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.

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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
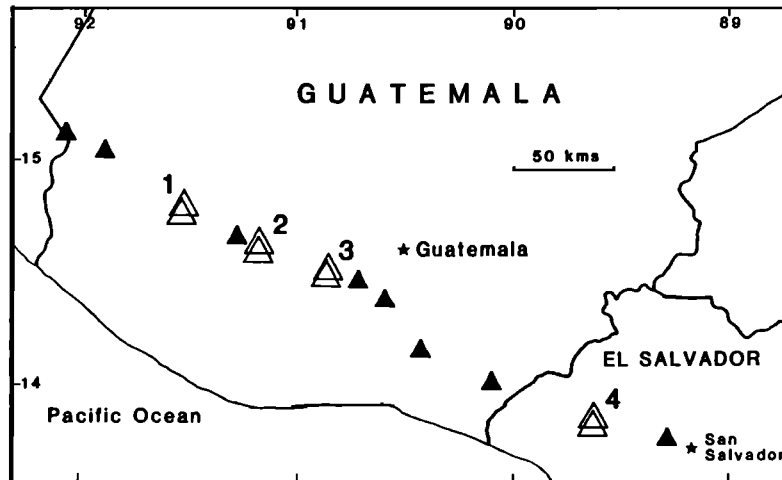than 100,000 years old. The ages of some

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

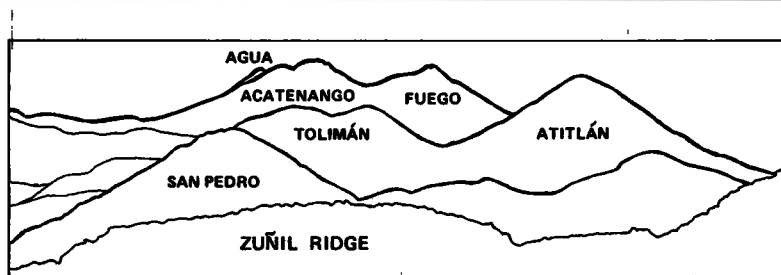| Pair No.	Landward Vent	Seaward Vent	Associated Silicic Center
1	Cerro Quemado [Johns,1975]	Santa María [Rose et al.,1977; Rose,1987]	Almolonga volcano [Johns,1975]
2	Tolimán [Rose et al.,1980; Penfield et al.,1986]	Atitlán [Rose et al.,1980; Penfield et al.,1986]	Atitlán caldera [Rose et al.,1987; 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
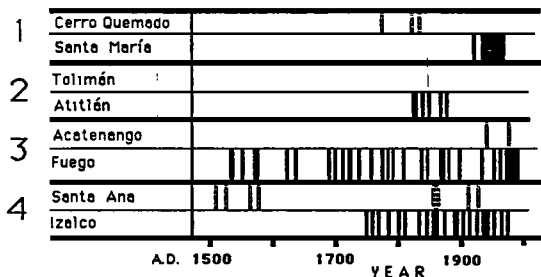

Fig. 3. Frequency of historic activity at volcano pairs (stippled bars represent landward volcano; solid bars, seaward volcano).
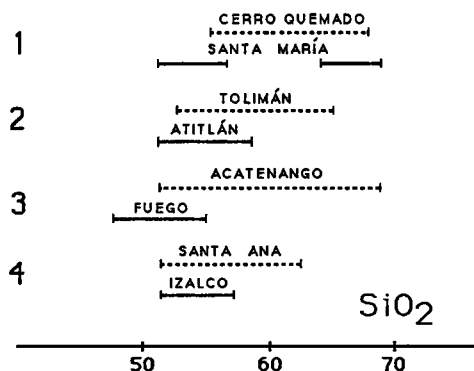

Fig. 4. Comparison of SiO_2 ranges in rocks recently erupted from paired volcanoes (dashed line represents landward volcano; solid line, seaward volcano).

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

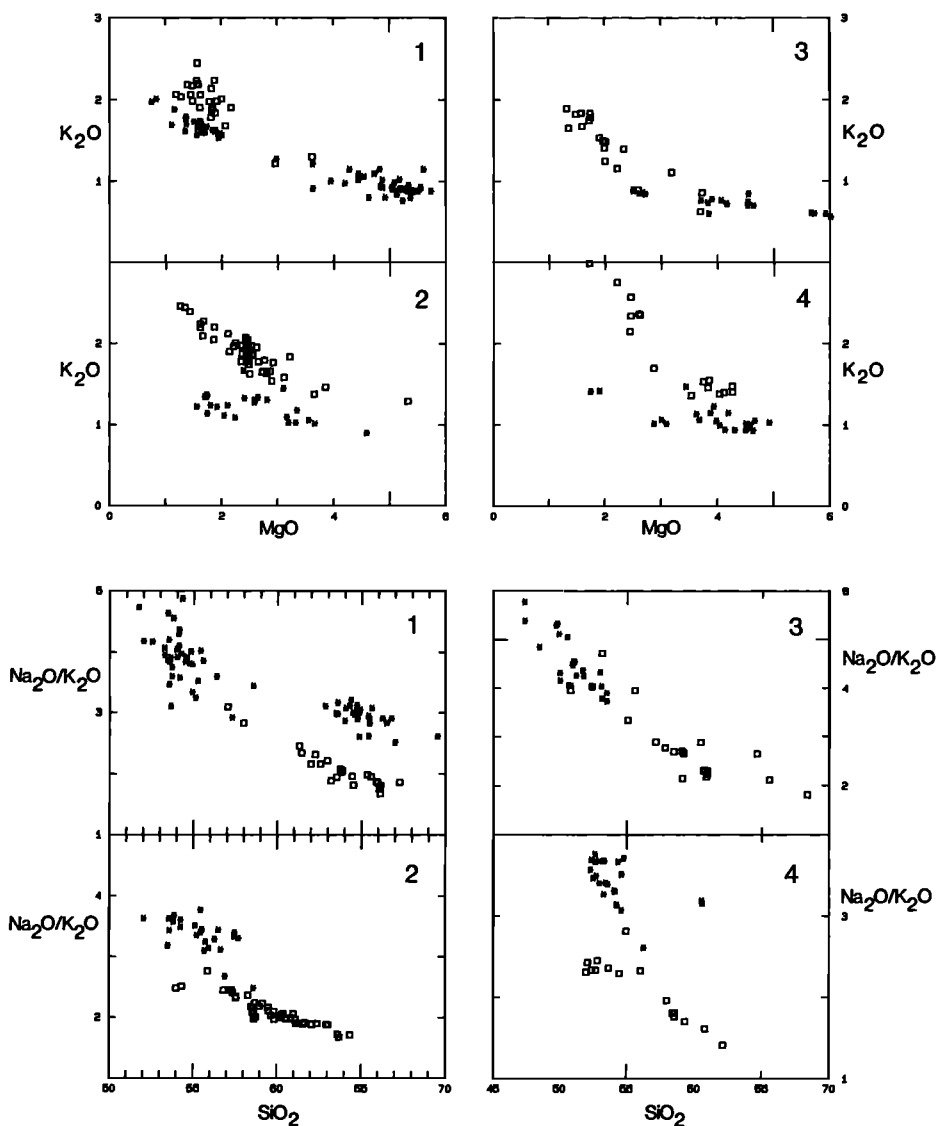|	Description	Volume, km^3	Recent Rock Type
Landward volcanoes (in order of increasing behavioral maturity)			
Acatenango	large, rarely active stratovolcano	70	andesite
Tolimán	large, rarely active stratovolcano	60	andesite
Santa Ana	large stratovolcano, deep crater	165	andesite
Cerro Quemado	dome complex 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).
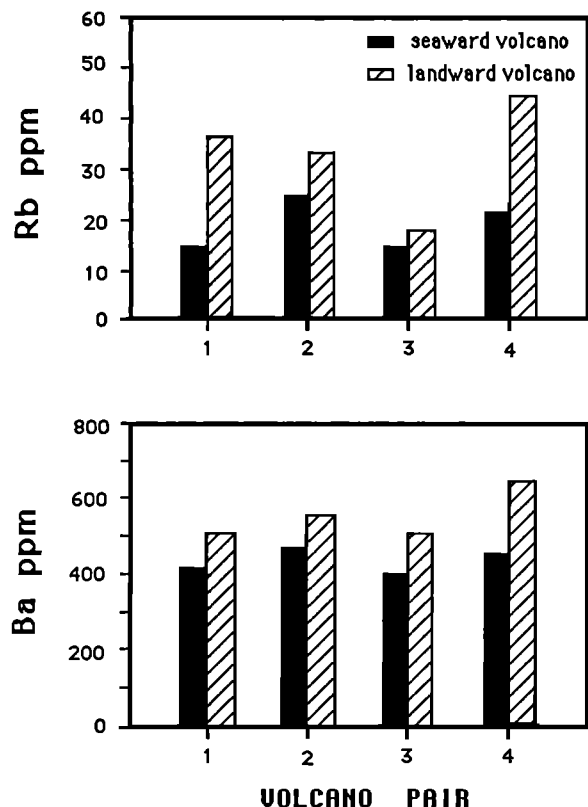
Fig. 6. Comparison of LIL element abundances
among volcano pairs.

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
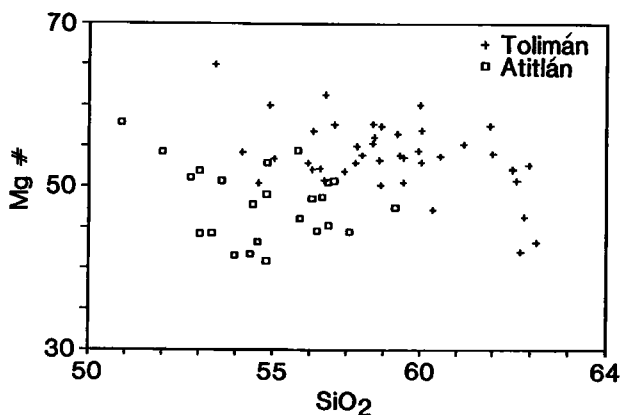

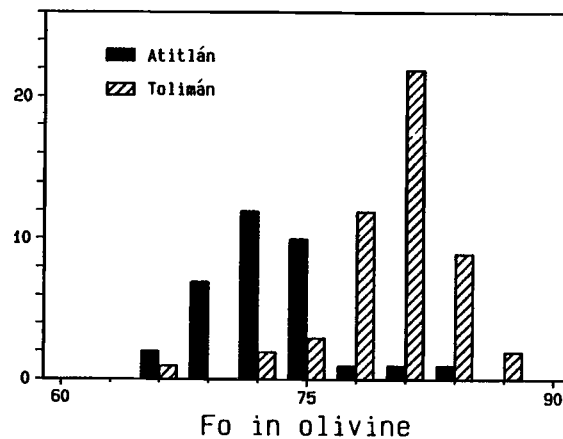Fig. 8. Variation in Mg# ($100[Mg/Mg+Fe^{2+}]$) of Tolimán and Atitlán rocks.

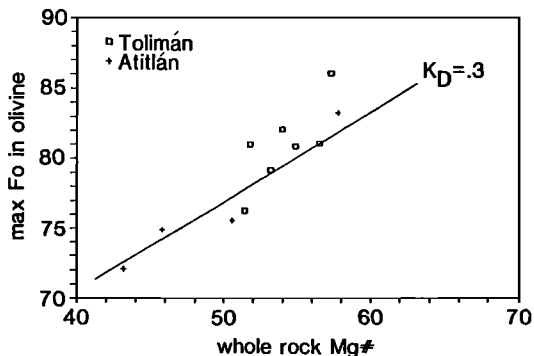Fig. 9a. Frequency distribution of forsterite component (Fo = atomic % Mg) in Tolimán and Atitlán olivines.

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
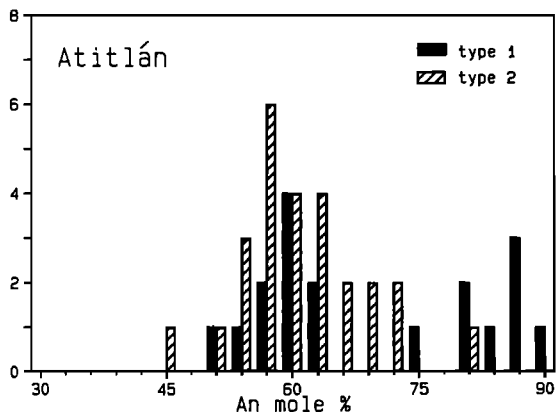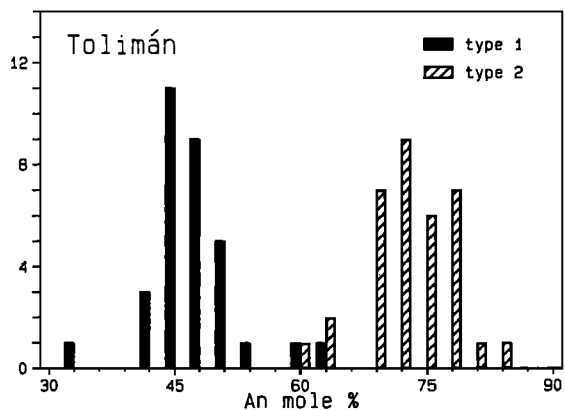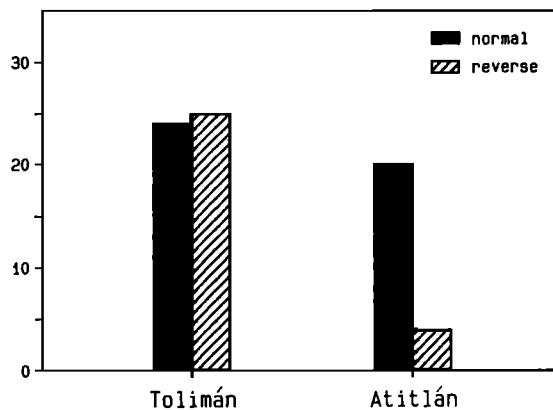volcano spacing (less than 5 km). This means
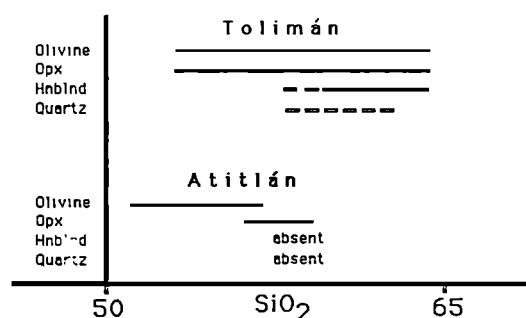

Fig. 10a.

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
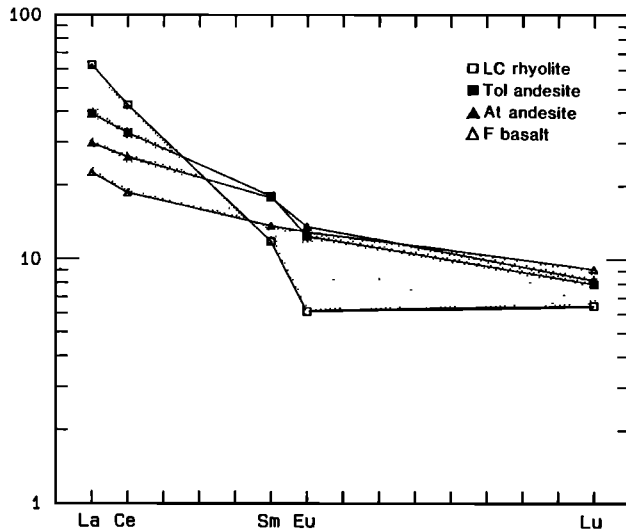compositional range at each volcano).

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.
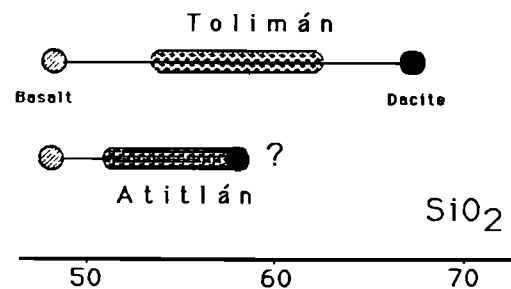

Fig. 12. Compositional range relationship between end-members and mixed Tolimán and Atitlán andesites.
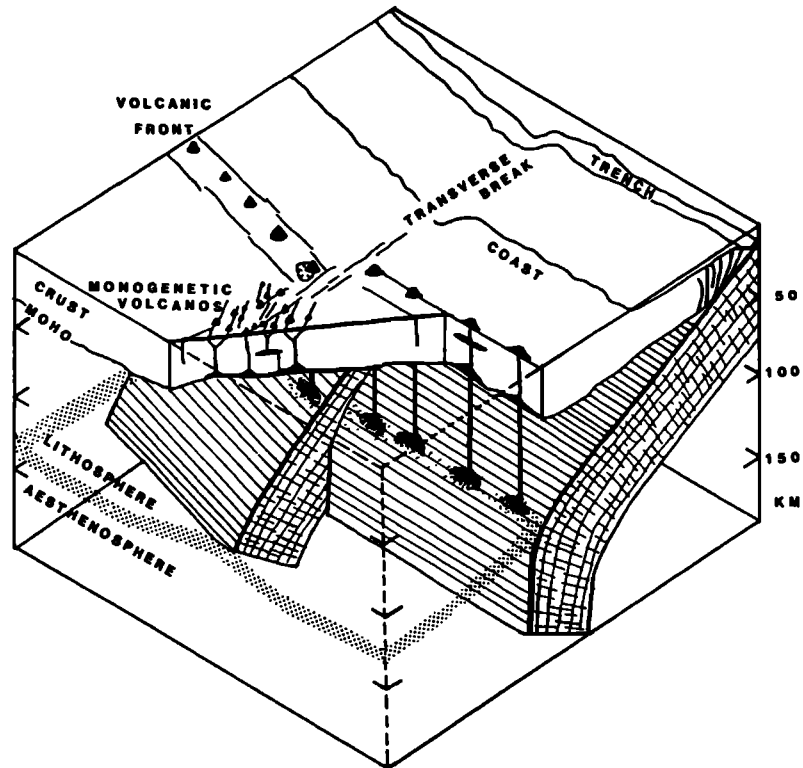
Fig. 13.   Block diagram illustrating principal features of a transverse break in Central America [Carr et al., 1982]. Note that the position of volcanic front segments is controlled by the intersection of lithosphere and asthenosphere with the underthrust slab. One possible way to develop volcano pairing in a trenchward direction is to increase the subduction angle of the underthrust slab.

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