Microcontinent Breakup and Links to Possible Plate Boundary Reorganization in the Northern Gulf of California, México

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Key Points:

- On Isla Ángel de la Guarda, we map the normal, north-striking, Almeja fault zone that projects into an active offshore basin.
- Luminescence ages from faulted terraces indicate late Quaternary fault activity.
- Similar orientation and extension direction suggest a kinematic linkage between the Almeja fault zone and the active offshore basin.

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Abstract

Faults on microcontinents record the dynamic evolution of plate boundaries. However, most microcontinents are submarine and difficult to study. Here, we show that the southern part of the Isla Ángel de la Guarda (IAG) microcontinent, in the northern Gulf of California rift, is densely faulted by a late Quaternary-active normal fault zone. To characterize the onshore kinematics of this Almeja fault zone, we integrated remote fault mapping using high-resolution satellite- and drone-based topography with neotectonic field-mapping. We produced 13 luminescence ages from sediment deposits offset or impounded by faults to constrain the timing of fault offsets. We found that north-striking normal faults in the Almeja fault zone continue offshore to the south and likely into the nascent North Salsipuedes basin southwest of IAG. Late Pleistocene and Holocene luminescence ages indicate that the most recent onshore fault activity occurred in the last ~50 kyr. These observations suggest that the North Salsipuedes basin is kinematically linked with and continues onshore as the active Almeja fault zone. We suggest that fragmentation of the evolving IAG microcontinent may not yet be complete and that the Pacific-North America plate boundary is either not fully localized onto the Ballenas transform fault and Lower Delfin pull-apart basin or is in the initial stage of a plate boundary reorganization.

Plain Language Summary

Earth's rocky outer layer is broken into several tectonic plates. These plates move against each other at plate boundaries, causing geologic hazards like earthquakes. The locations of plate boundaries also move through time by a process called plate boundary reorganization. Here, we examine Isla Ángel de la Guarda (IAG), an uninhabited island in the northern Gulf of California, to study a potential plate boundary reorganization between the Pacific and North America plates. We looked at the pattern and activity of faults on southern IAG to assess their connection to the

current plate boundary. We found that the faults have a similar orientation to an active, offshore part of the plate boundary southwest of IAG and that onshore faults are also active because they cut layers of sand and gravel that were deposited less than 50,000 years ago. Active faults that align with the plate boundary may imply that both are presently linked. A possible result of this linkage is the reorganization of the Pacific-North America plate boundary across IAG.

1 Introduction

Figure 1. Tectonic reconstruction of the northern Gulf of California and associated structures holding the North America plate fixed (Aragón-Arreola & Martín-Barajas, 2007; Bennett et al., 2016b; Stock, 2000) at (a) 6 Ma, (b) 3 Ma, (c) 2 Ma, and (d) present. Landmasses on the Pacific and North America plates are shown in green and orange, respectively. (e) Detailed map of southern Isla Ángel de la Guarda showing how the Almeja fault zone may connect with the North Salsipuedes basin (see location in Fig. 1d). BT – Ballenas transform fault, DM – De Mar fault, IAG – Isla Ángel de la Guarda, IT – Isla Tiburón, LDB – Lower Delfín basin, LTB –

Lower Tiburón basin, NAM – North America plate, NSB – North Salsipuedes basin, PAC – Pacific plate, PVP – Puertecitos Volcanic Province, TB – Tepoca Basin, TF – Tiburón fault, UDB – Upper Delfín basin, UTB – Upper Tiburón basin, WB – Wagner Basin.

Microcontinents are fragments of continental lithosphere rifted away from a continent, now surrounded by oceanic lithosphere (Abera et al., 2016; Müller et al., 2001). Various mechanisms have been proposed for the isolation and tectonic evolution of microcontinents, each governed by a different tectonic setting (Nemčok et al., 2016). Continental fragments can become isolated by wrench faulting that forms strike-slip duplexes and stepovers between shear zones (e.g., Antobreh et al., 2009) or by horsetail splays via shearing of intervening blocks (e.g., Misra et al., 2014). Rifting across relatively parallel and overlapping spreading centers can also isolate microcontinents by two zones of extension and two sub-parallel transform boundaries (Nemčok et al., 2016) that can accommodate block rotation (Molnar et al., 2018). The role of a given microcontinent formation mechanism in the evolution of a plate boundary can be evaluated by constraining the orientation, sense of slip, and age of faulting on a microcontinent. However, most microcontinents are submarine (e.g., Nemčok et al., 2016), making them difficult to study.

The Gulf of California is a suitable location to study microcontinent formation, as several studies suggest other continental fragments have been completely or partially isolated here (Abera et al., 2016; Lizarralde et al., 2007) since the late Miocene. Oblique rifting between the Pacific and North America plates initiated ~12.3 Ma across a broad region from west of Baja California (Spencer & Normark, 1979) to central Sonora (Gans, 1997). Transtensional strain localized into the 50 – 100 km-wide Gulf of California shear zone ~8 – 7 Ma (Bennett & Oskin, 2014; Bennett et al., 2016a). Continued focused rifting led to post-6.1 Ma (Oskin & Stock, 2003; Oskin et al., 2001) oblique opening of the Upper and Lower Tiburón pull-apart basins, which

were kinematically linked by the dextral Tiburón fault (Fig. 1a – b; e.g., Nagy & Stock, 2000). Then, the evolving plate boundary shifted westward (Aragón-Arreola & Martín-Barajas, 2007; Lonsdale, 1989) by ~2 Ma as the Ballenas transform fault linked with the nascent Lower Delfín pull-apart basin (Fig. 1b – c; Nagy & Stock, 2000). As a result, the Upper and Lower Tiburón basins and Tiburón fault became inactive, transferring Isla Ángel de la Guarda (IAG) from the Pacific plate to the North America plate. At ≤ 2 Ma, a short right-step in the Ballenas transform fault system formed the North Salsipuedes basin, a narrow zone of extension southwest of IAG (Fig. 1d – e; González- Fernández et al., 2005; Lonsdale, 1989).

Today, the Baja California microplate moves $N56^{\circ}W \pm 1^{\circ}$ at about 43 – 47 mm/yr (Plattner et al., 2007) with ~235 – 255 km of dextral displacement relative to Isla Tiburón (North America plate) since ~6 Ma (Bennett et al., 2016b; Bennett et al., 2015; Nagy & Stock, 2000; Oskin et al., 2001). The modern NW-striking Ballenas transform fault makes up the northwesternmost ~100 – 200 km of the >500 km-long Ballenas-Guaymas transform fault zone (Fig. 2a), which continues southeast from IAG along the northeast margin of the Guaymas basin (Aragón-Arreola et al., 2005; Lonsdale, 1989). Many young extensional basins have formed at releasing steps in the en echelon Ballenas transform fault (González- Fernández et al., 2005; Lonsdale, 1989), along with structures resembling horsetail splays and submarine volcanoes (Fig. 2b; Aragón-Arreola & Martín-Barajas, 2007; Aragón-Arreola et al., 2005; Persaud et al., 2003; Plattner et al., 2015). Near IAG, the Ballenas transform fault becomes less discernable in bathymetry, from the North Salsipuedes basin to the Upper Delfín basin, as slip is partitioned from the transform fault into each basin towards the north (Persaud et al., 2003). Additionally, the structural connection between the Ballenas transform fault and the North Salsipuedes basin is diffuse (Lonsdale, 1989), as the basin is composed of multiple SE- and NW-dipping normal

faults across a ~50 km-long zone of extension along the Ballenas transform fault (Plattner et al., 2015). Collectively, these characteristics indicate that the Ballenas transform fault is not simply a strike-slip or transform fault, but is instead a complex transtensional structure, which has led some to suggest that strain localization of the Pacific-North America plate boundary near IAG is incomplete (e.g., Persaud et al., 2003). Therefore, modern IAG is an evolving microcontinent, isolated as a distinct tectonic block but surrounded by transtensional faults, transitional crust, and pull-apart basins instead of true transform faults, oceanic crust, and spreading centers (Aragón-Arreola et al., 2005; González-Fernández et al., 2005).

Ongoing deformation surrounding IAG is recorded by the uplift of coastal terraces along the adjacent Baja California peninsula, with a mean uplift rate of 0.1 mm/yr since 1 Ma (Ortlieb, 1991). Such uplift is likely also deforming IAG. NE-SW lineaments in northern IAG are thought to accommodate extension that parallels the Lower Delfín basin (Delgado-Argote, 2000). In central IAG, geologic mapping and ages from deformed volcanic deposits suggest faults there are unrelated to modern deformation because post-Pliocene deposits are not deformed (Cavazos Alvarez, 2015). Interestingly, submarine volcanic hills (Fig. 2b), thinned crust observed in seismic reflection surveys (Paz-López, 2000; Persaud et al., 2003), and historic earthquakes up to ~Mw 7 near southern IAG (Castro et al., 2021; Castro et al., 2017; López-Pineda et al., 2014) suggest that extensional faults in the south could be active. However, the only published geologic map of southern IAG is 1:250,000-scale (Gastil et al., 1975) and does not show evidence for Quaternary fault activity or relate faults to active rifting or microcontinent formation processes.

Figure 2. (a) Structural map of the Pacific-North America plate boundary in the northern Gulf of California (e.g., Stock, 2000), showing the Ballenas transform fault (BT), Lower and Upper Delfín basins (LDB and UDB), Lower and Upper Tiburón basins (LTB and UTB), North Salsipuedes basin (NSB), Tiburón fault (TF), and historic earthquake epicenters (Castro et al., 2021; Castro et al., 2017) and focal mechanisms (Dziewonski et al., 1981; Ekström et al., 2012). Basemap is shaded relief, digital elevation, and bathymetry from GeoMapApp (Ryan et al., 2009). (Inset) Location of Isla Ángel de la Guarda (IAG) in the Gulf of California (GOC), México (MEX). (b) 3-m resolution shaded relief map from 0.5-m resolution Pleiades images of southern IAG showing the Almeja fault zone (thin black lines; Sabbeth, 2020) and earthquake epicenters.

In this paper, we examine the timing and kinematics of faults on southern IAG. Here, a modern, subaerial, and evolving microcontinent provides us with a rare opportunity to study microcontinent formation mechanisms. We focus on a fault zone that was first mapped, but not named, by Gastil et al. (1975), hereafter the Almeja fault zone. We characterize the orientation of this fault zone by remote analysis of high-resolution topography and neotectonic field mapping to document the extent and orientation of faults and determine their kinematic relation with offshore structures. We also determine depositional ages of faulted and unfaulted non-marine terraces and sediment from fault-related depressions using luminescence dating to constrain the local timing and slip rate on specific strands of the Almeja fault zone. Combining these results, we show that normal faults within the Almeja fault zone deform many generations of late Quaternary terraces on southern IAG and project offshore into the active North Salsipuedes extensional basin. Lastly, we discuss potential mechanisms of ongoing deformation and implications for the future evolution of IAG and the larger Pacific-North America plate boundary.

2 Methods

2.1 Fault mapping

We used high-resolution data from satellite and drone images to map faults using two independent methods: 1) remote- and field-mapping (Sabbeth, 2020) and 2) a semi-automatic scarp detection method. High-resolution satellite images are from Google Earth (e.g., WorldView) and two 0.5-m resolution Pleiades satellite images. Then, we constructed a 3-m resolution digital elevation model (DEM) of the 150 km² study area from the Pleiades satellite images (see extent in Fig. 2b) using the Ames Stereo Pipeline software (e.g., Beyer et al., 2018).

For small portions of the study area with particularly dense fault arrays, or with high potential to use luminescence ages to bracket the timing of fault activity, we performed drone-based photographic surveys with a DJI Phantom 3 Advanced drone to create ~0.1-m resolution DEMs. We used the structure-from-motion photogrammetry method with Agisoft PhotoScan software to process ~2500 drone images with ~70% overlap into three DEMs with a total area of ~5 km². We then rectified these products using ground control points recorded with a high-precision differential Trimble GPS receiver and processed using RTKLIB (Takasu et al., 2007).

2.1.1 Remote and field-based fault mapping

The Almeja fault zone cuts multiple generations of non-marine terraces, apparent in satellite images and DEMs of southern IAG (Figs. 2b, 3; Fig. S1). Sabbeth (2020) presented a stratigraphic framework for multiple generations of Quaternary terraces here. We applied this framework to our terrace mapping surrounding our luminescence sample sites while considering terrace height above the active channel, local terrace generations, and our luminescence ages (Fig. 4; Fig. S2; Supplementary Material S1).

We manually mapped the dense fault strands of the distributed Almeja fault zone from our DEMs and high-resolution satellite images (e.g., Worldview, Pleiades) using well-preserved landforms, such as terraces, as geomorphic markers whose original unfaulted geometry can be easily inferred (Fig. 2b; Fig. S1a; Burbank & Anderson, 2011). Faults are evident as measurable differences in topographic attributes such as elevation, slope, and aspect that abruptly cut through sedimentary terraces and volcanic hillslopes.

Based on inferred original terrace geometry, we can also determine whether dip-slip or strike-slip offsets are dominant. The dip-slip component of fault offset for any fault strand can be

measured from the vertical separation of terrace treads across its fault scarp. We estimated dip-slip displacements by extracting scarp-perpendicular topographic profiles from our ~0.1-m resolution drone-derived DEMs. Then, we fit lines to the correlative upthrown and downthrown terrace tread surfaces and estimated the displacement of these surfaces by varying fault dip using 100,000 Monte Carlo simulations per profile (Supplementary Material S1; Duckworth et al., 2020; Thompson et al., 2002). We used a wide fault dip range ($60^{\circ} - 90^{\circ}$) similar to Duckworth et al., (2020) because we did not directly observe fault dip in the field and aimed to capture the fullest range of dip-slip displacement. Next, we estimated any strike-slip component of fault offset from the horizontal separation of abandoned terrace risers, which ideally are no longer affected by fluvial erosion. In some locations, field checking was required to determine if the apparent offsets were formed by faults or non-tectonic processes such as river incision. We combined our mapping, which uses remote-sensing data, with conventional neotectonic field-mapping from Sabbeth (2020) to fully characterize the Almeja fault zone.

2.1.2 Semi-automatic template matching

The extent of neotectonic field-mapping is often limited by field conditions, inaccessibility, subtle topography, or dense arrays of distributed faulting. To overcome these limitations and identify unmapped faults across a large region of interest, we extracted topographic scarps from our large 3-m resolution DEM using Scarplet, an open-source software package that semi-automatically identifies scarps by matching topographic curvature in a DEM with that of ideal template scarp profiles from the hillslope diffusion equation (described and discussed in Supplementary Material S2; Hilley et al., 2010; Sare et al., 2019). This template matching algorithm searches for areas of scarp-like features (usually 10's of meters wide and 100's of meters long; Fig. S2) within DEMs and produces raster grid maps of scarp properties

such as best-fit orientation and amplitude (Fig. S1). We used a template length of 200 m, as in Sare et al. (2019), to capture scarp segments of similar length scales. Template matching also produces grid maps of morphologic age, also known as the degradation coefficient κt [m^2]. This variable is the product of the hillslope diffusion constant κ [m^2/ka] and absolute age of a scarp t [ka] and is also a proxy for scarp form. A high κt represents a diffuse scarp and results from either a high diffusion constant, old absolute scarp age, or both. Values of κ for scarps in extremely arid regions of the Dead Sea are $< 1 \text{ m}^2/\text{ka}$ while those in arid to semi-arid regions of the Basin and Range province and western China vary between $1 - 5.5 \text{ m}^2/\text{ka}$, showing a dependence on material properties and climate (e.g., Hanks, 2000). Because scarp diffusion processes assume the transport of unconsolidated material, morphologic ages reported for coherent volcanic lithologies cannot be used to infer scarp age but rather show the relative differences between the diffuseness of scarps. Lastly, template matching produces grid maps of signal-to-noise ratio (SNR; Fig. 3), defined as the ratio of squared scarp amplitude and the squared misfit of real and template curvature. Template matching uses SNR to identify best-fit fault scarps by choosing a scarp orientation that maximizes SNR.

Figure 3. Luminescence sites (white dots), faults from remote- and field-mapping (black lines = normal and oblique faults; Sabbeth, 2020), and scarps from template matching (colored by signal-to-noise ratio) on southern Isla Ángel de la Guarda. Basemap is a 3-m resolution shaded relief from 0.5-m resolution Pleiades images (extent shown in Fig. 2b). Rose diagrams show orientations of 3-m fault scarp segments from (a-c) template matching and (d-f) remote- and field-mapping for three study regions colored by lithology: the North and South Volcanic Hills (pink) and Central Terraces (west: maroon, east: tan). Radial unit is calculated as percent of segments in a bin relative to the total number of segments. Each rose petal is an orientation bin of 6°. Average orientation of the Ballenas transform fault and North Salsipuedes basin near Isla

Ángel de la Guarda are the thick black and red bars in each rose diagram, respectively. (Inset Map of three study regions colored by lithology (same colors as above). Refer to Sabbeth (2020) for geologic maps showing volcanic bedrock and terraces and Figure S2 for local-scale terrace generations.

We analyzed three regions of our 3-m resolution DEM with template matching: two regions of layered, gently east-dipping Miocene-Pliocene volcanic bedrock (hereafter, the North and South Volcanic Hills; Sabbeth, 2020) and a region of dissected, primarily fluvial and alluvial, Quaternary terraces (hereafter, the Central Terraces; Fig. 3). In all regions, our template matching analysis identified many scarp-like curvature profiles. SNR from template matching can be used as a binary classifier for these scarp-like features, where pixels above or below a certain threshold of $\log_{10}(\text{SNR})$ can be classified as fault scarp or non-fault scarp pixels, respectively. These pixels are compared against a master map of fault scarps from a 10 and 30 m buffer around the remote- and field-mapped faults for the Central Terraces and South Volcanic Hills, respectively. We only performed this and subsequent analyses over the Central Terraces and South Volcanic Hills, as the North Volcanic Hills contained only one remote- and field-mapped fault that overlaps with the area analyzed with template matching. A wider buffer was used in volcanic bedrock to identify wider scarps related to higher scarp heights from greater fault offsets accumulated over more protracted fault histories or better preservation from a more coherent lithology.

To evaluate the diagnostic ability of $\log_{10}(\text{SNR})$ to detect faults, we create receiver operating characteristic curves (Fig. S3) by plotting the true and false positive rates of fault identification at different $\log_{10}(\text{SNR})$ thresholds. True positive rate is the ratio of the total number of true fault scarp pixels classified by the $\log_{10}(\text{SNR})$ threshold as a fault and the total

number of fault scarp pixels in the master map. False positive rate is calculated as the ratio of the total number of non-fault scarp pixels identified falsely as a fault scarp and the total number of non-fault scarp pixels in the master map. Then, we use the area under the receiver operating characteristic curve (AUROC) to evaluate the performance of such binary classifiers, following Sare et al. (2019), where $AUROC = 1$ is a perfect classifier and $AUROC = 0.5$ is a random classifier. Next, we determined a threshold value of $\log_{10}(SNR)$, above which pixels will remain in our final fault scarp maps. We considered the median SNR from entire regions, median SNR within buffers around our remote- and field-mapped fault scarps, and the best classifier SNR to choose a threshold that best characterizes the Almeja fault zone in different lithologies (Supplementary Material S3). We present classifier performance metrics, including the true positive rate, false positive rate, true negative rate, false negative rate, precision, and accuracy of the binary classifier at the final $\log_{10}(SNR)$ threshold in Table S1.

Nonetheless, some topographic features identified after implementing the SNR threshold do not have tectonic origins, such as terrace risers, ridgelines, and erosional cliff bands related to resistant, gently east-dipping, volcanic units. We post-process the SNR-filtered map by the location of terrace risers (by high topographic slope) and ridgelines (by the location of drainage divides from Scherler & Schwanghart, 2020), as discussed in Supplementary Material S4. The classifier metrics for our post-processed fault map are also presented in Table S1.

Lastly, we use two-sample Kolmogorov-Smirnov and Wilcoxon rank sum statistical tests at the 5% significance level to compare the orientation of linearized fault scarps from template matching (Fig. 3a – c; linearization of template matching results discussed in Supplementary Material S5) to that from remote- and field-mapping (Fig. 3d – f) in approximately the same locations (Fig. S4). These tests examine whether two datasets have equal continuous

distributions and medians, respectively. First, we compare results from the same region (e.g., South Volcanic Hills) varying the mapping method to determine if both methods produce consistent results. Then we compare results obtained from the same mapping method (e.g., template matching), varying the region to determine if there is a significant difference in orientation between locations across southern IAG.

Figure 4. Luminescence sites and corresponding sample ages from the (a) ‘flight of terraces’ site with fault X, (b) ‘incised terrace’ site, (c) ‘sag pond’ site with local depression similar to a sag pond, and (d) ‘southern terraces’ site. Site locations in Figure 3. Basemaps are shaded relief from ~0.1-m resolution drone-derived elevation with 20-m elevation contours from 3-m resolution elevation from 0.5-m resolution Pleiades images. We follow the stratigraphic framework of terrace mapping by Sabbeth (2020) at nearby sites and present subdivided terrace levels here based on height above the active channel, local terrace generations, and luminescence ages.

2.2 Luminescence dating

To constrain the timing of fault offsets, we analyzed 13 sediment samples from five sites located on faulted terrace treads, in exposures of incised and faulted terraces, and from a fault-related local depression similar to a sag pond. Sites were chosen based on accessibility, the potential for material dateable using luminescence (e.g., sand-sized grains in laminated soft sediment), and proximity to well-characterized fault strands that offered opportunities to constrain their fault slip history.

Luminescence dating estimates the length of time sediment has been buried after sunlight exposure, which is often referred to as the depositional age, as the absorbed dose [Gy] divided by the geologic dose rate [Gy/ka]. The geologic dose rate refers to the natural radiation contribution from cosmic rays and radionuclides within grains and clasts in the surrounding sediment matrix, which are dominated by the radioactive isotopes of U, Th, and K. We use in-situ and sediment matrix samples to estimate the concentrations of these elements and implement standard attenuation factors (Brennan et al., 1991; Guérin et al., 2012; Liritzis et al., 2013), internal K content (Huntley & Baril, 1997), and calculations and error propagations (Durcan et al., 2015) to convert these factors to dose rates.

To estimate the natural, absorbed, burial dose, we measured the laboratory equivalent dose (D_e) for each grain using a post-infrared infrared stimulated luminescence (p-IR IRSL₂₂₅) protocol, which measures the time-stable signal from feldspars (Buylaert et al., 2009). We do not analyze that of quartz grains because previous studies in nearby southern California show poor quality luminescence signals from quartz, possibly because of rapid exhumation of source rock and limited reworking of sediment (Lawson et al., 2012). In such cases, quartz signals are commonly overprinted by zircon and feldspar inclusions (Guralnik et al., 2015). Conversely,

post-IR IRSL signals from K-feldspar samples have yielded excellent results in alluvial deposits from southern California (Rhodes, 2015) and southern Baja California (Brown et al., 2015). We use a TL-DA-20 Risø automated luminescence reader to make luminescence measurements (e.g., Fig. S5; Bøtter-Jensen et al., 2003; Rhodes, 2015). We examine the p-IR IRSL₂₂₅ signal over the p-IR IRSL₂₉₀ signal because although p-IR IRSL₂₉₀ is a more stable signal, it is also less bleachable (Colarossi et al., 2015; Li & Li, 2011). We also tested for anomalous fading at room temperature on timescales of hours to two weeks and found no signal loss.

Single-grain D_e values were summarized using standard age models. For typical samples, we used the minimum age model, which assumes that only some grains were fully bleached before deposition (Galbraith et al., 1999). This condition would be expected for high energy fluvial deposition, characteristic of desert storms, as sunlight may not fully bleach all sediment (Gray et al., 2017). For these calculations, we assume overdispersion (OD) values of 15%, a value typical of well-bleached single-grain feldspar samples in the region (Brown et al., 2015). Samples J1365 and J1370 exhibited low variability in D_e from individual grains with OD values of zero, suggesting that all grains comprise a single dose population that was well bleached before deposition. Based on the low OD, we use the central age model (Galbraith et al., 1999) assuming grains were fully bleached either during fluvial transport or on the surface before burial (Gray & Mahan, 2015; McGuire & Rhodes, 2015). Luminescent grains from sample J1324 were in field saturation and did not yield finite equivalent dose values. The resulting equivalent doses and ages for all samples are shown in Figure S6 and Table S2. Full sample preparation, geologic dose rate calculation, and methods for measuring equivalent dose are presented in Supplementary Material S6.

3 Results

3.1 Fault orientations, offsets, and senses of slip

Our mapping defines the ~6 km-wide, ~N-S-oriented Almeja fault zone (Fig. 3).

Remote- and field-mapping identified NNW-striking faults in the North Volcanic Hills (Fig. 3d), somewhat similar in orientation to the results from template matching (Fig. 3a). In the Central Terraces, we mapped ~NNW-striking faults in the west and NNE- striking faults in the east (Fig. 3e), which agree with those identified from template matching (Fig. 3b). In the South Volcanic Hills, remote- and field-mapping identified NNE-striking faults (Fig. 3f) that also agree with our template matching (Fig. 3c). The Almeja fault zone is mapped continuously to the southwest coast of IAG and projects offshore from sea cliff exposures of steep, NNE-striking, WNW-dipping normal faults (Sabbeth, 2020). We obtained AUROC values of 0.57 and 0.56 for the Central Terraces and South Volcanic Hills, respectively (Table S1). AUROC values between 0.43 – 0.68 were obtained from similar applications in Sare et al. (2019), discussed in Section 4.1.1. Lastly, Kolmogorov-Smirnov and Wilcoxon tests reject that the orientation from remote- and field-mapping and template matching have equal distributions and medians for both the Central Terraces and the South Volcanic Hills. When both tests are administered to compare orientations from the Central Terraces and South Volcanic Hills holding the mapping method constant, it was also determined that the regions have statistically different continuous distributions and median orientations. Therefore, remote- and field-mapping and template matching record an along-strike change of fault orientation across southern IAG, from roughly N-S in the Central Terraces to roughly NNE-SSW in the South Volcanic Hills. Results from the North Volcanic Hills are omitted because some scarps may be related to lithology and not faults. Such false positives are also likely in the other regions, particularly the South Volcanic Hills

where we do not analyze reconstructable geomorphic surfaces, such as terrace treads. Detection of false positives in volcanic rock is discussed in Section 4.1.1.

All faults mapped in the field by Sabbeth (2020) are normal faults, some with components of dextral slip. Here, we also identify several faulted late Quaternary terraces that suggest a dominance of normal dip-slip motion (Fig. 4). Additionally, we map a ~1 km-long and 0.5 km-wide graben (Fig. 5a), which displaces geomorphically young terrace treads. Its east-facing synthetic fault is suspected to continue north as a ~10 km-long, normal fault located at the toe of the major east-facing mountain front, hereafter the Mountain Front fault (Fig. 2b). Thirdly, we document several structural depressions throughout southern IAG (Fig. 6).

Many of the faults that cut the highest and presumably older Quaternary terraces surrounding the North Volcanic Hills and in the Central Terraces record little to no horizontal offset (e.g., Fig. 7a – c; Fig. S2). Younger terrace risers related to inactive inset terraces also record little to no horizontal offset. However, we observe many measurable vertical offsets of terrace treads. For example, we estimate vertical offsets along one NNW-striking fault, labeled X on Figures 4a, 5b, and 7a, that cuts the highest terrace, T1, and lower inset terraces T1b, T1c, and T2. Here at our ‘flight of terraces’ site, we estimate that the tread of terrace T2 is vertically offset by fault X ~3.6 m (95% confidence interval 3.1 – 4.4 m) from three scarp profiles (Fig. 7d). The T2 tread surface is affected by subtle fluvial incision on both sides of the fault (Fig. 7a – c; Fig. S7) but did not prevent us from creating a reliable planar fit to these terrace treads (Fig. S8). The lowest terrace, T3, records no vertical offset and likely post-dates the most recent fault activity here.

We found only two fault strands with possible strike-slip offset, both from fluvially active Quaternary terrace risers near the South Volcanic Hills. One possible offset is observed on a

NNE-striking fault with ~2 – 4 m of west-side-down offset located in the eastern part of the South Volcanic Hills, hereafter the Sag Pond fault as it forms a local depression similar to a sag pond (Fig. S9a – c). Here, we estimate ~100 m of right separation of the northern margin of the modern arroyo. We found that the downthrown block west of the fault only exposes terrace deposits while volcanic bedrock has been uplifted and exposed beneath the erosional strath on the upthrown block, east of the fault (Fig. S9c). Thus, we attribute this apparent horizontal offset to widening of the channel and ponding of sediments west of the more resistant, uphill-facing scarp. We find further corroborating evidence to the north, where we do not observe strike-slip offsets of volcanic bedrock or other arroyos (Sabbeth, 2020). The second fault strand with possible strike-slip offset is a NNE-striking, east-side-down fault located ~0.7 km east of the Sag Pond fault. A channel incised into abandoned late Quaternary terraces (T1 and T2) shows ~10 – 15 m of apparent dextral offset where it crosses this fault strand (Fig. S9d – e). Along strike ~0.5 and ~0.7 km farther south, two terrace risers (the T2/T1 riser) are right-laterally offset by ~12 – 20 m (Sabbeth, 2020). These observations suggest that these horizontal offsets could be from oblique-normal fault slip.

Figure 5. Map and field photo of the (a) graben showing (i) an inset graben and (ii) the synthetic fault. See Fig 2b for location of this graben along the Mountain Front fault. (b) View to southwest of 'flight of terraces' site and luminescence sample pits.

3.2 Late Quaternary ages of offset deposits

We determine the depositional ages of faulted and unfaulted sedimentary deposits to constrain the age of fault activity on southern IAG. We interpret that these extensive terraces have primarily non-marine, fluvial, and alluvial origins because we observe sediment deposits on strath surfaces with similar gradients to modern channels and risers that parallel those channels. At the ‘flight of terraces’ site (Section 3.1; Fig. 4a; Fig. 5b), we date sediment from terrace surfaces that provide ages of terrace abandonment. The surface age of the highest terrace (T1) is $> \sim 200$ ka (J1324, saturated signal), that of a faulted terrace (T2) is 11.7 ± 4.4 ka (J1365), and that of an unfaulted terrace (T3) is 6.5 ± 1.4 ka (J1366). A surface age from the lowest terrace (T3a) ~ 5 m above the active arroyo, located ~ 0.5 km downstream from the other samples, of 1.0 ± 0.2 ka (J1326) suggests ongoing fluvial incision. At the ‘incised terrace’ site, ~ 1 km south of the ‘flight of terraces’ site, we report two depositional ages from an incised and inset terrace (T3) near several normal faults (Fig. 4b). A west-facing cutbank exposes this inset terrace near a N-trending gully. We interpret this inset terrace as cut by a N-striking fault strand located at its back edge (Fig. S10). The luminescence samples taken here, vertically spaced ~ 3 m in the cutbank and from terrace fill material, gave stratigraphically consistent ages of 73.9 ± 7.9 ka (J1317) and 37.6 ± 4.3 ka (J1318; Fig. 6a). These ages are likely older than the abandonment age of T3 because these samples were taken from fill material beneath the T3 surface. Therefore, ages here provide a maximum age constraint for the most recent local fault offset to $< \sim 38$ ka.

At the ‘sag pond’ site (Fig. 4c), ~ 3 km south of the ‘incised terrace’ site, we report a depositional age of 9.4 ± 0.8 ka (J1370) from sediment in a local depression similar to a sag pond impounded against an uphill-facing scarp in volcanic bedrock along the Sag Pond fault (Fig. 6b).

However, the deposits are not cut by this fault. Therefore, we suggest that the most recent offset of the Sag Pond fault occurred before 9.4 ± 0.8 ka.

At the ‘southern terraces’ site, ~1.5 km east of the ‘sag pond’ site, we report maximum age constraints for fault activity at two locations where T3 terrace deposits are cut by NW-striking normal faults exposed in arroyo cutbanks (Fig. 4d). At the northern part of this site, faults form a ~30 m-wide graben, which is not discernable in the high-resolution DEMs because a 1 – 2 m-thick veneer of unfaulted T3 strath gravel overlies the faults that cut the underlying finer-grained sediments (blue line in Fig. 6c). Depositional ages from the finer-grained terrace fill in the horst blocks of the NW-striking graben are 129.7 ± 17.0 ka (J1320) and 100.2 ± 9.2 ka (J1375). We constrained normal fault offset here to post-date 52.0 ± 4.7 ka (J1322) and 53.1 ± 5.5 ka (J1321) from closely spaced samples in faulted terrace fill from the graben block (Fig. 6c). About 250 m south of this graben, we obtained depositional ages of 33.9 ± 3.0 ka (J1323) and 51.0 ± 4.5 ka (J1374) from faulted terrace fill under a T3 strath (Fig. 6d). These ages are inverted, possibly from bioturbation of sample J1323 or a structural disturbance between the two samples. Nonetheless, the natural luminescence signals from both samples are well below saturation and did not fade on laboratory timescales. Similar to the ‘incised terrace’ site, all samples at the ‘southern terraces’ are of terrace fill material. These ages are likely older than the abandonment age of the unfaulted T3 strath. Thus, we cannot use these ages to correlate T3 surface abandonment ages across drainages. However, these ages provide constraints on the timing of local fault offsets, which we interpret to have occurred $\leq \sim 50$ ka here.

4 Discussion

4.1 Fault distributions, orientations, and activity in southern IAG

4.1.1 Spatial patterns of fault orientations

Fault orientation analyses from both remote- and field-mapping and template matching record similar gradual changes of fault strike from north to south along the Almeja fault zone. In the North Volcanic Hills and Central Terraces, NNW- and N-striking normal faults do not align with either the NW-striking Ballenas transform fault or the NE-trending North Salsipuedes basin. Interestingly, in the South Volcanic Hills, NNE-striking normal faults from field-based mapping (Fig. 3f) and template matching (Fig. 3c) are sub-parallel to the nearby North Salsipuedes basin. Although we find agreeable changes of fault orientation from both mapping methods, there are minor discrepancies between their results.

In the North Volcanic Hills, both methods identify faults of somewhat similar orientations. However, the median fault orientation from template matching is $\sim 10^\circ$ counterclockwise of remote- and field-mapping. We find this mismatch because template matching is applied to volcanic bedrock where the method is capturing NW- to NNW-trending resistant cliff bands in gently E-dipping volcanic bedrock (Sabbeth, 2020) in addition to true fault scarps. But our remote- and field-mapping observes N-striking faults both within this volcanic bedrock and across terraces to the east and west of this exposure (Fig. 3; Fig. S4). Therefore, field context suggests our filtering of non-tectonic scarps performs poorly in this region and explains the mismatch.

In the Central Terraces and South Volcanic Hills, remote-and field-mapping and template matching cover a similar areal extent, allowing us to better compare the similarity between both

methods. Template matching in the Central Terraces has an AUROC value of 0.57 when compared to the 10 m buffer around remote- and field-mapped faults, which is lower than a value of 0.7 that is typically considered satisfactory. However, 0.57 is on par with AUROC from Sare et al. (2019; AUROC = 0.43 – 0.68) when scarp orientations allowed by the algorithm were not constrained to a certain range, as in this study. Also, median orientation from template matching is only $\sim 5^\circ$ clockwise of remote- and field-mapping. After post-processing, precision and accuracy increase from 0.11 to 0.22 and 0.61 to 0.83, respectively (Table S1). Therefore, we suggest template matching characterizes tectonic fault orientation and density well in the Central Terraces.

At the South Volcanic Hills, median orientation from template matching is $\sim 20^\circ$ clockwise of remote- and field-mapping. Nonetheless, we obtain an AUROC of 0.56 for this region, suggesting template matching performed similarly here compared to the Central Terraces. After post-processing, precision remains unchanged at 0.12 and accuracy increases from 0.68 to 0.85 (Table S1). Here, we observe template matching scarps that do not correspond to, but seem to be continuous with, remote- and field-mapped faults (Fig. S11a). We also find ridges over volcanic rock that are closely aligned with mapped faults (Fig. S11b). This pattern suggests that our template matching is detecting previously unmapped fault segments that may be controlling ridges here. Therefore, template matching may identify lineaments that are possible faults in the South Volcanic Hills, which can be confirmed with future field mapping.

Statistical tests show that results from both remote- and field-mapping and template matching in the same region are not statistically similar. Nonetheless, both methods suggest the same subtle changes in fault orientation from the Central Terraces to South Volcanic Hills, where we are confident that both methods capture tectonic fault scarps ($\sim 13^\circ$ clockwise change

for remote- and field-mapping and $\sim 30^\circ$ clockwise change for template matching, both from the median orientation of segments). Our comparison of remote- and field-mapping and template matching results, acceptable AUROC values, and consistent change of fault strike support that the Almeja fault zone is sub-parallel and likely linked to the NE-trending North Salsipuedes basin at the southwest coast of IAG. We also show that template matching with field context can assess fault characteristics in inaccessible regions.

Figure 6. Luminescence site field photos. (a) Arroyo cutbank at the 'incised terrace' site, looking east. (b) 'Sag pond' site, looking north, and sample pit. (c) 'Southern terraces' site annotated with faults (black lines) and select stratigraphic layers (colored lines), looking north. (d) Samples located ~250 m south of the 'southern terraces' site, looking southeast.

4.1.2 Late Quaternary fault activity

Our luminescence ages from five sites constrain late Quaternary fault activity within the Almeja fault zone by demonstrating that at least four fault strands have produced surface-rupturing earthquakes after ~50 ka (Fig. 4). Although we constrained late Quaternary offset on only a few faults in this highly distributed fault zone, strands that lack direct age control cut terrace deposits that are correlative to our dated terrace units (Fig S2; Sabbeth, 2020). Thus, we interpret that most fault strands in the Almeja fault zone are late Quaternary active. Additionally, our mapping suggests potential continuity of the Almeja fault zone some distance offshore to the southwest. Remote- and field-mapping here, field-mapping from Sabbeth (2020), and the strike of steep fault scarps in bathymetry (~N42°E, perpendicular to strike of Ballenas transform fault ~N48°W; Plattner et al., 2015) align well with each other and presumably connect across the gap in high-resolution bathymetric data between the southwest IAG coast and ~2 – 3 km offshore (Fig. 2b). Thus, we infer that faults in the North Salsipuedes basin are also late Quaternary active and linked with the Almeja fault zone.

We do not present a slip rate for the entire Almeja fault zone because dated terraces are spatially limited and we do not have a finite age for the highest terrace T1, where significant dip-slip occurred. This limitation prevents us from calculating an accurate cumulative dip-slip rate. However, we can determine the Holocene dip-slip rate of fault X based on finite ages from faulted and unfaulted terraces. Using the Monte Carlo dip-slip displacement of fault X on terrace T2 and luminescence ages from terraces T2 and T3, the median slip rate of fault X between ~5 – 15 ka is 0.64 mm/yr (95% confidence interval 0.35 – 1.6 mm/yr; Fig. 7e; Fig. S12) following methods from Gold & Cowgill (2011; Supplementary Material S1). Although this rate does not consider cumulative slip across the width of the Almeja fault zone, it is greater than the mean

uplift rate across Baja California since 1 Ma (~ 0.1 mm/yr; Ortlieb, 1991). Because both rates are calculated across different timescales, we cannot assess if the Almeja fault zone has consistently facilitated high uplift or if it has had a time-variable slip rate (e.g., Garlock fault, California; Rittase et al., 2014) since the late Miocene or Pliocene when offshore rift-related faulting commenced. Nonetheless, our data support that fault X has been active during the Holocene.

Historic seismicity also supports ongoing deformation on IAG, as the Ballenas transform fault, North Salsipuedes basin, and Almeja fault zone have hosted many large historic earthquakes, recently relocated onshore or directly offshore (Fig. 2a; Fig. S13; Castro et al., 2021; Castro et al., 2017). On 12 November 2003, a Mw 5.6 earthquake with a N-striking normal fault focal mechanism that has a minor dextral-oblique component occurred (López-Pineda et al., 2014) and was relocated < 1 km offshore of southern IAG's east coast, along strike of the Almeja fault zone (Fig. S13; Castro et al., 2021; Castro et al., 2017). On 3 August 2009, a Mw 6.9 strike-slip earthquake on the Ballenas transform fault struck directly west of IAG (Plattner et al., 2015). On 21 December 2009, a Mw 4.8 earthquake with a dextral oblique-normal focal mechanism occurred and was relocated in the southern mountain range of IAG (Fig. S13; Castro et al., 2021; Castro et al., 2017). These 2009 earthquakes may be related, similar to how north-south migrating earthquake swarms on the Ballenas transform fault between 1973 – 1977, 1980 – 1982, and 1997 – 2003 are thought to increase seismicity in the North Salsipuedes basin when residual elastic energy after the swarms were distributed to surrounding rocks (López-Pineda et al., 2014). Indeed, changes of Coulomb failure stress after large strike-slip earthquakes on the Ballenas transform fault bring normal faults in the North Salsipuedes basin closer to failure (Plattner et al., 2015). Therefore, the earthquake cycle on the Ballenas transform fault may increase activity in the North Salsipuedes basin.

4.2 Microcontinent isolation mechanisms and future plate boundary reorganization

We first consider two strike-slip microcontinent isolation models, the wrench and horsetail models (Nemčok et al., 2016), to be responsible for the deformation of the Almeja fault zone. Dextral oblique-normal earthquakes have been recorded in the fault zone. However, while the Tiburón fault and Ballenas transform fault bound IAG (Fig. 2a), the absence of a transtensional duplex across the island, which would have formed as both faults overlapped and developed stepovers, precludes that IAG is compatible with the wrench faulting isolation model (Fig. 8a; Antobreh et al., 2009). Also, we would expect the duplex to be inactive today, contrary to our luminescence ages, as the overlapping was completed by ~2 Ma.

We do observe normal faults at high angles to the Ballenas transform fault throughout our study area (Fig. 3) that may be associated with the tips of strike-slip horsetail structures terminating on the island (Fig. 8b; e.g., Misra et al., 2014). A related hypothesis posits that the Almeja fault zone could be an expression of distributed transtension, off-fault strike-slip faulting splaying off the Ballenas transform fault, or dextral shear and secondary extension on faults with orientations that vary 10° - 30° . However, there is little evidence from geomorphic markers (only that in Fig. S9d – e), field-mapping (Sabbeth, 2020), and earthquakes to suggest a significant, dextral component of fault motion onshore IAG. Therefore, it is unlikely that the entire Almeja fault zone represents horsetail strike-slip structures or is dominated by off-fault strike-slip faulting related to the Ballenas transform fault.

Figure 7. (a). Map of terrace tread surfaces, faults, and locations of three scarp profiles at the ‘flight of terraces’ site. Basemap is ~0.1-m resolution drone-derived shaded relief. (b) Stitched orthomosaic of drone images showing terrace surfaces with 10-m elevation contours from 3-m resolution digital elevation. (c) Slope map shows steep terrace risers (yellows to reds) with little to no horizontal offset. (d) Stacked scarp profiles of fault X on terrace T2 (3 profiles). We show sections of each profile colored by surface type. Reported fault displacement is the median from Monte Carlo simulations per terrace with fault dip between 60° – 90°, after Duckworth et al. (2020) and Thompson et al. (2002). (e) Slip history of fault X from depositional ages and Monte Carlo fault displacement estimates (after Gold & Cowgill, 2011). Distance-time envelopes are constrained by the standard deviation of depositional ages and 95% confidence interval of fault displacement.

Another hypothesis for the role of the Almeja fault zone involves the Mountain Front fault and graben just north of our study area (Fig. 2b). Marine seismic lines obtained from PEMEX Exploración y Producción (map extent in Mar-Hernández et al., 2012) suggest that the Mountain Front fault may continue offshore and intersect the NW-striking Tiburón fault east of IAG (Fig. 8c). This suggested intersection is similar to how extensional faults and spreading centers in the inactive Lower Tiburón basin intersect the Tiburón fault (e.g., Fig. 8a; Lonsdale, 1989). A related hypothesis is that the Almeja fault zone is an early splay of the North Salsipuedes basin and is becoming inactive while a hard link between the basin and the Ballenas transform fault is established. Both hypotheses require the Almeja fault zone to be a dying segment of the presumably inactive Lower Tiburón basin or active North Salsipuedes basin.

However, the mountain front graben vertically displaces geomorphically young terraces by ~1 – 7 m (Fig. 5a), which suggests recent activity that agrees with our late Quaternary offsets from luminescence ages farther south. These young offsets suggest that onshore activity is not waning, which does not support the wrench (Fig. 8a) nor dying splay (Fig. 8c) models as the driving mechanism that formed the Almeja fault zone.

Our data suggest that (1) the Almeja fault zone is kinematically linked to the North Salsipuedes basin and (2) is presently complementing extension in the overlapping Lower Delfín basin. We propose that the NW-SE-directed extension between the Ballenas transform fault and the Tiburón fault is partitioned between the Lower Delfin basin and the Almeja fault zone (Fig. 8d). Fault orientation, sense of slip, and the age of fault offsets collected here and in Sabbeth (2020) agree with this two-part hypothesis. First, the onshore, N-striking, normal faults within the Almeja fault zone mapped in this study (Fig. 3) and by Sabbeth (2020) suggest that the Almeja fault zone projects offshore into the North Salsipuedes basin (Fig. 8e). This orientation

and slip behavior agree with the stress field related to the transtensional Pacific-North America plate boundary. Therefore, we propose that the North Salsipuedes basin is kinematically linked to the Almeja fault zone. Second, our luminescence ages constrain that the most recent normal fault offset on multiple fault strands occurred after ~50 ka. These ages and our slip rate estimate are similar to the activity of the North Salsipuedes basin, inferred from its submarine volcanic hills (Fig. 2b), seismicity, and thinned crust (Paz-López, 2000). Together, the orientation, sense of slip, and activity of the Almeja fault zone suggest that it is presently active and kinematically linked to the North Salsipuedes basin rather than to the inactive Tiburón fault. This suggestion does not require that the Almeja fault zone is not structurally connected to the Tiburón fault via the Mountain Front fault. Offset sediment layers near the Upper Tiburón basin in the PEMEX seismic lines (e.g., Mar-Hernández et al., 2012) suggest such a linkage. Therefore, extension in the North Salsipuedes basin may be affecting normal slip across southern IAG up to the Tiburón fault.

Regardless of the mechanism, if the Almeja fault zone continues to extend, the southern tip of IAG may eventually break away from the larger, northern part of the island and could lead to further microcontinent fragmentation and produce a second, smaller block (Fig. 8d) stranded within the transtensional plate boundary. Such breakup may exploit dynamic instabilities of the plate boundary (Gerya, 2010), such as the Almeja fault zone, which serves as a lithospheric preexisting weakness (Molnar et al., 2018). Thus, fragmentation of IAG may not be complete, and the Pacific-North America plate boundary is either not fully localized onto the Ballenas transform fault or is in the initial stage of a plate boundary reorganization.

Figure 8. Proposed formation mechanisms of the Almeja fault zone as a (a) wrench fault or duplex structure with stepovers processing to the northwest, (b) horsetail or distributed transtensional structure from the Ballenas transform fault, (c) dying splay of the Tiburón fault or North Salsipuedes basin, and (d) kinematic link to the active North Salsipuedes basin. Tectonic structures from Aragón-Arreola & Martín-Barajas (2007), Bennett et al., (2016b), and Stock (2000) augmented by bathymetry. (e) Detailed interpretation of mapped faults in the Almeja fault zone. Abbreviations are the same as Figure 1.

5 Conclusions

IAG is an ideal location to study microcontinent evolution. The onshore, normal, Almeja fault zone is sub-parallel to and on-strike with the offshore North Salsipuedes extensional basin, which is compatible with the hypothesis that these fault systems are kinematically linked across the shoreline. This linkage is further supported by late Quaternary onshore fault activity constrained by luminescence ages, historical seismicity, and extensional volcanic activity in the offshore basin. Combined, our results indicate that fragmentation and breakup of IAG are not yet complete and have likely been controlled by offshore extension in the North Salsipuedes basin since its inception ≤ 2 Ma. Therefore, a small portion of Pacific-North America plate motion may have been accommodated east of IAG for the past few million years or we may be capturing the early signs of a reorganization of the Pacific-North America plate boundary through the breakup of an evolving microcontinent.

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Data availability statement

Topography and luminescence data produced here are available at the UCLA Dataverse repository (https://dataverse.ucla.edu/dataverse/iag1_project/).

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