Geology of the San Pedro – Ceboruco Graben, western Trans-Mexican Volcanic Belt

Luca Ferrari[1,*], Chiara M. Petrone[2], Lorella Francalanci[2,3], Takahiro Tagami[4], Mugihiko Eguchi[4], Sandro Conticelli[2,3], Piero Manetti[2,5], and Saúl Venegas-Salgado[6]

[1]Centro de Geociencias, Universidad Nacional Autónoma de México, Campus Juriquilla, Apdo. Postal 742-1, Centro, 76001 Querétaro, Qro., Mexico
[2]Dipartimento di Scienze della Terra, Universitá degli Studi di Firenze, Via G. La Pira 4, I-50121 Firenze, Italy
[3]Istituto di Geoscienze e Georisorse – Sezione di Firenze, Via G. La Pira 4, I-50121 Firenze, Italy
[4]Department of Geology and Mineralogy, Division of Earth and Planetary Sciences, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan.
[5]Istituto di Geoscienze e Georisorse, Via Moruzzi 1, Pisa, Italy
[6]Gerencia de Proyectos Geotermoeléctricos, Comisión Federal de Electricidad, Calle A. Volta 655, 58290 Morelia, Mich., Mexico
** luca@geociencias.unam.mx*

ABSTRACT

We present a detailed study of the geology of the San Pedro–Ceboruco graben (SPC) supported by extensive field work, subsurface information of eight exploratory wells drilled by the Comisión Federal de Electricidad, as well as the review of 74 published K–Ar and $^{40}Ar/^{39}Ar$ ages and seven new K–Ar unspiked age determinations. The SPC is the northwesternmost tectonic structure of the Tepic–Zacoalco rift, which has developed since the late Miocene in the western Trans-Mexican Volcanic Belt (TMVB). The SPC has a broad WNW–ESE orientation and is located at the boundary between two different basement blocks: the Cretaceous to Paleocene batholith of the Jalisco block to the south, and the Oligocene to early Miocene Sierra Madre Occidental silicic volcanic province to the north. Calcalkaline, transitional and Na-alkaline volcanic products of the TMVB cover the tectonic contact between the two blocks. The oldest volcanism related to the TMVB consists of a thick succession of mafic lava flows only found in a deep drilling beneath Ceboruco volcano. These lava flows have a late Miocene age and are the early fill of a paleo-graben that possibly formed in response to the opening of the Gulf of California. In the early Pliocene, a large amount of rhyolitic lavas and silicic pyroclastic flows shortly followed by mafic lavas were emplaced mainly to the north of the study area. A second phase of faulting occurred between the emplacement of the silicic rocks (~5–4.2 Ma) and the mafic ones (~3.8 Ma). Volcanism resumed at the end of Pliocene along a NW–SE alignment of cinder cones and domes that bounds the southern part of the SPC. Most activity occurred in the last 1 my. It first produced several dacitic to andesitic domes and a small calc-alkaline stratovolcano (Tepetiltic); then, after the formation of a small caldera (San Pedro) a mildly Na-alkaline succession of lava flows made up a small volcano (Amado Nervo). The recentmost volcanism is represented by intracaldera silicic domes, a northern WNW–ESE alignment of monogenetic volcanoes, and the active Ceboruco stratovolcano. Late Miocene to present cumulative extension in the area accounts for a modest 10%. A period of very low volcanic activity in late Pliocene coincides with a low convergence rate between the Rivera and North America plates, confirming a strong relation between subduction regime and upper plate volcanism.

Key words: San Pedro–Ceboruco, graben, Trans-Mexican Volcanic Belt, Mexico.

RESUMEN

Presentamos un estudio detallado de la geología del graben San Pedro–Ceboruco (SPC) apoyado por trabajo de campo detallado, información del subsuelo de ocho pozos de exploración perforados por la Comisión Federal de Electricidad, así como la revisión de 74 edades K–Ar y $^{40}Ar/^{39}Ar$ previamente publicadas y siete nuevas determinaciones de edades K–Ar. El SPC es la estructura tectónica más noroccidental del rift Tepic–Zacoalco, la cual se ha desarrollado desde el Mioceno tardío en la porción occidental del Cinturón Volcánico Mexicano (CVM). El SPC tiene una orientación aproximada WNW–ESE y se localiza en el límite entre dos diferentes bloques del basamento: el batolito del bloque de Jalisco (Cretácico–Paleoceno) al sur, y la provincia volcánica silícica de la Sierra Madre Occidental (Oligoceno–Mioceno temprano) al norte. Productos volcánicos calcialcalinos, transicionales y alcalinos sódicos del CVM cubren el contacto tectónico entre los dos bloques. El volcanismo más antiguo relacionado al CVM consiste en una gruesa sucesión de flujos de lava máficos, encontrados solamente en perforaciones profundas bajo el Volcán Ceboruco. Estos flujos de lava tienen una edad del Mioceno tardío y constituyen el relleno temprano de un paleograben que posiblemente se formó en respuesta a la apertura del Golfo de California. En el Plioceno temprano, una gran cantidad de lavas riolíticas y flujos piroclásticos silícicos, seguidos poco tiempo después por lavas máficas, se emplazaron principalmente hacia el norte de la zona de estudio. Una segunda fase de fallamiento ocurrió entre el emplazamiento de las rocas silícicas (~5–4.2 Ma) y las máficas (~3.8 Ma). El volcanismo reinició al final del Plioceno a lo largo de un alineamiento NW–SE de conos cineríticos y domos que limitan el SPC al sur. La mayor parte de la actividad ocurrió en el último millón de años, produciendo primero algunos domos dacíticos a andesíticos y un pequeño estratovolcán calcialcalino (Tepetiltic); después de la formación de una pequeña caldera (San Pedro), una sucesión de flujos de lava moderadamente alcalinos (sódicos) formaron un pequeño volcán (Amado Nervo). El volcanismo más reciente está representado por domos silícicos intracaldera, un alineamiento WNW–ESE de volcanes monogenéticos, y el estratovolcán activo Ceboruco. Del Mioceno tardío al presente, la extensión acumulativa en el área es de un modesto 10%. Un periodo de muy baja actividad volcánica en el Plioceno tardío coincide con una baja tasa de convergencia entre las placas de Rivera y Norteamérica, confirmando una fuerte relación entre el régimen de subducción y el volcanismo en la placa sobreyaciente.

Palabras clave: San Pedro–Ceboruco, graben, Cinturón Volcánico Mexicano, México.

INTRODUCTION

The San Pedro–Ceboruco graben (SPC) is a Neogene structure developed in the western Trans-Mexican Volcanic Belt (TMVB) in the proximity of the southern Gulf of California (Figures 1 and 2). From the geodynamic point of view, the SPC is particularly interesting because it lies just to the south of the southernmost limit of the Gulf Extensional Province (Gastil *et al.*, 1975) (Figures 1 and 2), where Na-alkaline volcanism is dominant (Nelson and Carmichael, 1984; Nelson and Livieres, 1986; Nelson and Hegre, 1990). The SPC is also the northernmost tectonic basin of the so-called Tepic–Zacoalco rift (Figure 2), where complex extensional tectonism occurred associated with both Na-alkaline and calc-alkaline volcanism since the late Miocene (Verma and Nelson, 1989a, 1989b; Ferrari *et al.*, 1994, 1997; Righter *et al.*, 1995; Rosas-Elguera *et al.*, 1996; Petrone, 1998; Ferrari and Rosas-Elguera, 2000; Ferrari *et al.*, 2000a; Righter 2000; Petrone *et al.*, 2003). Although many of the major volcanic centers of the western TMVB have been studied, the only well known center inside the SPC is the active Ceboruco volcano (Nelson, 1980, 1986; Gardner and Tait, 2000), whereas brief accounts on the

Figure 1. Geodynamic map of Mexico showing Tertiary extension and volcanism north of the Trans-Mexican Volcanic Belt and the present configuration of plates. The area of Figure 2 is boxed. Tertiary extension according to Ferrari *et al.* (2002).

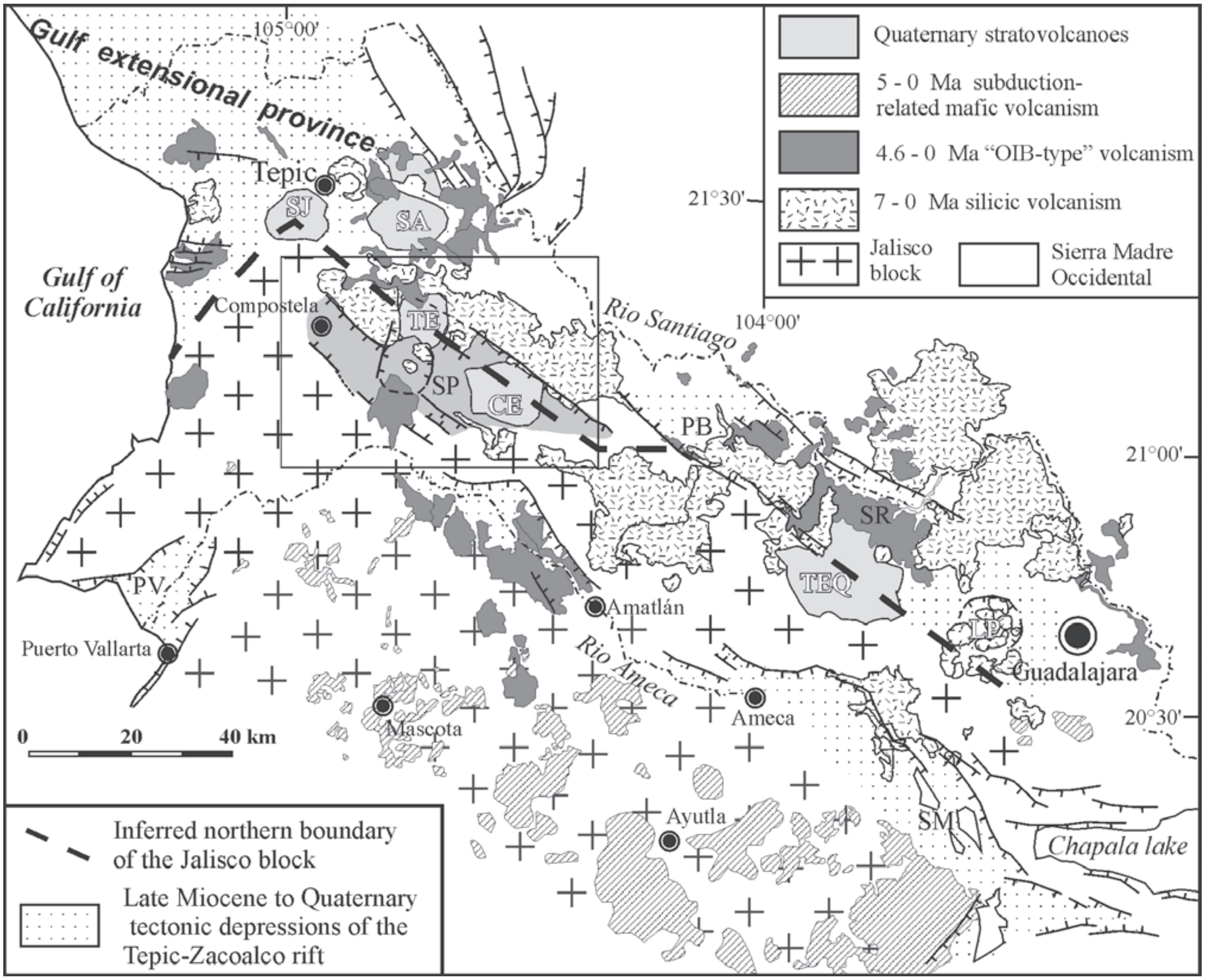


Figure 2. Map showing the main extensional faults and the post 7 Ma volcanism of the western Trans-Mexican Volcanic Belt (modified after Ferrari and Rosas-Elguera, 2000, and Ferrari *et al.*, 2000a). Box depicts the area covered by Figure 6. The area belonging to the SPC is in intermediate grey. The main volcanic structure are: SJ = San Juan, SA = Sanganguey, TE = Tepetiltic, CE = Ceboruco, TEQ = Tequila, LP = La Primavera caldera, SP = San Pedro caldera. The main tectonic structures are: PV = Puerto Vallarta graben, PB – SR = Plan de Barrancas–Santa Rosa graben, SM = San Marcos half-graben.

geology and the petrography of the other centers are found in Castillo and de la Cruz (1992) and Righter *et al.* (1995).

In the last four years we have carried out an extensive geologic, geochemical and geochronologic study of the SPC area. The petrology of the SPC is presented in Petrone *et al.* (2003), and a tectonic-petrogenetic model of the evolution of the whole western TMVB has been put forward in Ferrari and Rosas-Elguera (2000), Ferrari *et al.* (2001) and in Petrone *et al.* (2003). In this work we present in detail the geology and volcanic stratigraphy of the SPC supported by a review of 74 published K–Ar and $^{40}Ar/^{39}Ar$ ages (Gastil *et al.*, 1978; Righter *et al.*, 1995 ; Ferrari *et al.*, 2000a, 2000 b; Petrone *et al.*, 2001; Frey *et al.*, in press) along with seven new age determinations (Table 1). The recent work by Frey *et al.* (in press) provide many high precision $^{40}Ar/^{39}Ar$ ages that are generally younger than the K–Ar ages performed by CFE on the same units and reported in Ferrari *et al.* (2000a). These ages were normally preferred. Seven new K–Ar ages presented in this work were obtained with the K–Ar unspiked sensitivity method (see appendix). This method, along with the mass fractionation correction procedure, have allowed extension of the K–Ar dating method to volcanic rocks as young as ~10 Ka (Itaya and Nagao, 1988; Takaoka *et al.*, 1989; Matsumoto *et al.*, 1989; Matsumoto and Kobayashi, 1995).

The seven samples chosen for dating represent the compositional range of mafic rocks in the SPC recognized by Petrone *et al.* (2003). They are mostly characterized by low phenocryst contents and devitrified groundmasses. The samples also have a low volume percent of vescicles and

Table 1. New K–Ar age determinations by the unspiked sensitivity method.

Sample ID and location	Rock type	Weight (g)	K_2O (wt%)	$^{38}Ar/^{36}Ar$	$^{40}Ar/^{36}Ar$	$^{40}Ar/^{36}Ar$ Initial	^{40}Ar rad ($10^{-8}cm^3STP/g$)	^{40}Ar atm (%)	K-Ar age (Ma)
San Leonel									
SPC150-2	Na-Alkaline basalt	5.3358	1.38	0.1875 ± 0.0006	397.3 ± 0.6	297.4 ± 1.9	2.059 ± 0.051	74.9	0.46 ± 0.01
Camichin de Jauja									
SPC155-2	Na-Alkaline basalt	3.7837	1.63	0.1850 ± 0.0008	311.3 ± 0.5	289.7 ± 2.6	0.652 ± 0.079	93.1	0.12 ± 0.02
Cerro El Estafiate									
SPC21-2	Transitional basalt	3.1458	1.38	0.1846 ± 0.0006	323.8 ± 0.5	288.6 ± 1.9	1.335 ± 0.076	89.1	0.30 ± 0.02
Volcán Molcajete									
SPC39-2	Transitional basalt	2.9958	2.32	0.1871 ± 0.0011	295.5 ± 0.7	296.0 ± 3.7	-0.015 ± 0.117	100.2	0.00 ± 0.02
Cerro Colorado									
SPC106-3	Calk-alkaline basalt	0.2579	1.60	0.1874 ± 0.0006	300.6 ± 0.5	297.0 ± 1.9	2.214 ± 1.220	98.8	0.43 ± 0.24
SPC106-4		0.3674		0.1872 ± 0.0006	299.6 ± 0.5	296.3 ± 1.9	2.178 ± 1.273	98.9	0.42 ± 0.25
								Weighted mean	0.43 ± 0.17
Tepetiltic volcano									
SPC79-2	Calk-alkaline andesite	2.3313	1.48	0.1865 ± 0.0006	345.5 ± 0.6	294.3 ± 2.1	2.298 ± 0.104	85.2	0.48 ± 0.02
Bomb likely ejected from a cone to the north of Tepetiltic volcano									
SPC74-2	Na-Alkaline basalt (bomb)	0.7695	1.05	0.1863 ± 0.0006	296.6 ± 0.5	293.7 ± 1.9	0.672 ± 0.457	99.0	0.20 ± 0.13
SPC74-3		0.8327		0.1868 ± 0.0006	296.4 ± 0.5	295.1 ± 1.9	0.322 ± 0.481	99.6	0.09 ± 0.14
								Weighted mean	0.14 ± 0.10

are unaltered. Three of these samples are Na-alkaline (SPC 74, SPC 150, and SPC 155), two are calc-alkaline (SPC 79 and SPC 106), and the remaining two (SPC 21 and SPC 39) are transitional between Na-alkaline and calc-alkaline.

The present study includes samples and stratigraphic information gathered from the exploratory wells drilled for geothermal purposes by the Comisión Federal de Electricidad (CFE) in the SPC (Figures 3 and 4). Three deep wells, CB1, CB2, and CB3, reached depths of 2,700, 1,600, and 1,900 m, respectively, and cores were recovered at intervals of 500 m. Five shallow wells reached depths of 100 to 200 m with 3 to 5 cores each. The litho-stratigraphic sequence of each well was reconstructed using petrographic analysis of well cuttings. These drill-hole data provide an important control on the volcanic stratigraphy of the area.

REGIONAL GEOLOGIC AND TECTONIC SETTING

The western TMVB conceals the tectonic boundary between the Jalisco Block (JB) and the Sierra Madre Occidental (SMO) (Rosas-Elguera *et al.*, 1997; Ferrari *et al.*, 2000a, Ferrari and Rosas-Elguera, 2000) (Figure 2). The frontal part of the arc is built on the JB and is characterized by mafic Plio–Quaternary monogenetic centers and small shield volcanoes (Wallace and Carmichael, 1989, 1992; Lange and Carmichael, 1990, 1991; Righter and Carmichael, 1992; Righter and Rosas-Elguera, 2001). Volcanism in this area consists predominantly of K-alkaline rocks that show a subduction-related geochemical signature (Lange and Carmichael, 1990; Righter *et al.*, 1995). In the rear half of the arc, sub-alkaline subduction-related felsic domes and mafic-intermediate monogenetic centers and lava flows were emplaced since late Miocene, whereas andesitic to dacitic stratovolcanoes were built in the late Quaternary (Ferrari *et al.*, 2000a) (Figure 2). Na-alkaline magmas with intraplate affinity and transitional lavas were erupted in Pliocene and Quaternary times, mostly along extensional fault systems at the northern edge of the JB (Ferrari *et al.*, 2000b).

Following the first proposal of Luhr *et al.* (1985), several authors considered that the JB may have been rifting away from the Mexican mainland since the early Pliocene. This model requires a considerable amount of right-lateral shearing along the northern boundary of the Jalisco block, which coincides with the Tepic–Zacoalco rift, to permit the westward rifting of the block (Allan *et al.*, 1991; Borgois and Michaud, 1991; Moore *et al.*, 1994). Recent field studies in the region, however, have shown that the Plio–Quaternary tectonics is dominantly extensional (Barrier *et al.*, 1990; Nieto-Obregon *et al.*, 1992; Ferrari and Rosas-Elguera, 1994, 2000), although evidence for strike-slip deformation is found in older rocks (Michaud *et al.*, 1991; Ferrari 1994a, 1995; Ferrari *et al.*, 2000b). Rosas-Elguera *et al.* (1996) proposed that the northern boundary of the JB developed in early Tertiary times and has been reactivated several times since then. It is now established that the boundary was reactivated by shear tectonics related to the initial opening of the Gulf of California during the middle to late Miocene (Ferrari, 1995; Ferrari *et al.*, 2000b, 2002). Then, since the end of Miocene, NE extension eventually shaped the Tepic–Zacoalco rift (Ferrari and Rosas-Elguera, 2000).

VOLCANIC SUCCESSION OF THE SAN PEDRO–CEBORUCO GRABEN

The SPC is a complex, WNW–ESE striking extensional basin located along the boundary between the JB to the south and the SMO to the north. Magmatism has been intimately associated with formation of the SPC, with emplacement of volcanic and sub-volcanic bodies at least since the Pliocene. Volcanism in this area produced two

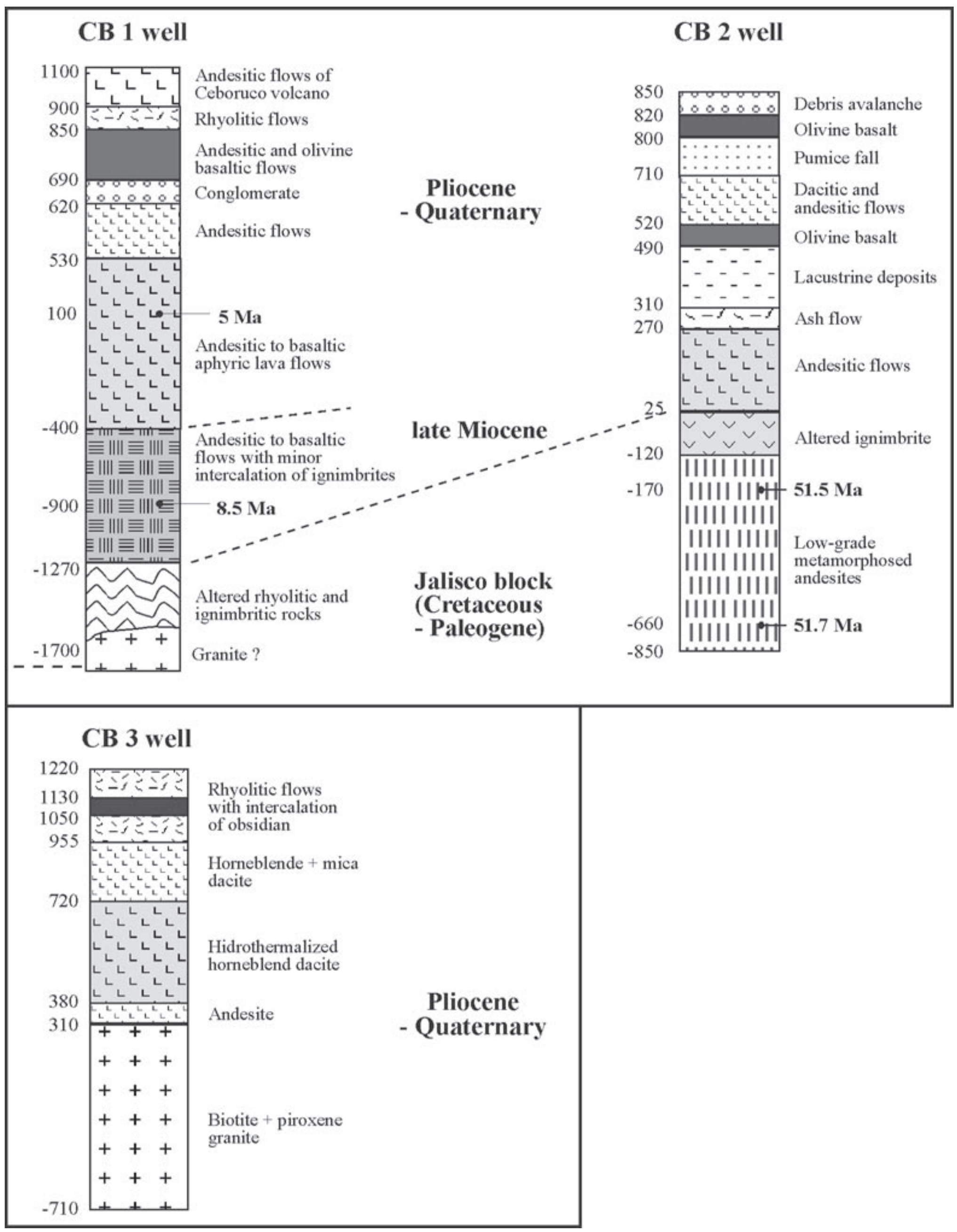


Figure 3. Stratigraphy of the deep exploratory wells drilled by Comisión Federal de Electricidad in the SPC area (not to scale). The depth of each lithologic unit is reported in meter above (or below) sea level. Ages of cores are from Ferrari *et al.* (2000a) and Ferrari *et al.* (2000b). The location of the wells is indicated in Figures 5 and 6.

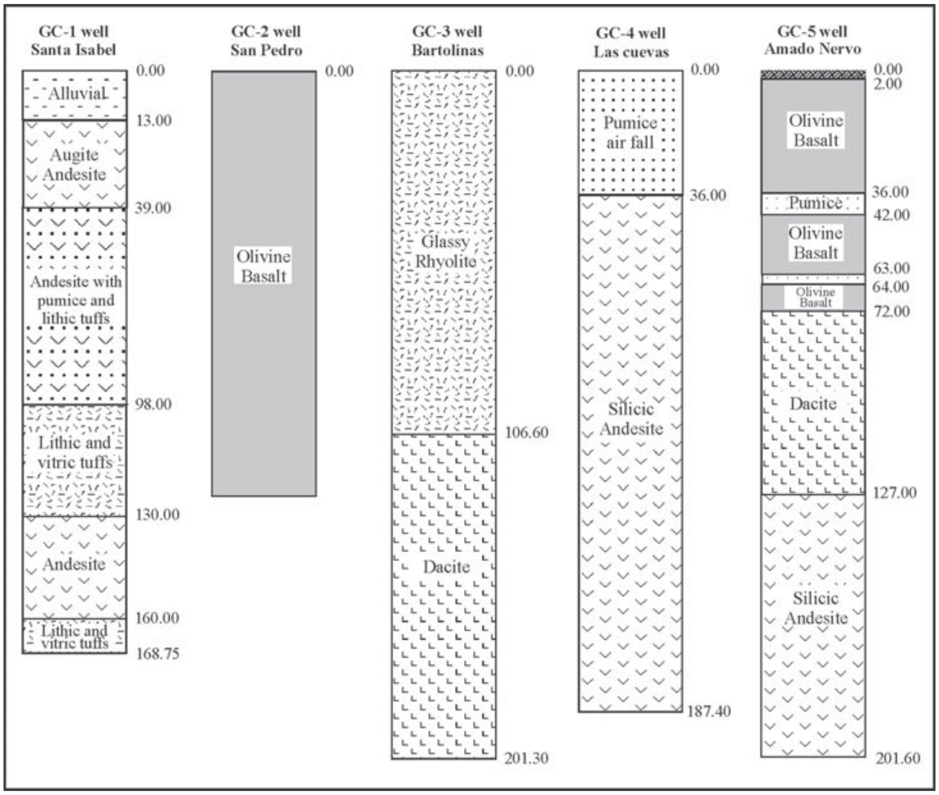


Figure 4. Stratigraphy of the shallow gradient wells drilled by Comisión Federal de Electricidad in the SPC area (at scale). The depth of each lithologic unit is reported in meter below the well top. The locations of the wells are indicated in Figures 5 and 6.

small calc-alkaline stratovolcanoes (Ceboruco and Tepetiltic), a dome-caldera complex (San Pedro–Cerro Grande Volcanic Complex), a mildly Na-alkaline succession of lava flows that made up a small volcano (*i.e.*, Amado Nervo) and two NNW–SSE alignments of mono-genetic cinder cones and lava domes (northern and southern volcanic chain) (Figures 5 and 6).

In the SPC we recognized 26 litho-stratigraphic units based on their stratigraphic position, petrography, and age. The stratigraphic relations among all late Pliocene to Quaternary vents of the SPC is illustrated in Figure 7. Chemical classification for the recognized main Pleistocene–Holocene geologic units is shown in the total-alkalis *vs.* silica diagram in Figure 8. A brief description of each of the geologic units follows, starting with the oldest Cretaceous–Early Tertiary units.

Jalisco block (Late Cretaceous–early Eocene)

The Jalisco Block (JB) is a distinctive geologic assemblage consisting of Late Cretaceous to early Tertiary volcanic and volcaniclastic deposits and marine sedimentary sequences underlain by a granitoid batholith that intruded low- to medium-grade metasedimentary rocks. These older rocks are mostly exposed east of Puerto Vallarta and east of Punta Mita, where Prol *et al.* (2002) suggest a Paleozoic age for the calcareous schists and gneisses exposed there. Turbidite sequences are commonly intercalated with the volcanic rocks and are dominant in the western JB. Volcanic rocks are rhyolitic ash-flow tuff and subordinate andesites, mainly exposed in the central part. Limestone and minor sandstone of probable Cretaceous age are confined to the northeastern and eastern part of the JB (Colima rift and Tapalpa region). The volcanic and sedimentary cover of the Jalisco block is affected by post-Early Cretaceous folding and faulting likely related to the Laramide orogeny.

K–Ar ages of the volcanic rocks exposed in the JB range from 114 Ma to 51 Ma (Gastil *et al.*, 1978; Wallace and Carmichael, 1992; Lange and Carmichael, 1991; Righter *et al.*, 1995; Ferrari *et al.*, 2000a). However, available $^{39}Ar/^{40}Ar$ ages of ignimbrites are restricted to the 83–58 Ma interval (Wallace and Carmichael, 1989; Righter *et al.*, 1995; Rosas-Elguera *et al.*, 1997; Frey *et al.*, in press). Plutonic rocks consist of granite, granodiorite, and tonalite, which form a large single batholith south of Puerto Vallarta and probably represent the basement of the whole JB. Zircon U–Pb dates and Rb–Sr isochrons indicate that the emplacement of these rocks range between ~100 and 90 Ma (Schaaf *et al.*, 1995). Hornblende and biotite K/Ar ages (cooling ages) from a large variety of rocks in the batholith range between 90 Ma and 50 Ma (Gastil *et al.*, 1978; Köhler *et al.*, 1988; Zimmermann *et al.*, 1988), suggesting that some of the intrusions may be younger than Cretaceous. Based on close similarity in ages and chemical and isotope composition, Schaaf *et al.* (2000) demonstrated that the Puerto Vallarta batholith is the equivalent of the Los Cabos batholith of southern Baja California. In fact, they were probably joined before the opening of the Gulf of California.

Rocks belonging to the JB are exposed in the Sierra de Zapotán and Sierra el Guamuchil, just south of the SPC (Figures 5 and 6) and were cored at well CB 2 (Figure 3). In the Sierra de Zapotán they consist of a dioritic to granitic batholith partly covered by remnants of Cretaceous limestone, and extensive silicic ash flow tuffs and lava flows. Andesitic lavas, often showing low-grade meta-morphism, are found intercalated with the silicic rocks in the Sierra el Guamuchil. Righter *et al.* (1995) dated a rhyolitic ash flows in the Sierra el Guamuchil by $^{39}Ar/^{40}Ar$ at 62.5 ± 0.1 Ma and Gastil *et al.* (1978) report a K/Ar age of 53.8 ± 1.5 Ma for a rhyolite about 1 km south of the village of Juan Escutia, at the northern edge of Sierra de Zapotán (Figure 6). The lower part of CB 2 well, drilled in the southern part of the SPC close to Amado Nervo village (Figure 6), found over 730 m of low grade metamorphosed andesites. Two cores, recovered at depth of 1,020 and 1,510 m, were dated at 51.5 ± 0.5 and 51.7± 0.6 Ma respectively by the $^{39}Ar/^{40}Ar$ method (Ferrari *et al.*, 2000a). Based on their lithology and age, these rocks were correlated with the upper part of the JB succession. This early Eocene andesitic volcanism seems to constitute a regional event on the northern edge of the JB. Indeed a well drilled west of Guadalajara, in the La Primavera caldera, also found an andesitic succession that yielded a K/Ar age of 51 ± 2.5 Ma (Ferrari *et al.*, 2000a).

Sierra Madre Occidental (Oligocene–early Miocene)

The SMO is a large silicic volcanic plateau that extends for over 2,000 km from the U.S.–Mexico border to the western TMVB. The northern and central part of the SMO mostly consists of silicic ignimbrites and, to a lesser extent, rhyolitic domes of Oligocene age (McDowell and Keizer, 1977; McDowell and Clabaugh, 1979). The southern SMO has been recently studied by Ferrari *et al.* (2002), who found that most of the region is covered by a

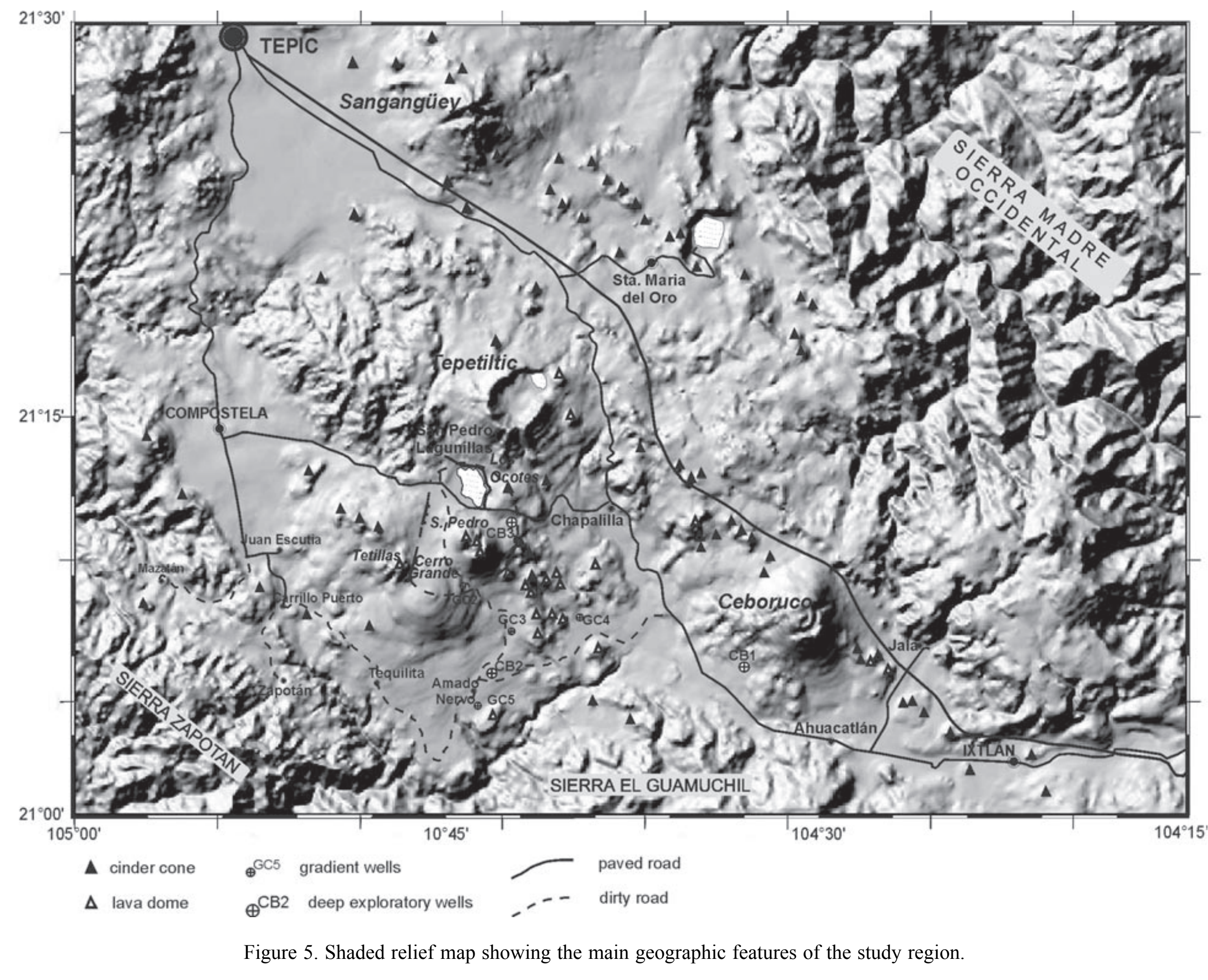
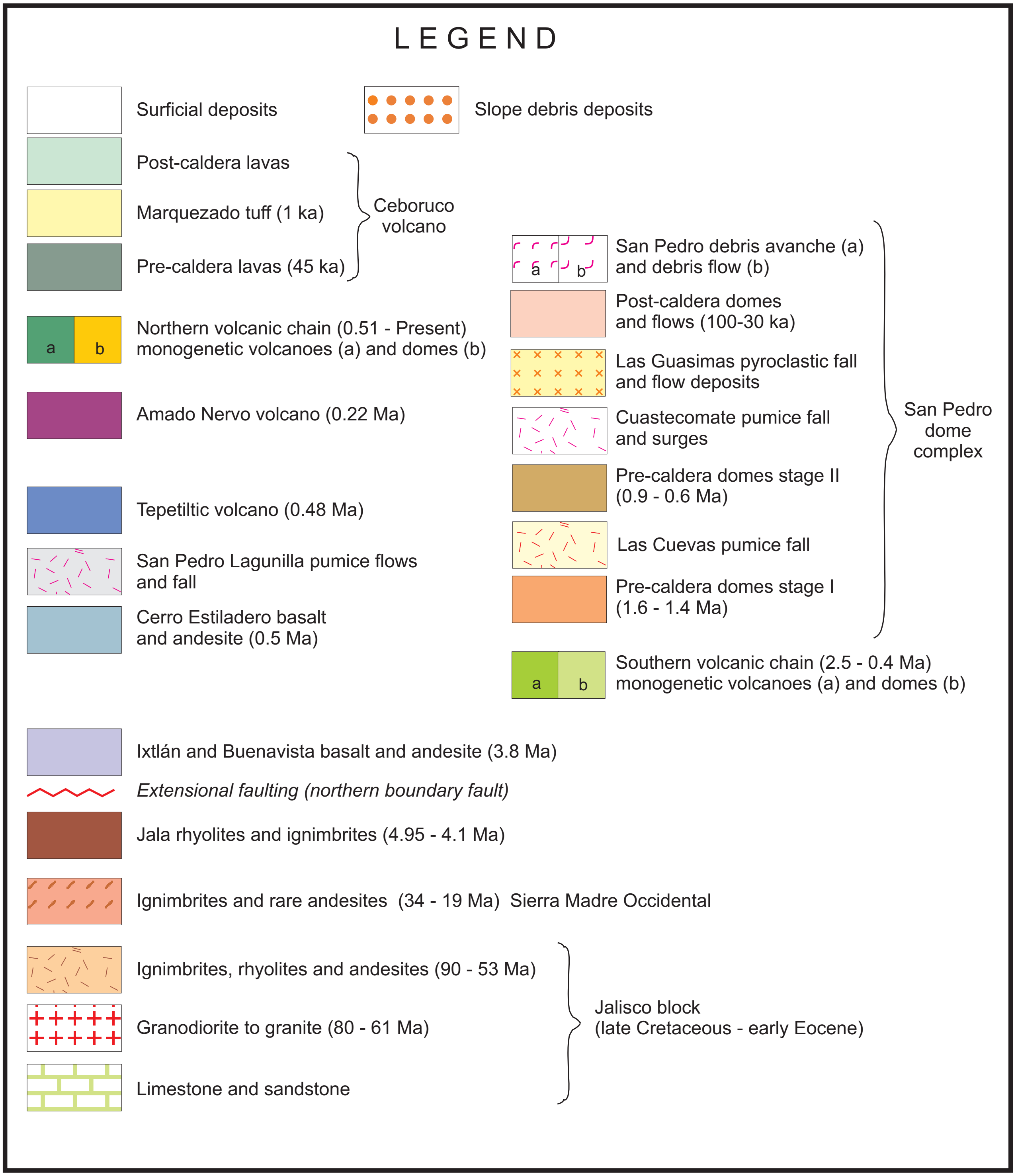


Figure 5. Shaded relief map showing the main geographic features of the study region.


LEGEND
Surficial deposits
Slope debris deposits
Post-caldera lavas
Marquezado tuff (1 ka)
Pre-caldera lavas (45 ka)
Ceboruco volcano
Northern volcanic chain (0.51 - Present) monogenetic volcanoes (a) and domes (b)
a
b
Amado Nervo volcano (0.22 Ma)
Tepetiltic volcano (0.48 Ma)
San Pedro Lagunilla pumice flows and fall
Cerro Estiladero basalt and andesite (0.5 Ma)
San Pedro debris avanche (a) and debris flow (b)
Post-caldera domes and flows (100-30 ka)
Las Guasimas pyroclastic fall and flow deposits
Cuastecomate pumice fall and surges
Pre-caldera domes stage II (0.9 - 0.6 Ma)
Las Cuevas pumice fall
Pre-caldera domes stage I (1.6 - 1.4 Ma)
San Pedro dome complex
Southern volcanic chain (2.5 - 0.4 Ma) monogenetic volcanoes (a) and domes (b)
Ixtlán and Buenavista basalt and andesite (3.8 Ma)
Extensional faulting (northern boundary fault)
Jala rhyolites and ignimbrites (4.95 - 4.1 Ma)
Ignimbrites and rare andesites (34 - 19 Ma) Sierra Madre Occidental
Ignimbrites, rhyolites and andesites (90 - 53 Ma)
Granodiorite to granite (80 - 61 Ma)
Limestone and sandstone
Jalisco block (late Cretaceous - early Eocene)

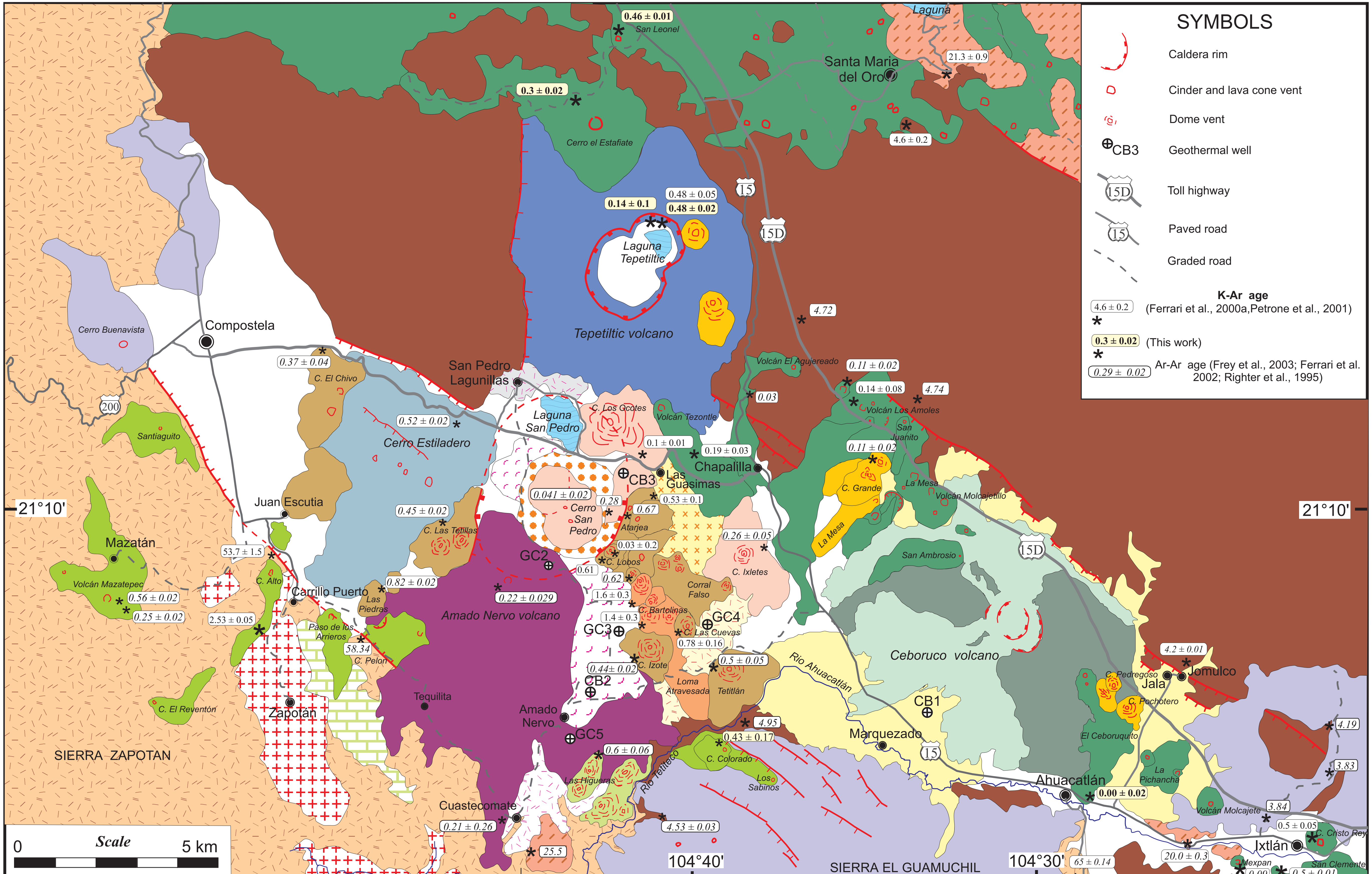


Figure 6. Geologic map of the San Pedro - Ceboruco area.

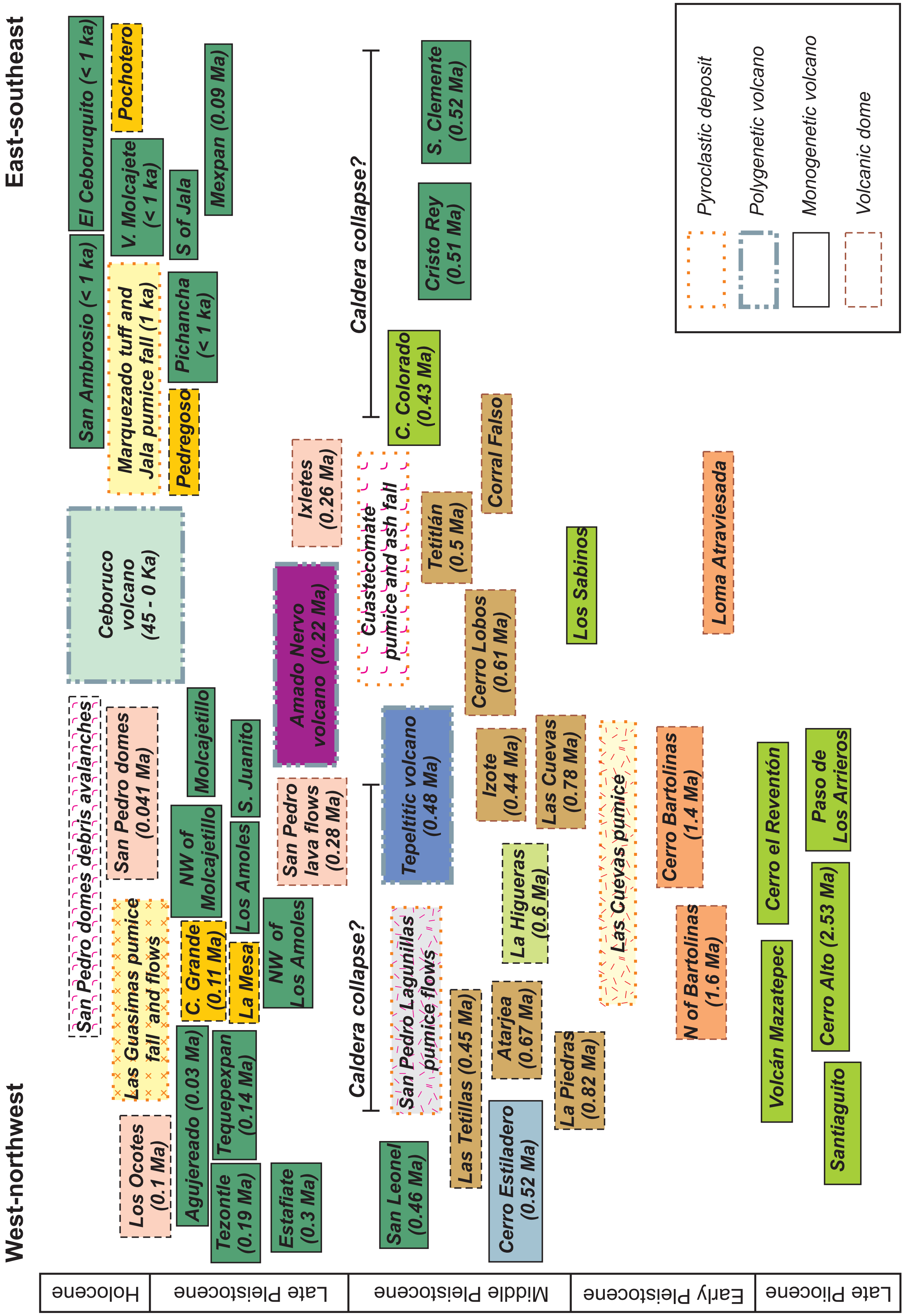


Figure 7. Location of the Pliocene and Quaternary volcanic edifices in space and time. Stratigraphic relation among units is based on direct field observation, age, or geologic correlation.

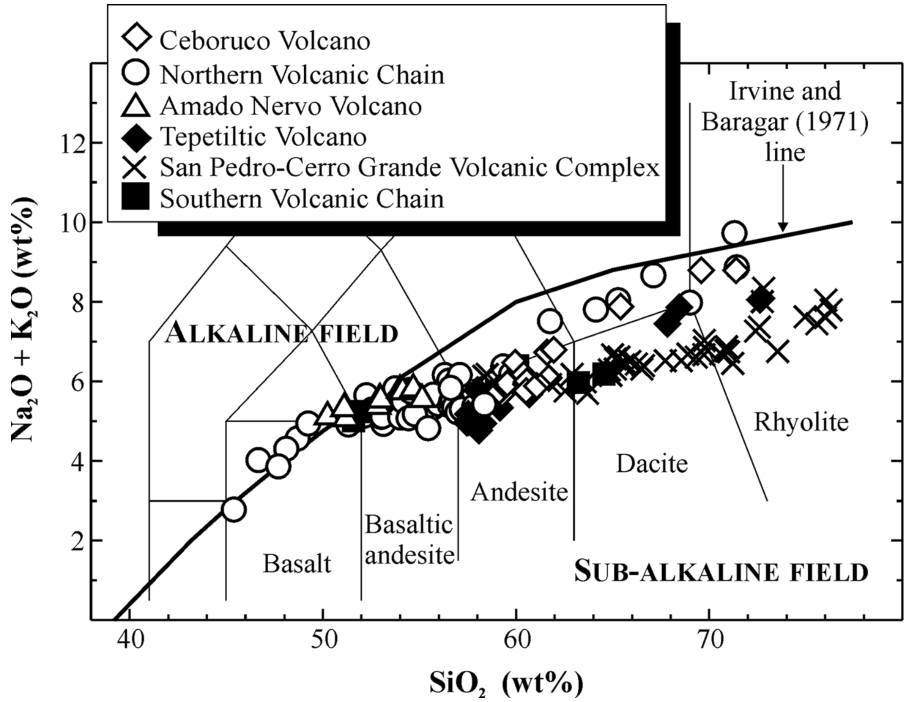


Figure 8. Total Alkalies *vs.* Silica (wt.%) (Le Bas *et al.*, 1992) diagrams for Pleistocene–Holocene rocks from San Pedro–Ceboruco graben (modified from Petrone, 1998 and Petrone *et al.*, 2003)

younger succession of ignimbrites with ages of 23 to 20 Ma, locally covered by basalts dated at 21–20 Ma (see also Rossotti *et al.*, 2002). This succession, however, overlies Oligocene ignimbrites and andesites, and Oligocene–Miocene subvolcanic bodies (Ferrari *et al.*, 2002).

The SMO succession, exposed in the Santa Fe area about 10 km north of Ceboruco volcano, is composed of ~800 m of rhyolitic ash flows and minor basaltic to andesitic lavas, which cover subvolcanic stocks and plutons with diorite to granite compositions. The entire succession has Oligocene to early Miocene ages and the subvolcanic rocks crop out at ~500 m asl at most. By contrast, Cretaceous granitic rocks belonging to the Puerto Vallarta batholith are exposed at elevation of 2,500 m asl to the south of the SPC. This implies that the JB has been uplifted considerably with respect to the SMO and that they are separated by a major tectonic discontinuity, now covered by the volcanism of the TMVB. Extensional reactivation of this tectonic boundary has formed the SPC tectonic depression since late Miocene (Ferrari *et al.*, 2000b).

Late Miocene basalts

A succession of late Miocene basalts is only found in the deeper part of well CB1 drilled by Comision Federal de Electricidad on the lower southern slope of Ceboruco volcano (Figures 3 and 5). The well cuttings and two cores indicate that the succession is composed of about 850 m of sub-aphyric mafic lava flows with minor intercalations of pumice and ash flows. They rest directly on altered volcanic rocks, tentatively correlated to the Jalisco block succession cored at well CB 2. Ferrari *et al.* (2000b) dated by K–Ar and $^{40}Ar/^{39}Ar$ methods a sample cored at a depth of ~2,000 m, near the base of the mafic succession. They conclude that the $^{40}Ar/^{39}Ar$ integrated age of 8.5 ± 0.2 Ma represents the best estimate of the age of this buried succession. The dated sample shows a basaltic andesite composition with a sub-alkaline affinity. The age and the geochemical affinity suggest that the basalts could be correlative with the 9 Ma old Cinco de Mayo basaltic plateau northwest of Tepic (Righter *et al.*, 1995; Ferrari *et al.*, 2000b). The existence of late Miocene basaltic rocks at the bottom of the Ceboruco graben indicates that the depression began to develop concurrently with the proto-Gulf of California extension during a late Miocene right-lateral transtensional episode (Ferrari *et al.*, 2000b).

Pliocene volcanism

The northern side of the SPC is bounded by WNW–ESE normal faults that cut a relatively high plateau formed by rhyolitic lava flows and silicic pyroclastic flows (*i.e.*, Jala rhyolites and ignimbrites, Figure 6). This succession is well exposed near the canyon north of Jala village and along the roadcuts of toll Highway 15D northwest of Ceboruco volcano. Rhyolitic lavas dominate towards the west and are frequently hydrothermally altered. Pyroclastic flows are more abundant to the east and contain ash, pumice and sanidine crystals. The succession has a maximum thickness of 400 m and has been dated at ~4.2 Ma east of Ceboruco volcano (Righter *et al.*, 1995; Frey *et al.*, in press) and 4.6 ± 0.2 near Santa María del Oro (Gastil *et al.*, 1978). Recently Frey *et al.* (in press) reported very similar ages for rhyolites north of Ceboruco and an age of 4.95 Ma for an ignimbrite in the lower northern slope of Sierra el Guamichil (Figure 6). The early Pliocene silicic lavas and pyroclastic flow deposits exposed in the SPC area extend up to 40 km to the east of the study area. Ferrari *et al.* (2001) estimated a cumulate volume of about 500 km^3 for this volcanism.

In the southern and south-eastern side of the SPC, the Jala rhyolitic succession is covered by basaltic to andesitic lava flow (Ixtlan and Buenavista basalt and andesite). One flow to the east of the study area was recently dated as early Pliocene (Ferrari *et al.*, in preparation). Similarly, Frey *et al.* (in press) dated two basaltic samples north of Ixtlán at 3.8 Ma. In the western side of the SPC, basaltic lavas of possible late Pliocene age constitute Cerro Buenaventura, a partly dissected polygenetic volcano located at the western end of the southern boundary fault of SPC.

Southern volcanic chain (late Pliocene–middle Pleistocene)

Several small cinder cones and a few domes were emplaced along the WNW trending faults that bound the SPC to the south. Collectively, they were named "Southern Volcanic Chain" by Petrone *et al.* (2001) and produced relatively thick lava flows whose composition range form basalt to andesite with only subordinate dacite (Figure 7). One of the flows along the southwestern boundary of the SPC was dated at 2.53 ± 0.05 Ma by Petrone *et al.* (2001) (Cerro Alto, Figure 6). Frey *et al.* (in press) obtained an age of 0.6 ± 0.06 for a dacitic dome located to the southeast (Las Higueras, Figure 6). In addition we have dated a flow from Cerro Colorado (Figure 6), which covers an older flow from the nearby Los Sabinos cinder cone. Duplicate K–Ar analyses for this sample (SPC 106) are in good agreement to each other although they gave a weighted mean age of 0.43 ± 0.17 Ma. The large analytical error is probably due to the high atmospheric ^{40}Ar contamination (see ^{40}Ar atm % and ^{40}Ar rad content in Table 1). The K–Ar age obtained for SPC 106 and for the Las Higueras dome (Frey *et al.*, in press) significantly expands the time span for the activity of the Southern Volcanic Chain.

San Pedro–Cerro Grande volcanic complex (Pleistocene)

The center of the SPC is the site of numerous andesitic to rhyolitic domes (Figure 7) having ages that span the whole Pleistocene (Figure 6). The San Pedro domes are the highest peaks and rise inside of a 7 to 10-km-wide elliptical caldera. We recognized three periods of activity.

During the first period at least 5 domes were emplaced along a NW trending alignment to the southeast of San Pedro. These domes yielded ages of 1.6 to 1.4 Ma (Ferrari *et al.*, 2000a). A pyroclastic sequence consisting of fall deposits alternating with surges and ash deposits, is well exposed near Las Cuevas and clearly underlie the domes of the second period of activity (Figures 6 and 7).

During the second period of activity, several domes and flows were emplaced without a clear alignment either on the ESE or on the WNW of San Pedro domes. These rocks were dated between 0.82 and 0.44 Ma (Ferrari *et al.* 2000a; Petrone *et al.*, 2001; Frey *et al.*, in press). This period ended with a caldera collapse in the San Pedro area, which is presently partially buried by younger volcanic products. The caldera rim is clearly observable on its eastern side, where it cuts the Cerro Lobos dome, dated 0.61 ± 0.21 Ma (Petrone *et al.*, 2001) and the Atarjea dome, dated 0.67 ± 0.06 Ma (Frey *et al.*, in press). In addition, the caldera seems to cut also Cerro Las Tetillas (Figure 6) recently dated at 0.45 ± 0.19 Ma (Frey *et al.*, in press). Although several pyroclastic deposits are found in the area, a more detailed volcanologic study is needed to clearly identify those associated with the caldera formation. The deposits most likely associated with the caldera collapse are pumice and ash falls deposits, up to 40 m thick, exposed about 10 km to the south of the caldera between Amado Nervo and Cuastecomate (Cuastecomate pumice and fall, Figure 6). In proximal areas, such pyroclastics are buried under younger rocks, but a similar deposit has been encountered between 50 and 90 m of depth in the CB 2 well, drilled south of the caldera (Figures 3 and 6). Similar pumice layers were also encountered in the GC5 well beneath the first succession of lavas of the Amado Nervo volcano (Figure 4).

The third period of volcanic activity is characterized by the outpouring of magmas along the caldera rim and inside the caldera. The activity spans between around 0.28 Ma and 0.030 Ma (Ferrari *et al.*, 2000a; Frey *et al.*, in press). The silicic (dacite and rhyolites, Figure 8) activity was renewed with the emplacement of Cerro Los Ocotes dome and its associated Las Guasimas pyroclastic fall and flow deposit at 0.1 ± 0.01 Ma (Ferrari *et al.*, 2000a). The dome was emplaced along the northwestern part of the caldera rim and exhibits spectacular flow banding. Mafic lava flows also vented from the southern caldera rim, making up the Amado Nervo volcano. Because its eruption style and chemical composition are completely different from domes of the San Pedro Volcanic Complex, this volcanic apparatus is described in a separate section below.

Inside the caldera, the three coalescing domes of Cerro San Pedro were emplaced at 0.027 ± 0.07 Ma and 0.055 ± 0.08 Ma (^{40}Ar/^{39}Ar dates by Frey *et al.*, in press) giving a mean age of 0.041± 0.02 Ma. The domes are aligned along a NW trending fracture. Two of the domes have partly collapsed and avalanche deposits are found to the northwest and to the southeast. The former deposit is clearly observable by the hummocky morphology given by slide blocks of the dacite. The southern collapse probably destroyed the southern rim of the caldera and the related deposit is found up to 10 km from the source (Figure 6).

The well CB 3 drilled just south of Cerro Los Ocotes (Figures 3 and 6) penetrated about 930 m of rhyolites and dacites of the San Pedro dome complex and then over 1,000 m of biotite–pyroxene granite. Structural and petrographic considerations suggest that this rock does not belong to the JB but, rather, to a Neogene (early Pleistocene?) subvolcanic intrusion related to the silicic magmatism in the San Pedro area.

Tepetiltic volcano (Middle Pleistocene)

Tepetiltic is a small calc-alkaline stratovolcano composed primarily of andesite and dacite lava flows with subordinate rhyolitic rocks (Figure 8). It is topped by an elliptical caldera measuring approximately 3 by 2 km (Figure 6). DeRemer and Nelson (1985) suggest that the complex was built by two cycles of andesite volcanism followed by differentiation into volumetrically subordinate dacites. The second pulse of andesitic lavas was more mafic than the first and could have been the result of reinjection of fresh mafic magma into the shallow andesitic magma chamber. Tepetiltic activity culminated in a large caldera-forming rhyolitic ash eruption, which resulted in plinian air fall, base surge, and ash flow deposits now found surrounding the volcano. After caldera formation, two rhyolite domes and associated ash fall deposits were emplaced on the eastern flank of the volcano and two small hornblende andesite domes were emplaced on the floor of the caldera. A lake now fills the northeastern corner of the caldera.

Lavas from the basal part of the Tepetiltic volcano were recently dated at 0.48 ± 0.05 Ma by Petrone *et al.* (2001). We have dated another andesitic flow from the northern caldera wall at 0.48 ± 0.02 (Table 1), confirming the previous age for a basal lava flow of this volcano. The newly dated sample (SPC 79) was taken along the caldera wall in a location closer to the caldera rim than the sample dated by Petrone *et al.* (2001), and both are part of the pre-caldera activity.

Amado Nervo volcano (Middle Pleistocene)

To the southwest of Cerro San Pedro, the caldera has been filled by several mafic lava flows that erupted from a vent located on the inferred caldera rim (Amado Nervo flows of Petrone *et al.*, 2003) (Figures 5 and 6). These flows form a shield-like structure that is called here Amado Nervo volcano. Different flows from Amado Nervo volcano were recently dated at 0.22 ± 0.029 and 0.21 ± 0.026 Ma by the $^{39}Ar/^{40}Ar$ method. The lavas of Amado Nervo volcano have sub-aphyric textures with euhedral olivine phenocrysts. They are mildly Na-alkaline basalts and basaltic andesites, and range in compositions from hawaiite to mugearite (Figure 8).

The volcano is elongated to the south probably because it was constructed on a south dipping slope outside the caldera. The stratigraphy of the wells indicates that the Amado Nervo volcano is over 120 m thick inside the caldera (GC 2 well, Figure 4) whereas it is only 50 to 70 m thick to the south (CB2 and GC5 wells, Figure 3 and 4).

Northern volcanic chain (middle to late Pleistocene)

A 30 km long, WNW trending alignment of cinder cones and domes is partly superimposed on the Tepetiltic and Ceboruco volcanoes and parallels the main fault system that bound the SPC to the north. The vents are aligned along a south dipping normal fault system (Ceboruco faults). The fault scarp can be seen only in places because it is covered by the younger basaltic flows of the cinder cone line. Most of the cones emitted lavas ranging in composition from basalt to andesite. However, some of the centers emplaced on the slope of Ceboruco volcano are more differentiated and consists of dacite-trachydacite and rhyolite (Figure 8). These rocks are mostly transitional between intra-plate and calc-alkaline affinity, but rocks with clear intra-plate type signature are also present (Figure 8) (Petrone *et al.*, 2003).

Petrone *et al.* (2001) and Frey *at al.* (2003) dated several of the cinder cones and obtained ages comprised between 0.5 and 0.01 Ma. We have dated four additional samples on the northernmost part of the alignment (SPC 21; SPC 39; SPC 74 and SPC 150) and obtained ages ranging from 0.46 Ma to present. A cinder cone north of Tepetiltic near San Leonel (SPC 150) was dated 0.46 ± 0.01 Ma (Table 1; Figure 6), which is significantly older than the other cones located around Tepetiltic volcano. A lava flows erupting from Cerro El Estafiate (SPC 21), a prominent cone northwest of Tepetiltic, yielded an age of 0.3 ± 0.02 Ma (Table 1; Figure 6). K–Ar analysis performed on a very fresh lava flow from Volcán Molcajete (SPC 39), located on the lower eastern flank of Ceboruco (Figure 6), gave an age of 0.00 ± 0.02 Ma, which indicates that this sample is too young to be dated even with the used K–Ar unspiked sensitivity method. Duplicate analyses performed on the sample SPC 74 are indistinguishable from each other at 1 sigma uncertainty level, with rather high atmospheric ^{40}Ar contamination. This gives a less precise weighted mean age of 0.14 ± 0.10 Ma (Table 1). The greater atmospheric ^{40}Ar contamination might be due to the abbundant of vescicles characterizing this sample. This sample is actually a bomb collected on the caldera rim of Tepetiltic volcano that was probably ejected from one of the cinder cones located around the volcano. Indeed, its age, chemical, and isotopic composition is indistinguishable from that of all other Na-alkaline volcanic rocks from the northern volcanic chain (Petrone *et al.*, 2003). Overall, these ages confirm and expand the range of ages obtained by Petrone *et al.* (2001) and Frey *et al.* (in press) for the volcanic activity of the Northern Volcanic Chain and indicate that the youngest volcanism is concentrated close to the active Ceboruco volcano

Ceboruco volcano (Holocene)

Volcán Ceboruco is the only volcano in the northwestern Trans–Mexican Volcanic Belt with reported historical activity. Its last eruption occurred during the years 1870 through 1875 A.D. (Iglesias *et al.*, 1877). The volcano rises to an elevation of about 2,200 m and is crowned by two concentric calderas. The volcano has an elevation of about 1,100 m above the surrounding valleys of Ahuacatlán and Jala, but it could have been 500 m higher before the caldera forming eruption. Nelson (1980, 1986) gives a comprehensive report on the geological history of Ceboruco. More recently Gardner and Tait (2000) provided a very detailed study of the plinian eruption that formed the outer caldera.

Volcán Ceboruco is a small calc-alkaline stratovolcano with andesitic lava flows predominant over felsic pyroclastic units (Figure 8; Petrone, 1998). One of the uppermost andesitic lavas has been dated at 45 ka (Frey *et al.*, in press). A period of repose of unknown duration is inferred after this main phase because several canyons are cut on the western and eastern flanks of the volcano. Before and during this repose period, cinder cones and trachydacitic domes of the northern volcanic chain erupted along a northwest trending line through Ceboruco.

About 1,000 years ago, a Plinian eruption produced thick deposits of chemically zoned trachydacitic and rhyolitic pyroclastic deposit (Jala pumice of Nelson, 1980), which consists of a main Plinian fall and several pyroclastic surge and flows. The main fall is presently found as far as 30 km to the northeast of the volcano. Gardner and Tait (2000) estimated that a total of 3 to 4 km^3 of magma was erupted, 95% of which was deposited as air falls. During the same eruption the Marquezado pyroclastic flow was erupted down the southwestern and northwestern flanks of the volcano. During these eruptions, a magma chamber beneath Ceboruco was evacuated and the top of the mountain collapsed to form the outer caldera with a diameter of about 4 km. After the caldera formation, a dacite volcanic dome was emplaced on the floor of the caldera. The dome subsequently collapsed after the eruption of dacite lava flows from its southwestern and western margins, and formed the inner caldera, 1.5 km in diameter. Many andesitic lava flows were emplaced in the last 1,000 years.

The Marquesado ash deposit is unwelded and contains a high proportion of andesitic lithic fragments and rounded rhyodacite pumice lapilli in a fine grained matrix consisting of vitric ash. High in the section, several lenses of concentrated pumice can be observed. The deposits show a maximum thickness of about 60 m, and have a volume estimated at about 0.2 km^3 (Nelson, 1980). The deposit on the southwestern flank of Ceboruco is distributed below the zone where the outer caldera wall is missing or has been breached. The andesitic lithic fragments within the Marquesado ash are all similar to rocks found in the outer caldera walls. This prompted Nelson (1980) to suggest that the outer caldera walls may have been explosively ejected along with the Marquesado ash. In some areas re-worked ash deposits cover the upper parts of the Marquesado ash. In other areas, the Jala Pumice is seen to overly the Marquesado ash without an erosional break between the two deposits. To the east of this locality the Marquesado ash and Jala pumice are overlain by lake deposits. It thus appears that the emplacement of the Marquesado ash blocked the drainage of the Río Ahuacatlán causing a lake to form in the eastern part of the Ceboruco valley until streams were able to cut through the deposit to drain the lake.

TECTONICS

Structure, kinematics and age of faulting

Although for simplicity we define the region of San Pedro – Ceboruco as a graben, the real structure is actually more complex. Indeed, the geothermal drillings indicate that three segments form this depression: 1) the Compostela graben to the west, 2) the San Pedro central depression, and 3) the Ceboruco asymmetric graben to the east (Ferrari and Rosas-Elguera, 2000). The Compostela graben is bounded by two WNW–ESE striking normal fault systems cutting an early Pliocene rhyolitic complex in the north, and Cretaceous to Paleocene ash flows and plutons of the JB in the south (Figure 6). Although no well was drilled inside the Compostela graben, simply considering the topography, the bounding faults must have a minimum displacement of 400 m. Inside the graben, middle Pleistocene lava flows of Cerro Estiladero are cut by a normal fault parallel to the bounding fault, but with less than 50 m of displacement, so the faults should have been active mostly in pre-Quaternary times.

The rhyolitic complex to the west of Tepetiltic is cut by N–S striking normal faults, which also appear to cut the eastern part of the Compostela graben and Cerro Las Tetillas (recently dated at 0.45 Ma by Frey *et al.*, in press). These N–S faults form the depression where the San Pedro–Cerro Grande caldera and Amado Nervo volcano developed (Figure 6). Both these volcanic structures are younger than the N–S striking faults, constraining the age of this extension to the middle Pleistocene. The deep geothermal well CB2 drilled just south of the San Pedro caldera found rocks correlative with the JB succession at 820 m of depth (Figure 3). Based on this data, Ferrari and Rosas-Elguera (2000) estimated that the JB rocks were down faulted a minimum of 1,100 m by the combined action of the WNW faults of the Compostela graben and the N–S fault bounding the San Pedro central depression.

The Ceboruco asymmetric graben is bounded to the north by WNW–ESE striking faults, which cut a rhyolitic and ignimbritic succession dated at 4.7 to 4.2 Ma (Righter *et al.*, 1995, Frey *et al.*, in press). North of Ixtlán, the fault scarps are covered by basaltic lavas dated at 3.8 Ma (Frey *et al.*, in press), thus constraining the extension to the early Pliocene. The southern side of the depression consists of a NNE dipping monocline made of early Pliocene (~ 4.9 Ma) rhyolites and andesites (Frey *et al.*, in press) that are also cut by WNW–ESE striking normal faults (Figure 6). This suggests that the normal faults to the north of Ceboruco have listric geometry and have tilted the Sierra El Guamuchil block to the NNE. The extension in the Ceboruco area however, may be older than Pliocene. In fact, as described before, well CB1, drilled on the southern slope of Ceboruco volcano (Figure 3 and 6) encountered about 1,800 m of aphyric to microporphyritic basaltic-andesitic flows from which a date of 8.5 ± 0.2 Ma ($^{40}Ar/^{39}Ar$) was obtained from near the base (Ferrari *et al.*, 2000b). The existence of late Miocene basalts at the bottom of the Ceboruco graben indicates that this extensional structure began to develop concurrently with the proto-Gulf extension. Ferrari *et al.* (2000b) suggest that this reactivation took place in a right lateral transtensional regime produced by a west-southwest motion of the Jalisco block.

Extension rate

The structure of the Ceboruco asymmetric graben is tentatively depicted in the geologic section of Figure 9 that is based on the stratigraphy of the CB 1 well. We used this section to estimate the amount of extension in this part of the Tepic–Zacoalco rift by means of the area-balance method described by Groshong (1994) (Figure 9). The major uncertainty in this case is the depth of the detachment level, which we realistically consider to be at 6 km below the surface. Our result indicates that since the late Miocene the extension has been less than 10%, in agreement with the low rate of deformation estimated by Ferrari and Rosas-Elguera (2000) for the whole Tepic–Zacoalco rift.

Relation between extension, volcanism, and subduction

Most of the Quaternary volcanism in the SPC is aligned along the main extensional fault systems that, therefore, control the locus of the volcanic activity (Figure 6). A temporal link between volcanism, extensional faulting and the evolution of subduction boundary is also apparent from our data. As mentioned before, the main WNW–ESE striking normal faults that bound the modern SPC developed after 4.2 Ma and before the emplacement of 3.8 Ma basaltic

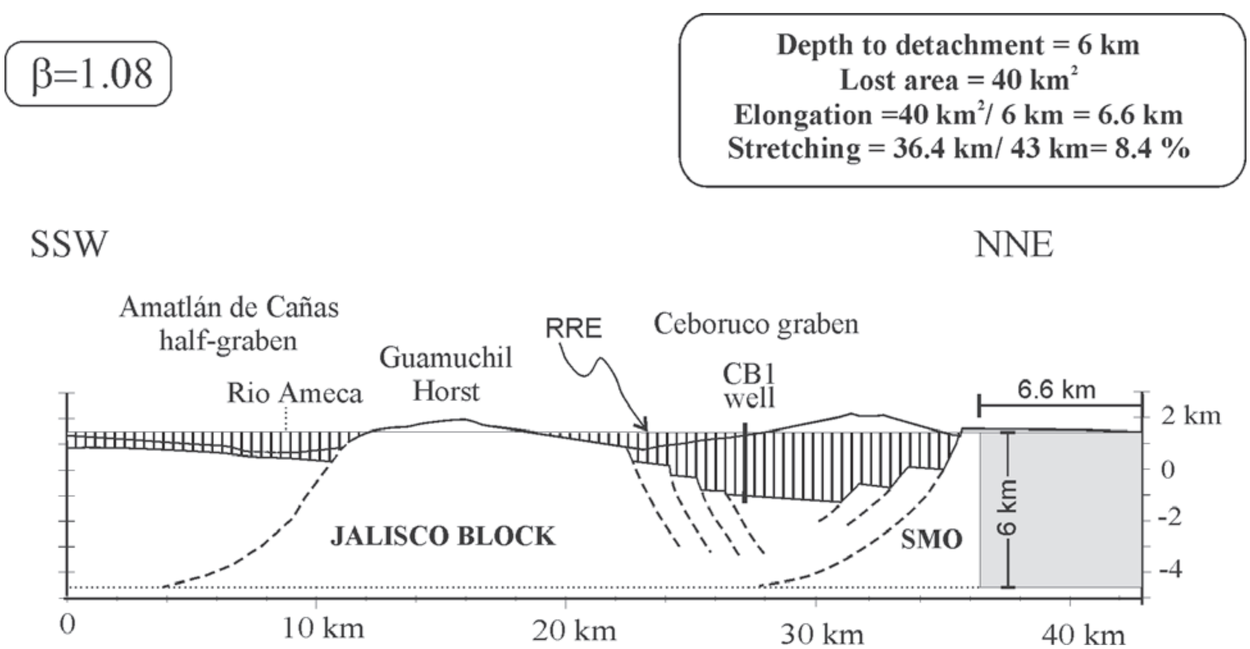


Figure 9. Estimation of amount of extension along the SPC and Ameca half graben using the area-balance method described by Groshong (1994). The area vertically ruled is equal to the gray one. The figure shows the most consistent solutions according to the geology of the region and is constrained by the results of the CB1 well. Dashed lines represent inferred faults at depth. RRE is the regional reference level that is our best estimate of the topographic surface before extension.

volcanism. A similar situation occurred in the region to the east of Ceboruco (Hostotipaquillo–Plan de Barrancas; Ferrari *et al.*, 2000a) where 3.8–3.3 Ma alkaline basalts were emplaced after the main extensional faulting. Interestingly, the early Pliocene episode of faulting and volcanism corresponds to a period of high convergence between the Rivera and North America plates (DeMets and Traylen, 2000). On the other hand, the available ages indicate very low to none volcanic activity between the emplacement of the 3.8 Ma basalts and the end of Pliocene, when the relative motion between the Rivera plate and North America also decreased to very low values (DeMets and Traylen, 2000). Finally, both convergence and volcanism resumed since 1 Ma when minor extensional faulting is also present. Traditionally, the style of deformation and volcanism in the upper plate has been related to the age of the subducting plate (*e.g.*, Jarrad, 1986). Extensional faulting, rifting and even back-arc spreading characterize arcs related to the subduction of very old lithosphere with high dip angle like in the western Pacific margin. In the case of the western TMVB, the subducting Rivera plate is very young (~10 Ma at the trench) but show about 50° of inclination. Our study in the SPC suggest that, rather than the age of the plate, both extensional faulting and volcanic activity are related to rate of convergence of the Rivera plate. This suggests that velocity of subduction is the main factor in controlling both the volcanic flux and the strain rate in the western TMVB.

ACKNOWLEDGEMENTS

This research was supported by a C.N.R. (Italy) – CONACyT (Mexico) bilateral grant, by UNAM–PAPIIT IN108196 grant (to Ferrari), and by Università degli Studi di Firenze (ex-60% funds). We thank Dr. Hiriart Le Bert, Gerencia de Proyectos Geotermoelectricos of Comisión Federal de Electricidad, for providing cores and stratigraphy of exploratory wells. L. Ferrari also thanks Francisco Romero Ríos and Daniel Castillo Hernández for an introduction to the geology of the area in an early phase of the fieldwork. Hugo Delgado provided a copy of manuscript in advance of publication. Holli Frey is thanked for clarifying several details of her paper. Reviews by Steve Nelson and Kevin Righter helped to improve the presentation of the paper.

APPENDIX

Analytical procedure of the geochronological experiments

For each sample, about 100 g of fresh rock were crushed in a stainless steel mortar and sieved to 30–60 mesh. The sieved samples were washed first with de-ionized water and then with acetone in an ultrasonic cleaner to remove fine grains. Phenocrysts were removed from the fraction in a Frantz isodynamic magnetic separator and by hand-picking, in order to minimize the possible influence of excess argon (Takaoka, 1989; Matsumoto *et al.*, 1989). An aliquot of each sample was ground further by an automatic agate mortar for potassium analysis.

Potassium concentrations were measured by flame emission photometry, with lithium internal standard and peak integration method (Matsumoto, 1989). The analysis was performed at the Kyoto University Geochronology Laboratory with a FP-33D flame emission photometer, made by Hekisa Kagaku Co., Japan. About 100 mg of sample was used for each analysis. See Matsumoto (1989) for details on handling procedures. In order to confirm the precision and accuracy of the present analysis, potassium concentrations were also determined at the same analytical condition on the Geological Survey of Japan (GSJ) standards JA-2 and JB-3 (Ando *et al.*, 1989; Matsumoto, 1989). The estimated precision and accuracy of the sample data was ~1% (1 sigma), which was propagated to the error of K–Ar age.

Argon isotopic measurements were performed by peak height comparison method (Matsumoto *et al.*, 1989; Sudo *et al.*, 1996). The analysis were performed at the Kyoto University Geochronology Laboratory with a VG 3600 mass spectrometer operated in the static mode, connected to extraction and purification lines made by Ayumi Co. Ltd., Japan. The extraction and analysis system as well as the techniques used for argon isotopic measurements were described by Sudo *et al.* (1996). The standard air, calibrated with Sori 93 biotite standard (Sudo *et al.*, 1998), and hot blanks were measured periodically during the experiments for system sensitivity, mass discrimination and background corrections. Samples ranging from 0.26 to 5.34 g were analyzed in this study. Preliminary analysis were conducted for each sample in order to obtain reliable analysis by loading optimized weight of samples. The duplicate analyses of radiogenic ^{40}Ar generally agree within error.

K–Ar ages were calculated using the isotopic abundances and decay constants for ^{40}K recommended by the IUGS Subcommission on Geochronology (Steiger and Jäger, 1977; $\lambda e = 0.581 \times 10^{-10}$ y^{-1}, $\lambda\beta = 4.962 \times 10^{-10}$ y^{-1}, ^{40}K/K = 1.167×10^{-4}).

REFERENCES

Allan, J.F., Nelson, S.A., Luhr, J.F., Carmichael, I.S.E., Wopat, M., Wallace, P.J., 1991, Pliocene–Recent rifting in SW Mexico and associated volcanism: an exotic terrain in the making, *in* Dauphin, J.P., Simoneit, B.R.T. (eds.), The Gulf and the Peninsular Province of the Californias: American Association of Petroleum Geologists, Memoir, 47, 425–445.

Ando, A., Mita, N., Matsumoto, A., 1989, 1987 compilation of K_2O concentrations in seventeen GSJ rock reference samples, "Igneous rock series": Geological Survey of Japan, Bulletin, 40, 19–45.

Barrier, E., Borgois, J., Michaud, F., 1990, Le systeme de rift actifs du point triple de Jalisco: vers un proto-golfe de Jalisco: Comptes Rendus de l'Academie des Science, Paris, 310, 1513–1520.

Bourgois, J., Michaud, F., 1991, Active fragmentation of the North America plate at the Mexican triple junction area off Manzanillo: Geo-Marine Letters, 11, 59–65.

Castillo, D., de la Cruz, V., 1992, Reconocimiento estructural y volcanológico en la zona termal del Domo San Pedro Lagunillas, Nayarit, México: Geofisica Internacional, 31, 407–415.

DeMets, C., Traylen, S., 2000, Motion of the Rivera plate since 10 Ma relative to the Pacific and North American plates and the mantle: Tectonophysics, 318, 119–159.

DeRemer, L.A., Nelson, S.A., 1985, Geologic and chemical evolution of Volcan Tepetiltic, Nayarit, Mexico: Geological Society of America, Abstracts with Programs, 17, 561.

Ferrari, L., 1995, Miocene shearing along the northern boundary of the Jalisco block and the opening of the southern Gulf of California: Geology, 23, 751–754.

Ferrari, L., Rosas-Elguera, J., 1994, Structure, kinematics and rate of deformation of the Tepic–Zacoalco rift, Western Mexico: EOS, Transactions, American Geophysical Union, Fall Meeting, 75 (44), 675.

Ferrari, L., Rosas-Elguera, J., 2000, Late Miocene to Quaternary extension at the northern boundary of the Jalisco block, western Mexico: the Tepic–Zacoalco rift revised, *in* Delgado-Granados, H., Aguirre-Díaz, G., Stock, J.M. (eds.), Cenozoic Tectonics and Volcanism of Mexico: Boulder, Geological Society America, Special Paper, 334, 41–64.

Ferrari,L., Pasquaré, G., Venegas, S., Castillo, D., Romero, F., 1994, Regional tectonics of western Mexico and its implications for the northern boundary of the Jalisco Block: Geofisica Internacional, 33, 139–151.

Ferrari, L., Nelson, S.A., Rosas-Elguera, J., Aguirre-Díaz, G., Venegas-Salgado, S., 1997, Tectonics and volcanism of the western Mexican Volcanic Belt, *in* Aguirre-Diaz, G., Aranda-Gómez, J, Carrasco-Núñez, G., Ferrari, L. (eds.), Magmatism and Tectonics in Central and Northwestern Mexico; A selection of the 1997 IAVCEI General Assembly, Excursions: México, D.F., Universidad Nacional Autónoma de México, Instituto de Geología, 85–129.

Ferrari, L., Pasquaré, G., Venegas, S., Romero, F., 2000a, Geology of the western Mexican Volcanic Belt and adjacent Sierra Madre Occidental and Jalisco block, *in* Delgado-Granados, H., Aguirre-Díaz, G., Stock, J.M. (eds.), Cenozoic Tectonics and Volcanism of Mexico: Boulder, Geological Society America, Special Paper, 334, 65–84.

Ferrari, L., Conticelli, S., Vaggelli, C., Petrone, C., Manetti, P., 2000b, Late Miocene mafic volcanism and intra-arc tectonics during the early development of the Trans-Mexican Volcanic Belt: Tectonophysics, 318, 161–185.

Ferrari, L., Petrone, C.M., Francalanci, L., 2001, Generation of OIB-type volcanism in the western Trans-Mexican Volcanic Belt by slab rollback, astenosphere infiltration and variable flux-melting: Geology, 29, 507–510.

Ferrari, L., López-Martínez, M., Rosas-Elguera, J., 2002, Ignimbrite flare up and deformation in the southern Sierra Madre Occidental, western Mexico: implications for the late subduction history of the Farallon plate: Tectonics, 21(4), 17–1/24.

Frey, H.M., Lange, R.A., Hall, C.M., Delgado-Granandos, H., in press, Magma eruption rate constrained by ^{40}Ar–^{39}Ar chronology and GIS for the Ceboruco–San Pedro volcanic field, western Mexico: Geological Society of America Bulletin.

Gardner, J.E., Tait, S., 2000, The caldera-forming eruption of Volcán Ceboruco, Mexico: Bulletin of Volcanology, 62, 20–33.

Gastil, R.G., Phillips, R.P., Allison, E.C., 1975, Reconnaissance geology of the state of Baja California: Geological Society of America, Memoir, 140, 170 p.

Gastil, G., Krummenacher, D., Jensky, A.W, 1978, Reconaissance geologic map of the west-central part of the state of Nayarit, Mexico: Geological Society of America, Map and Chart Series, MC-24, scale 1:200.000, 1 map.

Groshong, R.H., 1994, Area balance, depth of detachment, and strain in extension: Tectonics, 13, 1488–1497.

Iglesias, M., Barcena, M., Matute, J.I., 1877, Informe sobre los temblores de Jalisco y la erupción del Volcán Ceboruco: Anales del Ministerio de Fomento, México, 1, 115–196.

Irvine, T.N., Baragar, W.R.A., 1971, A guide to the chemical classification of the common rocks: Canadian Journal Earth Sciences, 8, 523–548.

Itaya, T., Nagao, K., 1988, K–Ar age determination of volcanic rocks younger than 1 Ma: Memoirs of the Society of Geological Japan, 29, 143–161 (in Japanese with English abstract).

Jarrard, R.D., 1986, Relations among subduction parameters: Reviews of Geophysics, 24, 2, 217–283.

Kohler, H., Schaaf, P., Muller, S.D., Emermann, R., Negendank, J.F.W., Tobschall, H.J., 1988, Geochronological and geochemical investigations on plutonic rocks from the complex of Puerto Vallarta, Sierra Madre del Sur: Geofisica Internacional, 27, 579–592.

Lange, R., Carmichael, I.S.E., 1990, Hydrous basaltic-andesites associated with minette and related lavas in Western Mexico: Journal of Petrology, 31, 1225–1259.

Lange, R., Carmichael, I.S.E., 1991, A potassic volcanic front in western Mexico: lamprophyric and related lavas of San Sebastian: Geological Society of America Bulletin, 103, 928–940.

Le Bas, M.J., Le Maitre, R.W., Woolley, A.R., 1992, The construction of the Total Alkali-Silica chemical classification of the volcanic rocks: Mineralogy and Petrology, 46, 1–22.

Luhr, J.F., Nelson, S.A., Allan, J., Carmichael, I.S.E., 1985, Active rifting in southwestern Mexico: manifestations of an incipient eastward spreading-ridge jump: Geology, 13, 54–57.

Matsumoto, A., 1989, Improvement for determination of potassium in K–Ar dating: Geological Survey of Japan, Bulletin, 40, 65–70.

Matsumoto, A., Kobayashi, T., 1995, K–Ar age determination of late Quaternary volcanic rocks using the "mass fractionation correction procedure": application to the Younger Ontake Volcano, central Japan: Chemical Geology, 125, 123–135.

Matsumoto, A., Uto, K., Shibata, K., 1989, K–Ar dating by peak comparison method; new technique applicable to rocks younger than 0.5 Ma: Geological Survey of Japan, Bulletin, 40, 565–597.

McDowell, F.W., Clabaugh S.E., 1979, Ignimbrites of the Sierra Madre Occidental and their relation to the tectonic history of western Mexico, *in* Chapin, C.E., Elston, W.E. (eds.), Ash-flow Tuffs: Boulder, Geological Society of America, Special Paper, 180, 113–124.

McDowell, F.W., Keizer, R.P., 1977, Timing of mid-Tertiary volcanism in the Sierra Madre Occidental between Durango city and Mazatlán, Mexico: Geological Society of America Bulletin, 88, 1479–1487.

Michaud, F., Quintero, O., Barrier, E., Burgois, J., 1991, La frontiére Nord du Bloc Jalisco (ouest Mexique): localisation et évolution de 13 Ma à l'actuel: Comptes Rendus de l'Academie des Science, Paris, II, 312, 1359–1365.

Moore, G., Marone, C., Carmichael, I.S.E., Renne, P., 1994, Basaltic volcanism and extension near the intersection of the Sierra Madre volcanic province and the Mexican Volcanic Belt: Geological Society of America Bulletin., 106, 383–394.

Nelson, S.A., 1980, Geology and petrology of Volcan Ceboruco, Nayarit, Mexico; Part II: Geological Society of America Bulletin., 91, 2290–2431.

Nelson, S.A., 1986, Geología del Volcán Ceboruco, Nayarit, México con una estimación de riesgos de erupciones futuras: Universidad Nacional Autónoma de México, Instituto de Geología, Revista, 6, 243–258.

Nelson, S.A., Carmichael, I.S.E., 1984, Pleistocene to recent alkalic volcanism in the region of Sanganguey volcano, Nayarit, Mexico: Contributions to Mineralogy and Petrology, 85, 321–335.

Nelson, S.A., Hegre, J., 1990, Volcan Las Navajas, a Pliocene–Pleistocene trachyte–peralkaline rhyolite volcano in the northwestern

Mexican Volcanic Belt: Bulletin of Volcanology, 52, 186–204.

Nelson, S.A., Livieres, R., 1986, Contemporaneous calc-alkaline and alkaline volcanism at Sanganguey Volcano, Nayarit, Mexico: Geological Society of America Bulletin, 97, 798–808.

Nieto-Obregón, J., Urrutia-Fucugauchi, J., Cabral-Cano, E., Guzman de la Campa, A., 1992, Listric faulting and continental rifting in western Mexico; a paleomagnetic and structural study: Tectonophysics, 208, 365–376.

Petrone, C.M., 1998, Studio magmatologico dei sistemi vulcanici del graben San Pedro–Ceboruco (Nayarit, Messico); coesistenza di magmi a diversa affinità petrologica: Firenze, Università degli Studi di Firenze (Italy), Tesis doctoral, 280 p. (in italian).

Petrone, C.M., Tagami, T., Francalanci, L., Matsumura, A., Sudo, M., 2001, Volcanic systems in the San Pedro–Ceboruco graben (Nayarit, Mexico) in the light of new K–Ar geochronological data: Geochemical Journal, 35, 77–88.

Petrone, C.M., Francalanci, L., Carlson, R.W., Ferrari, L., Conticelli, S., 2003, Unusual coexistence of subduction-related and intraplate-type magmatism: Sr, Nd and Pb isotope and trace elements data from the magmatism of the San Pedro–Ceboruco graben (Nayarit, Mexico): Chemical Geology, 193, 1–24.

Prol-Ledesma, R.M., Canet, C., Melgarejo, J.C., Tolson, G., Rubio-Ramos, M.A., Cruz-Ocampo, J.C., Ortega-Osorio, A., Torres-Vera, M.A., Reyes, A., 2002, Cinnabar deposition in submarine coastal hydrothermal vents, Pacific margin of central Mexico: Economic Geology, 97, 1331–1340.

Righter, K., 2000, A comparison of basaltic volcanism in the Cascades and western Mexico: compositional diversity in continental arcs: Tectonophysics, 318, 99–117.

Righter, K., Carmichael, I.S.E., 1992, Hawaiites and related lavas in the Atenguillo graben, western Mexican Volcanic Belt: Geological Society of America Bulletin, 104, 1592–1607.

Righter, K., Rosas-Elguera, J., 2001, Alkaline lavas in the volcanic front of the western Mexican Volcanic Belt: geology and petrology of the Ayutla and Tapalpa Volcanic Fields: Journal of Petrology, 42, 2333–2361.

Righter, K., Carmichael, I.S.E., Becker, T., 1995, Pliocene–Quaternary faulting and volcanism at the intersection of the Gulf of California and the Mexican Volcanic Belt: Geological Society of America Bulletin., 107, 612–627.

Rosas-Elguera, J., Ferrari, L., Garduño, V.H., Urrutia-Fucugauchi, J., 1996, The continental boundaries of the Jalisco block and their influence on the Plio–Quaternary kinematics of western Mexico: Geology, 24, 921–924

Rosas-Elguera, J., Ferrari, L., Lopez-Martinez, M., Urrutia-Fucugauchi J., 1997, Stratigraphy and tectonics of the Guadalajara region and the triple junction area, western Mexico: International Geology Review, 39, 125–140.

Rossotti, A., Ferrari, L., López-Martínez, M., Rosas-Elguera, J., 2002, Geology of the boundary between the Sierra Madre Occidental and the Trans-Mexican Volcanic Belt in the Guadalajara region, western Mexico: Revista Mexicana de Ciencias Geológicas, 19, 1–15.

Schaaf, P., Moran-Zenteno, D., Hernandez-Bernal, M., Solis-Pichardo, G., Tolson, G., Köhler, H., 1995, Paleogene continental margin truncation in southwestern Mexico: geochronological evidence: Tectonics, 14, 1339–1350.

Schaaf, P., Bohnel, H., Perez-Venzor, J.A., 2000, Pre-Miocene palaeogeography of the Los Cabos Block, Baja California Sur; geochronological and palaeomagnetic constraints: Tectonophysics, 318, 53–69.

Steiger, R.H., Jäger, E., 1977, Subcommission on geochronology; convention on the use of decay constants in geo- and cosmochronology, Earth and Planetary Science Letters, 36, 359–362.

Sudo, M., Tagami, T., Sato, K., Hasebe, N., Nishimura, S., 1996, Calibration of a new analytical system for the K–Ar dating method and analytical results of K–Ar age known samples: Memoirs of the Faculty of Science, Kyoto University, Series of Geology and Mineralogy, 58, 21–40.

Sudo, M., Uto, K., Anno, K., Ishizuka, O., Uchiumi, S., 1998, SORI93 biotite; a new mineral standard for K–Ar dating: Geochemical Journal, 32, 49–58.

Takaoka, N., 1989, Problem in K–Ar dating of Quaternary volcanic rocks: Journal of the Mass Spectrometry Society of Japan, 37 (6), 343–351. (in japanese)

Takaoka, N., Konno, K., Oba, Y., Konda, T., 1989, K–Ar dating of lavas from Zao Volcano, northeastern Japan: Geological Society of Japan, Journal, 95, 157–170 (in japanese with english abstract).

Verma, S.P., Nelson, S.A., 1989a, Isotopic and trace element constraints on the origin and evolution of alkaline and calc-alkaline magmas in the northwestern Mexican Volcanic Belt: Journal of Geophysical Research, 94, 4531–4544.

Verma, S.P., Nelson, S.A., 1989b, Correction to "Isotopic and trace element constraints on the origin and evolution of alkaline and calc-alkaline magmas in the northwestern Mexican Volcanic Belt": Journal of Geophysical Research, 96, 7679–7681.

Wallace, P., Carmichael, I.S.E., 1989, Minette lavas and associated leucitites from the western front of the Mexican Volcanic Belt: petrology, chemistry and origin: Contributions to Mineralogy and Petrology, 103, 470–492.

Wallace, P., Carmichael, I.S.E., 1992, Alkaline and calk-alkaline lavas near Los Volcanes, Jalisco, Mexico: geochemical diversity and its significance in volcanic arcs: Contributions to Mineralogy and Petrology, 111, 423–439.

Zimmermann, J.-L., Stussi, J.M, Gonzalez-Partida, E., Arnold, M., 1988, K–Ar evidence for age and compositional zoning in the Puerto Vallarta–Rio Santiago batholith (Jalisco, Mexico): Journal South America Earth Science, 1, 267–274.

Manuscript received: May 16, 2003
Corrected manuscript received: September 8, 2003
Manuscript accepted: September 9, 2003