Fissure ignimbrites: Fissure-source origin for voluminous ignimbrites of the Sierra Madre Occidental and its relationship with Basin and Range faulting

Gerardo J. Aguirre-Díaz* Centro de Geociencias, Campus-Juriquilla, Universidad Nacional Autónoma de México, Querétaro, Qro. 76230, Mexico

Guillermo Labarthe-Hernández* Instituto de Geología, Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

ABSTRACT

The Sierra Madre Occidental is mostly composed of middle Tertiary large-volume ignimbrites. From the United States–Mexico border (~31°N), the Sierra Madre Occidental extends southward to its intersection with the Mexican volcanic belt (~21°N). Ignimbrites of equivalent age extend into southern Mexico as discontinuous outcrops. Considering the average thickness of 1000 m for these ignimbrites based on representative measured sections, a conservative estimate of their total volume is ~393,000 km³. Fewer than 15 calderas have been identified in this province, and the source of most of these ignimbrites has been an unsolved problem. We present geologic evidence indicating that fissures, most of them with the regional trend of Basin and Range faults, served as conduits for the ignimbrites. These fissures can be several kilometers long and are represented by pyroclastic (ignimbrite) dikes, rhyolitic lava dikes, linearly aligned lava domes, and elongated ignimbrite lithic-lag breccias adjacent to Basin and Range faults. Considering that the Basin and Range extension overlapped in time and space with the ignimbrite flare-up, we propose a model in which batholith-sized magma chambers reached shallow crustal levels and erupted their contents when they reached Basin and Range normal faults. The faults acted as vents and caused fast decompression when the system was opened, and large volumes of silicic magmas were explosively erupted. Finally, devolatilized rhyolitic magmas were emplaced as domes or dikes. We propose the term “fissure ignimbrites” for ignimbrites formed in this way.

Keywords: ignimbrite, Basin and Range, pyroclastic dikes, Sierra Madre Occidental, Mexico.

INTRODUCTION

The Sierra Madre Occidental (SMO) is the largest continuous ignimbrite province in the world (Swanson and McDowell, 1984). In order to visualize its size, consider that the Sierra Madre Occidental would cover the equivalent area of peninsular Italy (Fig. 1). The Sierra Madre Occidental is at least 1200 km long and 200–500 km wide, extending continuously from the United States–Mexico border (~31°N) to its intersection with the younger Mexican volcanic belt (~21°N) (Fig. 1). However, middle Tertiary large-volume ignimbrites continue as discontinuous outcrops into the southwestern United States, as well as into southern Mexico and eastern Chihuahua. Swanson and McDowell (1984) estimated that at least 350 calderas the size of those of the San Juan volcanic field in Colorado would have been needed to produce these ignimbrites. However, fewer than 15 calderas have been identified in the Sierra Madre Occidental by studies beginning in about 1975. The scarcity of recognized calderas in the Sierra Madre Occidental could be due to several causes, e.g., the relatively poor knowledge of this province, implying that there are more calderas to be recognized, or burial of calderas by younger ignimbrite sheets. However, along three transects that have been geologically mapped in the Sierra Madre Occidental—in the north, Chihuahua to Hermosillo; in the center, Durango to Mazatlán; and in the south, Zacatecas to Tepic (Fig. 1)—and elsewhere throughout the Sierra Madre Occidental (see references in Table DR1), calderas are not evident for most ignimbrites.

We present evidence of ignimbrites related to fissures, most of them with the regional northwest to northeast trend of the Basin and Range faults, which served as conduits for the eruption of large-volume ignimbrites. We conclude that fissure-type eruptions served as an alternative, if not the most important, source for the ignimbrites of the Sierra Madre Occidental, which we term “fissure ignimbrites.”

LARGE VOLUME OF THE SIERRA MADRE OCCIDENTAL IGNIMBRITES

The area covered by the Sierra Madre Occidental proper, i.e., the largest continuous ignimbrite outcrop shown in Figure 1, is ~393,000 km² (Sierra Madre Occidental main in Table 1). On the basis of several studies in the sierra (Table DR1; see footnote 1), the thickness of the ignimbrite package averages 1000 m. Therefore, a conservative estimate of the volume of the Sierra Madre Occidental ignimbrites is ~393,000 km³. However, if we include other areas in Mexico with middle Tertiary ignimbrites, such as outcrops of eastern Chihuahua or those to the south of the Mexican volcanic belt, the volume estimate increases to 587,000 km³ (Table 1). By comparing this volume with that of the well-known middle Tertiary ignimbrites of the San Juan Mountains of Colorado (~20,000 km³; Lipman et al., 1970) and following the proportional approach of Swanson and McDowell (1984), we can deduce that the number of calderas responsible for the Sierra Madre Occidental ignimbrites should be 334 if we only consider the main area (Table 1). Even if we assume that the thickness of the main ignimbrite package is <1 km, e.g., 0.75 km (as occurs in the more eroded margins of the sierra), the number of calderas required is still 250 for the main area. Assuming common San Juan volcanic field caldera sizes (20–30 km) and a 1000 km³ ignimbrite for each caldera, the number of calderas required would be ~393. Either the conservative 250 or the larger 393, the number of calderas needed is impressive, especially considering that, at most, 15 calderas have been recognized, some of which are still questionable. Therefore, at least 235 calderas have not yet been found; but 235 large calderas would be difficult to not see, either in satellite images or in the mapped transects across the Sierra Madre Occidental. Do all these calderas really exist?

SOUTHERN BASIN AND RANGE AND THE IGNIMBRITE FLARE-UP

The southern part of the Basin and Range province is in Mexico (Henry and Aranda-Gómez, 1992), and Basin and Range faulting af

*E-mail: Aguirre-Díaz-ger@geociencias.unam.mx; Labarthe-Hernández-labarthe@uslp.mx.

© 2003 Geological Society of America. For permission to copy, contact Copyright Permissions, GSA, or editing@geosociety.org.

Geology; September 2003; v. 31; no. 9; p. 773–776; 3 figures; 1 table; Data Repository item 2003112.
Ignimbrite activity can be as old as 51 Ma (Aguirre-Dáaz and Mc- Dowell, 1993; Aranda-Gómez et al., 2000), with both limits probably occurring between at least 32 Ma and 12 Ma (Aguirre-Dáaz and McDowell, 1991, 1993; Aranda-Gómez et al., 2000), and the ignimbrite activity apparently migrated from the northeast to the southwest, i.e., from central Chihuahua (38–27 Ma) to Durango-Tayolita-Nazas (32–29 Ma) to Zacatecas-Tepic (24–23 Ma), finishing by 16 Ma at Jalisco-Nayarit, as deduced from the compilation of geologic works listed in Table DR1 (see footnote 1). It is unknown yet whether there was a southward migration of Basin and Range faulting and if the ignimbrite flare-up occurred episodically as peaks (38–27 Ma, 32–29 Ma, and 24–23 Ma) or was continuous. Nevertheless, by the time that the ignimbrite flare-up started, the Basin and Range extension was already active in Mexico. Therefore, it can be concluded that the emplacement of the Sierra Madre Occidental ignimbrites and the Basin and Range extensional regime coincided in time and space, and this coincidence occurred in different times and different places throughout the Sierra Madre Occidental volcanic province.

LARGE-VOLUME FISSURE-FED IGNIMBRITES OF THE SIERRA MADRE OCCIDENTAL

Field evidence in the Sierra Madre Occidental indicates that many large-volume ignimbrites were derived from linear fissures rather than from typical circular or oval calderas. These include (1) large pyroclastic (ignimbrite or tuff) dikes, (2) coignimbrite lithic-lag breccias (CILBs) next to large faults or grabens, (3) aligned postignimbrite rhyolitic domes and lava dikes following a fault trend, and (4) absence of calderas. We provide a few examples of these types of evidence in the following sections.

Pyroclastic Dike

Pyroclastic (ignimbrite) dikes have been observed in several places in the Sierra Madre Occidental, particularly in the southern part, which is the best studied by us. Two cases are presented as examples, the 50-m-wide dike that crops out along the western shoulder of the Juchipila graben (Fig. 1), and the dikes found along the Juachin fault next to San Luis Potosí (Fig. 1).

1. The dike at Juchipila is composite and includes four ignimbrites (1800 m deep, 20–25 km wide, and 150 km long) (Fig. 1). Basin and Range faulting occurred between at least 32 Ma and 12 Ma (Aguirre-Dáaz and McDowell, 1993; Aranda-Gómez et al., 2000), with both limits probably extending until the Eocene and the Quaternary (Aranda-Gómez et al., 1981), but most of the ignimbrite volume was erupted in the 38–28 Ma period (McDowell et al., 1990; Aguirre-Dáaz and McDowell, 1991; Table DR-1 [see footnote 1], which has been referred to as the “ignimbrite flare-up” (McDowell et al., 1990; Aguirre-Dáaz and McDowell, 1991). However, intense ignimbrite activity is evident until 23 Ma in the south-central and southwestern portions of the Sierra Madre Oc- cidental (e.g., Scheubell et al., 1988; Table DR-1 [see footnote 1]), which can be interpreted as the continuation to the southwest of the ignimbrite flare-up. Thus, the ignimbrite flare-up can be defined as a period of intense explosive volcanic activity that produced enormous volumes of silicic ignimbrite sheets, which took place mainly between 38 and 23 Ma in Mexico. The ignimbrite flare-up coincided in time with peaks in Basin and Range faulting (Aguirre-Dáaz and McDowell, 1991, 1993; Aranda-Gómez et al., 2000), and the ignimbrite activity apparently migrated from the northeast to the southwest, i.e., from central Chihuahua (38–27 Ma) to Durango-Tayolita-Nazas (32–29 Ma) to Zacatecas-Tepic (24–23 Ma), finishing by 16 Ma at Jalisco-Nayarit, as deduced from the compilation of geologic works listed in Table DR1 (see footnote 1). It is unknown yet whether there was a southward migration of Basin and Range faulting and if the ignimbrite flare-up occurred episodically as peaks (38–27 Ma, 32–29 Ma, and 24–23 Ma) or was continuous. Nevertheless, by the time that the ignimbrite flare-up started, the Basin and Range extension was already active in Mexico. Therefore, it can be concluded that the emplacement of the Sierra Madre Occidental ignimbrites and the Basin and Range extensional regime coincided in time and space, and this coincidence occurred in different times and different places throughout the Sierra Madre Occidental volcanic province.

Pyroclastic Dike

Pyroclastic (ignimbrite) dikes have been observed in several places in the Sierra Madre Occidental, particularly in the southern part, which is the best studied by us. Two cases are presented as examples, the 50-m-wide dike that crops out along the western shoulder of the Juchipila graben (Fig. 1), and the dikes found along the Juachin fault next to San Luis Potosí (Fig. 1).

1. The dike at Juchipila is composite and includes four ignimbrites (Fig. 2), each with distinct welding characteristics and crystal-lithic-pumice (fiamme) contents. The dike was emplaced along a major normal fault that formed the Juchipila graben, a north-northeast–trending, 110-km-long, 15–20-km-wide structure. Fiamme and cooling joints are aligned subvertically with about the same dip as that of the dike. The ignimbrites of the dike show shearing and cooking along their margins (Fig. 2). The ignimbrites cooked both the wall rock and the earlier-emplaced ignimbrite dikes. Shearing was formed mainly during ignimbrite’s intrusion, but postemplacement fault-related shearing also took place as the ignimbrite’s intrusion, but postemplacement fault-related shearing also took place.

<table>
<thead>
<tr>
<th>Province</th>
<th>Area  (km²)</th>
<th>Thickness (km)</th>
<th>Volume (km³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sierra Madre Occidental main</td>
<td>392,775</td>
<td>1 km</td>
<td>392,775</td>
</tr>
<tr>
<td>Eastern Chihuahua</td>
<td>66,583</td>
<td>1 km</td>
<td>66,583</td>
</tr>
<tr>
<td>Sonora</td>
<td>7982</td>
<td>1 km</td>
<td>7982</td>
</tr>
<tr>
<td>South of Mexican volcanic belt</td>
<td>35,287</td>
<td>1 km</td>
<td>35,287</td>
</tr>
<tr>
<td>Baja California</td>
<td>38,421</td>
<td>1 km</td>
<td>38,421</td>
</tr>
<tr>
<td>Infraed beneath the Mexican volcanic belt</td>
<td>32,136</td>
<td>1 km</td>
<td>32,136</td>
</tr>
<tr>
<td>Total</td>
<td>586,727</td>
<td></td>
<td>586,727</td>
</tr>
<tr>
<td>Total of San Juan Mountains*</td>
<td></td>
<td></td>
<td>20,000</td>
</tr>
</tbody>
</table>

Note: volume is approximated and related to 17 calderas.
*Data from Lipman et al. (1970).
place. Each ignimbrite of the dike corresponds to a flat-lying ignimbrite outside the graben. The dike can be followed as discontinuous outcrops for at least 25 km. At places along the dike trend, a lithic-rich ignimbrite constitutes the dike, which changes laterally to a CILB. Webber et al. (1994) reported two calderas within the Juchipila graben, but although we looked for them, we did not find any evidence for caldera structures.

2. The pyroclastic dikes at the Juachin fault (Fig. DR-1; [see footnote 1]) occur as small boudins along the northwest-trending normal fault zone of Juachin. The width of the boudins varies from 1 to 8 m; they are composed of a highly sheared pumiceous ignimbrite. Adjacent to the dikes consisting of the boudins and following the northwest trend of the Juachin fault zone is a major CILB that gradually changes laterally to a large-volume ignimbrite sheet, the 27 Ma Panalillo Tuff, which covers a widespread area of the San Luis Potosí volcanic field (Labarthe-Hernández et al., 1982). We have found pyroclastic dikes, some as wide as 100 m, at several other places in the Sierra Madre Occidental, generally next to large Basin and Range faults and grabens; e.g., at the Calvillo, Colotlán, and Atengo grabens (Fig. 1).

Coignimbrite Lithic-Lag Breccia

CILBs are the second-best indicators (after the pyroclastic dikes) of the location of the fissure-type vents of ignimbrites. In addition to the CILB examples next to the pyroclastic dikes at Juchipila and at the Juachin fault just described, at the Bolaños graben there is an excellent example for a vent location based on CILB. The Alacran ignimbrite (Scheubel et al., 1988), dated as 23 Ma, is a voluminous unit to 400 m thick in the proximal facies. It is well exposed at both sides of the north-trending graben. The CILB of the Alacran ignimbrite is found along the graben’s shoulders; i.e., both the Alacran ignimbrite and its corresponding CILB crop out to the west and to the east of the 25-km-wide graben. The CILB gradually changes to an ignimbrite poorer in lithic fragments with distance from the graben’s shoulders. Just beneath the Alacran ignimbrite’s CILB there is an associated layered pyroclastic sequence. This sequence is mostly composed of surge beds and minor ignimbrites. Within the surge deposits, and 4–5 km from the actual graben scarps, ballistic blocks, to 40 cm in diameter, produced impact-sag deformations indicating their provenance from the Bolaños graben. These ballistic blocks also occur on both sides of the graben.

Aligned Rhyolite Domes and Dike

At several places in the Sierra Madre Occidental, rhyolitic lava domes are aligned with the same northwest to northeast trends as the regional Basin and Range normal faults. In some areas, such as at the Bolaños and Atengo grabens and the Juachin fault, it is clear that the lava domes were emplaced just after the large-volume fissure-fed ignimbrites and that they occur close or next to the coarser parts of the CILBs that crop out next to normal faults. At the Atengo graben (Fig. 1), a 12-m-wide rhyolitic dike connects with high-standing rhyolitic lava domes. Both dike and domes are aligned with the north trend of the tectonic depression. In some other places, such as in San Luis Potosí, it is possible to see rhyolite dikes interconnecting aligned lava domes or lava domes with shapes of boudins aligned with regional normal faults of the Basin and Range, indicating strong structural control for the emplacement of the rhyolitic magmas. The lava domes and dikes are here interpreted as the devolatilized magma that erupted after the climactic explosive events that produced the major ignimbrites, as occurs in classic caldera cycles with the rim lava domes (Smith and Bailey, 1968), but in this case the domes were emplaced along Basin and Range faults.

MODEL

Figure 3 schematically depicts a model that summarizes our field observations for large-volume fissure-fed ignimbrites of the Sierra Madre Occidental and their relationship with the regional extensional regime of the Basin and Range province in Mexico.

In order to account for the large volume of ignimbrites in the Sierra Madre Occidental and considering the long grabens or fault zones to which they are related, a large magma chamber complex must be inferred. Thus, in our model we propose an elongated magma chamber or series of magma chambers with batholith-sized dimensions. Late Cretaceous–early Cenozoic representatives of these batholiths related to the lower volcano-plutonic complex are now exposed at the western margin of the Sierra Madre Occidental, e.g., the plutonic rocks in Sinaloa (Henry and Fredrikson, 1987) or at the more eroded northwest part of the Sierra Madre Occidental in Sonora (McDowell et al., 2001). These large magma chambers reached shallow crustal levels mainly because of the extensional regime of the Basin and Range in which they were emplaced; reaching the high crustal level caused magmas to become volatile rich by exsolution of gas bubbles due to decompression. Either because the roof of the chamber reached Basin and Range normal faults, or because the faults formed during a peak in intensity of extension and affected the magma chamber’s roof, the system was
A similar mechanism of fissure-vent ignimbrite emplacement was mentioned by Lipman (1997), who referred to the result as “volcanotectonic depressions,” and by Scheubel et al. (1988), who interpreted the ignimbrites of the Bolaños graben to have erupted through the graben’s faults. Our model for fissure ignimbrites is similar to those proposed for calderas; the main differences are the batholithic size of the magma chamber(s) to account for the impressively large volume of the ignimbrite package of the Sierra Madre Occidental and the fissure-type vent (represented by the pyroclastic or rhyolite lava dikes) and/or vents (represented by the domes) aligned along a normal fault instead of forming an arcuate structure. We do not contend that all ignimbrites in the Sierra Madre Occidental were formed in this way. It is well established that calderas were the sources of several ignimbrites, but we think that the dominant volume of the Sierra Madre Occidental ignimbrites was erupted from fissure-type vents related to Basin and Range faulting episodes.

ACKNOWLEDGMENTS
We are grateful to Grupo México and the personnel in the Bolaños mine project and to Minera El Pitón of San Martín de Bolaños for logistical help. The manuscript was improved by reviews of Jim Luhr and Joann Stock. We thank Jorge Nieto-Obregón, Ramón Torres, and Margarito Tristán for their assistance during field seasons. Financial support was obtained from Universidad Nacional Autonóma de México grants IN-120999 and IN-115302 and Consejo Nacional de Ciencia y Tecnología grant 33084-T to Aguirre-Díaz.

REFERENCES CITED

Manuscript received 19 March 2003
Revised manuscript received 29 May 2003
Manuscript accepted 30 May 2003

Printed in USA

GEOLOGY, September 2003