Prolonged history of silicic peralkaline volcanism in the eastern Pacific Ocean

Wendy A. Bohrson,1,2 Mary R. Reid,1 Anita L. Grunder,3 Matthew T. Heizler,1,4 T. Mark Harrison,1 and Jeffrey Lee5

Abstract. Socorro Island, Mexico, is an alkaline and peralkaline volcanic island located in the eastern Pacific Ocean on a mid-ocean ridge spreading center that was abandoned at ~3.5 Ma. Silicic peralkaline rocks comprise up to 80% of the surface of the island, rendering Socorro virtually unique in the Pacific Ocean. Precise, replicate 40Ar/39Ar ages of 21 peralkaline trachytes and rhyolites reveal a history of episodic volcanic activity from ~540 to 370 ka that may have culminated with caldera formation; repose periods between these episodes may have had maximum duration of ~30 kyr. After up to 200 kyr of quiescence, 40Ar/39Ar ages indicate that postcaldera silicic peralkaline activity commenced by 180 ka, forming the Cerro Evermann Formation. Postcaldera mafic alkaline lavas of the Lomas Coloradas Formation erupted dominantly between 70 and 150 ka based upon relative age relations. The dominant lithology of precaldera and syncaldera silicic peralkaline deposits on Socorro is nonfragmental and nonvesicular and lacks lithic fragments and fiamme; despite this, numerous lines of evidence including welding zonation, presence of a proximal ignimbrite or co-ignimbrite deposit, association with a caldera, and compositional heterogeneity within eruptive units suggest that they are dominantly ash flow tuffs. A change in eruptive style, from predominantly explosive to predominantly effusive, followed caldera formation and suggests that a change in the efficacy of magma degassing may be linked to caldera formation. On the basis of the presence of a caldera, the magma chamber associated with Socorro Island is shallow and probably resides within the upper oceanic crust or the edifice. This together with a prolonged history of silicic magmatism indicates that intrusion of mafic magma maintained thermal viability of the magmatic plumbing system. The minimum calculated growth rate for the entire volcanic edifice (7×10^-4 km^3/yr) exceeds those of nonhotspot off-axis volcanoes in the Pacific by almost an order of magnitude. Eruption rates for subaerial phases on Socorro may be several orders of magnitude smaller than this growth rate and are comparable to subaerial eruption rates of isolated ocean islands related to mantle plumes.

Introduction

The northern Mathematicians Ridge (inset, Figure 1) marks the location of a mid-ocean ridge spreading center that was abandoned at ~3.5 Ma when activity shifted to the East Pacific Rise [Mannering et al., 1988]. At the northern terminus of the ridge, Socorro and three other alkaline volcanic islands (San Benedicto, Clarion, and Roca Partida) comprise the Revillagigedo archipelago; except for Roca Partida, the islands have volumes in the upper 1-2% of Pacific seamounts and islands on Oligocene age oceanic crust [Batić, 1982]. Together with numerous seamounts in the mathematicians Ridge [Batić and Vanko, 1985], the Revillagigedo archipelago represents postabandonment alkaline magmatism. Volcanic activity in this region has continued to the present as demonstrated by a submarine basalt eruption ~3 km west of Socorro Island in January 1993 [McClelland et al., 1993; Siebe et al., 1995]. Other evidence that the area has been recently active includes eruption of San Benedicto Island in 1952-1953 [Richards, 1959], minor eruptive activity on Socorro Island in 1951 [Crowe and Crowe, 1955], a ~5 ka radiocarbon age for a lacustrine deposit stratigraphically underlying a basaltic cone on Socorro Island [Farmer et al., 1993], and young ages of submarine volcanic rocks inferred from manganese crust thicknesses (J. Hein, written communication, 1991) and 11Be isotope data [Graham et al., 1988]. Socorro Island is virtually unique in the Pacific Basin, being one of the few volcanic islands dominated by subaerial eruptions of silicic peralkaline composition. In this study, we present detailed mapping, lithofacies, stratigraphic, and 40Ar/39Ar chronological data for rocks from the southeastern quadrant of Socorro Island, where precaldera, syncaldera, and postcaldera deposits are relatively well exposed. In addition to establishing an eruptive chronology for the volcanic deposits on the island, these data quantify eruption rates, eruption durations, and magma volumes of an oceanic silicic peralkaline volcano, establish the framework by which to assess temporal changes in eruptive style and eruption rates, and allow general inferences to be made about the magma reservoir. We compare eruption and growth rates of volcanoes with known sources (e.g., off-axis seamounts, volcanoes

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related to mantle plumes) to those of Socorro in order to try to constrain the source of alkaline magmatism in this abandoned ridge setting.

**Previous Work**

The eruptive history of Socorro Island was divided into precaldera and postcaldera stages by Bryan [1959, 1966, 1976] (Figure 1). Premonitory stage rocks, exposed dominantly on the eastern side of the island, were characterized as products of effusive eruptions ranging from volumetrically dominant, older alkaline basalt to rare, younger cumbendite (peralkaline rhyolite). A summit caldera was identified, although synchronal deposits were not. Postcaldera phase rocks were divided into the Cerro Evermann and Lomas Coloradas Formations on the basis of composition and location (Figure 1). Rocks of the Cerro Evermann Formation, dominantly silicic peralkaline domes and lava flows with minor alkaline basalt flows and cones, are exposed in the caldera as well as on the northern, western, and southern flanks. The Lomas Coloradas Formation comprises dominantly alkaline basalt flows and cones confined to the southeastern quadrant. In addition, several trachyte domes located near the southeastern coast were included in the Lomas Coloradas Formation. Bryan [1959] could not decipher relative ages between rocks of the Cerro Evermann and Lomas Coloradas Formations but suggested that eruptions of the two formations may have been contemporaneous.

**Field and $^{40}$Ar/$^{39}$Ar Methods**

Seven weeks during 1990 and 1991 were spent mapping and sampling the southeastern quadrant of Socorro Island (Figures 1 and 2) where great compositional diversity (alkaline basalt to peralkaline rhyolite), the greatest temporal range, and the least vegetation occur. Correlation of postcaldera flows and vents was possible using phenocryst assemblage, flow lithology, and location. Relative stratigraphy for postcaldera deposits was established using relationships observed in stream drainages and at contacts between deposits. The $^{40}$Ar/$^{39}$Ar ages confirmed the relative stratigraphic relations of these units observed in the field. In distinct contrast, correlation of precaldera and synchronal deposits was difficult due to similarities of their lithologic characteristics (e.g., phenocryst assemblage, degree of weathering, and vesicularity). Stratigraphic relations were generally not established in the field because the deposits are lithologically similar and because exposure of an individual deposit was typically discontinuous, probably due to both erosion and its original distribution. For precaldera and synchronal deposits, $^{40}$Ar/$^{39}$Ar ages were used to define the stratigraphy.

Alkali feldspar ($K_2O$ range: 5-6 wt %) separates from 30 whole rock samples were obtained by crushing, magnetic separation, and hand picking to >99% purity. For ash flux tuffs, whole rock feldspar separates were used because fiamme or pumice are largely absent, and in cases where they are present, they are extensively altered. Feldspar separates that had visible alteration were cleaned ultrasonically in ~10% HF for 1-3 min and were rinsed several times in distilled water. The 100 to 150 mg separates were wrapped in aluminum foil, sealed in evacuated pyrex tubes, and irradiated in the University of Michigan Ford reactor (site L67, power level 2 MW) for 3 hours. Because of the large sample size, Fish Canyon Tuff sandstone (27.8 Ma [Miller et al., 1985]) flux monitors were interleaved every 5 mm (n=10) in order to monitor neutron flux gradients. $J$ factors were determined by averaging three analyses, each performed on a single 20-28 mesh crystal; reproducibility was ±0.5% (1σ). Measured irradiation parameters for CaF$_2$ and K$_2$SO$_4$ are ($^{36}$Ar/$^{39}$Ar) = 0.00029, ($^{39}$Ar/$^{37}$Ar)$_{Ca}$ = 0.00007, and ($^{40}$Ar/$^{39}$Ar)$_{K}$ = 0.001±0.015; the ($^{40}$Ar/$^{39}$Ar)$_{K}$ and associated uncertainty reflect shielding of thermal neutrons by (borated) pyrex tubes and the high atmospheric contamination of K$_2$SO$_4$. If a ($^{40}$Ar/$^{39}$Ar)$_{K}$ correction factor of, for example, 0.015 is used instead of 0.001, then model ages in Table 1 and ages reported in Table 2 will decrease by ~13 ky. Hence ages reported in Table 2 could be systematically older than actual eruption ages. While the large uncertainty on ($^{40}$Ar/$^{39}$Ar)$_{K}$ therefore may affect the apparent age, because this correction is systematic, proposed hiatus durations will not be affected by changing the ($^{40}$Ar/$^{39}$Ar)$_{K}$ correction factor. Uncertainties reported in Table 2 reflect inclusion of analytical uncertainty as well as estimates of uncertainty in $J$, backgrounds, and the ($^{40}$Ar/$^{39}$Ar)$_{K}$ correction factor.

Feldspar crystals were melted using a 5-W Ar-ion laser. Most sample ages were characterized by 6-12 individual analyses (each analysis aliquot weighed ~10-15 mg). Isotopic measurements were performed using the University of California, Los Angeles (UCLA) VG1200S mass spectrometer operated in the electron multiplier mode with a gain of ~150 relative to the Faraday cup. Mass spectrometer backgrounds ($^{40}$Ar 0.38-0.58 mV, $^{37}$Ar 0.71-1.18 mV, $^{38}$Ar 0.11-0.18 mV, $^{37}$Ar 0.74-1.23 mV, $^{38}$Ar 0.17-0.29 mV) and extinction line blanks (3-6x10$^{-16}$ coul $^{40}$Ar) were analyzed prior to the start of each sample. Sensitivity was 2 x 10$^{-17}$ mol/mV during the analyses, and mass discrimination was measured at 0.36%/amu; $^{40}$Ar/$^{36}$Ar for the atmospheric standard was 290±3 during the analysis period. All relevant isotope data and model ages are presented in Table 1.

Ages for each sample were calculated using the following methodology: (1) Weighted mean ages (using all model ages, Table 1) and isochron ages (calculated from regressions using the technique of York [1969]) and associated mean sum of weighted deviates (MSWD) were calculated for each sample. Where 6-12 analyses characterize a single sample age, MSWD of ≤2.0-2.6 represent homogeneous crystal populations [Wendt and Carl, 1991]. In both the weighted mean and isochron approaches, 17 samples had MSWD greater than these limits and are therefore apparently characterized by heterogeneous crystal populations. (2) Because of this apparent heterogeneity, a methodology similar to that reported by Deino and Potts [1990] and Spell and Harrison [1993] was adopted to assess the consequences of excluding analyses that may contribute to the large MSWD. Apparent outliers, which were identified from the isochron regression, were sequentially excluded, and the isochron age and MSWD were recalculated. The isochron age was considered "acceptable" when the age and $^{40}$Ar/$^{39}$Ar stabilized. With only one exception (91-67), all MSWD stabilized at ≤5.0 (similar to results of Spell and Harrison [1993]) after exclusion of 5 to 45% of the analyses. The resulting isochron age, MSWD, and $^{40}$Ar/$^{36}$Ar, are reported in Table 2. (3) Using the $^{40}$Ar/$^{36}$Ar composition, an age for each analysis (excluding outliers identified in step 2) was recalculated.
Figure 1. Simplified geologic map of Socorro Island, Mexico, illustrating precaldera and postcaldera phases (Cerro Evermann and Lomas Coloradas Formations) defined by Bryan [1959, 1966, 1976]. Place names are included for reference. The box outlines area of Figure 2. The summit, Cerro Evermann, rises to 1050 m. Inset is a tectonic map of the eastern Pacific Ocean modified from Howell et al. [1985]. Bathymetric contours show the location of the four Revillagigedo Islands and the northern Mathematicians Ridge.
Figure 2. Geologic map of the southeastern quadrant of Socorro Island. Numbers identify individual members of the Cerro Evermann or Lomas Coloradas Formations but do not have stratigraphic significance; in several cases, for clarity, small exposures of previously numbered units were omitted. Where stratigraphic relations were determined in the field, they are labeled with 'y/o'.
Table 1. The $^{40}$Ar/$^{39}$Ar Data

$^{40}$Ar/$^{39}$Ar, $4.3 	imes 10^{10}$ $^{40}$Ar/$^{39}$Ar, Age, $x$ $^{40}$Ar/$^{39}$Ar, Age, $y$ $^{40}$Ar/$^{39}$Ar, Age, $z$

A  B  C  D  E  F  G  H  I  J  K  L  M

|      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 100  |  200 |  300 |  400 |  500 |  600 |  700 |  800 |  900 | 1000 | 1100 | 1200 | 1300 | 1400 |
| 0.01  |  0.02 |  0.03 |  0.04 |  0.05 |  0.06 |  0.07 |  0.08 |  0.09 |  0.10 |  0.11 |  0.12 |  0.13 |  0.14 |

Table 1 (continued)

$^{40}$Ar/$^{39}$Ar, $4.3 	imes 10^{10}$ $^{40}$Ar/$^{39}$Ar, Age, $x$ $^{40}$Ar/$^{39}$Ar, Age, $y$ $^{40}$Ar/$^{39}$Ar, Age, $z$

A  B  C  D  E  F  G  H  I  J  K  L  M

|      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| 100  |  200 |  300 |  400 |  500 |  600 |  700 |  800 |  900 | 1000 | 1100 | 1200 | 1300 | 1400 |
| 0.01  |  0.02 |  0.03 |  0.04 |  0.05 |  0.06 |  0.07 |  0.08 |  0.09 |  0.10 |  0.11 |  0.12 |  0.13 |  0.14 |
Table 1. (continued)

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*Notes:*
- $^{40}$Ar/$^{39}$Ar$^a$, $^{37}$Ar/$^{39}$Ar$^b$, and $^{36}$Ar/$^{39}$Ar$^a$ are expressed in x 10^2, x 10^3, and x 10^14 mol, respectively.
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- Age is in ka, with ±1σ variation.
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<td>( ^{39} \text{Ar} / ^{38} \text{Ar} )</td>
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- Subscripts denote step-heated samples; e.g., \( J = 2.0-2.5 \) W step, \( J = 5.0 \) W step (full melting), analyses with \(<0.05 \times 10^{-14} \text{ mol} \) \(^{39} \text{Ar} \) excluded. \( \lambda = 5.543 \times 10^{-10} \text{ yr}^{-1} \). [Steiger and Jager, 1977].
- Uncertainty for model ages reflects analytical uncertainty only; uncertainty in \( J \) factor, backgrounds, correction factors not included.
- *Corrected for backgrounds and blanks.
- Subscripts denote step-heated samples; e.g., \( J = 2.0-2.5 \) W step, \( J = 5.0 \) W step (full melting), analyses with \(<0.05 \times 10^{-14} \text{ mol} \) \(^{39} \text{Ar} \) excluded. \( \lambda = 5.543 \times 10^{-10} \text{ yr}^{-1} \). [Steiger and Jager, 1977].
- Uncertainty for model ages reflects analytical uncertainty only; uncertainty in \( J \) factor, backgrounds, correction factors not included.
- *Corrected for backgrounds and blanks.
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<th>N</th>
<th>Mean Age ± 1σ_{S.E.}</th>
<th>Isochron Ages ± 1σ_{S.D.}</th>
<th>40Ar/39Ar</th>
<th>SIO₂, wt %</th>
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*pAll ages and associated uncertainties in ka; weighted mean and mean age uncertainties reflect quadratic combination of analytical uncertainty (1σ S.E.) and 1% uncertainty in J (which represents estimated analytical uncertainty in J plus estimated uncertainties in backgrounds and 40Ar/39Ar); isochron age uncertainty reflects quadratic combination of uncertainty in isochron fit and 1% uncertainty in J as noted.*

*2Weighted mean ages and associated MSWD_w include all model ages (Table 1); acceptable MSWD_w should be <2.1 for most samples (n=28); the exception is 91-64, which should be <5.7 (n=4).*

*3Indicates fraction of analyses used to calculate mean age, isochron age, 40Ar/39Ar, MSWD, and associated uncertainties.*

*4Mean age estimated using results of probability density function.*

*Model age data suggest presence of older xenocrysts. Excluding xenocrysts, recalculated weighted mean age ±1σ, (MSWD_w), respectively: 90-10 5892±4.10 (3.3); 91-38 3642±4.2 (4).*

*5Unit numbers (Figure 2) included in parentheses.*

Thereby accounting for deviations from atmospheric 40Ar/39Ar composition (295.5) assumed in model age calculations (see McDougall and Harrison [1988] for discussion). Using these recalculated ages, a probability density function [e.g., Taylor, 1982; Bevington and Robinson, 1992] was calculated for each sample. In several cases, additional outliers were excluded and steps 2 and 3 were repeated until the probability density function had a Gaussian-like distribution, which is indicative of a homogeneous crystal population [e.g., Bevington and Robinson, 1992]. Mean ages identified by the Gaussian-like distributions (hereafter referred to as mean age) along with the fraction of analyses that contribute to it are reported in Table 2. The weighted mean age and the mean age for 25 of 35 samples overlap at 1σ_{S.E.}. Of the five samples that do not overlap, two model ages for each of two samples (90-10 and 91 38) are significantly older than the remaining analyses, suggesting contamination by older xenocrysts.

**Geologic History: Mapping and 40Ar/39Ar Results**

Mapping of the southeastern quadrant of Socorro Island and 40Ar/39Ar results support Bryan's [1959, 1976] distinction of precaldera and postcaldera phases on Socorro, with the latter comprising two formations, the Cerro Evermann and the Lomas Coloradas; in addition, we tentatively identify a synvolcanic eruptive phase. Our map area is outlined in Figure 1, and our geologic map is illustrated in Figure 2. Eruptive
ages of precaldera and syncaledra and Cerro Evermann rocks
are constrained by $^{40}$Ar/$^{39}$Ar (Table 1) data whereas
plagioclase in alkaline basalts of the Lomas Coloradas
Formation are not amenable to this technique because of their
low $^{40}$Ar*/$^{39}$Ar yield (<1%) and high Ca/K (49±5).

Precaldera and Syncaledra Phase
The oldest units subaerially exposed on Socorro Island are
precaldera basalts and precaldera and syncaledra peralkaline
trachytes and rhyolites that are largely confined to the eastern
side of the island. Exposure of precaldera basalt is limited to
the base of an inaccessible cliff south of Cabo Pearce (Figure 2
and Bryan [1959]), where the basalts are overlain by
precaldera silicic peralkaline deposits. All precaldera and
precaldera silicic trachytes and rhyolites are phytic (up to 15
vol % total phenocrysts), with alkali feldspar $>$ Na-pyroxene
$+$ fayalite $>$ aenigmatite. Groundmass is typically composed
of alkali feldspar + Na-pyroxene $+$ aenigmatite $+$ sodic
amphibole. The total volume of precaldera and syncaledra
silicic peralkaline rock calculated using estimates of average
deposit thickness and average area is 2 km$^3$ (dense rock
equivalent) (Table 3); this estimate is a minimum because it
does not account for possible deposits in the ocean or those
concealed by younger units.

Stratigraphy of precaldera and syncaledra phase
based on $^{40}$Ar/$^{39}$Ar ages. Twenty-one $^{40}$Ar/$^{39}$Ar ages of
silicic peralkaline deposits provide evidence for a silicic
precaldera and syncaledra eruptive history characterized by
several distinct eruptive periods (Figures 3 and 4 and Table 2).
Most mean ages cluster at ~430 or ~375 ka, suggesting two
distinct eruptive episodes. Six samples yield older mean ages
that define two, or possibly three, additional eruptive
episodes. The eruptive products of these five periods are
informally designated from oldest to youngest as A, B(2), C,
D, E. Although in most locations, stratigraphic relations for
silicic precaldera and syncaledra deposits could not be
determined, those that could be resolved (n=2) are consistent
with $^{40}$Ar/$^{39}$Ar ages.

Deposits of A-D are unequivocally older than the exposed
caldera because they have ages older than those samples that
comprise the caldera wall. Two samples of E (90-95 and 91-
19) compose the caldera wall, suggesting that E is either
precaldera or syncaledra in age; we interpret E as syncaledra,
in part, because of the well-documented association between
explosive eruptions and caldera formation [Smith, 1979].

Rocks of the oldest silicic peralkaline eruptive period
sampled (A) range in mean age from 540±6 (90-53) to 525±6
ka (90-13). Consistent with their ages, sample 90-53 lies
stratigraphically below 90-13 in a single exposure north of
Cabo Pearce. Sample 91-67 yields a mean age of 306±6 ka and
is designated B(2). The questionable designation reflects the
unacceptable MSWD$^1$ (3.89, Table 2) and the lack of additional
samples of similar age. The bimodal probability density
function suggests that the crystal population may be
heterogeneous (e.g., contains xenocrysts), in which case, the
age may have little geologic meaning. C erupted at ~480 ka
and is represented by samples collected from near the eastern
coast, north of Cabo Pearce. Eruption of C followed a
quiescent period of at least 14 kyr since eruption of B(?) and
at least 33 kyr since eruption of A. D erupted between 433±5 and
420±4 ka following at least 36 kyr of quiescence and includes
samples from both the eastern and southern quadrants.

Eruption of E occurred between 384±5 and 367±5 ka,
following a minimum of 27 kyr of inactivity. E includes
samples from the caldera wall, as well as from the southern and
eastern flanks.

Lithofacies description. Silicic peralkaline
precaldera and syncaledra deposits on Socorro Island are
commonly holocrystalline, nonfragmental, nonvesicular
lava-like deposits that lack inclusions or lithic fragments.
However, horizons characterized by fayalite and lithic
fragments are locally preserved and are typically characterized
by well-developed cutaxitic foliation, vitroclastic texture, and
between 5% and 20% fayalite in a welded matrix. Fayalite are
typically flattened and stretched with the axis of elongation
trending downslope. Where exposed in paleostream valleys,
the welding zonation parallels paleo-valley walls, and fayalite
are lined parallel to the axis of the paleovalley, indicating
that rheomorphism may have occurred. Lithic abundances are
typically about 10% and include obsidian, vesicular
porphyritic basalt, and peralkaline trachyte or rhyolite.

North of Cabo Pearce, A comprises two densely welded
zones, each ~15 m thick, that lack both lithic fragments and
fayalite (Figure 5); these probably represent distinct cooling
units. The lower densely welded zone (90-53), the base of
which is not exposed, underlies a breccia composed of
subangular peralkaline trachyte and rhyolite clasts set in an
ash matrix. A partially welded zone containing partially
flattened pumice and angular lithic fragments, overlies the
breccia. The upper densely welded zone (90-13) is capped by
a partially welded zone. All internal contacts in A are
gradational except for those of the breccia. Unit B is densely
welded (91-67) throughout except for a 2-m-thick partially
welded zone at the top. Partially welded zones associated with
C are not observed.

Approximately 1.5 km south of Cabo Pearce, D is
distinguished by a complex and thick (1-5 m) basalt
layer dominated by lithic fragments and pumice. Proportions
of lithic fragments and pumice vary, with local concentrations
of lithics exceeding 40% and of pumice exceeding 70%. The
deposit is clast-supported, with less than 10% ash matrix. In
general, it is poorly sorted and massive, although crude
stratification defined by size-sorted lithics and fayalite is
present in some exposures. Lithic fragments (vesicular basalt
and peralkaline trachyte and rhyolite) and pumice range from
0.5 to 50 cm and from <1 cm to rarely >10 cm, respectively.
This pumice-lithic rich horizon underlies a densely welded unit
(91-64) and grades laterally into a partially welded horizon. In
a canyon adjacent to and north of this deposit, partially welded
tuff of D grades upsponction into a densely welded horizon (91-
66).

Twenty five meters of E is exposed in the upper portion of a
sea cliff 2 km south of Cabo Pearce. Here, a densely welded
layer of E (91-43) overlies A (91-46) and is separated from it
by a 1-mm-thick ash bed and a 2-mm-thick breccia. The ash bed,
which directly overlies a densely welded zone of A, is
extremely weathered and contains sparse lithics and pumice.
The breccia comprises dense, altered, angular silicic
peralkaline clasts. The contact between the breccia and E is
sharp.

Interpretation of eruptive and depositional
processes. Silicic peralkaline magma has relatively low
viscosity (compared to metaluminous magmas with similar
SiO$_2$) which can promote dense welding and rheomorphism of
## Table 3. Eruption and Growth Rates

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<th></th>
<th>Area, km²</th>
<th>Average Thickness, m</th>
<th>Volume, km³</th>
<th>Duration of Volcanism, Ma</th>
<th>Eruption Rate, km³/yr</th>
<th>Growth rate, km³/yr</th>
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<td>1.5</td>
<td>6 x 3 x 10⁻⁵</td>
<td></td>
</tr>
<tr>
<td>Bouvet</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.7</td>
<td>4 x 10⁻⁵</td>
<td></td>
</tr>
<tr>
<td>Nonhoihoa volcano</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.2</td>
<td>1 x 10⁻⁵</td>
<td></td>
</tr>
</tbody>
</table>

¹Arca and thickness estimates for Socorro from field data.
²Eruption rates for all edifices calculated for subaerial exposure using volume of eruptive phase (estimated using area extent and average thickness of deposit) and eruption duration. See Crip [1984] and Gerlach [1990] for calculation details on edifices other than Socorro; growth rates calculated using duration of volcanism and total edifice volume and therefore may include some intrusive rock.
³Maximum age of volcano based on age of underlying oceanic crust. Growth rate is therefore a minimum.
⁴Projected area for precaldera and syncaldera ash flow tuffs estimated on kilometer basis and assumes continuity between exposure of tuffs in SE quadrant; estimate in parentheses is total area of Socorro Island and assumes that tuff montes entire island. Volume and eruption rate in parentheses use this area estimate.
⁵Sum of thicknesses of several ash flow tuffs from exposures in crustal rift
⁶Crip [1984].
⁷Gerlach [1990].
⁸Buita [1982].
Figure 3. Probability density functions for ⁴⁰Ar/³⁹Ar ages for 30 samples are Gaussian-like, suggesting that the associated samples are characterized by a homogeneous crystal populations. The density functions are typically defined by 6 to 12 individual analyses. Four well-defined, discrete eruptive episodes, which produced precaldera and syncaledra deposits designated A, C, D, and E, range in age from ~540 to 370 ka. One sample (91-67) does not have a Gaussian-like distribution. Instead, the density function is bimodal, which may reflect a heterogeneous crystal population, and hence the associated deposit is designated B(?). Silicic peralkaline postcaldera volcanism, the Cerro Evermann Formation, initiated at ~180 ka after up to 200 kyr of quiescence and continued to at least 15 ka.

Figure 4. Location map for ⁴⁰Ar/³⁹Ar analyses shows geographic distribution of samples for precaldera and syncaledra deposits and the Cerro Evermann Formation.
pyroclastic deposits [e.g., Mahood, 1984]; consequently, silicic peralkaline pyroclastic deposits and extensive lava flows can resemble one another [cf. Henry and Wolff, 1992]. Welding zonation such as that described in the previous section is not found in extensive silicic lava flows [e.g., Henry and Wolff, 1992] and indicates that many of the precaldera and synca. ldera silicic peralkaline deposits on Socorro Island are ash flow tuffs. Other evidence which supports an explosive origin for many of these deposits includes (1) eutaxitic foliation and vitroclastic texture in partially welded zones, (2) broken phenocrysts in some deposits, (3) compositional heterogeneity within a single unit (e.g., D, E, Figure 6) which is more common in ash flow tuffs than lava flows [Henry and Wolff, 1992], and (4) tentative association of E with caldera formation.

Further evidence that explosive eruptions dominate the silicic precaldera and synca. lderaphase on Socorro is tied to the origin of the lithic-pumice rich horizon associated with D. Characteristics of this zone, including abundant lithic fragments and pumice and a lack of fine particles, are consistent with those described for coarse proximal ignimbrite or co-ignimbrite facies [Walker, 1985]. On the basis of the lack of fine particles, the deposit is either a ground layer or a lag breccia (see Sparks et al. [1973], Drutt and Sparks [1982], and Walker [1985] for descriptions of lag deposit and ground layer). Although it can be difficult to distinguish between these deposits [Walker, 1985], characteristics of the deposit on Socorro (including thickness, internal stratification, and intimate but irregular association with the ignimbrite) favor the interpretation that the zone is a lag deposit. The significance of this deposit lies less with its exact origin than with its identification as a proximal ignimbrite or co-ignimbrite facies: such deposits have explosive origins, and similar deposits have not been observed with silicic lava flows.

Broken phenocrysts, which are common in pyroclastic deposits, are only moderately abundant in ash flow tuffs from Socorro Island, suggesting that although the eruptions were explosive, the eruption columns may have been low, and fragmentation was not extreme. This is consistent with lower column heights hypothesized for silicic peralkaline eruptions [Mahood, 1984] and with the lack of recovery of silicic peralkaline ash in near-by Deep Sea Drilling Project (DSDP) holes (Shipboard Party, 1982a, b; Schmincke, 1983).

The Caldera

At approximately 600 m elevation on the southeastern side of the summit of Socorro Island, a steep, well-defined, arcuate escarpment forms the eastern boundary of an alluvium filled depression (Figure 2). This prominent topographic feature is probably the remnant of a caldera wall [Bryan, 1959]. Only about 30% of the caldera wall is presently exposed. Using the trajectory of this exposure and the 600-m contour as guides, the reconstructed caldera is 4.5 x 3.8 km and is elongated NW SE; such a size is consistent with typical caldera dimensions for peralkaline volcanoes [Mahood, 1984]. The best exposure of the wall, which bounds a triangular area of caldera-filling alluvium (caldera floor) defined by two postcaldera lava flows (flows 24 and 26, Figure 2), has more than 30 m of relief, consistent with tens to hundreds of meters of throw that characterize other calderas associated with silicic peralkaline volcanic centers [Mahood, 1984]. The western half of the caldera wall is not exposed; Bryan [1966] suggested that burial of this section beneath postcaldera flows may have been facilitated by downfaulting along an approximately north-south trending fault, but field evidence for such a fault is absent.

Although nested calderas have been reported for a number of peralkaline edifices (e.g., Pantelleria, Aden, Garibaldi [Mahood, 1984]; Mayor Island [Houghton et al., 1992]; Terceira [Self, 1976]), structural evidence for nested calderas is absent or covered on Socorro Island, perhaps suggesting that caldera formation did not occur with each of the explosive eruptions. Subhorizontal plate jointing and poorly developed mineral lineation in the caldera wall indicate that the deposit which forms the caldera wall flowed outward from its source prior to caldera formation and was not plastered on an older caldera wall; thus the age of the samples composing the caldera wall are equal to or older than the age of caldera formation. Formation of the caldera therefore occurred between ~370 and 182 ka based on mean ages of the caldera wall and caldera floor, respectively. If the caldera formed at ~370 ka, then collapse may have accompanied eruption of E, which is consistent with the association between caldera formation and explosive eruptions [Smith, 1979]. If caldera formation occurred after eruption of E, then collapse may have been triggered by lateral migration of magma or by withdrawal of magma at depth [e.g., Bryan, 1966; Mahood, 1984], both of which would remove roof support.

Postcaldera Phase

Eruption of E and possible associated caldera formation were apparently followed by up to 200 ky of volcanic quiescence. Postcaldera silicic peralkaline volcanism, which formed the Cerro Evermann Formation, initiated by ~180 ka and continued until at least 15 ka. Alkaline basaltic Lomas Colorado Formation also added to caldera in age based upon stratigraphic relations.

Cerro Evermann Formation. The Cerro Evermann Formation, which covers ~70% of the island and has a total volume of ~0.8 km3 (Table 3), includes peralkaline trachytes and rhyolites that erupted in the caldera as well as on the northern, western, and southern flanks (Figures 1 and 2). It is dominated by lava domes, cones, and flows. Saccro evidence of minor explosive activity occurs as thin layers of silicic pumice fallout that are preserved in soils and sediments associated with some vents of the Lomas Colorado Formation. The phenocryst assemblage for deposits of the Cerro Evermann Formation is andesite, feldspar > Na-pyroxene > fayalite > olivine, with glass + Na-amphibole. Lithographic descriptions presented here were made primarily on observations made in the map area but are supplemented by reconnaissance work to the north and west. Additional descriptions are presented by Bryan [1959, 1966].

The oldest recovered sample (9117, peralkaline rhyolite) of the Cerro Evermann Formation erupted at 182±2 ka and is part of the caldera floor. A glassy, vesicular peralkaline rhyolite lava flow (90-94) with a mean age of 152±2 ka is located to the southeast of the caldera wall, although the source for this flow was not identified. An intracaldera peralkaline rhyolite dome (90-98, flow 24) erupted at 150±2 ka and was confined by the caldera wall to the east. Summit activity at 175±1 ka produced a dome and flow (91-9, flow 25)
<table>
<thead>
<tr>
<th>Deposit</th>
<th>Age range (ka)</th>
<th>Cumulative thickness (m)</th>
<th>Log</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>350 400 450 500 550 600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>150</td>
<td>Partially welded zone at base increases in degree of welding upsection</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>120</td>
<td>Partially welded zone at base increases in degree of welding upsection</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>90</td>
<td>Poorly sorted, clast supported; grades laterally into partially welded zone and vertically into densely welded zone.</td>
<td></td>
</tr>
<tr>
<td>B(?)</td>
<td>60</td>
<td>Basal partially welded zone increases in degree of welding upsection</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>30</td>
<td>Breccia; subangular lithic fragments set in ash matrix</td>
<td></td>
</tr>
</tbody>
</table>

**Legend**

- Contact between units
- Densely welded zone; lacks lithics and fiamme
- Partially welded zone, lithics, pumice and fiamme present
- Breccia
- Mixed lithic fragment + pumice deposit

**Figure 5.** Schematic composite stratigraphic column summarizing age range, welding zonation, and typical thickness for precaldera and syncaledera ash flow tuffs. Age ranges for samples associated with each eruptive episode shown by shaded area. Numbers included in the column represent samples of densely welded tuff taken at or near the location where partially welded deposits were identified. Two densely welded zones separated by a breccia were identified in A; the upper and lower boundaries of the breccia are defined by horizontal black lines. Welding zonation observed for A, B(?), D, and E provides evidence that these deposits are ash flow tuffs rather than lava flows as originally proposed by Bryan [1966].
with a pumiceous carapace. A glassy peralkaline rhyolite dome and flow (90-99, flow 26) which erupted at 41±4 ka was apparently confined in the caldera by the caldera wall to the southeast. A peralkaline rhyolite obsidian dome and flow (flow 27) erupted near the summit after 41 ka but before -15 ka based on stratigraphic relations. At 15±7 ka, an eruption was initiated at about 700 m elevation within the caldera and produced a peralkaline trachyte dome and a lava flow (90-91, flow 28) that traveled 4 km southward into the ocean.

Three peralkaline trachyte domes and a peralkaline trachyte cinder cone originally included in the Lomas Coloradas Formation by Bryan [1976] erupted near the southeastern coast between 60 and 70 ka. Because of their silicic peralkaline composition, we include them here in the Cerro Evermann Formation. One dome (90-29, flow 20) and the cinder cone (90-122, flow 21) erupted at 68±6 and 62±5 ka, respectively. Because of the lithologic and compositional similarities between these units and the two undated domes (flows 22 and 23), we suggest they all probably have similar eruption ages.

**Lomas Coloradas Formation.** The Lomas Coloradas Formation, which covers about 20% of the island and has an estimated volume of 0.1 km³, comprises alkaline basaltic cones and lava flows that are largely restricted to the southeastern quadrant of the island. Seventeen basaltic cinder to spatter cones were identified (Figure 2). Vents could not be identified for three large volume, well preserved flows (flows 17, 18, and 19, Figure 2) indicating that little explosive material was left at their sources. Lava flow morphologies are mainly pahoehoe, with locally well-developed lava tube systems, whereas aa is subordinate. Total phenocryst abundances range from 0 to 35 vol %, with plagioclase >> olivine = clinopyroxene. Groundmass is composed of plagioclase + olivine + clinopyroxene + Fe Ti oxides.

All contacts between basalt and precaldera and syncladera deposits demonstrate that the basalts are younger. One of the oldest basalts (flow 19) overlies a ~150 ka old Cerro Evermann flow, indicating that most of the rocks of the Lomas Coloradas are probably younger than 150 ka. Postcaldera coastal domes and cones of the Cerro Evermann Formation (flows 20 and 21), dated at ~70 ka, postdate one of the younger basalt flows (flow 4), based upon the following observations: (1) in a stream drainage, a trachytic dome (flow 20) overlies the basalt lava flow, (2) basaltic lithic fragments are present in these domes, and (3) the basalt was deformed by intrusion of trachyte (flow 23). Thus the dominant volume of basalt probably erupted between 150 and 70 ka, demonstrating the Lomas Coloradas and Cerro Evermann Formations erupted contemporaneously. At least one episode of basaltic activity postdates the 70 ka old trachyte cones as illustrated by a radiocarbon age of 5040±460 years for lacustrine deposits stratigraphically underlying a volcanic cone (flow 7) located near the southern coast [Farmer et al., 1993].

Stratigraphic relations among the basaltic flows and cones of the Lomas Coloradas Formation were deciphered in most cases using outcrops in stream beds or crosscutting relationships established by dikes (Figure 2; "y/o"). No systematic temporal progression in the distribution of vents and no well-developed, large-scale rift systems are discernible. Where two or more basaltic units could be observed in contact, they were usually barely separated by soils, indicating that the time between basaltic eruptions was probably fairly short.

**Discussion**

**Eruptive Periodicity**

The clustering of ⁴⁰Ar/³⁹Ar ages of precaldera and syncladera deposits from Socorro (Figure 3) implies a periodicity to these eruptions, with eruptive hiatuses of ~30 ka. It has not been possible to confirm the absence of eruptions during these hiatuses because of the difficulty of establishing a stratigraphic framework in the field. However, similarities in apparent hiatus duration despite sampling that covered a wide geographic and elevation range suggest to us that the hiatuses probably have geologic meaning. In the limiting case, the ~30 ka reposes are the highest values of reposes.

Reference to other silicic peralkaline systems shows that episodic explosive activity and reposes of 10⁴ years are typical. For example, over the last 190 kyr, Pamir sector has...
had a silicic eruption every 13±6 ka [Mahood and Hildreth, 1986]: among these, many were explosive. The Mogan Formation. Gran Canaria, which is dominated by silicic peralkaline pyroclastic deposits, is characterized by repose periods of 30-50 kyr [Boggaard et al., 1988; Clark and Spera, 1990]. The 130 kyr subaerial history of Mayor Island, which comprises intercalated lava and pyroclastic flows, is typified by average repose periods of ~4 kyr [Houghton et al., 1992]. In general, the small eruptive volumes and the short repose times for many peralkaline volcanoes probably reflect small to medium volumetric magmatic systems [Spera and Crisp, 1981; Boggaard et al., 1988; Houghton et al., 1992].

**Magma Plumbing System**

The presence of a small summit caldera on Socorro suggests that the silicic magma reservoir was shallow [e.g., Mahood, 1984], probably located within the volcanic edifice or the upper oceanic crust. This is also supported by phase equilibria for both precaldera and synclavera and postcaldera silicic peralkaline rocks (W. A. Bohrson and M. R. Reid, manuscript in preparation, 1996). In order to maintain a long history of silicic peralkaline activity, mafic recharge probably maintained thermal viability of the magma reservoir. As a comparison, complete crystallization of the Skagard Intrusion (modeled as a single pulse of basaltic magma 3 times larger than that estimated for the chamber associated with Socorro intruded at a depth of 4 km, which is probably equal to or greater than the depth of the chamber associated with Socorro) occurred in 130 ka [Norton and Taylor, 1979; Norton et al., 1984]. Evidence for low pressure differentiation for postcaldera basaltic rocks [Bohrson and Reid, 1995] coupled with the observation that postcaldera basaltic and silicic eruptions on Socorro were contemporaneous support the inference that basaltic and silicic magma coexisted at shallow levels [cf. Bryan, 1966].

Precaldera and synclavera silicic peralkaline ash flow tuffs are compositionally heterogeneous, as are domes and flows of the Cerro Evermann Formation; in fact, the two phases of activity share similar ranges of compositions as indicated by SiO2 and Zr (Table 2 and Figure 6). Given the lack of stratigraphic control in the field and the uncertainties in the Ar data, it is not possible to determine whether the ash flow tuffs are vertically compositionally zoned, and thus, whether the silicic magma chamber was itself compositionally zoned or whether compositional heterogeneity within the tuffs reflects a process such as magma mixing. In any case, the transition from explosive to more effusive explosive style following caldera formation on Socorro suggests an associated change in the magma plumbing system. Factors which control explosivity (changes in magma viscosity, vesiculation depth [Fisher and Schmincke, 1984], or parameters of magma ascent [Eichelberger, 1995]) were probably more strongly influenced by volatile abundance and type or the degassing history of the magma than by changes in chamber depth or magma bulk composition from the precaldera and synclavera to postcaldera phases. Lowenstern and Mahood [1991] demonstrated that preeruptive volatile abundances of silicic peralkaline magmas from Pantelleria correlate poorly with explosivity and suggested that the decompression history of the magma constitutes the critical element in determining eruption style. On Socorro, ring fractures produced during caldera formation may have facilitated degassing for postcaldera magma. A slower ascent rate for postcaldera magma may have also permitted degassing, thereby producing effusive eruptions, whereas a faster ascent rate for precaldera and synclavera magmas may have inhibited degassing, thereby producing explosive eruptions [cf. Eichelberger, 1995].

**Eruption Rates and Possible Source of Magmatism**

Calculated eruption rates for Socorro Island decrease with time (Table 3); rates of 4 x 10^-6 km^3/yr for the Cerro EvermannFormation and of 1 x 10^-5 km^3/yr for the Lomas Coloradas Formation are collectively half that estimated for the precaldera and synclavera phase (10^-5 km^3/yr). Similar decreases in eruption rates have been noted for other volcanic edifices (e.g., Hawaii [Clague, 1987] and Gran Canaria [Boggaard et al., 1988]). Calculating an eruption rate for the submariine part of the edifice is difficult due to uncertainties in the age of inception of volcanism and an accurate assessment of the intrusive to extrusive ratio. A minimum growth rate of >7 x 10^-4 km^3/yr for the edifice, delimited by a ~3.5 Ma age of the underlying ocean crust and a total edifice volume of ~2400 km^3, represents primarily submarine growth because the subaerial volume of the volcano (~40 km^3) is ~2% of the total edifice volume. Even given the uncertainties noted above, the greater than order of magnitude difference between this growth rate and subaerial eruption rates suggest that either subaerial eruption rates are less than submarine ones or that the growth of the volcano has continued to be dominantly submarine.

Growth and eruption rates permit comparisons of possible sources for different volcanic edifices (Table 3). Growth rates for nonhotspot off-rift volcanoes [Batiza, 1982] are almost an order of magnitude less than that of Socorro, suggesting that magmatism associated with Socorro is probably not solely the product of residual mantle upwelling associated with ridge abandonment. Although eruption rates for ocean island chains such as the Canary Islands are higher than those of Socorro (Table 3), isolated ocean islands thought to be associated with mantle plumes (e.g., Bouvet and Ascension [Gerlach, 1990]) have similar subaerial eruption rates to those of Socorro. On the basis of these comparisons, we suggest that the source of alkaline magmatism associated with Socorro may be consistent with a mantle plume [cf. Duncan and Richards, 1991].

**Conclusions**

1. Precise, replicate 40Ar/39Ar analyses and relative stratigraphy reveal 0.5 Myr of alkaline and peralkaline volcanism on Socorro Island, a volcanic edifice located on a mid-ocean ridge spreading center abandoned at ~3.5 Ma. The oldest dated rocks, which range in age from ~540 to 370 ka, are precaldera and synclavera silicic peralkaline ash flows formed by several distinct periods of explosive activity; repose periods between these explosive episodes may have had maximum durations of ~30 kyr. Formation of a small summit caldera occurred during or after eruption of the youngest ash flow tuff. The ~200 kyr hiatus that followed caldera formation ended with postcaldera silicic peralkaline activity (Cerro Evermann Formation) that commenced at ~180 ka and continued to at least 15 ka. Postcaldera alkaline basalts (Lomas Coloradas Formation) erupted between 150 and 70 ka, demonstrating that contemporaneous eruption of silicic and basaltic magmas occurred on Socorro Island.
2. Precaldera and syncaldera deposits are dominantly densely welded ash flow tuffs. Although these deposits resemble lava flows, the presence of welding zonation, a co-ignimbrite or proximal ignimbrite deposit, association with a caldera, and compositional heterogeneity within single eruptive units provide evidence that the deposits are pyroclastic.

3. The magma reservoir beneath Socorro is inferred to reside at shallow depths, probably in the ocean crust or within the volcanic edifice. The shallow depth of the magma chamber coupled with the prolonged history of silicic peralkaline magmatism during both precaldera and syncaldera phases are used to infer that intrusion of basaltic magma maintained thermal viability of the magma reservoir. This requirement coupled with contemporaneous eruption of postcaldera silicic and basaltic magma may be consistent with coexistence of mafic and silicic magma at shallow levels.

4. The short repose periods, small volume eruptions, small caldera and shallow level magma chamber that characterize Socorro Island are similar to those of peralkaline volcanoes located on continental crust (e.g., Pantelleria and Mayor Island), indicating that these features may be independent of crustal structure.

5. Eruption rates for Socorro Island probably decrease with time. Socorro Island's current growth rate exceeds those of non-hotspot off-ridge volcanoes [Batiza, 1982], whereas its subaerial eruption rates are similar to those of isolated ocean islands [Gerlach, 1990] where mantle plumes are proposed sources.

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