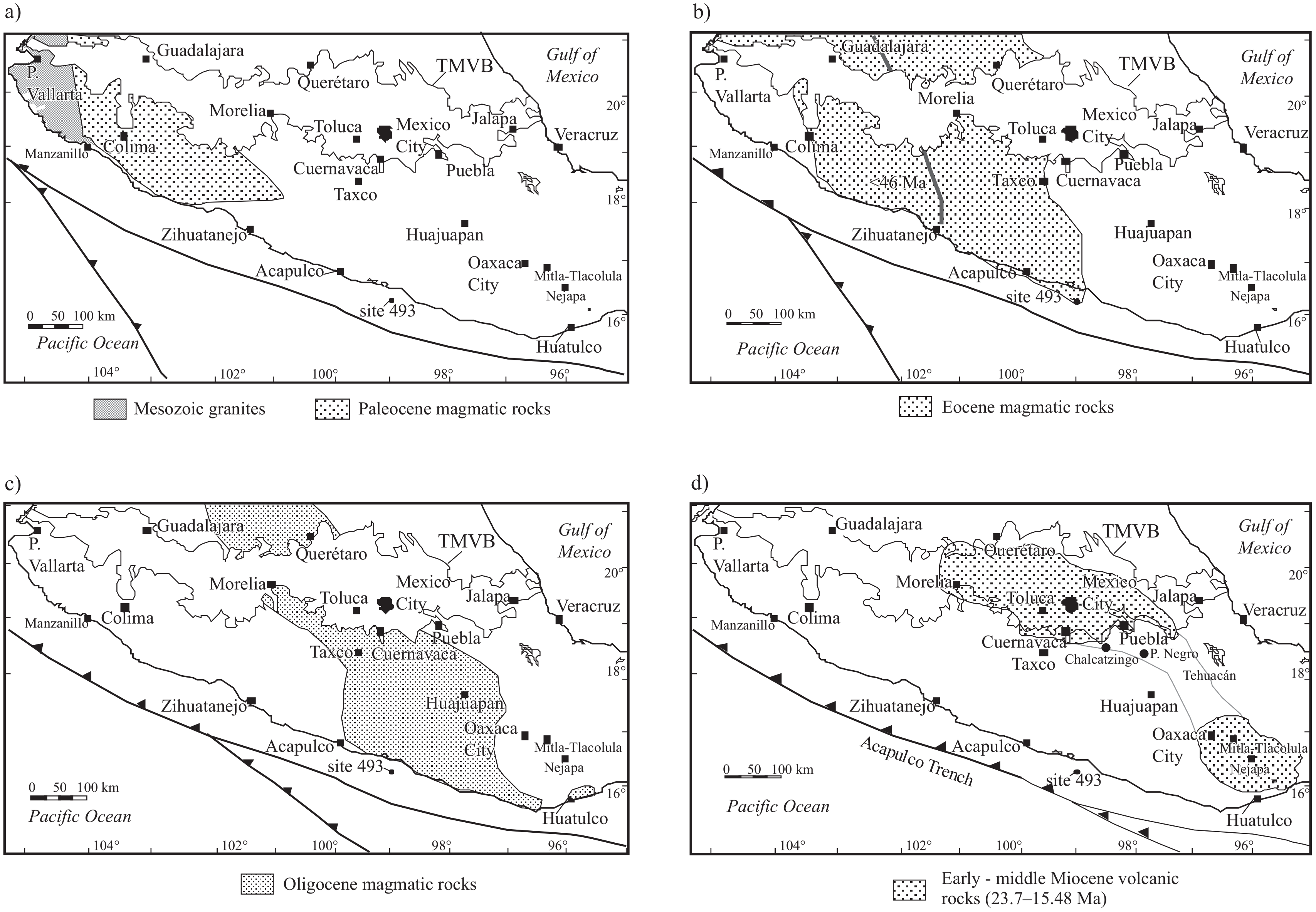

Figure 12. Distribution of the Cenozoic magmatic arc rocks of the Sierra Madre del Sur at different times. Age data from Schaaf *et al.* (1995), Morán-Zenteno *et al.* (1999), and Gómez-Tuena *et al.* (2005) were used to define the NW-SE magmatic events and their evolution. In d) some early-middle Miocene magmatic events have been identified between central-southeastern Oaxaca and the Trans-Mexican Volcanic Belt (TMVB), gray lines.Site 493 of Deep Sea Drilling Project (Bellon *et al.*, 1982).

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