Supplementary Material for:

High $^3$He/$^4$He in central Panama reveals a distal connection to the Galápagos plume

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Figure S1: Regional tectonic setting of the central-eastern Pacific Ocean and southern CAM. (a) Galápagos islands (black areas) and main hotspot tracks (blue areas, Cocos ridge, Coiba ridge, Mapelo ridge and Carnegie ridge). Four tectonic plates are represented: the Cocos plate, Nazca plate, Caribbean plate and Panama micro-plate (PmP). At the transform–trench–trench triple junction between the Cocos plate, Nazca plate and overriding Panama microplate (the Panama Triple Junction, PTJ), the dextral Panama Fracture Zone (PFZ) subducts beneath the Caribbean plate along the Middle America Trench (MAT). As a result, the PFZ juxtaposes near-orthogonal subduction of the young and buoyant Cocos plate to its West, against oblique subduction of the Nazca plate to its East(1)(2). The Cocos–Caribbean convergence also involves subduction of the prominent aseismic Cocos Ridge, a ∼200 km wide paleo-Galápagos Hotspot track that lies >1500m above the surrounding seafloor(3)(4). One prominent and puzzling feature of the southern CAM is the cessation of typical calc-alkaline arc volcanism at ~5 Ma(5). This cannot be explained by near-horizontal subduction of the Cocos Ridge resulting in the displacement of the asthenospheric wedge(6)(7), because the Cocos Ridge (i) did not begin to subduct until 2-3 Ma, i.e., after calc-alkaline volcanism cessation(5)(8)(9)(10), and (ii) the Cocos plate currently subducts at a steep angle(11). (b) and (c) expansion of the rectangle in (a) show locations of our hydrothermal fluids (springs, seeps and wells; blue circles) and gas (orange diamonds) relative to the volcanic fronts in Costa Rica (black triangles) and Panama (white triangles). (c) Age migration of volcanism in the back-arc units from (12). MAT: Middle America Trench; PFZ: Panama fracture zone; PTJ: Panama triple junction.
Helium isotope composition of deeply sourced hydrothermal fluid (a) and gas (b) samples collected in Costa Rica and Panama is shown as a function of longitude. Color-coding is based on the year of sample collection, from 2005 to 2018, with previous data from (13) being reported in grey. Hydrothermal sites that have been sampled several times over the last 15 years show good agreement between replicate measurements, hence providing strong validation that high $^{3}\text{He}/^{4}\text{He}$ signal is a stable geochemical feature of central Panama. In contrast to Costa Rica, the lack of low $^{3}\text{He}/^{4}\text{He}$ (i.e., 0.05-4 $R_A$) in the volcanically dormant region of central Panama could potentially reflect the absence of radiogenic He contribution from the subducting slab, in agreement with the purported absence of a slab beneath the region (14)(15)(16).
Figure S3: Compilation of literature data for the helium isotopic composition of volcanic gases in arcs, after (17)(18)(19)(20). The color-coding of circles refers to the maximum air-corrected $^{3}\text{He}/^{4}\text{He}$ ($R_\text{C}/R_\text{A}$) of corresponding arc volcanic regions. The black circle labeled with an asterisk corresponds to the highest $^{3}\text{He}/^{4}\text{He}$ ever measured along the Americas volcanic arc chain (prior to our study), from high-temperature ($\geq 300^{\circ}\text{C}$) crater fumaroles of Galeras volcano (Colombia) before the 1992 explosive eruption ($8.84\pm0.63R_\text{A}(21)$). Helium data from this study (Costa Rica and Panama, zoomed in panel) are reported as diamonds in the inset. The coordinates of two points are given as cross marks to help localization.
Figure S4: Crustal thickness across CAM from the GEMMA model(22), highlighting a generally constant thickness (inset) along a transect (red line) in the sampled region (yellow dots). Distance in inset is from west to east in the transect (red line).
Figure S5: Comparison of crustal He contributions in central Panama geothermal fluids <70°C and hot (>70°C) crater fumaroles from Costa Rica and Nicaragua, in the framework of scenario 1 (Figure 1). In this scenario, we explore the possibility for the elevated $^3\text{He}/^4\text{He}$ observed in central Panama (CP) to be explained by magma upwelling from the upper mantle, with limited crustal contribution. We assume a homogeneous upper mantle source $^3\text{He}/^4\text{He}$ of 9 $R_A$ across southern CAM (i.e., at the upper end of the canonical upper mantle range ($R/R_A=8\pm1(23)$)) and compute the fractions of crustal He (% crustal He) required to explain the maximum $^3\text{He}/^4\text{He}$ measured for geothermal fluids in central Panama (8.9 $R_A$ (purple circle) ± 0.44 $R_A$ (purple area)) and crater fumaroles (triangles) from Turrialba (8.1 $R_A$), Poás (7.6 $R_A$), Irazú (7.2 $R_A$) volcanoes in Costa Rica and Mombacho volcano (7.6 $R_A$) in Nicaragua(24)(25)(26). Invariably, this scenario requires the crustal He contribution in geothermal fluids <70°C in central Panama to be lower than for high temperature fumaroles from active craters of CAM. This is however highly unlikely due to the absence of active volcanism in central Panama since late Miocene(5) and inherent addition of crustal He in geothermal fluids that are remote from volcanic active centers(17)(13)(27)(28)(29)(30)(31). Furthermore, the absence of significant crustal He contribution in central Panama is inconsistent with the roughly constant continental crust thickness (~35 km) across the southern CAM (Figure S4), implying that significant crustal He contributions as observed in cold geothermal fluids of Costa Rica(13)(24) should also be expected in central Panama. For these reasons, we favor scenario 2 (Figure 2, Figures S6-8), which requires the existence of a $^3\text{He}$-rich mantle source beneath central Panama.
Supplementary text 1: Estimating of the mantle source $^{3}\text{He}/^{4}\text{He}$ in central Panama (scenario 2).

Geochemical heterogeneities identified in the source of lavas erupted in CAM over the last ~5 Myr are considered to reflect magma source heterogeneities associated with the recycling of slab-derived Galápagos hotspot track material\(^{(12)(32)(33)(8)}\). Because subducted He likely does not reach depths of arc magma generation\(^{(34)}\), most – if not all – of the initial budget of predominantly radiogenic He in the slab must be readily lost to the forearc, regardless of the age of the slab\(^{(17)}\). Hence, crustal He contributions to geothermal fluids in subduction zones are primarily contolled by contributions from the underlying continental crust. Given that the crustal thickness in southern CAM is roughly constant\(^{(22)}\) (Figure S4), the widespread occurrence of crustal He in geothermal fluids $<$70°C of Costa Rica\(^{(13)(24)}\) indicates that crustal He is also likely present in geothermal fluids $<$70°C of central Panama.

Figure S4 illustrates how the $^{3}\text{He}/^{4}\text{He}$ of the mantle source in central Panama can be estimated using plausible crustal He fractions (%) derived for typical geothermal fluids $<$70°C from Costa Rica (where the potential influence of Galápagos mantle influx is expected to be negligible, Figure 2c). The maximum and average air-corrected $^{3}\text{He}/^{4}\text{He}$ in geothermal fluids $<$70°C from Costa Rica (maximum = 6.88 Ra, average = 2.77 Ra) are used to derive minimum and average estimates of crustal He contribution in southern CAM (minimum = 14%, average = 66%; Figure S6). These crustal He contribution estimates are then used to derive the minimum (10.3 Ra) and average (26 Ra) $^{3}\text{He}/^{4}\text{He}$ of the mantle source in central Panama, as implied by the detection of $^{3}\text{He}/^{4}\text{He}$ = 8.9 Ra in geothermal fluids $<$70°C. Note that these estimates are derived by considering that $^{3}\text{He}/^{4}\text{He}$ in geothermal fluids $<$70°C from Costa Rica reflect a binary mixture between known upper mantle (8 Ra) and crustal (0.05 Ra) sources. Considering a higher mantle source $^{3}\text{He}/^{4}\text{He}$ in Costa Rica (up to 9 Ra) would increase our estimates of crustal He contribution in southern CAM (Figure S7) and produce higher estimates of mantle source $^{3}\text{He}/^{4}\text{He}$ in central Panama, therefore reinforcing the requirement for a $^{3}\text{He}$-rich mantle source beneath the region.

Note that our minimum estimate for the $^{3}\text{He}/^{4}\text{He}$ of the mantle source in central Panama (10.3 Ra) is obtained by considering the minimum correction for crustal He contribution (i.e., the maximum $^{3}\text{He}/^{4}\text{He}$ of a typical geothermal fluids $<$70°C from Costa Rica: 6.88 Ra, Figure S4). However, this $^{3}\text{He}/^{4}\text{He}$ of 6.88 Ra has been reported in the vicinity (i.e., within 8 km) of Rincón de la Vieja volcano\(^{(13)}\), where the crustal He contribution is expected to be lower than in central Panama, hundreds of kilometers away from any active volcanic center. This suggests that actual crustal He contributions in central Panama could be markedly higher than inferred here using the $^{3}\text{He}/^{4}\text{He}$ of 6.88 Ra, implying that the $^{3}\text{He}/^{4}\text{He}$ of the mantle source in central Panama could be $>>$10.3 Ra, potentially as high as 26 Ra (Figure S6). It is also noteworthy that He is extracted more efficiently than other elements during mantle upwelling\(^{(35)}\), implying that pristine He could be (at least partially) lost during upwelling in the mantle flow. Furthermore, the
Galápagos Archipelago is highly heterogeneous with magmatic $^{3}\text{He}/^{4}\text{He}$ ranging from 6.9 to 27 $R_a$(36), so a mantle source $^{3}\text{He}/^{4}\text{He}$ as high as 26 $R_a$ may not be expected in CAM.

Figure S6: Estimating the $^{3}\text{He}/^{4}\text{He}$ of the mantle source in central Panama using plausible crustal He fractions (%) derived for typical geothermal fluids $<70^\circ\text{C}$ from Costa Rica. (a) The maximum (6.88 $R_a$, [1]) and average (2.77 $R_a$, [2]) $^{3}\text{He}/^{4}\text{He}$ in Costa Rica are used to derive minimum (14%) and average (66%) estimates of crustal He contribution in southern CAM. (b) These crustal He contribution estimates are then used in to derive the minimum (10.3 $R_a$, [1]) and average (26 $R_a$, [2]) $^{3}\text{He}/^{4}\text{He}$ of the mantle source in central Panama implied by the detection of $^{3}\text{He}/^{4}\text{He} = 8.9 R_a$. The two formulas used here to estimate the crustal He contribution in southern CAM (% crustal He) and mantle source $^{3}\text{He}/^{4}\text{He}$ in central Panama are given in panels a and b, respectively.
Figure S7: Testing the sensitivity of the $^{3}\text{He}/^{4}\text{He}$ of the estimated mantle source in central Panama (CP) to the assumed $^{3}\text{He}/^{4}\text{He}$ of the mantle source in Costa Rica (CR). (a) Our minimum estimate for the $^{3}\text{He}/^{4}\text{He}$ of the mantle source in central Panama is obtained by considering the minimum correction for crustal He contribution (i.e., the maximum $^{3}\text{He}/^{4}\text{He}$ of a typical geothermal fluids $<70^\circ\text{C}$ from Costa Rica: $6.88\text{ R}_A$, Figure S4). Increasing the assumed $^{3}\text{He}/^{4}\text{He}$ of the mantle source in Costa Rica from $8\text{ R}_A$ to $9\text{ R}_A$ (i.e., up to the upper end of the canonical upper mantle range ($\text{R}_A=8\pm1$ (23))) raises the minimum estimate of crustal He contribution in southern CAM from 14% up to 24%. This higher crustal He contribution estimate raises the minimum $^{3}\text{He}/^{4}\text{He}$ of the mantle source in central Panama ($^{3}\text{He}/^{4}\text{He}_{\text{CP}}$) from $10.3\text{ R}_A$ up to $11.6\text{ R}_A$ (b). The difference between the mantle source $^{3}\text{He}/^{4}\text{He}$ in central Panama and Costa Rica ($\Delta^{3}\text{He}/^{4}\text{He}_{\text{CP-CR}} = ^{3}\text{He}/^{4}\text{He}_{\text{CP}} - ^{3}\text{He}/^{4}\text{He}_{\text{CR}}$, where $^{3}\text{He}/^{4}\text{He}_{\text{CR}}$ is the assumed $^{3}\text{He}/^{4}\text{He}$ of the mantle source in Costa Rica) also increases from 2.35 to 2.65 $\text{R}_A$ (c).
Figure S8: Summary cartoon of He systematics in Costa Rica (left) and central Panama (right). In volcanic settings, $^{3}\text{He}/^{4}\text{He}$ of hydrothermal fluids are typically observed to be highest close to eruptive vents and rapidly decrease toward radiogenic values ($^{3}\text{He}/^{4}\text{He} < 1\ R_{A}$) away from volcanic centers, due to reduced mantle input and enhanced contribution from the underlying continental crust (17)(30)(28)(31)(13)(27). The roughly constant continental crust thickness (~35 km) across the southern CAM (Figure S4) implies that significant crustal He contributions as observed in cold geothermal fluids of Costa Rica (13)(24) should also be expected in central Panama, where $^{3}\text{He}/^{4}\text{He}$ up to 8.9 $R_{A}$ are yet measured in low temperature geothermal fluids. Hence, we consider that the high $^{3}\text{He}/^{4}\text{He}$ in the volcanically-dormant region of central Panama are best explained by the presence of a $^{3}\text{He}$-rich mantle source beneath the region, with a $^{3}\text{He}/^{4}\text{He}$ arguably greater than 10.3 $R_{A}$ and potentially as high as 26 $R_{A}$ (Figure S6, S7).
Supplementary text 2: Carbon isotopes systematics.

It is noteworthy that there is no obvious reason why the lack of significant C isotope fractionation due to calcite precipitation in the Panama samples would preclude a significant contribution of crustal He in low temperature geothermal samples. For the two samples with DIC ~60 mmol.l\(^{-1}\) (Figure S10) in central Panama (sample sites “El Salao Campollano” and “Los Bajos Correra”), measured Ca, Mg and SO\(_4\) concentrations in the fluids can be used to calculate DIC derived from in situ dissolution of carbonates (C\(_{\text{diss\_carb}}\)), following C\(_{\text{diss\_carb}}\) = [Ca + Mg − SO\(_4\)]. Assuming that (i) measured DIC values are the sum of dissolved carbonate and external C sources from the mantle wedge (C\(_{\text{ext}}\)) (i.e., C\(_{\text{ext}}\) = DIC − C\(_{\text{diss\_carb}}\)), and (ii) carbonate and sulfate minerals contributes the vast majority of Ca and Mg (i.e., Ca + Mg contributions from water-rock interaction with silicates are of secondary importance), we find that >75% and >97% of the DIC at “El Salao Campollano” and “Los Bajos Correra”, respectively, originates from the deep mantle wedge and not in situ carbonate dissolution. As described in the main text, high C concentrations in fluids from central Panama could be explained by substantial contributions from mantle-derived and/or recycled carbonates components – a significant contribution from sediments being unlikely here as these are characterized by largely negative \(\delta^{13}\)C, around -30‰ (Figure S9). The volcanic gas sampled at “Los Bajos Correra” corresponds to the blue diamond on Figure S9, which plots next to the pure carbonate end-member, with an extremely high $\text{CO}_2$/$^3\text{He}$ of $\sim 5 \times 10^{14}$.

**Isotope fractionation modelling**

Helium–carbon studies in volcanic arc settings(24)(37)(29)(38)(13) have coupled He and C isotopes to distinguish carbon from different provenances using a three-component mixing model (Figure 3b). In such acidic settings, volcanic activity has been suggested to release previously sequestered CO\(_2\) (18)(39)(40)(41), which mixes with slab/mantle carbon and results in the characteristic signatures. In summary, carbon is released from the slab/mantle and reacts with shallow groundwater forming an initial pool of dissolved carbon (DC). An isotopic fractionation factor between DC and calcite is calculated on the basis of the best fit to the observed data by varying the temperature iteratively. The starting \(\delta^{13}\)C of DC is considered to range between +0.5‰ and +5.0‰(13), presumably controlled by different slab inputs. Here, data from the 2018 field campaign require a starting \(\delta^{13}\)C of DC at +2‰ (Figure S10). The presumed slab inputs are consistent with positive isotope values measured in carbonate
sediments off the coast of CAM(42). As assumed in (13), starting δ¹³C input conditions are considered to be the same for the forearc, backarc and arc regions. As the Rayleigh fractionation progresses, calcite is precipitated and the isotope composition of residual DC reflects open system (Rayleigh) fractionation processes. Rayleigh distillation curves are computed following:

\[
\delta^{13}\text{C}_{\text{DC,f}} \sim (\delta^{13}\text{C}_{\text{DC,i}} + 1000) \times F^{\alpha-1} - 1000
\]

with \( \alpha = (-8.91 \times 10^6 \times T^{-3} + 8.56 \times 10^6 \times T^{-2} - 1.88 \times 10^4 \times T^{-1} + 8.27) \)

where \( F \) is the fraction of DC remaining in the fluid, \( \delta^{13}\text{C}_{\text{DC,f}} \) is the C isotope composition of DC at \( F \), \( \delta^{13}\text{C}_{\text{DC,i}} \) is the initial C isotope composition of DC, \( \alpha \) is the fractionation factor between DC and calcite at a given temperature \( T \) (in K).
Figure S9: CO\textsubscript{2}/\textsuperscript{3}He versus \(\delta^{13}\text{CO}_2\) relationships for hydrothermal fluid and gas samples. Color-coding is based on the year of sample collection, from 2005 to 2018, with previous data from (13) being reported in grey. Mantle and subduction-related end-member compositions (organic sediments and carbonates) are given along with mixing lines after (37). Predicted calcite fractionation model trends at 25°C, 75°C, 125°C and 290°C are also shown, with maximum considered fractions of C lost (%) shown as black stars. Fluid samples with \(\delta^{13}\text{CO}_2 > 0\) are most consistent with either (i) calcite precipitation at high temperature (up to ~290°C), (ii) biologically induced carbon fixation resulting in kinetic fractionation of C isotopes preferentially removing \(^{12}\text{C}\) from CO\textsubscript{2}(43), or (iii) equilibrium isotopic fractionation (EF, black arrow) associated with dissolution of CO\textsubscript{2} gas into aqueous fluids(44). Interestingly, we find that CO\textsubscript{2}/\textsuperscript{3}He for water samples are generally lower (and associated with more negative \(\delta^{13}\text{CO}_2\)) than for gas samples, which is the opposite of what is commonly observed for hydrothermal degassing and/or solubility-controlled phase separation(45) whereby higher CO\textsubscript{2}/\textsuperscript{3}He for the water phase are due to greater solubility of CO\textsubscript{2} in aqueous solution relative to He. This further supports our interpretation that C sequestration via calcite precipitation from aqueous C (i.e. DIC) is the dominant process controlling CO\textsubscript{2}/\textsuperscript{3}He variations in Costa Rica and Panama. In addition, we measured \(\delta^{13}\text{C}\) in DIC for 19 hydrothermal fluid samples collected during our most recent field campaign in 2018 (Figure S10).
Figure S10: Carbon isotopes as a function of DIC concentrations from the 2018 field expedition. (a) Rayleigh fractionation curves associated with calcite precipitation (fraction of C sequestered as calcite given as percentage) are shown as dotted lines. $\delta^{13}C$ composition of DIC (b) and total DIC (c) as a function of longitude, from the 2018 field expedition, suggesting an along-arc progressive increase of $\delta^{13}C$ DIC (i.e., lower effect of calcite precipitation) towards central Panama (blue arrow). Vertical dashed lines correspond to the approximate longitude of the border between Costa Rica and Panama (Figure S1). Y-axis is shown on a logarithmic scale for (c).
Figure S11. Age-corrected Pb isotopes systematics for the magmas of southern Central America. Data are from (33)(12) and this study. This diagram shows that our new data from La Providencia do not plot on the trends of mixing towards Galápagos end-members, indicating that their $^{206}\text{Pb}/^{204}\text{Pb}$ composition, at the upper end of the MORB range (Figure 2a), reflects minimal (if any) contribution from Galápagos-derived material. Conversely, we note that even arc front volcanoes in southern Nicaragua do show evidence of mixing with Galapagos slab-derived northern domain material, as previously shown from $^{206}\text{Pb}/^{204}\text{Pb}$ vs. $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ isotope diagrams (33). Symbol shapes are the same as Figure 2 of the main text.
Figure S12. Central America convergent margin earthquake distribution. Bottom: Map showing seismicity from the USGS-ANSS catalog (1960–2020) as small circles. Circle size is proportional to earthquake magnitude while color denotes earthquake depth. Offshore dark gray line shows the location of the trench from (46). Top: longitude projection of the depth of the earthquakes showing the lack of deep seismicity beneath west Panama, where the presence of a slab window is inferred.
Figure S13: SLAB2 model (47) of slab contours in central America (coloured lines), and trench locations (magenta lines) from (46). Sample locations from this study are yellow circles, and volcanoes extracted from the Global Volcanism Program database (48) are red triangles. The location of the surface projection of the slab window contours broadly matches the locations of the borders between Panama and Costa Rica to the North-West, and between Panama and Columbia to the South-East. This ~600 km wide slab opening allows for the influx of Galápagos-derived material that directly affects the geochemistry of volcanism in southern CAM (i.e., He isotopes of geothermal fluids (Figure 1) and Pb isotope-Ce/Pb-Nb/U systematics of lavas (Figure 2)).
Figure S14: Cross sections of seismic tomography of the mantle beneath CAM highlighting the presence of a) subducting slab materia (blue material), and b) a slab window (red/brown material) beneath Panama. The P-wave tomography MIT-P09 from Li et al. (2008) [top panels] and UU-P07 from van der Meer et al. (2017) [bottom panels] are extracted along vertical profiles that include the Galápagos plume (approx. 10° arc distance along the profile) and the central American continental terranes. Earthquakes with magnitudes greater than 4 (green points on map) from the ANSS catalogue (USGS 2017) are also extracted within 200 km of the vertical profiles (red points on map, and white points on cross-section), and the SLAB2 (Hayes et al. 2018) structure is also plotted (green line on cross-sections). X-axis is great circle arc distance along profile.
Figure S15: Cross sections of seismic tomography of the mantle beneath CAM line of arc volcanoes extracted from the Global Volcanism Program database (48). The P-wave tomography MIT-P09 from (49) (top panel) and UU-P07 from (50) (bottom panel). Earthquakes with magnitudes greater than 4 (green points on map) from the ANSS catalogue (USGS 2017) are also extracted within 200 km of the vertical profiles (red points on map, and white points on cross-section), and the SLAB2 (47) structure is also plotted (green line on cross-sections). X-axis is great circle arc distance along profile.
Figure S16: Depth slices through the P-wave tomography MIT-P09 from (49) (left panels) and UU-P07 from (50) (right panels), highlighting the spatial association between the slabs (blue regions on maps) and trench locations (green line) from (46).
Plate reconstructions of central America embedded in a GPlates (www.gplates.org) global plate motion model(51) show the eastward subduction of the Farallon Plate beneath North, Central, and South America that splits into the Cocos (north) and Nazca (south) plates by ~23 Ma. The contemporary Galapagos Plume trail emerges from ~17 Ma with eruptions that build the diverging trail of oceanic plateaus. The plate reconstructions indicate that the Cocos-Nazca spreading ridge starts interacting with the Panama segment of the Central American convergent margin from ~23 Ma, resulting in a slab window that evolves to the present day. Present-day

Figure S17: Screenshots of the plate tectonic reconstruction provided as Supplemental video.
continental topography is reconstructed through time, and the seafloor age-grid is plotted in the oceanic regions. Mid oceanic ridges and transforms are plotted as thick black lines, while subduction zones are plotted as teethed magenta lines. Plate velocities are plotted as arrows, and mantle plume volcanic products are plotted as dark grey polygons. Two motions paths, plotted in red (yellow dots every 1 Myr), represent the motion of the Nazca and Cocos plates with respect to the Galapagos Plume, with the plume position (red triangle) set at 17 Ma when the contemporary preserved portions of the plume trail appear.

Dataset Legends

**Dataset S1**: Helium and carbon isotope and concentration data for water and gas samples.

**Dataset S2**: New geochemical data for La Providencia.

**Dataset S3**: Geochemical data compilation for lavas of CAM.

Movie Legends

**Supplemental Movie**: Plate reconstructions of central America for the last 25 Myr, embedded in a GPlates (www.gplates.org) global plate motion model(51).
Supplementary References

1. D. F. Argus, R. G. Gordon, C. Demets, Geologically current motion of 56 plates relative to the no-net-rotation reference frame. *Geochemistry, Geophys. Geosystems* 12, 1–13 (2011).
2. D. Kobayashi, *et al.*, Kinematics of the western Caribbean: Collision of the Cocos Ridge and upper plate deformation. *Geochemistry, Geophys. Geosystems* 15, 1671–1683 (2014).
3. V. Sallarès, P. Charvis, E. R. Flueh, J. Bialas, Seismic structure of Cocos and Malpelo Volcanic Ridges and implications for hot spot-ridge interaction. *J. Geophys. Res.* 108, 1–21 (2003).
4. C. H. E. Walther, The crustal structure of the Cocos ridge off Costa Rica. *J. Geophys. Res. Solid Earth* 108, 1–21 (2003).
5. I. MacMillan, P. B. Gans, G. Alvarado, Middle Miocene to present plate tectonic history of the southern Central American Volcanic Arc. *Tectonophysics* 392, 325–348 (2004).
6. S. McGeary, A. Nur, Z. Ben-Avraham, Spatial gaps in arc volcanism: The effect of collision or subduction of oceanic plateaus. *Tectonics* 119, 195–221 (1985).
7. R. A. Kolarsky, P. Mann, W. Montero, Island arc response to shallow subduction of the Cocos Ridge, Costa Rica. *Spec. Pap. Soc. Am.*, 235–235.
8. K. D. Morell, Late Miocene to recent plate tectonic history of the southern Central America convergent margin. *Geochemistry, Geophys. Geosystems* 16(10), 3362–3382 (2015).
9. P. Vannucchi, Fast rates of subduction erosion along the Costa Rica Pacific margin: Implications for nonsteady rates of crustal recycling at subduction zones. *J. Geophys. Res.* 108, 1–13 (2003).
10. J. F. Mescua, *et al.*, Middle to Late Miocene Contractional Deformation in Costa Rica Triggered by Plate Geodynamics. *Tectonics* 36, 2936–2949 (2017).
11. O. H. Lücke, I. G. Arroyo, Density structure and geometry of the Costa Rican subduction zone from 3-D gravity modeling and local earthquake data. *Solid Earth* 6, 1169–1183 (2015).
12. E. Gazel, *et al.*, Plume-subduction interaction in southern Central America: Mantle upwelling and slab melting. *Lithos* 121, 117–134 (2011).
13. P. H. Barry, *et al.*, Forearc carbon sink reduces long-term volatile recycling into the mantle. *Nature* 568, 487–492 (2019).
14. M. Abratis, G. Wörner, Ridge collision, slab-window formation, and the flux of Pacific asthenosphere into the Caribbean realm. *Geology* 29, 127–130 (2001).
15. S. T. Johnston, D. J. Thorkelson, Cocos-Nazca slab window beneath Central America. *Earth Planet. Sci. Lett.* 146, 465–474 (1997).
16. E. A. Herrstrom, M. K. Reagan, J. D. Morris, Variations in lava composition associated with flow of asthenosphere beneath southern Central America. *Geology* 23, 617–620 (1995).
17. D. R. Hilton, T. P. Fischer, B. Marty, Noble gases and volatile recycling at subduction zones. *Rev. Mineral. Geochemistry* 47 (2002).
18. E. Mason, M. Edmonds, A. V Turchyn, Dominate Volcanic Arc Emissions. *Science (80-. ).* 294, 290–294 (2017).
19. S. A. Halldórsson, D. R. Hilton, V. R. Troll, T. P. Fischer, Resolving volatile sources along the western Sunda arc, Indonesia. *Chem. Geol.* 339, 263–282 (2013).
20. R. Poreda, H. Craig, Helium isotope ratios in circum-Pacific volcanic arcs. *Nature* 338, 473–478 (1989).
21. Y. Sano, T. Gamo, S. N. Williams, Secular variations of helium and carbon isotopes at
Galeras volcano, Colombia. *J. Volcanol. Geotherm. Res.* **77**, 255–265 (1997).

22. M. Reguzzoni, D. Sampietro, GEMMA: An Earth crustal model based on GOCE satellite data. *Int. J. Appl. Earth Obs. Geoinf.* **35**, 31–43 (2015).

23. D. N. Barfod, C. J. Ballentine, A. N. Halliday, J. G. Fitton, Noble gases in the Cameroon line and the He, Ne, and Ar isotopic compositions of high mu (HIMU) mantle. *J. Geophys. Res.* **104** (1999).

24. A. M. Shaw, D. R. Hilton, T. P. Fischer, J. A. Walker, G. E. Alvarado, Contrasting He-C relationships in Nicaragua and Costa Rica: Insights into C cycling through subduction zones. *Earth Planet. Sci. Lett.* **214**, 499–513 (2003).

25. D. R. Hilton, *et al.*, Monitoring of temporal and spatial variations in fumarole helium and carbon dioxide characteristics at Poás and Turrialba Volcanoes, Costa Rica (2001-2009). *Geochim. J.* **44**, 431–440 (2010).

26. T. P. Fischer, *et al.*, Temporal variations in fumarole gas chemistry at Poás volcano, Costa Rica. *J. Volcanol. Geotherm. Res.* **294**, 56–70 (2015).

27. Y. Sano, H. Wakita, S. N. Williams, Helium-isotope systematics at Nevado del Ruiz volcano, Colombia: implications for the volcanic hydrothermal system. *J. Volcanol. Geotherm. Res.* **42**, 41–52 (1990).

28. G. A. M. de Leeuw, D. R. Hilton, F. T.P., W. J.A., The He–CO2 isotope and relative abundance characteristics of geothermal fluids in El Salvador and Honduras: New constraints on volatile mass balance of the Central American Volcanic Arc. *Earth Planet. Sci. Lett.* **258** **258**, 132–146 (2007).

29. G. Snyder, R. Poreda, A. Hunt, U. Fehn, Central American volcanic arc. *Geochemistry, Geophys. Geosystems* **2** (2001).

30. Y. Sano, T. P. Fischer, *The noble gases as geochemical tracers* (2013) https://doi.org/10.1007/978-3-642-28836-4.

31. M. C. Ray, D. R. Hilton, J. Muñoz, T. P. Fischer, A. M. Shaw, The effects of volatile recycling, degassing and crustal contamination on the helium and carbon geochemistry of hydrothermal fluids from the Southern Volcanic Zone of Chile. *Chem. Geol.* **266**, 38–49 (2009).

32. E. R. Benjamin, *et al.*, High water contents in basaltic magmas from Irazú Volcano, Costa Rica. *J. Volcanol. Geotherm. Res.* **168**, 68–92 (2007).

33. K. Hoernle, *et al.*, Arc-parallel flow in the mantle wedge beneath Costa Rica and Nicaragua. *Nature* **451**, 1094–1097 (2008).

34. D. V. Bekaert, *et al.*, Subduction-Driven Volatile Recycling: A Global Mass Balance. *Annu. Rev. Earth Planet. Sci.* **49** (2021).

35. M. D. Kurz, D. Geist, Dynamics of the Galapagos hotspot from helium isotope geochemistry. *Geochim. Cosmochim. Acta* **63**, 4139–4156 (1999).

36. M. D. Kurz, S. K. Rowland, J. Curtice, A. E. Saal, T. Naumann, Eruption Rates for Fernandina Volcano: A New Chronology at the Galápagos Hotspot Center. *Galapagos A Nat. Lab. Earth Sci.*, 41–54 (2014).

37. Y. Sano, B. Marty, Origin of carbon in fumarolic gas from island arcs. **2541** (1995).

38. H. Wehrmann, K. Hoernle, M. Portnyagin, M. Wiedenbeck, K. Heydolph, Volcanic CO2 output at the Central American subduction zone inferred from melt inclusions in olivine crystals from mafic tephras. *Geochim. Geophys. Geosystems* **12**, 1–16 (2011).

39. B. de Moor, J. M., Aiuppa, A., Avard, G., Wehrmann, H., Dunbar, N., Muller, C., ... & Galle, Journal of Geophysical Research : Solid Earth. *J. Geophys. Res. Solid Earth* **121**(8), 5761–5775 (2016).

40. P. Dawson, B. Chouet, A. Pitt, Tomographic image of a seismically active volcano: Mammoth Mountain, California. *J. Geophys. Res. Solid Earth* **121**, 114–133 (2016).

41. G. Chiodini, L. Pappalardo, A. Aiuppa, S. Caliro, The geological CO2 degassing history of a long-lived caldera. *Geology* **43**, 767–770 (2015).
42. L. Li, G. E. Bebout, Carbon and nitrogen geochemistry of sediments in the Central American convergent margin: Insights regarding subduction input fluxes, diagenesis, and paleoproductivity. *J. Geophys. Res. Solid Earth* **110**, 1–17 (2005).
43. M. J. Whiticar, Carbon and hydrogen isotope systematics of bacterial formation and oxidation of methane. *Chem. Geol.* **161**, 291–314 (1999).
44. W. G. Mook, J. C. Bommerson, W. H. Staverman, Carbon isotope fractionation between dissolved bicarbonate and gaseous carbon dioxide. *Earth Planet. Sci. Lett.* **22**, 169–176 (1974).
45. P. H. Barry, *et al.*, Helium and carbon isotope systematics of cold “mazuku” CO2 vents and hydrothermal gases and fluids from Rungwe Volcanic Province, southern Tanzania. *Chem. Geol.* **339**, 141–156 (2013).
46. P. Bird, An updated digital model of plate boundaries. *Geochemistry, Geophys. Geosystems* **4** (2003).
47. G. P. Hayes, *et al.*, Zone Geometry Model. **61**, 58–61 (2018).
48. E. (ed. . Venzke, Global Volcanism Program. Volcanoes of the World, v. 4.9.4. Smithson. Inst. https://doi.org/https://doi.org/10.5479/si.GVP.VOTW4-2013.
49. C. Li, R. D. Van Der Helst, E. R. Engdahl, S. Burdick, A new global model for P wave speed variations in Earth’s mantle. *Geochemistry, Geophys. Geosystems* **9** (2008).
50. D. G. van der Meer, D. J. J. van Hinsbergen, W. Spaakman, Atlas of the underworld: Slab remnants in the mantle, their sinking history, and a new outlook on lower mantle viscosity. *Tectonophysics* **723**, 309–448 (2018).
51. R. D. Müller, *et al.*, A Global Plate Model Including Lithospheric Deformation Along Major Rifts and Orogens Since the Triassic. *Tectonics* **38**, 1884–1907 (2019).