5-10-1988

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Recommended Citation

Halsort, S. P., & Rose, W. I. (1988). Common characteristics of paired volcanoes in northern Central America. *Journal of Geophysical Research, 93*(B5), 4467-4476. http://dx.doi.org/10.1029/JB093iB05p04467
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JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 93, NO. B5, PAGES 4467-4476, MAY 10, 1988

COMMON CHARACTERISTICS OF PAIRED VOLCANOES IN NORTHERN CENTRAL AMERICA

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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 María, 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. Intravolcano pair 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 Na_2O/K_2O 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 K_2O 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 $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ 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 amoung 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 María, 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

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Paper number 7B7075.
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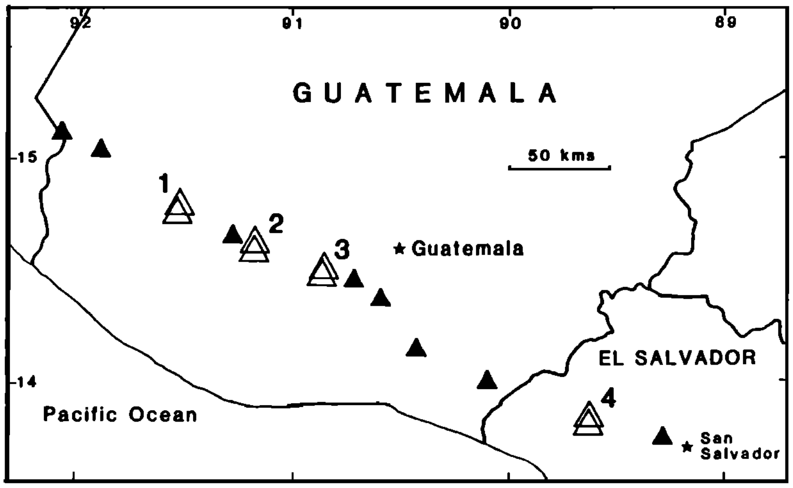

Fig. 1. Map of southern Guatemala and western El Salvador showing the locations of active paired volcanoes. Volcano pairs are numbered 1 to 4 (volcano names are listed in Table 1). Solid triangles are nonpaired active volcanoes.

volcanoes have been estimated by various methods. An age of 30,000 years is estimated for Santa María 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 María. 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 caldera 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 acativity [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 María, 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 1. Principal References of Paired Volcanoes and Associated Silicic Centers

Pair No.	Landward Vent	Seaward Vent	Associated Silicic Center
1	Cerro Quemado [Johns,1975]	Santa María [Rose et al.,1977; Rose,1987]	Almolonga volcano [Johns,1975]
2	Tolimán [Rose et al.,1980; Penfield et al.,1986]	Atitlán [Rose et al.,1980; Penfield et al.,1986]	Atitlán caldera [Rose et al.,1987; Newhall, 1987]
3	Acatenango [Chesner and Rose,1984]	Fuego [Martin and Rose,1981; Chesner and Rose,1984]	Baharona caldera [Bornhorst and Rose,1982]
4	Santa Ana [Carr and Pontier,1981]	Izalco [Carr and Pontier,1981]	Coatepeque caldera [Meyer,1964]

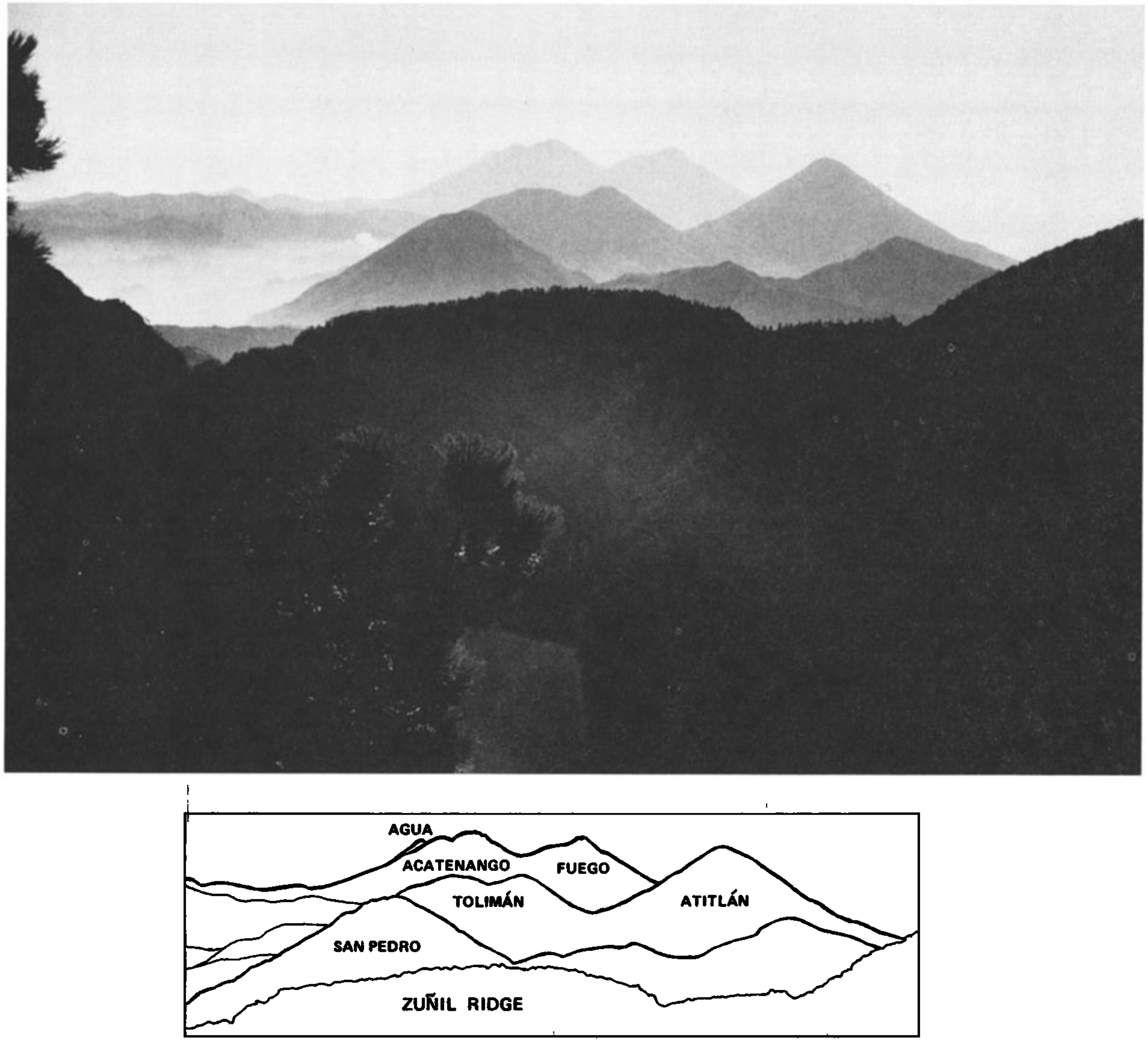

Fig. 2. View looking east of two volcano pairs in Guatemala.

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

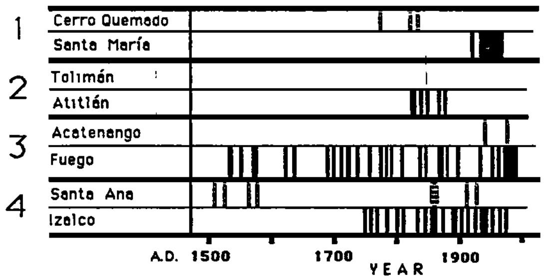

Fig. 3. Frequency of historic activity at volcano pairs (stippled bars represent landward volcano; solid bars, seaward volcano).

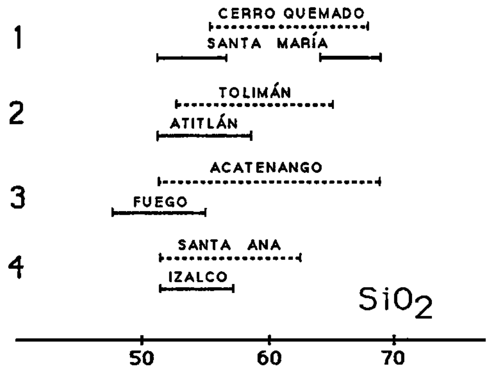

Fig. 4. Comparison of SiO_2 ranges in rocks recently erupted from paired volcanoes (dashed line represents landward volcano; solid line, seaward volcano).

TABLE 2. Descriptive Features and Relative Ages (Based on Behavioral Maturity) of Landward and Seaward Volcanoes

	Description	Volume, km^3	Recent Rock Type
Landward volcanoes (in order of increasing behavioral maturity)			
Acatenango	large, rarely active stratovolcano	70	andesite
Tolimán	large, rarely active stratovolcano	60	andesite
Santa Ana	large stratovolcano, deep crater	165	andesite
Cerro Quemado	dome complex on ring of older cone	?	dacite
Seaward volcanoes (in order of increasing behavioral maturity)			
Izalco	small, continually active cone	<5	basalt
Fuego	large, frequently active stratovolcano	40	basalt
Atitlán	large, sporadically active stratovolcano	50	andesite
Santa María	large strataovolcano, dome-building stage	20	dacite

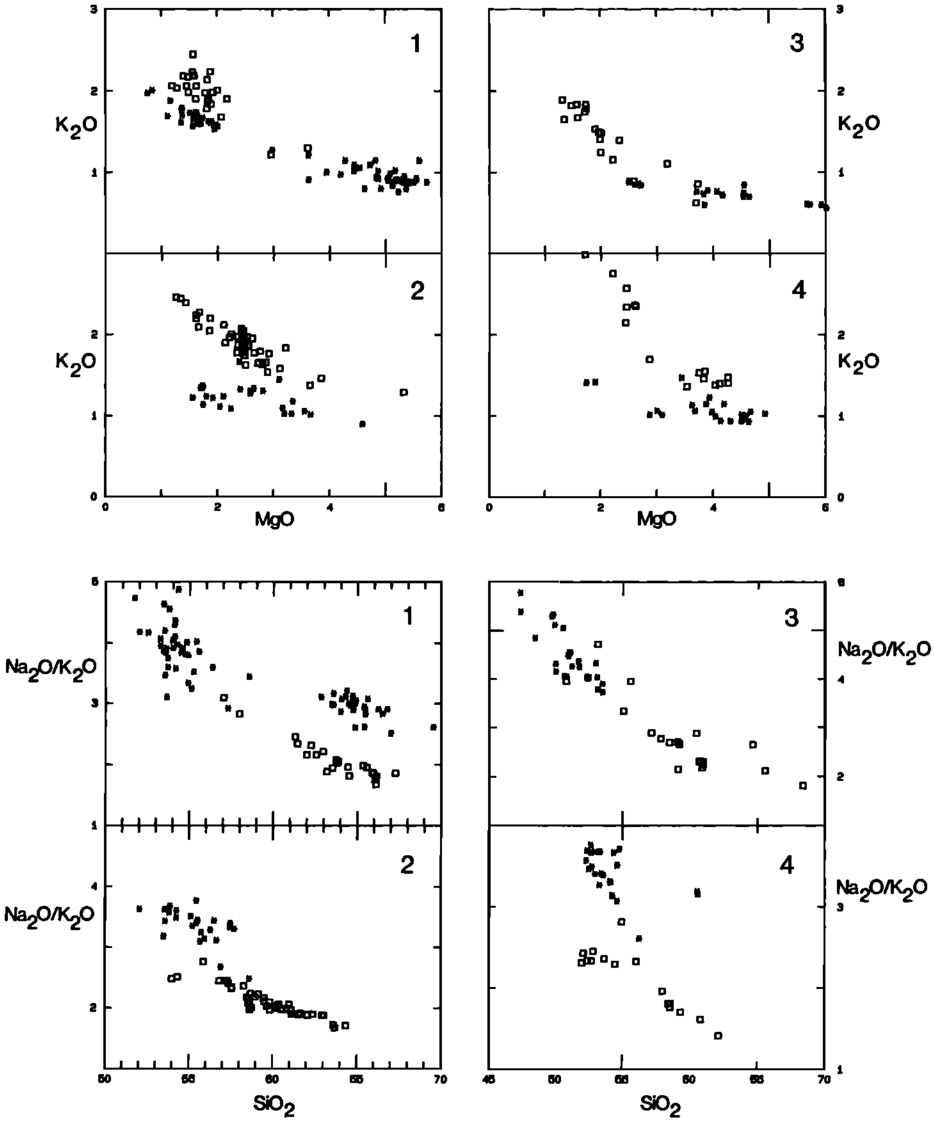

Fig. 5. Variation diagrams for volcanic rocks of paired volcanoes (open squares represent landward volcanoes; asterisks, seaward volcanoes).

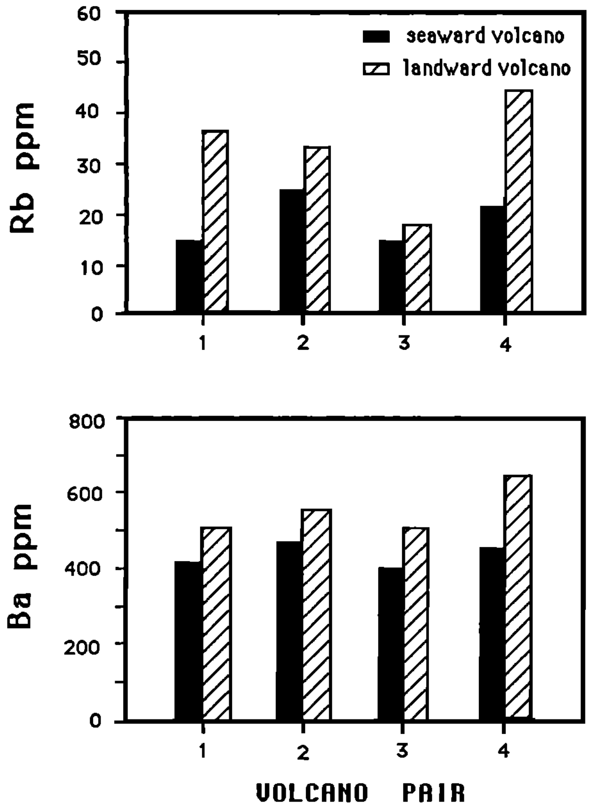

Fig. 6. Comparison of LIL element abundances among volcano pairs.

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 Na_2O/K_2O ratios and flatter slopes on K_2O 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 María, where crustal thickness approaches a regional maximum (~45 km), Na enrichment is a very erratic localized phenomenon. Regionally, K_2O 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.

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% SiO_2 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).

Tolimán-Atitlán

Petrographic and geochemical differences observed at Atitlán and Tolimán volcanoes (Figure 7) offer insight into the causes of intrapair compositional and behavioral variation.

Like other landward volcanoes, Tolimán erupts more silicic products than its seaward neighbor (Figure 4); however, at a given SiO_2 value, Tolimán rocks possess more magnesium than Atitlán rocks (Figure 8). This is contrary to compositional variation produced by simple liquid line of descent of common parental magma. The presence of forsteritic olivine showing disequilibrium texture (Figure 9) reflects the high-magnesium bulk composition and nonequilibrated nature of Tolimán silicic andesites.

Tolimán rocks have much more conspicuous evidence of disequilibrium than do Atitlán specimens. Tolimán samples show stronger bimodality in plagioclase composition, more prevalent reverse zoning in pyroxene phenocrysts, and a persistent nonreaction relationship between orthopyroxene and olivine (Figure 10). Some of these disequilibrium features are observed at other landward volcanoes, such as Cerro Quemado [Johns, 1975] and Santa Ana [Carr and Pontier, 1981]. Several Tolimán andesites also contain embayed or reaction-rimmed quartz xenocrysts and large, silicic glass inclusions in some sodic plagioclase phenocrysts.

The above-mentioned disequilibrium features are evidence for magma mixing and have been cited with growing frequency at other andesite localities [Anderson, 1976; Eichelberger, 1978; Luhr and Carmichael, 1980; Gerlach and Grove, 1982; Sakuyama, 1981, 1984; Koyaguchi, 1986]. At Tolimán, the common coexistence of orthopyroxene, quartz, hornblende, and silicic glasses included in sodic plagioclase points to a silica-rich end-member (dacite-rhyolite) mixing with a basaltic end-member containing forsteritic olivine and clinopyroxene. Because of the close spatial and temporal relationahip between Tolimán volcano and the Atitlán caldera, strontium isotope and rare earth element (REE) analyses were made on andesites from the volcano and rhyolites from the caldera to test whether andesites are basalt-rhyolite mixing products. Although andesite and rhyolite have nearly

Fig. 7. View looking southwest at Tolimán-Atitlán volcano pair. Tolimán is the foreground volcano.

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

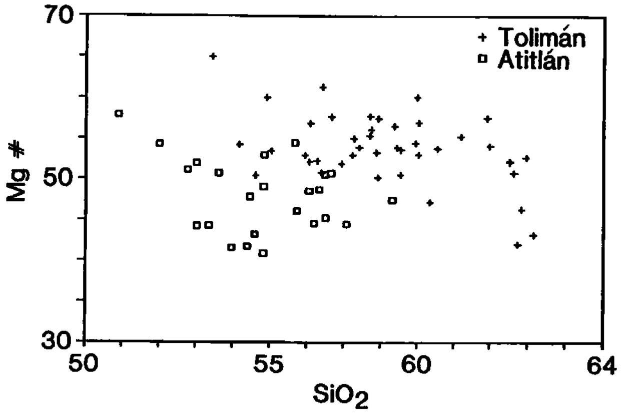

Fig. 8. Variation in Mg# (100[Mg/Mg+Fe^{2+}]) of Tolimán and Atitlán rocks.

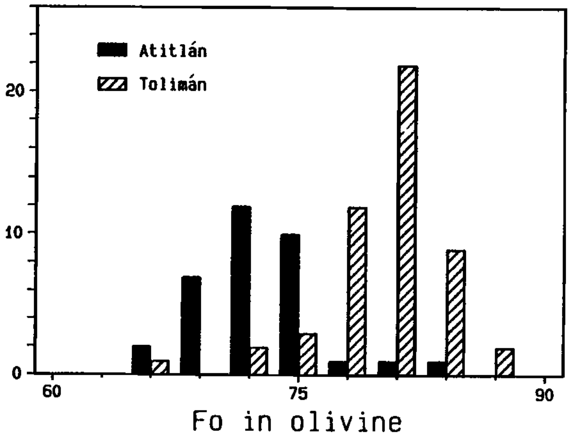

Fig. 9a. Frequency distribution of forsterite component (Fo = atomic % Mg) in Tolimán and Atitlán olivines.

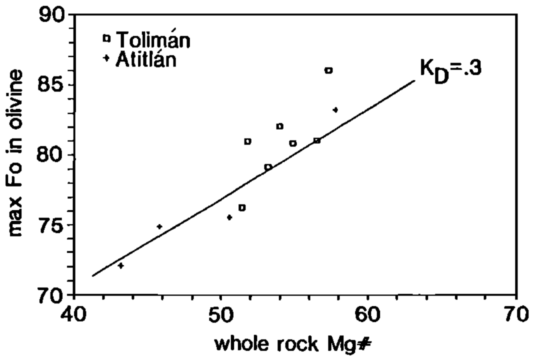

Fig. 9b. Most forsteritic olivine compositions versus whole rock Mg#. The equilibrium curve assumes $K_D = 0.3$, where $K_D = (FeO/MgO)_{ol}/(FeO/MgO)_{liq}$.

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 supplid 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 María 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

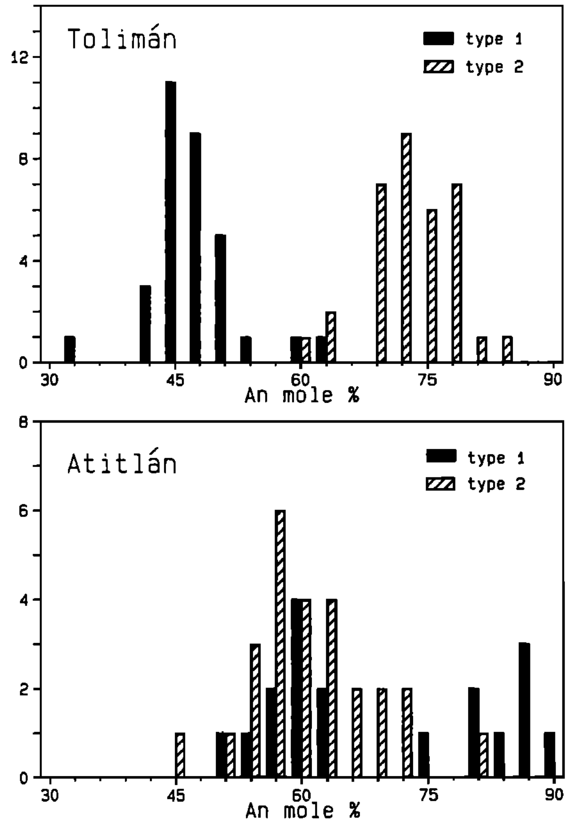

Fig. 10a.

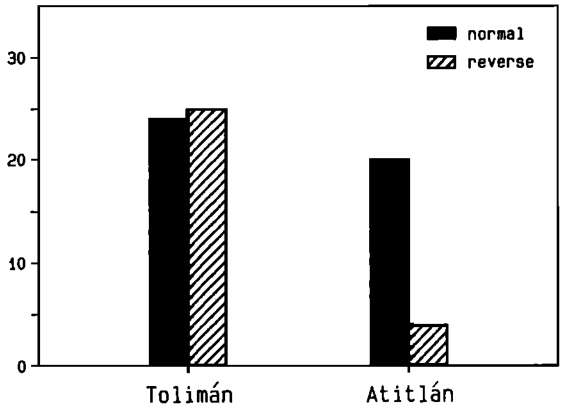

Fig. 10b.

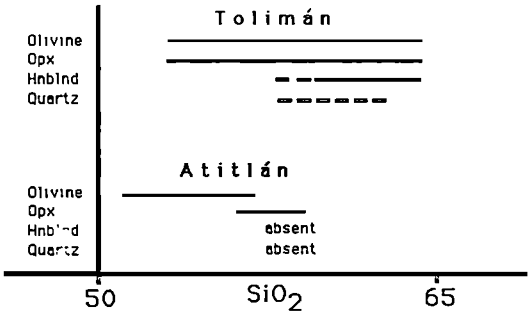

Fig. 10c.

Fig. 10. Petrographic differences observed in Tolimán and Atitlán rocks. (a) 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. (b) Diagram showing the relative proportions of normal and reverse zoning in augite phenocrysts. (c) Phenocryst mineralogy versus SiO_2 (plagioclase and cpx are omitted but occur throughout the compositional range at each volcano).

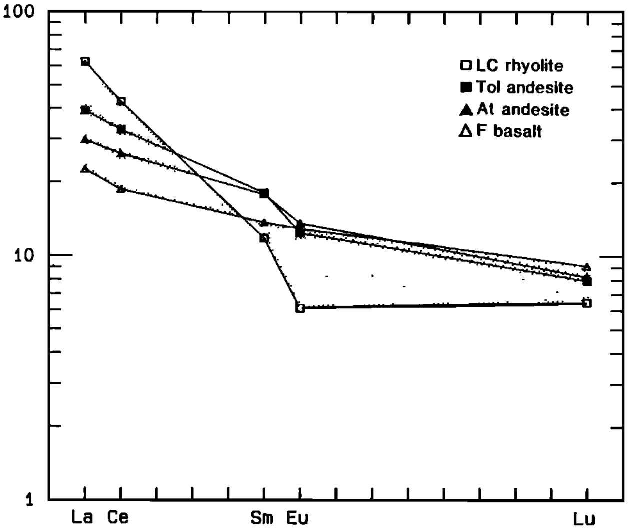

Fig. 11. Average chondrite normalized REE abundances in Tolimán (Tol, n=10) and Atitlán (At, n=6) andesites. The stippled field is bracketed by Fuego high alumina basalt (F basalt, n=31) and Los Chocoyos rhyolite (LC rhyolite, n=15).

that parental magmas rising beneath volcano pairs could originate from the same magma reservoir, and implies that their magmas develop compositional differences as they traverse the crust along different routes.

We propose that the reason the southern volcanoes are younger and have experienced more frequent historic activity is due to southward migration of magma reservoirs near the base of the crust. Carr et al. [1982] have shown that offsets and changes in strike of volcanic lineaments along the Central American volcanic front are due to transverse breaks that segment the plate margin (Figure 13). This concept suggests that melting occurs at a common depth on each segment. Segments with steeper dipping underthrust slabs have volcanoes that lie nearer to the trench. If the dip continues to increase, the magma reservoir at the base of the crust will move oceanward (southwest) as the focus of melting moves "updip" near the slab. Steepening of the slab and southward migration of the reservoirs might be caused by a decrease in the convergence rate between the Cocos and the overriding Caribbean plates. Admittedly, this is only one speculative explanation, and various geometric mechanisms exist to shift relative plate positions.

The shift in focus of activity from the landward to seaward volcano in each pair is not abrupt but gradual, such that both volcanoes may experience activity in the same interval of time. Izalco, the youngest southern volcano, has dominated the site of activity since its emergence; still, Santa Ana has had several historic eruptions. The same observations seem to apply for Fuego and Acatenango. At a more mature volcano pair, Tolimán and Atitlán, active periods have largely overlapped, although Atitlán has been more active in the last several centuries [Rose et al., 1980]. These intrapair eruptive relationships suggest that the seaward volcano tends to defuse magmatic activity slowly from the landward volcano. Furthermore, we believe the time at which the seaward volcano emerges is critical to the evolving activity at the landward volcano. Rose [1987] has outlined a three-phase history of activity at Santa María: a long period of growth of the composite cone, a dramatic plinian eruption, and a period of dome extrusion. It is possible that the large-scale plinian eruption requires an evolutionary period lasting centuries and regular supply of magma from depth. We suggest that other landward volcanoes have not had large plinian eruptions because the "defusing" effect, or shift in focus of activity to the seaward volcano, inhibits supply of magma from depth. Santa María may not have evolved to a plinian eruption stage if a new vent had emerged to the south of it. The defusing effect of the "magma reservoir piracy" concept suggests that it is unlikely the landward volcanoes Tolimán, Acatenango, and Santa Ana will produce plinian eruptions. It also suggests that nonpaired volcanoes in the same area, like Agua, are potential sites for major explosive activity.

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.

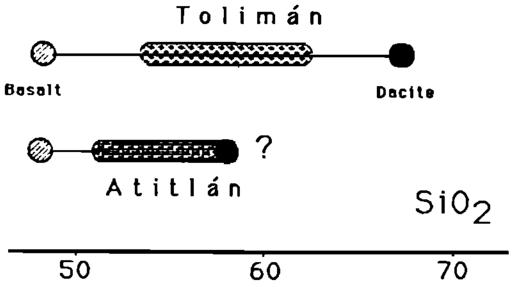

Fig. 12. Compositional range relationship between end-members and mixed Tolimán and Atitlán andesites.

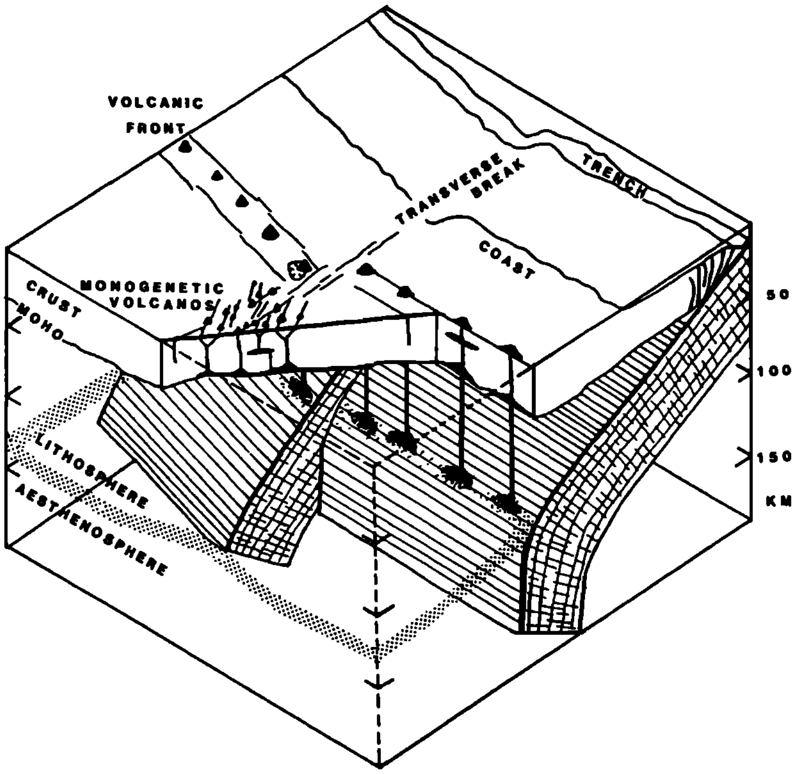

Fig. 13. Block diagram illustrating principal features of a transverse break in Central America [Carr et al., 1982]. Note that the position of volcanic front segments is controlled by the intersection of lithosphere and asthenosphere with the underthrust slab. One possible way to develop volcano pairing in a trenchward direction is to increase the subduction angle of the underthrust slab.

Acknowledgments. Financial support for this work came from the National Science Foundation through grant EAR 82-05606, the Smithsonian Institution, and Michigan Technological University. Michael Carr, Alexander McBirney, and an anonymous reviewer helped us improve the text.

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(Received May 14, 1987;
revised September 21, 1987;
accepted October 20, 1987.)