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COMMON CHARACTERISTICS OF PAIRED VOLCANOES IN NORTHERN CENTRAL AMERICA

Sid P. Halsor and William I. Rose

Department of Geology and Geological Engineering, Michigan Technological University, Houghton

Abstract. Four pairs of active volcanoes along the northern Central American volcanic front have erupted basalt-andesite magmas that show consistent intrapair behavioral and compositional differences. These differences are found in records of volcanic activity and complete major and minor element data on over 200 samples. From northwest to southeast along the volcanic front the four volcano pairs are Cerro Quemado-Santa Maria, Tolimán-Atitlán, Acatenango-Fuego, and Santa Ana-Izalco. The volcano pair relations help explain compositional differences, apart from those reflecting variation in crustal thickness of about 15 km along the volcanic front, providing insight into across-arc variations and closely spaced subvolcanic plumbing systems. Intrapair volcano spacing is less than 5 km compared with an average intervolcano spacing of 25 km along the entire volcanic front. Within each volcano pair, the seaward volcano has had more frequent historic activity, erupting magmas that are generally more mafic, lower in large ion lithophile elements and higher in Na2O/K2O than magmas erupted from its landward counterpart. Each paired volcano site lies in close proximity to a rhyolitic caldera, situated north or northeast of the volcano pair. However, rare earth element data at the Tolimán-Atitlán volcano pair imply that mixing between caldera rhyolite and the mafic magma of the paired volcanoes does not occur. Petrographic, isotopic, and other geochemical data from the Tolimán-Atitlán volcano pair suggest that separate but contemporaneous magma bodies beneath each volcano evolve and pass through the crust at different rates. Atitlán magmas are processed through the crust more efficiently and with greater frequency than Tolimán magmas, which undergo longer periods of stagnation interrupted by mafic injection and rapid eruption. This relation appears to hold at the other paired volcano sites and is further evidence that closely spaced volcanoes, with similar subcrustal magma sources, evolve over separate magmatic plumbing systems that traverse the crust. The pairing pattern probably reflects the regional southward migration of the volcanic front.

Introduction

Spatial patterns of volcanoes provide a context to study chemical evolution of volcanic arcs. Compositional variation in rocks contemporaneously erupted along arcs records the regional effects of changing physical parameters (crustal thickness, segmentation of subducted slab, volcano spacing, and volcano size) at a given moment in time [Carr, 1984]. Compositional variation in rocks erupted across arcs may partly monitor changes in volcanic systems with time. Some of the important across-arc variations summarized by Gill [1981] are (1) increasing K2O and other incompatible element abundances away from the oceanic trench; (2) increasing silica range of rocks containing olivine, hornblende, and biotite phenocrysts away from the volcanic front; and (3) in some cases a decrease in 87Sr/86Sr and 206Pb/204Pb away from the plate boundary. Increasing water and alkali content and differing source regions and extent of contamination in magmas away from the trench are often called upon to explain these across-arc variations [Sakuyama, 1977; Gill, 1981; Morrice and Gill, 1986].

This comparative study examines the eruptive histories and geochemical similarities among four pairs of active volcanoes, each pair situated across the northern Central American volcanic front. The geochemical data base consists of over 200 whole rock major and trace element analyses. (The data base used in this study is a subset of a larger Central American data file compiled by Carr and Rose [1987] called CENTAM.) Carr [1984; Carr et al., 1987] has shown that crustal thinning and segmentation influence some regional physical and chemical variations in Central America. A southeastward 15-km thinning of the crust occurs along the 250-km portion of the volcanic front that includes the pairs. Three of the volcano pairs are in Guatemala, from west to east: Cerro Quemado-Santa Maria, Tolimán-Atitlán, Acatenango-Fuego, and the fourth pair, Santa Ana-Izalco, is in western El Salvador (Figure 1). Intrapair volcano spacing is less than 5 km at all sites. Each volcano pair is also spatially associated with a silicic volcano center (Table 1). An aerial view of two of the Guatemalan volcano pairs is shown in Figure 2. The comparison of paired volcanoes was stimulated by detailed petrographic and geochemical examinations of the Tolimán-Atitlán lavas, providing an extensive data base which so far exists only for that pair.

Age Relationships

All the paired volcanoes are probably less than 100,000 years old. The ages of some
volcanoes have been estimated by various methods. An age of 30,000 years is estimated for Santa Maria based on systematic variations in the magnetic declination of lavas [Rose et al., 1977; Rose, 1987]. No age information is available for the Cerro Quemado dome complex, though its morphology and erosion suggest that the early stage of dome growth preceded the emergence of Santa Maria. Tolimán and Atitlán volcanoes have a probable maximum age of 84,000 years based on the extrapolated position of underlying Los Chocoyos ash [Rose et al., 1980]. Cone growth at these two volcanoes has largely overlapped, although only Atitlán has had historic activity. Extrapolation of historic eruption rates at Fuego suggests a minimum age of 17,000 years [Chesner and Rose, 1984]. The age of Acatenango is unknown. Cross-cutting structural relationships between Santa Ana and Coatepeque calderas suggest that Santa Ana is much older than the 10,000-year-old caldera [Carr and Pontier, 1981]. The first eruption of Izalco occurred in 1770 [Carr and Pontier, 1981], making this cone clearly the youngest vent of all the paired volcanoes. The behavior of these volcanoes seems to be related to their age, with centers evolving from frequently active basaltic vents to sporadically or rarely active, but potentially more explosive, dacitic centers. Our estimates of the relative age and behavioral maturity of landward and seaward volcanoes are given in Table 2.

**Historic Activity**

Changes in the focus of activity among across-arc volcano pairs are more systematic than volcano activity patterns parallel to the volcanic front. Records of historic activity [Simkin et al., 1981] show that at each volcano pair the seaward volcano has had more frequent historic activity (Figure 3). This is consistent with observations first made by Dollfus and de Montserrat [1868]. This implies migration of the volcanic front in a seaward direction. Figure 3 does not distinguish between styles of activity in which there are some important differences among the younger seaward volcanoes. For instance, the more mature seaward volcano, Santa Maria, underwent a major plinian eruption in 1902, followed in 1922 by continuous dome-building eruptions which have continued to the present. This style contrasts sharply with

<table>
<thead>
<tr>
<th>Pair No.</th>
<th>Landward Vent</th>
<th>Seaward Vent</th>
<th>Associated Silicic Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cerro Quemado</td>
<td>Santa Maria</td>
<td>Almolonga volcano</td>
</tr>
<tr>
<td></td>
<td>[Johns, 1975]</td>
<td>[Rose et al., 1977;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rose, 1987]</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Tolimán</td>
<td>Atitlán</td>
<td>Atitlán caldera</td>
</tr>
<tr>
<td></td>
<td>[Rose et al., 1980;</td>
<td>[Rose et al., 1980;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Penfield et al., 1986]</td>
<td>Penfield et al., 1986</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Acatenango</td>
<td>Fuego</td>
<td>Baharona caldera</td>
</tr>
<tr>
<td></td>
<td>[Chesner and Rose, 1984]</td>
<td>[Martin and Rose, 1981;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Chesner and Rose, 1984</td>
<td>[Bornhorst and Rose, 1982]</td>
</tr>
<tr>
<td>4</td>
<td>Santa Ana</td>
<td>Izalco</td>
<td>Coatepeque caldera</td>
</tr>
</tbody>
</table>
the nearly continuous Strombolian activity at Izalco, a seaward volcano in a more immature evolutionary stage (see Table 2).

Compositional Range

Within each pair, the seaward volcano erupts a predominance of basalt or basaltic andesite which contrasts with a broader compositional range and predominance of more evolved rocks from its landward counterpart (Figure 4). The bimodal distribution of rocks erupted at Santa María is anomalous and reflects the more mature behavioral state of that center. Tolimán-Atitlán and Santa

Fig. 2. View looking east of two volcano pairs in Guatemala.

Fig. 3. Frequency of historic activity at volcano pairs (stippled bars represent landward volcano; solid bars, seaward volcano).

Fig. 4. Comparison of SiO₂ ranges in rocks recently erupted from paired volcanoes (dashed line represents landward volcano; solid line, seaward volcano).
TABLE 2. Descriptive Features and Relative Ages (Based on Behavioral Maturity) of Landward and Seaward Volcanoes

<table>
<thead>
<tr>
<th>Description</th>
<th>Volume, km³</th>
<th>Recent Rock Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Landward volcanoes (in order of increasing behavioral maturity)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acatenango large, rarely active stratovolcano</td>
<td>70</td>
<td>andesite</td>
</tr>
<tr>
<td>Tolimán large, rarely active stratovolcano</td>
<td>60</td>
<td>andesite</td>
</tr>
<tr>
<td>Santa Ana large stratovolcano, deep crater</td>
<td>165</td>
<td>andesite</td>
</tr>
<tr>
<td>Cerro Quemado dome complex on ring of older cone</td>
<td>7</td>
<td>dacite</td>
</tr>
<tr>
<td><strong>Seaward volcanoes (in order of increasing behavioral maturity)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Izalco small, continually active cone</td>
<td>&lt;5</td>
<td>basalt</td>
</tr>
<tr>
<td>Fuego large, frequently active stratovolcano</td>
<td>40</td>
<td>basalt</td>
</tr>
<tr>
<td>Atitlán large, sporadically active stratovolcano</td>
<td>50</td>
<td>andesite</td>
</tr>
<tr>
<td>Santa Maria large stratovolcano, dome-building stage</td>
<td>20</td>
<td>dacite</td>
</tr>
</tbody>
</table>

Fig. 5. Variation diagrams for volcanic rocks of paired volcanoes (open squares represent landward volcanoes; asterisks, seaward volcanoes).
Halsor and Rose: Volcano Pairs in Central America

Large Ion Lithophile Element Abundances

Potash enrichments at landward volcanoes are mirrored by elevated large ion lithophile (LIL) element abundances. Rubidium and barium abundances normalized to 55% SiO₂ for each volcano are higher at landward volcanoes, with Rb showing greater intrapair differences (Figure 6). Ba and Rb vary sympathetically among seaward volcanoes but not at landward vents. Carr et al. [1987] report a poorly understood positive correlation of incompatible elements with volume among Central American volcanic centers. This relationship is evident at any given volcano pair (except perhaps at Cerro Quemado-Santa Ana) where the volume and LIL element contents are higher at the landward volcano. However, there is no clear relationship between volume and LIL elements (and behavioral maturity) in comparing only landward volcanoes or only seaward volcanoes. For instance, Izalco is clearly at an immature behavioral stage and has a very small volume, but it has Rb contents higher than two other southern volcanoes (Table 2, Figure 6).

Fig. 6. Comparison of LIL element abundances among volcano pairs.

Ana-Izalco pairs show similar compositional ranges even though their southern volcanoes differ in behavioral maturity. Although Izalco is the youngest seaward volcano, Fuego has erupted the least evolved basaltic compositions.

Variation Diagrams

Other consistent intrapair geochemical differences can be seen in elemental variation diagrams. Seaward volcanoes show higher Na₂O/K₂O ratios and flatter slopes on K₂O versus MgO plots (Figure 5). Sodium enrichment with increasing crustal thickness is part of a regional northwesterly trend present along the Central American volcanic front [Carr et al., 1979; Carr, 1984]. Rose [1987] has shown that in andesites from several volcanoes in the vicinity of Santa Maria, where crustal thickness approaches a regional maximum (~45 km), Na enrichment is a very erratic localized phenomenon. Regionally, K₂O correlates positively with the volumes of volcanoes [Carr, 1984]. This is consistent among volcano pairs where greater volumes and potash contents are associated with landward volcanoes.

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identical isotopic signatures and these data produce inconclusive results, REE patterns show that andesites cannot be simple two-component mixtures of high-alumina basalt and Atitlán rhyolite (Figure 11).

Tolimán andesites probably preserve their high degree of disequilibrium by rapid eruption following internal mixing in a graded magma chamber [McBirney, 1980]. Mixing in the chamber might be induced by an injection of hot mafic magma which subsequently causes the chamber to erupt poorly mixed, nonequilibrated intermediate lavas. This hypothesis is consistent with the observed petrographic relations: forsteritic olivines, calcium-enriched plagioclase rims, reversely zoned pyroxenes from a basaltic end-member, and orthopyroxene, quartz, and hornblende from a silicic end-member. Because basaltic andesites of Atitlán contain equilibrated olivines, augite phenocrysts with normal and reverse zoning, mildly bimodal plagioclase rim compositions, and lack
orthopyroxene, quartz, and hornblende, they may represent more thorough mixtures of basalt and intermediate andesitic magmas (Figure 12). The behavioral patterns at Atitlán and Tolimán volcanoes are linked to the differences in the nature of their open-system magma bodies. The magma chamber beneath Atitlán may undergo rapid recharge, causing frequent eruptions of completely mixed magma. Frequent eruptions impede the development of a silicic cap. The magma chamber beneath Tolimán endures longer static evolution with infrequent mafic injections quickly followed by eruptions.

**Magma Reservoir Piracy**

Carr [1984] and a series of other workers [Chesner and Rose, 1984; Grant et al., 1984; Rose, 1987; Halsor et al., 1985] have shown that magma and crustal densities together with volcanic edifice heights imply that Central American volcanoes have been supplied by magma accumulated at the base of the crust. The sizes of magma reservoirs are proportional to edifice volumes. Rose [1987] has estimated the deep-level magma body beneath Santa María to have had a size of at least 30-40 km$^3$. Because Santa Maria has one of the smaller edifice volumes, its magma reservoir volume can be viewed as generally small when compared with the size of reservoirs underlying the other paired volcanoes. The envisioned dimensions of deep-level magma reservoirs, then, is greater than intrapair volcano spacing (less than 5 km). This means

![Fig. 9b. Most forsteritic olivine compositions versus whole rock Mg#. The equilibrium curve assumes $K_D = 0.3$, where $K_D = (\text{FeO}/\text{MgO})_{\text{ol}}/(\text{FeO}/\text{MgO})_{\text{liq}}$.](image)

![Fig. 10a. Frequency distribution of compositions of two types of plagioclase phenocrysts: type 1 generally have clear interiors, normal $>$ reverse zoning, and type 2 possess dusty or cellular morphology, reverse $>$ normal zoning.](image)

![Fig. 10b. Diagram showing the relative proportions of normal and reverse zoning in augite phenocrysts.](image)

![Fig. 10c. Phenocryst mineralogy versus SiO$_2$ (plagioclase and cpx are omitted but occur throughout the compositional range at each volcano).](image)
Conclusions

The aim of this study is to call attention to volcano pairing. Several aspects of pairing of volcanoes in Central America appear to be present in parts of other volcanic arcs: Colima and Nevado de Colima volcanoes in the Mexican volcanic belt, San Pedro and San Pablo volcanoes in the central Andes (J. Luhr, personal communication, 1987), and across-chain volcanoes of the Mariana arc (P. Fryer, personal communication, 1987). We encourage consideration of this concept in other areas.

Conclusions from this study are as follows.

1.) Across-arc paired volcanoes occur in several places in northern Central America.

2.) Intrapair volcanoes overlie separate plumbing systems fed by common parental magmas.

3.) Landward volcanoes erupt poorly mixed andesite, possibly triggered by influx of mafic basalt.

4.) Seaward volcanoes erupt more frequently and tend to produce well-mixed basaltic andesite.

5.) Southward migration of the volcanic front is a probable cause of pairing and preserves the spacing of centers.

6.) Magma reservoir piracy occurs when a seaward volcano emerges and slowly defuses magmatic activity from the landward volcano.
Fig. 13. Block diagram illustrating principal features of a transverse break in Central America [Carr et al., 1982]. Note that the position of volcanic front segments is controlled by the intersection of lithosphere and asthenosphere with the underthrust slab. One possible way to develop volcano pairing in a trenchward direction is to increase the subduction angle of the underthrust slab.

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References


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