

Continental crust generated in oceanic arcs

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Thin oceanic crust is formed by decompression melting of the upper mantle at mid-ocean ridges, but the origin of the thick and buoyant continental crust is enigmatic. Juvenile continental crust may form from magmas erupted above intra-oceanic subduction zones, where oceanic lithosphere subducts beneath other oceanic lithosphere. However, it is unclear why the subduction of dominantly basaltic oceanic crust would result in the formation of andesitic continental crust at the surface. Here we use geochemical and geophysical data to reconstruct the evolution of the Central American land bridge, which formed above an intra-oceanic subduction system over the past 70 Myr. We find that the geochemical signature of erupted lavas evolved from basaltic to andesitic about 10 Myr ago—coincident with the onset of subduction of more oceanic crust that originally formed above the Galápagos mantle plume. We also find that seismic P-waves travel through the crust at velocities intermediate between those typically observed for oceanic and continental crust. We develop a continentality index to quantitatively correlate geochemical composition with the average P-wave velocity of arc crust globally. We conclude that although the formation and evolution of continents may involve many processes, melting enriched oceanic crust within a subduction zone—a process probably more common in the Archaean—can produce juvenile continental crust.

Earth's crust is the interface between our planet's deep interior and surface. Most 'terrestrial' planets have basaltic crusts similar to Earth's oceanic crust, but the continental masses, areas of buoyant, thick silicic crust, are a unique characteristic of Earth^{1–3}. Therefore, understanding the processes responsible for the formation of continents is fundamental to reconstructing the evolution of our planet. Partial melting at mid-ocean ridges results in the production of relatively thin basaltic crust (~7 km), whereas continental crust has an average thickness of ~40 km (refs 1,2). Mantle plume activity can produce thicker crust, but the composition remains basaltic³. Thus, the best candidates for the continuous production of juvenile continental crust are intra-oceanic volcanic arcs, but when silicic magmas (SiO₂ > 60 wt%) are produced, the incompatible-element compositions are generally too depleted to be a good match for continental crust estimates^{4–6}.

Previous studies suggested that melting of subducting oceanic crust is a requirement for the generation of continental crust^{4,6}, a process that was probably more common in the Archaean than today^{6,7}. Here we test this model with a careful examination of the geologic history of the Central American land bridge (CALB, Costa Rica and Panama) to bring new answers to this longstanding debate. Reconstruction of the geochemical evolution of arc lavas at the CALB (70 Ma to present, Supplementary Tables 1 and 2) reveals a strong correlation between the appearance of the isotopic signature of the subducting Galápagos tracks (for example, elevated Pb-isotope ratios, Fig. 1) and incompatible-element enrichments (in which elements not abundant in Earth's mantle are enriched in the crust; for example, La/Yb > 10, Fig. 1)^{8,9}. We document at least

two pulses of melting of subducted Galápagos crust recorded in the CALB (~50–40 Ma and <10 Ma; Fig. 1), which correlate with the production of primitive andesites^{9–11} (this study; wt% SiO₂ > 55; molar Mg/(Mg + Fe) > 0.6; details in Supplementary Information). Subduction of the Galápagos tracks resulted in lavas enriched in incompatible elements with Galápagos isotopic compositions^{8,9} (Fig. 1). A shift from dominantly basaltic to more andesitic compositions (for example, increase in SiO₂ and K₂O, Fig. 2), reaching continental crust values², represents a major change in the evolution of this segment of the Central American arc. We can rule out assimilation of a pre-existing old continental 'root' or fractional crystallization to explain the enriched composition of the andesitic melts from the volcanic front because they have the same enriched geochemical signatures as contemporaneous mafic lavas within the same segment^{11,12} (Supplementary Information). Moreover, the enriched signature is clearly derived from the Galápagos input into the subduction system beneath the CALB (refs 8,9).

Seismic evidence for continental crust production

From a geochemical perspective we propose that the CALB evolved to be a young continental mass. We examined this model in light of recent geophysical observations. At depths of 10–40 km, most modern oceanic arcs have P-wave velocities (V_p) 0.5–2.0 km s⁻¹ higher than average continental crust at a given depth (Fig. 3). In contrast, variation of V_p with depth in central and northern Costa Rica¹³ is transitional between the velocity structure of oceanic arc and continental crust¹⁴ (Fig. 3b). Moho reflections at the base of the crust in central and northern Costa Rica^{13,15} are consistent with

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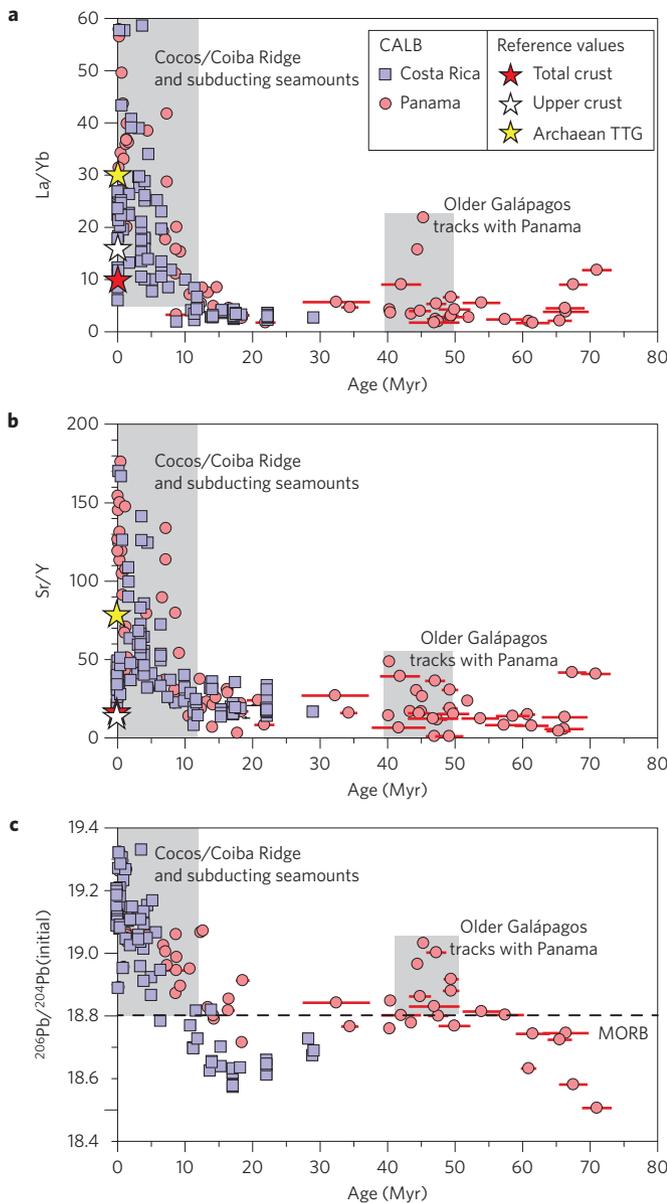


Figure 1 | Geochemical evolution in the CALB over the past 70 Myr.

a–c. The two peaks in the La/Yb (**a**) and Sr/Y (**b**) ratios in the volcanic output correspond to increases in Pb-isotope ratios (above local MORB values) (**c**) and record the interaction of the subduction system with Galápagos tracks^{8,9}. The presence of accreted Galápagos terranes with ages of 50–65 Myr in the CALB suggests that there was an interaction with Galápagos tracks between 40 and 60 Ma (ref. 8). The last interaction, starting ~10 Ma, resulted in a magmatic output that reached values ranging from bulk/upper continental crust² to Archaean tonalite–trondhjemite–granodiorite (TTGs; ref. 7). The error bar in age represents the 2- σ uncertainty of ⁴⁰Ar/³⁹Ar plateaux from step heating experiments. The legend in **a** applies to all panels. Data from Supplementary Table 1, refs 8,9,11,44.

a thick (>40 km) crust and a relatively high V_p/V_s ratio (~1.8 or higher). A crustal thickness of 40–45 km (Fig. 3c) is greater than in most modern oceanic arcs¹⁶ and nearly twice as thick as the Caribbean Plateau offshore Costa Rica¹³ (Fig. 3). Thus, the seismic velocity structure and crustal thickness of Costa Rica are representative of an arc that probably evolved from the Caribbean Plateau and older mafic arc-volcanic rocks to a composition that is similar to continental crust¹³.

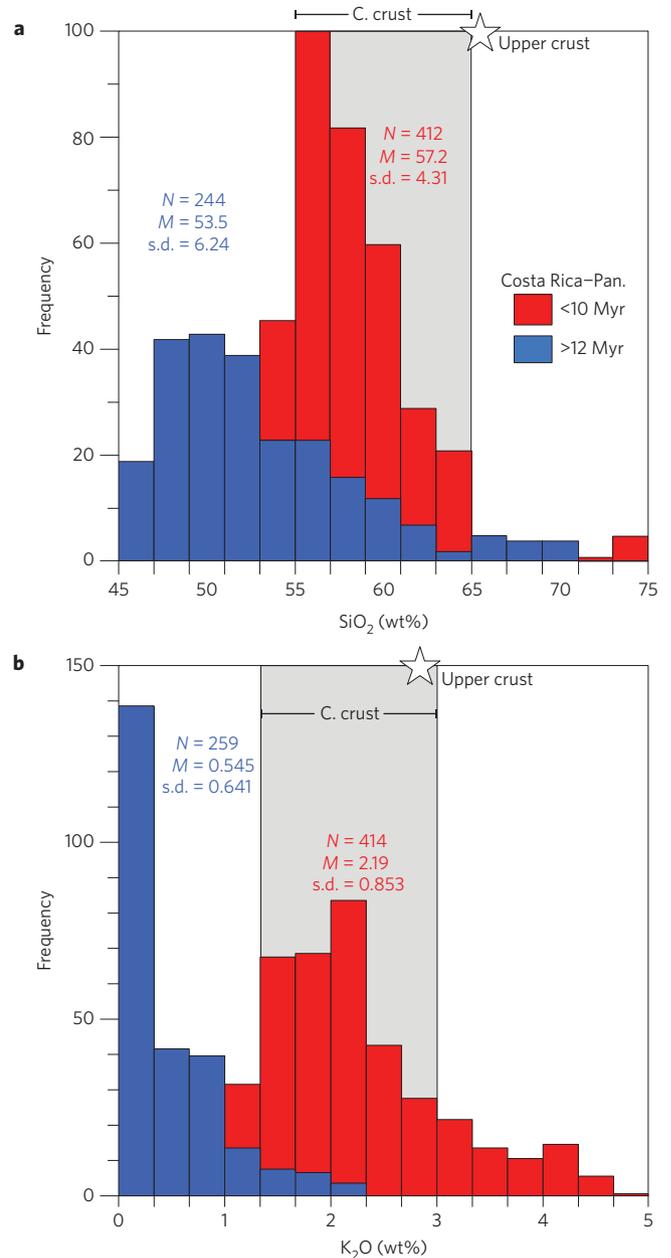


Figure 2 | Evolution from basaltic to andesitic compositions in the CALB in the past 10 Myr. **a, b.** Major element evolution of CALB magmas from normal arc compositions (basaltic (**a**), low K₂O (**b**)) to compositions similar to bulk, and even upper continental crust values², in the past 10 Myr. A global comparison of intra-oceanic arcs is given in Supplementary Information Section 2. C. crust, continental crust; Pan, Panama; N, number of samples; M, mean; s.d., standard deviation.

Any ‘recipe’ for making continental crust must contend with the problem of dense residues that form when buoyant silicic magmas are produced. Such dense residues do not form significant proportions of the continental crust. Specifically, V_p predicted for the Mg- and Fe-rich rocks of magmatic crystallization in arcs are ~7.5 km s⁻¹ at lower-crustal depths¹⁷, whereas typical lower continental crust has $V_p < 7$ km s⁻¹ (ref. 14). A possible solution to this problem is to remove the lower part of island arc crust via mechanical delamination driven by the density contrast between the dense crystal products of magmatic fractionation and less dense upper mantle peridotite¹⁸. It is also possible that dense residues are ‘hidden’ beneath the crust–mantle transition, because their V_p

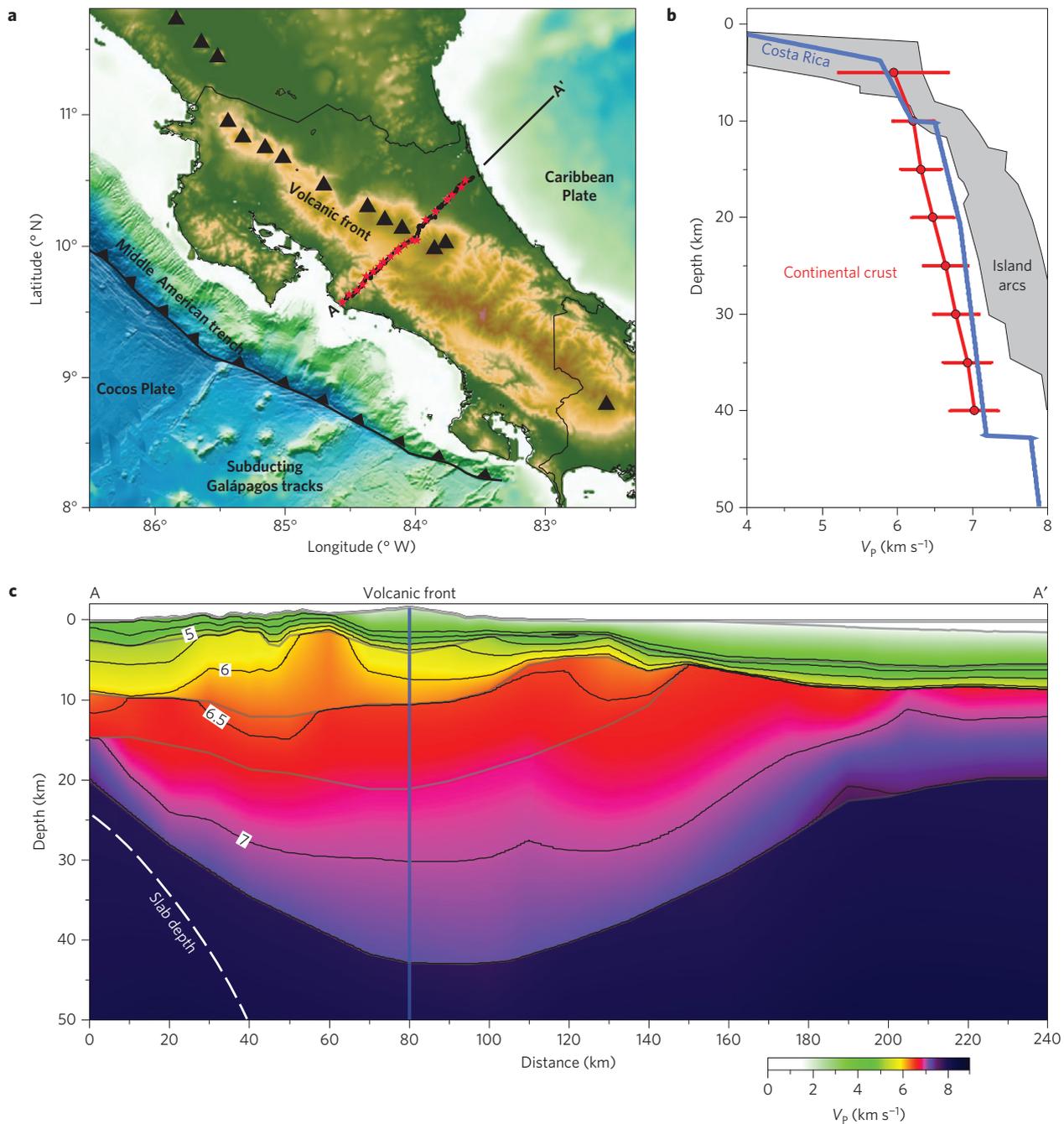


Figure 3 | Seismic signature of Costa Rica from active source experiments. P-wave velocity (V_p) model from active source experiments across Costa Rica. **a**, Location of the seismic experiment and modelled cross-section. Stars denote explosion sources and triangles are active volcanoes. **b**, Compressional velocity model in central Costa Rica (blue line) is closer to continental crust velocities (red line)¹⁴ than any other arc without older continental crust (grey field¹⁶). **c**, P-wave velocity model across Costa Rica (Supplementary Information). Locations of the boundary interfaces used in ray tracing are shown in grey and velocity contours in black. Location of the one-dimensional profile from **b** is shown in blue. Note the thickness is ~ 45 km in the arc and ~ 20 km in the Caribbean Plate. The error bar in V_p for continental crust represents the range for all continental crust (ref. 14).

approaches those of mantle peridotite^{5,17}. An alternative explanation is that silicic melts were produced by partial melting of subducting oceanic crust, followed by metasomatic reactions in the mantle that form primitive andesites^{4,6,19–21}. In this process, dense residues of partial melt extraction in the subducting slab are recycled into the mantle. In Costa Rica, we suggest that almost the entire thick, relatively felsic crust has formed via this latter process since 10 Ma. Older, mafic high- V_p crust from the Caribbean Plateau and the pre-10 Ma mafic arc form thinner, higher-velocity crustal sections that flank the younger andesitic-dominated crust^{8,13}. The last model

would be analogous to the Talkeetna arc section in Alaska, which contains no identifiable remnants of the older oceanic crust into which it was emplaced⁶. In the first alternative model, mafic lower crust in Costa Rica has been removed by delamination¹⁸, as mentioned before.

Global survey of intra-oceanic arcs

Average continental crust is andesitic in composition and enriched in elements incompatible in the mantle (for example, K_2O , LREE; refs 1,2,5). Although silicic magmas ($\text{SiO}_2 > 60$ wt%) are common

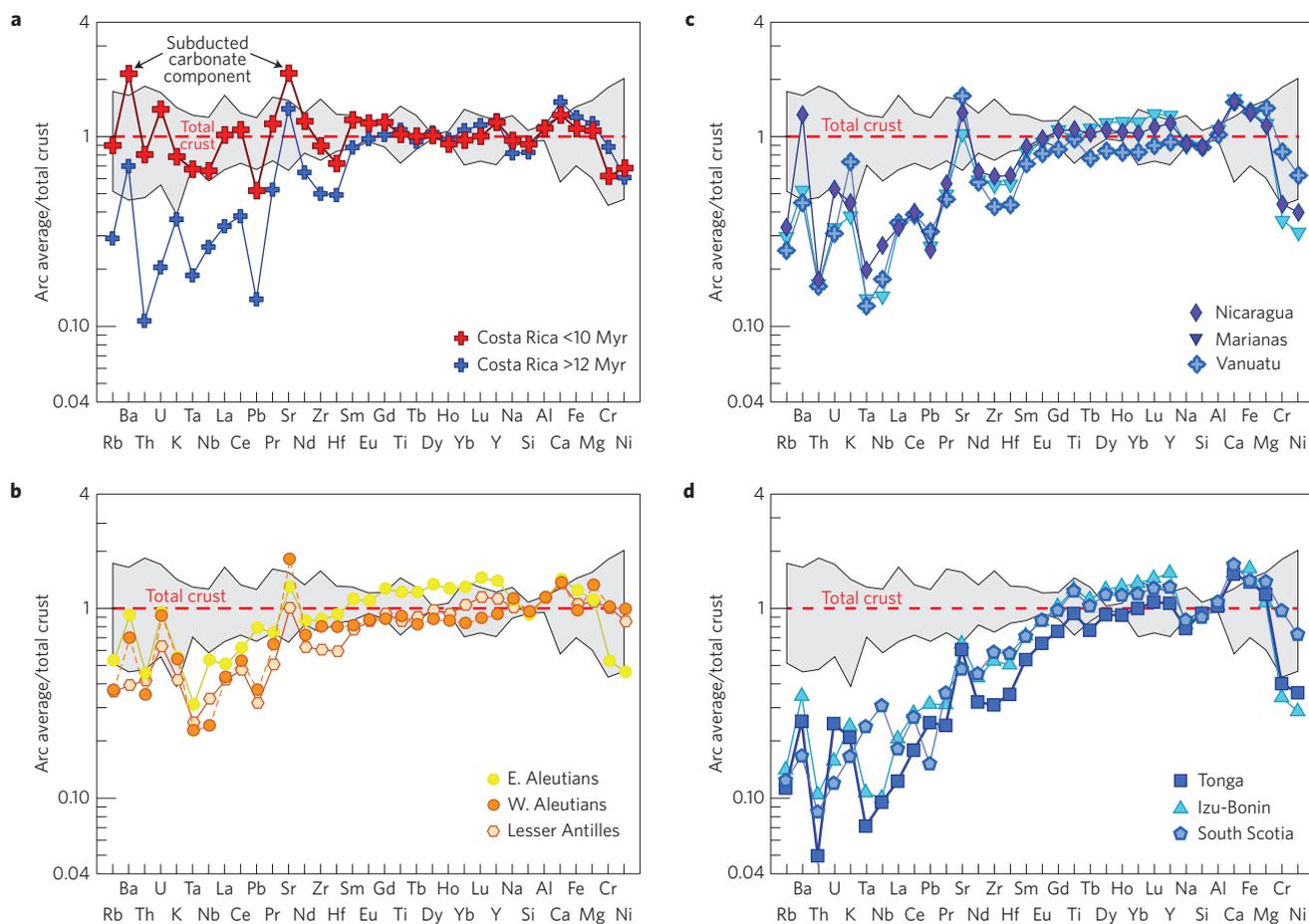


Figure 4 | Average compositions of intra-oceanic arcs. a–d, Average compositions of intra-oceanic arcs normalized to the estimated bulk composition of continental crust (averages in Supplementary Table 3). The grey areas show the range of continental crust estimates in the literature compiled in Supplementary Table 3. Other arc averages are not shown for clarity purposes, but are available in Supplementary Table 3. Details in Supplementary Information Section 2.

in all arc systems we evaluated only the CALB, western Aleutians and the Lesser Antilles show a normal distribution with a significant portion (more than half) of the data in the range of estimated, bulk continental crust (Supplementary Fig. 4). The remaining arcs have bimodal distributions dominated by basaltic compositions with a minor population of silicic melts. K_2O shows an overall log-normal distribution, with the exception of CALB, Iwo-Jima, the eastern and western Aleutians and Vanuatu, which clearly reach continental crust K_2O values.

To further evaluate if intra-oceanic arcs are at present producing magmas with chemical compositions close to continental crust estimates, we first calculated an average composition for each intra-oceanic arc (Supplementary Table 3). We omit arcs emplaced within older continental crust (for example, Andes, Cascades, New Zealand, Indonesia, Japan) to ensure that the locations evaluated in this study are forming from juvenile sources and not inheriting geochemical signatures from pre-existing continental material. Figure 4 shows that average compositions of Costa Rica arc magmas <10 Ma are the closest to continental crust compositions, followed by the western and eastern Aleutians and the Lesser Antilles, whereas the remaining arcs are not good matches for continental crust. However, to present this data in a more quantitative way, including all the available samples in an arc or arc segment and to be able to relate these observations with seismic properties measured at different intra-oceanic arcs, we developed an integrated geochemical continental index (CI). We did this by finding the mean and mode of the density of the Monte Carlo approximation to the

bootstrap distribution of the CI (see Supplementary Information for details) given by the equation:

$$CI = \frac{1}{36} \sum_{i=1}^{36} \left| \frac{\log(Earc_i) - \log(Econt.crust_i)}{\log(Econt.crust_i)} \right| \times 100$$

where $Earc_i$ is a sample of the element (E) i (for example, K_2O , Nb, La, and so on) from the arc values. The expected continental crust for the same element i ($Econt.crust_i$) is the average continental crust value from Supplementary Table 3. We used the same equation for the 36 elements plotted in Supplementary Fig. 4 (also including P_2O_5 and MnO, not shown for clarity purposes). For the integrated CI of each arc (Fig. 4a), using statistical analyses further explained in the Supplementary Information, we calculated the most likely estimate of the CI using all the available data from each arc. The mean, mode and uncertainty of the CI for each arc are reported in Supplementary Table 3. The integrated CI of continental crust (~18) plotted in Fig. 5a as a red star represents the range obtained using the bulk composition estimates in Supplementary Table 3. Therefore, the higher the integrated CI is, the farther the composition of the arc/arc segment is away from global estimates of the bulk composition of continental crust reported in Supplementary Table 3.

Only magmas from Costa Rica (<10 Ma) have CI < 50, closer to continental crust with a CI ~ 18 (Supplementary Information). Transitional CI values of 50–100 are found in the Aleutians, the Iwo-Jima segment of Izu-Bonin, the Lesser Antilles, Panama, Nicaragua and Vanuatu. The Iwo-Jima segment geochemistry is controlled by the subducting intraplate Ogasawara Plateau and associated

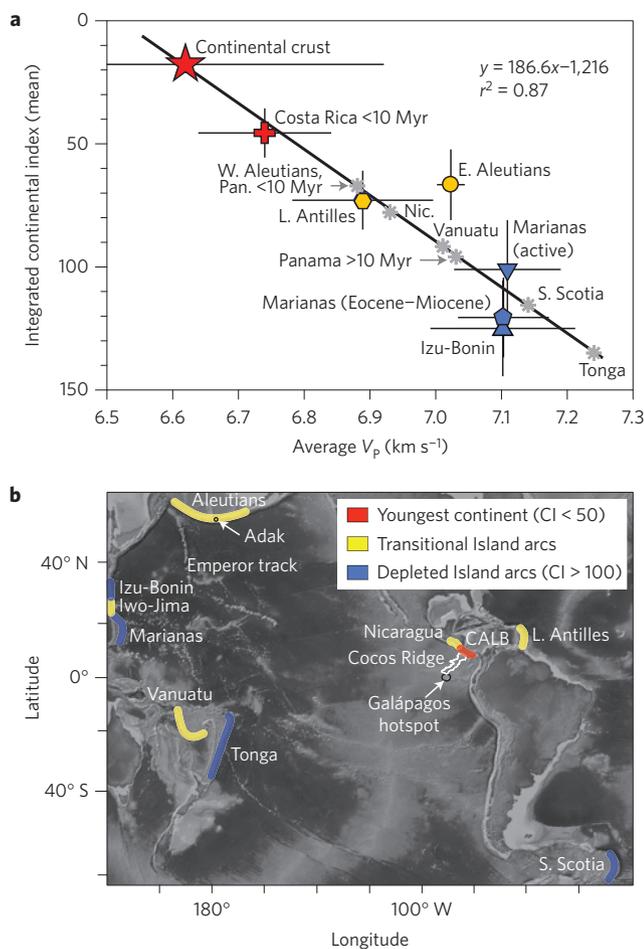


Figure 5 | Integrated continental index results. **a**, CI versus average V_p (from depth >10 km to a maximum velocity of 7.6 km s^{-1} , Supplementary Table 4). Arcs with no P-wave velocity data are represented as grey asterisks and their V_p values are from the correlation equation in Fig. 4a. Uncertainties in the CI are one standard deviation of the mean (Supplementary Table 3). Error bars for V_p represent one standard deviation of the V_p model average (Supplementary Table 4). The error bar in V_p for continental crust represents the range for all continental crust¹⁴. **b**, Map with additional CI range for other arcs/arc segments.

seamounts²². In the western Aleutians and Panama melts from the subducting oceanic crust are thought to have a significant control on the geochemical signature^{6,20}. In the Lesser Antilles and eastern Aleutians the continental signature may reflect recycling of a component derived from subducting continental sediments^{23,24}. The geochemistry of Vanuatu magmas is influenced by the subduction of intraplate seamounts and an aseismic ridge²⁵. Most of Izu-Bonin, Marianas, South Scotia and Tonga arcs with a CI of >100 have the least continent-like geochemical signatures. In these arcs the subducting plate is old (>100 Ma, Supplementary Information), not overprinted by enriched intraplate volcanism, and the arc geochemistry is most likely dominated by slab-derived, aqueous fluids²⁶.

We found a strong correlation between CI and average crustal P-wave velocity ($r^2 = 0.87$, Fig. 5a). We restricted the average V_p to the region between 10 km depth, with the goal of excluding sediments and highly porous or fractured rocks near the surface³ and assuming crust–mantle transition at a V_p of 7.6 km s^{-1} . The correlation between the geochemical signature and the seismic signature of an arc, and the lack of a significant component derived from recycled, continentally derived sediment, suggests that formation of juvenile continental crust is in progress at the CALB and also

possibly in the Iwo-Jima segment of Izu-Bonin and the western Aleutians, making these locations additional natural laboratories to understand the processes that formed continental crust in the past.

Continental crust by melting enriched oceanic crust

Although fractional crystallization can produce silicic melts, unless the primary magmas start with enriched compositions, fractional crystallization itself will not produce the incompatible-element composition of continental crust^{4,6,21}. Partial melting of enriched subducting Galápagos hotspot tracks resulted in the output of young, andesitic continental crust beginning at ~ 10 Ma, as recorded in the CALB geochemical evolution⁸. Thus, we suggest that the process required to produce ‘young’ continents initiates with partial melting of the subducting oceanic crust and reaction of those melts with the mantle wedge.

This process would be facilitated if the slab was enriched in incompatible elements, reproducing the enriched source (relative to modern mid-ocean ridge basalt) required to produce Archaean continental crust^{27,28}. In a recent study, Martin *et al.*²⁸ concluded that recycling of enriched oceanic crust derived from mantle plume activity is necessary to produce Archaean continental crust (especially tonalite–trondjemite–granodiorite TTG suites). The proposed model used the subducting Carnegie Ridge (Galápagos track) offshore of Ecuador as an analogue for recycling an oceanic plateau produced in this case by the Galápagos hotspot, to generate Archaean-like crust in the active volcanic front of Ecuador²⁸. This model agrees with the interpretation presented here for the production of juvenile continental crust in the CALB, where, contrary to Ecuador²⁹, the arc developed and evolved on oceanic crust^{14,15}.

In a similar tectonic scenario, the input of the Ogasawara Plateau and associated seamounts in the subduction system of the Iwo-Jima segment of the Izu-Bonin arc results in incompatible-element enrichment of the volcanic output²². We found a bimodal distribution (reflecting a mafic and felsic bimodality in the available samples) of the integrated CI for this segment. The data analysed yielded an integrated CI of 78, with the lower end at 64 (mean value, Supplementary Table 3). Active seismic studies along this segment of the Izu-Bonin arc also suggest a low V_p of $6.71 \pm 0.1 \text{ km s}^{-1}$ (ref. 30; including the mantle–crust transition), making this location interesting for future detailed research on the generation of continental crust in intra-oceanic arcs. The western Aleutians serve as another example where primitive andesites/adakites with a clear slab signature are widespread along this part of the arc (refs 4,6,20). It is possible that, to some extent, the western Aleutians also interacted with ocean floor related to the Emperor Ridge (Hawaiian track) interaction with southern Central America. Nevertheless, it is important to also consider that the compositions of these lavas have been successfully modelled as the outcome of reaction between small degree partial melts of subducting MORB-like oceanic crust and the overlying mantle wedge^{4,6}. Thus, the role of a subducting intraplate component (if any) in the western Aleutians needs further evaluation, including sampling the actual subducting crust (additional discussion in the Supplementary Information).

Reconciling Archaean and young continental crust

During the peak of cratonization in the Archaean, mantle temperatures reached a maximum (up to $\sim 1,700^\circ\text{C}$)^{31–33}. These conditions would have been favourable for partial melting of subducting (or delaminated) mafic igneous rocks^{10,28}. These melts then reacted with the overlying mantle^{11,34}, producing the starting material to generate high volumes of continental crust. Since then, the potential temperature of the convecting mantle has dropped to $\sim 1,350^\circ\text{C}$ (refs 32,33). Today, the production of young continental crust with compositions similar to Archaean continental crust in intra-oceanic arcs as shown in this study is an unusual process,

limited to locations where there are especially voluminous partial melts of oceanic crust due to the subduction of a young hot plate¹⁰, in the case of the CALB overprinted by young (<15 Ma; ref. 35) enriched intraplate magmas^{8,9,11}, or where fluid-fluxed melting of the mantle is minimal owing to a combination of oblique subduction and an abnormally cold mantle wedge⁶. Although it is possible that partial melting of subducting oceanic crust supplies a component to arc magmatism globally, it is obscured by fluid-fluxed melting of the mantle wedge and/or by a substantial component of recycled subducted sediment³⁶. Consequently, in response to the thermal and chemical evolution of the Earth, the modern dominant processes in most intra-oceanic subduction systems result in mafic young continents depleted in chemical composition relative to Archaean continental crust. However, it is also possible that later recycling of depleted arcs during subduction processes (at continental-arc or arc-arc collisions) will segregate buoyant components that will also contribute to the evolution of continents by underplating felsic material at lower-crustal levels³⁷.

Global impact of juvenile continental crust in the CALB

The evolution of the CALB from depleted basaltic to enriched andesitic compositions as a result of recycling Galápagos tracks resulted in a new continental landmass. Although the surface expression of this juvenile continent is ~65–250 km wide, it contains high elevations of up to ~4 km above sea level in the axis, supported by a buoyant crustal thickness of about 40–45 km¹³. The production of new continental crust culminated with the closure of the Central American seaway, starting ~15 Ma and ending ~3 Ma (refs 38–40). This closure resulted in global effects in ocean circulation, separating marine species, and allowing the exchange of fauna between the Americas^{41–43}, making the evolution of the CALB not only relevant to understanding geologic processes, but also its considerable impact on the evolution of life and climate on the planet. Our data from the CALB shows a clear evolution to a young continent, suggesting that although the origin and evolution of continents may require a combination of multiple and complex processes mentioned before, melting enriched oceanic crust in a subduction system facilitates the initial components necessary to start a continent.

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References

- Taylor, S. R. & McLennan, S. M. The geochemical evolution of the continental crust. *Rev. Geophys.* **33**, 241–265 (1995).
- Rudnick, R. L. & Gao, S. The composition of the continental crust. *Treatise Geochem.* **3**, 1–64 (2003).
- Korenaga, J., Kelemen, P. B. & Holbrook, S. W. Methods for resolving the origin of large igneous provinces from crustal seismology. *J. Geophys. Res.* **107**(B9), 2178 (2002).
- Kelemen, P. B. Genesis of high Mg# andesites and the continental crust. *Contrib. Mineral. Petrol.* **120**, 1–19 (1995).
- Rudnick, R. L. Making continental crust. *Nature* **378**, 571–578 (1995).
- Kelemen, P. B., Yogodzinski, G. M. & Scholl, D. W. in *Inside the Subduction Factory* (ed. Eiler, J.) 223–276 (American Geophysical Union, 2004).
- Martin, H. Adakitic magmas: Modern analogues of Archaean granitoids. *Lithos* **46**, 411–429 (1999).
- Hoernle, K. *et al.* Arc-parallel flow in the mantle wedge beneath Costa Rica and Nicaragua. *Nature* **451**, 1094–1097 (2008).
- Gazel, E. *et al.* Galápagos-OIB signature in southern Central America: Mantle refertilization by arc-hot spot interaction. *Geochem. Geophys. Geosyst.* **10**, Q02S11 (2009).
- Defant, M. J. & Drummond, M. B. Derivation of some modern arc magmas by melting of young subducted lithosphere. *Nature* **387**, 662–665 (1990).
- Gazel, E. *et al.* Plume-subduction interaction in southern Central America: Mantle upwelling and slab melting. *Lithos* **121**, 117–134 (2011).
- Vogel, T. *et al.* Origin of silicic magmas along the Central American volcanic front: Genetic relationship to mafic melts. *J. Volcanol. Geotherm. Res.* **156**, 217–228 (2006).
- Hayes, J. L. *et al.* Crustal structure across the Costa Rican Volcanic Arc. *Geochem. Geophys. Geosyst.* **14**, 1087–1103 (2013).
- Christensen, N. I. & Mooney, W. D. Seismic velocity structure and composition of the continental crust: A global view. *J. Geophys. Res.* **100**, 9761–9788 (1995).
- MacKenzie, L. *et al.* Crustal structure along the southern Central American volcanic front. *Geochem. Geophys. Geosyst.* **9**, Q08S09 (2008).
- Calvert, A. J. in *Arc-Continent Collision* (eds Brown, D. & Ryan, P. D.) 87–119 (Springer, 2011).
- Behn, M. D. & Kelemen, P. B. Stability of arc lower crust: Insights from the Talkeetna arc section, south central Alaska, and the seismic structure of modern arcs. *J. Geophys. Res.* **111**, B11207 (2006).
- Kay, R. W. & Kay, S. M. Crustal recycling and the Aleutian arc. *Geochim. Cosmochim. Acta* **52**, 1351–1359 (1988).
- Kay, R. W. Aleutian magnesian andesites: Melts from subducted Pacific Ocean crust. *J. Volcanol. Geotherm. Res.* **4**, 117–132 (1978).
- Yogodzinski, G. M., Kay, R. W., Volynets, O. N., Kolosov, V. & Kay, S. M. Magnesian andesite in the western Aleutian Komandorsky region: Implications for slab melting and processes in the mantle wedge. *Geol. Soc. Am. Bull.* **107**, 505–519 (1995).
- Rapp, R. P., Shimizu, N., Norman, M. D. & Applegate, G. S. Reaction between slab-derived melts and peridotite in the mantle wedge: Experimental constraints at 3.8 GPa. *Chem. Geol.* **160**, 335–356 (1999).
- Staudigel, H., Koppers, A. A. P., Plank, T. & Hanan, B. B. Seamounts in the subduction factory. *Oceanography* **23**, 176–181 (2010).
- White, W. M. & Dupre, B. Sediment subduction and magma genesis in the Lesser Antilles: Isotopic and trace element constraints. *J. Geophys. Res.* **91**, 5927–5941 (1986).
- Miller, D. M., Goldstein, S. L. & Langmuir, C. H. Cerium/lead and lead isotope ratios in arc magmas and the enrichment of lead in the continents. *Nature* **368**, 514–520 (1994).
- Raos, M. A. & Crawford, A. J. Basalts from the Efate Island Group, central section of the Vanuatu arc, SW Pacific: Geochemistry and petrogenesis. *J. Volcanol. Geotherm. Res.* **134**, 35–56 (2004).
- Elliot, T., Plank, T., Zindler, A., White, W. & Bourdon, B. Element transport from slab to volcanic front at the Marinas Arc. *J. Geophys. Res.* **102**, 14991–15019 (1997).
- Condie, K. C. High field strength element ratios in Archean basalts: A window to evolving sources of mantle plumes? *Lithos* **79**, 491–504 (2005).
- Martin, H. *et al.* Why Archaean TTG cannot be generated by MORB melting in subduction zones. *Lithos* **198–199**, 1–13 (2014).
- Bryant, J. A., Yogodzinski, G. M., Hall, M. L., Lewicki, J. L. & Bailey, D. G. Geochemical constraints on the origin of volcanic rocks from the Andean Northern Volcanic Zone, Ecuador. *J. Petrol.* **47**, 1147–1175 (2006).
- Takahashi, N. *et al.* Structural variations of arc crusts and rifted margins in the southern Izu-Ogasawara arc-back arc system. *Geochem. Geophys. Geosyst.* **10**, Q09X08 (2009).
- Albarede, F. Growth of continental crust. *Tectonophysics* **296**, 1–14 (1998).
- Korenaga, J. Thermal evolution with a hydrating mantle and the initiation of plate tectonics in the early Earth. *J. Geophys. Res.* **116**, B12403 (2011).
- Herzberg, C., Condie, K. & Korenaga, J. Thermal history of the Earth and its petrological expression. *Earth Planet. Sci. Lett.* **292**, 79–88 (2010).
- Kelemen, P. B., Hart, S. R. & Bernstein, S. Silica enrichment in the continental upper mantle via melt/rock reaction. *Earth Planet. Sci. Lett.* **164**, 387–406 (1998).
- Werner, R., Hoernle, K., Hauff, F. & Barckhausen, U. Geodynamic evolution of the Galápagos hot spot system (Central East Pacific) over the past 20 m.y.: Constraints from morphology, geochemistry, and magnetic anomalies. *Geochem. Geophys. Geosyst.* **4**, 1108 (2003).
- Plank, T. & Langmuir, C. H. Tracing trace elements from sediment input to volcanic output at subduction zones. *Nature* **362**, 739–741 (1993).
- Hacker, B. R., Kelemen, P. B. & Behn, M. D. Differentiation of the continental crust by reamination. *Earth Planet. Sci. Lett.* **307**, 501–516 (2011).
- Hoernle, K. *et al.* Missing history (16–71 Ma) of the Galápagos hot spot: Implications for the tectonic and biological evolution of the Americas. *Geology* **30**, 795–798 (2002).
- Montes, C. *et al.* Evidence for Middle Eocene and younger land emergence in central Panama: Implications for isthmus closure. *Geol. Soc. Am. Bull.* **124**, 780–799 (2012).
- Coates, A. G., Collins, L. S., Aubry, M.-P. & Berggren, W. A. The Geology of the Darien, Panama, and the Late Miocene–Pliocene collision of the Panama arc with northwestern South America. *Geol. Soc. Am. Bull.* **116**, 1327–1344 (2004).
- Marshall, L. G. Land mammals and the great American interchange. *Am. Sci.* **76**, 380–388 (1988).

42. Lucas, S. & Alvarado, G. E. The role of Central America in land-vertebrate dispersal during the Late Cretaceous and Cenozoic. *Profil* **7**, 401–411 (1994).
43. Collins, L. S., Budd, A. F. & Coates, A. G. Earliest evolution associated with closure of the Tropical American Seaway. *Proc. Natl Acad. Sci. USA* **93**, 6069–6072 (1996).
44. Wegner, W., Worner, G., Harmon, R. S. & Jicha, B. R. Magmatic history and evolution of the Central American Land Bridge in Panama since Cretaceous times. *Geol. Soc. Am. Bull.* **123**, 703–724 (2011).

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Author contributions

E.G. planned the project, compiled and modelled the geochemical data and derived the continental index. E.G., J.L.H., W.S.H., K.H., E.A.V. and P.K. contributed to writing the paper and developing the ideas. J.L.H., E.E. and W.S.H. conducted the active seismic experiment in Costa Rica and modelled the geophysical data. K.H., E.G., F.H. and P.v.d.B. carried out field studies and generated geochemical data from the CALB. E.G., E.A.V. and S.C. developed the statistical codes and conducted data analysis. P.K., M.J.C., A.J.C. and G.M.Y. collaborated in the project with data and data analysis.

Additional information

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Competing financial interests

The authors declare no competing financial interests.