Geological Society of America
Special Paper 422
2007

Magmatism and tectonics of the Sierra Madre Occidental and its relation with the evolution of the western margin of North America

Luca Ferrari*
Centro de Geociencias, Universidad Nacional Autónoma de México, Campus Juriquilla, Querétaro, Qro., 76230 México

Martín Valencia-Moreno*
Estación Regional del Noroeste, Instituto de Geología, Universidad Nacional Autónoma de México, Hermosillo, Son. México

Scott Bryan*
Department of Geology and Geophysics, Yale University, New Haven, Connecticut 06520-8109, USA

ABSTRACT

The Sierra Madre Occidental is the result of Cretaceous-Cenozoic magmatic and tectonic episodes related to the subduction of the Farallon plate beneath North America and to the opening of the Gulf of California. The stratigraphy of the Sierra Madre Occidental consists of five main igneous complexes: (1) Late Cretaceous to Paleocene plutonic and volcanic rocks; (2) Eocene andesites and lesser rhyolites, traditionally grouped into the so-called Lower Volcanic Complex; (3) silicic ignimbrites mainly emplaced during two pulses in the Oligocene (ca. 32–28 Ma) and Early Miocene (ca. 24–20 Ma), and grouped into the "Upper Volcanic Supergroup"; (4) transitional basaltic-andesitic lavas that erupted toward the end of, and after, each ignimbrite pulse, which have been correlated with the Southern Cordillera Basaltic Andesite Province of the southwestern United States; and (5) postsubduction volcanism consisting of alkaline basalts and ignimbrites emplaced in the Late Miocene, Pliocene, and Pleistocene, directly related to the separation of Baja California from the Mexican mainland. The products of all these magmatic episodes, partially overlapping in space and time, cover a poorly exposed, heterogeneous basement with Precambrian to Paleozoic ages in the northern part (Sonora and Chihuahua) and Mesozoic ages beneath the rest of the Sierra Madre Occidental.

The oldest intrusive rocks of the Lower Volcanic Complex (ca. 101 to ca. 89 Ma) in Sinaloa, and Maastrichtian volcanics of the Lower Volcanic Complex in central Chihuahua, were affected by moderate contractile deformation during the Laramide orogeny. In the final stages of this deformation cycle, during the Paleocene and Early Eocene, ~E-W to ENE-WSW–trending extensional structures formed within the

---

*E-mails, Ferrari and Valencia-Moreno: luca@geociencias.unam.mx; valencia@geologia.unam.mx. Current address, Bryan: School of Earth Sciences & Geography, Kingston University, Kingston Upon Thames, Surrey KT1 2EE, UK; s.bryan@kingston.ac.uk.

Ferrari, L., Valencia-Moreno, M., and Bryan, S., 2007, Magmatism and tectonics of the Sierra Madre Occidental and its relation with the evolution of the western margin of North America, *in* Alaniz-Álvarez, S.A., and Nieto-Samaniego, Á.F., eds., Geology of México: Celebrating the Centenary of the Geological Society of México: Geological Society of America Special Paper 422, p. 1–39, doi: 10.1130/2007.2422(01). For permission to copy, contact editing@geosociety.org.

Lower Volcanic Complex, along which the world-class porphyry copper deposits of the Sierra Madre Occidental were emplaced. Extensional tectonics began as early as the Oligocene along the entire eastern half of the Sierra Madre Occidental, forming grabens bounded by high-angle normal faults, which have traditionally been referred to as the southern (or Mexican) Basin and Range Province. In the Early to Middle Miocene, extension migrated westward. In northern Sonora, the deformation was sufficiently intense to exhume lower crustal rocks, whereas in the rest of the Sierra Madre Occidental, crustal extension did not exceed 20%. By the Late Miocene, extension became focused in the westernmost part of the Sierra Madre Occidental, adjacent to the Gulf of California, where NNW-striking normal fault systems produced both ENE and WSW tilt domains separated by transverse accommodation zones. It is worth noting that most of the extension occurred when subduction of the Farallon plate was still active off Baja California.

Geochemical data show that the Sierra Madre Occidental rocks form a typical calc-alkaline rhyolite suite with intermediate to high K and relatively low Fe contents. Late Eocene to Miocene volcanism is clearly bimodal, but silicic compositions are volumetrically dominant. Initial ^{87}Sr/^{86}Sr ratios mostly range between 0.7041 and 0.7070, and initial εNd values are generally intermediate between crust and mantle values (+2.3 and −3.2). Based on isotopic data of volcanic rocks and crustal xenoliths from a few sites in the Sierra Madre Occidental, contrasting models for the genesis of the silicic volcanism have been proposed. A considerable body of work led by Ken Cameron and others considered the mid-Tertiary Sierra Madre Occidental silicic magmas to have formed by fractional crystallization of mantle-derived mafic magmas with little (<15%) or no crustal involvement. In contrast, other workers have suggested the rhyolites, taken to the extreme case, could be entirely the result of partial melting of the crust in response to thermal and material input from basaltic underplating. Several lines of evidence suggest that Sierra Madre Occidental ignimbrite petrogenesis involved large-scale mixing and assimilation-fractional crystallization processes of crustal and mantle-derived melts.

Geophysical data indicate that the crust in the unextended core of the northern Sierra Madre Occidental is ~55 km thick, but thins to ~40 km to the east. The anomalous thickness in the core of the Sierra Madre Occidental suggests that the lower crust was largely intruded by mafic magmas. In the westernmost Sierra Madre Occidental adjacent to the Gulf of California, crustal thickness is ~25 km, implying over 100% of extension. However, structures at the surface indicate no more than ~50% extension. The upper mantle beneath the Sierra Madre Occidental is characterized by a low-velocity anomaly, typical of the asthenosphere, which also occurs beneath the Basin and Range Province of the western United States.

The review of the magmatic and tectonic history presented in this work suggests that the Sierra Madre Occidental has been strongly influenced by the Cretaceous-Cenozoic evolution of the western North America subduction system. In particular, the Oligo-Miocene Sierra Madre Occidental is viewed as a silicic large igneous province formed as the precursor to the opening of the Gulf of California during and immediately following the final stages of the subduction of the Farallon plate. The mechanism responsible for the generation of the ignimbrite pulses seems related to the removal of the Farallon plate from the base of the North American plate after the end of the Laramide orogeny. The rapid increase in the subduction angle due to slab roll-back and, possibly, the detachment of the deeper part of the subducted slab as younger and buoyant oceanic lithosphere arrived at the paleotrench, resulted in extension of the continental margin, eventually leading to direct interaction between the Pacific and North American plates.

Keywords: Sierra Madre Occidental, Gulf of California, continental magmatism, silicic large igneous province, extensional tectonics, subduction dynamics.

1. INTRODUCTION

Large volcano-plutonic belts dominated by rhyolitic and/or granitic rocks are common features of most continents. They typically display rock volumes between 10^5 to $>10^6$ km^3, and were emplaced in time periods of 10–40 millions of years. These belts have been referred to as "silicic large igneous provinces" by Bryan et al. (2002) (Table 1). The silicic magmatic event that produced these large provinces is not a common phenomenon in the geologic record, and must be associated with global tectonic processes. This type of magmatism strongly contributes to the modification of the rheologic structure and the composition of the continental lithosphere, as well as to the generation of a variety of ore deposits. Additionally, the concentration of large explosive eruptions over a relatively short time span may have significant impact on the global climate. The main pulses of ignimbritic volcanism of the Sierra Madre Occidental overlap with a global low-temperature paleoclimatic event at the Eocene-Oligocene boundary, as well as with a cooling event of shorter duration in the Early Miocene (Cather et al., 2003).

The Sierra Madre Occidental (Fig. 1) is one of the larger silicic igneous provinces on Earth, and is the largest of the Cenozoic era (Table 1). The ignimbritic carpet of the Sierra Madre Occidental covers an area of ~300,000 km^2 (McDowell and Keizer, 1977; McDowell and Clabaugh, 1979; Ward, 1995) with an upper estimate of ~393,000 km^2 (Aguirre-Díaz and Labarthe, 2003). However, intracontinental Basin and Range–type extension and the opening of the Gulf of California have obscured a significant part of the original size of this province, which may have been significantly larger. Although the ignimbritic cover is the most obvious feature of the Sierra Madre Occidental, the "Lower Volcanic Complex" (McDowell and Keizer, 1977) that underlies it is also important. The Lower Volcanic Complex comprises Cretaceous to Paleocene plutonic and volcanic rocks that are similar in age and composition to the Peninsular Ranges batholith and the Jalisco block, and is the main host to world-class silver and copper ore deposits (e.g., Fresnillo and Juanicipio, Zacatecas; Cananea and Nacozari, Sonora; see also Staude and Barton, 2001; Damon et al., 1983). The location and age of the Lower Volcanic Complex, interpreted to be the remnants of the suprasubduction zone magmatic arc, are critical to understand the Laramide orogeny that affected the western margin of the North American continent.

Given the scientific and economic importance of the Sierra Madre Occidental, the available literature concerning this major geologic feature of México is still relatively limited. Despite the passage of ~30 years since the first formal publications on the Sierra Madre Occidental, detailed geological knowledge is mostly restricted to relatively small areas accessible by roads, or has been based largely on remote sensing studies. Geochemical studies have been from small areas, often with results extrapolated to encompass the entire province. In contrast, geophysical studies are essentially at regional or continental scale. Consequently, many problems on the origin and evolution of the Sierra Madre Occidental remain, and are open to scientific discussion. There is no consensus, for example, regarding the mechanism(s) that produced this huge magmatic pulse and, in particular, how much the continental crust contributed to the generation of the silicic magmas. In addition, the causes of Cenozoic extension and its relationship to the final stages of subduction are little understood. Thus, the Sierra Madre Occidental in many ways is an important frontier in the geologic knowledge of México.

This work intends to summarize the current state of geologic knowledge of the Sierra Madre Occidental, particularly focusing on the evolution of the Cretaceous-Cenozoic magmatism and associated tectonics. In the first part, we present a synthesis of the stratigraphy based on the available geochronologic data, as well as a summary of the geometry, kinematics, and age of the faulting that have affected the Sierra Madre Occidental. We then summarize the available geophysical data, and geochemical and petrological studies. Finally, we discuss the time-space evolution of the magmatism and tectonics, the models to explain the origin of the silicic volcanism, and the problems that still remain unsolved to better understand this volcanic province. To support the present work, we

TABLE 1. CATALOGUE OF LARGE SILICIC IGNEOUS PROVINCES ORDERED IN TERMS OF MAXIMUM EXTRUSIVE VOLUMES

Province	Age (Ma)	Volume (km^3)	Size (km)	Magma flux (km^3 kyr^{-1})*	Reference
Whitsunday (Eastern Australia)	ca. 132–95	$>2.2 \times 10^6$	>2500 × 200	>55	Bryan et al. (1997, 2000); Bryan (2005b)
Kennedy-Connors-Auburn (Northeast Australia)	ca. 320–280	$>5 \times 10^5$	>1900 × 300	>12.5	Bain and Draper (1997); Bryan et al. (2003)
Sierra Madre Occidental	ca. 38–20	$>3.9 \times 10^5$	>2000 × 200 to 500	>22	McDowell and Clabaugh (1979); Ferrari et al. (2002)
Chon Aike (South America–Antarctica)	188–153	$>2.3 \times 10^5$	>3000 × 1000	>7.1	Pankhurst et al. (1998, 2000)
Altiplano–Puna (Central Andes)	ca. 10–3	$>3 \times 10^4$	~300 × 200	>4.3	De Silva (1989a, 1989b)
Taupo Volcanic Zone (New Zealand)	1.6–0	$\sim2 \times 10^4$	300 × 60	~9.4–13	Wilson et al. (1995); Houghton et al. (1995)

Note: From Bryan (2005a). All provinces are dominated by rhyolitic igneous compositions and ignimbrite.
*Magma flux rate is averaged eruptive flux, based on known extrusive volumes for the provinces.

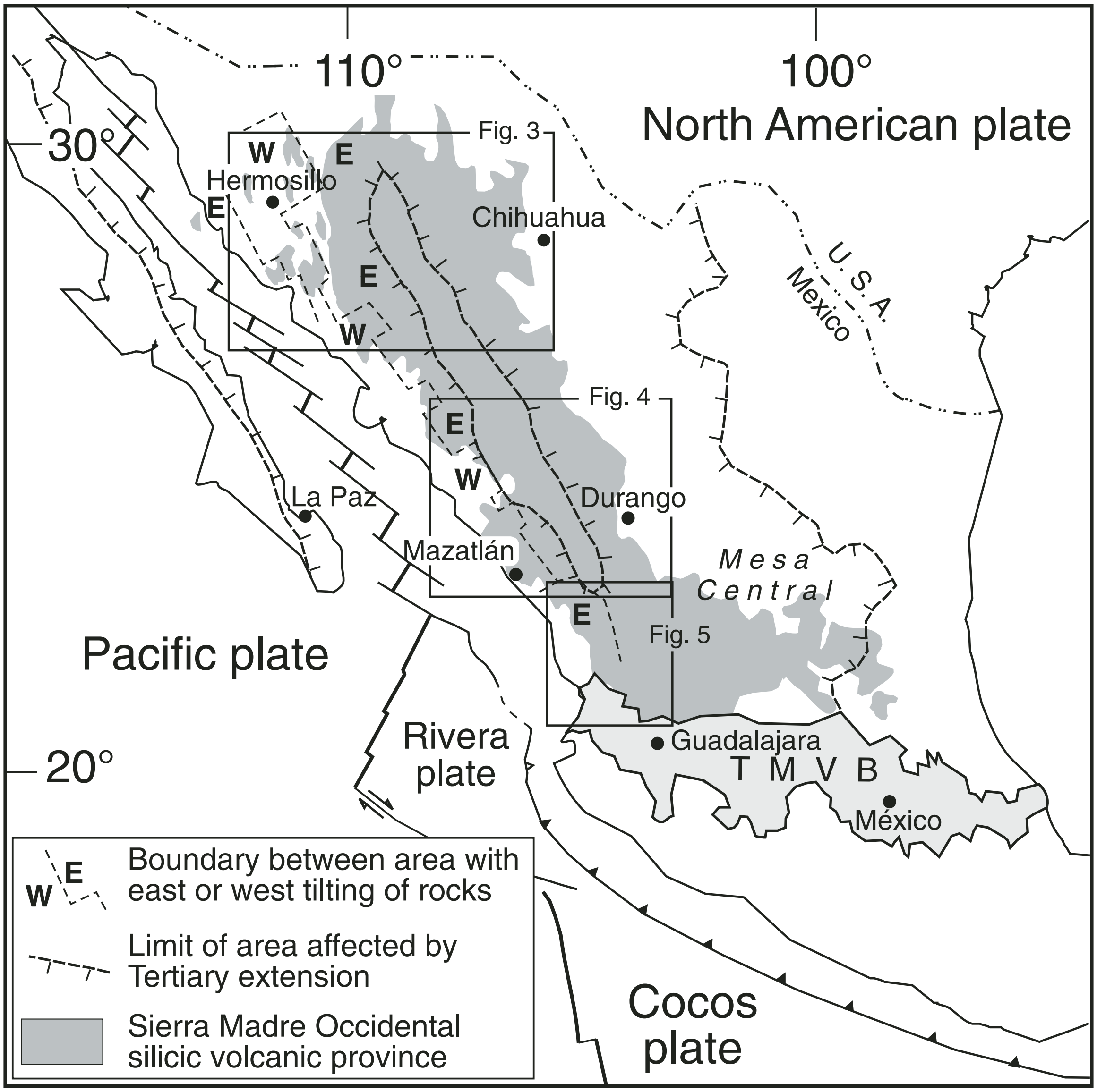


Figure 1. Tectonic sketch map of México showing Tertiary extension (after Henry and Aranda-Gómez, 2000, and Ferrari et al., 2002), the Sierra Madre Occidental (SMO) volcanic province, and the present plate configuration. TMVB—Trans-Mexican Volcanic Belt. The regional tilt domains are according to Stewart et al. (1998).

offer a series of regional synthetic geological maps of the magmatic episodes (Figs. 2–5), and tectonic maps based on interpretation of high-resolution satellite images, plus literature data (Figs. 6–9).

Several summary and review works previously published on the Sierra Madre Occidental are relevant to this paper. McDowell and Clabaugh (1979) summarized the pioneering studies in the 1970s, and provided the first general stratigraphic framework of the Sierra Madre Occidental. Most of the geologic and geochronologic knowledge of the northern and central parts of the Sierra Madre Occidental results from work done by researchers and students of the University of Texas at Austin and the Hermosillo regional station of the *Instituto de Geología* of *Universidad Nacional Autónoma de México* (UNAM), studies which were largely coordinated by Fred W. McDowell for about three decades, and summarized in various papers mainly published in the *GSA Bulletin* between 1994 and 2001. Other important contributions to the geology and tectonics of the central part of the Sierra Madre Occidental are the works by Chris Henry of the University of Nevada, and Jorge Aranda-Gómez and Gerardo Aguirre-Díaz of *Centro de Geociencias* of UNAM. An updated synthesis of these works was provided by Aranda-Gómez et al. (2003) and Henry et al. (2003). Until a few years ago, the southern part of the Sierra Madre Occidental remained little studied compared to the rest of the province. Nieto-Samaniego et al. (1999) provided

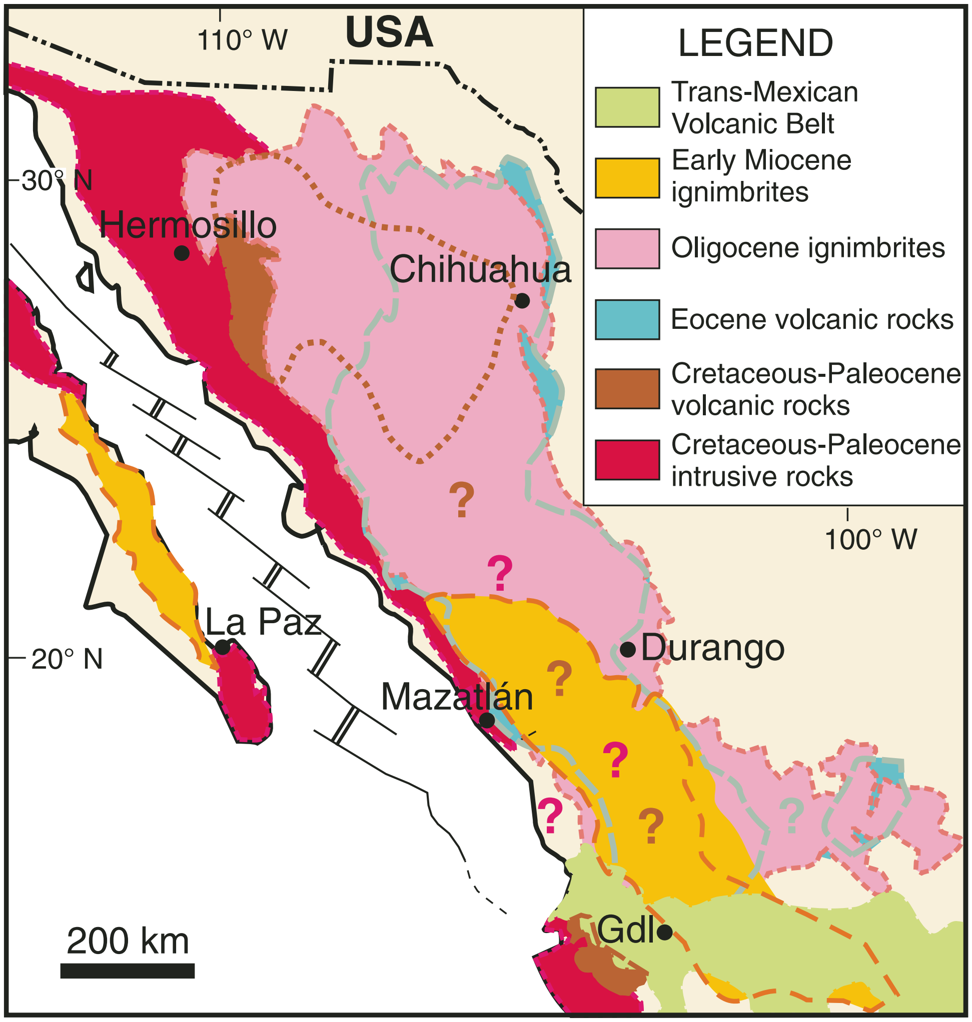


Figure 2. Geographic extension of the Sierra Madre Occidental igneous assemblages based on Figures 3, 4, and 5. The extension of the Cretaceous to Eocene assemblages is partly inferred from the extensive cover by the Oligocene and Early Miocene ignimbrites. Scarce Oligocene volcanic rocks in Baja California are not shown because of the scale of the figure.

the first review of this region along with the magmatic evolution of the Mesa Central. More recently, Ferrari et al. (2002) provided a geologic and tectonic framework for this southern section, and proposed a general model for the occurrence of the ignimbritic pulses of the Sierra Madre Occidental. Review papers on the age, geology, and tectonics of ore deposits within the Sierra Madre Occidental have been published by Damon et al. (1983), Staude and Barton (2001), and Camprubí et al. (2003).

2. REGIONAL STRATIGRAPHY

Introduction

The term "Sierra Madre Occidental" has traditionally been used to describe a large physiographic province of western México, characterized by a high plateau with an average elevation exceeding 2000 m asl, and covering an area ~1200 km long and 200–400 km wide. It extends south from the border with the United States to the Trans-Mexican Volcanic Belt, and is bounded to the west by the Gulf of California, and by the Mesa Central (Mexican Central Plateau) to the east (Fig. 1). The opening of the Gulf of California promoted the formation of deep canyons along the west flank of the Sierra Madre Occidental, whereas *Basin and Range* extensional tectonics produced wide tectonic depressions along the eastern flank of the province. The term "Sierra Madre Occidental" is also used to describe the Tertiary volcanic province characterized by large volumes of silicic ignimbrites (Fig. 1). The Tertiary volcanic province extends beyond the physiographic province to include the Mesa Central and part of eastern Chihuahua, although less abundant Late Eocene to Oligocene silicic ignimbrites are also present to the south of the Trans-Mexican Volcanic Belt in the Sierra Madre del Sur (Michoacan, Guerrero, México, and Oaxaca

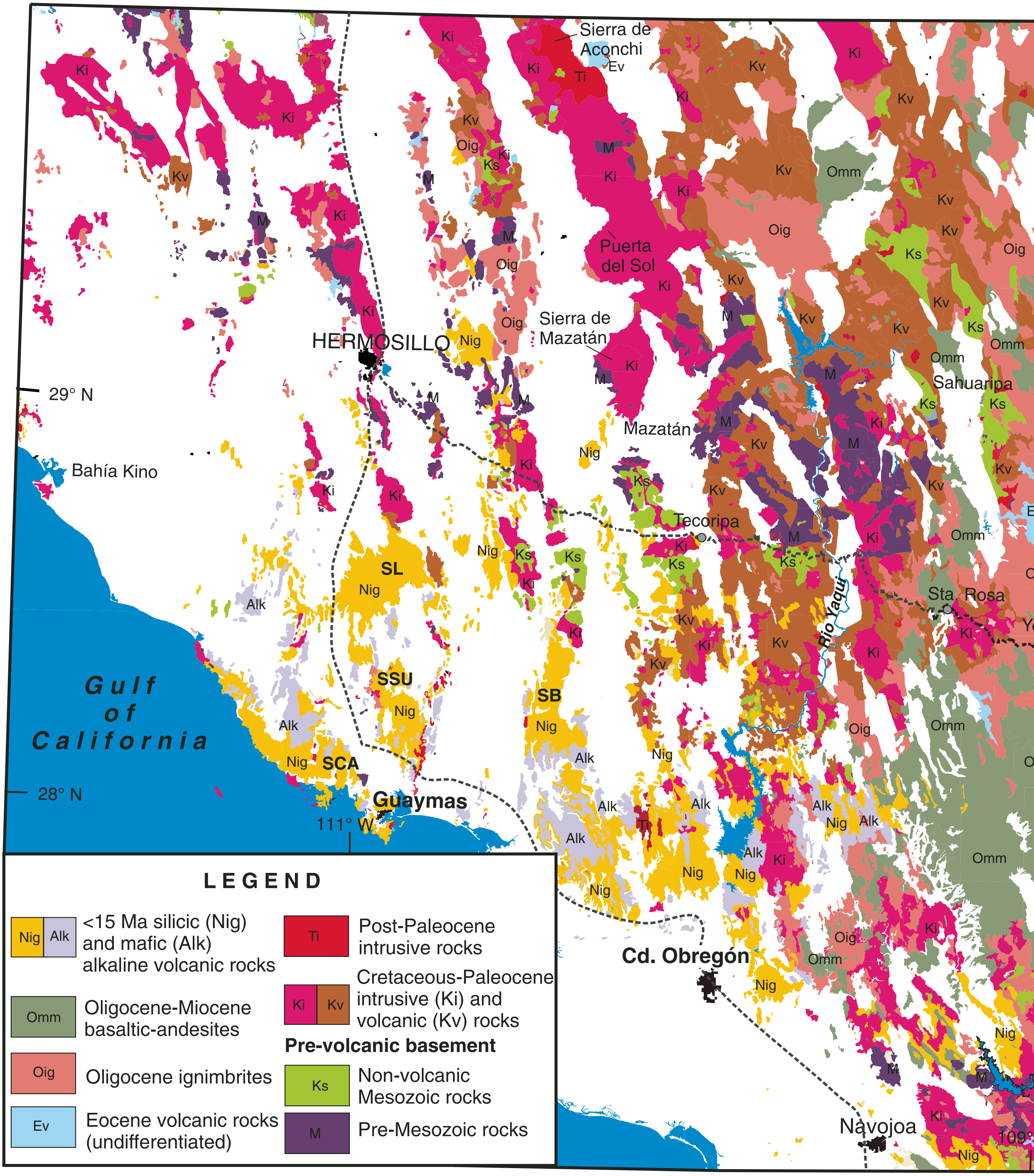
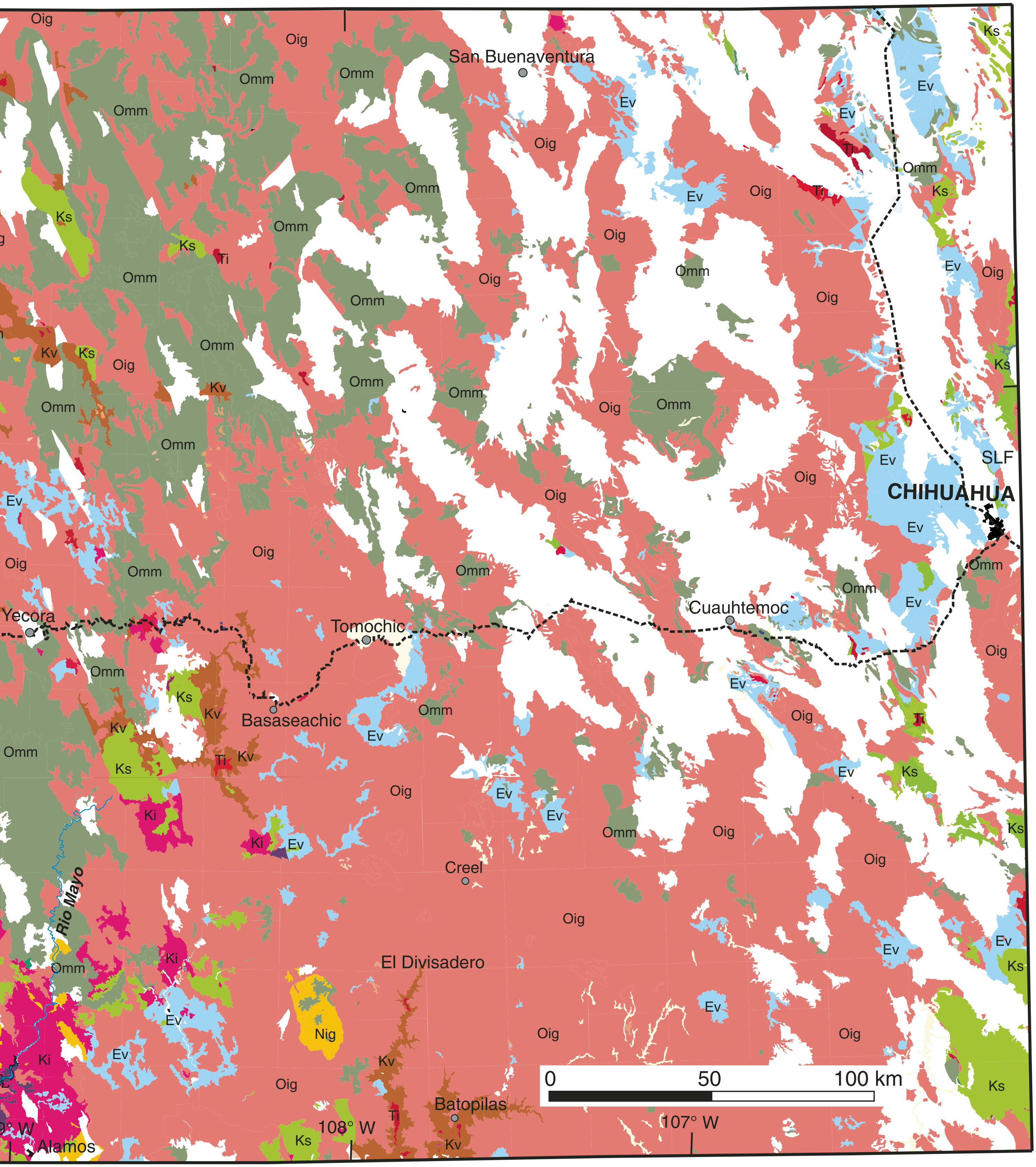


Figure 3. Geologic map of the northern part of the Sierra Madre Occidental elaborated based on a reinterpretation of the geologic cartography at 1:250,000 scale of Servicio Geológico Mexicano (sheets Hermosillo, Madera, Buenaventura, Sierra Libre, Tecoripa, Chihuahua, Guaymas, Ciudad Obregón, and San Juanito). SLF—Sierra de Los Filtros; SSU—Sierra Santa Úrsula; SB—Sierra del Bacatete; SL—Sierra Libre.


Oig
Oig
San Buenaventura
Omm
Omm
Ks
Ev
Omm
Ev
Oig
Ti
Omm
Omm
Ks
Ev
Oig
Ti
Ks
Omm
Oig
Ks
Ti
Omm
Oig
Omm
Ev
Oig
Omm
Oig
Omm
Ks
Kv
Ks
Oig
Omm
Kv
Omm
Omm
Oig
Omm
Omm
Omm
Ev
SLF
Oig
CHIHUAHUA
Oig
Ev
Ev
Oig
Omm
Oig
Omm
Omm
Cuauhtemoc
Ev
Yecora
Tomochic
Oig
Omm
Ev
Ks
Kv
Basaseachic
Omm
Oig
Ti
Kv
Ev
Omm
Ks
Ti
Kv
Ev
Ks
Oig
Ev
Ki
Ev
Omm
Oig
Ks
Ki
Ev
Oig
Creel
Rio Mayo
Oig
Ev
Ev
Ks
Ki
Omm
El Divisadero
Ev
Ev
Nig
Oig
Oig
Ks
Ki
Ev
Kv
Oig
0
50
100 km
Batopilas
Ti
108° W
107° W
Ks
Kv
Alamos

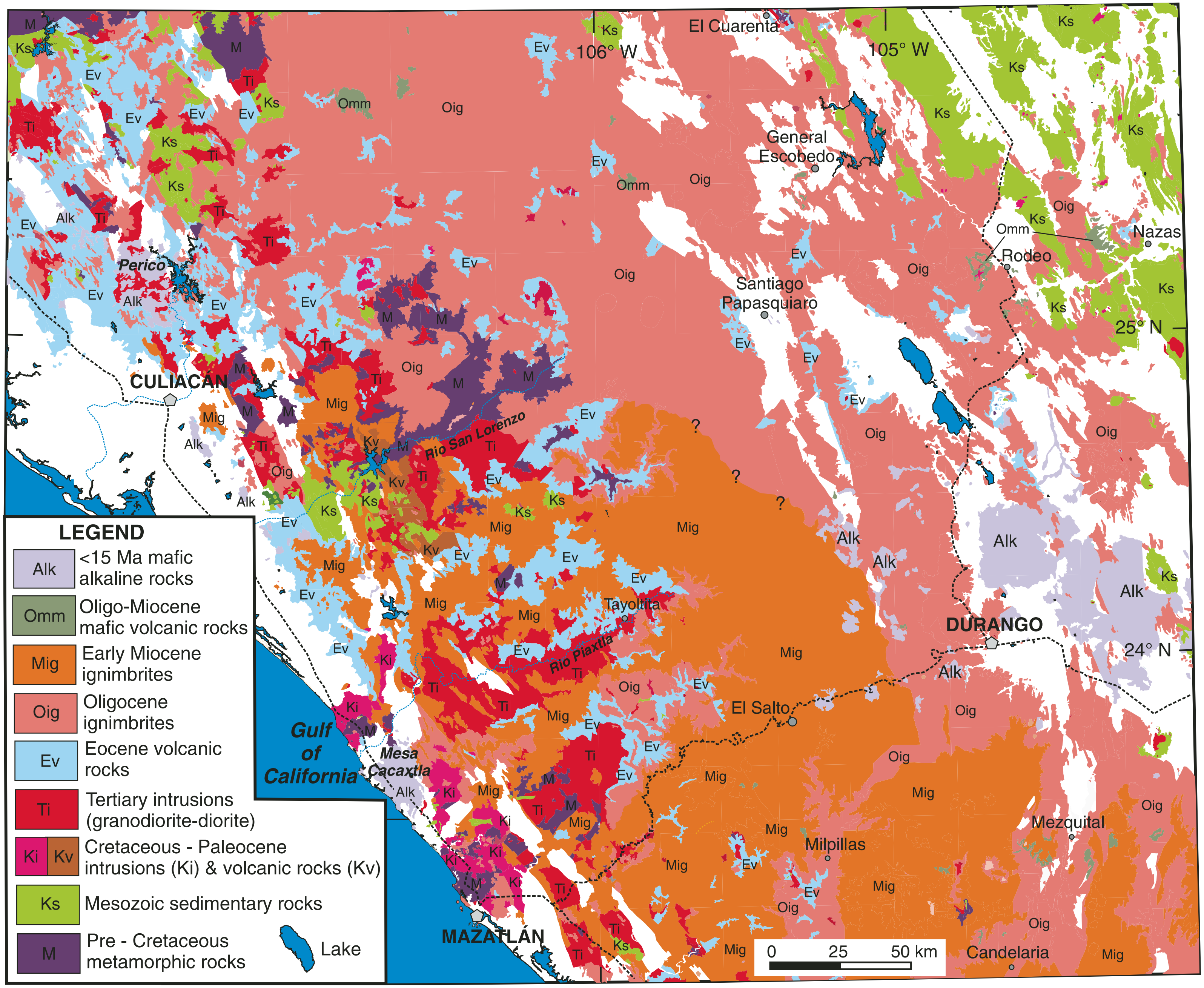


Figure 4. Geologic map of the central part of the Sierra Madre Occidental elaborated based on a reinterpretation of the geologic cartography at 1:250,000 scale of Servicio Geológico Mexicano (sheets Pericos, Santiago Papasquiaro, Culiacán, Durango, Mazatlán, and El Salto).

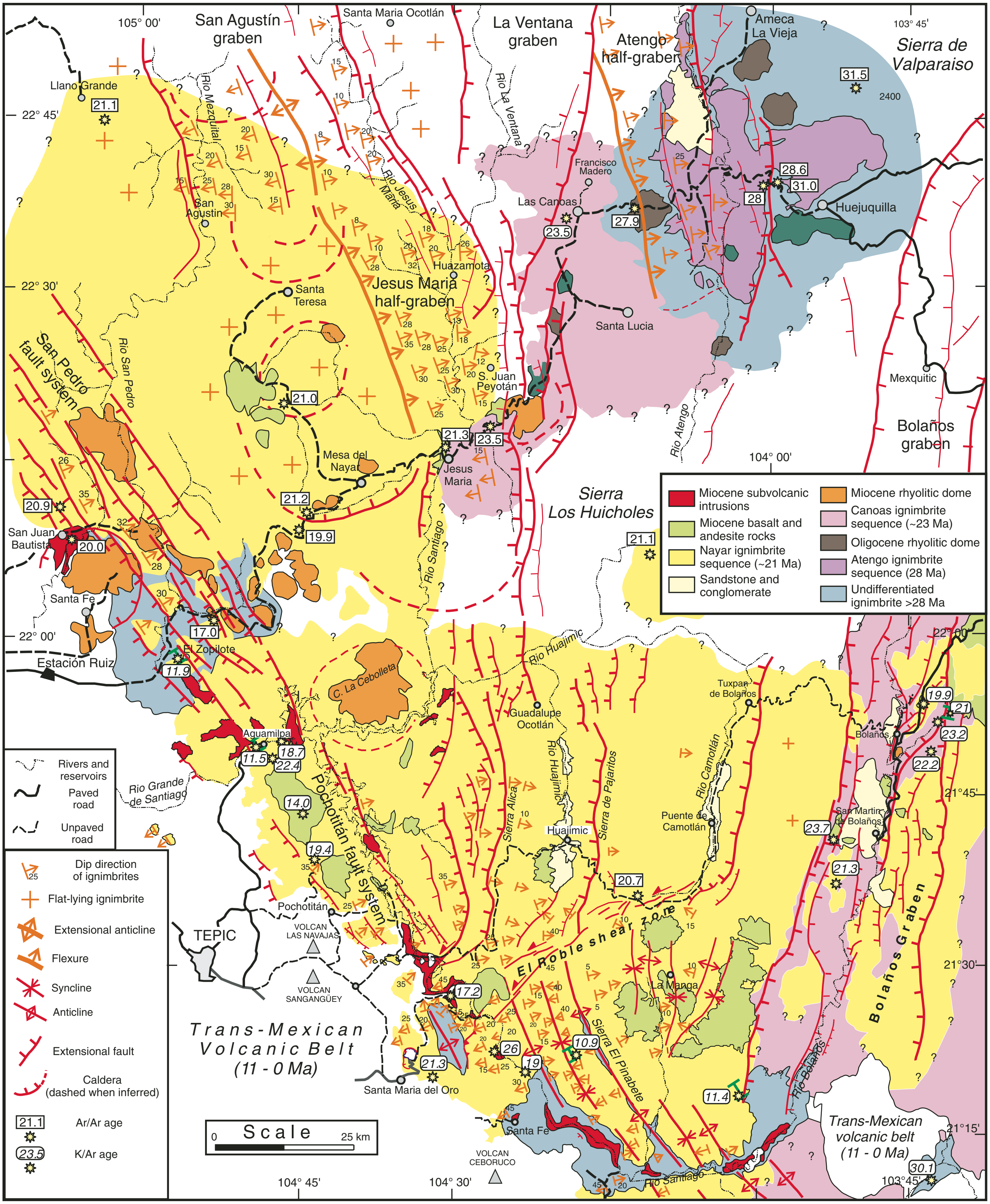


Figure 5. Geologic map of the southern part of the Sierra Madre Occidental based on Ferrari et al. (2002).

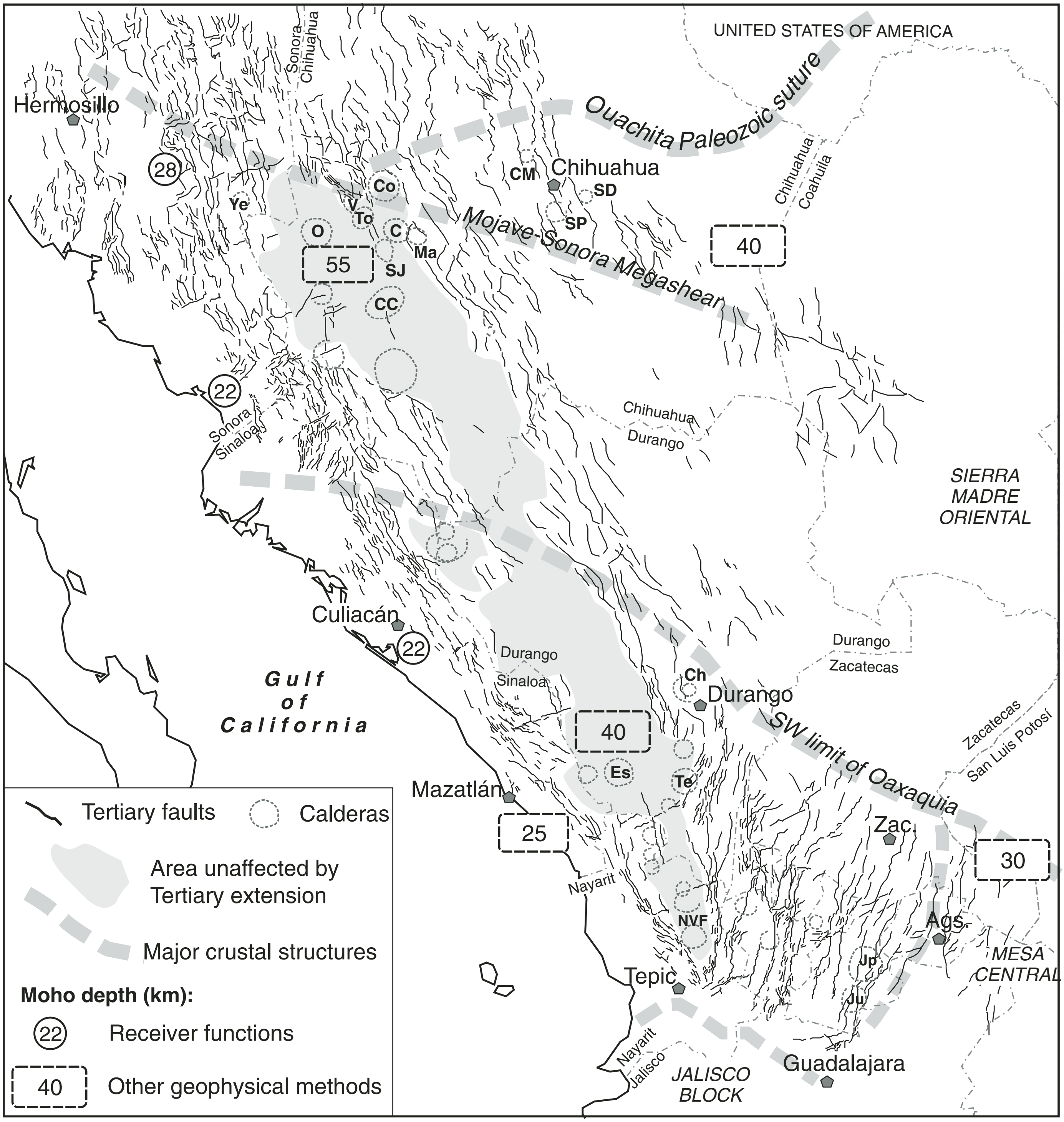


Figure 6. Tectonic map of the Sierra Madre Occidental. The map includes the main Tertiary faults reported in the literature (see text), integrated with an interpretation of a mosaic of orthorectified images of Landsat Enhanced Thematic Mapper (7, 4, and 2 bands) with a resolution of 14.25 m. The southwestern limit of Oaxaquia (after Lawlor et al., 1999) also corresponds to the limit of the continent at the end of the Paleozoic. The boundary between the Sierra Madre Occidental and the Mesa Central is according to Nieto-Samaniego et al. (1999). The main calderas are: SD—Santo Domingo (Megaw, 1986); SP—Sierra Pastoría (Megaw, 1990); CM—Caldera Majalca (Mauger, 1992; or San Marcos, *in* Ferriz, 1981); To—Tómochic and V—Las Varas (Wark et al., 1990); Co—Corralito and O—Ocampo (Swanson and McDowell, 1984); C—El Comanche; Ma—Manzanita; SJ—San Juanito and CC—Copper Canyon (Swanson et al., 2006); Ye—Yécora (Cochemé and Demant, 1991); Ch—Chupaderos (Swanson and McDowell, 1985); Te—Temoaya and Es—El Salto (Swanson and McDowell, 1984); NVF—Nayar caldera field (Ferrari et al., 2002); Ju—Juchipila and Jp—Jalpa (Webber et al., 1994). Other calderas inferred based on remote sensing. See text for reference on crustal thickness. Ags.—Aguascalientes; Zac.—Zacatecas.

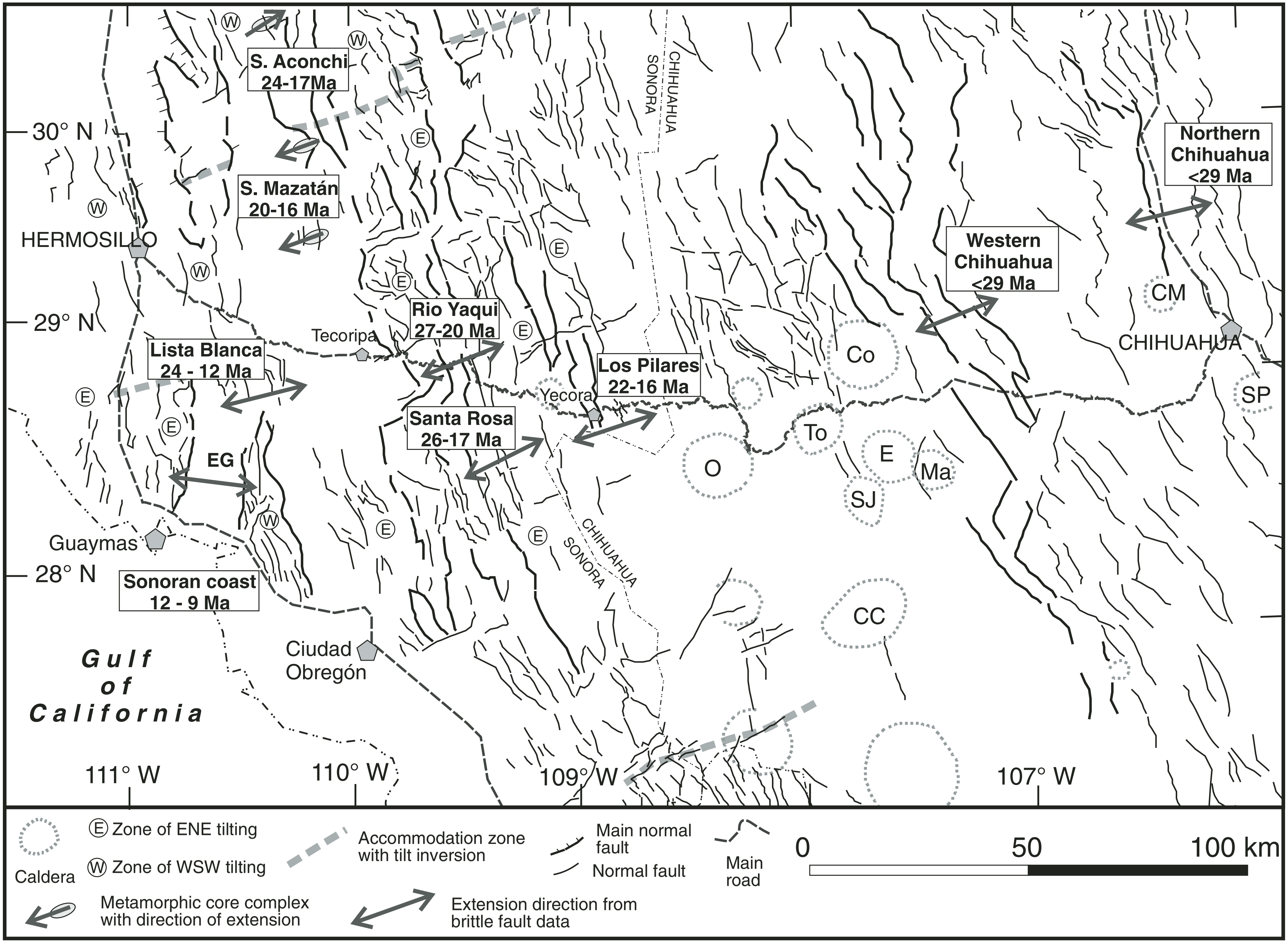


Figure 7. Tectonic map of northern part of the Sierra Madre Occidental showing orientation and age of extensional deformation (see text for details and references). Faults and calderas as in Figure 6. EG—Empalme graben.

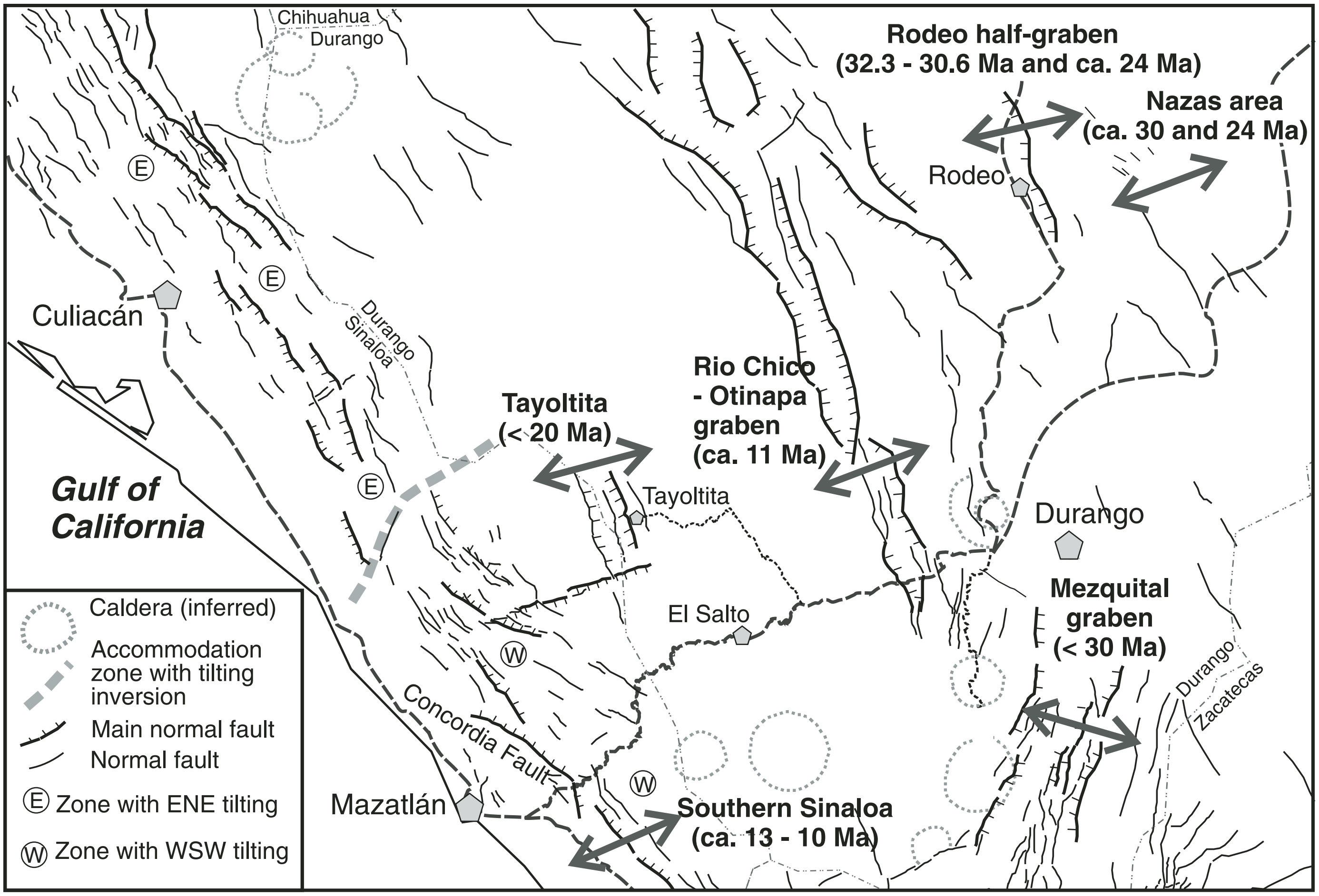


Figure 8. Tectonic map of central part of the Sierra Madre Occidental showing orientation and age of extensional deformation (see text for details and references). Faults and calderas as in Figure 6.

States) (Morán-Zenteno et al., 1999). The present work focuses on the geology within the Sierra Madre Occidental physiographic province, since the geology of the Mesa Central plateau is treated in a companion paper (Nieto-Samaniego et al., this volume).

The Sierra Madre Occidental comprises several different igneous rock assemblages emplaced while subduction of the Farallon plate occurred beneath the North American plate (Fig. 2), and includes: (1) plutonic and volcanic rocks of Late Cretaceous-Paleocene age; (2) Eocene andesitic and lesser dacitic-rhyolitic volcanic rocks; (3) silicic ignimbrites emplaced in two main pulses in the Early Oligocene and Early Miocene; (4) basaltic lavas erupted during the later stages of, and after, each ignimbritic pulse; and (5) repeated episodes of alkaline basaltic lavas and ignimbrites generally emplaced along the periphery of the Sierra Madre Occidental in the Late Miocene, Pliocene, and Quaternary. Assemblages 1–2 and 3 have been defined as the “Lower Volcanic Complex” and the “Upper Volcanic Supergroup,” respectively (McDowell and Keizer, 1977). Mafic volcanic rocks of assemblage 4, in the northern part of the Sierra Madre Occidental, have been considered an extension of the “southern Cordillera basaltic andesite” belt, defined by Cameron et al. (1989). Basalts of assemblage 5 have been directly related to various episodes of extension and opening of the Gulf of California (Henry and Aranda-Gómez, 2000). The products of all these magmatic episodes, which are partly superimposed (Fig. 2), cover a heterogeneous and poorly exposed Precambrian, Paleozoic, and Mesozoic basement (James and Henry, 1993; McDowell et al., 1999; Dickinson and Lawton, 2001).

In order to summarize the regional stratigraphy of the Sierra Madre Occidental, one must take into account that our knowledge is significantly diminished by difficulties in access, the scarcity of outcrops of pre-Oligocene units, and the intense post-Eocene extensional faulting. In particular, the true extent and significance of Cretaceous-Eocene magmatism in the region is not readily appreciable (Figs. 2–5). For practical purposes, in describing the Cretaceous-Tertiary magmatism and tectonics, the Sierra Madre Occidental is divided into three sectors: northern (Sonora-Chihuahua), central (Sinaloa-Durango) and southern (Nayarit-Jalisco-Zacatecas) sectors; these sectors center on the three main highways that cross the Sierra Madre Occidental from west to east. The regional geology of these sectors is illustrated in

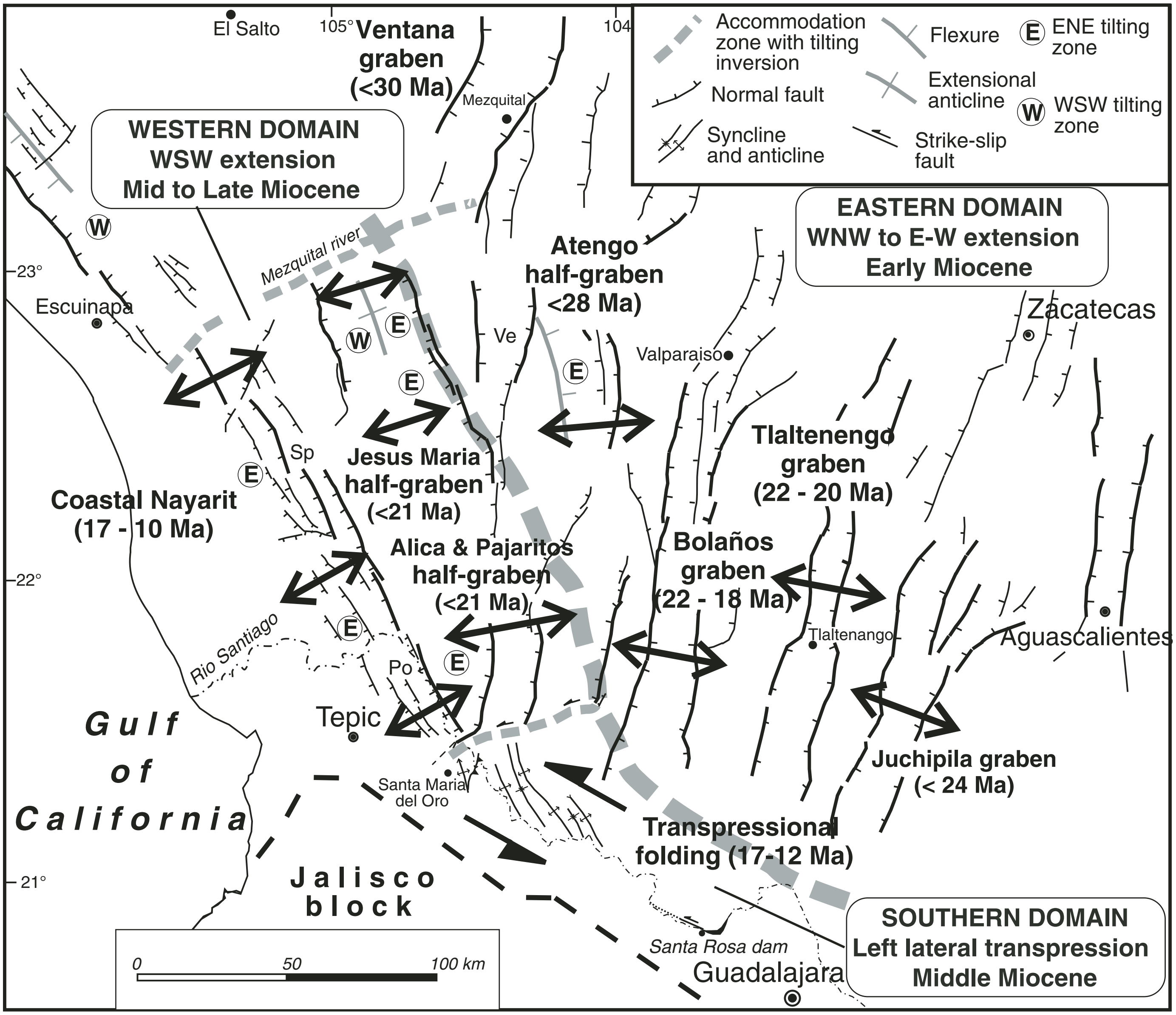


Figure 9. Tectonic map of southern part of the Sierra Madre Occidental (based on Ferrari et al., 2002) showing orientation and age of extensional deformation (see text for details and references). Faults and calderas as in Figure 6. Sp—San Pedro fault system; Ve—La Ventana graben.

the maps provided in Figures 3, 4, and 5. The first two maps are based on the 1:250,000 scale geological cartography published in the past 9 years by the former *Consejo de Recursos Minerales* (CRM), presently named *Servicio Geológico Mexicano* (SGM), and particularly the geological sheets for Hermosillo, Madera, Buenavista, Sierra Libre, Tecoripa, Chihuahua, Guaymas, Ciudad Obregón, San Juanito, Pericos, Santiago Papasquiaro, Culiacán, Durango, Mazatlán, and El Salto. These geologic maps were reinterpreted for this work and verified on the basis of the geochronologic data available in the literature. Although the geology of the SGM maps has been partly inferred, they represent the most detailed and updated map sheets covering the Sierra Madre Occidental province. For the southern sector of the Sierra Madre Occidental, the geologic map shown in Figure 5 is modified from those presented by Ferrari et al. (2002), as they provide more stratigraphic detail than SGM maps for the region.

Prevolcanic Basement

Paleo- and Mesoproterozoic

Abundant outcrops of Proterozoic rocks of the North American craton are recognized particularly in the basement of northwestern Sonora. Part of this basement was presumably displaced ~800 km southeast during the Mid to Late Jurassic, by a left lateral fault called the "Mojave-Sonora megashear" (Silver and Anderson, 1974; Anderson and Silver, 1979). Since its conception, the model of the Mojave-Sonora megashear has been controversial, however, it appears to be a fundamental feature in most tectonic reconstructions of México (e.g., Anderson et al., 2005; Sedlock et al., 1993). According to this model, the basement transported to the southeast, also defined as the Caborca terrane (Campa and Coney, 1983), is characterized by granitic plutons, gneiss, and schist, which yielded isotopic ages between 1.8 and 1.7 Ga. In contrast, the autochthonous basement to the north of the megashear is mostly characterized by metamorphosed clastic and volcanic rocks of the Pinal schist, with ages between 1.7 and 1.6 Ga (Anderson and Silver, 1979; Anderson and Schmidt, 1983). Recently proposed alternative models for the tectonic reconstruction of the Proterozoic basement of Sonora (Dickinson and Lawton, 2001; Iriondo et al., 2004a) still require an important shear zone, similar to that proposed by Anderson and Silver (1979).

Except in northeastern Sonora, Proterozoic crystalline rocks do not outcrop in the Sierra Madre Occidental province. To the east, granitic rocks of Grenvillian age (ca. 1.0 Ga) cut by amphibolitic dikes are recognized in east-central Chihuahua, in the Sierras of Los Filtros and El Carrizalillo (Ruiz et al., 1988b; McDowell and Mauger, 1994) (Fig. 3). Proterozoic rocks are known to occur at depth in northeastern and southeastern Chihuahua based on the occurrence of lower crustal xenoliths brought to the surface by recent alkali basalts exposed at El Potrerillo and La Olivina (Ruiz et al., 1988b; Cameron et al., 1992). Old North American basement is therefore considered to underlie the Sierra Madre Occidental and particularly the northern sector, and may have modified the final isotopic composition of the Cenozoic volcanic rocks. McDowell et al. (2001) and Albrecht and Goldstein (2000) used the Sr, Nd, and Pb isotopic compositions of Eocene-Oligocene ignimbrites to indirectly locate the boundary of the North American Proterozoic basement beneath the Sierra Madre Occidental in Chihuahua. In both studies, changes in whole-rock isotopic compositions defined a roughly WNW- or NW-trending boundary, located between the city of Chihuahua to the northeast and the Tómochic caldera to the southwest (Figs. 3 and 6). Isotopic studies of Laramide granitic rocks from northwestern Mexico suggest that this Proterozoic crustal boundary may be located further to the south, near the Sonora-Sinaloa-Chihuahua state borders (Valencia-Moreno et al., 2001, 2003) (Fig. 6).

Neoproterozoic and Paleozoic

Extensive sequences of marine sedimentary rocks cover the Proterozoic crystalline rocks of northern and northwestern Mexico. These sequences display a clear temporal continuity from the Neoproterozoic through most of the Paleozoic, and for this reason it is more convenient to treat them here as a single assemblage. A comprehensive descriptive inventory of known exposures of these rocks in Sonora was presented by Stewart and Poole (2002). In general, the sedimentary sequences represent two main geological environments: (1) a shallow-water marine platform, mostly occurring in western and central Sonora, and (2) a deep-marine basin extending further to the south and represented by the Paleozoic sedimentary sequences (e.g., Poole et al., 1991). The latter was considered part of the Cortéz terrane (Coney and Campa, 1987; Valencia-Moreno et al., 1999), however, other authors consider these sedimentary rocks to have been deposited in a basin fringing the North American continent, and therefore to be part of the same tectonic block that was transported in the Jurassic along the Mojave-Sonora megashear (e.g., Sedlock et al., 1993; Ortega-Gutiérrez et al., 1994). In eastern Sonora, the Neoproterozoic and Paleozoic rocks clearly continue beneath the Tertiary volcanic rocks of the Sierra Madre Occidental, and are observable west of Yécora and to the southeast of Sahuaripa (Stewart et al., 1999; Almazán-Vázquez, 1989), and along the western edge of the Sierra Madre Occidental (Fig. 3). In the northern part of Sinaloa, deformed deep-water marine rocks of Paleozoic age have also been recognized (Carrillo-Martínez, 1971; Mullan, 1978; Gastil et al., 1991), with exposures likely extending further north to near Álamos, in southern Sonora (Fig. 3).

The contact between these two Paleozoic environments is well known in central Sonora (e.g., Poole et al., 1991; Valencia-Moreno et al., 1999), but its extension to the east is hidden beneath the volcanic rocks of the Sierra Madre Occidental. East of the Sierra Madre Occidental, outcrops of Paleozoic rocks are relatively scarce, but they occur in northern Chihuahua where they are considered an extension of the Ouachita orogenic belt (Stewart, 1988) (Fig. 6). Further to the south in this region, Paleozoic low-grade metamorphic rocks and volcanic and volcaniclastic sequences of the Coahuila block, and associated with the Las Delicias arc (McKee et al., 1988; Sedlock et al., 1993; Dickinson and Lawton, 2001), are interpreted as the remnants of the accretion of Gondwana and Laurentia at the beginning of the Permian.

The southernmost exposures of pre-Mesozoic rocks in the Sierra Madre Occidental occur in northern Durango and northern Sinaloa. Limited exposures of muscovite schist outcrop beneath the Oligocene ignimbrites to the southwest of San Juan del Rio, Durango (Fig. 4). A minimum age for the associated metamorphic event has recently been assigned to the Permo-Triassic boundary, based on a $^{40}Ar/^{39}Ar$ dating of muscovite (Iriondo et al., 2003). Another metamorphic volcano-sedimentary sequence (El Fuerte Group) is widely exposed east of Culiacán, mainly in the valley of the San Lorenzo River (Fig. 4). The age of the El Fuerte Group is uncertain, however, Mullan (1978) considered this sequence to be Jurassic or possibly older.

Prevolcanic Mesozoic

Mesozoic rocks are abundant to the west of the Sierra Madre Occidental in Sonora, but they are less common toward the south of the state. In the east-central part of Sonora, the older Mesozoic rocks consist of a sequence of clastic continental and minor marine sedimentary rocks of Late Triassic–Early Jurassic age (Stewart and Roldán-Quintana, 1991; Valencia-Moreno et al., 1999). These rocks are locally known as the Barranca Group (Alencaster and de Cserna, 1961), which contains important coal horizons defining a middle member, as well as two conglomeratic members. The sediments of the Barranca Group were deposited in an E-W–oriented basin, whose northern limit abuts exposures of Paleozoic rocks (Valencia-Moreno et al., 1999). This basin extends to the western margin of the Sierra Madre Occidental, and presumably continues further east. It is considered to be genetically associated with a "pull-apart" type extensional rupture developed at the beginning of the Triassic (Stewart and Roldán-Quintana, 1991). Marine sedimentary rocks of similar age are also reported in northwestern Sonora as the Antimonio Group (González-León, 1997), but the relationship between this and the Barranca Group is poorly understood. The Antimonio Group is unconformably overlain by an interbedded sequence of clastic sedimentary and volcanic rocks, and both paleontologic and isotopic data indicate an age between Early and Late Jurassic. Although most commonly exposed in northwestern Sonora, exposures extend further east to north-central Sonora (Anderson and Silver, 1979; Rodríguez-Castañeda, 1996). Antimonio Group rocks and associated plutonic rocks have been interpreted as the products of a Jurassic continental arc. The presence of a single Late Triassic pluton exposed in the northwestern tip of Sonora has been used to suggest that magmatic arc activity in Sonora was relatively continuous from ca. 220–140 Ma (e.g., Anderson and Silver, 1979; Damon et al., 1981; Stewart, 1988). Igneous rocks of similar ages reported in southern Chihuahua and northern Durango have been interpreted as an extension of the Triassic-Jurassic arc, but as being displaced to the east by the Mojave-Sonora megashear (Grajales-Nishimura et al., 1992). Uncomformably overlying these Jurassic sequences are Late Jurassic to Early Cretaceous fluvio-deltaic and marine sedimentary rocks of the Bisbee Group that were deposited in a series of subsiding basins (González-León, 1994). Bisbee Group sedimentary rocks outcrop primarily in central and northern Sonora, but are also reported from Arivechi (Almazán-Vázquez, 1989) and Lampazos (González-León, 1988) in the eastern part of the state, and near Caborca, in northwestern Sonora (Jacques-Ayala, 1995).

At a more regional scale, similar sedimentary sequences have been reported east of the Sierra Madre Occidental, in the Chihuahua and Sabinas basins (Dickinson et al., 1989; Haenggi, 2002). Temporally equivalent rocks to the west correspond to the Alisitos Formation, exposed mainly in the northern part of the peninsula of Baja California, which represents the accreted remnants of a rifted oceanic arc terrane (e.g., Busby et al. [1998]). This Albian-Aptian formation consists of volcanic, volcaniclastic, and carbonate sequences deposited mainly in marine environments (Almazán-Vázquez, 1989; Dickinson and Lawton, 2001), and forms the basis for the Alisitos terrane (Campa and Coney, 1983) that was later redefined as the Yuma terrane (Sedlock et al., 1993). In the Late Cretaceous, syntectonic basins associated with the Laramide orogeny developed in northeastern Sonora, and accumulated fluvial and lacustrine sediments, followed by thick clastic sedimentary wedges (González-León and Lawton, 1995). Locally, these sedimentary rocks, which are collectively known as the Cabullona Group, contain horizons with abundant plant fragments, and invertebrate and vertebrate fossils, including dinosaur bones (Lucas et al., 1995).

In Sinaloa, orthogneisses, metasedimentary, and metavolcanic rocks are intruded by Cretaceous batholiths (Henry et al., 2003). The orthogneisses are intensely foliated and have been interpreted as Jurassic in age (Mullan, 1978). Keppie et al. (2006), however, recently interpret U-Pb ages zircons from the amphibolite facies Francisco gneiss in northern Sinaloa as Late Triassic. Henry and Mortensen (written communication, 2005) obtained a U-Pb zircon age near the Jurassic-Cretaceous boundary for other orthogneiss in central Sinaloa. The U/Pb age of two concordant fractions is 134.7 ± 0.4 Ma, which is indistinguishable from K-Ar hornblende dates obtained by the same authors from a layered gabbro exposed in the same area. The metasedimentary rocks consist of phyllite, quartzite, and quartz-muscovite-biotite schist of probable Jurassic age, as well as marble formed at the contact with the batholithic rocks (Henry et al., 2003). The marbles of Sinaloa are Albian in age, and are locally underlain by andesitic lavas and conglomerate (Bonneau, 1970). Scarce outcrops of amphibolite of pre-Albian age are also reported in southern Sinaloa (Henry et al., 2003).

In the southern part of the Sierra Madre Occidental, the existence of a pre-Cenozoic sedimentary basement is indicated by the presence of small outcrops of slate, greywacke, and limestone exposed in the canyon of the Santiago River prior to construction of the Aguamilpa reservoir (Fig. 5) (Gastil et al., 1978; Ferrari et al., 2000). These rocks are spatially associated with Oligocene to Early Miocene granitic intrusive bodies (Gastil et al., 1978; Nieto-Obregón et al., 1985; Ferrari et al., 2002). Older igneous rocks are not known in this region, but do outcrop further south of the Trans-Mexican Volcanic Belt in the Jalisco block (Fig. 2) (Ferrari et al., 2000).

Late Cretaceous–Paleocene Magmatism

Northern Sector

At the end of the Cretaceous and at the beginning of the Tertiary, magmatism in northern México was dominated by the activity of the so-called Laramide magmatic arc, since it was contemporaneous with Laramide deformation occurring in the western United States and Canada. Laramide-age magmatism produced significant volumes of plutonic and volcanic rocks, collectively grouped into the Lower Volcanic Complex by McDowell and Keizer (1977). Large composite batholiths vary in composition from diorite and quartz-diorite to alkaline granite (e.g., Roldán-Quintana, 1991; Valencia-Moreno et al., 2001), whereas coeval volcanic sequences are dominated by andesitic lavas, and locally known as the Tarahumara Formation (Wilson and Rocha, 1949). The Lower Volcanic Complex includes an upper member of rhyolitic and dacitic tuffs and lavas interbedded with sedimentary rocks that locally contain plant fossils (González-León et al., 2000; McDowell et al., 2001). According to Damon et al. (1983), the plutonic rocks of the Lower Volcanic Complex in northwestern México have ages between 90 and 40 Ma, and become progressively younger to the east. A more recent study of the volcanic rocks of the Tarahumara Formation, in the east-central part of Sonora, shows that eruptions occurred between 90 and 60 Ma

(McDowell et al., 2001). This suggests that Laramide magmatism in northern México may have been much more complex than indicated in earlier models, suggesting that a single magmatic arc migrated eastward (e.g., Coney and Reynolds, 1977; Damon et al., 1983). In general, it is accepted that igneous rocks of the Lower Volcanic Complex were emplaced as part of Cordilleran magmatic activity temporally associated with the Laramide orogeny. It should be noted, however, that the Lower Volcanic Complex of McDowell and Clabaugh (1979) also included older rocks of the Peninsular Ranges batholith of Baja California and its extension into Sinaloa (ca. 120–85 Ma).

In the westernmost portion of Sonora, the Lower Volcanic Complex is very well exposed even though considerable uplift associated with Cenozoic extension has resulted in substantial erosion of the associated volcanic sequences and exposure of the plutonic rocks. The rocks of the Tarahumara Formation are best preserved in the east-central and north-northeast portions of Sonora (e.g., González-León et al., 2000; McDowell et al., 2001). One of the most notable features of the Lower Volcanic Complex, besides its great extent of exposures, is that it has been host to the formation of a variety of ore deposits, largely exposed during Late Tertiary tectonic unroofing. Numerous porphyry copper deposits are distributed mostly in the eastern portion of the Lower Volcanic Complex belt (Damon et al., 1983; Staude and Barton, 2001), but especially in northeastern Sonora, where the world-class deposits of Cananea and La Caridad represent the best examples (Valencia-Moreno et al., 2001).

In Sonora, the Lower Volcanic Complex belt is considerably wider than its extension to the south into Sinaloa, which may reflect the greater effect of Neogene extension to the north (Damon et al., 1983). The Lower Volcanic Complex rocks disappear to the east under the ignimbritic volcanic province of the Sierra Madre Occidental, but there are indications that the complex extends into central Chihuahua. About 30 km northwest of the city of Chihuahua, Mauger (1981, 1983) described a >3000-m-thick volcanic sequence (Peñas Azules volcanics), which is interpreted as a complex of stratocone-related volcanic successions dated at 68.2 ± 1.6 Ma (K-Ar in plagioclase) and 67.5 ± 1.0 Ma (U-Pb in zircons) (McDowell and Mauger, 1994). Additionally, these authors reported small intrusive bodies and silicic tuffs with Paleocene ages in the region adjacent to the city of Chihuahua.

Central Sector

In the central sector, Cretaceous-Paleocene magmatism has been studied in more detail along the western margin of the Sierra Madre Occidental in Sinaloa, where crustal extension associated with the opening of the Gulf of California has exposed batholiths of the Lower Volcanic Complex. Cretaceous-Paleocene batholiths most likely underlie a large part of the Sierra Madre Occidental, given that Cretaceous dioritic intrusions are also reported in the Nazas area in western Durango (Aguirre-Díaz and McDowell, 1991). All known intrusive rocks are calc-alkaline in composition, and vary from diorite to granite, but granodioritic plutons are by far the dominant composition. Granitic rocks associated with the Sinaloa batholith have U-Pb and K-Ar ages between 101 and 46 Ma, and have been divided into two groups: pre- or syntectonic rocks and post-tectonic rocks (Henry and Fredrikson, 1987; Henry et al., 2003). Pre- or syntectonic intrusions are characterized by mineral foliations and lineations, suggesting emplacement prior to or during deformation that began ca. 85 Ma. Post-tectonic intrusions are more homogeneous and massive. The pre- and syntectonic rocks were emplaced along a belt close to the coast, whereas post-tectonic intrusive rocks are found further east, ~30 km away from the coast (Fig. 4).

Volcanic rocks of the Lower Volcanic Complex have received little study in the central part of the Sierra Madre Occidental, mainly due to the intense hydrothermal alteration. In general, they comprise a sequence of andesitic and rhyolitic lavas and silicic ignimbrites generally restricted to exposures in deep canyons. The main outcrops occur in the canyons of the Piaxtla and Presidio Rivers, as well as in the proximity to Pánuco and Copales, on the Mazatlán–El Salto road (Fig. 4) (Henry and Fredrikson, 1987).

Southern Sector

Isolated Cretaceous-Paleocene intrusive rocks outcrop along the eastern edge of the Sierra Madre Occidental in Zacatecas. In the area of La Tesorera-Zacatón, 20 km east of Zacatecas, the capital city of the state, Campanian K-Ar biotite ages (74 ± 6 Ma) were obtained from plutonic rocks of granodioritic composition (Mújica-Mondragón and Jacobo-Albarrán, 1983; Sole and Salinas, 2002). These plutonic bodies commonly intrude Lower Cretaceous marine sedimentary rocks (CRM, 1997). Further west in western Jalisco and Nayarit, there are no reports of pre-Cenozoic magmatic rocks. The scarcity of exposures of the Cretaceous-Paleocene igneous rocks in the southern sector of the Sierra Madre Occidental is largely due to the extensive cover of ignimbrites of Oligocene and particularly Early Miocene age, which attain their maximum areal extent in this region.

Eocene Magmatism

Previous reviews on the geology of Sierra Madre Occidental (e.g., McDowell and Clabaugh, 1979) included Eocene igneous rocks in the Lower Volcanic Complex along with the Cretaceous-Paleocene batholithic and volcanic rocks. However, later works (e.g., Aguirre-Díaz and McDowell 1991) have documented the space-time extent of this volcanism, which can be considered a distinct episode in the magmatic evolution of western México. For this reason, we discuss the Eocene igneous activity, which in several areas may be interpreted as a precursor to the Oligocene ignimbritic event, separately.

Northern Sector

Eocene volcanic rocks in the northern sector are exposed mainly in Chihuahua along the eastern edge of the Sierra Madre Occidental and in deeply incised canyons within the interior of the province (Fig. 3). In general, the first Eocene ignimbrites of the northern part of the Sierra Madre Occidental are porphyritic, crystal-rich, and commonly biotite-bearing (Magonthier, 1988). Eocene volcanic rocks near the city of Chihuahua are well exposed in a N-S belt that includes the sierras of El Gallego (Keller et al., 1982), del Nido, Sacramento, Pastorías, Las Palomas, Magistral (McDowell and Mauger, 1994 and references therein), Santa Eulalia (Megaw, 1990), and Los Arados (Iriondo et al., 2003) (Fig. 3). This episode began at 46 Ma after a period of scarce and intermittent magmatism, and continued almost without interruption until 27.5 Ma. Consequently, distinguishing between Eocene magmatism and the ignimbritic pulse of the "Upper Volcanic Supergroup" in this part of the Sierra Madre Occidental is extremely difficult. In central Chihuahua, the Eocene rocks comprise two sequences of silicic ignimbrites, which are separated by a thick sequence of massive lavas of intermediate to felsic composition (McDowell and Mauger, 1994 and references therein). A similar sequence, but less complete, is exposed further west in the area of Tómochic, in the interior of the Sierra Madre Occidental. In this region, Wark et al. (1990) reported a succession of andesitic lavas with ages between ca. 38–35 Ma, which are in turn covered by a 34-Ma-old ignimbritic sequence associated with the formation of Las Varas caldera. This sequence is partly covered by volcanic products from the two Oligocene calderas of Tómochic and Ocampo (Swanson and McDowell, 1985; Wark et al., 1990). The Las Varas sequence may extend further west into eastern Sonora, where Montigny et al. (1987) obtained a K-Ar age of 35.3 Ma on sanidine from a porphyritic ignimbrite exposed east of Yécora. In Sonora, however, Eocene volcanism is generally, distinctly older. In the area of Santa Rosa (Fig. 3), Gans (1997) obtained two $^{40}Ar/^{39}Ar$ ages on sanidine at 54.3 ± 0.2 Ma and 43.8 ± 0.2 Ma, from a several hundred-meters-thick sequence of ignimbrites and dacitic lavas. This sequence may be coeval with a granodioritic pluton dated at ca. 60.0 ± 0.5 Ma and exposed close to the town of Santa Rosa (Gans, 1997). These ages indicate the Santa Rosa sequences could be correlated with the upper, more felsic member of the Lower Volcanic Complex, which is exposed in an adjacent area to the west (McDowell et al., 2001). Additional geochronologic studies are needed to establish more precisely, the timing and spatial distribution of Eocene volcanism in the northern sector of the Sierra Madre Occidental, and its relationship with the Oligocene ignimbrite pulse.

Central Sector

In the central part of the Sierra Madre Occidental, the largest thickness of Eocene volcanic rocks occurs near the Sinaloa-Durango state boundary, particularly in the area of Tayoltita (Figs. 4, 8) (Henry and Fredrikson, 1987). In this area, the Piaxtla River has carved a deep canyon that exposes at least 1500 m of the Eocene sequence hosting important gold and silver mineralization (Horner, 1998; Horner and Enríquez, 1999; Enríquez and Rivera, 2001). The sequence, which is strongly tilted to the E-NE, consists of rhyolitic and andesitic lavas, and subvolcanic intrusions of dioritic composition that have yielded K-Ar ages from 39.9 to 36.6 Ma. The volcanic rocks cover, and the dioritic intrusion crosscuts, a granodioritic to dioritic batholith dated at 45.1 Ma (Enríquez and Rivera, 2001). Dating of adularia from mineralized veins yielded younger ages than the batholith (40.4 ± 0.4 Ma, Henry et al., 2003; 38.5–32.9 Ma, Enríquez and Rivera, 2001), and suggests a genetic relationship with the Eocene sequence. The Eocene rocks and mineralization are separated from an overlying Early Miocene ignimbritic sequence by a fluvio-lacustrine succession of conglomerates, sandstone, and shale (Horner and Enríquez, 1999). By analogy with the stratigraphy in the Piaxtla River valley, andesitic rocks reported in many areas elsewhere in Sinaloa beneath the Oligo-Miocene ignimbritic cover are interpreted here as Eocene in age (Fig. 4). However, there are no geochronological data supporting this correlation.

Another area where important Eocene magmatic activity has been documented occurs along the eastern edge of the Sierra Madre Occidental. In the region of Nazas (Fig. 4), two andesitic lavas have been dated at 48.8 and 40.3 Ma. They are separated by rhyolitic lavas and ignimbrites dated between 45.2 and 42.9 Ma, and with younger rhyolitic lavas dated at 34 Ma (Aguirre-Díaz and McDowell, 1991). Red-bed deposits also separate the Eocene volcanics from Oligocene rhyolitic ignimbrites. In the area of El Cuarenta, ~210 km NNW of the city of Durango (Fig. 4), an ignimbrite from the base of a rhyolitic volcanic succession has been dated by $^{40}Ar/^{39}Ar$ at 39.6 Ma (whole rock, Tuta et al., 1988). To the south of the city of Durango, in El Mezquital graben (Fig. 8), McDowell and Keizer (1977) also reported a thick sequence of andesitic lavas, from which they obtained a single whole-rock K-Ar age of ca. 52 Ma.

Southern Sector

Several exposures of Eocene volcanic rocks are known from the southern part of the Sierra Madre Occidental (Nieto-Samaniego et al., 1999). Silicic ignimbrites, rhyolitic domes, and andesitic lavas with K-Ar ages between 38 and 34 Ma locally outcrop in the area of Fresnillo and Sain Alto, Zacatecas (Ponce and Clark 1988; Lang et al., 1988; Tuta et al., 1988), whereas Nieto-Samaniego et al. (1996) reported a K-Ar age of 40.6 ± 1.0 Ma (sanidine) for a rhyolite exposed in the Cerro El Picacho, Aguascalientes. Further west, a sequence of pervasively altered andesitic lavas from which a K-Ar age of 48.1 ± 2.6. Ma (K-feldspar) was obtained, is exposed at the base of a Paleocene sequence in the area of Juchipila (Webber et al., 1994). This sequence is covered by reddish sandstone and conglomerate containing clasts of andesite volcanic rocks, which separate the Paleocene rocks from the Oligo-Miocene ignimbrites. Ferrari et al. (2000) reported a similar sequence in the area of Santa María del Oro (Fig. 5), but this section lacks absolute age constraints. Andesites dated by $^{40}Ar/^{39}Ar$ at ca. 51 Ma (plagioclase and feldspar) occur beneath the Trans-Mexican Volcanic Belt, being intersected in geothermal wells drilled in the San Pedro–Ceboruco graben (Ferrari et al., 2000, 2003), located immediately to the south of the Sierra Madre Occidental (Fig. 5).

Oligocene–Early Miocene Ignimbritic Pulses ("Ignimbrite Flare-Up")

As a volcanic province, the Sierra Madre Occidental is commonly associated with the huge ignimbritic succession, which reaches more than 1000 m in thickness and covers most of the western part of México (McDowell and Clabaugh, 1979). This sequence, known also as the Upper Volcanic Supergroup, was largely, unconformably emplaced on top of the Lower Volcanic Complex (McDowell and Keizer, 1977) and Eocene igneous rocks. The Upper Volcanic Supergroup comprises a thick sequence of rhyolitic ignimbrites, air-fall tuffs, silicic to intermediate lavas, and lesser mafic lavas that are particularly well exposed along the edges of the volcanic province (McDowell and Clabaugh, 1979; Cochemé and Demant, 1991). Averaging 250 km wide by 1200 km long and a present volume exceeding 300,000 km^3, the Sierra Madre Occidental volcanic province is the most notable geological feature of the Mexican subcontinent. In addition to its huge areal extent, another feature that must be emphasized is the relatively short time in which the ignimbrites were emplaced. Several geochronologic studies have shown that the first and more extensive ignimbritic pulse occurred at the beginning of the Oligocene with an impressive synchronicity across the entire province, while a second pulse in the Early Miocene was more restricted to the southwestern part of the Sierra Madre Occidental and central México beneath the Trans-Mexican Volcanic Belt. The characteristics of these explosive volcanic episodes are discussed further below.

Northern Sector

Several sections studied at different locations at the longitude of the city of Chihuahua contain a sequence of ignimbrites with K-Ar ages of ca. 33–30 Ma (McDowell and Mauger, 1994), overlain by peralkaline tuffs with a more restricted distribution and yielding ages from 30.5 to 29 Ma (Mauger, 1981). In San Buenaventura (Fig. 3), in northwestern Chihuahua, the volcanic sequence includes rhyolitic ignimbrites interbedded with dacite, rhyolite, and minor basalt lavas, which were emplaced onto Proterozoic basement (Albrecht and Goldstein, 2000). These authors reported an Rb/Sr age of 33.2 Ma for the lower part of the sequence. In the core of the province, where the ignimbritic sequence reaches its maximum thickness of ~1 km, age ranges for the exposed ignimbrite sections are no more than 3 Ma. Wark et al. (1990) reported ages from 31.8 to 31.4 Ma for the Rio Verde tuff, which is associated with the formation of the Tómochic cauldron (Figs. 4 and 6) and 29.0 Ma for the Cascada tuff, whose intracauldron facies form the spectacular waterfall of Basaseachic (Fig. 3). Further south, the thick ignimbritic sequence of Batopilas (Fig. 3) has been dated by K-Ar between 30.1 and 28.1 Ma (Lanphere et al., 1980). Ages obtained for the sequence of volcanic rocks exposed in the Barranca del Cobre also lie within this range, and are similar to the age of 29.3 Ma obtained in the area of Pito Real (Montigny et al., 1987) (Fig. 3). This indicates that over 1.5 km of ignimbrites were deposited between ca. 30 and ca. 29 Ma in the region of El Divisadero–Creel (Albrecht and Goldstein, 2000) for which several calderas have been recognized as sources for most of these ignimbrite sheets (Swanson et al., 2006).

The ignimbritic carpet of the Sierra Madre Occidental extends into eastern Sonora (Fig. 3), with the best-studied section located in the region of Yécora (Fig. 3), which was documented by Bockoven (1980), Cochemé and Demant (1991), and more recently by Gans (1997). In this region, the Sierra Madre Occidental volcanic rocks were unconformably deposited on an eroded section of the Lower Volcanic Complex, with a conglomeratic horizon containing clasts of an underlying granodioritic pluton occurring along the contact (Bockoven, 1980; Cochemé and Demant, 1991). Although in this part of Sonora the ignimbritic sequence remains to be systematically dated, an ^{40}Ar/^{39}Ar age of 33 Ma (sanidine) in Santa Rosa (Fig. 3) (Gans, 1997), plus two K-Ar ages of 33.5 ± 0.8 Ma (plagioclase) and 27.1 ± 0.9 Ma (K-feldspar) in the valley of the Yaqui River (Fig. 3) (McDowell et al., 1997), indicate a similar age range for ignimbrite eruptions to that in Chihuahua. However, the ignimbritic cover becomes considerably thinner in this part of the Sierra Madre Occidental than in the region of western Chihuahua. In the area of Tecoripa, McDowell et al. (2001) reported an average thickness of only 100 m for the rhyolitic ignimbrites erupted from volcanic centers located further east.

Central Sector

In the central sector of the Sierra Madre Occidental, the ignimbritic sequence outcrops mainly in the state of Durango, where it has been studied in some detail along the Durango-Mazatlán highway and in the area of Nazas (Fig. 4). In Nazas, Aguirre-Díaz and McDowell (1993) recognized two Oligocene ignimbritic sequences that reach a combined thickness of ~500 m, from which K-Ar ages of 32.2 ± 0.7 and 29.5 ± 0.6 Ma were obtained, respectively, on sanidine. ^{40}Ar/^{39}Ar dating in the area adjacent to Rodeo has yielded similar ages of 32.3 ± 0.7 and 30.6 ± 0.09 Ma (sanidine) (Luhr et al., 2001). In this same age range, a ^{40}Ar/^{39}Ar age from sanidine was obtained by Iriondo et al. (2004b) for an andesitic vitrophyre in the locality of Ignacio Ramírez, ~90 km to the south. Oligocene rocks also outcrop near the coast of Sinaloa (Fig. 4). Henry and Fredrikson (1987) reported K/Ar ages of 31.7 ± 0.4 Ma (biotite) for a quartz-dioritic dike in the area of Tayoltita and a 28.3 ± 0.7 Ma (biotite) for a faulted and tilted rhyolitic ignimbrite exposed north of Mazatlán.

An Oligocene ignimbrite sequence exposed around the city of Durango has an approximate thickness of 800 m, and has been related to the formation of the Chupaderos caldera (Swanson et al., 1978). K-Ar ages between 32.8 and 29.5 Ma (McDowell and Keizer, 1977; Swanson et al., 1978) were obtained from the Durango ignimbrite successions, however, ages obtained by ^{40}Ar/^{39}Ar on the same feldspar separates yielded a slightly more restricted age range between 32 and 30 Ma (Aranda-Gómez et al., 2003). To the southwest of the city of Durango, in the area between Mezquital and Milpillas (Fig. 4), three ignimbrites have been dated by K-Ar between ~28 (sanidine) and ca. 27 Ma (plagioclase) (Sole and Salinas, 2002).

Further southwest along the Durango-Mazatlán highway, the Durango ignimbrite sequence is covered beneath an extensive rhyolitic dome (Las Adjuntas) dated at 28 Ma, and by the Early Miocene ignimbritic sequence of the El Salto–Espinazo del Diablo (McDowell and Keizer, 1977) (Fig. 4). The El Salto–Espinazo del Diablo sequence has a total thickness of ~1000 m, consisting of four packages of ignimbrites with lesser rhyolitic and basaltic lavas. The K-Ar ages obtained from this section cluster at ca. 23.5 Ma (McDowell and Keizer, 1977). Iriondo et al. (2004b) obtained a nearly identical ^{40}Ar/^{39}Ar date on plagioclase from a vitrophyric ignimbrite from this sequence, sampled ~15 km west of El Salto. Early Miocene ignimbrites outcrop along most of the Durango-Mazatlán transect, however, it is not known how far they may extend to the north (Fig. 4). The northernmost localities where Early Miocene silicic rocks are known occur in the region of Tayoltita and Culiacán. In Tayoltita, ignimbrites and lavas that lie on the top of this sequence have been dated by K-Ar at 24.5 and 20.3 Ma (Enríquez and Rivera, 2001), whereas north of Culiacán, Iriondo et al. (2003) obtained a ^{40}Ar/^{39}Ar hornblende date of 23.2 ± 0.15 Ma for a subvolcanic granodioritic pluton. Sole and Salinas (2002) report a whole rock K-Ar age of 24.0 ± 1.0 Ma for a basaltic andesite lava that underlies one of the uppermost ignimbrites in the sequence exposed in the area of Milpillas (Fig. 4).

Southern Sector

The southern part of the Sierra Madre Occidental is covered by silicic ignimbrites that have traditionally been considered as Oligocene in age (e.g., McDowell and Clabaugh, 1979) by correlation with rocks exposed more to the east in the Mesa Central (Nieto-Samaniego et al., 1999). However, it has been recently shown that two distinct ignimbritic pulses occurred in this region of Early Oligocene and Early Miocene age (Ferrari et al., 2002). Oligocene ignimbrites dominate exposures in the eastern part through Aguascalientes, Zacatecas, and northern Jalisco (Nieto-Samaniego et al., 1999 and references therein). In the area of Fresnillo, to the north of Zacatecas, rhyolite lavas and ignimbrites of the Sierra Valdecañas have yielded K-Ar ages between 29.1 and 27.5 Ma, whereas ages between 33.5 and 32.2 Ma were obtained from subvolcanic bodies associated with silver mineralization (Lang et al., 1988). To the southeast, good exposures of the Oligocene rocks occur in the Sierra de Morones, between Jalpa and Tlaltenango (Fig. 9), where Nieto-Obregón et al. (1981) reported a K-Ar date of 29.1 ± 0.6 Ma (sanidine) for one of the ignimbrites higher in the sequence. In this zone, the Oligocene sequence is composed of areally extensive, but relatively thin rhyolitic ignimbrites, which regularly do not exceed 10–20 m each. They are separated from underlying Eocene andesitic volcanics by beds of continental sandstone and red conglomerate. Further west, in the Huejuquilla–Estación Ruiz transect, ignimbrites and rhyolites with ^{40}Ar/^{39}Ar ages (sanidine) between 31.5 and 28 Ma constitute much of the Sierra de Valparaíso, and are also exposed to the west in the area of Huejuquilla and the Atengo half graben (Fig. 5) (Ferrari et al., 2002). A ^{40}Ar/^{39}Ar age of 27.9 ± 0.3 Ma on sanidine was obtained for a complex of rhyolitic exogenous domes in the western part of the half graben (Ferrari et al., 2002). These ages are almost identical to those observed for the sequence of Durango and the dome of Las Adjuntas, respectively, exposed ~80 km to the north (McDowell and Keizer, 1977).

West of Atengo and along all of the Bolaños-Tepic transect (Fig. 5), Early Miocene ignimbrites are dominant, although the Oligocene sequence could be underlying all the eastern part of the region (Fig. 5), since a package of ignimbrites with a K-Ar age of 30.1 Ma has been recognized in the southern part of the Bolaños graben (Ferrari et al., 2002). The Early Miocene ignimbritic sequence covers the Sierra Madre Occidental in Nayarit. Ferrari et al. (2002) recognized the Las Canoas and El Nayar sequences that represent two ignimbrite packages of different ages and provenance. The Las Canoas sequence is ~350 m thick and has been dated by K-Ar (Clark et al., 1981) and by ^{40}Ar/^{39}Ar (Ferrari et al., 2002) at 23.5 Ma, and temporally overlaps with the El Salto–Espinazo del Diablo sequences exposed ~80 km to the north (McDowell and Keizer, 1977). To the south, the age of the Las Canoas sequence overlaps that of the lower part of the succession exposed in the Bolaños graben (Fig. 5), where Scheubel et al. (1988) reported K-Ar ages of 23.7 and 23.2 Ma for an andesite and an ignimbrite, respectively. Similarly aged ignimbritic sequences outcrop in the area of Teúl to the southeast (ca. 23 Ma, Moore et al., 1994), in the area of the Santa Rosa dam (23.6 Ma, Nieto-Obregón et al., 1985), in Juchipila (ca. 24–23 Ma, Webber et al., 1994) (Fig. 9), and in the Sierra de Pénjamo (ca. 24 Ma, Castillo-Hernández and Romero-Ríos, 1991; Sole and Salinas, 2002).

The El Nayar sequence is a NNW-oriented belt, which has an average width of 75 km along the western edge of the Sierra Madre Occidental (Fig. 5). This sequence reaches its maximum thickness in the region of the Mesa del Nayar where Ferrari et al. (2002) reported the presence of a series of calderas and cauldrons that may represent the main eruptive sites (Fig. 5). In the interior of El Nayar caldera, 11 different ignimbritic units can be observed, with an average total thickness of ~1000 m (Ferrari et al., 2002). Seven ^{40}Ar/^{39}Ar ages were obtained from different stratigraphic levels of the El Nayar sequence, which partially overlap but define an age range between 21.2 and 19.9 Ma, with an average of 20.9 Ma for the sequence (Ferrari et al., 2002). Southwards, the sequence correlates with ignimbrites exposed in Santa María del Oro (21.3 Ma, Gastil et al., 1979), Aguamilpa (22.4 Ma, Damon et al., 1979), and in the upper part of the Bolaños graben (21.3–20.1 Ma, Scheubel et al., 1988) (Fig. 5). For the El Nayar sequence, Ferrari et al. (2002) estimated that a volume of ~4500 km^3 may have been erupted in ~1.4 m.y.

The sequence of El Nayar is truncated to the west by extensional faulting associated with the opening of the Gulf of California. However, in the southern part of the Baja California peninsula (areas of La Paz and Loreto), Hausback (1984) and Umhoefer et al. (2001) obtained K-Ar ages ranging between ca. 23 and ca. 17 Ma for different ignimbrites interbedded in the lower part of the Comondú Formation. They include the La Paz tuff, a sequence exposed near the city of La Paz, for which Hausback (1984) reported K-Ar ages from 21.8 ± 0.2 to 20.6 ± 0.2 Ma. Due to the large areal extent of volcanic rocks of El Nayar age, Ferrari et al. (2002) suggested that the La Paz tuff may be a distal deposit from a caldera-forming eruption in the region of La Mesa de El Nayar. The original distance between La Paz and the Mesa del Nayar is difficult to estimate, however, the edge of the El Nayar caldera is ~42 km from the coastal plain of Nayarit, whereas La Paz is located at a similar distance from the eastern coast of Baja California Sur. Therefore, the La Paz tuff may have been related to a caldera located less than 100 km further east.

The ignimbritic volcanism of the Sierra Madre Occidental does not continue further south of the Trans-Mexican Volcanic Belt in the Jalisco block. In contrast to what has been reported on several regional geological maps (e.g., Ortega-Gutiérrez et al., 1992; López-Ramos, 1995), ignimbrites of Eocene-Miocene age are not known in the Jalisco block. Different geochronologic studies have shown that the ignimbrites, which are widely exposed in the northern part of the block, have $^{40}Ar/^{39}Ar$ ages from 81 to 60 Ma (Wallace and Carmichael, 1989; Lange and Carmichael, 1991; Righter et al., 1995; Rosas-Elguera et al., 1997), and therefore most likely correlate with the Lower Volcanic Complex exposed in Sonora (McDowell et al., 2001). Oligocene and Early Miocene ignimbrites are reported south of the Trans-Mexican Volcanic Belt in Michoacán, to the south of the Chapala lake (31.8 Ma, Rosas-Elguera et al., 2003; 23.5 Ma, Ferrari et al., 2002) and to the south of Morelia (21 Ma; Pasquarè et al., 1991).

Postignimbritic Volcanism

After the ignimbritic pulse (the "ignimbrite flare up" of McDowell and Clabaugh, 1979), magmatism became more heterogeneous and dispersed in the Sierra Madre Occidental. Volcanism was generally bimodal and discontinuous, and tended to migrate west toward the region of the future Gulf of California. Among the mafic rocks, a group of basaltic-andesites has been distinguished, which was emplaced soon after the ignimbritic pulse, and a second group of more mafic and alkaline rocks that generally followed the ending of subduction. In the northern part of the Sierra Madre Occidental, the beginning of the second event was preceded by the emplacement of a series of alkaline ignimbrites with a distinctive character. In this section, we briefly synthesize the distribution and age of these rocks.

Postignimbritic Transitional Mafic Volcanism (Southern Cordillera Basaltic Andesite Province)

Across all of the Sierra Madre Occidental, basaltic-andesite lavas were emplaced discontinuously in the final stages of, and after, each ignimbritic episode. The main exposures of these lavas are distributed along a belt roughly oriented NNE between San Buenaventura and Chihuahua to the north, and Navojoa and Sinaloa to the south, and crossing Yécora (Fig. 3). These mafic volcanic rocks were grouped into the Southern Cordillera Basaltic Andesite Province, which was proposed by Cameron et al. (1989) for a regionally widespread assemblage that extends further north into Arizona and New Mexico, and is interpreted as representing an initial phase of extension in an intra-arc setting. The ages reported for these rocks in Chihuahua and Sonora vary between 33 and 17.6 Ma (Cameron et al., 1989 and references therein; McDowell et al., 1997; Paz-Moreno et al., 2003). However, most ages are Oligocene. In northeastern Sonora, some rhyolitic tuffs are interbedded with the basaltic-andesitic lavas from which a $^{40}Ar/^{39}Ar$ age of 25.4 Ma on sanidine was obtained (González-León et al., 2000). Volcanism became younger and progressively more silicic in composition to the west. In the Sierra Santa Úrsula north of Guaymas (Fig. 3), ignimbrites, andesites, and dacitic domes are reported with ages between ca. 23 and 15 Ma (Mora-Álvarez and McDowell, 2000). These rocks also outcrop to the northwest in the region of Bahía Kino (Fig. 3), where ca. 18 Ma andesitic rocks are reported (Gastil and Krummenacher, 1977).

In the central sector of the Sierra Madre Occidental, basaltic lavas dated between 30 and 29 Ma cover the ignimbritic sequence of Durango (Caleras basalts of Swanson et al., 1978). Due to their composition and age, Luhr et al. (2001) associated these rocks with the Southern Cordillera Basaltic Andesite Province. In addition, ca. 24 Ma basalts cover Oligocene ignimbrites in Nazas (Aguirre-Díaz and McDowell, 1993) and El Rodeo (Aranda-Gómez at al., 2003; Sole and Salinas, 2002). Cameron et al. (1989) included the Nazas basalts among the SCORBA-type. However, later studies by Luhr et al. (2001) and Aranda-Gómez et al. (2003) have shown that these alkaline rocks (hawaiites) have a geochemical signature more akin to intraplate basalts, and more typical of the Mexican Basin and Range Province.

For the southern part of the Sierra Madre Occidental, there are no geochemical and petrologic studies on postignimbritic mafic rocks, although they can be observed in different places. Basaltic lavas emplaced shortly after the Early Oligocene ignimbrites are exposed in the area of Huejuquilla (Fig. 5) and are reported in the 1:250,000 geological maps of the Consejo de Recursos Minerales in western Zacatecas and northern Jalisco. Basaltic lavas emplaced after the Early Miocene ignimbritic pulse have been mapped in the area of Milpillas (Fig. 4), from which whole rock K-Ar dates of ca. 21 Ma have been obtained (Sole and Salinas, 2002). Mafic volcanic rocks have also been observed in the area of the Mesa del Nayar and Jesús María (Fig. 5), and have been dated by $^{40}Ar/^{39}Ar$ at 21.3 Ma (whole rock; Ferrari et al., 2002). Similar basaltic lavas are also found in the Bolaños graben, with K-Ar ages between 21 and 19.9 Ma (Nieto-Obregón et al., 1981). Some of these basalts are intercalated with the ignimbrites in the upper part of the Bolaños section.

Alkaline and Peralkaline Volcanism

In the northwestern part of the Sierra Madre Occidental, post-subduction magmatism is marked by the eruption of a distinctive sequence of ignimbrites and peralkaline rhyolitic and rhyodacitic lavas, locally known as the Lista Blanca Formation. These rocks are widely exposed elsewhere in southwestern Sonora (Fig. 3) and have a relatively restricted age range between ca. 14 and 11 Ma (Gastil and Krummenacher, 1977; Bartolini et al., 1994; McDowell et al., 1997; Mora-Álvarez and McDowell, 2000; Oskin et al., 2003; Mora-Klepeis and McDowell, 2004; Vidal-Solano et al., 2005). Some of these ignimbrites have comenditic compositions and relatively high concentrations of iron and alkalis ($Na_2O + K_2O = 8–10$ wt%). These alkaline geochemical signatures have been related to an asthenospheric mantle origin after an important period of crustal thinning during the initial opening of the Gulf of California, which promoted the up rise of convective mantle to the base of the continental crust (Vidal-Solano et al., 2005). Mora-Klepeis and McDowell (2004) interpreted the 12–11-Ma-old silicic rocks of the Sierra de Santa Úrsula as the first stage of postsubduction volcanism in Sonora, although it may more likely be a final magmatic phase related to intracontinental extension (Vidal-Solano et al., 2005). The 12.6 Ma San Felipe tuff is an important and widespread ignimbrite related to this event (Oskin et al., 2001; Oskin and Stock, 2003). It has been genetically associated with the Puertecitos volcanic province in Baja California, and has been correlated with different rock exposures along the Gulf of California up to coastal Sonora, and including Tiburón Island (Oskin et al., 2001).

In the rest of the Sierra Madre Occidental, alkaline volcanism essentially consists of alkali basalts that were emplaced as modest volumes of fissure-fed lavas, as well as large monogenetic volcanic fields. In general, these mafic rocks are found at the edges of the Sierra Madre Occidental, at the boundary with the Mesa Central, as well as in the eastern part of the Gulf of California. The alkali basalts are associated with three main extensional episodes that occurred during the Early Miocene (ca. 24–22 Ma), the Late Miocene (ca. 13–11 Ma), and the Plio-Quaternary (ca. 4–0 Ma) (Henry and Aranda-Gómez, 2000). At the eastern edge of the Sierra Madre Occidental, the main formations include: the Rodeo and Nazas basalts (Fig. 4) that were erupted from 24.1 to 23.3 Ma (Aranda-Gómez et al., 2003; Sole and Salinas, 2002) and at ca. 24 Ma (Aguirre-Díaz and McDowell, 1993), respectively; Metates Formation hawaiites in the southern part of the Rio Chico–Otinapa graben (Figs. 4 and 8), with ages of 12.7–11.6 Ma (McDowell and Keizer, 1977; Henry and Aranda-Gómez, 2000); the Camargo volcanic field, with ages from 4.7 Ma to the Holocene (Aranda-Gómez et al., 2003); and the Quaternary volcanic field of Durango (Smith et al., 1989). Extensive basaltic lavas exposed along the southern edge of the Sierra Madre Occidental in the area of La Manga (Fig. 5) have not been dated yet, but may correlate with this volcanic episode since mafic dikes exposed in nearby areas have been dated at ca. 11 Ma (Damon et al., 1979). Along the western edge of the Sierra Madre Occidental along the Gulf of California, postsubduction mafic rocks include: ca. 11–10 Ma tholeiitic basalts along the Sonora coast (Mora-Álvarez and McDowell, 2000; Mora-Klepeis and McDowell, 2004); the Pericos volcanic field to the north of Culiacán (this has not been studied, but is interpreted to be Latest Pliocene to Quaternary in age based on its young morphology); and the basalts of Punta Piaxtla and Mesa de Cacaxtla, exposed to the north of Mazatlán (3.2–2.1 Ma, Aranda-Gómez et al., 2003) (Fig. 5). Additionally, alkaline mafic dikes with a dominant NNW direction are common in the southwestern part of the Sierra Madre Occidental, from which Late Miocene ages (ca. 12–10 Ma) have been obtained in southern Sinaloa (Henry and Aranda-Gómez, 2000), as well as in Nayarit (Ferrari et al., 2002 and references therein). Available geochemical data are scarce but indicate that these rocks are also subalkaline in composition.

3. TECTONICS OF THE SIERRA MADRE OCCIDENTAL IGNEOUS COMPLEXES

Pre-Oligocene Deformation

Deformation that preceded Cenozoic extension has not been studied in detail. This is partly due to the scarcity of outcrops, the intense weathering of rocks, and the intense normal faulting that may obscure previous episodes of deformation in some areas. In Sonora, the Aptian-Albian marine succession is affected by folds and reverse faults but they did not produce any significant deformation in the overlying Lower Volcanic Complex rocks. In Sinaloa, Henry et al. (2003) recognized foliation and dynamic recrystallization textures in some tonalites and granodiorites of the coastal batholitic complex. The foliation is vertical on ENE-striking planes in the batholith and subparallel to the host rocks (orthogneiss, gabbro, and marble), suggesting that all these rocks were deformed at the same time (Henry 1986; Henry et al., 2003). K-Ar ages of different minerals and U-Pb ages of zircons from pre-, syn-, and post-tectonic plutons were interpreted by Henry et al. (2003) to indicate that deformation occurred between ca. 101 and ca. 89 Ma.

The Late Cretaceous to Paleocene volcanic succession of the Tarahumara Formation (ca. 90–60 Ma) is faulted and tilted, but folding and thrust faulting are not observed such that tilting may be related to Neogene normal faulting (McDowell et al., 2001). Further east in central Chihuahua, tilting of the ca. 68 Ma Peña Azules volcanic sequence was attributed to the Laramide orogeny by McDowell and Mauger (1994). However, the absence of reverse faulting or folding again raises the possibility that tilting was the result of Late Cenozoic normal faulting. East of Zacatecas, Campanian age intrusive rocks in the La Tesorera–Zacatón area are undeformed, as opposed to the Early Cretaceous marine succession that they intrude, which is involved in thrusts and open folds.

In summary, the few available data seem to indicate that between the Coniacian and Eocene, contractile deformation was negligible across most of the Sierra Madre Occidental, which was restricted to northwestern México, and in contrast to the western North American cordillera to the north. In Sonora and Sinaloa in the western part of the Sierra Madre Occidental, it is also common to find ENE-WSW–trending extensional fractures and faults that affected pre-Oligocene rocks (Horner and Enríquez, 1999; Staude and Barton, 2001). Most of the Cu-Mo porphyry deposits of the Sierra Madre Occidental are emplaced in highly fractured zones, developed concurrently, or at a late stage, during this phase of deformation (Barton et al., 1995; Horner and Enríquez, 1999). Geochronology studies of these deposits have consistently produced Paleocene and Eocene K-Ar ages (Damon et al., 1983; Staude and Barton, 2001), some of which have been recently confirmed by Re-Os dating (Barra et al., 2005). Horner and Enríquez (1999) interpreted the E-W– and ENE-WSW–trending structures as the result of a final phase of the Laramide shortening. However, the available data also permit these structures to be related to a different deformational episode that was transitional between the Laramide orogeny and the Oligo-Pliocene phase of extension.

Extensional Tectonics

Most of the Sierra Madre Occidental has been affected by different episodes of dominantly extensional deformation that began in the Oligocene and potentially at the end of Eocene. Extensional deformation has not affected the core of the Sierra Madre Occidental, which now represents a physiographic boundary between what has been defined as the "Mexican Basin and Range," to the east, and the "Gulf Extensional Province," to the west (Henry and Aranda-Gómez, 2000). In this work, we use the term "Basin and Range" essentially in a physiographic sense, with no genetic implications (i.e., in the sense of Dickinson, 2002). At the northern and southern ends of the Sierra Madre Occidental (i.e., northern Sonora and Chihuahua and Nayarit-Jalisco, respectively), these two provinces merge where extension has affected the entire width of the Sierra Madre Occidental (Fig. 6).

Northern Sector

Understanding the tectonic events that affected the northern part of the Sierra Madre Occidental is particularly complex since various extensional episodes overlap in space and time with igneous activity. It is evident that extension had begun in the Eocene, since a moderate angular unconformity exists between a 42–37 Ma succession and Oligocene ignimbrite south of Chihuahua (Megaw, 1990). In contrast, McDowell and Mauger (1994) considered that the transition between a contractile and an extensional deformation regime was at ca. 33 Ma, as recorded by the first occurrences of peralkaline ignimbrites and transitional basalts (SCORBA) in the region. The first extensional episode that can be documented regionally from structural evidence immediately follows the Oligocene silicic volcanism, whose maximum activity occurred between 34 and 29 Ma (McDowell and Clabaugh, 1979). Extension in Chihuahua is limited to Basin and Range structures that formed after 29 Ma based on different depositional relationships between pre- and post-29 Ma ignimbrites. No detailed structural studies are available for this region, but the presence of high-angle normal faults and the modest tilting of the volcanic successions suggest a limited amount of extension.

In Sonora, extension was much more intense and slightly younger than in Chihuahua. During a major episode of intracontinental deformation, rocks formed at middle crustal depths were locally exhumed along a wide belt subparallel to the Sierra Madre Occidental between Hermosillo and Tecoripa (Fig. 7) (Nourse et al., 1994; Vega-Granillo and Calmus, 2003; Wong and Gans, 2003, 2004). Along this belt are both high- and low-angle normal faults as well as metamorphic core complexes, which are characterized by detachment faults along which undeformed upper plate rocks are juxtaposed with lower plate milonite, gneiss, and peraluminous plutons (Davis and Coney, 1979; Nourse et al., 1994). Crustal extension during this episode is estimated to have locally exceeded 100% (Gans, 1997), and also formed tectonic troughs that were filled by clastic sediments with occasional accumulation of borate, lavas, and pyroclastic rocks (Fig. 3 and 7). Metamorphic core complexes are well known in the Magdalena (Nourse et al., 1994), Acónchi (Rodríguez-Castañeda, 1996; Calmus et al., 1996), Puerto del Sol (Nourse et al., 1994), and Mazatán areas (Vega-Granillo and Calmus, 2003; Gans et al., 2003; Wong and Gans, 2003) (Figs. 3 and 7). Peraluminous plutons exposed in these areas are thought to have been generated by partial melting of deformed crust (e.g., Nouse et al., 1994). Modeling $^{40}Ar/^{39}Ar$ ages in K-Feldspar, Gans et al. (2003) and Wong and Gans (2003) suggested an age between 20 and 16 Ma for the exhumation of the Mazatán core complex (Fig. 3), which is in agreement with an age of 18 ± 3 Ma obtained from apatite fission-track analysis for the same area (Vega-Granillo and Calmus, 2003). Published ages compiled by Nourse et al. (1994) for the different metamorphic core complexes in Sonora indicate an age range of ca. 25–15 Ma for this episode of crustal extension.

In addition to core complexes, extensional basins bounded by high-angle normal faults are common in central-eastern Sonora, and provide an additional constraint on the age of this extensional event. They are generally oriented NNW-SSE to ~N-S (Fig. 7), and contain thick successions of highly compacted conglomerate and sandstone that were initially defined as the Baucarit Formation (King, 1939). Basaltic to andesitic lavas ranging in age between 27 and 20 Ma are common toward the base of these clastic successions (McDowell et al., 1997; Paz-Moreno et al., 2003). The upper parts of these rift basin successions are less compacted and contain intercalated Middle Miocene tuff and rhyolite to rhyodacite lavas. Extension in these basins is much less than in the core complexes, indicating that extension may have been focused in areas where the basement had been previously weakened, and that the high values of stretching of ~100% obtained for some areas (Gans, 1997) is not representative for all of Sonora.

Along a coastal belt in Sonora, volcanic successions of Middle Miocene age are modestly tilted, with inclinations between 10° and 35° to the E or the W (McDowell et al., 1997; Mora-Álvarez and McDowell, 2000; MacMillan et al., 2003; Gans et al. 2003). The tilted blocks are covered in angular unconformity by flat-lying alkaline basalt lavas. In the Guaymas, Sierra Libre and Sierra del Bacatete areas, age dating constrains the boundary between the tilted rocks and flat-lying basalts to between ca. 12 and 10 Ma (Mora-Álvarez and McDowell, 2000; MacMillan et al., 2003) and between 10.7 and 9.3 Ma in the San Carlos–El Agujaje area (Gans et al., 2003) (Fig. 7). To the NW of Guaymas (Fig. 2), however, alkaline basalts dated at 8.3 Ma are cut by normal faults related to a younger extensional episode producing the "Empalme graben" described by Roldán-Quintana et al. (2004) (Fig. 7). The Empalme graben has been interpreted as marking the transition between Basin and Range–style block faulting and a strike-slip deformational regime associated with the beginning of the opening of the Gulf of California.

Although it is low in intensity, tectonic activity is still active in northeastern Sonora and northwestern Chihuahua. At least 64 historic earthquakes were recorded from 1887 to 1999 (Suter, 2001). The largest of these events is the Bavispe, Sonora, earthquake, of 3 May 1887, with $M_w = 7.4$. The earthquake rupture has been traced for over 100 km along three segments of a N-S fault active since the Miocene (Suter and Contreras, 2002).

Central Sector

In the central sector, extensional tectonics affected the Sierra Madre Occidental mainly along its borders, leaving a relatively unextended zone at its center (Fig. 6). Along its easternmost margin in Durango State, high-angle normal faults define basins much like those found in Chihuahua. The age of extensional deformation in this area dates back at least to the Oligocene and is characterized by a general ENE-WSW direction of elongation. In the Nazas area, ignimbrites dated by K-Ar at 29.9 ± 1.6 Ma are tilted up to 35° to the NE and are covered by flat-lying ignimbrites dated at 29.5 ± 0.6 Ma (Aguirre-Díaz and McDowell, 1993). In the Rodeo area of Durango State, Luhr et al. (2001) recognized an early episode of extension between 32.3 and 30.6 Ma that led to the formation of a NNW-trending half graben with an estimated ~3 km of vertical displacement. In addition, Aranda-Gómez et al. (2003) related the eruption of ca. 24 Ma alkaline lavas in both Nazas and Rodeo to a second extensional episode (Fig. 8). To the SSW of Durango city, the Mezquital graben is a 40-km-wide structure with a NNE orientation. The graben has not been studied in detail but the rocks cut by the high-angle–bounding faults are Oligocene in age, as the youngest is an ignimbrite dated at 27.0 ± 1.0 Ma (K-Ar age reported in Aranda-Gómez et al., 1997). In this area, these authors observed two generations of striae in the normal fault planes: the oldest one indicated extension oriented NW whereas the younger generation suggested a NE direction of extension.

To the west of Durango city, the Rio Chico–Otinapa graben is a 160-km-long and 20-km-wide extensional structure with a N-S to NNW-SSE orientation and a minimum vertical displacement estimated at 900 m (Aranda-Gómez et al., 2003) (Fig. 8). The high-angle normal faults bounding the graben cut the Oligocene ignimbrite sequence, which is covered by hawaiite lavas of the Metates Formation (Córdoba, 1963); the faults also acted as feeders for the hawaiite lavas. Amphibole separated from these lavas yielded ages of 12.7 ± 0.4 Ma by the K-Ar method (McDowell and Keizer, 1977) and 11.60 ± 0.07 Ma by the ^{40}Ar/^{39}Ar method (Henry and Aranda-Gómez, 2000). Based on these tectonic and stratigraphic relationships, it is concluded that the Rio Chico–Otinapa graben must have initiated before the eruption of the lavas, likely around ~12 Ma in response to WSW-ENE extension (Aranda-Gómez et al., 2003).

The western side of the Sierra Madre Occidental in Sinaloa has been profoundly affected by extensional faulting producing half grabens with a general NNW orientation. A NE-trending accommodation zone north of Tayoltita divides the region into two tilt domains, with the volcanic succession inclined to the ENE to the north, and to the WSW to the south (Fig. 8). The Concordia Fault is a major NW-trending structure to the east of Mazatlán (Fig. 8) that dips 40° to 70°NE, and with a vertical displacement of ~5 km (Aranda-Gómez et al., 2003). The Late Cretaceous to Paleocene Sinaloa batholith occurs in the footwall of the Concordia Fault, whereas the hanging wall consists of Oligocene to Early Miocene ignimbrites covered by poorly consolidated and weakly graded gravels that are also intruded by mafic dikes. Two mafic dikes have been dated at 10.7 ± 0.2 and 11.03 ± 0.16 Ma by ^{40}Ar/^{39}Ar on whole rock (Henry and Aranda-Gómez, 2000). Some dikes are also tilted indicating that extension continued after their emplacement. Extension in this region is estimated to range between 20% and 50% for a listric or plane geometry, respectively, to the Concordia Fault (Henry, 1989).

Close to the Sinaloa-Durango state boundary along the Durango-Mazatlán federal highway, the Early Miocene ignimbrite sequence is flat-lying and only minor faults are observed. However, to the north of the highway the same sequence is tilted by up to 30° due to normal faulting both in the Presidio River area (Aranda Gómez et. al, 2003) and in the valley of Piaxtla River close to Tayoltita (Horner and Enríquez, 1999; Enríquez and Rivera, 2001). This indicates that Middle to Late Miocene extension preceding the opening of the Gulf of California must have discontinuously affected the interior of the Sierra Madre Occidental.

Southern Sector

In the southern sector, all of the Sierra Madre Occidental has been affected by extensional tectonics (Figs. 6 and 9). At the northeastern boundary of this region in Fresnillo, Zacatecas State, an early phase of extension is evident with 39-Ma-old ignimbrites tilted up to 30° to the SW, which are covered by horizontal tuffs whose secondary alteration has been dated by K-Ar at 29.1 Ma (Lang et al., 1988). In the rest of the southern sector, however, there is no evidence of a pre-Oligocene phase of extension. In southern Zacatecas and northern Jalisco, several grabens are the continuation of extensional structures affecting the Central Mesa to the east (Nieto-Samaniego et al., 1999), whereas further west in Nayarit, half grabens are the dominant structures (Fig. 9). Ferrari et al. (2002) grouped the structure of the southern part of the Sierra Madre Occidental into three main domains (Fig. 9). An eastern domain is dominated by NNE- to N-S–oriented grabens between 40 and 120 km long that cut into Late Oligocene or Early Miocene ignimbrites. In the Tlaltenango graben, the youngest ignimbrite of the succession is 22 Ma (Moore et al., 1994) and is cut by normal faults with a minimum displacement of 400 m. Inside the graben, a shield volcano dated at 21 Ma (Moore et al., 1994) has fault scarps less than 50 m high, which suggests that some extension may have occurred between ca. 22 and ca. 20 Ma (Ferrari et al., 2002). In the Bolaños graben, which has a vertical displacement exceeding 1400 m, crosscutting relations among the different volcanic units indicate extension in the Early Miocene, which likely occurred in several phases (Ferrari et al., 2002; Lyons, 1988). For the other grabens, the present state of knowledge is insufficient to precisely constrain the inception of extension, but in all cases, normal faults related to WNW to E-W extension cut Early Miocene ignimbrites. In summary, extension leading to the development of grabens was generally synchronous across the eastern domain and began during the Early Miocene (Fig. 9).

The main structures of the western domain are the Alica, Pajaritos, and Jesús María half grabens, as well as the Pochotitán and San Pedro normal fault systems (Fig. 9). All these structures have a N-S to NNW-SSE orientation and systematically tilt blocks of Early Miocene ignimbrites to the ENE. An NE-trending accommodation zone across which there is a tilting reversal is inferred along the Mezquital River, such that to the north the tilt vergence is to the WSW (see also discussion for the northern sector). Master faults of the half grabens cut ignimbrites of the Nayar succession dated at ca. 21 Ma (Ferrari et al., 2002) but no minimum age can be inferred for fault activity. The San Pedro and Pochotitán fault systems were formed by an ENE- to NE-SW-directed extension and can be considered part of the Gulf Extensional Province. The Pochotitán fault system tilts rocks as young as 17 Ma, which are covered by flat-lying basaltic lavas dated at ca. 10 Ma (Ferrari and Rosas-Elguera, 2000). In this region, many mafic dikes intrude NNW normal faults or strike parallel to them. As in southern Sinaloa, the mafic dikes were intruded between 11.9 and 10.9 Ma, and were concurrent with the extensional tectonics (Ferrari et al., 2002).

The structural character of the southern domain contrasts with that of the rest of the southern sector as Oligocene and Early Miocene volcanic sequences of the Sierra Madre Occidental are characterized by open folds in an en echelon array, small thrusts and several left lateral faults all of which developed in the Middle Miocene (Ferrari, 1995). These structures are distributed in a belt with a WNW-ESE orientation at the southernmost boundary of the Sierra Madre Occidental with the Jalisco block basement. The folds are cut by vertical mafic dikes dated at ca. 11 Ma (Damon et al., 1979), providing a minimum age for the deformation. Ferrari (1995) interpreted these structures as a left lateral transpressional shear zone produced by the opposite motion between the Sierra Madre Occidental, during the waning of subduction of the Magdalena microplate, and the Jalisco block, beneath which subduction of the Cocos plate continued.

4. PETROLOGY AND GEOCHEMICAL CHARACTERISTICS OF THE SIERRA MADRE OCCIDENTAL MAGMATISM

Volcanic rocks of the Sierra Madre Occidental form a typical calc-alkaline association, characterized by intermediate to high potassium contents (Cochemé and Demant, 1991), together with a relatively low Fe enrichment (Cameron et al., 1980a). The main petrologic characteristics of these rocks are shown in Figure 10, which is based primarily on data from the northern sector of the Sierra Madre Occidental. The data indicate a broad range of compositions between ~49 and 78 wt% SiO_2, although igneous compositions are predominantly bimodal with silicic (~66–78 wt% SiO_2) and mafic (49–62 wt% SiO_2) groupings. Intermediate compositions (~62–66 wt% SiO_2) are rare. The Oligo-Miocene rhyodacite and rhyolite ignimbrites define the silicic compositional grouping whereas the mafic grouping includes andesite, basaltic andesite, and basalts of the Lower Volcanic Complex and postignimbritic transitional and alkaline mafic volcanism. The total alkalis-silica plot indicates a dominantly subalkaline association with a subordinate group of samples plotting in the alkaline field, which are mainly the postignimbritic mafic volcanic rocks. The postignimbritic mafic volcanic rocks also extend to subalkaline compositions and overlap the field of the southern Cordillera basaltic andesites (SCORBA), supporting the extension of this province to the northern part of the Sierra Madre Occidental as suggested by Cameron et al. (1989). Lower Volcanic Complex igneous compositions are broadly similar to the rest of the Sierra Madre Occidental rocks (Fig. 10), but are entirely subalkaline, have a more restricted range of silica contents with true basaltic compositions absent, and do not display a bimodal character (e.g., Valencia-Moreno et al., 2001, 2003). It is also worth comparing the Eocene to Oligocene and Neogene (ca. 25–10 Ma) rocks of Sierra Madre Occidental. Although only a few data are available for the Neogene volcanic rocks, they display a similar range of silica contents but rhyolitic compositions sensu stricto are absent. The limited trace element data available for the Sierra Madre Occidental rocks are indicative of a continental margin setting influenced by subduction. Linear trends in basalt-andesite-rhyolite suites in the Batopilas region for elements such as Rb, Sr, Nb, Y, Th, Zr, and REE were interpreted in early studies as the result of assimilation and fractional crystallization of mantle-derived mafic magmas (Cameron et al., 1980b; Bagby et al., 1981).

The mechanism responsible for the generation of the huge volume of silicic ignimbrites of the Sierra Madre Occidental has become highly debated since the first geochemical studies were published in the early 1980s (e.g., Cameron et al., 1980a and b; Cameron and Hanson., 1982; Verma, 1984; Ruiz et al., 1988a; Cameron et al., 1992; McDowell et al., 1999; Albrecht and Goldstein, 2000). Most approaches addressing this issue have relied on the whole-rock isotopic signatures of the volcanic rocks. Numerous studies have established that the initial $^{87}Sr/^{86}Sr$ ratios range between 0.7041 and 0.7070 and εNd between +2.3 and –3.2 for ignimbrites from several sites of the Sierra Madre Occidental. Lower εNd values (–5.2 to –5.8), and higher $^{87}Sr/^{86}Sr$ ratios (0.7089 and 0.7086) have been reported for areas of the northern Sierra Madre Occidental in the Tómochic and San Buenaventura areas (McDowell et al., 1999; Albrecht and Goldstein, 2000). Figure 11 shows the distribution of both εNd and $^{87}Sr/^{86}Sr$ isotopic data available for the Sierra Madre Occidental rocks. In general,

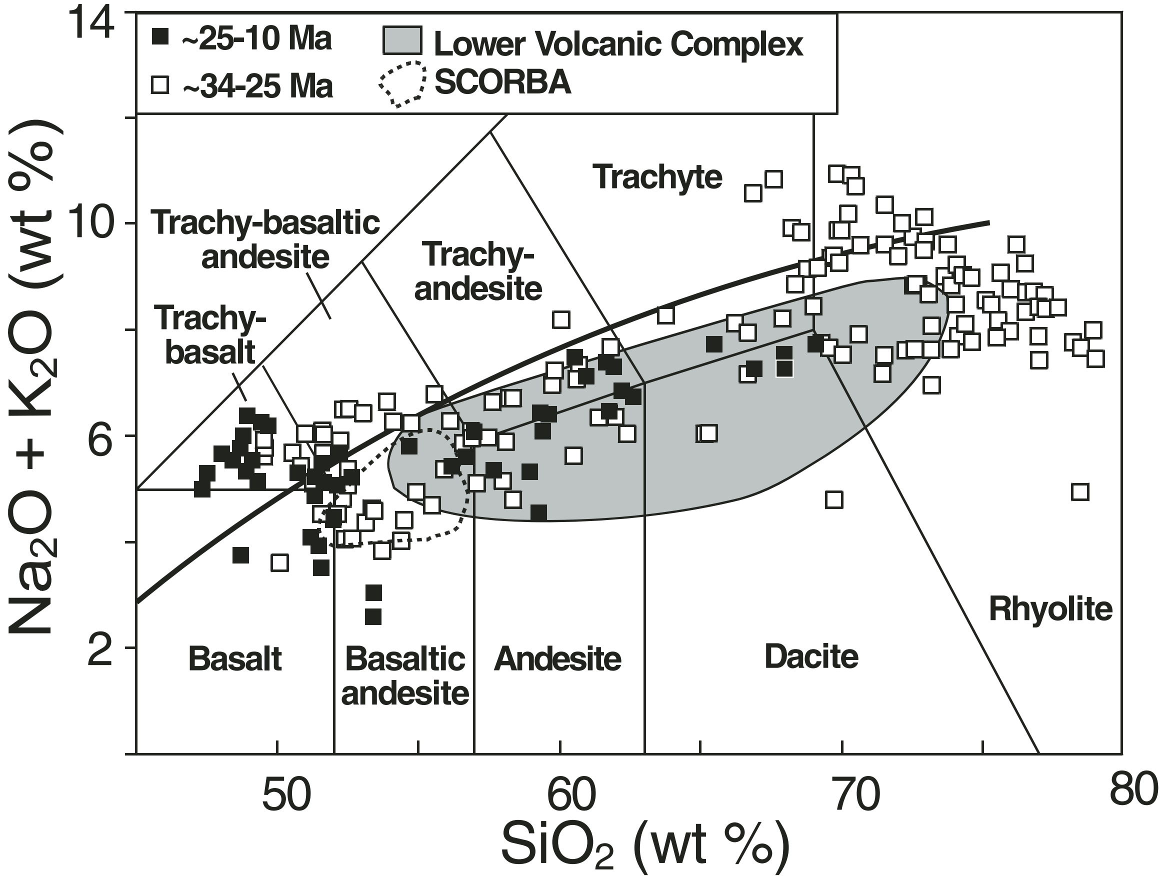


Figure 10. Total alkali-silica diagram (TAS) according to LeMaitre et al. (1989) for volcanic rocks of the northern Sierra Madre Occidental (open squares). The boundary between the alkaline and subalkaline fields (thicker line) is according to Irvine and Baragar (1971). The black squares represent volcanic rocks from the eastern Sierra Madre Occidental, within the Basin and Range Province. The field of the Southern cordillera basaltic andesites (SCORBA), based on Figure 5 of McDowell et al. (1997), is included here for comparison (dotted line). The field of magmatic rocks of the Lower Volcanic Complex (LVC) (shaded), based mainly on data from granitic intrusives, is also included. Sources: Sierra Madre Occidental—Cameron et al., 1980; Lanphere et al., 1980; Piguet, 1987; Wark, 1991; Gans, 1997; McDowell et al., 1997, 1999; Albrecht and Goldstein, 2000; González-León et al., 2000; Mora-Álvarez and McDowell, 2000. Post–Sierra Madre Occidental—Gastil and Krummenacher, 1977; Gastil et al., 1979; Bartolini et al., 1994; Gans, 1997; McDowell et al., 1997; González-León et al., 2000; Mora-Álvarez and McDowell, 2000; Henry et al., 2003. Lower Volcanic Complex—Bagby et al., 1981; Mora-Álvarez and McDowell, 2000; Roldán-Quintana, 1991; Valencia-Moreno et al., 2001, 2003; Henry et al., 2003.

many of the ignimbrites have isotopic compositions similar to the bulk Earth composition. The plot also shows a relatively continuous trend between samples with a more pronounced mantle signature (positive εNd and relatively primitive Sr values) to samples with negative εNd values and higher Sr ratios, suggesting significant crustal involvement in their petrogenesis.

To generate the rhyolites, Cameron et al. (1980a) proposed an AFC (assimilation and fractional crystallization) model for mantle-derived mafic magmas where the ignimbrites represented no more than 20% of the initial basaltic magma volume. This model implied that ~80% of the initial volume must have remained as residual material, adding some kilometers of new gabbroic crust beneath the Sierra Madre Occidental (Ruiz et al., 1988b; Cameron et al., 1992). Although isotopic studies are limited to a few areas, Cameron et al. (1986) suggested that the AFC model may be representative for the whole Sierra Madre Occidental and proposed that less than 25% crustal assimilation was involved in the generation of the ignimbrites. Verma (1984) put forward a similar genetic model for ignimbrites in Zacatecas and San Luis Potosí areas (Fig. 6), but also considered a second, shallower stage of fraction crystallization, which led to crustal assimilation being in the order of 80% before the final emplacement of the ignimbrites. In contrast, based on the modeling of many lower crustal xenoliths from areas to the east of the Sierra Madre Occidental, Ruiz et al. (1988b) proposed that most, if not all, of the volume of Sierra Madre Occidental ignimbrites may have been generated by partial melting of the lower continental crust since the isotopic compositions of the

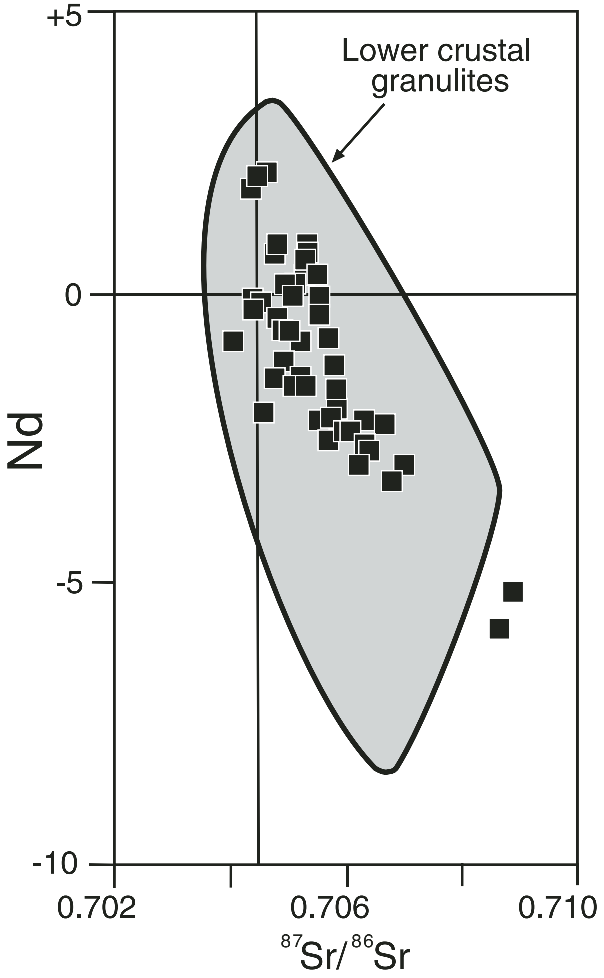


Figure 11. Sr-Nd correlation diagram showing the isotopic variation of volcanic rocks of the mid-Tertiary Sierra Madre Occidental. The cross hairs represent the bulk Earth composition. The field of the lower crustal granulites corresponds to intermediate and mafic orthognesiss xenoliths after Ruiz et al. (1988a). Sources: Wark, 1991; McDowell et al., 1999; Albrecht and Goldstein, 2000.

available crustal xenoliths (mafic to intermediate granulites of Paleozoic to Precambrian age) were identical to those of the Sierra Madre Occidental ignimbrites (Fig. 11). An important implication of this interpretation was that the magmatic episode that generated the Sierra Madre Occidental did not represent a period of significant crustal growth. Although mafic granulites/metaigneous xenoliths have the most appropriate chemical and isotopic compositions to be potential source materials for the Sierra Madre Occidental rhyolites, it remains unclear whether the xenoliths represent old lithosphere that was melted to generate the rhyolites (Ruiz et al., 1988b) or juvenile underplated material (i.e., cognate cumulate) essentially coeval with the rhyolites, and therefore representing several km of new crust that formed during the middle Tertiary beneath México (Cameron and Robinson, 1990).

5. THE CRUST AND THE MANTLE BENEATH THE SIERRA MADRE OCCIDENTAL: GEOPHYSICAL DATA

Despite its scientific and economic significance, few geophysical studies are available for the Sierra Madre Occidental. Most studies have a regional character and, although they define the major structures of the crust and upper mantle, and have not correlated the geophysical features with the detail of the surface geology.

The gross structure of the upper mantle beneath the Sierra Madre Occidental is mainly known from regional or global seismic tomography studies using different kinds of seismic waves and processing methods (Grand, 1994; Alsina et al., 1996; Van der Lee and Nolet, 1997; Bijwaard and Spakman, 2000; Ritzwoller et al., 2002; Ritsema et al., 2004). All of these studies have noted that mantle lithosphere beneath the Sierra Madre Occidental is thin or lacking. Although differing in details, all tomographic models show a low-velocity zone extending from ~80 km to ~250 km. This negative velocity anomaly extends from the Gulf of California to the Mesa Central, and from the U.S. Basin and Range Province to latitude 20° N in southern México. Estimations of the thermal structure based on tomographic models indicate that in this wide region, the mantle has a temperature ~500 °C higher than beneath the North America cratón to the east (Goes and van der Lee, 2002). These observations suggest that the lithospheric mantle has been mostly removed and replaced by asthenosphere.

Seismological data show a significant difference in crustal thickness between the Sierra Madre Occidental core and its margins. In a regional seismic study using surface and S-wave velocities, Gomberg et al. (1988) estimated an average thickness of 40 km for northern México. Given the ray trajectories used in this study, the authors also considered this crustal thickness as representative of the region to the east of the Sierra Madre Occidental, and the northern part of the Mesa Central.

More recently, Bonner and Herrin (1999) defined the crustal thickness of the northern part of the Sierra Madre Occidental by studying dispersion of surface waves generated by earthquakes occurring in the Gulf of California and received in Texas. Given this geographic array, the results may be considered representative of the central, less extended, part of the northern Sierra Madre Occidental. A crustal profile 55 km thick and with three layers: an ~5-km-thick layer with low velocity (Vs ~2.8 km/sec), an intermediate layer of ~20 km with Vs ~3.6 km/sec, and a lower layer of ~30 km characterized by high seismic velocity (Vs ~4.0 km/sec) provided the best fit to the seismic data (Bonner and Herrin, 1999).

In another recent study, Persaud (2003) used receiver functions at three points along the western side of the Sierra Madre Occidental to constrain the Moho depth in this part of the province where the crust has been thinned by extension that led to the formation of the Gulf of California. Moho depths reported in this study range from 28 km east of Hermosillo to 22 km both in southern Sonora (Navojoa) and northern Sinaloa (Culiacán) (Fig. 6).

Integrating gravimetric and seismic refraction data, Couch et al. (1991) estimated a minor contrast in crustal thickness in the central-southern part of the Sierra Madre Occidental where the crust at the center of the Sierra Madre Occidental is ~40 km but thins to 25 km at the coast south of Mazatlán (Fig. 6). Crustal thickness is also less to the east of the Sierra Madre Occidental beneath the Mesa Central; Fix (1975) estimated a value of ~30 km based on surface waves, whereas Campos-Enríquez et al. (1994) estimated a Moho depth of 33 km (Fig. 6).

Assuming a maximum Moho depth of 55 km for the unextended core of the northern Sierra Madre Occidental (Fig. 6) at the end of the ignimbritic pulse and an average of ~25 km for the Moho in Sonora and Sinaloa, Oligo-Miocene stretching of the crust on the western side of the Sierra Madre Occidental must have exceeded 100% if extension was uniform. This value is comparable with the extension calculated at surface for the region of core complexes in Sonora (e.g., Gans, 1997), but contrasts with geologic estimates in other areas of Sonora (McDowell et al., 1997) and Sinaloa (Henry, 1989), where less than 50% of extension and more likely in the order of ~20%–30% is indicated. The extreme extension estimated in certain areas of Sonora is a local feature where basement structures permitted the focusing of deformation, and/or there was decoupling between brittle and ductile crust, such that the latter may have flowed laterally during continental extension and opening of the Gulf of California (Persaud, 2003). This situation is not too different from in the western United States, where areas of highly extended crust are adjacent to areas of relatively unextended crust (Gans and Bohrson, 1998; Gans et al. 1989).

6. DISCUSSION

Space-Time Evolution of Convergent Margin Magmatism and Extensional Tectonics

The magmatic history of the Sierra Madre Occidental is intimately related to the evolution of the western margin of North America and the history of subduction of the Farallon plate. In a simplistic way, the magmatic evolution of the Sierra Madre Occidental fits into the pattern of inland migration and subsequent trenchward return of igneous activity already recognized for the southwestern part of the North America Cordillera between the Late Cretaceous and the Present (e.g., Coney and Reynolds, 1977; Damon et al., 1981; Damon et al., 1983) (Fig. 12A). According to this model, arc migration was primarily controlled by the variation in the dip of the Farallon plate being subducted beneath North America. At the beginning of the Late Cretaceous, the arc was located relatively close to the trench, with the Sierra Nevada and Peninsular Range batholiths (including Baja California) and the Lower Volcanic Complex of the Sierra Madre Occidental interpreted as the eroded remnants of this supra-subduction zone magmatic arc. The eastward migration of magmatism at the end of the Cretaceous has been related to the progressive decrease in slab dip associated with the Laramide orogeny. Once compression waned at the end of the Eocene, supra-subduction zone magmatism retreated westwards toward the trench as the dip of the subducted slab steepened.

Superficially, the space-time patterns of magmatism in México and the Sierra Madre Occidental show this type of pattern (Fig. 12). Eastward migration of magmatism is more evident in the United States and the northern Sierra Madre Occidental, where it reaches ~1000 km from the paleotrench (Damon et al. 1981), than in its central and southern parts. Henry et al. (2003) showed that magmatism in the central sector of the Sierra Madre Occidental only reached 400 km from the paleotrench and that the rate of eastward migration of magmatism took place at an order of magnitude lower (1–1.5 km/Ma) than the westward migration toward the trench. For the southern part of the Sierra Madre Occidental, the easternmost position of magmatism was in the Oligocene, when it reached a maximum of 600 km from the paleotrench (Nieto-Samaniego et al., 1999).

In the northern part of the Sierra Madre Occidental, eastward migration volcanism seems to postdate contractile deformation. The volcanic rocks of the Lower Volcanic Complex (ca. 90–60 Ma), both in Sonora (Tarahumara Fm.) and in Chihuahua (Peñas Azules volcanics), are only tilted and do not show clear evidence of having been affected by shortening. In the central part of the Sierra Madre Occidental, the ca. 101–89 Ma syntectonic plutons of Sinaloa (Henry et al., 2003) record deformation in the Lower Volcanic Complex that pre-dates Paleogene Laramide deformation of the Sierra Madre Oriental (Eguiluz de Antuñano et al., 2000). An additional point is that the Eocene rocks along the entire Sierra Madre Occidental do not show any evidence of contractile deformation.

The presence, during Late Cretaceous to Paleogene times, of magmatism located between the paleotrench and the deformation front in México precludes any model of flat subduction, as invoked to explain the Laramide orogeny in the United States (e.g., Coney and Reynolds, 1977, Bird, 1984, 1988; Saleeby, 2003), since the necessary coupling between subducting and upper plates would close the mantle wedge and shut-off arc magmatism. This is a similar situation for the Canadian sector of the Laramide orogen (English et al., 2003) and an alternative model is required to explain magmatism and deformation in México and Canada.

At a continental scale, volcanism during the Oligocene extended westwards toward the trench, although in detail, time-space patterns at the local scale may be more complex. Importantly, the Late Oligocene ignimbrite flare-up has essentially the same age across the entire Sierra Madre Occidental (ca. 32–28 Ma), and is distributed in a wide belt with a general NNW orientation (Fig. 2) without any apparent internal migration. In contrast, Early Miocene volcanism is clearly displaced toward the western half of the Sierra Madre Occidental and shows significant differences from north to south. In the northern Sierra Madre Occidental, Early Miocene volcanism is less abundant and was dominantly mafic in composition, whereas in the central and southern Sierra Madre Occidental, volcanism was more

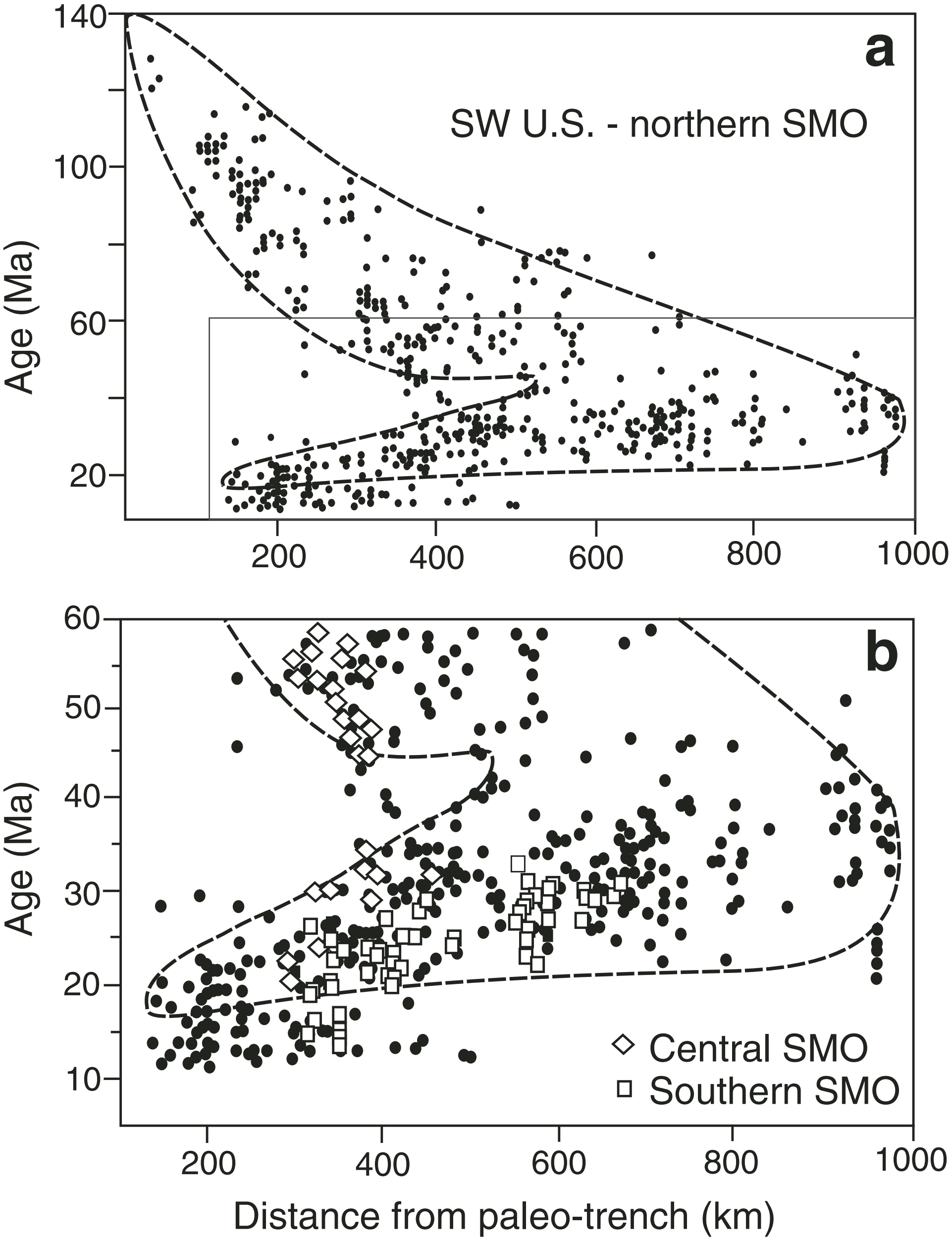


Figure 12. Distribution of available ages of Early Cretaceous to Miocene igneous rocks from México versus distance from the paleotrench. (A) Distribution of ages between ca. 140 and 10 Ma (modified from Damon et al., 1981) showing the inland migration of Cordilleran magmatism up to ~1000 km from the paleotrench between the Cretaceous and the end of Laramide orogeny (ca. 40 Ma). The inland migration was followed by an apparent rapid retreat of the magmatic activity toward the coast. The ages younger than 20 Ma and outside the enclosed field of ages mostly correspond to extension-related basalts. (B) Detailed time-space plot for ages between 60 and 10 Ma. Solid circles are data from Damon et al. (1981). The ages compiled by Nieto-Samaniego et al. (1999) for the southern part of the Sierra Madre Occidental (open squares), as well as those reported by Henry et al. (2003) for southern Sinaloa (open rhombs), are also shown.

bimodal with a second pulse of silicic ignimbrites and minor amounts of basalt. The eruption of andesite in the Early to Middle Miocene occurred further west in Baja California (the Comondú arc; Sawlan, 1991; Umhoefer et al., 2001) (Fig. 2), marking the first clear reestablishment of typical supra-subduction zone arc magmatism and ending the broad extension and migration of magmatism trenchward beginning ca. 40 Ma. In the southern part of the Sierra Madre Occidental, however, the pattern of migration appears more complex. Ferrari et al. (1999) showed that the orientation of the volcanic belt tended to rotate counterclockwise since the Oligocene from a NNW orientation to a WNW trend in the Early to Middle Miocene when volcanism extended to southern Baja California, but was absent south of latitude 20° N. In more detail, Ferrari et al. (2002, their Fig. 6) showed that during the Early Miocene, ignimbrite volcanism migrated to the ESE as far as longitude 101° W.

At the provincial scale, the onset of extension corresponds to the westward expansion of magmatic activity toward the trench. Data summarized section 3 indicate that extension, or more likely the extensional front, migrated episodically from east to west along the entire Sierra Madre Occidental (see also Stewart, 1998). Importantly, the onset of upper crustal extension seems to follow the first ignimbrite pulse. Extension probably began in the Eocene in the Mesa Central (Aranda-Gómez and McDowell, 1998; Nieto-Samaniego et al., 1999; Nieto-Samaniego et al., this volume), although more rapid extension began at ca. 30 Ma, after emplacement of the first rhyolites (Orozco-Esquivel et al., 2002). In the eastern part of the Sierra Madre Occidental, the earliest extension also occurs in mid-Oligocene times, after the emplacement of the first ignimbrite sheets ca. 30 Ma at Nazas and Rodeo, Durango (Aranda-Gómez et al., 2003), and between ca. 39 and ca. 29 Ma in Fresnillo, Zacatecas (Lang et al., 1988).

A second episode affected the central part of the Sierra Madre Occidental, with an extensional front moving westward between the end of the Oligocene and the Early Miocene. In western Chihuahua and Durango, high-angle normal faulting postdates ca. 28–27 Ma ignimbrites (see section 3 and Figures 4 and 5). Extension propagated northwestwards to eastern Sonora, where the main basins hosting the Báucarit Formation and *core complexes* developed mostly between ca. 26 and 16 Ma (Fig. 7). In the central part of the Sierra Madre Occidental, this episode is only expressed by the eruption of alkaline basalts in Rodeo and Nazas, Durango, at ca. 24 Ma (Aranda-Gómez et al., 2003). In the southern Sierra Madre Occidental, this extensional episode is expressed by the formation of various grabens with ~NNE-SSW to N-S orientation in southern Zacatecas and northwestern Jalisco (Fig. 9) between ca. 22 and 18 Ma, and after the beginning of the second ignimbritic pulse at 24–20 Ma.

At the end of the Middle Miocene (ca. 12 Ma), a third extensional episode affected the westernmost belt of the Sierra Madre Occidental. The age of this deformation, commonly referred to as the "Gulf Extensional Province" or "Proto-Gulf extension," is remarkably similar along the entire Sierra Madre Occidental occurring between ca. 12 and 9 Ma in Sonora (Gans et al., 2003), Sinaloa (Henry and Aranda-Gómez, 2000), and Nayarit (Ferrari and Rosas-Elguera, 2000; Ferrari et al., 2002). Although with less intensity, extension of this age occurred to the east of the Sierra Madre Occidental, with the formation of the Río Chico–Otinapa graben (Henry and Aranda-Gómez, 2000), other extensional structures in the Mesa Central, which are still seismically active in the Durango and Tepehuanes volcanic fields (Nieto-Samaniego et al., this volume), as well as with the eruption of alkaline lavas in the Los Encinos volcanic field in San Luis Potosí (Luhr et al. 1995).

The evolving geographic pattern of extensional tectonics summarized in the previous paragraphs clearly indicates a progression of extension through discrete episodes that discontinuously affected the entire region encompassing the Sierra Madre Occidental and Gulf of California (Fig. 1). Consequently, it is difficult to establish a limit between the Gulf Extensional Province and the Mexican Basin and Range, such that Henry and Aranda-Gómez (2000) proposed that the Gulf Extensional Province is part of the Basin and Range Province, and that the relatively unextended core of the Sierra Madre Occidental geographically separates the two provinces (Fig. 6). Therefore, continental extension was a widespread event that affected the entire southwestern part of the North American plate. These extensional processes, however, led to fundamentally different extended continental margins in the United States and México. In the western United States, Tertiary deformation eventually created an extensional province over 1000 km in width without rupturing the continental lithosphere. In México, after over 20 m.y., extension became localized in the Gulf of California region, resulting in the formation of a rift floored by oceanic crust since the Pliocene. In this framework, the region of Sonora—characterized by much higher extension than the rest of the Sierra Madre Occidental—marks the transition between thinned continental crust and oceanic crust flooring the Gulf of California.

At a continental scale, two causes may explain this differing behavior: (1) crustal rheologic contrasts, and (2) a thermal weakening of the zone in which the Gulf of California eventually developed. Crustal rheologic contrasts were proposed by Langenheim and Jachens (2003) who suggested that the Peninsular Range batholiths (together with its deeper mafic counterpart) represents a more rigid crustal block that controlled the localization of extensional deformation to the east, eventually leading to the separation of Baja California from mainland México. Thermal weakening to focus extension in the Gulf of California has been related to prior volcanic arc activity (i.e., the Comondú arc in southern Baja California) that occurred in this region before opening of the rift. Although Early to Middle Miocene rocks occur in Baja California (e.g., Sawlan, 1991; Stock and Lee, 1994), the older successions commonly comprise massive sedimentary deposits (fluvial conglomerate produced by the erosion of volcanics) and distal facies of ignimbrites (e.g., Hausback, 1984; Dorsey and Burns, 1994; Umhoefer et al., 2001), indicating minimal magmatism and therefore thermal input into the crust in this region. It was from the Middle to Late Miocene (ca. 15–12 Ma) that an andesitic arc was active and close to the coast of Baja California (see section 2 for Sonora and Umhoefer et al., 2001, for Baja California Sur). Thermal weakening of the crust may alternatively have been caused by the Oligo-Miocene volcanism in the region, and the Comondú arc may have only assisted in focusing extension in the region of the future Gulf of California.

Genesis of the Silicic Magmatism

Clearly, the most peculiar aspect of the Sierra Madre Occidental magmatism is the eruption of large volumes of silicic magma in a relatively short time. These ignimbrite pulses are not common, and large-volume silicic volcanism only characterizes volcanic arcs when undergoing extension, or rifting to form a backarc basin (e.g., Taupo Volcanic Zone), and the formation of volcanic rifted margins (Bryan et al., 1997, 2002). Discussions on the petrogenesis of the silicic magmas in the Sierra Madre Occidental have been recurrent in the literature and have generally been divided between two end-member models. The first model suggests that the rhyolites formed largely by partial melting of the crust (e.g., Huppert and Sparks, 1988) as a consequence of the arrival of large amounts of basaltic magmas from the mantle, which provide the heat necessary to melt the crust (Ruiz et al., 1988a, 1990; Albrecht and Goldstein, 2000; Ferrari et al., 2002). This model has been invoked for the generation of other silicic large igneous provinces (Pankhurst and Rapela, 1995; Ewart et al., 1998; Riley et al., 2001; Bryan et al., 2002). In the second model, the rhyolites are interpreted as the final product of the differentiation of basaltic magmas with small or negligible contributions from the crust (Cameron and Hanson, 1982; Cameron and Cameron, 1985; Cameron et al., 1980a, b; Cameron and Robinson, 1990; Wark, 1991; Smith et al., 1996). The basis for some of these models is limited as they have been formulated from data gathered from a few sites and representative of a limited time scale (e.g., 1–2 Ma), yet the results have been generalized to explain the origin of large volumes ($>10^5$ km^3) of rhyolite over a relatively large time span (10–20 m.y.). It is worth emphasizing that existing studies on the petrogenesis of the Sierra Madre Occidental rhyolites are restricted to Oligocene sections from four sites in western Chihuahua (Batopilas, Divisadero, San Buenaventura, and Tómochic), one site in Zacatecas at the southeastern margin of the Sierra Madre Occidental, and two sections located in the Mesa Central (La Olivina, Chihuahua, and San Luis Potosí).

In principle, discriminating between the two end-members (anatexis versus fractional crystallization) and assessing crustal contributions to rhyolitic magmatism may appear relatively straightforward, as mantle and continental crust are thought to have distinctive ^{87}Sr/^{86}Sr and εNd (and other isotopic) compositions. The use of whole rock geochemical and isotopic data and lower crustal xenoliths, which have provided a more direct sampling of the lower crust, have been the main approach used in the Sierra Madre Occidental (Cameron and Hanson, 1982; Cameron and Cameron, 1985; Cameron et al., 1980a, b; Ruiz et al., 1988a, 1990; Cameron and Robinson, 1990; Wark, 1991; Smith et al., 1996; Albrecht and Goldstein, 2000). The results, however, have frequently been ambiguous (see section 4), since the rhyolites and the scarce associated mafic lavas have Sr and Nd isotopic compositions intermediate between those inferred for a mantle metasomatized by subduction fluids, and the Paleozoic or Mesozoic lower crust though which they emplaced (e.g., εNd of ~+4 to –4, Fig. 11) (Wark, 1991; Johnson, 1991). Nevertheless, some crustal contribution to rhyolite magmatism is generally required from isotopic considerations (Cameron and Cameron, 1985; Wark, 1991).

The debate on a dominantly mantle versus crustal origin for the Sierra Madre Occidental rhyolitic ignimbrites has several implications that have been discussed in the literature for other silicic large igneous provinces. If rhyolite generation is due primarily to fractional crystallization of mantle-derived basaltic magmas, then significant material transfer and new crust formation is implied. Furthermore, if the rhyolites are the product of basalt differentiation only, then a fourfold volume of mafic cumulates in the crust is required (e.g., Cameron et al., 1980a; Cameron and Hanson, 1982; Ruiz et al., 1988a). In turn, if these mafic residues are formed in the proximity of the Moho, this may lead to convective instability at the base of the crust (e.g., Kay and Mahlburg-Kay, 1991; Kay et al., 1992; Meissner and Mooney, 1998; Jull and Kelemen, 2001). Alternatively, if cumulates formed at a different level in the crust, then a variation in the composition, thermal structure, and isostatic, seismic, and rheologic properties of the crust is expected (Gans, 1997; Gans et al., 1989; Klemperer, 1989; Glazner and Ussler, 1989; Johnson, 1991; Miller and Paterson, 2001). In contrast, if rhyolites formed primarily by partial melting of the crust, then a substantially lower volume of basaltic magma is required and residual cumulates produced (Ruiz et al., 1988a), resulting in a different crustal thickness and petrologic and rheologic crustal profiles.

Whether a basaltic magma contributes heat and/or mass to the generation of the rhyolites, an important question that can be addressed by geophysical data is the localization and the fate of the cumulate residual material (Smith et al., 1996; Jull and Kelemen, 2001; Ducea, 2002). The geophysical data synthesized in this work indicate that the crust in the unextended core of the Sierra Madre Occidental is thicker than along its margins (Fig. 6): in the northern Sierra Madre Occidental the unextended part is ~55 km versus ~40 km to the east and ~28–22 km along the coast of the Gulf of California. The thickness of the Sierra Madre Occidental core also appears thicker than that of other Precambrian or Paleozoic crustal sections (e.g., Mooney et al., 1998). Even for the central and southern part of the Sierra Madre Occidental where only post-Paleozoic basement is inferred to exist, the crust is ~10 km thicker than its counterpart in the Mesa Central to the east (see also Nieto-Samaniego et al., 1999). These anomalous thicknesses, coupled with the high seismic velocity contrast of the lower layer detected by Bonner and Herrin (1999) in the northern part of the Sierra Madre Occidental, suggest that the lower crust has been heavily intruded by mafic magmas.

The intrusion or underplating of mafic magma represents new additions to the continental crust and, by consequence, a lowering of the Moho, which is a process common in many active continental margins (Klemperer, 1989). The regional character of the seismic studies available for the Sierra Madre Occidental, together with a lack of detailed estimations of the volume of ignimbrites and their intrusive equivalent, currently prevent robust discrimination between the fractional crystallization and partial melting models and relative contributions of crust and mantle to Sierra Madre Occidental rhyolite generation. However, the presence of a significant volume of mafic intrusions in the lower crust is consistent with the cause of the ignimbrite pulses resulting from the arrival of large volumes of basaltic magma from the mantle.

A more general and important question is what controls the generation of large volumes of rhyolite or basalt to form a Large Igneous Province (LIP)? The fertility of the crust has been invoked as a determining factor in the generation of large volumes of rhyolites (Bryan et al., 2002), since many of the silicic LIPs are found on Phanerozoic crust, whereas most LIPs, as typified by the Mesozoic to Recent continental flood basalt provinces, are located on Archean crust and generally mafic. Numeric modeling of magma intrusion into the lower crust has demonstrated that the presence of hydrous minerals and basalts with high T and low water content promote crustal melting (Annen and Sparks, 2002). For the Sierra Madre Occidental, despite the presence of Precambrian crust in the northern part of the province, little involvement of Precambrian crust in rhyolite magma generation is indicated by whole-rock isotopic compositions of the ignimbrites, and from the observation that the Oligocene ignimbrite pulse produced similar volumes across the whole province. Nevertheless, the fertility of the lithosphere was likely increased by geologic events prior to the ignimbrite flare-up. Humphreys et al. (2003) proposed that sub-horizontal subduction of the Farallon plate during the Laramide orogeny may have hydrated and fertilized the Precambrian lithosphere of the North America plate. Once the Farallon plate was removed from the base of the North America plate in the Tertiary, the uprise of asthenospheric mantle led to crustal heating, partial melting, and the outburst of silicic volcanism. This general model, originally proposed to explain mid-Tertiary silicic volcanism in the southwestern United States, may be equally applicable to the Sierra Madre Occidental, which shares a similar tectonic history.

In conclusion, a range of possibilities exist to explain the generation of the Sierra Madre Occidental silicic magmas, with fractional crystallization and crustal anatexis as end-members. Geophysical information and petrologic studies are still too scarce to fully understand the processes of silicic magma generation and if fractional crystallization or partial melting played a dominant role. Nevertheless, the presence of (1) crustal isotopic signatures and isotopic differences between ignimbrites erupted through different types of crustal basement (McDowell et al., 1997; Albrecht and Goldstein, 2000; Valencia-Moreno et al., 2001); (2) Precambrian, Mesozoic, and Tertiary inheritance in magmatic zircons within the ignimbrites (McDowell et al., 1997; Bryan et al., 2006); and (3) the essentially bimodal character of the Oligocene and Early Miocene volcanic pulses suggest that assimilation and/or melting of the crust was significant in the Sierra Madre Occidental. We consider that the petrogenesis of the Sierra Madre Occidental ignimbrites was dominated by processes of large-scale magma mixing and/or AFC capable of producing large amounts of silicic magmas and lesser volumes of variably contaminated basalt and basaltic andesite. In detail, the locus of the crust involved in assimilation and melting likely varied with time with progressively shallower zones potentially affected as the intrusion of mafic magmas induced a densification of the lower crust and/or remelted earlier intruded magma.

Geodynamic Causes of Magmatism and Extension

Based on the considerations of the previous section, it seems clear that, regardless of the mechanism responsible for the generation of rhyolites, each ignimbrite pulse was related to the arrival of considerable amounts of mantle-derived mafic magma at the base of the crust. The remarkable synchronism and large volume of the first ignimbrite pulse extending across the entire Sierra Madre Occidental indicate that this phenomenon cannot be the result of a "normal" subduction regime but, rather, the consequence of a continental scale mechanism related to plate dynamics. The results of different seismic tomography studies indicate that the upper mantle beneath the Sierra Madre Occidental is characterized by a significant thermal anomaly (see section 5), which is interpreted to be asthenosphere. The tectono-magmatic evolution of the Sierra Madre Occidental indicates this thermal anomaly is the result of the removal of the Farallon plate from the base of the North American plate in mid-Tertiary times (e.g., Humphreys, 1995). In México, the removal of the subducted Farallon plate occurred at different stages, each one characterized by different mechanisms. Eocene volcanics, if interpreted as supra-subduction zone volcanism in the eastern part of the Sierra Madre Occidental, would indicate that by this time, fluid-induced melting of a mantle wedge was occurring after the foundering of the Farallon plate. This volcanic episode coincides with the first signs of a decrease in the velocity of convergence between the Farallon and North America plates between 43 and 39 Ma (Norton, 1995). The first ignimbrite pulse (ca. 32–28 Ma) of the Sierra Madre Occidental coincides with a second stage of decrease in convergence rates between ca. 33 and 25 Ma (Norton, 1995), and the first contact between the East Pacific Rise and North America occurring south of California at ca. 28 Ma (Atwater and Stock, 1998). The decrease in convergence velocity occurred when progressively younger and more buoyant oceanic crust arrived at the paleotrench and, eventually, the northern part of the Farallon plate lost some fragments which became the Monterey and Jasper plates between ca. 28.5 and ca. 27.5 Ma (Lonsdale, 2005). Decreases in subduction velocity typically produce an increase in slab dip. This, in turn, induces a strong convection as it "pulls" asthenospheric mantle into the opening mantle wedge. This process of bringing asthenospheric mantle to shallower depths and in contact with the base of the continental crust led to a sudden increase in partial melting of the mantle and the generation of an ignimbrite pulse within a short period of time.

The second ignimbrite pulse in the southern part of the Sierra Madre Occidental (ca. 24–20 Ma) mostly coincided with the formation of metamorphic core complexes in the northern Sierra Madre Occidental (and southern United States). During this period, the Farallon plate was still being subducted beneath parts of western México after the Pacific and North America plates had come into direct contact further north, in southern California. The interaction between the Pacific and North America plates, with a diverging relative motion, resulted in the formation of a slab window in front of the contact zone (Atwater and Stock, 1998; Dickinson, 1997, 2002). In this zone, the deeper part of the subducting Farallon slab must have detached from the shallower part of the plate. Ferrari et al. (2002) proposed that once initiated, the detachment may have propagated toward the south-southwest because of an increase in the slab pull on that part of the plate still attached, documented in other areas of the world (e.g., Wortel and Spakman, 2000). Consequently, there may have been asthenospheric flow into the mantle wedge. In the northern part of the Sierra Madre Occidental, the flow of the asthenospheric material, together with plate boundary forces (e.g., Sonder and Jones, 1999), may have produced the high-magnitude extension that formed the metamorphic core complexes. In the southern Sierra Madre Occidental, slab rupture may have induced a second episode of asthenospheric underplating, triggering crustal partial melting and the subsequent ignimbrite pulse.

The review of the magmatic and tectonic history of the Sierra Madre Occidental presented in this work indicates that this geologic province is closely connected to the evolution of the Cretaceous-Cenozoic subduction system of the Farallon beneath the North America plate. In particular, the Sierra Madre Occidental as an Oligo-Miocene silicic LIP was the result of events that occurred at the end of subduction of the Farallon plate. The Sierra Madre Occidental shares many characteristics with other silicic LIPs (Table 1), some of which preceded the formation of volcanic rifted margins (Bryan et al., 1997). In this sense, the ignimbrite pulses of the Sierra Madre Occidental are not the product of normal supra-subduction zone volcanism, but rather, the precursors of lithospheric rupture that eventually led to the formation of the Gulf of California.

ACKNOWLEDGMENTS

Some of the results reported in this work for the northern and southern part of the Sierra Madre Occidental are a product of grants CONACyT I29887 T and DGAPA/UNAM IN10660 (M. Valencia) and CONACyT P-0152 T (L. Ferrari). Centro de Geociencias, UNAM, and the Damon Wells Research Fellowship to S. Bryan at Yale University supported fieldwork related with this project in Chihuahua, Zacatecas, and Jalisco during 2004. We thank the editors of this special issue for encouraging us to carry out this review. We are also thankful for the detailed reviews of Chris Henry and Ángel Nieto-Samaniego and the informal reviews of Enrique González Torres and Gabriel Chávez Cabello, which helped improve the clarity of the final manuscript, and Peter Reiners for discussions on aspects of Sierra Madre Occidental magmatism.

REFERENCES CITED

Aguirre-Díaz, G.J., and Labarthe, G., 2003, Fissure ignimbrites: Fissure-source origin for voluminous ignimbrites of the Sierra Madre Occidental and its relationship with Basin and Range faulting: Geology, v. 31, p. 773–776, doi: 10.1130/G19665.1.

Aguirre-Díaz, G.J., and McDowell, F.W., 1991, The volcanic section at Nazas, Durango, Mexico, and the possibility of widespread Eocene volcanism within the Sierra Madre Occidental: Journal of Geophysical Research, v. 96, p. 13373–13388.

Aguirre-Díaz, G.J., and McDowell, F.W., 1993, Nature and timing of faulting and syn-extensional magmatism in the southern Basin and Range, central-eastern Durango, Mexico: Geological Society of America Bulletin, v. 105, p. 1435–1444, doi: 10.1130/0016-7606(1993)105<1435:NATOFA>2.3.CO;2.

Albrecht, A., and Goldstein, S.L., 2000, Effects of basement composition and age on silicic magmas across an accreted terrane-Precambrian crust boundary, Sierra Madre Occidental, Mexico: Journal of South American Earth Sciences, v. 13, p. 255–273, doi: 10.1016/S0895-9811(00)00014-6.

Alencaster, G., and de Cserna, Z., 1961, Paleontología del Triásico Superior de Sonora Parte 1, Estratigrafía del Triásico Superior de la parte central del Estado de Sonora: Universidad Nacional Autónoma de México, Instituto de Geología, Paleontología Mexicana, v. 11, 18 p.

Almazán-Vázquez, E., 1989, El Cámbrico-Ordovícico de Arivechi, en la región centro-oriental del Estado de Sonora: Universidad Nacional Autónoma de México, Instituto de Geología, Revista, v. 8, p. 58–66.

Alsina, D., Woodward, R.L., and Sneider, R.K., 1996, Shear wave velocity structure in North America from large-scale waveform inversions of surface waves: Journal of Geophysical Research, v. 101, p. 15969–15986, doi: 10.1029/96JB00809.

Anderson, T.H., and Schmidt, V.A., 1983, The evolution of Middle America and the Gulf of Mexico-Caribbean Sea region during Mesozoic time: Geological Society of America Bulletin, v. 94, p. 941–966, doi: 10.1130/0016-7606(1983)94<941:TEOMAA>2.0.CO;2.

Anderson, T.H., and Silver, L.T., 1979, The role of the Mojave-Sonora megashear in the tectonic evolution of northern Sonora, *in* Anderson, T.H., and Roldán-Quintana, J., eds., Geology of Northern Sonora: Guidebook-Field Trip 27, Annual meeting of the Geological Society of America, Universidad Nacional Autónoma de México, Instituto de Geología and the University of Pittsburgh, Pittsburgh, p. 59–68.

Anderson, T.H., Nourse, J.A., McKee, J.W., and Steiner, M.B., eds., 2005, The Mojave-Sonora Megashear Hypothesis: Development, Assessment, and Alternatives: Geological Society of America Special Paper 393, 693 p.

Annen, C., and Sparks, R.S.J., 2002, Effects of repetitive emplacement of basaltic intrusions on thermal evolution and melt generation in the crust: Earth and Planetary Science Letters, v. 203, p. 937–955, doi: 10.1016/S0012-821X(02)00929-9.

Aranda-Gómez, J.J., and McDowell, F.W., 1998, Paleogene extension in the southern basin and range province of Mexico: Syndepositional tilting of Eocene red beds and Oligocene volcanic rocks in the Guanajuato mining district: International Geology Review, v. 40, p. 116–134.

Aranda-Gómez, J.J., Henry, C.D., Luhr, J.F., and McDowell, F.W., 1997, Cenozoic volcanism and tectonics in NW Mexico—a transect across the Sierra Madre Occidental volcanic field and observations on extension related magmatism in the southern Basin and Range and Gulf of California tectonic provinces, *in* Aguirre-Díaz, G.J., Aranda-Gómez, J.J., Carrasco-Núñez, G., and Ferrari, L., eds., Magmatism and Tectonics in the Central and Northwestern Mexico—A Selection of the 1997 IAVCEI General Assembly Excursions, México, D.F., Universidad Nacional Autónoma de México, Instituto de Geología, p. 41.

Aranda-Gómez, J.J., Luhr, J.F., Housh, T.B., Connor, C.B., Becker, T., and Henry, C.D., 2003, Synextensional Pliocene-Pleistocene eruptive activity in the Camargo volcanic field, Chihuahua, México: Geological Society of America Bulletin, v. 115, p. 298–313, doi: 10.1130/0016-7606(2003)115<0298:SPPEAI>2.0.CO;2.

Atwater, T., and Stock, J.M., 1998, Pacific-North America plate tectonics of the Neogene southwestern United States: An update: International Geology Review, v. 40, p. 375–402.

Bagby, W.C., Cameron, K.L., and Cameron, M., 1981, Contrasting evolution of calc-alkalic volcanic and plutonic rocks of western Chihuahua, Mexico: Journal of Geophysical Research, v. 86, p. 10402–10410.

Bain, J.H.C., and Draper, J.J., eds., 1997, North Queensland Geology: Queensland Geology, vol. 9: Australian Geological Survey Organisation bulletin: Geological Survey of Queensland, Department of Mines and Energy, 600 p.

Barra, F., Ruiz, J., Valencia, V.A., Ochoa-Landín, L., Chesley, J.T., and Zürcher, L., 2005, Laramide porphyry Cu–Mo mineralization in northern Mexico: Age constraints from Re–Os geochronology in molybdenites: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 100, p. 1605–1616.

Bartolini, C., Damon, P.E., Shafiqullah, M., and Morales-Montaño, M., 1994, Geochronologic contributions to the Tertiary sedimentary-volcanic sequences (“Baucarit Formation”) in Sonora: Geofísica Internacional, v. 34, p. 67–77.

Barton, M.D., Staude, J.-M.G., Zürcher, L., and Megaw, P.K., 1995, Porphyry copper and other intrusion-related mineralization in Mexico, *in* Pierce, F.W., and Bolm, J.G., eds., Bootprints of the Cordillera: Arizona Geological Society Digest, v. 20, p. 487–524.

Bijwaard, H., and Spakman, W., 2000, Non-linear global P-wave tomography by iterated linearized inversion: Geophysical Journal International, v. 141, p. 71–82, doi: 10.1046/j.1365-246X.2000.00053.x.

Bird, P., 1984, Laramide crustal thickening event in the Rocky Mountain foreland and Great Plains: Tectonics, v. 3, p. 741–758.

Bird, P., 1998, Kinematic history of the Laramide orogeny in latitudes 35°–49° N, western United States: Tectonics, v. 17, p. 780–801, doi: 10.1029/98TC02698.

Bockoven, N.T., 1980, Reconnaissance geology of the Yecora-Ocampo area, Sonora and Chihuahua, Mexico [Ph.D. thesis]: Austin, University of Texas, 197 p.

Bonneau, M., 1970, Una nueva área cretácica fosilífera en el estado de Sinaloa: Boletín de la Sociedad Geológica Mexicana, v. 32, p. 159–167.

Bonner, J.L., and Herrin, E.T., 1999, Surface wave study of the Sierra Madre Occidental of northern Mexico: Bulletin of the Seismological Society of America, v. 89, p. 1323–1337.

Bryan, S.E., 2005a, Silicic Large Igneous Provinces: http://www.mantleplumes.org/SLIPs.html (November 2006).

Bryan, S.E., 2005b, The Early Cretaceous Whitsunday Silicic Large Igneous Province of eastern Australia: http://www.largeigneousprovinces.org/LOM.html, August 2005 Large Igneous Province (November 2006).

Bryan, S.E., Constantine, A.E., Stephens, C.J., Ewart, A., Schön, R.W., and Parianos, J., 1997, Early Cretaceous volcano-sedimentary successions along the eastern Australian continental margin: Implications for the break-up of eastern Gondwana: Earth and Planetary Science Letters, v. 153, p. 85–102, doi: 10.1016/S0012-821X(97)00124-6.

Bryan, S.E., Ewart, A., Stephens, C.J., Parianos, J., and Downes, P.J., 2000, The Whitsunday Volcanic Province, central Queensland, Australia: Lithological and Stratigraphic investigations of a silicic-dominated large igneous province: Journal of Volcanology and Geothermal Research, v. 99, p. 55–78, doi: 10.1016/S0377-0273(00)00157-8.

Bryan, S.E., Riley, T.R., Jerram, D.A., Leat, P.T., and Stephens, C.J., 2002, Silicic volcanism: an undervalued component of large igneous provinces and volcanic rifted margins, *in* Menzies, M.A., Klemperer, S.L., Ebinger, C.J., and Baker J., eds., Magmatic Rifted Margins: Geological Society of America Special Paper 362, p. 99–120.

Bryan, S.E., Holcombe, R.J., and Fielding, C.R., 2003, The Yarrol terrane of the northern New England Fold Belt: Forearc or backarc?: Reply: Australian Journal of Earth Sciences, v. 50, p. 271–293.

Bryan, S.E., Ferrari, L., Reisner, P.W., Allen, C.M., and Campbell, I.H., 2006. New insights into large volume rhyolite generation at the mid-Tertiary Sierra Madre Occidental Province, Mexico, revealed by U-Pb geochronology: GEOS, Boletín Unión Geofísica Mexicana, vol. 26, n. 1. p. 134.

Busby, C., Smith, D., Morris, W., and Fackler-Adams, B., 1998, Evolutionary model for convergent margins facing large ocean basins: Mesozoic Baja California, Mexico: Geology, v. 26, p. 227–230, doi: 10.1130/0091-7613(1998)026<0227:EMFCMF>2.3.CO;2.

Calmus, T., Pérez-Segura, E., and Roldán-Quintana, J., 1996, The Pb–Zn ore deposits of San Felipe (Sonora, Mexico): An example of detached mineralization in the basin and range Province: Geofísica Internacional, v. 35, p. 115–124.

Cameron, K.L., and Cameron, M., 1985, Rare earth element, ^{87}Sr/^{86}Sr, and ^{143}Nd/^{144}Nd compositions of Cenozoic orogenic dacites from Baja California, northwestern Mexico, and adjacent West Texas: Evidence for the predominance of a subcrustal component: Contributions to Mineralogy and Petrology, v. 91, p. 1–11, doi: 10.1007/BF00429422.

Cameron, K.L., and Hanson, G.N., 1982, Rare earth element evidence concerning the origin of voluminous mid-Tertiary rhyolitic ignimbrites and related volcanic rocks, SMO, Chihuahua, Mexico: Geochimica et Cosmochimica Acta, v. 46, p. 1489–1503, doi: 10.1016/0016-7037(82)90309-X.

Cameron, K.L., and Robinson, J.V., 1990, Nd-Sr isotopic compositions of lower crustal xenoliths—evidence for the origin of mid-Tertiary felsic volcanics in Mexico: Comment: Contributions to Mineralogy and Petrology, v. 104, p. 609–618, doi: 10.1007/BF00306668.

Cameron, M., Bagby, W.C., and Cameron, K.L., 1980a, Petrogenesis of voluminous mid-Tertiary ignimbrites of the Sierra Madre Occidental: Contributions to Mineralogy and Petrology, v. 74, p. 271–284, doi: 10.1007/BF00371697.

Cameron, K.L., Cameron, M., Bagby, W.C., Moll, E.J., and Drake, R.E., 1980b, Petrologic characteristics of mid-Tertiary volcanic suites, Chihuahua: Geology, v. 8, p. 87–91, doi: 10.1130/0091-7613(1980)8<87:PCOMVS>2.0.CO;2.

Cameron, K.L., Cameron, M., and Barreiro, B., 1986, Origin of voluminous mid-Tertiary ignimbrites of the Batopilas region, Chihuahua: Implications for the formation of continental crust beneath the Sierra Madre Occidental: Geofisica Internacional, v. 25, no. 1, p. 39–59.

Cameron, K.L., Nimz, G.J., Kuentz, D., Niemeyer, S., and Gunn, S., 1989, Southern Cordilleran basaltic andesite suite, southern Chihuahua, Mexico; a link between Tertiary continental arc and flood basalt magmatism in North America: Journal of Geophysical Research, v. 94, p. 7817–7840.

Cameron, K.L., Robinson, J.V., Niemeyer, S., Nimz, G.J., Kuentz, D.C., Harmon, R.S., Bohlen, S.R., and Collerson, K.D., 1992, Contrasting styles of Pre-Cenozoic and mid-Tertiary crustal evolution in northern Mexico: Evidence from deep crustal xenoliths from La Olivina: Journal of Geophysical Research, v. 97, p. 17353–17376.

Campa, M.F., and Coney, P.J., 1983, Tectono-stratigraphic terranes and mineral resource distribution in Mexico: Canadian Journal of Earth Sciences, v. 20, p. 1040–1051.

Campos-Enríquez, J.O., Kerdan, T., Morán-Zenteno, D.J., Urrutia-Fucugauchi, J., Sánchez-Castellanos, E., and Alday-Cruz, R., 1994, Estructura de la litósfera superior a lo largo del Trópico de Cáncer: GEOS, Boletín Union Geofisica Mexicana, v. 12, p, 75–76.

Camprubí, A., Ferrari, L., Cosca, M., Cardellach, E., and Canals, A., 2003, Age of epithermal deposits in Mexico: Regional significance and links with the evolution of Tertiary volcanism: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 98, p. 1029–1037.

Carrillo-Martínez, M., 1971, Geología de la hoja San José de Gracia, Sinaloa (B.Sc. thesis): México, D.F., Universidad Nacional Autónoma de México, 154 p.

Castillo-Hernández, D., and Romero-Ríos, F., 1991, Estudio geológico-regional de Los Altos de Jalisco y El Bajío, Open-File Report 02-91, Comisión Federal de Electricidad, Gerencia de Proyectos Geotermoeléctricos, Departamento de Exploración, Morelia, Michoacán, México, 35 p.

Cather, S.M., Dunbar, N.W., McDowell, F.W., McIntosh, W.C., and Sholle, P.A., 2003, Early Oligocene global cooling, volcanic iron fertilization, and the ignimbrite flare-up of southwestern North America: Geological Society of America Abstracts with Programs, v. 35, p. 255.

Clark, K.F., Damon, P.E., Shafiquillah, M., Ponce, B.F., and Cárdenas, D., 1981, Sección geológica-estructural a través de la parte sur de la Sierra Madre Occidental, entre Fresnillo y la costa de Nayarit: Asociación Ingenieros de Minas, Metalurgistas y Geólogos de México, Memoria Técnica, v. XIV, p. 69–99.

Cochemé, J.J., and Demant, A., 1991, Geology of the Yécora area, northern Sierra Madre Occidental, Mexico, *in* Pérez-Segura, E., and Jacques-Ayala, C., eds., Studies of Sonoran Geology: Geological Society of America Special Paper 254, p. 81–94.

Coney, P.J., and Campa, M.F., 1987, Lithotectonic Terrane Map of Mexico (west of the 91st meridian): Miscellaneous Field Studies, Map MF 1874-D.

Coney, P.J., and Reynolds, S.J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403–406, doi: 10.1038/270403a0.

Consejo de Recursos Minerales (CRM), 1997, Carta geológico-minera Hoja Zacatecas F13-6, escala 1:250 000, Secretaria de Comercio y Fomento Industrial, 1 sheet.

Córdoba, D.A., 1963, Geología de la región entre Río Chico y Llano Grande, Municipio de Durango, Estado de Durango. Universidad Nacional Autónoma de México, Instituto de Geología, Boletín v. 71, Part 1, 21 p.

Couch, R.W, Ness, G.E., Sanchez-Zamora, O., Calderon-Riveroll, G., Doguin, P., Plawman, T., Coperude, S., Huehn, B., and Gumma, W., 1991, Gravity anomalies and crustal structure of the Gulf and Peninsular Province of the Californias, *in* Dauphin, J.P., and Simoneit, B.R.T., eds., The Gulf and the Peninsular Province of the Californias: American Association of Petroleum Geologists, Memoir, v. 47, p. 47–70.

Damon, P.E., Nieto-Obregón, J., and Delgado-Argote, L., 1979, Un plegamiento neogénico en Nayarit y Jalisco y evolución geomórfica del Río Grande de Santiago: Asociación Ingenieros de Minas, Metalurgistas y Geólogos de México, Memoria Técnica, v. XIII, p. 156–191.

Damon, P.E., Shafiqullah, M., and Clark, K.F., 1981, Age trends of igneous activity in relation to metallogenesis in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 137–154.

Damon, P.E., Shafiqullah, M., and Clark, K., 1983, Geochronology of the porphyry copper deposits and related mineralization in Mexico: Canadian Journal of Earth Sciences, v. 20, p. 1052–1071.

Davis, G.H., and Coney, P.J., 1979, Geological development of metamorphic core complexes: Geology, v. 7, p. 120–124, doi: 10.1130/0091-7613(1979)7<120:GDOTCM>2.0.CO;2.

De Silva, S.L., 1989a, Altiplano-Puna volcanic complex of the central Andes: Geology, v. 17, p. 1102–1106, doi: 10.1130/0091-7613(1989)017<1102:APVCOT>2.3.CO;2.

De Silva, S.L., 1989b, Geochronology and stratigraphy of the ignimbrites from the 21°30′S to 23°30′S portion of the central Andes of northern Chile: Journal of Volcanology and Geothermal Research, v. 37, p. 93–131, doi: 10.1016/0377-0273(89)90065-6.

Dickinson, W.R., 1997, Tectonic implications of Cenozoic volcanism in coastal California: Geological Society of America Bulletin, v. 109, p. 936–954, doi: 10.1130/0016-7606(1997)109<0936:OTIOCV>2.3.CO;2.

Dickinson, W.R., 2002, The Basin and Range Province as a composite extensional domain: International Geology Review, v. 44, p. 1–38.

Dickinson, W.R., and Lawton, T.F., 2001, Carboniferous to Cretaceous assembly and fragmentation of Mexico: Geological Society of America Bulletin, v. 113, p. 1142–1160, doi: 10.1130/0016-7606(2001)113<1142:CTCAAF>2.0.CO;2.

Dickinson, W.R., Fiorillo, A.R., Hall, D.L., Monreal-Saavedra, R., Potochnik, A.R., and Swift, P.N., 1989, Cretaceous strata of southern Arizona, *in* Jenney, J.P., and Reynolds, S.J., eds., Geologic Evolution of Arizona: Arizona Geological Society Digest, v. 17, p. 447–461.

Dorsey, R.J., and Burns, B.A., 1994, Regional stratigraphy, sedimentology and tectonic significance of Oligocene-Miocene sedimentary and volcanic rocks, northern Baja California, Mexico: Sedimentary Geology, v. 88, p. 231–251, doi: 10.1016/0037-0738(94)90064-7.

Ducea, M.N., 2002, Constraints on the bulk composition and root foundering rates of continental arcs—a California arc perspective: Journal of Geophysical Research, v. 107, p. 2304, doi: 10.1029/2001JB000643, doi: 10.1029/2001JB000643.

Eguiluz de Antuñano, S., Aranda-García, M., and Marrett, R., 2000, Tectónica de la Sierra Madre Oriental, México: Boletín de la Sociedad Geológica Mexicana, Tomo, v. LIII, no. 1, p. 1–26.

English, J., Johnston, S.T., and Wang, K., 2003, Thermal modelling of the Laramide orogeny: Testing the flat slab subduction hypothesis: Earth and Planetary Science Letters, v. 214, p. 619–632, doi: 10.1016/S0012-821X(03)00399-6.

Enríquez, E., and Rivera, R., 2001, Timing of magmatic and hydrothermal activity in the San Dimas District, Durango, Mexico, *in* New Mines and Mineral Discoveries in Mexico and Central America, Society of Economic Geologists Special Publication, n. 8, p. 33–38.

Ewart, A., Milner, S.C., Armstrong, R.A., and Duncan, A.R., 1998, Etendeka volcanism of the Goboboseb Mountains and Messum Igneous Complex, Namibia, Part II: Voluminous quartz latite volcanism of the Awahab magma system: Journal of Petrology, v. 39, p. 227–253, doi: 10.1093/petrology/39.2.227.

Ferrari, L., 1995, Miocene shearing along the northern boundary of the Jalisco block and the opening of the southern Gulf of California: Geology, v. 23, p. 751–754, doi: 10.1130/0091-7613(1995)023<0751:MSATNB>2.3.CO;2.

Ferrari, L., and 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.J., and Stock, J.M., eds., Cenozoic Tectonics and Volcanism of Mexico: Geological Society of America Special Paper 334, p. 41–64.

Ferrari, L., López-Martínez, M., Aguirre-Díaz, G., and Carrasco-Núñez, G., 1999, Space-time patterns of Cenozoic arc volcanism in central Mexico: From the Sierra Madre Occidental to the Mexican Volcanic Belt: Geology, v. 27, p. 303–306, doi: 10.1130/0091-7613(1999)027<0303:STPOCA>2.3.CO;2.

Ferrari, L., Pasquarè, G., Venegas, S., and Romero, F., 2000, Geology of the Western Mexican Volcanic Belt and Adjacent Sierra Madre Occidental and Jalisco Block, *in* Delgado-Granados, H., Aguirre-Díaz, G.J., and Stock, J.M., eds., Cenozoic Tectonics and Volcanism of Mexico: Geological Society of America Special Paper 334, p. 65–84.

Ferrari, L., López-Martínez, M., and 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, v. 21, doi: 10.1029/2001TC001302.

Ferrari, L., Petrone, C.M., Francalanci, L., Tagami, T., Eguchi, M., Conticelli, S., Manetti, P., and Venegas-Salgado, S., 2003, Geology of the San Pedro-Ceboruco graben, western Trans-Mexican Volcanic Belt: Revista Mexicana de Ciencias Geológicas, v. 20, p. 165–181.

Fix, J.E., 1975, The crust and upper mantle of central Mexico: Geophysical Journal of the Royal Astronomical Society, v. 43, p. 453–499.

Ferriz, H., 1981, Geología de la caldera de San Marcos, Chihuahua: Universidad Nacional Autónoma de México, Instituto de Geología, Revista, v. 5, p. 65–79.

Gans, P.B., 1997, Large-magnitude Oligo-Miocene extension in southern Sonora: Implications for the tectonic evolution of northwest Mexico: Tectonics, v. 16, p. 388–408, doi: 10.1029/97TC00496.

Gans, P.B., and Bohrson, W.A., 1998, Suppression of volcanism during rapid extension in the Basin and Range Province, United States: Science, v. 279, p. 66–68, doi: 10.1126/science.279.5347.66.

Gans, P.B., Mahood, G.A., and Schermer, E.R., 1989, Synextensional magmatism in the Basin and Range Province—a case study from the eastern Great Basin: Geological Society of America Special Paper 233, p. 1–53.

Gans, P.B., MacMillan, I., and Roldán-Quintana, J., 2003, Late Miocene (Proto Gulf) extension and magmatism on the Sonoran margin: EOS, Transactions AGU, v. 84(46), Fall Meeting Supplement, p. F1405.

Gastil, R.G., and Krummenacher, D., 1977, Reconnaissance geology of coastal Sonora between Puerto Lobos and Bahía de Kino: Geological Society of America Bulletin, v. 88, p. 189–198, doi: 10.1130/0016-7606(1977)88<189:RGOCSB>2.0.CO;2.

Gastil, R.G., Krummenacher, D., and Jensky, W.E., 1978, Reconnaissance geology of west-central Nayarit, Mexico: Geological Society of America, text to accompany Map and Chart Series, Map MC-24.

Gastil, R.G., Krummenacher, D., and Minch, J., 1979, The record of Cenozoic volcanism around the Gulf of California: Geological Society of America Bulletin, v. 90, p. 839–857, doi: 10.1130/0016-7606(1979)90<839:TROCVA>2.0.CO;2.

Gastil, R.G., Miller, R., Anderson, P., Crocker, J., Campbell, M., Buch, P., Lothringer, C., Leier Englehardt, P., DeLattre, M., Hoobs, J., and Roldán-Quintana, J., 1991, The relation between the Paleozoic strata on opposite sides of the Gulf of California, *in* Pérez-Segura, E., and Jacques-Ayala, C., eds., Studies of Sonoran Geology: Geological Society of America Special Paper 254, p. 7–18.

Glazner, A.F., and Ussler, W., III, 1989, Crustal extension, crustal density, and the evolution of Cenozoic magmatism and the Basin and Range of the western United States: Journal of Geophysical Research, v. 94, p. 7952–7960.

Goes, S., and van der Lee, S., 2002, Thermal structure of the North American uppermost mantle inferred from seismic tomography: Journal of Geophysical Research, v. 107, doi: 10.1029/2000JB000049, doi: 10.1029/2000JB000049.

Gomberg, J.S., Priestley, K.F., Masters, G., and Brune, J., 1988, The structure of the crust and upper mantle in northern Mexico: Geophysical Journal, v. 94, p. 1–20.

González-León, C.M., 1988, Estratigrafía y geología estructural de las rocas sedimentarias cretacicas del área de Lampazos, Sonora: Universidad Nacional Autónoma de México, Instituto de Geología, Revista, v. 7, p. 148–162.

González-León, C.M., 1994, Early Cretaceous tectono-sedimentary evolution on the southwestern margin of the Bisbee basin: Revista Mexicana de Ciencias Geológicas, v. 11, p. 139–146.

González-León, C.M., 1997, Sequence stratigraphy and paleogeographic setting of the Antimonio Formation (Late Permian-Early Jurassic), Sonora, Mexico: Revista Mexicana de Ciencias Geológicas, v. 14, p. 136–148.

González-León, C.M., and Lawton, T.F., 1995, Stratigraphy, depositional environments and origin of the Cabullona basin, northwestern Sonora, *in* Jacques-Ayala, C., González-León, C.M., and Roldán-Quintana, J., eds., Studies on the Mesozoic of Sonora and Adjacent Areas, Geological Society of America Special Paper 301, p. 121–143.

González-León, C.M., McIntosh, W.C., Lozano-Santacruz, R., Valencia-Moreno, M., Amaya-Martínez, R., and Rodríguez-Castaneda, J.L., 2000, Cretaceous and Tertiary sedimentary, magmatic, and tectonic evolution of north-central Sonora (Arizpe and Bacanuchi Quadrangles), northwest Mexico: Geological Society of America Bulletin, v. 112, p. 600–610, doi: 10.1130/0016-7606(2000)112<0600:CATSMA>2.3.CO;2.

Grajales-Nishimura, J.M., Terrell, D.J., and Damon, P.E., 1992, Evidencias de la prolongación del arco magmático cordillerano del Triásico Tardío-Jurásico en Chihuahua, Durango y Coahuila: Boletín de la Asociación Mexicana de Geólogos Petroleros, v. XLII, no. 2, p. 1–18.

Grand, S.P., 1994, Mantle shear structure beneath the Americas and surrounding oceans: Journal of Geophysical Research, v. 99, p. 11591–11621, doi: 10.1029/94JB00042.

Hausback, B.P., 1984, Cenozoic volcanic and tectonic evolution of Baja California Sur, Mexico, *in* Frizzell, A., ed., Geology of the Baja Peninsula: Society of Economic Paleontologists and Mineralogists Special Paper 39, p. 219–236.

Haenggi, W.T., 2002, Tectonic history of the Chihuahua trough, Mexico and adjacent USA, Part II: Mesozoic and Cenozoic: Boletín de la Sociedad Geológica Mexicana, tomo LV, p. 38–94.

Henry, C.D., 1986, East-northeast trending structures in western México: Evidence for oblique convergence in the late Mesozoic: Geology, v. 14, p. 314–317, doi: 10.1130/0091-7613(1986)14<314:ESIWME>2.0.CO;2.

Henry, C.D., 1989, Late Cenozoic Basin and Range structure in western Mexico adjacent to the Gulf of California: Geological Society of America Bulletin, v. 101, p. 1147–1156, doi: 10.1130/0016-7606(1989)101<1147:LCBARS>2.3.CO;2.

Henry, C.D., and Aranda-Gómez, J.J., 2000, Plate interactions control middle-late Miocene proto-Gulf and Basin and Range extension in the southern Basin and Range: Tectonophysics, v. 318, p. 1–26, doi: 10.1016/S0040-1951(99)00304-2.

Henry, C.D., and Fredrikson, G., 1987, Geology of part of southern Sinaloa, Mexico, adjacent to the Gulf of California: Geological Society of America Map and Chart Series, MCH063, 1 sheet, 14 p.

Henry, C.D., McDowell, F.W., and Silver, L.T., 2003, Geology and geochronology of the granitic batholithic complex, Sinaloa, México: Implications for Cordilleran magmatism and tectonics, *in* Johnson, S.E., Paterson, S.R., Fletcher, J.M., Girty, G.H., Kimbrough, D.L., and Martín-Barajas, A., eds., Tectonic Evolution of Northwestern México and the Southwestern USA: Geological Society of America Special Paper 374, p. 237–274.

Horner, H., 1998, Structural Geology and Exploration in the San Dimas District, Durango, Mexico—An Alternative Geologic Model: Faculty of Natural Sciences, University of Salzburg, 120 p.

Horner, J.T., and Enríquez, E., 1999, Epithermal precious metal mineralization in a strike-slip corridor: The San Dimas district, Durango, Mexico: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 94, p. 1375–1380.

Houghton, B.F., Wilson, C.J.N., McWilliams, M., Lanphere, M.A., Weaver, S.D., Briggs, R.M., and Pringle, M.S., 1995, Chronology and dynamics of a large silicic magmatic system: Central Taupo Volcanic Zone, New Zealand: Geology, v. 23, p. 13–16.

Huppert, H.E., and Sparks, R.S.J., 1988, The generation of granitic magmas by intrusion of basalt into continental crust: Journal of Petrology, v. 29, p. 599–642.

Humphreys, E.D., 1995, Post-Laramide removal of the Farallon slab, western United States: Geology, v. 23, p. 987–990, doi: 10.1130/0091-7613(1995)023<0987:PLROTF>2.3.CO;2.

Humphreys, E.D., Hessler, E., Dueker, K., Erslev, E., Farmer, G.L., and Atwater, T., 2003, How Laramide-age hydration of North America by the Farallon slab controlled subsequent activity in the western U.S.: International Geology Review, v. 45, p. 575–595.

Iriondo, A., Kunk, M.J., Winick, J.A., and Consejo de Recursos Minerales, 2003, ^{40}Ar/^{39}Ar dating studies of minerals and rocks in various areas in Mexico: USGS/CRM Scientific Collaboration (Part I): U.S. Geological Survey Open-File Report 2003-020, 79 p.

Iriondo, A., Premo, W.R., Martínez-Torres, L.M., Budahn, J.R., Atkinson, W.W., Siems, D.F., and Guarás-González, B., 2004a, Isotopic, geochemical, and temporal characterization of Proterozoic basement rocks in the Quitovac region, northwestern Sonora, Mexico: Implications for the reconstruction of the southwestern margin of Laurentia: Geological Society of America Bulletin, v. 116, p. 154–170, doi: 10.1130/B25138.1.

Iriondo, A., Kunk, M.J., Winick, J.A., and Consejo de Recursos Minerales, 2004b, ^{40}Ar/^{39}Ar dating studies of minerals and rocks in various areas in Mexico: USGS/CRM Scientific Collaboration (Part II): U.S. Geological Survey Open-File Report, 2004-1444, 46 p.

Irvine, T.N., and Baragar, W.R.A., 1971, A guide of the chemical classification of common volcanic rocks: Canadian Journal of Earth Science, v. 8, p. 523–548.

Jacques-Ayala, C., 1995, Paleogeography and provenance of the Lower Cretaceous Bisbee Group in the Caborca-Santa Ana area, northwestern Sonora, *in* Jacques-Ayala, C.., González-León, C.M., and Roldán-Quintana, J., eds., Studies on the Mesozoic of Sonora and Adjacent Areas: Geological Society of America Special Paper 301, p. 79–98.

James, E.V., and Henry, C.D., 1993, Compositional changes in Trans-Pecos Texas magmatism coincident with Cenozoic stress realignment: Journal of Geophysical Research, v. 96, p. 13561–13575.

Johnson, C.M., 1991, Large-scale crust formation and lithosphere modification beneath Middle to Late Cenozoic calderas and volcanic fields, western North America: Journal of Geophysical Research, v. 96, p. 13,485–13,507.

Jull, M., and Kelemen, P.B., 2001, On the conditions for lower crustal convective instability: Journal of Geophysical Research, v. 106, p. 6423–6446, doi: 10.1029/2000JB900357.

Kay, R.W., and Mahlburg-Kay, S., 1991, Creation and destruction of lower continental crust: International Journal of Earth Sciences, v. 80, p. 259–278.

Kay, R.W., Mahlburg-Kay, S., and Arculus, R.J., 1992, Magma genesis and crustal processing, *in* Fountain, D.M., Arculus, R., and Kay, R.W., eds., Continental Lower Crust: Developments in Geotectonics, v. 23, p. 423–445.

Keller, P., Bockoven, N., and McDowell, F.W., 1982, Tertiary volcanic history of the Sierra del Gallego area, Chihuahua, Mexico: Geological Society of America Bulletin, v. 93, p. 303–314, doi: 10.1130/0016-7606(1982)93<303:TVHOTS>2.0.CO;2.

Keppie, J.D., Dostal, J., Millar, B.V., Ortega-Rivera, M.A., Roldan-Quintana, J., and Lee, J.W.K., 2006, Geochronology and Geochemistry of the Francisco Gneiss: Triassic Continental Rift Tholeiites on the Mexican Margin of Pangea Metamorphosed and Exhumed in a Tertiary Core Complex: International Geology Review, v. 48, p. 1–16.

King, R.E., 1939, Geologic reconnaissance in the northern Sierra Madre Occidental of Mexico: Geological Society of America Bulletin, v. 50, p. 1625–1722.

Klemperer, S.L., 1989, Deep seismic reflection profiling and the growth of the continental crust: Tectonophysics, v. 161, p. 233–244, doi: 10.1016/0040-1951(89)90156-X.

Lang, B., Steinitz, G., Sawkins, F.J., and Simmons, S.F., 1988, K-Ar Age studies in the Fresnillo Silver District, Zacatecas, Mexico: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 83, p. 1642–1646.

Lange, R., and Carmichael, I.S.E., 1991, A potassic volcanic front in western Mexico: Lamprophyric and related lavas of San Sebastian: Geological Society of America Bulletin, v. 103, p. 928–940, doi: 10.1130/0016-7606(1991)103<0928:APVFIW>2.3.CO;2.

Langenheim, V.E., and Jachens, R.C., 2003, Crustal structure of the Peninsular Ranges batholith from magnetic data: Implications for Gulf of California rifting: Geophysical Research Letters, v. 30, p. 1597, doi: 10.1029/2003GL017159.

Lanphere, M.A., Cameron, K.L., and Cameron, M., 1980, Sr isotopic geochemistry of voluminous rhyolitic ignimbrites and related rocks, Batopilas area, western Mexico: Nature, v. 286, p. 594–596, doi: 10.1038/286594a0.

Lawlor, P.J., Ortega-Gutierrez, F., Cameron, K.L., Ochoa-Camarillo, H., López, R., and Sampson, D.E., 1999, U-Pb geochronology, geochemistry and provenance of the Grenvillian Huiznopala Gneiss of eastern Mexico: Precambrian Research, v. 94, p. 73–99.

Le Maitre, R.W., 1989, A Classification of Igneous Rocks and Glossary of Terms: Recommendations of the IUGS Subcommission on the Systematics of Igneous Rocks: London, Blackwell Scientific, 193 p.

Lonsdale, P., 2005, Creation of the Cocos and Nazca plates by fission of the Farallon plate: Tectonophysics, v. 404, p. 237–264, doi: 10.1016/j.tecto.2005.05.011.

López-Ramos, E., 1995, Carta geológica de los estados de Jalisco y Aguascalientes, escala 1:750,000, con resumen: Universidad Nacional Autónoma de México, Instituto de Geología, Cartas Geológicas Estatales, 1 sheet.

Lucas, S.G., Kues, B.S., and González-León, C.M., 1995, Paleontology of the Upper Cretaceous Cabullona Group, northeastern Sonora, *in* Jacques-Ayala, C.., González-León, C.M., and Roldán-Quintana, J., eds., Studies on the Mesozoic of Sonora and Adjacent Areas: Geological Society of America Special Paper 301, p. 143–165.

Luhr, J.F., Pier, J.G., Aranda-Gómez, J.J., and Podosek, F.A., 1995, Crustal contamination in early Basin-and-Range hawaiites of the Los Encinos Volcanic Field, central Mexico: Contribution to Mineralogy and Petrology, v. 118, p. 321–339, doi: 10.1007/s004100050018.

Luhr, J.F., Henry, C.D., Housh, T.B., Aranda-Gómez, J.J., and McIntosh, W.C., 2001, Early extension and associated mafic alkalic volcanism from the southern Basin and Range Province: Geology and petrology of the Rodeo and Nazas volcanic fields, Durango (Mexico): Geological Society of America Bulletin, v. 113, p. 760–773, doi: 10.1130/0016-7606(2001)113<0760:EEAAMA>2.0.CO;2.

Lyons, J.I., 1988, Geology and ore deposits of the Bolaños silver district, Jalisco, Mexico: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 83, p. 1560–1582.

MacMillan, I., Gans, P.B., and Roldán-Quintana, J., 2003, Voluminous mid-Miocene silicic volcanism and rapid extension in the Sierra Libre, Sonora, Mexico: Geological Society of America Abstracts with Programs, v. 35, no. 4, p. 26.

Magonthier, M.C., 1988, Distinctive rhyolite suites in the mid-Tertiary ignimbritic complex of the Sierra Madre Occidental, western Mexico: Bulletin de la Société Géologique de France, Serie 8, v. 4, p. 57–68.

Mauger, R.L., 1981, Geology and petrology of the Calera-del Nido block, Chihuahua Mexico, *in* Goodell, P.C., ed., Uranium in Volcanic and Volcaniclastics Rocks: American Association of Petroleum Geologists, Studies in Geology, v. 13, p. 202–242.

Mauger, R.L., 1992, The mid-Eocene Majalca Canyon caldera, Chihuahua, Mexico, *in* Clark, K.F., et al., eds., Geology and Mineral Resources of the Northern Sierra Madre Occidental, Mexico: El Paso Geological Society 1992, Field Conference Guidebook, p. 127–132.

Mauger, R.L., 1983, Geologic map of the Majalca-Punta de Agua area, central Chihuahua, Mexico, *in* Clark, K.F., and Goodell, P.C., eds., Geology and Mineral Resources of North-central Chihuahua: Guidebook of the El Paso Geological Society Field Conference, p. 169–174.

Megaw, P.K.M., 1986, Geology and geological history of the Santa Eulalia Mining District, Chihuahua, Mexico, *in* Clark, K.F., et al., eds., Field Excursion Guidebook: Society of Economic Geology, p. 213–232.

Megaw, P.K.M., 1990, Geology and geochemistry of the Santa Eulalia mining district, Chihuahua, Mexico [Ph.D. thesis]: University of Arizona, Tucson, Arizona, 463 p.

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

McDowell, F.W., and 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, v. 88, p. 1479–1487, doi: 10.1130/0016-7606(1977)88<1479:TOMVIT>2.0.CO;2.

McDowell, F.W., and Mauger, R.L., 1994, K-Ar and U-Pb zircon chronology of Late Cretaceous and Tertiary magmatism in central Chihuahua State, Mexico: Geological Society of America Bulletin, v. 106, p. 118–132, doi: 10.1130/0016-7606(1994)106<0118:KAAUPZ>2.3.CO;2.

McDowell, F.W., Roldán-Quintana, J.J., and Amaya-Martínez, R., 1997, Interrelationship of sedimentary and volcanic deposits associated with Tertiary extension in Sonora, Mexico, Geological Society of America Bulletin, v. 109, p. 1349–1360.

McDowell, F.W., Housh, T.B., and Wark, D.A., 1999, Nature of crust beneath west-central Chihuahua, Mexico, based upon Sr, Nd, and Pb isotopic compositions at the Tómochic volcanic center: Geological Society of America Bulletin, v. 111, p. 823–830, doi: 10.1130/0016-7606(1999)111<0823:NOTCBW>2.3.CO;2.

McDowell, F.W., Roldán-Quintana, J., and Connelly, J., N., 2001, Duration of Late Cretaceous–early Tertiary magmatism in east-central Sonora, Mexico: Geological Society of America Bulletin, v. 113, p. 521–531.

McKee, J.W., Jones, N.W., and Anderson, T.H., 1988, Las Delicias basin: a record of late Paleozoic arc volcanism in northeastern Mexico: Geology, v. 16, p. 37–40, doi: 10.1130/0091-7613(1988)016<0037:LDBARO>2.3.CO;2.

Meissner, R.O., and Mooney, W.D., 1998, Weakness of the lower continental crust; a condition for delamination, uplift, and escape: Tectonophysics, v. 296, p. 47–60, doi: 10.1016/S0040-1951(98)00136-X.

Miller, R.B., and Paterson, S.R., 2001, Influence of lithological heterogeneity, mechanical anisotropy, and magmatism on the rheology of an arc, North Cascades, Washington: Tectonophysics, v. 342, p. 351–370, doi: 10.1016/S0040-1951(01)00170-6.

Miranda-Gasca, M.A., and De Jong, K.A., 1992, The Magdalena mid-Tertiary extensional basin, *in* Clark, K.F., Roldán-Quintana, J., and Schmidt, R.H., eds., Geology and Mineral Resources of the Northern Sierra Madre Occidental, México: Guidebook of the El Paso Geological Society Field Conference, p. 377–384.

Miranda-Gasca, M.A., Gómez-Caballero, J.A., and Eastoe, C.J., 1998, Borate deposits of Northern Sonora, Mexico—Stratigraphy, tectonics, stable isotopes, and fluid inclusions: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 93, p. 510–523.

Montigny, R., Demant, A., Delpretti, P., Piguet, P., and Cocheme, J.J., 1987, Chronologie K/Ar de sequences volcanique tertiaires du nord de la Sierra Madre Occidental, Mexique: Académie des Sciences Comptes Rendus, Paris: Ser. D, v. 304, p. 987–992.

Mooney, W.D., Laske, G., and Masters, G.T., 1998, Crust 5.1: A global crustal model at 5x5 degrees: Journal of Geophysical Research, v. 103, p. 727–747, doi: 10.1029/97JB02122.

Moore, G., Marone, C., Carmichael, I.S.E., and 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, v. 106, p. 383–394, doi: 10.1130/0016-7606(1994)106<0383:BVAENT>2.3.CO;2.

Mora-Álvarez, G., and McDowell, F.W., 2000, Miocene volcanism during late subduction and early rifting in the Sierra Santa Ursula of Western Sonora, Mexico, *in* Stock, J.M., Delgado-Granados, H., and Aguirre-Díaz, G., eds., Cenozoic Tectonics and Volcanism of Mexico: Geological Society of America Special Paper 334, p. 123–141.

Mora-Klepeis, G., and McDowell, F.W., 2004, Late Miocene calc-alkalic volcanism in northwestern Mexico: An expression of rift or subduction-related magmatism?: Journal of South American Earth Sciences, v. 17, p. 297–310, doi: 10.1016/j.jsames.2004.08.001.

Morales-Montaño, M., Bartolini, C., Damon, P.E., and Shafiqullah, M., 1990, K-Ar dating, stratigraphy, and extensional deformation of Sierra Lista Blanca, Central Sonora, Mexico: Geological Society of America Abstracts with Programs, v. 22, p. A364.

Moran-Zenteno, D.J., Tolson, G., Martiny, B., Martinez-Serrano, R.G., Schaaf, P., Silva Romo, G., Macias, C., Alba-Aldave, L., Hernandez Bernal, M.S., and Solis-Pichardo, G., 1999, Tertiary arc-magmatism of the Sierra Madre del Sur, Mexico, and its transition to the volcanic activity of the Trans-Mexican Volcanic Belt: Journal of South American Earth Sciences, v. 12, p. 513–535.

Mujica-Mondragón, M.R., and Jacobo-Albarrán, J., 1983, Estudio petrogenético de las rocas ígneas y metamórficas del Altiplano Mexicano: Instituto Mexicano del Petróleo, Subdirección Técnica de Exploración, Proyecto C-1156, 78 p. (Open-File Report.)

Mullan, H.S., 1978, Evolution of part of the Nevada orogen in northwest Mexico: Geological Society of America Bulletin, v. 111, p. 347–363.

Nieto-Obregón, J., Delgado-Argote, L., and Damon, P.E., 1981, Relaciones petrológicas y geocronológicas del magmatismo de la Sierra Madre Occidental el Eje Neovolcánico en Nayarit, Jalisco y Zacatecas: Asociación de Ingenieros de Minas, Metalurgistas y Geólogos de México, Memoria Técnica, v. XIV, p. 327–361.

Nieto-Obregón, J., Delgado-Argote, L., and Damon, P.E., 1985, Geochronologic, petrologic, and structural data related to large morphologic features between the Sierra Madre Occidental and the Mexican volcanic belt: Geofísica Internacional, v. 24, p. 623–663.

Nieto-Samaniego, Á.F., Macias-Romo, C., and Alaniz-Álvarez, S.A., 1996, Nuevas edades isotópicas de la cubierta volcánica cenozoica de la parte meridional de la Mesa Central, México: Revista Mexicana de Ciencias Geológicas, v. 13, p. 117–122.

Nieto-Samaniego, Á.F., Ferrari, L., Alaniz-Álvarez, S.A., Labarthe-Hernández, G., and Rosas-Elguera, J., 1999, Variation of Cenozoic extension and volcanism across the southern Sierra Madre Occidental volcanic province, Mexico: Geological Society of America Bulletin, v. 111, p. 347–363, doi: 10.1130/0016-7606(1999)111<0347:VOCEAV>2.3.CO;2.

Norton, I., 1995, Plate motions in the North Pacific: The 43 Ma nonevent: Tectonics, v. 14, p. 1080–1094, doi: 10.1029/95TC01256.

Nourse, J.A., Anderson, T.H., and Silver, L.T., 1994, Tertiary metamorphic core complexes in Sonora, northwestern Mexico: Tectonics, v. 13, p. 1161–1182, doi: 10.1029/93TC03324.

Orozco-Esquivel, M.T., Nieto-Samaniego, Á.F., and Alaniz-Álvarez, S.A., 2002, Origin of rhyolitic lavas in the Mesa Central, Mexico, by crustal melting related to extension: Journal of Volcanology and Geothermal Research, v. 118, p. 37–56, doi: 10.1016/S0377-0273(02)00249-4.

Ortega-Gutiérrez, F., Mitre-Salazar, L.M., Roldán-Quintana, J., and Aranda-Gómez, J.J., Morán- Zenteno, D., Alaniz-Álvarez S.A., and Nieto-Samaniego, Á.F., 1992, Carta geológica de la Republica Mexicana: Universidad Nacional Autónoma de México, scale 1:2,000,000, 1 sheet, with text of 74 p.

Ortega-Gutiérrez, F., Sedlock, R.L., and Speed, R.C., 1994, Phanerozoic tectonic evolution of Mexico, *in* Speed, R.C., ed., Phanerozoic Evolution of North American Continent-Ocean Transitions: Geological Society of America, Decade of North American Geology Summary Volume to accompany the DNAG Continent-Ocean Transects Series, p. 265–306.

Oskin, M., and Stock, J., 2003, Cenozoic volcanism and tectonics of the continental margins of the Upper Delfín basin, northeastern Baja California and western Sonora, *in* Johnson, S.E., Paterson, S.R., Fletcher, J.M., Girty, G.H., Kimbrough, D.L., and Martín-Barajas, A., eds., Tectonic Evolution of Northwestern México and the Southwestern USA: Geological Society of America Special Paper 374, p. 421–438.

Oskin, M., Stock, J.M., and Martín-Barajas, A., 2001, Rapid localization of Pacific–North America plate motion in the Gulf of California: Geology, v. 29, p. 459–462, doi: 10.1130/0091-7613(2001)029<0459:RLOPNA>2.0.CO;2.

Oskin, M., Iriondo, A., and Nourse, J., 2003, Geologic reconnaissance and geochronology of proto-Gulf of California extension, western Sonora: Geological Society of America Abstracts with Programs, 99th Cordilleran Meeting.

Pankhurst, R.J., and Rapela, C.R., 1995, Production of Jurassic rhyolite by anatexis of the lower crust of Patagonia: Earth and Planetary Science Letters, v. 134, p. 23–36, doi: 10.1016/0012-821X(95)00103-J.

Pankhurst, R.J., Leat, P.T., Sruoga, P., Rapela, C.W., Márquez, M., Storey, B.C., and Riley, T.R., 1998, The Chon Aike silicic igneous province of Patagonia and related rocks in Antarctica: A silicic large igneous province: Journal of Volcanology and Geothermal Research, v. 81, p. 113–136, doi: 10.1016/S0377-0273(97)00070-X.

Pankhurst, R.J., Riley, T.R., Fanning, C.M., and Kelley, S.R., 2000, Episodic silicic volcanism along the proto-Pacific margin of Patagonia and the Antarctic Peninsula: plume and subduction influences associated with the break-up of Gondwana: Journal of Petrology, v. 41, p. 605–625, doi: 10.1093/petrology/41.5.605.

Paterson, B.A., Stephens, W.E., Rogers, G., Williams, I.S., Hinton, R.W., and Herd, D.A., 1992, The nature of zircon inheritance in two granitic plutons: Transactions of the Royal Society of Edinburgh: Earth Sciences, v. 83, p. 459–471.

Pasquarè, G., Ferrari, L., Garduño, V.H., Tibaldi, A., and Vezzoli, L., 1991, Geological map of the central sector of Mexican Volcanic Belt, States of Guanajuato and Michoacan: Geological Society of America Map and Chart Series, MCH 072, 1 sheet, 20 p.

Paz-Moreno, F., Demant, A., Cochemé, J.J., Dostal, J., and Montigny, R., 2003, The Quaternary Moctezuma volcanic field: A tholeiitic to alkali basaltic episode in the central Sonoran Basin and Range Province, Mexico, *in* Johnson, S.E., Paterson, S.R., Fletcher, J.M., Girty, G.H., Kimbrough, D.L., and Martín-Barajas, A., eds., Tectonic Evolution of Northwestern México and the Southwestern USA: Geological Society of America Special Paper 374, p. 439–455.

Perry, F.V., DePaolo, D.J., and Baldridge, W.S., 1993, Neodymium isotopic evidence for decreasing crustal contributions to Cenozoic ignimbrites of the western United States: Implications for the thermal evolution of the Cordilleran crust: Geological Society of America Bulletin, v. 105, p. 872–882, doi: 10.1130/0016-7606(1993)105<0872:NIEFDC>2.3.CO;2.

Persaud, P., 2003, Images of early continental breakup in and around the Gulf of California and the role of basal shear in producing wide plate boundaries [Ph.D. thesis]: California Institute of Technology, 144 p.

Piguet, P., 1987, Contribution à l'étude de la Sierra Madre Occidental (Mexique): la séquence volcanoque tertiaire de la transversale Moctezuma-La Norteña [Ph.D. thesis]: Université de Droit, d'Économie et des Sciences D'Aix-Marseille, 300 p.

Ponce, B., and Clark, K., 1988, The Zacatecas mining district—a Tertiary caldera complex associated with precious and base metal mineralization: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 83, p. 1668–1682.

Poole, F.G., Madrid, R.J., and Oliva-Becerril, J.F., 1991, Geological setting and origin of stratiform barite in central Sonora, Mexico, *in* Raines, G.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W.H., eds., Geology and Ore Deposits of the Great Basin: Geological Society of Nevada, v. 1, p. 517–522.

Poole, F.G., Stewart, J.H., Berry, W.B.N., Harris, A.G., Repetski, J.E., Madrid, R.J., Ketner, K.B., Carter, C., and Morales-Ramírez, J.M., 1995, Ordovician ocean-basin rocks of Sonora, Mexico, *in* Cooper, J.D., Droser, M.L., and Finney, S.C., eds., Ordovician Odyssey: Short Papers for the Seventh International Symposium on the Ordovician System, Las Vegas: Fullerton, California: Pacific Section Society for Sedimentary Geology (SEPM), n. 77, p. 277–284.

Righter, K., Carmichael, I.S.E., and 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, v. 107, p. 612–627, doi: 10.1130/0016-7606(1995)107<0612:PQVAFA>2.3.CO;2.

Riley, T.R., Leat, P.T., Pankhurst, R.J., and Harris, C., 2001, Origins of large volume rhyolitic volcanism in the Antarctic Peninsula and Patagonia by crustal melting: Journal of Petrology, v. 42, p. 1043–1065, doi: 10.1093/petrology/42.6.1043.

Ritsema, J., Van Heijst, H., and Woodhouse, J., 2004, Global transition zone tomography: Journal of Geophysical Research, v. 109, doi: 10.1029/2003JB002610.

Ritzwoller, M.H., Shapiro, N.M., Barmin, M.P., and Levshin, A., 2002, Global surface wave diffraction tomography: Journal of Geophysical Research, v. 107, p. 2335, doi: 10.1029/2002JB001777.

Rodríguez-Castañeda, J.L., 1996, Late Jurassic and mid-Tertiary brittle-ductile deformation in the Opodepe region, Sonora, México: Revista Mexicana de Ciencias Geológicas, v. 13, p. 1–9.

Roldán-Quintana, J., 1991, Geology and chemical composition of El Jaralito and Aconchi batholiths in east-central Sonora, *in* Pérez-Segura, E., and Jacques-Ayala, C., eds., Studies of Sonoran Geology: Geological Society of America Special Paper 254, p. 19–36.

Roldán-Quintana, J., Mora-Klepeis, G., Calmus, T., Valencia-Moreno, M., and Lozano-Santacruz, R., 2004, El graben de Empalme, Sonora, México: magmatismo y tectónica extensional asociados a la ruptura inicial del Golfo de California: Revista Mexicana de Ciencias Geológicas, v. 21, p. 320–334.

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

Rosas-Elguera, J., Alva-Valdivia, L.M., Goguitchaichvili, A., and Urrutia-Fucugauchi, J., 2003, Counterclockwise rotation of the Michoacan block: Implications for the tectonics of western Mexico: International Geology Review, v. 45, p. 814–826.

Rossotti, A., Ferrari, L., López-Martínez, M., and 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, v. 19, p. 1–15.

Ruiz, J., Patchett, P.J., and Arculus, R.J., 1988a, Nd-Sr isotope composition of lower crustal xenoliths: Evidence for the origin of mid-Tertiary felsic volcanics in Mexico: Contributions to Mineralogy and Petrology, v. 99, p. 36–43, doi: 10.1007/BF00399363.

Ruiz, J., Patchett, P.J., and Ortega-Gutiérrez, F., 1988b, Proterozoic and Phanerozoic basement terranes of Mexico from Nd isotopic studies: Geological Society of America Bulletin, v. 100, p. 274–281, doi: 10.1130/0016-7606(1988)100<0274:PAPBTO>2.3.CO;2.

Ruiz, J., Patchett, P.J., and Arculus, R.J., 1990, Comments on Nd-Sr isotopic compositions of lower crustal xenoliths—Evidence for the origin of mid-Tertiary volcanics in Mexico: Reply: Contributions to Mineralogy and Petrology, v. 104, p. 615–618, doi: 10.1007/BF00306669.

Saleeby, J., 2003, Segmentation of the Laramide Slab—evidence from the southern Sierra Nevada region: Geological Society of America Bulletin, v. 115, p. 655–668, doi: 10.1130/0016-7606(2003)115<0655:SOTLSF>2.0.CO;2.

Sawlan, M.G., 1991, Magmatic evolution of the Gulf of California rift, *in* Dauphin, J.P., and Simoneit, B.A., eds., The Gulf and Peninsular Province of the Californias: American Association of Petroleum Geologists Memoir, 47, p. 301–369.

Scheubel, F.R., Clark, K.F., and Porter, E.W., 1988, Geology, tectonic environment, structural controls in the San Martin de Bolaños District, Jalisco: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 83, p. 1703–1720.

Sedlock, R., Ortega-Gutiérrez, F., and Speed, R.C., 1993, Tectonostratigraphic terranes and tectonic evolution of Mexico: Geological Society of America Special Paper 278, 153 p.

Silver, L.T., and Anderson, T.H., 1974, Possible left-lateral early to middle Mesozoic disruption of the southwestern North America craton margin: Geological Society of America Abstracts with Programs, v. 6, p. 955–956.

Smith, J.A., Luhr, J.F., Pier, J.G., and Aranda-Gómez, J.J., 1989, Extension-related magmatism of the Durango volcanic field, Durango, Mexico: Geological Society of America Abstracts with Programs, v. 21, p. A201.

Smith, R.D., Cameron, K.L., McDowell, F.W., Niemeyer, S., and Sampson, D.E., 1996, Generation of voluminous silicic magmas and formation of mid-Cenozoic crust beneath north-central Mexico—evidence from ignimbrites, associated lavas, deep crustal granulites, and mantle pyroxenites: Contributions to Mineralogy and Petrology, v. 123, p. 375–389, doi: 10.1007/s004100050163.

Sole, J., and Salinas, J.C., 2002, Edades K-Ar de 54 rocas ígneas y metamórficas del occidente, centro y sur de México: GEOS, Boletín de la Unión Geofísica Mexicana, v. 22, n. 2, p. 260.

Sonder, L.J., and Jones, C.H., 1999, Western United States extension: How the West was widened: Annual Review of Earth and Planetary Sciences, v. 27, p. 417–462, doi: 10.1146/annurev.earth.27.1.417.

Staude, J.M., and Barton, M.D., 2001, Jurassic to Holocene tectonics, magmatism, and metallogeny of northwestern Mexico: Geological Society of America Bulletin, v. 113, p. 1357–1374, doi: 10.1130/0016-7606(2001)113<1357:JTHTMA>2.0.CO;2.

Stewart, J.H., 1988, Latest Proterozoic and Paleozoic southern margin of North America and the accretion of Mexico: Geology, v. 16, p. 186–189, doi: 10.1130/0091-7613(1988)016<0186:LPAPSM>2.3.CO;2.

Stewart, J.H., 1998, Regional characteristics, tilt domains, and extensional history of the later Cenozoic Basin and Range Province, western North America, *in* Faulds, J.E., and Stewart, J.H., eds., Accommodation Zones and Transfer Zones: The Regional Segmentation of the Basin and Range Province: Geological Society of America Special Paper 323, p. 47–74.

Stewart, J.H., and Poole, F.G., 2002, Inventory of Neoproterozoic and Paleozoic strata in Sonora, Mexico: U.S. Geological Survey Open-File Report 02-97, 50 p.

Stewart, J.H., and Roldán-Quintana, J., 1991, Upper Triassic Barranca Group; Nonmarine and shallow-marine rift-basin deposits of northwestern Mexico, *in* Pérez-Segura, E., and Jacques-Ayala, C., eds., Studies of Sonoran Geology: Geological Society of America Special Paper 254, p. 19–36.

Stewart, J.H., Anderson, R.E., Aranda-Gómez, J.J., Beard, L.S., Billingsley, G.H., Cather, S.M., Dilles, J.H., Dokka, R.K., Faulds, J.E., Ferrari, L., Grose, T.L.T., Henry, C.D., Janecke, S.U., Miller, D.M., Richard, S.M., Rowley, P.D., Roldán-Quintana, J., Scott, R.B., Sears, J.W., and Williams, V.S., 1998, Map showing Cenozoic tilt domains and associated structural features, western North America, *in* Faulds, J.E., and Stewart, J.H., eds., Accommodation Zones and Transfer Zones: The Regional Segmentation of the Basin and Range Province: Geological Society of America Special Paper 323, plate 1.

Stewart, J.H., Poole, F.G., Harris, A.G., Repetski, J.E., Wardlaw, B.R., Mamet, B.L., and Morales-Ramirez, J.M., 1999, Neoproterozoic (?) to Pennsylvanian inner-shelf, miogeoclinal strata in Sierra Agua Verde, Sonora, Mexico: Revista Mexicana de Ciencias Geológicas, v. 16, p. 35–62.

Stock, J.M., and Lee, J., 1994, Do microplates in subduction zones leave a geologic record?: Tectonics, v. 13, p. 1472–1487, doi: 10.1029/94TC01808.

Suter, M., 2001, The historical seismicity of northeastern Sonora and northwestern Chihuahua, Mexico (28–32° N, 106–111° W): Journal of South American Earth Sciences, v. 14, p. 521–532, doi: 10.1016/S0895-9811(01)00050-5.

Suter, M., and Contreras, J., 2002, Active Tectonics of Northeastern Sonora, Mexico (Southern Basin and Range Province) and the 3 May 1887 Mw 7.4 Earthquake: Seismological Society of America Bulletin, v. 92, p. 581–589, doi: 10.1785/0120000220.

Swanson, E.R., and McDowell, F.W., 1984, Calderas of the Sierra Madre Occidental volcanic field, western Mexico: Journal of Geophysical Research, v. 89, p. 8787–8799.

Swanson, E.R., and McDowell, F.W., 1985, Geology and geochronology of the Tómochic caldera, Chihuahua, Mexico: Geological Society of America Bulletin, v. 96, p. 1477–1482, doi: 10.1130/0016-7606(1985)96<1477:GAGOTT>2.0.CO;2.

Swanson, E.R., Keizer, R.P., Lyons, J.I., Jr., and Clabaugh, S.E., 1978, Tertiary volcanism and caldera development near Durango City, Sierra Madre Occidental, Mexico: Geological Society of America Bulletin, v. 89, p. 1000–1012, doi: 10.1130/0016-7606(1978)89<1000:TVACDN>2.0.CO;2.

Swanson, E.R., Kempter, K., McDowell, F.W., and McIntosh, W.C., 2006, Major ignimbrites and volcanic centers of the Copper Canyon area: A view into the core of Mexico's Sierra Madre Occidental: Geosphere, v. 2, p. 125–141, doi: 10.1130/GES00042.1.

Tuta, Z., Sutter, J.H., Kesler, S.E., and Ruiz, J., 1988, Geochronology of mercury, tin, and fluorite mineralization in northern Mexico: Economic Geology and the Bulletin of the Society of Economic Geologists, v. 83, p. 1931–1942.

Umhoefer, P.J., Dorsey, R., Willsey, S., Mayer, L., and Renne, P., 2001, Stratigraphy and geochronology of the Comondú Group near Loreto, Baja California Sur, Mexico: Sedimentary Geology, v. 144, p. 125–147, doi: 10.1016/S0037-0738(01)00138-5.

Valencia-Moreno, M., Ruiz, J., and Roldán-Quintana, J., 1999, Geochemistry of Laramide granitic rocks across the southern margin of the Paleozoic North American continent, Central Sonora, Mexico: International Geology Review, v. 41, p. 845–857.

Valencia-Moreno, M., Ruiz, J., Barton, M.D., Patchett, P.J., Zürcher, L., Hodkinson, D., and Roldán-Quintana, J., 2001, A chemical and isotopic study of the Laramide granitic belt of northwestern Mexico: Identification of the southern edge of the North American Precambrian basement: Geological Society of America Bulletin, v. 113, p. 1409–1422, doi: 10.1130/0016-7606(2001)113<1409:ACAISO>2.0.CO;2.

Valencia-Moreno, M., Ruiz, J., Ochoa-Landín, L., Martínez-Serrano, R., and Vargas-Navarro, P., 2003, Geology and Geochemistry of the Coastal Sonora Batholith, Northwestern Mexico: Canadian Journal of Earth Sciences, v. 40, p. 819–831, doi: 10.1139/e03-020.

van der Lee, S., and Nolet, G., 1997, Upper mantle S velocity structure of North America: Journal of Geophysical Research, v. 103, p. 22815–22838, doi: 10.1029/97JB01168.

Vega-Granillo, R., and Calmus, T., 2003, Mazatán metamorphic core complex (Sonora, Mexico): Structures along the detachment fault and its exhumation evolution: Journal of South American Earth Sciences, v. 16, 193–204.

Verma, S.P., 1984, Sr and Nd isotopic evidence for petrogenesis of mid-Tertiary felsic volcanism in the mineral district of Zacatecas, Zac. (Sierra Madre Occidental), Mexico: Isotope Geoscience, v. 2, p. 37–53.

Vidal-Solano, J.R., Paz-Moreno, F.A., Iriondo, A., Demant, A., and Cochemé, J.J., 2005, Middle Miocene peralkaline ignimbrites in the Hermosillo region (Sonora, México): Geodynamic implications: Compte Rendue Geosciences, v. 337, p. 1421–1430, doi: 10.1016/j.crte.2005.08.007.

Wallace, P., and Carmichael, I.S.E., 1989, Minette lavas and associated leucitites from the western front of the MVB: Petrology, chemistry and origin: Contribution to Mineralogy and Petrology, v. 103, p. 470–492, doi: 10.1007/BF01041754.

Ward, P.L., 1995, Subduction cycles under western North America during the Mesozoic and Cenozoic eras, *in* Miller, D.M., and Busby, C., eds., Jurassic Magmatism and Tectonics of the North American Cordillera: Geological Society of America Special Paper 299, p. 1–45.

Wark, D.A., 1991, Oligocene ash flow volcanism, northern Sierra Madre Occidental: Role of mafic and intermediate-composition magmas in rhyolite genesis: Journal of Geophysical Research, v. 96, p. 13389–13411.

Wark, D.A., Kempter, K.A., and McDowell, F.W., 1990, Evolution of waning, subduction-related magmatism, northern Sierra Madre Occidental, Mexico: Geological Society of America Bulletin, v. 102, p. 1555–1564, doi: 10.1130/0016-7606(1990)102<1555:EOWSRM>2.3.CO;2.

Webber, K.L., Fernández, L.A., and Simmons, W.B., 1994, Geochemistry and mineralogy of the Eocene-Oligocene volcanic sequence, southern Sierra Madre Occidental, Juchipila, Zacatecas, Mexico: Geofísica Internacional, v. 33, p. 77–89.

Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Weaver, S.D., and Briggs, R.M., 1995, Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: A review: Journal of Volcanology and Geothermal Research, v. 68, p. 1–28.

Wilson, F.I., and Rocha, S.V., 1949, Coal deposits of the Santa Clara district near Tónichı, Sonora, Mexico: U.S. Geological Survey Bulletin 962A, 80 p.

Wong, M., and Gans, P.B., 2003, Tectonic implications of early Miocene extensional unroofing of the Sierra Mazatán metamorphic core complex, Sonora, Mexico: Geology, v. 31, p. 953–956, doi: 10.1130/G19843.1.

Wong, M., and Gans, P.B., 2004, Evidence for Early crustal thickening, polyphase Oligo-Miocene Extension, and footwall rotation at the Sierra Mazatán metamorphic core complex, Sonora, Mexico: EOS, American Geophysical Union, Fall Meeting 2004, abstract T41E–1270.

Wortel, R., and Spakman, W., 2000, Subduction and slab detachment in the Mediterranean-Carpathian region: Science, v. 290, p. 1910–1917, doi: 10.1126/science.290.5498.1910.

Manuscript Accepted by the Society 29 August 2006

Printed in the USA