Ignimbrite flare-up and deformation in the southern Sierra Madre Occidental, western Mexico:
Implications for the late subduction history of the Farallon plate

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[1] The Sierra Madre Occidental (SMO) of western Mexico is one of the largest silicic volcanic provinces on Earth, but the mechanism for the generation of such a large volume of ignimbrites has never been clearly defined. We present new 40Ar/39Ar ages, geologic mapping, and structural data for the southern part of the SMO demonstrating that most of this volcanic province was built in two episodes of ignimbrite flare-up in Oligocene (31.5–28 Ma) and early Miocene (23.5–20 Ma) time, and that extensional deformation occurred mostly before the transfer of Baja California to the Pacific plate. Extensive ignimbrite successions, with 40Ar/39Ar ages clustering at \( \sim 23 \) and \( \sim 21 \) Ma, cover most of the southern SMO, thus correlating in age with ignimbrites exposed in southern Baja California and central Mexico. Grabens with a 020° to N-S orientation developed in the east almost concurrently with this volcanic episode. Half grabens and NNW striking listric normal fault systems formed at the end of middle Miocene as far as 150 km from the present coast. A belt of left-lateral transpressional structures formed along the southern boundary of the SMO during the same period. We link these magmatic and tectonic events to the evolution and dynamics of the Farallon and North America plates during the Miocene. Particularly, we propose that a first detachment of the lower part of the Farallon plate in early Miocene time produced a transient thermal event and partial melting of the crust via mafic underplating. Middle Miocene extension would be related to a second detachment event, resulting from the slowing subduction that preceded the final capture of the Magdalena microplate by the Pacific plate at 12.5 Ma. Transpression at the southernmost end of the SMO occurred along the inland projection of the Magdalena-Cocos plate boundary and may be explained by a difference in subduction rate and by a temporal convergence between the two plates in the eve of the end of subduction of the Magdalena plate. INDEX TERMS: 5480 Planetology: Solid Surface Planets: Volcanism (0905); 8150 Tectonophysics: Evolution of the Earth: Plate boundary—general (3040); 8109 Tectonophysics: Continental tectonics—extensional (0905); KEYWORDS: ignimbrite flare-up, Sierra Madre Occidental, western Mexico, extensional tectonics, slab detachment

1. Introduction

1.1. Purpose and Objectives

[2] The huge silicic volcanic plateau of the Sierra Madre Occidental of western Mexico (SMO) is an enigmatic feature in the geology of the North America plate. The SMO runs for over 2000 km from the U.S.-Mexico border to the Trans-Mexican Volcanic Belt (TMVB) (Figure 1). It mostly consists of silicic ignimbrites and, to a lesser extent, rhyolitic domes that cover about 300,000 km² with an average thickness of 1 km [McDowell and Keizer, 1977; McDowell and Clabaugh, 1979]. With an estimated volume of 300,000 km³ the SMO ranks among the major silicic large igneous provinces on Earth. These kind of provinces are generally related to continental breakup with variable interaction of mantle plumes [e.g., Bryant et al., 2000; Pankhurst et al., 2000], which provide sufficient thermal energy to thin the continental lithosphere and, eventually, to melt the crust. By contrast, in the SMO the production of massive silicic volcanism occurred during subduction of a young plate with no involvement of mantle plumes and took place 20 to 10 Ma before the breaking of the continental crust which led to the formation of the Gulf of California. The inception of silicic volcanism in the SMO has been generally considered as a marker of the beginning of extension following the Laramide orogeny [e.g., Wark et al., 1990; Luhr et al., 2001]. A plate tectonics mechanism

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for the occurrence of massive ignimbritic volcanism, however, has not been provided.

[3] The SMO has been also strongly affected by extensional tectonics during the Tertiary. Extensional structures form two broad, NNW-SSE trending, belts on both sides of the SMO [Stewart et al., 1998], which merge in Sonora and Chihuahua, to the north, and in Nayarit-Jalisco, to the south (Figure 1). The western belt borders the Gulf of California and is also known as the Gulf Extensional Province [Gastil et al., 1975]; the eastern belt extends for several hundreds of kilometers east of the core of the SMO and has been considered the southern continuation of the Basin and Range province of the western United States [Henry and Aranda-Gomez, 1992]. Henry and Aranda-Gomez [2000] further suggested that most of the Mexican Basin and Range was linked to the interaction between the Pacific and the North America plates during late Miocene time, after the end of the subduction of the last remnant of the Farallon plate (12.5 Ma) [Atwater and Stock, 1998]. Several studies, however, indicate that extension initiated as early as late Oligocene time both in the north [Nourse et al., 1994; Gans, 1997; McDowell et al., 1997; Stewart et al., 1998] and in the south [Nieto-Samaniego et al., 1999; Luhr et al., 2001]. Therefore this first part of the extensional history remains to be explained. In summary, despite a number of studies published in the last two decades the causes of the ignimbrite flare-up and extension in the SMO are still not completely understood.

[4] This paper presents new geologic, geochronologic, and structural data that define the timing of silicic volcanism and extension as well as the tectonic setting of the SMO south of the Tropic of Cancer (latitude 23°30’). This vast region, which was previously very poorly known, holds an important piece of information for the geologic reconstruction of the whole province since it faces the last and larger fragment of the Farallon plate (Magdalena microplate) to be subducted before the initial rifting of the Baja California peninsula [Lonsdale, 1991]. Our data fill the last gap in the geologic reconnaissance of the SMO and enable us to analyze at a global scale the temporal pattern of ignimbrite

Figure 1. Geodynamic map of Mexico showing Tertiary extension and volcanism north of the Trans-Mexican Volcanic Belt (TMVB) and the present configuration of plates. Tertiary extension is from Henry and Aranda-Gomez [2000] and this work. Regional tilt domains are from Stewart et al. [1998]. Abbreviations are as follows: Nay., Nayarit; Jal., Jalisco.
flare-up and extension. On the basis of this rationale, we propose a possible mechanism for the occurrence of these phenomena with implications for the dynamics of the Farallon slab during its final stage of subduction.

1.2. Location and Methodology

South of the Tropic of Cancer the Sierra Madre Occidental volcanic province can be divided into the physiographic provinces of the Mesa Central high plateau to the east and the Sierra Madre Occidental proper to the west [Nieto-Samaniego et al., 1999]. The Sierra Madre Occidental can be further divided into three domains: (1) an eastern domain affected by several NNE to N-S trending grabens, (2) a western domain where NNW trending half grabens dominate the landscape, and (3) a southern domain characterized by left-lateral transpressional structures (Figure 2). Our fieldwork mostly focused on the latter two domains, bounded by the Guadalajara-Fresnillo highway to the east, the Gulf of California to the west, the Mezquital River to the north, and the Trans-Mexican Volcanic Belt to the south (Figure 2).

Only sparse geologic and structural works were available in this region, mainly along its borders [Damon et al., 1979; Clark et al., 1981; Nieto-Obregon et al., 1981; Lyons, 1988; Scheubel et al., 1988; Ferrari, 1995]. The paucity of studies was mostly due to the difficult access to
this region. The volcanic plateau, with elevations ranging from 2100 to 2900 m, is dissected by valleys with elevations as low as 500 m that cut along the main extensional structures. No paved roads exist, and only two graded roads were recently completed to traverse this part of the SMO in a WSW-ENE direction (Figure 2). To make fieldwork more efficient in this complicated area we have first studied 1:250,000 satellite images, 1:80,000, and 1:50,000 air photos, and digital terrain models at various scales to compile a geologic base map. This was subsequently integrated with fieldwork mainly along two transects (Valparaíso-Estación Ruiz; Bolaños-Tepic) and eventually completed with a few helicopter flights. The resulting volcanic stratigraphy and geologic mapping are illustrated in Figures 3, 4, and 5, and will be described in the next section.

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**Figure 3.** Composite stratigraphic columns for the study region indicating typical thickness of units and existing ages. New ages presented in this work are in bold. Full references of other ages are given in the text.
Figure 4. Geologic map of the Valparaiso–Estación Ruiz transect. Question marks indicate contacts between units inferred from air photos only or unknown extension of units. Curved dashed lines indicate calderas inferred by aerial photos and topographic features.
Figure 5. Geologic map of the Bolaños-Tepic transect. Symbols as in Figure 4.
Ferrari et al. - Figure 5
[7] Our geologic reconnaissance is supported by 17 new
$^{40}$Ar/$^{39}$Ar ages (Table 1), 2 new K-Ar ages (Table 1), and 16
published K-Ar data (details in the following section). The
$^{40}$Ar/$^{39}$Ar ages were obtained at Centro de Investigación
Científica y Educación Superior de Ensenada’s (CICESE)
geochronology laboratory using a MS-10 mass spectrom-
eter; details on the methodology are given in Appendix 1,
which is available as electronic supplementing material. The
samples were step-heated between 700°C and 1500°C. A
summary of the $^{40}$Ar/$^{39}$Ar is given in Table 1; the plateau
of sample TS-28 is taken from the isochron age calculated
saddle-shaped age spectrum. Our best estimate for the age
The four fractions collected on the plagioclase yielded a
ducted on the biotite with one and two fractions collected.
milligrams could be obtained. Two experiments were con-
ducted on the biotite with one and two fractions collected.
Because of the scarcity of these minerals, only a few
milligrams could be obtained. Two experiments were con-
donated with one and two fractions collected. The four fractions collected on the plagioclase yielded a
saddle-shaped age spectrum. Our best estimate for the age
of sample TS-28 is taken from the isochron age calculated
with the combined fractions of the duplicate experiments is also reported in Table 1. The majority of the
samples yielded well-defined isochron ages which we take
as the best estimate of the age for the sample; however, we
had cases where the distribution of the data on the correla-
tion diagram did not permit a realistic calculation of the
regression line or only the intercept with one of the axes
could unequivocally be calculated. This is the case for
samples TS-10, TS-21, and TS-46, for which we took the
plateau age as our best estimate of the age. For sample TS-
28 we analyzed concentrates of plagioclase and biotite, and
because of the scarcity of these minerals, only a few milligrams could be obtained. Two experiments were con-
donated on the biotite with one and two fractions collected.
The four fractions collected on the plagioclase yielded a
saddle-shaped age spectrum. Our best estimate for the age
of sample TS-28 is taken from the isochron age calculated
with the combined fractions of the biotite and plagioclase.

[8] Scarce access and dense vegetation prevented a
detailed microtectonic study of the fault systems observed
in the region. However, the geometry and sense of slip of
over 200 striated faults and 57 dikes could be measured at
18 sites. The local paleostress regime responsible for the
observed deformation was computed by fault slip data
inversion with the method of Angelier [1990], and the relative results are listed in Table 1. Using different
approaches, Pollard et al. [1993], Cashman and Ellis
[1994], Nieto-Samaniego and Alaniz-Alvarez [1997], and
Twiss and Unruh [1998] demonstrated that the assumptions
of the stress inversion methods are not always satisfied and
that caution should be used in using them. Particularly
simplistic assumptions often not fulfilled in nature are (1)
a homogeneous stress field, (2) no dynamic and kinematic
interaction between faults, and (3) the parallelism between
the maximum resolved shear stress on a fault plane and the
slickenline. To minimize this problem, we inverted slip data
of faults affecting previously unfaulted rock units and/or
the fault planes cutting all the other ones, i.e., those with
the higher probability of complying with the assumptions of
the inversion methods. Some faults with incongruous ori-
entations or striations relative to the dominant population
appeared in the data set, but they were discarded in the final
computation. These results should then be representative of
the local paleostress conditions.

2. Geology and Geochronology

[9] In this section we present an overview of the geology
of the study region on the basis of information gathered
mostly along two ENE-WSW transects, 70 to 100 km apart,
that cross the southwestern SMO (Figures 2, 4, and 5).
Reconnaissance field geologic mapping was often extended
for 25 to 50 km to both sides of the transect when dirt roads
or tracks were available. Composite stratigraphic sections
were elaborated for the four areas with more information
and are illustrated in Figure 3.

2.1. Oligocene Volcanism

[10] The oldest rocks observed are exposed in the north-
eastern part of the study region and, possibly, in the west
along the coast (Figure 4). In the northeast they are silicic
ignimbrites and rhyolitic domes that extend widely to the
east outside the study region at elevations ranging between
2100 and 2400 m. In the Sierra de Valparaíso the ignim-
brites attain at least 300 m of thickness. We obtained an age
of 31.5 ± 0.3 Ma for a sanidine concentrate of a welded ash
flow tuff also rich in quartz and plagioclase widely exposed
in the central part of Sierra de Valparaíso (sample TS 56,
Table 1). Similar ignimbrites are widespread toward the
south, in the Huejúquilla area (Figures 3 and 4). We have
dated two ignimbrites exposed in the footwall of the Atengo
half graben (Figure 4). A feldspar separate yielded an age of
31.0 ± 0.7 Ma (sample TS-5, Table 1), indistinguishable
from the Sierra de Valparaíso one. A sanidine concentrate
from an ignimbrite at an upper stratigraphic position pro-
duced an age of 28.6 ± 0.3 Ma (sample TS-10, Table 1). In
the western part of the study region, massive andesitic flows
constitute the base of the succession east of Estación Ruiz
(Figures 3 and 4). These rocks proved to be too altered to be
dated. Farther to the south, in the Santa María del Oro area
and along the Rio Santiago valley, a succession of ignim-
brites and subordinated andesitic lavas underlie the Miocene
ignimbrite succession. We have dated a biotite separate
from a welded ash flow tuff at the southernmost edge of the
SMO, ~50 km northwest of Guadalalara, at 30.1 ± 0.8
Ma by K-Ar method (sample ES 1, Table 1; Figure 5).

[11] Andesites and Oligocene ignimbrites are locally
covered by volcanic conglomerate and/or red sandstone.
Outcrops of volcano-sedimentary beds are normally too
small to appear on the geologic maps of Figures 3 and 4
but were observed in the Huejúquilla area (Figure 4), ~15 km
NW of El Zopilote (Figure 4), in the Santa María del Oro and
Santa Fe areas (Figure 5), and in the Rio Santiago valley
southeast of these towns (Figure 5). Small plateaus of
basaltic to andesitic flows also cover the late Oligocene
ignimbrites in the northwestern part of the study region
(Figure 4). These, in turn, are capped by a distinct pyro-
clastic succession of poorly to mildly welded and crystal
Table 1. Summary of New Isotopic Ages for the Southern Sierra Madre Occidental

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
<th>Longitude, West</th>
<th>Latitude, North</th>
<th>Elevation, m</th>
<th>Rock Type</th>
<th>Material Dated</th>
<th>t_p Ma</th>
<th>t_e Ma</th>
<th>(39Ar/36Ar)</th>
<th>SumS/n</th>
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<tbody>
<tr>
<td>TS 56</td>
<td>Sierra Valparaíso, Zac.</td>
<td>103°43.305'</td>
<td>22°53.225'</td>
<td>2450</td>
<td>ignimbrite</td>
<td>san</td>
<td>31.6 ± 0.3</td>
<td>31.5 ± 0.3</td>
<td>306 ± 27</td>
<td>1.2/3</td>
</tr>
<tr>
<td>TS 5</td>
<td>west of Huejuquilla, Jal.</td>
<td>103°59.251'</td>
<td>22°39.554'</td>
<td>1480</td>
<td>ignimbrite</td>
<td>feld</td>
<td>31.1 ± 0.4</td>
<td>31.0 ± 0.7</td>
<td>291 ± 21</td>
<td>3.4/4</td>
</tr>
<tr>
<td>TS 10</td>
<td>west of Huejuquilla, Jal.</td>
<td>103°59.195'</td>
<td>22°40.089'</td>
<td>1330</td>
<td>ignimbrite</td>
<td>san</td>
<td>28.6 ± 0.3</td>
<td>27.9 ± 0.3</td>
<td>324 ± 18</td>
<td>0.1/4</td>
</tr>
<tr>
<td>TS 15</td>
<td>NNE of Sta. Lucía, Zac.</td>
<td>104°13.103'</td>
<td>22°37.589'</td>
<td>2445</td>
<td>rhyolite</td>
<td>san</td>
<td>27.9 ± 0.3</td>
<td>27.9 ± 0.2</td>
<td>276 ± 44</td>
<td>0.4/3</td>
</tr>
<tr>
<td>TS 11 1st exp</td>
<td></td>
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</tr>
<tr>
<td>TS 11 2nd exp</td>
<td>Rio Atengo, Zac.</td>
<td>103°59.195'</td>
<td>22°40.089'</td>
<td>1330</td>
<td>ignimbrite</td>
<td>san</td>
<td>28.1 ± 0.8</td>
<td>27.6 ± 0.8</td>
<td>318 ± 12</td>
<td>2.6/4</td>
</tr>
<tr>
<td>TS 11 all exp</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>28 ± 2/3</td>
</tr>
<tr>
<td>TS 22</td>
<td>east of Jesus María, Nay.</td>
<td>104°28.091'</td>
<td>22°17.445'</td>
<td>650</td>
<td>ignimbrite</td>
<td>pl</td>
<td>23.3 ± 0.5</td>
<td>23.5 ± 0.4</td>
<td>283 ± 15</td>
<td>1.1/4</td>
</tr>
<tr>
<td>TS 21</td>
<td>Jesus María, Nay.</td>
<td>104°30.667'</td>
<td>22°15.145'</td>
<td>550</td>
<td>bas-and.</td>
<td>w.r.</td>
<td>21.3 ± 0.3</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>ESC-3</td>
<td>west of Llano grande, Nay.</td>
<td>105°04.540'</td>
<td>22°45.600'</td>
<td>1780</td>
<td>ignimbrite</td>
<td>pl</td>
<td>21.1 ± 0.7</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>TS 25</td>
<td>Arroyo El Frayle, Nay.</td>
<td>104°43.566'</td>
<td>22°10.362'</td>
<td>1120</td>
<td>ignimbrite</td>
<td>san</td>
<td>21.1 ± 0.3</td>
<td>21.1 ± 0.3</td>
<td>294 ± 21</td>
<td>2.7/3</td>
</tr>
<tr>
<td>ESC-2</td>
<td>north San Juan Bautista, Nay.</td>
<td>105°06.563'</td>
<td>22°11.096'</td>
<td>870</td>
<td>ignimbrite</td>
<td>feld</td>
<td>21.1 ± 0.4</td>
<td>20.9 ± 0.4</td>
<td>302 ± 14</td>
<td>2.5/4</td>
</tr>
<tr>
<td>ESC-4</td>
<td>south of Santa Lucía, Nay.</td>
<td>104°10.691'</td>
<td>22°05.630'</td>
<td>2050</td>
<td>ignimbrite</td>
<td>san</td>
<td>21.1 ± 0.3</td>
<td>21.2 ± 0.3</td>
<td>294 ± 8</td>
<td>8.0/4</td>
</tr>
<tr>
<td>TS 46</td>
<td>west of Mesa del Nayar, Nay.</td>
<td>104°45.333'</td>
<td>22°20.630'</td>
<td>2100</td>
<td>ignimbrite</td>
<td>san</td>
<td>21.0 ± 0.2</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>TS 26 1st exp</td>
<td></td>
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<td></td>
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<td>20.4 ± 0.5</td>
</tr>
<tr>
<td>TS 26 2nd exp</td>
<td>SW Mesa del Nayar, Nay.</td>
<td>104°44.697'</td>
<td>22°09.645'</td>
<td>1550</td>
<td>ignimbrite</td>
<td>san</td>
<td>19.7 ± 0.4</td>
<td>19.9 ± 0.4</td>
<td>283 ± 48</td>
<td>0.2/4</td>
</tr>
<tr>
<td>TS 26 all exp</td>
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<td>19.9 ± 0.4/9</td>
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<td>308 ± 41</td>
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<tr>
<td>ESC 1 2nd exp</td>
<td>San Juan Bautista, Nay.</td>
<td>105°05.671'</td>
<td>22°08.610'</td>
<td>100</td>
<td>granodiorite</td>
<td>feld</td>
<td>21 ± 4</td>
<td>22 ± 1</td>
<td>296 ± 5</td>
<td>1.8/4</td>
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<td>ESC 1 3rd exp</td>
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<td>21 ± 1</td>
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<td>ESC 1 all exp</td>
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<td>20 ± 2</td>
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<tr>
<td>TSS 1 1st exp</td>
<td>Sierra Los Pajaritos, Nay.</td>
<td>104°12.292'</td>
<td>21°35.061'</td>
<td>1710</td>
<td>ignimbrite</td>
<td>bio</td>
<td>20.7 ± 0.2</td>
<td>20.6 ± 0.2</td>
<td>314 ± 17</td>
<td>1.2/4</td>
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<tr>
<td>Gdl 228 1st exp</td>
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<td>19.9 ± 0.3</td>
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<tr>
<td>Gdl 228 2nd exp</td>
<td>Mexpan, Nay.</td>
<td>104°25.700'</td>
<td>21°01.800'</td>
<td>1050</td>
<td>ignimbrite</td>
<td>gms</td>
<td>19.9 ± 0.2</td>
<td>19.8 ± 0.4</td>
<td>307 ± 10</td>
<td>17/15</td>
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<tr>
<td>Gdl 228 all exp</td>
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<td>20.0 ± 0.3</td>
</tr>
<tr>
<td>TS 28</td>
<td>Arroyo El Naranjo, Nay.</td>
<td>104°25.700'</td>
<td>21°01.800'</td>
<td>1050</td>
<td>ignimbrite</td>
<td>gms</td>
<td>19.9 ± 0.2</td>
<td>20.0 ± 0.3</td>
<td>299 ± 5</td>
<td>34.3/9</td>
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<td>19.0 ± 0.6</td>
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<td>18.3 ± 0.4</td>
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<td>TS 28 all exp</td>
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<td>17 ± 1/3</td>
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</tbody>
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Average 40Ar*/ Ar-39 Ar = ppm

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
<th>Longitude, West</th>
<th>Latitude, North</th>
<th>Elevation, m</th>
<th>Rock Type</th>
<th>Material Dated</th>
<th>Average K, wt %</th>
<th>Average 40Ar*, ppm</th>
<th>40Ar*, wt %</th>
<th>Age, Ma</th>
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</thead>
<tbody>
<tr>
<td>ES 2</td>
<td>Rio Chico, Jal.</td>
<td>103°46.252'</td>
<td>21°10.490'</td>
<td></td>
<td>ignimbrite</td>
<td>Bartonite</td>
<td>5.967</td>
<td>0.01258</td>
<td>42.5</td>
<td>30.1 ± 0.8</td>
</tr>
<tr>
<td>CO 1</td>
<td>Cotija area, Mich.</td>
<td>103°02.476'</td>
<td>19°53.705'</td>
<td></td>
<td>ignimbrite</td>
<td>Bartonite</td>
<td>0.946</td>
<td>0.001301</td>
<td>19.5</td>
<td>23.5 ± 0.9</td>
</tr>
</tbody>
</table>

a All errors are 1σ. The abbreviations are exp, experiment(s); t_p, plateau age with the error in J included; t_e, isochron age calculated from the 39Ar/40Ar versus 39Ar/40Ar correlation diagram; SumS of York [1969] n, number of points fitted; San, sanidine; Bio, Bartonite; feld, feldspar; gms, groundmass; pl, plagioclase; w.r., whole rock. Preferred ages are shown in bold. Detailed results are given in Appendix A, which is available as electronic supporting material.

b Isochron age calculated with the combined fractions of more than one experiment.
poor ash flow tuffs, pumice flows, and ash and pumice falls deposits. The latter was named the Atengo ignimbrite succession and attains a minimum thickness of 200 m. A sandine concentrate for an ash flow tuff from the middle part of this succession was analyzed twice, yielding an isochron age of 28 ± 2 Ma (sample TS 11, Table 1). Moderately welded conglomerate and sandstone cover the Atengo succession inside the half graben. On the western side of the Atengo half graben a large rhyolitic dome complex was dated at 27.9 ± 0.2 Ma (sample TS-15, Table 1).

2.2. Miocene Volcanism

[12] The Oligocene succession of the Huejuquilla-Atengo area is covered by a younger ignimbrite succession ~6 km east of the village of Las Canoas (Figure 4). The Las Canoas succession is made of several ash and pumice flows and pumice falls that reach an aggregate thickness of at least 350 m. The most representative unit is a gray to pink, moderately welded ash flow tuff with small phenocrysts of biotite, plagioclase, alkali-feldspar and hornblende. Clark et al. [1981] dated this ignimbrite in the vicinity of Las Canoas by the K-Ar method obtaining an age of 23.5 ± 0.5 Ma for a plagioclase, alkali-feldspar and hornblende.

Atengo half graben a large rhyolitic dome complex was dated at 27.9 ± 0.2 Ma (sample TS-15, Table 1). Immediately to the west of Jesus Maria (Figure 4), Clark et al. [1981] for basaltic flows and dikes dated a number of ignimbrite sheets located at different stratigraphic levels in the succession. The 

40Ar/39Ar experiments performed on sandine separates yielded ages of 21.1 ± 0.3 Ma for the lowermost ignimbrite and 21.0 ± 0.2 Ma for the uppermost sheet, located ~1000 m above the previous one (samples TS-25 and TS-46, Table 1, respectively). A third, moderately welded ignimbrite, at ~3 km to the west of the Nayar caldera rim, was dated 19.9 ± 0.4 Ma (sample TS 26, Table 1). The Nayar succession can be followed for tens of kilometers from the Mesa del Nayar area along the coastal area at least up to the latitude of Acaponeta (Figure 2). To the north of Mesa del Nayar the succession caps the last 600 to 1000 m of the volcanic plateau. Plagioclase phenocrysts from one of the highest ignimbrites of the succession in the Llano Grande area (105°03'W, 22°45'N, Figure 4) produced an age of 21.1 ± 0.7 Ma (sample ESC 3, Table 1). West of Mesa del Nayar the succession is found up to the present coast where we have dated the uppermost ignimbrite of a tilted block north of the village of San Juan Bautista at 20.9 ± 0.4 Ma (Figure 4; sample ESC 2, Table 1). To the east the topmost ignimbrite in the Sierra Los Huicholes (Figure 4) provided an age of 21.2 ± 0.3 Ma (sample ESC 4, Table 1). To the south we have dated again the uppermost ignimbrite of the succession exposed in the Sierra de Pajaritos (Figure 5). Here a biotite separate yielded an age of 20.7 ± 0.2 Ma (sample TSS 1, Table 1). In addition, several K-Ar ages reported in previous works for ignimbrites in the Aguamilpa and Santa Maria del Oro area (Figure 5) fall within the limits of our 

40Ar/39Ar ages [Gastil et al., 1979; Damon et al., 1979; Soto and Ortega, 1982]. Similarly, in the Bolaños graben, Scheubel et al. [1988] report K-Ar ages of 21.3 ± 0.5 Ma and 20.1 ± 0.4 Ma for ignimbrites of their Huichol group, made of silicic ash flows and minor basalts (Figures 3 and 5), which dominate the succession exposed in the San Martin de Bolaños area. As a whole, the Nayar ignimbrite succession covers at least 5000 km². Taking into account erosion removal, we consider an average of 900 m as a reasonable estimate of the original thickness. This would imply an original volume of ~4500 km³ emplaced in ~1.4 Ma, a value comparable to modern large caldera systems like the Taupo Volcanic Zone and Yellowstone [Christiansen, 1984; Houghton et al., 1995].

14 Several rhyolitic domes are intercalated with the Nayar ignimbrite succession along the ring fault of the inferred calderas. Toward the coast, rhyolitic domes are more abundant and in some cases postdate the Nayar succession (Figure 4). We obtained an isochron age of 17
± 1 Ma for a biotite and feldspar separate from a rhyolitic dome in the El Zopilote area (Figure 4; sample TS-28, Table 1).

[15] The Nayar ignimbrite succession is capped in places by basaltic flows with a thickness of 50 to 100 m. In the Mesa del Nayar area these lavas are undated. However, in the Bolaños areas the uppermost basalts yielded a K-Ar age of 19.9 ± 0.4 Ma [Nieto-Obregon et al., 1981]. Subvolcanic intrusive bodies with granitic to quartz-monzonitic composition crop out on the western and southern margins of the SMO along the San Pedro and Santiago rivers where they flow at 150 to 50 m of elevation (Figures 4 and 5). We have performed three 40Ar/39Ar experiments for a sample of the San Juan Bautista granodiorite, one of the largest bodies in the area (Figure 4). The resulting isochron age of 20 ± 2 Ma (sample ESC 1, Table 1) is comparable to the K-Ar age of 17.2 ± 1.0 Ma reported by Rodríguez-Castañeda and Rodríguez-Torres [1992] for another granitic body ~70 km to the south, and indicates that these rocks may be the intrusive equivalent of the Nayar ignimbrite succession.

[16] Mafic volcanism represent the last volcanic event in the study region. Many mafic dikes are commonly emplaced parallel to NNW striking extensional faults in the westernmost part of the area (Figures 4 and 5). Previous K-Ar determinations for these dikes have consistently yielded ages between 11.9 Ma and 10.9 Ma [Damon et al., 1979; Clark et al., 1981]. Henry and Aranda-Gómez [2000] obtained nearly identical ages for similar mafic dikes in southern Sinaloa, just to the north of our study area. A thick succession of basaltic flows that marks the inception of the TMVB volcanism is emplaced at the boundary between the SMO and the Jalisco block between Tepic and Ixtlán del Río and to the north of Guadalajara (Figure 2) [Ferrari et al., 2000b]. The emplacement of these lavas began at ~11 Ma [Ferrari et al., 2000b, and references therein].

2.3. Regional Correlation of the Silicic Volcanism

[17] Our geochronology results for the southwestern SMO fit well with previous studies in the surrounding regions. Particularly, part of our stratigraphy and ages resemble closely those reported by McDowell and Keizer [1977] along the Durango-Mazatlán transect, located ~100 km to the north. Our ages for the Valparaíso-Huejjuquilla area (31.5–28 Ma) overlap with those obtained by these authors in the Durango area, and our age of 27.9 Ma for the rhyolitic dome on the western side of the Atengo valley is identical to their age for a large rhyolitic dome at Las Adjuntas, ~110 km west of Durango city. Similarly, the ages of the Las Canoas succession are identical to the 1000 m thick El Salto-Espinazo del Diablo ignimbrite sequence, for which McDowell and Keizer [1977] obtained eight ages, indistinguishable within error, which cluster at 23.5 Ma. Henry and Fredrikson [1987] also obtained similar ages for rhyolite and dacite lavas in Sinaloa. The El Salto succession can be followed several tens of kilometers to the SSE in the direction of the Las Canoas area. A possible caldera structure lies in between, centered on the village of Temoaya [Swanson and McDowell, 1984] (Figure 2). Inside this area we found a widespread fluvi-lacustrine sedimentary succession, which would confirm the existence of a volcano-tegmental depression. Other early Miocene calderas may be located west of Temoaya and southeast of Santa Lucia (Figure 2), but their existence was only suggested by remotely sensed features and helicopter surveys. Southeast of Bolaños, ignimbrites ~23 m.y. old are reported in the Teul area [Moore et al., 1994] (Figure 2) and can be followed to the south up to the Rio Santiago, where Nieto-Obregon et al. [1985] report a K-Ar age of 23.6 ± 0.6 for a plagioclase concentrate from an ignimbrite 15 km to the northwest of the Santa Rosa dam (Figure 2). South of the river the early Miocene ignimbrites are covered by the younger volcanism of the Trans Mexican Volcanic Belt (review by Rosas-Elguera et al. [1997]). However, isolated blocks of ignimbrites tilted to the NNE crop out from the northernmost part of the Pliocene succession of the Trans Mexican Volcanic Belt near the village of Ixtlán del Río (Figure 2). We have dated a groundmass concentrate from a welded ash flow tuffs in this area at 20.0 ± 0.3 Ma (sample Gdl 228, Table 1).

[18] Previous workers reported ignimbrites with early Miocene ages farther east. In the Juchipila area (Figure 2), Webber et al. [1994] describe a succession of 10 ash flow tuffs, four of which were dated by the fission track method and yielded ages between 25.2 ± 2.2 and 24.9 ± 2.7 Ma. However, the tuffs cover mafic lavas with a K-Ar age of 23.7 ± 1.4 Ma, leaving the possibility that the age of the ignimbrite succession could still be ~23 Ma. In the Los Altos de Jalisco region, located west of Guadalajara (Figure 2), ignimbrite and rhyolitic topographic highs emerged from a late Miocene basaltic plateau. Castillo-Hernandez and Romero-Rios [1991] obtained K-Ar ages of 24.1 ± 0.8 Ma and 24.7 ± 1.0 Ma, for sanidine separated from an ignimbrite and a rhyolite, respectively. The easternmost occurrence of early Miocene ignimbrites is found in central Guanajuato (Figure 6). Remnants of a single ignimbrite sheet cover Oligocene rhyolitic domes in the La Sauceda area. This ignimbrite, dated by K-Ar at 24.8 ± 0.6 Ma [Nieto-Samaniego et al., 1996], represents a distal facies and probably came from the Los Altos de Jalisco area.

[19] Ignimbritic successions are also widespread to the south of the TMVB but are typically Late Cretaceous to early Paleocene in age within the Jalisco block [Ferrari et al., 2000a]. However, Tertiary ignimbrite units are exposed more to the east (Figure 6). Although most of the silicic volcanism in Michoacán and Guerrero is Oligocene [Morán-Zenteno et al., 1999], some younger ignimbrites are reported immediately to the south of the TMVB. About 35 km south of Lake Chapala (Figures 2 and 6), a thick pyroclastic succession overlies Tertiary intrusives and Cretaceous sedimentary rocks from the Michoacán block. The uppermost ignimbrite of this succession is a light brownish moderately welded unit with microphenocrysts of sanidine and white pumice supported by an ash matrix, which we called the Cazos ignimbrite. We have obtained a K-Ar age of 23.5 ± 0.9 Ma for a feldspar separate from the Cazos ignimbrite (sample CO-1, Table 1). In the Morelia area (Figure 6), a 200–300 m thick rhyolitic ignimbrite succession forms prominent cliffs ~15 km south of the city (Puerto la Sosa area). Peaks
et al. [1991] dated a ignimbrite from the upper part of the succession by K-Ar at 21 ± 1 Ma. These ages suggest a possible continuation of the 23 and ~21 Ma silicic volcanism up to some tens of kilometers south of the TMVB.

[20] In southern Baja California, Hausback [1984] and Umhoefer et al. [2001] obtained ages in the range 23–17 Ma for ignimbrites intercalated in the lower part of the Comondú Formation. Particularly interesting are the ages obtained for the “La Paz tuff”, a distinct succession of welded ash flow tuffs exposed in the La Paz-Punta Coyote area. Hausback [1984] reports K-Ar ages ranging between 21.8 ± 0.2 and 20.6 ± 0.2 Ma for this succession, which largely overlap our ages for the Nayar succession. Given the large geographic extent of the Nayar ignimbrite succession, the possibility exists that the La Paz tuff could be part of the latter. This correlation poses an additional constraint on the prerifting position of Baja California and confirms that the Los Cabos block was located immediately to the northwest of the Jalisco block prior to the opening of the Gulf of California [Schaaf et al., 2000] (Figure 6).

3. Tectonics of the Southwestern SMO

3.1. Geometry, Kinematics, and Time of Faulting

[21] Several large structures cut the Tertiary succession of the southwestern SMO (Figures 2, 4, and 5). According to the geometry and kinematics they can be grouped in an eastern and a western extensional domains, and in the Santa María del Oro-Santa Rosa transpressional corridor (Figure 2).

3.1.1. Eastern Extensional Domain

[22] This domain comprises six full grabens 30 to 40 km apart: Aguascalientes, Juchipila, Tlaltenango, Bolan˜os, La Ventana, and Mezquital (Figure 2). The last two were not studied but are grouped with the others because of their orientation and probable age. The first four grabens trend 010° to N-S and are typically over 100 km long and 20 km wide. The grabens are bounded by high-angle faults with dominant dip-slip displacements. Inside the graben, volcanic or sedimentary beds show tilts of 10° to 20° either to the east or west. Offset of stratigraphic units can only be observed in the Bolan˜os graben, where it may reach 1800 m. Nieto-Samaniego et al. [1999] interpreted the four grabens as the results of ~E-W extension during the 23 to 21 Ma pulse. During our fieldwork, however, we observed that two normal fault scarps, <50 m high, also affect the shield volcano. Furthermore, we found that the ~21 Ma ignimbrite succession is faulted in the Bolaños graben.
[23] In the Bolaños mining area (103°45'W, 21°49'N; Figure 5) Lyons [1988] estimates 1 to 1.5 km of normal offset of the mineralized body. The mineralization was dated at 20.8 ± 1.0 Ma, but it is unequivocally covered by basaltic flows dated 21.0 ± 0.4 Ma [Nieto-Obregon et al., 1981]. According to our observations in the Bolaños area the offset of the ~21 Ma succession does not exceed 400–500 m. In the San Martín de Bolaños area (Figure 5), Scheubel et al. [1988] dated at 21.3 ± 0.5 Ma an ash flow tuff on the floor of the graben, which is also found outside the graben over 1300 m higher. However, the geologic cross section of Scheubel et al. [1988] shows the ash flow tuff emplaced against the upper part of the western graben wall with a subvertical contact, suggesting that it could have flowed into a preexisting depression. Lyons [1988] also observed three generations of faults in the Bolaños area: A 060° normal fault set is cut by a 030° set which is in turn cut by N-S normal faults. Our regional observations, however, seem to indicate that this is not the rule along the Bolaños graben. In fact, the mining area is located within a broad accommodation zone that corresponds to a faulted relay ramp between two right stepping N-S trending normal faults. In this context the progression of faulting observed by Lyons [1988] may be interpreted as the progressive reorientation of secondary extensional structure during the northward propagation of the southernmost fault.

[24] We interpret the above observations in the following way. The eastern extensional domain was extended shortly after the emplacement of the 23 Ma ignimbrite succession. The extensional pulse probably start to wane during the emplacement of the shield volcano in the Tlaltenango graben (21.8 ± 1.0 Ma) and after the deposition of the Nayar ignimbrite succession (~21 Ma) in the Bolaños graben area. Alternatively, the Bolaños graben could have been involved in the younger episode of extension that affected the western domain.

3.1.2. Western Extensional Domain

[25] The region between the Bolaños graben and the coastal plain is affected by N-S to NNW trending major structures that cut the grabens of the eastern domain (Figure 2). They are the Jesus Maria half graben and its northern continuation, the San Agustín graben, the Sierra Alica, Atengo, Sierra de Pajaritos, and Puente de Camotlán half grabens. To the west of these structures lies the relatively undeformed zone of the Nayar caldera field. Farther to the west the Pochotitán and San Pedro normal fault systems bound the Gulf of California (Figures 2, 4, and 5). They obtained 40Ar/39Ar ages of 10.7 ± 0.2 and 11.0 ± 0.4 Ma for dikes with an average strike of N238°E, some of which are tilted up to 70°. At this latter location we measured 39 dikes with an average strike of N238°E, some of which are tilted up to 70° (Figure 7 and Table 2, site 2). Between Aguamilpa and Tepic (Figure 4), however, basaltic flows dated 8.93 ± 0.11 Ma at El Zopilote [Clark et al., 1981] and 11.5 ± 0.5 Ma at Aguamilpa [Ferrari et al., 2000a] (Figures 2 and 5). At this latter location we measured 39 dikes with an average strike of N238°E, some of which are tilted up to 70° (Figure 7 and Table 2, site 2). Between Aguamilpa and Tepic (Figure 4), however, basaltic flows dated 8.93 ± 0.11 Ma [Richter et al., 1995] are horizontal and cover tilted blocks of SMO ignimbrites. In Sinaloa, just to the north of our study region, Henry and Aranda-Gomez [2000] observed a similar situation. They obtained 40Ar/39Ar ages of 10.7 ± 0.2 and 11.0 ± 0.2 Ma for dikes moderately tilted and intruded in the conglomerate filling of the NNW trending half graben bounded by the Concordia fault. Accordingly with the above observations we consider that extension along this part of the eastern margin of the Gulf of California may have initiated a
few millions of years before the intrusion of the dikes and continued for 1–2 m.y. after their emplacement. A middle to late Miocene age for faulting at the southern end of the Gulf of California is also confirmed by recent thermochronologic studies on the exhumation of the Los Cabos block, which would have been located just to the west of our study region at that time [Fletcher et al., 2000]. Particularly, they indicate that fast extensional exhumation of the Los Cabos block commenced by /C2412 Ma.

3.1.3. Santa Maria del Oro-Santa Rosa Transpressional Corridor

The southernmost part of the SMO, located close to the boundary of the Jalisco block, contrasts markedly with areas to the north. Instead of extensional structures contractile deformation dominates. The most striking structures are 10 to 40 km long NNW trending open folds arranged in an en echelon pattern between Santa Maria del Oro and the Santa Rosa dam (103°44’W, 20°55’N; Figures 2 and 5) [Ferrari, 1995]. Ignimbrites involved in the folds typically dip 30°–35° with the exception of the western flank of the Sierra El Pinabete asymmetric fold (Figure 5), where strata dip up to 75°–80° on its western limb. In the field the rocks are affected by many 135° to 150° striking left-lateral oblique thrust and strike-slip faults (Figure 8). All these structures are indicative of a left-lateral transpressional shearing. A second group of folds with ~N-S trending and parallel axes lies to the WNW of the en echelon folds in the La Manga area (Figures 5 and 8). The strata are only gently tilted with dip of 5°–10°. These folds appear to be formed by low-intensity ~E-W compression on the rear of the northern part of the transpressional shear zone.

Folds and faults cut rocks as young as 19.0 ± 0.4 Ma east of Santa Maria del Oro [Damon et al., 1979] and 16.9 ± 0.5 Ma [Nieto-Obregon et al., 1985] in the Santa Rosa dam area. The folds are cut by vertical mafic dikes dated at 11.4 ± 0.3 Ma and 10.9 ± 0.2 Ma [Damon et al., 1979] (Figure 5).

The average direction of horizontal compression (σHmax) was 100° ± 26° (Table 2). However, the style of deformation varies from compression in the northwest (sites 11–13, Table 2; Figure 8) to left-lateral transpression and oblique thrusting at the center of the area (sites 14–17), to almost left-lateral transcurrent in the Santa Rosa area (site

**Figure 7.** Tectonic map and microtectonic data collected in the western extensional domain. Bold arrow indicates the inferred direction of motion of a block to the west (Los Cabos block?) needed to produce the observed faulting.
## Table 2. Kinematics of the Deformation

<table>
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<tr>
<th>Site Number and Location&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Longitude, West</th>
<th>Latitude, North</th>
<th>Lithology</th>
<th>Age of Rocks&lt;sup&gt;b&lt;/sup&gt;</th>
<th>$\sigma_1$&lt;sup&gt;c&lt;/sup&gt;</th>
<th>$\sigma_2$&lt;sup&gt;c&lt;/sup&gt;</th>
<th>$\sigma_3$&lt;sup&gt;c&lt;/sup&gt;</th>
<th>$N^d$</th>
<th>Phi&lt;sup&gt;e&lt;/sup&gt;</th>
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<tbody>
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<td>1, east of Jesus Maria</td>
<td>104°26'59&quot;</td>
<td>22°18'21&quot;</td>
<td>ignimbrite</td>
<td>23.2 Ma</td>
<td>33/81</td>
<td>129/1</td>
<td>219/9</td>
<td>19</td>
<td>0.35</td>
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<td>2, Aguamilpa Dam</td>
<td>104°45'00&quot;</td>
<td>21°51'00&quot;</td>
<td>basaltic dikes</td>
<td>11.9 Ma</td>
<td>39/72</td>
<td>147/6</td>
<td>238/16</td>
<td>39</td>
<td></td>
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<td>3, Bolaños Graben</td>
<td>103°41'51&quot;</td>
<td>21°57'28&quot;</td>
<td>ignimbrite</td>
<td>20.1 Ma</td>
<td>323/79</td>
<td>140/11</td>
<td>230/1</td>
<td>20</td>
<td>0.50</td>
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<td>21°36'39&quot;</td>
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<td>early Miocene</td>
<td>235/1</td>
<td>15</td>
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<td>5, Presa El Bañadero</td>
<td>104°41'10&quot;</td>
<td>21°30'30&quot;</td>
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<td>early Miocene</td>
<td>101/9</td>
<td>9/10</td>
<td>230/76</td>
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<td>0.75</td>
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<td>6, Paso De Lozada 1</td>
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<td>21°30'30&quot;</td>
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<td>17.2 Ma</td>
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<td>4/26</td>
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<td>230/76</td>
<td>8</td>
<td>0.75</td>
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<td>9, east Bolaños Graben</td>
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<td>various sites</td>
<td>basaltic dikes</td>
<td>early Miocene</td>
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<td>230/76</td>
<td>8</td>
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</tr>
</tbody>
</table>

### Western Domain: Extensión<sup>f</sup>

### Southern Domain: Left Lateral Transpression<sup>g</sup>

<sup>a</sup> Number of sites as in Figures 7 and 8.

<sup>b</sup> Age of rocks according to dated samples (details in the text) or to stratigraphic relations.

<sup>c</sup> Trend and plunge of stress tensor axes determined by fault slip data inversion according to the method of Angelier [1990] except at sites 2 and 9, where they are eigenvectors of pole to dikes obtained by density analysis with the program Orient [Charlesworth et al., 1988].

<sup>d</sup> Number of planes used in the computation.

<sup>e</sup> Tensor shape is $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$.

<sup>f</sup> Average direction $\sigma{H}_{max} = N55^\circ \pm 17^\circ$.

<sup>g</sup> Average direction of $\sigma{H}_{max} = N100^\circ \pm 26^\circ$. 

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18). This variety of structures is likely related to the original geometry of the boundary between the Jalisco block and the SMO, which was reactivated by WNW-ESE compression in middle Miocene time (Figure 8).

3.2. Magnitude of Extension

[31] Although the normal faults of the study region are prominent features on satellite images and aerial photos, the deformation they accommodated was modest. Nieto-Samaniego et al. [1999] estimated an 8% of stretching in a nearly E-W direction from a profile crossing the Juchipila, Tlaltenango, and Bolaños graben. In the western extensional domain the relatively steep dipping (70°–60°) of faults and modest (≤30°) tilting of blocks are also indicative of a limited amount of extension. The present detail of mapping and the lack of a clear stratigraphic marker prevent the construction of a precise retrodeformable cross section in this area. However, we have tried to give a rough estimate of the amount of extension along a profile normal to the major extensional structure, the Jesus Maria half graben, using the area balance method described by Groshong [1994] (Figure 9). In this case we have considered the top of the 23 Ma ignimbrite as the reference level prior to extension and erosion (Figure 9). Since this surface outcrops at ~2200 m elevation east of the fault system and at ~1400 m west of the deformed zone, an average height of 1800 m was chosen. We took into account different depths of detachment and chose 10 km as a realistic, though conservative, approximation. This value gives a horizontal extension of ~9% (Figure 9). In the less likely case of a shallower detachment level the extension would remain

Figure 8. Tectonic map and microtectonic data collected in the Santa Maria del Oro-Santa Rosa transpressional corridor. The geometry of the northern boundary of the Jalisco block is inferred on the basis of Ferrari et al. [2000a]. Bold arrow indicates the inferred direction of motion of the Jalisco block needed to produce the observed deformation.
relatively small: For a detachment at 5 km depth, extension would be 17%.

4. Discussion

4.1. Episodic Nature of Ignimbrite Volcanism in the SMO

Previous studies recognized that most of the silicic volcanism in the SMO occurred in early Oligocene time (32–28 Ma) throughout the province and in early Miocene time (~23 Ma) in the southern part of the province [McDowell and Keizer, 1977; McDowell and Clabaugh, 1979; Henry and Fredrikson, 1987; Wark et al., 1990; Aguirre-Díaz and McDowell, 1993; McDowell et al., 1997; Gans, 1997; Nieto-Samaniego et al., 1999]. Our new geochronologic data confirm these results but also demonstrate the regional significance of the early Miocene episode. Ignimbrites in the southwestern SMO actually cluster in the 32–28 Ma and 24–20 Ma time spans, and the latter episode covers about two thirds of the southwestern SMO. Thus our data confirm that ignimbritic volcanism in the SMO was concentrated in two pulses. The episodic nature of this volcanism can be appreciated in the probability density histogram of Figure 10, where all the available ages of silicic rocks of the southern SMO are plotted. Even so, the real size and the short duration of the two pulses of ignimbrite volcanism are not completely evident because available ages between 28 and 24 Ma often show large experimental errors and because the volume of volcanism is only loosely related with the number of available ages.

Figure 9. Interpretative cross section through the Jesus Maria half graben with estimation of minimum amount of extension using the method proposed by Groshong [1994]. The top of the 23 Ma Las Canoas ignimbrite succession was taken as reference level. Vertical exaggeration 1.65X.

4.2. Generation of Silicic Volcanism in the SMO

Voluminous episodes of silicic volcanism have been related to different causes. The most common situation is continental break-up with variable involvement of mantle plumes as in the case of the huge Whitsunday Volcanic

Figure 10. Histogram and cumulative probability curve for ages of silicic volcanic rocks in the Sierra Madre Occidental south of the Tropic of Cancer plotted constructed with Isoplot/Ex [Ludwig, 1999]. Note the marked pulse of silicic volcanism at ~23 and ~21 Ma.
Province of northeastern Australia [Bryant et al., 2000] or the Chon Aike volcanic province of Patagonia and western Antarctica [Pankhurst et al., 2000]. On the other hand, the late Miocene-Quaternary central Andean silicic province has been explained as a consequence of delamination of the lower lithosphere and, possibly, the lower crust, with subsequent rising of hotter asthenospheric mantle [Kay and Kay, 1993]. In all the above cases a rapid increase in the uppermost mantle temperature is thought to have driven extensive melting of the mantle lithosphere and partial melting of the lower crust via basaltic underplating.

[35] Isotope studies indicated contrasting scenarios for the generation of the Oligocene silicic volcanism in the SMO. On one hand, K. L. Cameron and coworkers [e.g., Cameron et al., 1980; Smith et al., 1996, and reference therein] have suggested that fractional crystallization of mafic magmas with relatively small crustal interaction generated the Oligocene ignimbrites in Chihuahua, while Ruiz et al. [1988, 1990] advocate a major involvement of the crust through anatexis. From binary mixing calculations, Verma [1984] also estimated values of involvement as high as 80% for Oligocene ignimbrites in the Zacatecas area. More recently, Albrecht and Goldstein [2000] modeled Sr, Nd, and Pb isotopic data from the central SMO in Chihuahua and obtained values of crustal involvement of up to 70%. Particularly, they propose that the silicic rocks were the result of assimilation/fractional crystallization or melting, assimilation, storage, and homogenization processes affecting first the lowermost crust and later the middle crust, as the thermal anomaly would rise into higher sections of the crust.

[36] Although no isotope and geochemical studies are available for the early Miocene ignimbrite flare-up of the southern SMO, several lines of reasoning also suggest that melting of the crust played an important role in generating this massive silicic volcanism. First, the rate of silicic magma production and emplacement in the SMO during the early Miocene episodes is very high. The two silicic successions (∼23 and ∼21 Ma) have a thickness of ∼1000 m close to the source, which gradually decreases to ∼100 m in distal areas. They form a 700 km long and 120 km wide belt from central Sinaloa to western Guanajuato (Figure 6), covering an area of ∼84,000 km². Thus, considering a mean thickness of 500 m, a volume of 42,000 km³ appears to have been emplaced in ∼2 m.y. These values approximate those of plume-related silicic large igneous provinces and suggest a similar mechanism. Second, partial melting of the crust needs much less amount of primary mafic magmas to produce a rhyolite. Several studies [Huppert and Sparks, 1988; Harry and Leeman, 1995] have shown that one volume unit of basalt may be able to produce from two thirds to one equivalent volume of rhyolite by crustal melting over timescale of 10² to 10³ years. By contrast, fractional crystallization needs much more basalt volume, takes longer time periods, and implies the formation of rocks of intermediate composition. Our study of the southern SMO shows that volcanism occurred in fast and short pulses and that rocks of intermediate composition are absent. We thus conclude that the early Miocene ignimbrite flare-up was primarily produced by a massive and fast generation of subcrustal mafic melts, which provided sufficient thermal energy to melt the crust.

4.3. Plate Tectonic Control of Ignimbrite Flare-Up

[37] The rapid generation of mafic melts in the subcrustal lithosphere over several hundreds of kilometers asks for a plate tectonic mechanism. In the western United States, the Tertiary silicic flare-up has been related to the removal of the Farallon slab from beneath the North America plate [e.g., Coney, 1978; Humphreys, 1995] as the slab, which was subhorizontal during the Laramide orogeny, progressively rolled back and founndered in the mantle, exposing the upper plate to hotter asthenospheric mantle. This mechanism may have worked as well in Mexico during the Oligocene episode of ignimbrite flare-up that was coeval over a large area from the U.S.-Mexico border to the south of the Trans-Mexican Volcanic Belt. Indeed, it could have been triggered by a relatively sudden rollback of the subducted plate [Nieto-Samaniego et al., 1999] following the slowing in the Farallon-North America relative convergence that should have occurred some millions of years before the first contact of the East Pacific Rise with the continent [Atwater, 1989].

[38] For the early Miocene episode, however, we propose that the detachment of the Farallon slab (also called “slab breakoff”) was the ultimate control over the timing and localization of silicic volcanism and extension in the southern SMO. Seismic tomography studies [Van der Lee and Nolet, 1997] have shown that the upper mantle beneath the SMO and north central Mexico is characterized by two subparallel high velocity anomalies (Figure 11). The most obvious interpretation of this double anomaly is that it represents two fragments of the subducted Farallon slab that detached at different times. Detachment of the subducted slab is well known in the Mediterranean-Carpathian region as a consequence of the arrival of the more buoyant continental crust in the subduction zone (see Wortel and Sparkman [2000] for a review). In a similar way, in western Mexico the initiation of detachment was the natural consequence of the approach of the East Pacific Rise to the paleotrench west of Baja California. The arrival of very young (<10 m.y. old) and buoyant oceanic crust in the subduction zone eventually results in the waning and cessation of subduction of the last remnant of the Farallon plate and their capture by the Pacific plate [Lonsdale, 1991]. The captured portion of the subducted slab began to move in an opposite direction (with the absolute motion of the Pacific plate), whereas the rest of the slab kept on sinking in the mantle. Therefore a tear in the subducted slab should have initiated at the time of the stalling of subduction and should have propagated laterally following the progressive termination of subduction off North America. According to the reconstruction of Atwater and Stock [1998] the first breakoff of the subducted part of the Farallon slab initiated at ∼28 Ma at the latitude of southern California, after the first interaction between the Pacific and the North America plates. At this time a trench parallel tear started to separate the short slab attached to the young Monterey and Arguello
microplates from the deeper and sinking part of the Farallon slab (Figure 12a). We propose that the tear in the subducted slab propagated laterally toward the SSE until reaching the southern SMO at the beginning of early Miocene time (Figures 12a and 13a). The seismic velocity contrast between the slab and the surrounding mantle observed in tomography studies may correspond to a temperature difference of several hundreds of degrees \[Van der Lee and Nolet, 1997; Schmid et al., 2001\]. Thermomechanical models of slab detachment also confirm that the temperature may increase over 500°C above the lithospheric gap filled with upwelling hot asthenosphere \[van de Zedde and Wortel, 2001\]. Thus the abrupt removal of the slab via its detachment may have increased the temperature at the base of the crust of an amount analogous to that of a mantle plume. Unlike a mantle plume, however, this advective-type source of heat has a transient nature and should produce only a temporal episode of melting \[van de Zedde and Wortel, 2001\], which is what we observed in the southern SMO.

**Figure 11.** Map and cross section showing the main upper mantle seismic anomaly detected by the tomographic model of \textit{Van der Lee and Nolet} [1997]. A double-high velocity anomaly corresponds broadly to the upper mantle region below the SMO in the early Miocene. Light shaded area in the cross section represents a positive anomaly exceeding \(~50\) m/s, which is interpreted as portions of subducted slabs. Bold dashed line shows a possible geometry of the slab fragments (proposed in this work). Dark shading indicates a low-velocity anomaly below \(~50\) m/s, corresponding to the shallow warm region which underlain the Gulf of California rift.

**4.4. What Caused Deformation in the Southern SMO?**

As outlined in section 3.1, two episodes of extension may be recognized in the southern SMO. The first one produced regularly spaced grabens between \(~23\) and \(~20\) Ma, whereas the second affected the western part of the study region approximately between 15 and 11 Ma. In both cases the magnitude of extension was moderate and below 10–15%. In addition, left-lateral transpression affected the...
The first episode is bracketed by the two peaks of ignimbrite flare-up at ~23 and ~21 Ma. The orientation of the grabens produced during this episode defines a sort of fan from the N15°E trend of the easternmost graben (Juchipila) to the N-S trend of the westernmost one (La Ventana graben) (Figures 2 and 14). The area affected by...
this episode has also the highest topography within the southern SMO, with elevation ranging from 2400 to 3000 m (Figures 4 and 14). Moreover, elevation contours are roughly perpendicular to the graben orientation (Figure 14). Considering these facts, we speculate that the first episode was driven by magmatic intrusion into the crust and/or removal of the mantle lithosphere. The volume of granitic magma that remains in the crust is often 4–5 times the volume of silicic rocks emplaced at surface [Crisp, 1984]. However, part of this volume was already in place since we propose that a considerable amount of the crust was melted. It is reasonable to think, therefore, that material addition due to intrusion in the crust was about equivalent to the extruded material. Recent studies [Cruden, 1998; Améglio and Vigneresse, 1999; Grocott et al., 1999] showed that granitic batholiths frequently grow by lateral intrusion at the ductile/brittle

**Figure 13.** Schematic cross section of the two slab detachment event postulated in this work that produced the early Miocene episode of ignimbrite flare up (SMO) and the late Miocene mafic volcanism at the eastern side of the Gulf of California (GCMV). Abbreviations are Farallon, Farallon plate; NOAM, North America plate; M, Magdalena microplate; BC, Baja California.
transition zone by depressing the floor and uplifting the roof. Considering this mechanism one possibility is that the regional topography of part of the southern SMO and the fanning grabens of the eastern extensional domain are related to the intrusion of a tabular granitic batholith that fed the ~23 and, particularly, the ~21 Ma ignimbrite pulses. In addition, another mechanism capable of producing the observed topography and extension is the thermal removal of the mantle lithosphere beneath the southwestern SMO. In fact the material rising at the base of the plate may have replaced the cold mantle lithosphere with hotter asthenosphere, resulting in a doming and stretching of the crust (Figure 13a). The two mechanisms, however, may have worked concurrently.

The second extensional episode overlaps in time with the last subduction of the Guadalupe and Magdalena microplates and the initial transfer of Baja California to the Pacific plate (Figure 12b). Indeed, plate tectonic reconstructions indicate that subduction of the Farallon plate ended along the southern half of Baja California at ~12.5 Ma, when the Peninsula and a short slab fragment stalled beneath it began to be captured by the Pacific plate [Atwater, 1989; Lonsdale, 1991; Atwater and Stock, 1998]. We agree with Henry and Aranda-Gomez [2000] in considering this episode of extension as a general manifestation of the "proto-Gulf extension," driven by the capture of Baja California by the Pacific plate. However, Henry and Fredrikson [1987] and the data presented in this work suggest the possibility that extension may have initiated some time before the end of spreading between the Magdalena and Pacific plates. Indeed the component of active subduction of the Magdalena microplate beneath North America in the few million years before the end of spreading was likely small or close to zero. That is because after 15 Ma the ridge started to rotate clockwise tending to be perpendicular to the absolute motion of the Pacific plate and oblique to the trench. This implies that the spreading was driven by the Pacific motion rather than by slab pull. We propose that trench-normal extension observed in the western extensional domain may have initiated in response to the waning of subduction of the Magdalena microplate in middle Miocene time that, in turn, triggered a second slab detachment event (Figures 12b and 13b). This mechanism would have produced also a partial melting of the mantle below the present Gulf of California. In this case, however, the extensional regime induced by plate boundary forces allowed rapid upraise of mafic melts (12–10 Ma mafic dikes and flows) rather than the formation of silicic crustal melts (Figure 13b).

The transpressional deformation observed at the southern boundary of the SMO has no trivial explanation. The plate configuration west of Baja California for that time is not precisely defined because the amount of right-lateral motion along the Tosco-Abreojos fault zone (Figure 12c) is uncertain [e.g., Fletcher, 2001]. However, it is reasonable to think that the middle Miocene plate boundary between the

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**Figure 14.** Topography and structures of the southern SMO. The NW trending elliptical uplift and the fanning graben broadly coincide with the early Miocene ignimbrite successions and are thought to be due to magmatic intrusion at the ductile/brittle transition in the crust.
Magdalena and Cocos plates was located in front of the part of the mouth of the Gulf [Lyle and Ness, 1991; Stock and Lee, 1994]. In this case the transpressional deformation zone would be located along the inland projection of the Magdalena-Cocos plate boundary; it also corresponds to the boundary between the SMO and the Jalisco block (Figure 12c). These observations led Ferrari [1995] to relate this event to an east-southeastward motion of the Jalisco block shortly before the end of subduction of the Magdalena microplate. In addition, we note that the magnetic anomaly pattern preserved on the western side of the East Pacific Rise indicates a progressive clockwise reorientation of the spreading ridge between the Magdalena and the Pacific plates between 14.1 and 12.9 Ma (Figure 12c). The contrast between the waning subduction of the Magdalena microplate and the steady subduction of the Cocos plate added to the small convergent direction between them at 14–12.9 Ma may have produced the left-lateral transpressional deformation observed along the inland continuation of their subducted boundary.

5. Concluding Remarks

Massive generation of silicic volcanism occurred in the southern SMO during two episodes at 31.5–28 Ma and 23.5–20 Ma. Widespread but moderate extension affected the southern SMO during two episodes at 31.5–28 Ma and 14–12.9 Ma (Figure 12c). The easternmost part of the SMO underwent left-lateral transpression roughly at 14–12.9 Ma may have produced the left-lateral transpressional deformation that may be quantified by petrologic studies. We hope that this work may stimulate further studies that may unravel the enigma of the Sierra Madre Occidental.

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