Pleistocene volcanism along the margins of the Canal de Ballenas transform fault, Gulf of California

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ABSTRACT

Pleistocene subaerial volcanism along the margins of the Ballenas Channel, northern Gulf of California, is represented by two morphologically young dacite dome complexes exposed at the opposite edges of sheared continental crust: Isla Coronado in coastal Baja California, and the Lobera volcanic complex in west-central Isla Ángel de la Guarda. Single crystal zircon U-Pb crystallization ages of Coronado and Lobera volcanoes range between ca. 250 and 1000 ka, indicating maximum ages for the eruptions. Eruption ages are directly constrained by an 40Ar/39Ar whole-rock age of 692 ± 164 ka for one of the lava units in the Lobera volcanic complex. Trace elements in Pleistocene zircon indicate continental affinity, which supports radiogenic (Nd, Sr) isotopic data that were modeled using different mixing and AFC scenarios indicating a MORB-type primary magma with significant (~10–20 %) crustal assimilation involving tonalitic basement of the eastern Peninsular Ranges Batholith.

Keywords: Gulf of California; Ballenas fault; evolved volcanism; geochronology; geochemistry; Mexico.

INTRODUCTION

The Gulf of California hosts the trans-tensional domain of the Pacific-North America plate boundary (Fletcher et al., 2014). This boundary is defined by lengthwise dominant transform faults that contain an en-echelon array of pull-apart basins at variable stages of crustal separation and sea-floor spreading (Figure 1). The maturity of the pull-apart basins and their interconnecting transform faults decreases north of the Guaymas basin where the Guaymas transform fault splays into several strike slip faults that shear continental crust (Lonsdale, 1989). The geological transition from mature oceanic spreading centers and transform faults in the southern Gulf of California to typically much smaller basins in the northern Gulf of California coincides with major oceanographic and faunal changes in the region of the so-called Midriff Islands which include Isla Ángel de la Guarda, San Esteban, and Tiburón (Figure 1).

Within the Ballenas channel, an ~80 km long submarine continental transform fault system separates the Baja California peninsula from Isla Ángel de la Guarda. The Ballenas Transform Fault (BTF) juxtaposes continental crustal blocks of similar structure and composition along most of its length: on the east side, the continental block of Isla Ángel de la Guarda has become part of the North American plate, whereas the Baja California peninsula moves with the Pacific plate, with both blocks passing each other at a velocity of 47.3 ± 0.8 mm/yr (Plattner et al., 2015). It further connects two young rift basins, the Lower Delfín basin to the north, and the more diffuse Ballenas and Salsipuedes basins in the south (Figure 1). The length of new oceanic crust is < 20 km for the Lower Delfín basin, where new crust is inferred to occupy a narrow rift with several submarine volcanoes located in the axial trough and over the faulted margins (Persaud et al., 2003). The extent of new oceanic crust is likely smaller in the Salsipuedes basins where new crust is inferred to occupy several submarine volcanoes located in the axial trough and over the faulted margins (Persaud et al., 2003). The extent of new oceanic crust is likely smaller in the Salsipuedes basins (Figure 1), although multibeam bathymetry also depicts volcanoes in the southern Salsipuedes and the centrally located Ballenas basins (Plattner et al., 2015). The seamounts in the Ballenas basin form a north-northeast alignment of small volcanoes that projects south onto Isla Coronado (ICO), locally also referred to as Isla Smith (Figure 2). This island is a 300 m-high dacite dome offshore the Main Gulf Escarpment where continental crustal rocks are down-faulted towards the basin. Another volcanic field occurs in the west central part of Isla Ángel de la Guarda, which shows a more pristine morphology compared to the regional volcanic deposits of Miocene age (Figure 2). This newly defined Lobera Volcanic Complex (LVC) is named after the eponymous seal colony (lobo marino) that permanently occupies the clifffy shore of the LVC.

RESUMEN

El volcanismo del Pleistoceno a lo largo de los márgenes del Canal de Ballenas, norte del Golfo de California, está representado por dos domos dacíticos que afloran en lados opuestos de la zona de cizalla continental: Isla Coronado en la costa de Baja California y el complejo volcánico La Lobera en la costa oeste de Isla Ángel de la Guarda. Las edades de cristalización obtenidas por el método U-Pb en circones individuales, varían entre ca. 250 y 1000 ka e indican la edad máxima de erupción. La edad de erupción está directamente acotada por una edad Ar-Ar en roca total de 692 ± 164 ka en uno de los flujos de lava en el complejo volcánico La Lobera. La composición de elementos traza en circones indica una afinidad continental, lo cual es consistente con datos isotópicos de Nd y Sr. Los datos isotópicos se modelaron utilizando diferentes escenarios de mezcla, asimilación y cristalización fraccionada (AFC) e indican un magma primario MORB con asimilación cortical significativa (~10 a 20 %) del basamento tonalítico peninsular.

Palabras clave: Golfo de California; falla Canal de Ballenas; volcanismo diferenciado; geocronología; geoquímica; México.
To better understand the timing and origin of magmas in sheared and thinned transitional continental crust, we investigate volcanic rocks from ICO and the LVC on Isla Ángel de la Guarda. Their youthful, but not quite pristine morphology (cf. Isla San Luis; Paz-Moreno and Demant, 1999), is consistent with Pleistocene activity, but no radiometric age constraints have been reported so far. In this paper we present U-Pb zircon and Ar-Ar whole-rock geochronologic data to constrain magmatic differentiation and eruption ages, and report reconnaissance major and trace element geochemistry as well as Nd-Sr isotopic compositions of lavas to evaluate the source and composition of parental magmas in this important transitional part of Gulf of California rift zone.

TECTONIC AND GEOLOGIC FRAMEWORK

The BTF accommodates nearly all of the Pacific-North America plate motion in the northern Gulf of California, with less than ~10 % of plate motion occurring along the Tosco-Abreojos fault in the Pacific margin of Baja California (Plattner et al., 2007). It connects two proto-oceanic pull-apart basins, the Lower Delfín in the north and the Ballenas-Salsipuedes basins located in southeast end of the BTF (Figure 1). This transform fault developed in the late Pliocene when the Tiburón continental transform fault became inactive and the main plate boundary shifted west into the BTF, resulting in the capture of the continental block of Isla Ángel de la Guarda (Aragón-Arreola and Martín-Barajas, 2007; Martín-Barajas et al., 2013).

Low-temperature thermochronology of crystalline rocks onshore the Ballenas transform margin in Baja California suggests that dextral shearing and uplift of the transform margin in Baja California occurred by ~1.8 Ma (Seiler et al., 2009). Furthermore, correlation of distinctive volcanic deposits across the Ballenas Channel constrains dextral offset in the BTF between ~100 and 130 km (Stock et al., 2009). This displacement is broadly consistent with the ~90 km length separation of continental crust in both the Upper and Lower Delfín basins based on interpretation of industry seismic profiles (Martín-Barajas et al., 2013; Téllez-Velázquez, 2018).

Extension in the Lower and Upper Delfín basins is transferred to dextral shear in the BTF and has detached the continental block of Isla Ángel de la Guarda from the Baja California peninsula. Although the BTF concentrates most of the North America – Baja California relative motion, the capture of Isla Ángel de la Guarda is probably incomplete.

Figure 1. a). Simplified tectonic map of the Gulf of California rift zone with the Pacific (PAC) – North America (NAM) plate boundary (in red). Abbreviations for pull-apart basins (overview) S = Salton Trough, CP = Cerro Prieto, W = Wagner, D = Delfín, G = Guaymas, C = Carmen, F = Farallón, P = Pescador, A = Alarcón, EPR = East Pacific Rise, IT = Isla Tiburón, SE = Isla San Esteban. b). Bathymetry and topography map of the Canal de Ballenas Transform fault zone and the Lower Delfín basin at the northwest end. Red spots and stars are Plio-Pleistocene volcanoes. Major faults from Plattner et al (2015) and Martín-Barajas et al. (2013). Abbreviations (main map): IAG = Isla Ángel de la Guarda, ICO = Isla Coronado, BA = Bahía de los Ángeles, BB = Ballenas basin, TB = Tiburón basin. Bathymetry and topography is from the GEBCO_2021 Grid. Isobaths are 200 m contours.
as Quaternary deformation in the south part of Isla Ángel de la Guarda produces a north-northeast trend of normal and oblique faults (Higa et al., 2022), and significant historic seismicity is reported east of the BTF (Castro et al., 2017).

Magmatism in this young rift-transform system is ubiquitous, and submarine volcanoes are identified in high-resolution seismic profiles (Persaud et al., 2003; Hurtado-Brito, 2012), and sea-beam bathymetry (Plattner et al., 2015). Some of these submarine volcanoes are rhyolite and andesite pumice cones (Martín-Barajas et al., 2008; Heney and Bishop, 1973), and a seamount reported by Plattner et al. (2015) in the Ballenas basin is composed of basaltic lava (P. Lonsdale written comm.) (Figure 2). The ICO and LVC volcanoes may represent magmatic activity at the intersection between rift basins and transform faults under the influence of adjacent continental crust that is being actively sheared along the transform boundaries.

GEOCHEMISTRY AND GEOCHRONOLOGY METHODS

Whole rock geochemistry

Several kilograms of non-weathered rock were crushed and sieved, and ~250 grams of rock chips 2 to 5 mm in diameter where hand-picked and cleaned with deionized water in ultrasound bath, and then treated with deionized water. Rock chips were grounded in a Tungsten carbide ring mill into a powder of <60 µm. Major oxide and trace element composition was obtained by XRF and ICP-MS, respectively at the Peter Hooper GeoAnalytical Laboratory at Washington State University (WSU) in Pullman, Washington (Table 1). Analytical procedures and uncertainties for major oxides and trace elements using XRF are described in Hooper et al. (1993). Precision for the ICP-MS analysis is typically better than 5 % (RSD) for the rare earth elements (REE) and 10 % for the remaining trace elements (see Technical notes of the WSU GeoAnalytical Lab web page).

Sm-Nd-Sr isotope geochemistry

Chemical preparation for whole-rock isotope analysis (Table 2) was performed in PicoTrace clean lab facilities at Departamento de Geología, Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE) in the state of Baja California (Mexico). About 100 mg of powdered rock sample was weighed together with 44Sr-144Nd-149Sm tracer solutions into Teflon bombs of a Picotrace DAS® pressure digestion system and dissolved in a mixture of HF, HNO3 and HClO4 at ca. 165 °C. After evaporation and sample-spike equilibration, Sm, Nd, and Sr element separation was achieved in two steps, first with quartz-glass columns filled with DOWEX AG 50W-X8 resin to separate Sr and REE and then with Ln-Spec® resin to separate Nd (Weber et al., 2012). Samarium, Nd and Sr isotopes were analyzed by thermal ionization mass spectrometry (TIMS). The LVC samples were analyzed with a Thermod Triton Plus® installed at Laboratorio Universitario de Geología Isotópica (LUGIS) of the Universidad Nacional Autónoma de México (UNAM), Mexico City (e.g. Weber et al., 2012), whereas ICO samples were measured with a Nu Instruments equipment (Nu-TIMS) at CICESE (e.g., Cisneros de León et al., 2019). Correction for mass bias for Sr and Nd was achieved by normalizing to 86Sr/88Sr = 0.1194 and 146Nd/144Nd = 0.7219, respectively. Neodymium standards JNd-1 and La Jolla analyzed in the same run as the unknowns yielded 143Nd/144Nd = 0.512106 ± 4 (2 s.e.) and 0.511831 ± 4, respectively. Strontium NIST 987 standard yielded 87Sr/86Sr = 0.710258 ± 7 (2 s.e.).

U-Pb and U-Th zircon geochronology and trace element analysis

The ICO and LVC rocks are zircon poor, and >60 kg of rock had to be processed to extract ~20 zircon crystals per sample. Crystals were handpicked and mounted in epoxy, sectioned and polished, and imaged using a cathodoluminescence detector. Secondary ionization mass spectrometry analyses of ICO and LVC zircon crystals were carried out on the UCLA CAMECA ims 1270 and the Heidelberg University CAMECA ims 1280, respectively, using methods for U-Pb and U-Th geochronology described in Schmitt et al. (2003) and Schmitt et al. (2010). All U-Pb ages are reported against AS3 reference zircon (1099 Ma), and analytical accuracy was monitored through analysis of 91500 reference zircon for which an age of 1082 ± 18 Ma (n = 6; mean square of weighted deviates MSWD = 0.46) was obtained. Radiogenic 206Pb/238U and corresponding ages were determined from the concordia intercept of a linear regression in a Tera Wasserburg concordia diagram with a fixed y-axis intercept corresponding to 238U/206Pb = 0.828 (Stacey-Kramers model Pb for 0 ka; Stacey-Kramers, 1975); only for xenocrystic zircon >20 Ma, 206Pb-corrected 206Pb/238U or 207Pb/206Pb (>500 Ma) ages are reported using corresponding Stacey-Kramers model Pb compositions. The U-Th relative sensitivity factor (RSF) was calibrated following Reid and Coath (1997) and monitored by analyzing AS3 reference zircon for which a secular equilibrium value of 230Th/206Pb = 1.004 ± 0.036 Ma (n = 5; MSWD = 0.01) was determined. An isochron age was fitted through the data to determine the U-Th age, excluding xenocrystic (secular equilibrium) crystals identified by U-Pb dating. Trace elements were analyzed by SIMS on the instruments stated above with analytical procedures described in...
Table 1. Major oxides (wt%) and trace elements (ppm) content in lavas from Isla Coronado (ICO) and Lovera volcanic complex (LVC) in Isla Ángel de la Guarda.

| Sample ID  | IAG07–40 | IAG07–38 | ICO08–1 | ICO08–2 | ICO08–3 |
|------------|----------|----------|----------|----------|----------|
| Area/Unit  | Lobera Qv2 | Lobera Qv1 | 1 Coronado | 1 Coronado | 1 Coronado |
| Lat N      | 29° 18’ 40.13” | 29° 18’ 36.23” | 29° 5’ 16.62” | 29° 5’ 49.62” | 29° 5’ 49.62” |
| Lon W      | 113° 29’ 14.2” | 113° 30’ 20.1” | D | 113° 30’ 43.3” | 113° 31’ 46.7” |
| Lithology  | D | D | D | D | D |
| SiO₂       | 64.33 | 67.9 | 67.38 | 68.73 | 67.37 |
| TiO₂       | 0.86 | 0.47 | 0.47 | 0.47 | 0.47 |
| Al₂O₃      | 15.74 | 15.55 | 15.64 | 14.95 | 14.95 |
| FeO*       | 4.85 | 3.48 | 3.39 | 3.25 | 3.25 |
| MnO        | 0.09 | 0.07 | 0.07 | 0.07 | 0.07 |
| MgO        | 1.43 | 1.4 | 1.19 | 1.09 | 1.09 |
| CaO        | 4.35 | 4.09 | 3.62 | 3.59 | 3.59 |
| Na₂O       | 4.69 | 4.7 | 4.76 | 4.72 | 4.72 |
| K₂O        | 0.25 | 0.14 | 0.14 | 0.14 | 0.14 |
| LOI (%)    | 0.83 | 0.08 | 0.08 | 0.08 | 0.08 |
| Trace elements ICP-MS |
| La | 16.13 | 14.61 | 14.76 | 15.24 | 16.77 |
| Ce | 35.58 | 32.77 | 31.44 | 32.71 | 35.86 |
| Pr | 4.8 | 4.08 | 4.26 | 4.65 | 4.65 |
| Nd | 20.04 | 18.77 | 16.93 | 17.58 | 19.26 |
| Sm | 4.97 | 4.73 | 3.93 | 4.11 | 4.49 |
| Eu | 1.34 | 1.02 | 1.08 | 1.13 | 1.13 |
| Gd | 5.03 | 3.88 | 4.2 | 4.55 | 4.55 |
| Tb | 0.85 | 0.66 | 0.7 | 0.75 | 0.75 |
| Dy | 5.1 | 4.03 | 4.32 | 4.79 | 4.79 |
| Ho | 1.08 | 0.83 | 0.9 | 0.99 | 0.99 |
| Er | 2.96 | 2.26 | 2.47 | 2.76 | 2.76 |
| Tm | 0.44 | 0.34 | 0.36 | 0.41 | 0.41 |
| Yb | 2.68 | 2.13 | 2.29 | 2.51 | 2.51 |
| Lu | 0.42 | 0.34 | 0.37 | 0.4 | 0.4 |
| Ba | 688.54 | 757.53 | 752.74 | 676.19 | 693.51 |
| Th | 3.95 | 3.11 | 3.34 | 3.98 | 3.98 |
| Nb | 5.6 | 4.67 | 4.94 | 5.31 | 5.31 |
| Y | 27.82 | 21.89 | 23.06 | 25.65 | 25.65 |
| Hf | 4.4 | 4.38 | 4.62 | 4.91 | 4.91 |
| Ta | 0.43 | 0.34 | 0.36 | 0.4 | 0.4 |
| U | 1.38 | 1.04 | 1.15 | 1.35 | 1.35 |
| Pb | 8.84 | 7.75 | 8.31 | 8.8 | 8.8 |
| Rb | 41.93 | 35.13 | 38.9 | 45.8 | 45.8 |
| Cs | 1.31 | 1.17 | 1 | 1.7 | 1.7 |
| Sr | 410.13 | 472.91 | 466.13 | 433.95 | 433.95 |
| Sc | 10.62 | 8.2 | 8.3 | 8.1 | 8.1 |
| Zr | 164.08 | 168.7 | 158 | 169 | 182 |

Schmitt and Vazquez (2017). NIST SRM 610 glass with trace elemental abundances of Pearce et al. (1997) was used to determine RSF values for high energy ions (-100 eV offset). 91500 reference zircon was analyzed in the same session for monitor accuracy, and only minor deviations from nominal values (Wiedenbeck et al., 2004 for Hf, REE, and U; Szymanowski et al., 2018 for Ti) were observed, which for the plotted elements are +3.7 % (Eu/Eu*), +2.4 % (Hf), +4.7 % (Ti), +3.4 % (Y), +2.8 % (Yb), and +14.7 % (U).

Ar-Ar geochronology

Isotopic dating by ⁴⁰Ar/³⁹Ar was performed in the Geochronology Laboratory at CICESE using a VG5400 mass spectrometer and laser step-heating experiments. One whole-rock sample of the LVC was ground (355–710 µm), washed with de-ionized water, and cleaned under a stereomicroscope to eliminate phenocrysts and altered material. The samples were irradiated in the nuclear reactor at the University of McMaster in Hamilton, Canada, for 10 hours at 2 MW/hour. Samples FCT-2 (28.201 ± 0.046 Ma; Kuiper et al, 2008), and TCR-2 (24.34 ± 0.28 Ma; Renne et al., 1998) were used as internal standards (see Supplementary Material). The Ar extraction line include a laser beam connected in line with the mass spectrometer. Aliquots of atmospheric composition were analyzed at the end of each day to correct for discrimination effects of the mass spectrometer. Argon isotopes were corrected for radioactive decay of ³⁷Ar and ³⁹Ar. Corrections...
for interfering reactions of isotopes of Ca and K were applied using the factors reported by Bottomley and Yorke (1976) for the McMaster reactor. The Cl interference on 36Ar suggested by Roddick (1983) was also corrected, and the constants recommended by Steiger and Jäger (1977) were applied in all the calculations. The samples were laser-heated between 0.3 and 7.0 W. The integrated age was calculated by abundance addition for each fraction, and the error in the integrated age includes the uncertainty due to factor J; all errors are reported at 1σ level (Table S1 in the Supplementary Material).

RESULTS

Lobera Volcanic Complex (LVC)

We conducted field reconnaissance and satellite spectral analysis on EO-1 data and Google Earth images of the LVC in the western-central part of Isla Ángel de la Guarda (Figure 3). LVC is a composite lava dome complex with three main lava units, the lower lava unit (Qv1) is exposed at the northwest cliffy shore (sample IAG07-38; supplementary Figure S2), but its vent location is obscured. The eroded cliff indicates

| Sample ID | Field description | Unit | Sr (ppm) | 87Sr/86Sr | 2 s.e. ×10⁶ | Sm (ppm) | Nd (ppm) | 147Sm/144Nd | 143Nd/144Nd | 2 s.e. ×10⁶ | εNd (a) |
|-----------|-------------------|------|----------|---------|-------------|----------|----------|-------------|------------|-------------|--------|
| IAG07-40  | Dark grey, blocky lava at the top of Qv2, aphanitic | Qv2  | 413      | 0.704341 |          | 4.43     | 19.2    | 0.1494     | 0.512822   | 4           | 3.75   |
| IAG07-38  | Black glassy lava flow with columnar structure | Qv1  | 425      | 0.704133 |          | 4.68     | 20.1   | 0.1513     | 0.512842   | 3           | 4.14   |
| ICO-08-1  | Dacite dome composed of two individual flows | Qd1  | 462      | 0.704164 |          | 3.68     | 16.8   | 0.1321     | 0.512734   | 3           | 2.02   |
| ICO-08-3  | Dark grey dacite lava collected in the northern islet separated ~25 meters from the main dome | Qd2  | 418      | 0.704169 |          | 4.16     | 19.0   | 0.1326     | 0.512756   | 3           | 2.46   |

(a) Epsilon Nd (εNd) is the deviation of 143Nd/144Nd of the sample relative to the chondritic uniform reservoir (CHUR) times 10000. CHUR 143Nd/144Nd = 0.512630 (after Bouvier et al. 2008).

Table 2. Sr, Sm-Nd isotope data.
Recent volcanism in the Ballenas transform margins

Recent volcanism in the Ballenas transform margins

This lava flow is at least 20–30 m-thick and displays ramp structures and columnar jointing. The top of Qv1 is brecciated and overlain by whitish pyroclastic deposits ranging a few meters in thickness (Qt in Figure 3). Pumice lapilli in this deposit are reworked towards the top and grade upwards into a ~15–20 m-thick conglomerate covered by the uppermost lava flow unit (Qv3).

The two younger lava units Qv2 and Qv3 crop out along the S-SE and NE flanks of LVC (Figure 3). The largest and morphologically youngest flow is a ~2 km long coulee, displaying arcuate pressure-ridges that indicate E-SE directed transport (Figure 3). An isolated lobe in the NE corner of the volcanic complex displays a circular ridge crest nearly 200 m in diameter (Qv2), which suggests a local vent or alternatively, this lobe could be part of a larger lava flow of intermediate age between the lower and upper lava units.

All three LVC lava units have similar mineral composition although they display textural differences. The lower flow (Qv1) is composed of a dark grey, aphanitic glassy lava, with <1 % plagioclase and pyroxene microphenocryst <1.5 mm long (see photomicrographs in the Supplementary Material). The plagioclase microlites are commonly aligned within the glassy matrix, and glomerophyric plagioclase and pyroxene are common. Lava units Qv2 and Qv3 are dark grey to black with an aphanitic to microporphyritic texture. Plagioclase microlites within the glassy matrix define a hypohyaline flow texture. In this matrix, agglomerates of plagioclase (andesine)-orthopyroxene phenocrysts and opaque minerals along with zoned plagioclase microphenocrysts are common.

Isla Coronado (ICO)

The ICO comprises a ~300 meter-high dacite dome located in the north end of the island (Figure 4), situated north of Bahía de los Ángeles (BLA in Figure 1b) This lava dome overlies a low relief crystal-line basement composed of Mesozoic granitic rocks and hornblende schist of presumably Paleozoic age. The lava dome includes two cooling units (ICO08-1 and ICO08-2) separated by a flow breccia, which also comprises most of the small islet near the northern tip of ICO (e.g., sample ICO08-3

The ICO lavas are dominantly hypohyaline to felsitic in texture with common glomerophyric plagioclase, pyroxene, and rare hornblende. Glomerophyric plagioclase is commonly euhedral and up to 1.5 mm in diameter; it displays oscillatory zonation and complex twinning. Plagioclase microlites are euhedral to subhedral and commonly associated with disseminated orthopyroxene and opaque minerals.

Major oxide and trace elements

Major oxide geochemistry in both ICO and LVC indicates dacitic composition of lavas (Figure 5a), although ICO samples are high-silica dacite compared to LVC lavas. The higher differentiation of ICO lavas is also reflected in lower content of MgO, TiO2 and FeOt, and higher K2O (Table 1). Rare Earth elements display similar patterns in both ICO and LVC samples (Figure 5b), with a slightly higher LREE fractionation and Eu depletion in ICO lavas (La/Yb, 3.75–3.91) compared to LVC dacite (La/Yb, 3.20–3.39).

Sr and Sm-Nd isotopes of whole rock samples

Two ICO lava samples have within errors identical 87Sr/86Sr ratios of 0.704164 and 0.704169, slightly below the bulk earth and similar Nd isotope ratios yielding εNd values of +2.0 and +2.5, indicating a slightly depleted source (Table 2). comparatively low 147Sm/144Nd ratios of 0.1321 and 0.1326 reflect the fractionated character of these high-

Figure 4. Google Earth image of Isla Coronado (Smith). The dacite dome is ±300 m high and erupted over granitic and metamorphic continental crust.

Figure 5. a) Total alkalis vs silica plot (from Le Bas et al., 1986) with ICO and LVC samples analyzed for major oxide and trace elements geochemistry. b) Chondrite-normalized REE diagrams of selected samples from LVC (Isla Ángel de la Guarda) and Isla Coronado (ICO).
silica lavas. The LVC lavas display higher $^{147}\text{Sm}/^{144}\text{Nd}$ of 0.1494 and 0.1513, which is also consistent with their lower silica content. More radiogenic Nd isotope compositions, yielding $\varepsilon\text{Nd}$ values of +3.8 and +4.1 suggest a larger component from the depleted mantle source in LVC dacites compared to ICO lavas. Strontium isotopes, however, do not reflect this tendency for the LVC samples. Their $^{87}\text{Sr}/^{86}\text{Sr}$ are either insignificantly lower (IAG07-38 = 0.704133) or higher (IAG07-40 = 0.704341) than ICO lavas, indicating some secondary process affecting Sr isotopes like hydrothermal processes or magma contamination with carbonates.

**Geochronology and zircon trace elements**

Two U-Pb and one Ar-Ar ages were determined for lava flows from the LVC. The Ar-Ar whole-rock analysis obtained from one sample of Qv2 lava of LVC comprises two experiments that yielded overlapping ages for the high-temperature release steps which average 692 ± 164 ka ($n = 10$; MSWD = 1.0) (Figure 6).

Due to large error obtained in the Ar-Ar whole rock analysis we processed a larger amount of rock in search of young zircon crystals. In spite of the low zircon yield, we obtained U-Pb crystallization ages for the high-temperature release steps which average 692 ± 164 ka ($n = 10$; MSWD = 1.0) (Figure 6).

**DISCUSSION**

Radiometric ages for LVC and ICO reveal Pleistocene evolved magmatism along the onshore margins of the Ballenas basin. Activity in the LVC appears to be older, with zircon ages (representing maximum eruption ages) in the lower Pleistocene. A stratigraphically consistent younger age was determined for zircon from the upper lava flow (Qv3), which is concluded to be of mid Pleistocene age. The lava flow Qv2 located in the northeastern part of the complex is intermediate in age between both lava flows dated using zircon separates, and yielded a $^{40}\text{Ar}/^{39}\text{Ar}$ whole rock age of 692 ± 164 ky (Figure 6) that is consistent with its intermediate stratigraphic position in the LVC.

Zircon ages for ICO, again interpreted as maximum eruption ages, postdate LVC zircon, and suggest activity at or after ca. 250 ka (Figure 7c and 7d), also during the mid-Pleistocene.

To further elucidate the age significance of zircon in these lavas, zircon trace element geochemistry is compared to whole rock compositions via published zircon-melt partition coefficients (table 5 in Sano et al., 2002) (Figure 9). Because zircon saturates early in metaluminous melts, and the investigated rocks are crystal-poor, melt compositions may be reasonably well approximated by whole-rock compositional data. Thus, the comparison between predicted melt compositions (using measured zircon REE abundances divided by zircon-melt partition coefficients that range from 0.00046 for La to 325 for Lu, Sano et al., 2002) and actual whole rock data is a first-order assessment whether zircon is in equilibrium with its host rock. Although the calculated range of REE from LVC zircon is wider than observed whole rock compositions (Figure 9b), they broadly overlap, some deviations for La and Ce notwithstanding. Both elements, however, are difficult to model as La is only present in very small amount in zircon, and Ce partitioning is redox dependent so that the values from Sano et al. (2002) may not be adequate for LVC zircon-melt equilibria. Nonetheless, the REE models of Figure 9b suggest that zircon from LVC crystallized from a melt similar to the whole rock compositions. Zircon genetic

![Figure 6](image-url)
Recent volcanism in the Ballenas transform margins

classification diagrams (Grimes et al., 2007) also indicate a larger crustal input into LVC zircon-crystallizing melts compared to those for Pleistocene volcanoes in the northern Gulf of California (Figure 8) (Schmitt et al., 2013).

In contrast to LVC zircon, trace element abundances in ICO zircon are higher, suggesting that they crystallized from a more evolved melt (Figure 9a). This is also underscored by a pronounced negative Eu anomaly displayed by ICO zircon. Calculated melt compositions in ICO samples (see above) are significantly higher in REE (except Eu) than REE measured in whole rock samples (Figure 9b), again disregarding La and Ce for the reasons stated above. The mismatch between modelled and actual whole rock (melt) compositions implies that ICO zircon crystallized from a significantly more evolved melt than the dacitic host lava. In the light of the higher U/Yb of ICO zircon compared to LVC (e.g. Figure 8), a stronger crustal input into the zircon-crystallizing melt is also invoked for ICO. This is supported by whole rock radiogenic isotope data (Table 2) discussed below.

Magmatism associated with the Ballenas continental transform faults may result from decompression melting of the upper mantle in regions where oblique rifting generates trans-tensional domains at right steepened strike-slip faults. Similarly, volcanic products in the western margin of the Cerro Prieto and Wagner pull-apart basin are commonly evolved, reflecting protracted ascent and residence times within

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**Figure 7.** U-Pb and U-Th zircon geochronology results. U-Pb data are plotted uncorrected for common Pb with a linear regression fixed at common $^{207}\text{Pb}^{206}\text{Pb} = 0.828$ where the radiogenic component and age is determined from the lower Concordia intercept. U-Th data are shown in an equiline diagram where isotopic activities are indicated by parentheses. The age is determined from the slope of the isochron defined by zircon with young U-Pb ages. Open symbols are omitted from regression.

**Figure 8.** Zircon trace element classification diagram after Grimes et al. (2007). Data for northern Gulf zircons from Schmitt et al. (2013) shown for comparison.
ages between 113 and 98 Ma were also found, but the remainder being the second largest population (30%). In ICO samples, Cretaceous as well as metamorphic rocks including hornblende schists. Tonalites belonging to the eastern Peninsular Ranges Batholith suite, Tertiary volcanic rocks that are abundant on the surface, Mesozoic assimilate as indicated from regional geological mapping include crustal Basin in the southern Gulf of California (Castillo et al., 2002). Crustal MORB composition was taken from submarine basalts of the Alarcón drilled by zircon crystallization ages. Radiogenic (Nd, Sr) isotopes suggest of the northernmost Gulf of California (Schmitt et al., 2013). LVC data are identical in εNd to Roca Consag, but displaced to higher 87Sr/86Sr. Similar sub horizontal trends are displayed by submarine lavas from the Lower Delfín Basin (Martín-Barajas et al., 2008) and also known for volcanic rocks from geothermally active onshore basins of the northern Gulf of California rift (Schmitt et al., 2013). They are interpreted as results of hydrothermal alteration, and therefore high εNd/86Sr data are considered unreliable as indicators of magmatic compositions. It is therefore concluded that binary mixing and/or AFC involving MORB magmas and tonalitic basement can explain the compositions of the Ballenas Channel evolved volcanic rocks. The amount of crustal material added to the erupted magma, as indicated by the different models, is at most ~10–20 %, within the range of other Pleistocene volcanic rocks from the northern Gulf of California magmatic province (Schmitt et al., 2013; Figure 10). A slightly larger crustal input into the ICO source relative to LVC is consistent with findings from zircon and whole-rock geochemistry.

**CONCLUSIONS**

Two sets of volcanic vents have developed during the Pleistocene on opposite sides of the Ballenas transform fault within the Midriff section of the Gulf of California. These vents form Isla Coronado (ICO) at the southwestern terminus of the Ballenas basin, and the Lobera Volcanic Complex (LVC) on Isla Ángel de la Guarda on the northeastern end. Both volcanoes are located on the edge of sheared crystalline basement comprising tonalite and hornblende schists, which are overlain by Miocene volcanic rocks. This crustal segment has been previously thinned in dilatational domains of the transform fault system such as the Ballenas basin, which comprises several submarine volcanic knolls (Plattner et al., 2015). Zircon crystallization ages of the ICO and LVC volcanoes range between ca. 250 and 1000 ka. Exact eruption ages are unknown, except for a ca. 700 ka 40Ar/39Ar age for a lava unit (Qv2) in the northeastern part of the LVC, but younger than the zircon crystallization ages. The young morphology of unit Qv3 in the southeastern LVC is consistent with the youngest zircon ages detected for the LVC of ca. 360 ka. The ICO eruption postdates ca. 250 ka as indicated by zircon crystallization ages. Radiogenic (Nd, Sr) isotopes suggest a MORB-type primary magma with significant (~10–20 %) crustal assimilation involving tonalitic basement of the eastern Peninsular Ranges Batholith.

**SUPPLEMENTARY MATERIAL**

Supporting supplementary material can be found in the html version of this paper at the RMCG website: www.rmcg.unam.mx.
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