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RADIOCARBON AGES OF LACUSTRINE DEPOSITS IN VOLCANIC SEQUENCES OF THE LOMAS COLORADAS AREA, SOCORRO ISLAND, MEXICO

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ABSTRACT. Extensive eruptions of alkalic basalt from low-elevation fissures and vents on the southern flank of the dormant volcano, Cerro Evermann, accompanied the most recent phase of volcanic activity on Socorro Island, and created the Lomas Coloradas, a broad, gently sloping terrain comprising the southern part of the island. We obtained ^{14}C ages of 4690 ± 270 BP (5000–5700 cal BP) and 5040 ± 460 BP (5300–6300 cal BP) from lacustrine deposits that occur within volcanic sequences of the lower Lomas Coloradas. Apparently, the sediments accumulated within a topographic depression between two scoria cones shortly after they formed. The lacustrine environment was destroyed when the cones were breached by headward erosion of adjacent stream drainages. This was followed by the eruption of a thin basaltic flow from fissures near the base of the northernmost cone. The flow moved downslope for a short distance and into the drainages that presently bound the study area on the east and west. The flow postdates development of the present drainage system and may be very recent. Our ^{14}C data, along with historical accounts of volcanic activity over the last century, including submarine eruptions that occurred a few km west of Socorro in early 1993, underscore the high risk for explosive volcanism in this region and the need for a detailed volcanic hazards plan and seismic monitoring.

INTRODUCTION

Socorro Island, located 460 km southwest of Cabo San Lucas and 650 km west of Manzanillo, Mexico, lies at the northern end of the Mathematician Ridge near its intersection with the Clarion Fracture Zone (Fig. 1). The Revillagigedo Archipelago comprises Socorro, Clarion, San Benedicto and Roca Partida Islands, which form the emergent part of a chain of seamounts that make up the north-trending Mathematician Ridge.

The topography and paleomagnetic record of the sea floor in this region (Anderson & Davis 1973; Klitgord & Mammerickx 1982) provide evidence for the most recent plate-tectonic reorganization in the eastern Pacific (Handschumacher 1976). The Mathematician Ridge lies at a much shallower depth than expected, based on the average sea-floor age of the region (Parsons & Sclater 1977), and is interpreted to be a failed spreading center (Mammerickx & Klitgord 1982). Ridge abandonment was completed by *ca.* 3.15 Ma BP, with a shift in the principal locus of sea-floor spreading to its present position on the East Pacific Rise (Mammerickx, Naar & Tyce 1988).

Socorro, the largest of the Revillagigedo Islands (18°47'N, 110°57'W), is broadly oval in outline and covers *ca.* 140 km^2. It comprises the emergent portion of a large basaltic shield volcano that rises from a sea-floor depth of about 3000 m. The highest point on the island is the dormant volcanic peak, Cerro Evermann (1130 m asl). The island landscape is dominated by lava flows, cinder cones and volcanic domes. The lavas of Socorro Island are predominantly trachyte, ranging to pantellerite; evidently, Socorro is the only volcanic island in the Pacific exhibiting siliceous, highly peralkaline compositions (Bryan 1976; Batiza & Vanko 1985).

Early expeditions to the Revillagigedos focused primarily on the biology of the islands (Richards & Brattstrom 1959). However, the unexpected explosive eruption of Volcán Bárcena on San Benedicto in 1952 led to several studies that addressed the stratigraphy, geochemistry, petrology and eruptive history of the islands (Bryan 1959, 1964, 1966, 1967, 1976; Richards 1957, 1959,

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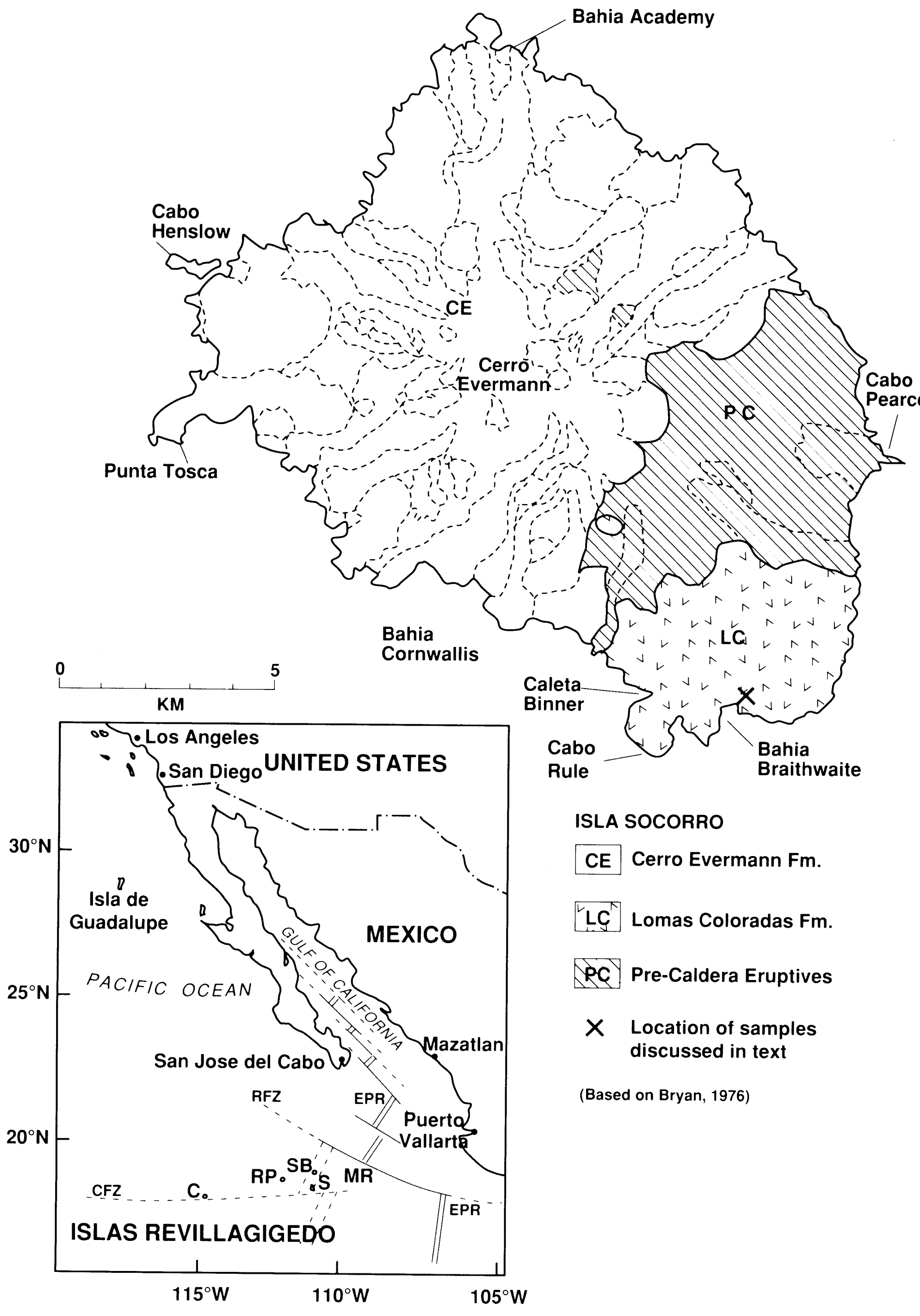

Fig. 1. Generalized geological map of Socorro Island, showing important place names, sample location and major lithostratigraphic units (after Bryan 1976) with inset of regional map of the Eastern Pacific showing the location of major sea floor features and Revillagigedo Islands. (EPR= East Pacific Rise; MR= Mathematician Ridge; RFZ= Rivera Fracture Zone; CFZ= Clarion Fracture Zone; SB= San Benedicto Island; S= Socorro Island; C= Clarion Island; RP= Roca Partida Island).

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1964, 1966). Continuing interest in the tectonics of rift propagation and abandonment (Hey & Wilson 1982; Mammerickx, Naar & Tyce 1988) and the petrogenesis of alkalic magmas in failed rift settings (Batiza & Vanko 1985; Castillo *et al.* 1988; Bohrson, Reid and Grunder 1991) underscore the significance of present geologic studies.

The Revillagigedo Islands exhibit high faunal and floral endemism (Brattstrom 1990; Walter 1989 a,b), suggesting the existence of viable island habitats for at least several hundred thousand years (H. Walter, personal communication 1990). However, previous attempts to date the volcanic sequences on Socorro Island by potassium-argon (K-Ar) and argon-argon (Ar-Ar) methods have met difficulties, perhaps from inherited argon, or because the island is geologically very young.

We conducted reconnaissance fieldwork in the summer of 1990. Given the apparently young age of rocks on Socorro, our approach emphasized the search for sedimentary facies (*e.g.*, lacustrine, fluvial, paleosol horizons) that could be ^{14}C dated. We believe that this approach, coupled with palynologic or other biostratigraphic techniques, will eventually provide a reliable basis for developing a chronostratigraphic framework for Socorro Island. Here, we report ^{14}C ages for lacustrine/paludal deposits that we discovered within volcanic sequences of the Lomas Coloradas area.

We hope that our preliminary work will heighten awareness of the potential volcanic hazard to the resident population. The major population center on Socorro Island is located in the southern Lomas Coloradas at Cabo Rule (Fig. 2). Explosive eruptions devastated San Benedicto Island in 1952 (Richards 1959, 1966; Brattstrom 1963); this, along with the young age of volcanism indicated by our study, serves to direct attention to the regional volcanic hazard. This concern was amplified in early 1993 when explosive eruptions occurred *ca.* 2.4 km west of Socorro Island (personal communication, RIDGE Office, February 1993).

Eruptive history of Socorro Island

Despite abandonment of the Mathematician Ridge as an active spreading center by 3.15 Ma BP (Mammerickx, Naar and Tyce 1988), the Revillagigedo Islands have remained volcanically active. Richards and Dietz (1956) discussed in detail the recent eruptive history of Socorro Island. Explosive eruptions apparently occurred on Socorro Island in 1848, 1896 and 1953, although the activity was poorly documented and reportedly very localized. Present activity on the island seems to be restricted to fumaroles near the summit of Cerro Evermann, and steam emissions from several lava tunnels on the southwest side of the island.

Three primary eruptive phases are recognized in the stratigraphic record of Socorro Island (Bryan 1959, 1966, 1976). The earliest period was a shield-building phase that created the submerged portion of the island; Bryan (1966) suggested that the volcanoes emerged as islands in the late Tertiary. Based on sea-floor ages in the area, the Mathematician Ridge was active as a spreading center between *ca.* 6.5 and 3.0 Ma BP (Mammerickx & Klitgord 1982; Mammerickx, Naar & Tyce 1988). The stratigraphically oldest rocks on the island are thin flows of alkalic basalt (transitional to tholeiite), which are exposed in the sea cliffs at Cabo Pearce (Fig. 1). This early phase apparently preceded an explosive period when peralkaline silicic pyroclastics were erupted, mostly as ash flows, accompanying caldera collapse (Bohrson, Reed & Grunder 1991). This was followed by a period of quiescence, weathering and paleosol development (Bryan 1966). The most recent eruptive period was initiated by downfaulting of the western half of the island, accompanied by pyroclastic eruptions and pumice/obsidian flows that built Cerro Evermann, filling and largely obliterating the caldera. Late in this period, viscous rhyolite and trachyte flows issued from high-level vents on Cerro Evermann (Bryan 1966).

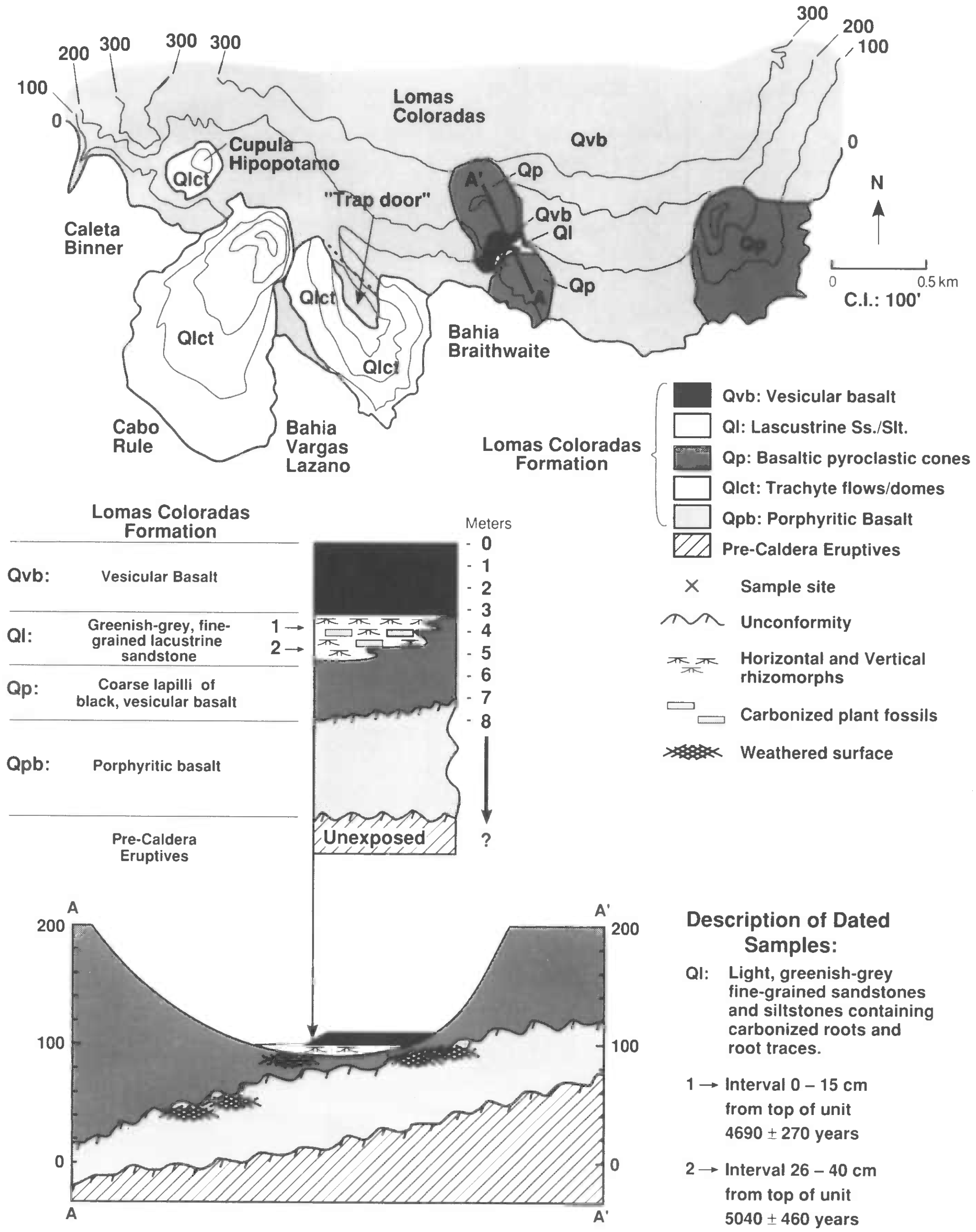

Fig. 2. Composite topographic-geologic map of the Lomas Coloradas area of south Socorro Island (after Bryan 1959), with a generalized cross-section (A-A') and stratigraphic column for sample location (X), located just north of Bahia Braithwaite. The older units of the Lomas Coloradas are porphyritic alkalic basalt flows (Qpb) that erupted on the lower slopes of Cerro Evermann. Dated samples were obtained from lacustrine deposits (Ql) associated with the pyroclastic cones (Qp) north of Bahia Braithwaite. The youngest unit is a thin, vesicular basalt flow (Qvb) that erupted from a small fissure at the base of the northernmost pyroclastic cone (Qp) near the sample location (X). The pyroclastic cones and trachyte domes postdate alkalic fissure basalts (Qpb) that underlie the Lomas Coloradas. The relative ages of the trachyte domes and pyroclastic cones (Qp) remain unresolved; they may actually overlap. (Reprinted with permission of author)

In the southeastern portion of the island, flows of alkalic basalt erupted extensively from lower elevation fissures and vents located near a line of pyroclastic cones that bound the upper slopes of the Lomas Coloradas. These flows range from porphyritic alkalic basalt to aphyric hawaiite (Bohrson, Reid & Grunder 1991), and cover *ca.* 15 km^2 at the southeastern end of the island. Although areally extensive, the basalts are volumetrically insignificant, averaging <30 m thick (Bryan 1966).

Northeast of Caleta Binner (Fig. 2), the alkalic basalts of the Lomas Coloradas are overlain by cones and domal extrusions of peralkaline trachyte. These stratigraphic relations are exposed in the creek along the northwest side of the small trachyte dome designated "Cupula Hipopotamo" in Figure 2 (see also Bryan 1959). In this area, a bulbous mass of trachyte was extruded onto basalt flows of the Lomas Coloradas. The trachyte dome immediately west of Bahia Braithwaite exhibits a similar relation, where a slab of Lomas Coloradas basalt (the "trap door" structure of Bryan 1959) was uplifted to an elevation 150–200 m above the surrounding flow surface by intrusion of the trachyte dome immediately west of Bahia Braithwaite (Fig. 2). As dome growth proceeded, trachyte flows eventually broke through and were extruded onto the uplifted surface of the basalt flow (Bryan 1959).

Sample Location

The sample locality is in the southern portion of the Lomas Coloradas, in "a peculiar area of flat-lying, tuffaceous sediments between two scoria cones near Bahia Braithwaite. . ." (Bryan 1959: 61). Stratigraphic relations are best exposed in the saddle area between the two cinder cones (Figs. 2, 3A) and within the southerly flowing drainage that bounds the scoria cones to the east (Fig. 3B). The cones differ compositionally, the northern one being peralkaline trachyte, the southern one, hawaiite (Wendy Bohrson, personal communication 1991). Interfingering of the basal pyroclastic units of the two cones suggests temporal overlap, although the southern cone appears to have persisted longer.

The two scoria cones north of Bahia Braithwaite sit upon the gently, seaward-sloping surface formed by alkalic basalt flows of the lower Lomas Coloradas. Along the eastern margin of the southern cone, the creek has exposed the upper surface of the flows, which are mantled by 20–30 cm of buff-colored, fine-grained tuffaceous sandstone. At the base of this unit is a thin, irregular deposit of matrix-supported, reddish-brown conglomerate containing weathered boulders derived from the underlying basalt. This sequence is overlain by a massively bedded pyroclastic deposit of coarse, black, vesicular lapilli, which forms the base of the southern cone. The cinder deposit is interstratified with fine-grained, moderately indurated, tuffaceous sandstone and siltstone, which is exposed along the creek to the southeast (Fig. 3B), and further west, between the two cones.

In the saddle between the cones (Fig. 3B, arrow) the lower contact of the sandstone-siltstone sequence is gradational with the underlying cinder deposit, which has been extensively weathered, locally, to a rusty yellow color. The lower 5 cm of the sequence contains a dense zone of vertically oriented rhizoliths (root traces) that are preserved as casts in a friable, iron oxide-cemented sandstone. Above this zone is a thinly bedded, light greenish-gray tuffaceous sandstone and siltstone that weathers tan to rusty brown. Extensive, horizontal networks of branching root traces are preserved as casts on several of the exposed bedding plane surfaces (Fig. 4B, arrows). In addition, silicified roots and branches (up to 1 cm in diameter), small fragments of carbonized plant material, and rare, back-filled burrows, were found at several horizons within the deposit.

Fig. 3A. View eastward across Bahia Braithwaite from the trachyte dome just west of the "trap door" structure in Fig. 2. Arrow indicates "saddle area" between scoria cones, where dated samples were collected.

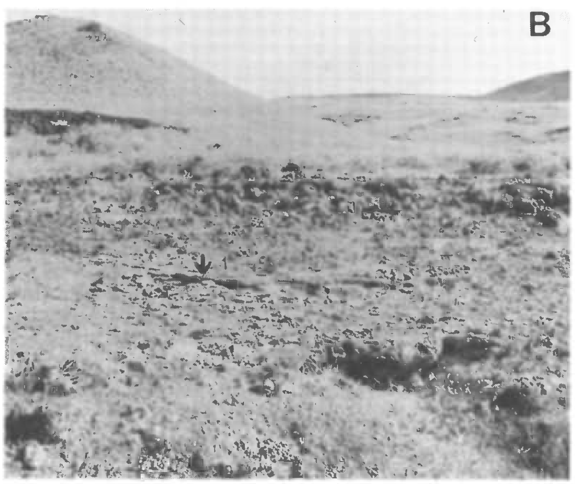

Fig. 3B. View looking northeast from within the saddle area indicated by arrow in Fig. 3A. Rock hammer to right of arrow in center of photo rests upon lacustrine sandstones (Ql) near position of oldest dated horizon (Sample 1, UCLA-2618, Fig. 2). The lacustrine deposit is overlain locally by a black vesicular basalt, Qvb, (upper left at base of cone), the stratigraphically youngest unit in the map area. This flow issued from fissures near the base of the northern cone, and flowed downslope, entering the upper part of the stream drainages that breached the cones from the east and west.

Retallack (1988) points out that fossil root traces are best preserved in formerly waterlogged sedimentary profiles. The location of the deposit in the low area between the scoria cones, the well-sorted nature of the sediment, absence of marine indicators and abundance of plant fossils, suggest deposition in a terrestrial aquatic (lacustrine) or perhaps paludal (swampy) environment, similar to the ephemeral lakes that are found within the craters of some cinder cones on the west side of Socorro Island (*e.g.*, Lago Luna, Fig. 3 of Bryan 1959). The lacustrine units exhibit a broadly lenticular geometry and low-angle cross-bedding that dips gently to the north, toward the saddle area (Fig. 4A). The extensively developed, *in-situ* root networks, fine-grained and well-sorted texture of the sediments and abundance of organic material argue strongly against a pyroclastic surge origin for the sampled units.

A black, fine-grained, vesicular basalt overlies the lacustrine deposit in the saddle area between the two cones (Fig. 3B). The flow, which attains a maximum thickness of *ca.* 3 m, moved south a short distance from an east-west oriented fissure at the base of the northern cone. Apparently, the present drainage system existed prior to this eruption, because lobes of this flow moved downslope

Fig. 4A. View looking southwest from creek bounding the study area on the east. Outcrop in foreground exposes well-stratified lacustrine sandstones (Ql, arrow) underlain by a cinder deposit containing coarse lapilli of fine-grained, vesicular basalt, which makes up the base of the southernmost cone (hill in background). Note the northward-dipping, low-angle cross-stratification of the lower beds of the sandstone sequence, which thicken toward the saddle area between the two cones.

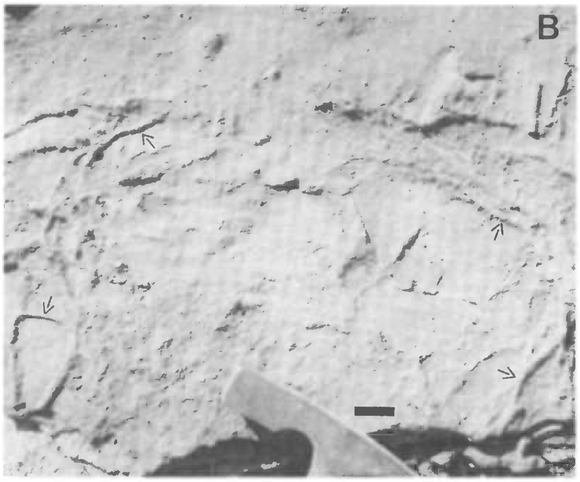

Fig. 4B. Bedding plane exposure of lower part of lacustrine sequence (Ql) at the location of the arrow shown in Fig. 3B. The bedding plane surface is covered by a dense, branching network of horizontal root casts (rhizoliths) and permineralized wood. Scale bar is 2.0 cm.

and into the stream valleys that incise the saddle area from the east and west. The eastern lobe of the flow evidently moved beyond the lateral extent of the lacustrine sequence and far enough downslope so that, in places, the distal edges actually lie at a lower elevation than the stratigraphically older lacustrine sequence. This relation is most visible in the southerly flowing stream that bounds the area to the east. At that location, erosion has stripped back the edge of the younger flow, exposing its basal contact, an irregular unconformable surface lying just above the weathered surface of the older alkalic basalts of the Lomas Coloradas Formation.

Methods and Results

We collected bulk sediment samples for ^{14}C dating from two intervals within the fossiliferous lacustrine sequence described above (see Fig. 2; Locality 83901C, Samples UCLA-2617 and -2618. The samples were collected from fine-grained, greenish-gray sandstones and siltstones containing permineralized roots, root traces and carbonized woody material (Fig. 4B). To minimize contamination from younger sources (*e.g.*, the grass-covered slopes above the outcrops), we collected samples by excavating back about 1 m from the surface of the outcrop. Samples were wrapped in aluminum foil, or dropped into sterile glass vials and sealed with screw caps over aluminum foil, placed in zip-lock bags and double-bagged in plastic-coated cloth bags.

Samples were pretreated first by mechanically removing root hairs, *etc.,* to free them from gross contamination. Thereafter, samples were treated with dilute HCl to remove carbonate (found to be minimal). After repeated washing with distilled water, samples were placed in dilute, carbonate-free NaOH to eliminate any humic acids introduced from hypothetical younger sources. Samples were then washed with distilled water, and oven-dried at 110°C for several days. Standard lab procedures were used to obtain analytically pure CO_2 from the samples, which were stored for more than a month in pressure cylinders to allow radon decay. They were then proportionally counted in a 200-ml anticoincidence system with the following results:

Sample interval: UCLA-2617 (0–15 cm below top of bed): 4690 ± 270 BP (5000–5700 cal BP)
Sample interval: UCLA-2618 (26–40 cm below top of bed): 5040 ± 460 BP (5300–6300 cal BP).

Discussion

Although the results obtained for the two samples are consistent with the expected relative age relationships based on stratigraphic order, the ^{14}C ages overlap for the sampled intervals and have a 50% probability of being contemporaneous (Austin Long, personal communication). Averaging the results for the two sample intervals gives an age estimate of 5575 cal BP. Combining the ages plus errors for the two intervals suggests a maximum age range of 5000–6300 cal BP.

Given the proposed geomorphic setting for the dated deposits, namely, a crater basin with internal drainage, it seems reasonable that a lacustrine/paludal environment would have developed there rather quickly, probably within tens to hundreds of years after the formation of the scoria cones. Sedimentologic evidence suggests that lacustrine deposition was fairly continuous over the time interval sampled and was apparently uninterrupted by pyroclastic eruptions. Thus, we believe that the age of the lacustrine deposits approximates the end of the pyroclastic activity that created the cones.

It is likely that the lacustrine environment that existed at this site was short-lived and that breaching and capture of the internal drainage by existing streams terminated deposition. The saddle area then became a site of erosion. Some time after erosion began, a thin vesicular basalt flow erupted from fissures at the base of the northernmost cone. Lobes of this young flow extend downslope to the east and west, entering the existing stream drainages. This indicates that the eruption postdates establishment of the present drainage system and, therefore, may be very young.

Without exception, the scoria cones and trachyte domes of the Lomas Coloradas are superimposed on the more widespread flood basalts, indicating that this activity postdates the fissure eruptions that created the southern portion of the island. The cones and domes do not overlap spatially, and their relative ages cannot be determined using field stratigraphic methods. Therefore, the relative timing of dome emplacement and the pyroclastic eruptions that produced these younger units, is presently unresolved. However, weathering profiles suggest that they may be similar in age.

Wave-cut terraces and coral platforms have been recognized on many islands (Stearns 1945) and coastal areas (Upson 1951) around the Pacific, lying at *ca.* 2 m asl. Bryan (1959) documented a well-developed coral bench near this elevation on Clarion Island. The age of the "2-m" terrace in the Pacific is not well-defined, although Stearns (1945) suggested an age of *ca.* 5000 BP. A comparable terrace has not yet been identified on Socorro Island, and Bryan (1959) suggested that it may have been buried by younger flows (*e.g.*, the flows that created the Lomas Coloradas). If we accept an age of *ca.* 5000 BP for the terrace on Clarion, and attribute its absence on Socorro to burial by younger flows, it follows that the basalts of the Lomas Coloradas must be younger than this estimate. In this study, we establish that the lacustrine deposits overlying Lomas Coloradas basalts are between 5000 and 6300 cal BP. Adopting this scenario significantly compresses the time frame available for creation of the Lomas Coloradas to an interval of perhaps a few hundred years, separating the development of the 2-m terrace and the cessation of lacustrine deposition at the study site. A corollary of this hypothesis is that the most recent phase of volcanism on Socorro Island is younger than that on Clarion.

We emphasize, however, that the age of the terrace on Clarion Island is presently unknown. Given the controversy surrounding late Holocene eustatic sea-level change (Goudie 1983; Newman, Pardi & Fairbridge 1989), it is not possible to place any confidence in the implied age of 5000 BP for the 2 m terrace on Clarion. Further evaluation of the above hypotheses will depend on 1) obtaining a radiometric age for the Clarion terrace, and 2) demonstrating the presence or absence of a comparable terrace on Socorro Island.

Geochemical and isotopic studies suggest a complex magmatic history for Socorro Island (Bohrson, Reid & Grunder 1991). Data from such studies, in combination with palynologic methods, may eventually provide the most reliable basis for correlating stratigraphic units and constructing a relative time scale of events. However, establishment of an absolute chronology, particularly for the younger sequences on Socorro Island, may require the targeting of non-volcanic facies (*e.g.*, lacustrine deposits, paleosols), which can be ^{14}C dated.

The suggestion that the Lomas Coloradas has a very recent origin is important for assessing volcanic risk. Given the remote location of Socorro Island, it seems prudent at this time to develop a volcanic hazards plan that will afford some measure of safety to the resident population. This is evident when we recall the devastation that resulted from the 1952 eruption of Volcán Bárcena on San Benedicto Island. Shortly after this eruption, a small seismic station was installed on Socorro. In recent years, the seismic station has not been maintained. During our field season in 1990, we experienced several small-magnitude earthquakes that suggested the possibility of subsurface magma movement. In addition, eruptions were reported a few kilometers west of Socorro in early 1993 (RIDGE office, personal communication, February, 1993). Accordingly, we recommend that seismic monitoring on Socorro Island be resumed immediately to assist in developing an ongoing program of volcanic risk assessment.

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