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Seamounts control subducted carbonate recycling in Central America – evidence from stable Sr isotopes

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1 Abstract

2 Accurate estimates of carbon recycling efficiency at subduction zones are crucial for
3 understanding the long-term evolution of the planet’s climate. Estimating subducting carbon
4 recycling efficiency is difficult, however, due to magmatic degassing deep within the crust.
5 Stable strontium ($\delta^{88}\text{Sr}$) isotopes have the potential to serve as an additional proxy for
6 carbonate recycling due to carbonate’s high Sr concentrations and unique $\delta^{88}\text{Sr}$ composition.
7 New data from Nicaraguan lavas and sediments verify that Sr can indeed be used to track
8 subducting carbon. When interpreted in conjunction with other magmatic trace element
9 abundances, these data reveal systematic variations that are best understood as the effects
10 of seamount subduction. Seamounts erupting at the same time carbonate-dominated
11 sedimentation ceased on the Cocos plate could potentially ‘cap’ the carbonate layer and
12 control the degree to which carbonate material is transported to the arc. This model can also
13 be used to quantify the flux of carbonate sediment from the slab to the arc and thus provides
14 an independent method to estimate the magmatic carbon recycling efficiency for the
15 Nicaraguan Arc. Our model shows, absent seamounts, 26% to 52% of carbon from subducted
16 carbonate is returned to the arc, an estimate consistent with recent estimates made from
17 volcanic gases.

18 Introduction

19 Carbon cycling in subduction zones has played a key role in maintaining the planet's
20 climate and long-term habitability¹⁻⁵. Some fraction of the carbon initially subducted is quickly
21 returned to the surface through volcanic arcs, with the remainder transported to the deep
22 mantle. The proportion of initially subducted carbon that is returned from the slab to arc is
23 often referred to as the “carbon recycling efficiency.” Though accurate estimates of the carbon
24 recycling efficiencies of volcanic arcs are essential to our understanding of Earth's planetary
25 evolution, recent estimates range widely, from 14% to 100%^{1,6-19}. This range persists largely
26 because arc magmas lose most of their initial carbon budget to degassing deep in the crust.
27 Even melt-inclusions hosted in primitive olivines likely sample liquids that have lost CO₂ prior to
28 entrapment²⁰. As such, direct sampling of the primary arc magma carbon concentrations or
29 isotope ratios may not be possible in most cases.

30 Most estimates of carbon recycling efficiency are instead derived from measurements
31 of CO₂ abundances and/or isotope ratios of volcanic gases^{9-11,13}, which also have limitations. For
32 example, carbon fluxes at volcanic arcs are spatially and temporally variable, and the extent of
33 diffuse degassing is not usually well constrained^{10-12,19}. Carbon isotopes can also fractionate
34 during slab devolatilization and volcanic degassing²¹, crustal contamination, and shallow
35 processes such as calcite precipitation in the forearc¹¹.

36 Here, we investigate the potential of Sr stable isotope ratios as a tracer of carbonate
37 recycling from a subducting slab to a volcanic arc using high-precision double-spike stable Sr
38 isotope (Sr isotope data are reported as ⁸⁸Sr/⁸⁶Sr in standard delta notation, relative to NIST
39 SRM-987 in units of permil as: $\delta^{88}\text{Sr} (\text{‰}) = [({}^{88}\text{Sr}/{}^{86}\text{Sr})_{\text{sample}}/({}^{88}\text{Sr}/{}^{86}\text{Sr})_{\text{SRM987}} - 1] \times 1000$) and

40 radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ measurements of Cocos plate sediments and arc lavas from Telica, Cerro
41 Negro, and Masaya volcanoes in the Nicaraguan segment of the Central American Volcanic Arc.
42 These Sr isotope data, in conjunction with traditional radiogenic isotopes and trace element
43 abundances, provide a novel way to quantify carbon recycling efficiency. Our results also
44 motivate a re-evaluation of the origins of geochemical variability present among Central
45 American arc lavas, which appears to be importantly regulated by subducting seamounts.

46 The Central American Volcanic Arc (Fig. 1a) extends ~1400 km from the Mexico-
47 Guatemala boarder to Panama, where the Cocos Plate subducts underneath the Caribbean at a
48 rate of 5.6 - 6.4 cm/yr²². The subducting plate consists of 20 Ma oceanic crust produced at the
49 East Pacific Rise and carries numerous seamounts with elevations up to 2000 m above the
50 seafloor and diameters of up to 14 km²³. The ocean floor offshore of Central America is covered
51 by two sediment packages of similar thickness: an upper hemiplegic unit and a lower unit
52 dominated by pelagic carbonate (Fig. 2a and b)²⁴⁻²⁸. The mid-Miocene carbonate crash led to a
53 rapid shift in sediment composition between these layers²⁹. Cores from Deep Sea Drilling
54 Program site 495 off Guatemala and Ocean Drilling Program site 1039 off the Nicoya Peninsula
55 of Costa Rica (Fig. 1a) show that the sediments remain uniform in thickness and distribution
56 along the entire length of the arc^{26,30}.

57 As with all arc-front stratovolcano lavas, the volcanic rocks of the Central American
58 volcanic front inherited the distinct geochemical signatures of subducted materials. Studies of
59 the Northern Guatemala-El Salvador²⁸ and Southern Costa Rica-Panama^{31,32} segments have also
60 identified isotope compositions that appear to originate from the lithospheric mantle and the
61 Galapagos hotspots, respectively. The volcanic rocks of Nicaraguan segment, by contrast,

62 mostly reflect a depleted MORB mantle (DMM) source overprinted with the incompatible trace
63 element pattern of a typical arc lava (e.g. enrichment of Rb, Ba, Th, U, Pb, and Sr and depletion
64 in Nb, Ta)²⁶. The upper plate of the Nicaraguan segment is thin and mostly oceanic in origin
65 with little evidence for crustal assimilation³³. A comparison between thermo-mechanical
66 models of the slab beneath Nicaragua and experimentally determined solidus temperatures^{34,35}
67 (Fig. 1b) indicates that at least the upper 1 km of the slab reaches temperatures that exceed the
68 H₂O-saturated solidi for carbonate and pelitic sediments³⁵⁻³⁷, altered oceanic crust (AOC)³⁸, and
69 unaltered MORB³⁹. A similar comparison shows that progressive lawsonite dehydration in the
70 lower slab layers should provide a continuous source of water to the slab top (Fig. 1b)³⁵. This
71 suggests that hydrous slab melting is the dominant process by which subducting materials are
72 transferred to the mantle wedge in the Nicaraguan segment, and that carbonate melting may
73 mediate the CO₂ flux from the slab to the arc.

74 Our current understanding of carbon fluxes out of the Central American arc are mostly
75 derived from measurements of volcanic gases and fluid seeps. Most estimates of arc CO₂ fluxes
76 utilize direct measurements of fumarole CO₂/³He or CO₂/SO₂ alongside an assumed ³He flux or
77 an independently measured SO₂ flux. Using this approach, Shaw et al. (2003) estimated that the
78 carbon flux from Costa Rican and Nicaraguan arc segments accounted for only ~15% of the total
79 subducting carbon budget. Carbon fluxes estimated by Mather et al. (2006) and Aiuppa (2014)
80 are similar to that of Shaw (2003), while de Moor et al. (2017)'s study of carbon outgassing
81 from 2015-2016 are much higher, indicating carbon recycling efficiencies as high as ~76%. The
82 increased carbon recycling efficiency estimate of de Moor et al. (2017) could be due to
83 improved methodology and much denser sampling, but also coincided with a net increase in

84 volcanic activity during their study period. This suggests that arc CO₂ fluxes can be highly
85 variable across years-long timescales. Recent work by Barry et al. (2019) measured deeply
86 sourced hot springs along two across-arc transects in Costa Rica and estimated that an
87 additional ~19% of subducted carbon may be lost from the slab beneath the forearc. Their total
88 slab-derived carbon outputs are consistent with recent global carbon recycling efficiency
89 estimates of 46%-65%^{8,15}.

90 Helium and carbon isotope ratios in gas samples can also be used to determine the
91 relative contributions of subducting materials to the overall carbon budget of arcs. Isotope
92 studies of Central American gases largely agree that most of the carbon emitted through the
93 arc originates from subducting carbonate^{9,40,41}, consistent with the fact that the sedimentary
94 carbonate layer dominates the carbon budget of the subducting slab.

95 Trace element abundances in Central American lavas serve as additional proxies for
96 carbonate and hemipelagic sediment recycling from the slab to the arc²⁶. This is possible
97 because the hemipelagic sediment has high concentrations of most incompatible trace
98 elements, while the carbonate layer is diluted in most trace elements aside from Sr, Ba, La, and
99 Pb (Fig. 2a), leading to distinct downcore variations in trace element ratios such as Ba/Th and
100 U/La (Fig. 2b). Central American arc lavas exhibit correlated variations in Ba/Th and U/La,
101 presumably due to varying recycling efficiencies of these sediment layers. In some arcs, these
102 ratios could be controlled by the addition of aqueous fluids from the slab, which fractionate
103 'fluid mobile' elements such as Ba and U from 'fluid immobile' elements such as Th and La⁴².
104 The negative correlation between these ratios among Nicaraguan lavas (Fig. 3) is inconsistent
105 with aqueous fluid control for the Nicaraguan arc, however, and accords well with variance

106 expected for contributions from the different sediments. The hypothesis that the incompatible
107 trace element compositions of these lavas are controlled by variable subducting sediment
108 compositions is further confirmed by a correlation⁴³ between U/La and $^{10}\text{Be}/^9\text{Be}$ ^{33,44}.

109 These trace element proxies show that the sediment recycled from the slab to the arc
110 must be highly variable even though core samples all reflect similar offshore sediment profiles.
111 Patino et al. (2000) postulated that this could be due either to off-scraping of the upper
112 hemipelagic sediments from horsts to grabens or to a more complicated multi-stage slab
113 melting process. Others have proposed mechanisms relating to slab dip, differing extents of
114 lithospheric serpentinization, varying extents of fore-arc erosion, or temporal variability in the
115 spatial distribution of the carbonate sediment layer^{10,26,29,45}.

116 While the trace element approach has produced important qualitative constraints on
117 sediment recycling in Central America, these proxies cannot be used to accurately quantify the
118 absolute recycling efficiency of either sediment package. For U/La, this is because U decreases
119 significantly down the entire sediment core (Fig. 2b), including within the hemipelagic layer, as
120 the proportion of preserved organic-rich sediments decreases^{26,29}. The relationship between
121 Ba/Th in sediments vs lavas is complicated by the fact that Ba concentrations in pore fluids and
122 sediments offshore of Costa Rica indicate that upwards of ~60% of the incoming bulk sediment
123 Ba may be lost to the forearc⁴⁶. Uncertainties such as these make it difficult to directly estimate
124 the recycling efficiencies of the individual sediment layers from trace element data alone.

125 The high Sr concentrations and distinct Sr isotope compositions of carbonates make Sr
126 stable isotopes a promising proxy for recycled carbonate that is free from the uncertainties
127 inherent in gas data or trace element ratios. Sr^{2+} can readily substitute for Ca^{2+} , leading to

128 elevated Sr abundances in most carbonate-rich marine sediments. Seawater inherits
129 terrigenous Sr with high $\delta^{88}\text{Sr}$ (0.39‰)^{47,48}, whereas biogenic marine carbonates are typically a
130 mix of foraminifera and coccoliths with much lower $\delta^{88}\text{Sr}$ (0.14‰ to 0.27‰; Fig.4)^{47,48}. High-
131 precision TIMS measurements of $\delta^{88}\text{Sr}$ in typical MORB samples are limited, but thus far cluster
132 around $0.28 \pm 0.05\%$ ⁴⁹. Experimental work shows that high-temperature hydrothermal
133 alteration of basalt leads to elevated $\delta^{88}\text{Sr}$ ⁵⁰, and while actual AOC $\delta^{88}\text{Sr}$ measurements are also
134 limited, existing data support this general process⁴⁹. High-temperature magmatic processes, on
135 the other hand, have little effect on Sr isotope fractionation in systems for which Sr behaves as
136 an incompatible element. Plagioclase fractionation may have a small impact on magmatic
137 $\delta^{88}\text{Sr}$ ⁵¹. The application of Sr to carbonate recycling during subduction also benefits from the
138 fact that Sr and C partition similarly between carbonate and melt^{52,53}. Together, these studies
139 show that subducting materials, and marine carbonates in particular, exhibit distinct $\delta^{88}\text{Sr}$
140 compositions that should be reflected as recycled components in mafic arc lavas. This proxy has
141 the potential to constrain carbon recycling from measurements of lava samples without the
142 complications that can arise from early carbon degassing and the various processes that can
143 fractionate trace element ratios. Stable Sr isotopic compositions thus could provide an
144 alternative method to estimate long-term carbon fluxes at subduction zones.

145 Lavas from the Nicaraguan arc were chosen for this study due to their strong sediment
146 signature and lack of evidence for crustal assimilation or influence from the Galapagos
147 plume^{28,29,54,55}. Nine samples were selected to encompass the full range of U/La and Ba/Th
148 found among Nicaraguan lavas (Fig. 3). The samples include lavas from Cerro Negro, Masaya,
149 and Telica volcanoes that were obtained from the Rutgers CAVA sample repository⁵⁶ and have

150 been previously analyzed for major elements, trace elements, and radiogenic isotopes (Pb, Nd,
151 and some Sr)^{26,57}. These prior studies showed that the selected samples exhibit compositional
152 variations that largely reflect slab and mantle processes.

153

154 **Results**

155 **Variation in $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{88}\text{Sr}$ in Central American lavas and sediments**

156 $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{88}\text{Sr}$ data are presented in Table 1 and shown in Figure 5. External
157 precision, reported as the average 2-SE for $\delta^{88}\text{Sr}$ values is $<0.02\text{‰}$. Carbonate sediment $\delta^{88}\text{Sr}$
158 ranges from $0.170\pm 0.016\text{‰}$ to $0.219\pm 0.016\text{‰}$, consistent with the calcareous Aegean
159 sediments ($\delta^{88}\text{Sr}=0.195\text{‰}$ to 0.213‰) measured by Klaver et al. (2020). Surprisingly, the
160 hemipelagic sediment sample is isotopically lighter ($\delta^{88}\text{Sr}=0.146\text{‰}\pm 0.021\text{‰}$) than the
161 carbonate, which suggests that the Sr budget of the hemipelagic sediments is also dominated
162 by biogenic material. Both sediments have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios near that of modern seawater
163 (~ 0.709), consistent with Patino et al. (2000). Nicaraguan arc lavas ($\delta^{88}\text{Sr}=0.212\pm 0.013\text{‰}$ to
164 $0.322\pm 0.015\text{‰}$) exhibit a greater relative variation in $\delta^{88}\text{Sr}$ than the sediments. Samples from
165 Masaya and Cerro Negro define heavy and light $\delta^{88}\text{Sr}$ end members, respectively, while Telica
166 $\delta^{88}\text{Sr}$ varies between the two ($0.243\pm 0.014\text{‰}$ to $0.279\pm 0.019\text{‰}$). Arc lava $^{87}\text{Sr}/^{86}\text{Sr}$ ratios
167 (0.7040 to 0.70419) are uniform relative to the range of subducting materials and have
168 compositions closer to DMM or AOC than sediments (Fig. 5). The altered ocean crust composite
169 samples ($\delta^{88}\text{Sr}=0.247\pm 0.008\text{‰}$ to $0.263\pm 0.014\text{‰}$; $^{87}\text{Sr}/^{86}\text{Sr} = 0.70330$ to 0.70679) are consistent
170 within uncertainty to measurements of the same samples by Klaver et al. (2020) but are

171 unlikely to represent the compositional range of actual subducting ocean crust as discussed in
172 greater detail in the Online Supplement.

173

174 **$\delta^{88}\text{Sr}$ provides new insights into Nicaraguan subduction dynamics**

175 The primary goal of this study was to assess stable Sr isotopic variability as a proxy for
176 carbonate recycling at subduction zones, but these data also shed new light on important
177 subduction zone systematics that directly influence the geochemical variability of Nicaraguan
178 arc magmas. Because the hemipelagic and carbonate sediment packages both have low $\delta^{88}\text{Sr}$,
179 and because the arc data unexpectedly span a larger range in $\delta^{88}\text{Sr}$ than the subducting
180 sediments, a robust estimate of sediment recycling efficiencies requires interpretations of Sr
181 isotope data alongside other trace element compositions. To quantify the provenance of Sr
182 erupted in the arc, we first employ a simple Sr mass balance utilizing trace element abundances
183 and $^{87}\text{Sr}/^{86}\text{Sr}$ data. This approach can determine the general proportion of Sr in the arc lavas
184 originating from all sediments, AOC, and mantle. Next, we incorporate the $\delta^{88}\text{Sr}$ data to
185 distinguish between the inputs of the carbonate vs hemipelagic sediment. These constraints
186 indicate that Nicaraguan arc lavas require both a high- $\delta^{88}\text{Sr}$ altered ocean crust component and
187 an unaltered crustal component with low- $\delta^{88}\text{Sr}$. We propose that these combined signals may
188 result from the subduction of seamounts along the Cocos plate, and present an internally
189 consistent, quantitative model that supports this hypothesis. This model can also be used to
190 quantify the flux of carbonate sediment from the slab to the arc and thus provides an
191 independent method to estimate the magmatic carbon recycling efficiency for the Nicaraguan
192 Arc.

193 **Quantifying strontium sources from sediment, AOC, and the ambient mantle**

194 The fact that the arc lava $^{87}\text{Sr}/^{86}\text{Sr}$ data lie much closer to the DMM and AOC
195 compositions than the sediments (Fig. 5) means that the Sr budget of the arc lavas is dominated
196 by Sr from sources with MORB- or AOC-like $^{87}\text{Sr}/^{86}\text{Sr}$. This suggests that the $\delta^{88}\text{Sr}$ variability of
197 the arc lavas is at least partially inherited from $\delta^{88}\text{Sr}$ variability among ambient mantle or mafic
198 crustal sources that have low $^{87}\text{Sr}/^{86}\text{Sr}$, rather than sediments. For example, the high $\delta^{88}\text{Sr}$ and
199 moderate $^{87}\text{Sr}/^{86}\text{Sr}$ possibly are inherited from AOC, whereas low $\delta^{88}\text{Sr}$ and DMM-like $^{87}\text{Sr}/^{86}\text{Sr}$
200 are contributed from the ambient mantle. Alternatively, the low $^{87}\text{Sr}/^{86}\text{Sr}$ could be inherited
201 from the subducting basaltic crust, which itself may have variable $\delta^{88}\text{Sr}$.

202 A conventional mass balance using trace element ratios and $^{87}\text{Sr}/^{86}\text{Sr}$ demonstrates that
203 the Sr contribution from the subducting slab far outweighs Sr inherited from the ambient
204 mantle, however, and instead supports a model with varied $\delta^{88}\text{Sr}$ inherited from the subducting
205 ocean crust. The thermal model in Figure 1b shows that the slab surface temperatures
206 significantly exceed the hydrous solidi of all subducting lithologies, while lawsonite dehydration
207 in the lower portions of the slab should provide a consistent source of H_2O . Our mass balance
208 calculation makes use of published AOC hydrous melt compositions and sediment melt
209 partition coefficients⁵⁸, though with $DSr^{\text{carbonate/melt}}=1$ ⁵³. As shown on Figure 6a, adding slab melt
210 (either sediment or AOC melt) to the DMM leads to a rapid drop in Sr/Yb, because Yb is
211 retained by residual garnet in the slab. To reach the Sr/Yb composition of the arc requires ~7%-
212 15% total slab melt addition. The amount of sediment melt in the mantle source is then
213 quantitatively constrained by $^{87}\text{Sr}/^{86}\text{Sr}$ to be <2% carbonate melt or <4% hemipelagic sediment

214 melt, while the amount of AOC melt is between 6% and 13% (Fig. 6a). This mass balance shows
215 that only ~10% of the Sr in the arc lavas could have originated from the ambient mantle.

216 Because very little of the Sr in erupted arc lavas is derived from the ambient mantle, the
217 ambient mantle source has a negligible influence on $\delta^{88}\text{Sr}$. An alternative low- $\delta^{88}\text{Sr}$, low-
218 $^{87}\text{Sr}/^{86}\text{Sr}$ reservoir is thus required from the slab. This is depicted quantitatively by the two mixing
219 triangles on Figure 6b. The first (blue) mixing triangle spans between hemipelagic sediment,
220 carbonate sediment, and a hypothetical AOC melt composition with $\delta^{88}\text{Sr} = 0.36\text{‰}$ (consistent
221 with experimental data⁵⁰, and discussed in more detailed in the Online Supplement), which is
222 the minimum AOC value capable of producing a mixing triangle that overlaps the composition
223 of Cerro Negro, the high $\delta^{88}\text{Sr}$ arc end member. For the second (gray) mixing triangle, the pure
224 AOC melt end member is replaced by a mixture of 94% DMM and 6% AOC melt, which is the
225 minimum possible AOC melt addition inferred from figure 6a. Varying the influence of the DMM
226 within this allowable range on figure 6b does not significantly shift the position of the mixing
227 triangle, and neither triangle overlaps the remainder of the arc data. To account for the full
228 range of the arc data, there must instead be an additional slab component with both low
229 $^{87}\text{Sr}/^{86}\text{Sr}$ and low $\delta^{88}\text{Sr}$. Figure 6c shows that a second ocean crust component with a $\delta^{88}\text{Sr}$
230 equal to average unaltered MORB ($\delta^{88}\text{Sr} = 0.28 \pm 0.05\text{‰}$)⁴⁹ could plausibly serve as this
231 additional slab component. In this case, the high $\delta^{88}\text{Sr}$ composition of Cerro Negro would
232 reflect a large contribution of AOC melt, while the low- $\delta^{88}\text{Sr}$ composition of Masaya would be
233 dominated by a melt of unaltered ocean crust.

234 To summarize, the arc lava Sr budget is dominated by low- $^{87}\text{Sr}/^{86}\text{Sr}$ sources that must
235 have variable $\delta^{88}\text{Sr}$. Mass balance shows that the low- $\delta^{88}\text{Sr}$, low- $^{87}\text{Sr}/^{86}\text{Sr}$ source cannot be the

236 DMM. Instead, two distinct ocean crust components are needed to account for the full range of
237 arc lava $\delta^{88}\text{Sr}$. The Cerro Negro lava end member requires an AOC melt with a $\delta^{88}\text{Sr} > 0.36\text{‰}$
238 whereas the Masaya end member must have an ocean crust component with $\delta^{88}\text{Sr} < 0.28\text{‰}$.
239 We propose that this second low- $^{87}\text{Sr}/^{86}\text{Sr}$, low- $\delta^{88}\text{Sr}$ component represents oceanic crust with
240 an unaltered MORB composition.

241

242 **Evidence for co-variation of ocean crust and sediment components**

243 A surprising result is that the proportions of high- $\delta^{88}\text{Sr}$ vs low- $\delta^{88}\text{Sr}$ ocean crust appear
244 to co-vary with the proportions of hemipelagic and carbonate sediment. Figure 6c shows that a
245 low- $\delta^{88}\text{Sr}$, DMM-like, ocean crust component (gray hexagon) produces an ocean crust-sediment
246 mixing triangle that overlaps the compositions of the Telica (gray triangles) and Masaya (red
247 diamond) samples but does not encompass the composition of the Cerro Negro (blue circle). An
248 alternative mixing triangle starting from a high- $\delta^{88}\text{Sr}$ AOC is required to account for the Cerro
249 Negro composition, but it does not encompass any other samples. The Cerro Negro
250 composition is reproduced within uncertainty by a mixture of high- $\delta^{88}\text{Sr}$ AOC and a range of
251 different sediment proportions, though other trace element constraints (e.g., Fig. 3) suggest
252 that a dominantly hemipelagic sediment component is implausible for this volcano. In contrast,
253 the composition of the Masaya end member can only be reproduced using the low- $\delta^{88}\text{Sr}$ ocean
254 crust component and a sediment that is almost entirely dominated by the hemipelagic
255 component. The Masaya composition thus requires a dominantly hemipelagic sediment and
256 less altered oceanic crust, while the Cerro Negro composition requires high- $\delta^{88}\text{Sr}$ altered
257 oceanic crust and a greater contribution from carbonate sediment.

258 Plausible quantitative mixing scenarios for these two end members are shown on Figure
259 6d. Mixing between an AOC melt with $\delta^{88}\text{Sr} = \sim 0.36\text{‰}$ and a sediment melt composed of 70%
260 carbonate and 30% hemipelagic sediment (Mixing Scenario A, Fig. 6d) is consistent with the
261 composition of Cerro Negro. Sediment proportions in Scenario A are based on the relative
262 masses of each sediment layer observed on the modern Cocos plate. A more complete solution
263 assumes 9% Sr from AOC melt (pink cross, Fig. 6d). There is no solution using either of these
264 sediment or ocean crust compositions, however, that is consistent with the composition of
265 Masaya. A successful Masaya model instead requires an ocean crust component with
266 $\delta^{88}\text{Sr} \sim \text{NMORB}$ (0.28‰) and a sediment melt containing $<5\%$ carbonate material (Mixing
267 Scenario B, Fig. 7d; or blue cross, which includes 7.5% Sr from AOC melt).

268 These new constraints from $\delta^{88}\text{Sr}$ measurements and our models raise three primary
269 questions, (1) What is the source of the second low- $\delta^{88}\text{Sr}$ ocean crust component? (2) Why is
270 Masaya less impacted by carbonate sediment? And (3) What causes the sediment proportions
271 and ocean crust compositions to vary simultaneously?

272

273 **Covariations in slab melt compositions driven by seamount subduction**

274 The numerous seamounts on top of the Cocos plate offshore of Nicaragua (Fig. 1a)
275 provide a plausible source for the low- $\delta^{88}\text{Sr}$ ocean crust component and may also regulate
276 carbonate recycling from the slab to the arc. Herbich et al. (2015) found that these seamounts
277 erupted from 22.4 Ma to 7 Ma and that most have low $^{87}\text{Sr}/^{86}\text{Sr}$ compositions ($^{87}\text{Sr}/^{86}\text{Sr} < 0.703$),
278 from which we infer they likely have NMORB-like $\delta^{88}\text{Sr}$. Seamounts erupted after 11 Ma –

279 which post-date the “carbonate crash”²⁹ – could potentially ‘cap’ the carbonate layer and
280 prevent the transfer of carbonate material from the slab to the mantle wedge.

281 The seamounts provide a reasonable explanation for why samples that mix to the low-
282 $\delta^{88}\text{Sr}$ ocean crust component also require a smaller contribution from subducting carbonate
283 (e.g., Fig. 6c-d). Absent seamounts, the down-going slab surface consists of typical AOC overlain
284 by a carbonate and hemipelagic sediment (Fig. 7a), in which case melts of the upper slab would
285 be a mixture of typical AOC and carbonate+hemipelagic sediment in proportions comparable to
286 the total subducting sediment masses. This scenario accounts best for the end-member
287 composition of Cerro Negro (Mixing Scenario A, Fig. 6d). If a seamount erupted following the
288 carbonate crash, however, it would cap the carbonate layer and become blanketed in
289 hemipelagic sediment prior to subduction (Fig. 7b). In this case, the slab melts would be a
290 mixture of depleted and less-altered seamount material combined with hemipelagic sediment,
291 consistent with the end-member composition of Masaya (Mixing Scenario B, Fig. 6d).

292 Intermediate scenarios are also possible. Older seamounts erupted prior to the
293 carbonate crash could produce slab melts composed of depleted ocean crust and varying
294 proportions of hemipelagic and carbonate sediment (Fig. 7c). Alternatively, where the
295 subducting plate is capped by thinner outlying seamount lava flows, melting might affect both
296 high- and low- $\delta^{88}\text{Sr}$ ocean crust alongside both sediment units (Fig. 7d). Either of these
297 intermediate scenarios might account for the range of compositions observed among the Telica
298 samples.

299 **Testing the seamount hypothesis with quantitative trace element modeling**

300 If the Sr isotope variations of the arc lavas reflect changing sediment proportions due to
301 the presence of seamounts on the subducting plate, then systematic compositional differences
302 in a variety of trace element abundances should also be observed. To evaluate this hypothesis,
303 we first consider the Th/Nd ratio, which is sensitive to hemipelagic sediment input. Mixing
304 model component compositions in Figure 8 are based on the same sources as those in Figure 6.
305 Figures 8a-b show that the mixing scenarios determined from Sr isotope constraints are also
306 successful for Th/Nd: Mixing Scenario A, which includes a bulk sediment mixture comparable to
307 total subducting sediment along with typical AOC, produces a sediment mixing curve that
308 passes through the lower Th/Nd of Cerro Negro. Mixing Scenario B, which is dominated by
309 hemipelagic sediment and melt from unaltered ocean crust, produces a mixing curve that
310 passes through the higher Th/Nd composition of Masaya. The same parameters used in the
311 preferred Masaya and Cerro Negro quantitative models based on Sr isotopes alone (Fig. 6) also
312 reproduce these volcano Th/Nd compositions (Fig. 8a-b).

313 Though it is difficult to distinguish between the two ocean-crust end member
314 components on figure 8a and b, Th/Nd ratios clearly show that the high- $\delta^{88}\text{Sr}$ and low- $\delta^{88}\text{Sr}$
315 lavas of Cerro Negro and Masaya, respectively, require significantly different sediment inputs
316 consistent with the proportions determined by Sr isotope constraints (Fig. 6d). Masaya lavas
317 require little to no carbonate input and a low- $\delta^{88}\text{Sr}$, DMM-like, unaltered ocean crust whereas
318 Cerro Negro can be explained by mixing between a sediment melt with a ~70% carbonate
319 component and a high- $\delta^{88}\text{Sr}$ AOC.

320 A further test of this conceptual model can be conducted using the full array of
321 commonly measured incompatible trace element abundances. Figure 9 shows that after
322 accounting for differences in fractional crystallization and extents of mantle melting, the end
323 member mixing scenarios developed using only Sr isotope ratios (Fig. 6) and Th/Nd (Fig. 8) also
324 reproduce the full array of trace element abundances for both Masaya and Cerro Negro. All
325 elements that are strongly controlled by the slab exhibit a close match in our model except for
326 Ba (dotted lines and open symbols in Fig. 9). A possible mechanism to reconcile the Ba
327 mismatch is the partial loss of Ba from the sediments into the forearc before reaching sub arc
328 depths, as observed in Costa Rica by Solomon and Kastner (2012). The Ba abundances of both
329 Masaya and Cerro Negro can both be reproduced by the model if 50% to 60% of Ba is lost from
330 the hemipelagic sediment prior to subduction (solid lines and closed symbols in Fig. 9).
331 Model results consistent with measured arc lava trace element abundances support our
332 proposed seamount subduction model based on the Sr stable isotope data. This new
333 geochemical framework provides a first-order explanation for the longstanding observation of
334 variable sediment recycling in Central America that was previously not well understood.
335 Additionally, our model results suggest that Ba in the sediments must be lost to the forearc
336 prior to melting.

337

338 **Carbon recycling efficiency estimates**

339 The calculated proportions of Sr contributed to the arc can now be used to estimate
340 carbon recycling efficiency. Given ~200 m of subducting carbonate sediment with a density of
341 1.75 g/cm³ and a convergence rate of 71.5 km/Ma²², the subducting CO₂ input into the

342 subduction zone from carbonate sediment alone is 27 metric tons per day (t/d). To determine
343 how much of this CO₂ is recycled back to the arc, we take advantage of the fact that
344 experimental water saturated melting Sr and C solid/melt partition coefficients for
345 carbonate^{52,53} are both close to unity. Our Sr model (Mixing scenario A, absent seamounts)
346 indicates that the subducting carbonate contributed 48 ppm Sr to the primary arc magmas
347 (compared to ~1500 ppm in the carbonate-rich sediment), which translates to a contribution of
348 ~1.25 wt.% CO₂ to the arc magma (compared to 40% CO₂ in the carbonate-rich sediment).
349 Assuming an eruption rate of rate of ~14 km³/Ma/km¹⁴, the output flux from the arc is
350 therefore between 7 and 14 t/d (based on an intrusive:extrusive ratio of 5-10), which amounts
351 to 26% to 52% of the subducted carbon from carbonate sediment. We note that this estimate
352 of carbon recycling efficiency is specific to carbon initially subducted as carbonate sediment,
353 though as previously noted, this accounts for up to 92% of the total subducting carbon
354 input^{10,14}. This result is consistent with the recent estimate for northwestern Costa Rica (~34%
355 to ~46%) from Barry et al. (2019) based on gas measurements. These results thus showcase the
356 potential of a Sr stable isotope proxy based purely on lava compositions to trace magmatic
357 carbon flux in subduction zones.

358

359 **Discussion**

360 Strontium stable isotope measurements of Nicaraguan arc basalts not only enable
361 direct estimates of magmatic carbon flux from the arc but also shed new light on the
362 subduction zone systematics that give rise to the geochemical variability in Central American
363 arc lavas. $\delta^{88}\text{Sr}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ constraints dictate that (1) in addition to AOC, a second, unaltered,

364 DMM-like crustal component is required to account for the low- $\delta^{88}\text{Sr}$ lava from Masaya lavas;
365 and (2) co-variation of the ocean crust components with the hemipelagic and carbonate
366 sediment components can account for the full $\delta^{88}\text{Sr}$ array of the measured Nicaraguan arc
367 lavas. The low- $\delta^{88}\text{Sr}$ ocean crust component likely comes from subducting seamounts atop the
368 Cocos plate that exhibit mantle-like $^{87}\text{Sr}/^{86}\text{Sr}$. With diameters up to 14 km and elevations up to
369 2 km above the surrounding seafloor, the seamounts erupted after the carbonate crash
370 plausibly cap the underlying carbonate sediments and AOC producing a “seamount effect” that
371 only allows for the transfer of a hemipelagic+depleted and less-altered seamount material to
372 the arc. End-member mixing proportions for sediment and crustal components are consistent
373 for both Sr isotopes and trace elements. Low- $\delta^{88}\text{Sr}$ Masaya lavas require mixing of a pure
374 depleted unradiogenic crustal component with a nearly 100% hemipelagic sediment. The high-
375 $\delta^{88}\text{Sr}$ Cerro Negro end member requires a pure AOC ocean crust component mixing with a
376 sediment component that is ~70% carbonate material. Telica lava $\delta^{88}\text{Sr}$ values fall between
377 Cerro Negro and Masaya end members and likely were produced by intermediate scenarios
378 that reflect variable proportions of all four components.

379 Our conceptual model is supported by quantitative forward model results which
380 reproduce the Cerro Negro and Masaya lava end member Sr isotope compositions and most
381 trace element abundances within uncertainty. Using our quantified carbonate flux determined
382 from Sr stable isotope data we estimate that ~26% to ~52% of the carbon from the subducting
383 carbonate sediments is recycled back out of the arc. These estimates are consistent with recent
384 carbon recycling efficiencies from Barry et al. (2019) and Bekaert et al. (2020). The results of
385 this study provide a new quantitative framework to explain the local variations in arc lava

386 geochemistry in Nicaragua and highlight the power of stable Sr isotope compositions as a tool
387 to understand subduction components and carbonate fluxes at arcs. Strontium stable isotopic
388 data have enormous potential to serve as a robust proxy for carbon transfer across subduction
389 zones alongside traditional CO₂ gas and carbon isotope measurements.

390

391 **Methods**

392 **Sample selection**

393 Only samples with $Eu^* > 0.95$ ($Eu/Eu^* = Eu_{cn}/[Sm_{cn} * Gd_{cn}]^{1/2}$) were selected to minimize
394 the potential influence of plagioclase fractionation. Hemipelagic and carbonate sediments from
395 124 m, 238 m and 362 m core depths recovered from DSDP site 495 were also analyzed to
396 constrain the Sr isotope compositions of the subducting Cocos plate sediments. Two AOC
397 composite powders from Kelly et al. (2003) previously measured for $\delta^{88}Sr$ by Klaver et al. (2020)
398 were also analyzed.

399

400 **Strontium double spike TIMS analysis and sample preparation**

401 Strontium isotope analyses were conducted via Thermal Ionization Mass Spectroscopy
402 (TIMS) using a Sr double-spike to correct for instrumental mass fractionation. Two ~10 mg
403 aliquots of each sample – one containing the Sr double spike and one unspiked – were digested
404 in a 4:1 solution of 16N Aristar Plus trace metal analysis grade HNO₃ and 48N ultra-pure HF in
405 Savillex beakers at 150° C for 48 hours in clean labs at the University of Massachusetts,
406 Amherst. Samples were evaporated to dryness at 100° C then dissolved twice in 20ul of 16N
407 Aristar Plus trace metal analysis grade HNO₃ and evaporated to dryness at 100° C. Following the

408 second dry down, samples were re-digested in 1.5 ml of 8N Aristar Plus trace metal analysis
409 grade HNO₃ for 24 hr at 120° C. Ion exchange chromatography was developed to separate both
410 Rb and Ba from Sr, as the presence of either element has undesirable effects on Sr isotope
411 measurements. For example, eluted Sr solutions with greater than 1 ppm Ba concentrations
412 exhibit deviations of up to 0.8‰ and 0.001 in $\delta^{88}\text{Sr}$ and $^{87}\text{Sr}/^{86}\text{Sr}$, respectively, compared to
413 ratios measured in pure Sr⁵⁹. Following Sr purification, samples were loaded onto degassed Re
414 filaments along with a TaO₂ activator and measured using a Thermo Finnigan Triton TIMS at the
415 Carnegie Institution for Science Earth and Planets Laboratory in Washington, D.C. (see Online
416 Supplement for additional details).

417

418 **Forward quantitative modeling approach**

419 The forward trace element and isotopic geochemical model builds off the quantitative
420 framework for global arc lava variations established by Turner and Langmuir (2022c). The goal
421 of this modeling approach is to ascertain the plausibility of a model hypothesis using melting
422 parameters and trace element partition coefficients that are consistent with experimental
423 petrology. The extent of fractional crystallization for the Cerro Negro and Masaya samples were
424 estimated to be 10% and 20%, respectively, using Petrolog modeling software. Extents of
425 mantle melting are estimated from heavy rare earth element abundances. The model uses AOC
426 and sediment melt trace element partition coefficients determined by Turner and Langmuir
427 (2022b).

428 The ambient mantle was assigned the trace element abundances of the 'DMM' from
429 Workman and Hart (2005), $\delta^{88}\text{Sr}$ (~0.28‰) that matches the average N-MORB $\delta^{88}\text{Sr}$ reported

430 by Klaver et al. (2020), and $^{87}\text{Sr}/^{86}\text{Sr}$ (~ 0.7028) based on back arc basalts from La Providencia
431 Island⁶¹. The carbonate sediment composition is based off the weighted average from Patino et
432 al. (2000) for DSDP 495, while the upper hemipelagic sediment composition was re-calculated
433 in bulk to exclude the youngest upper layers, which should not be present on the deeply
434 subducted portion of the slab beneath the arc. For AOC we assume an $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7032^{58}
435 which is between the average Pacific MORB ($^{87}\text{Sr}/^{86}\text{Sr} = 0.70257$)⁶² and an upper altered slab
436 layer with $^{87}\text{Sr}/^{86}\text{Sr}$ equal to $\sim 0.7045^{58}$. This is based on the observation that alteration
437 processes raise the average $^{87}\text{Sr}/^{86}\text{Sr}$ of the upper 500 m of ocean crust by $\sim 0.0017^{58,63}$ with
438 only minor increases in deep portions of the slab. For the unaltered seamount ocean crust
439 component, we use an $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7026^{23} . Complete modeling results and parameters are
440 available in Online Supplement Table S1 and S2.

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639 **Author Contributions**

640 S.J.T. and R.P. conceived of the project and acquired funding. All authors contributed to method
641 development. A.J.H. performed column calibration experiments and conducted all sample preparation
642 of unknowns and conducted TIMS analysis with R.W.C. A.J.H. and S.J.T primarily contributed to data
643 interpretation; all authors participated in data discussion. A.J.H. wrote the manuscript with input from
644 all authors.

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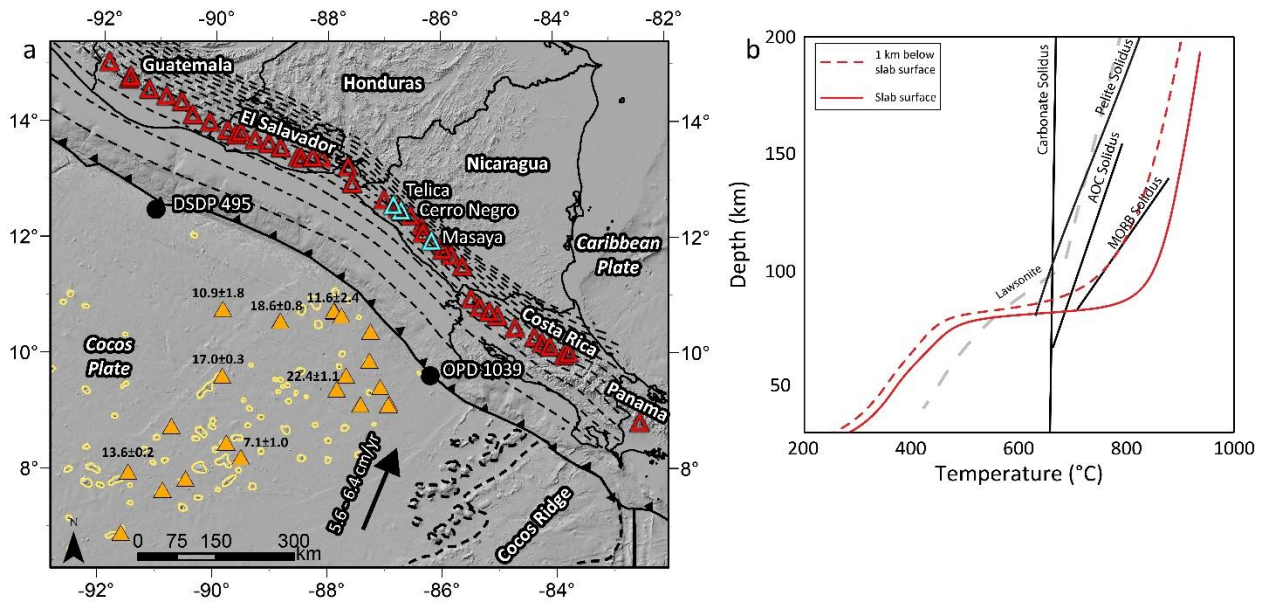
646 **Ethics declarations**

647 Competing interests

648 The authors declare no competing interests

649 **Figures**

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652 **Figure 1. Map of Central American Volcanic Arc and phase diagram of Nicaraguan slab**
thermal profiles. A Open red triangles are Arc front volcanoes. Open blue triangles are
 653 volcanoes analyzed in this study. Cocos plate seamounts outlined in yellow. Solid orange
 654 triangles are Cocos plate seamounts sampled by Herbrich et al. (2015). Seamounts with
 655 measured ages are labeled. Location of DSDP site 495 and ODP 1039 indicated by solid black
 656 circles. Thin black dashed lines are slab surface contours (CI = 20 km). **B** Slab thermal profiles
 657 at the surface (solid red line) and 1 km below the slab surface (dashed red line) are plotted
 658 over H₂O-saturated solidus for carbonate³⁶ and pelitic sediments³⁷, AOC³⁸, and MORB³⁹.

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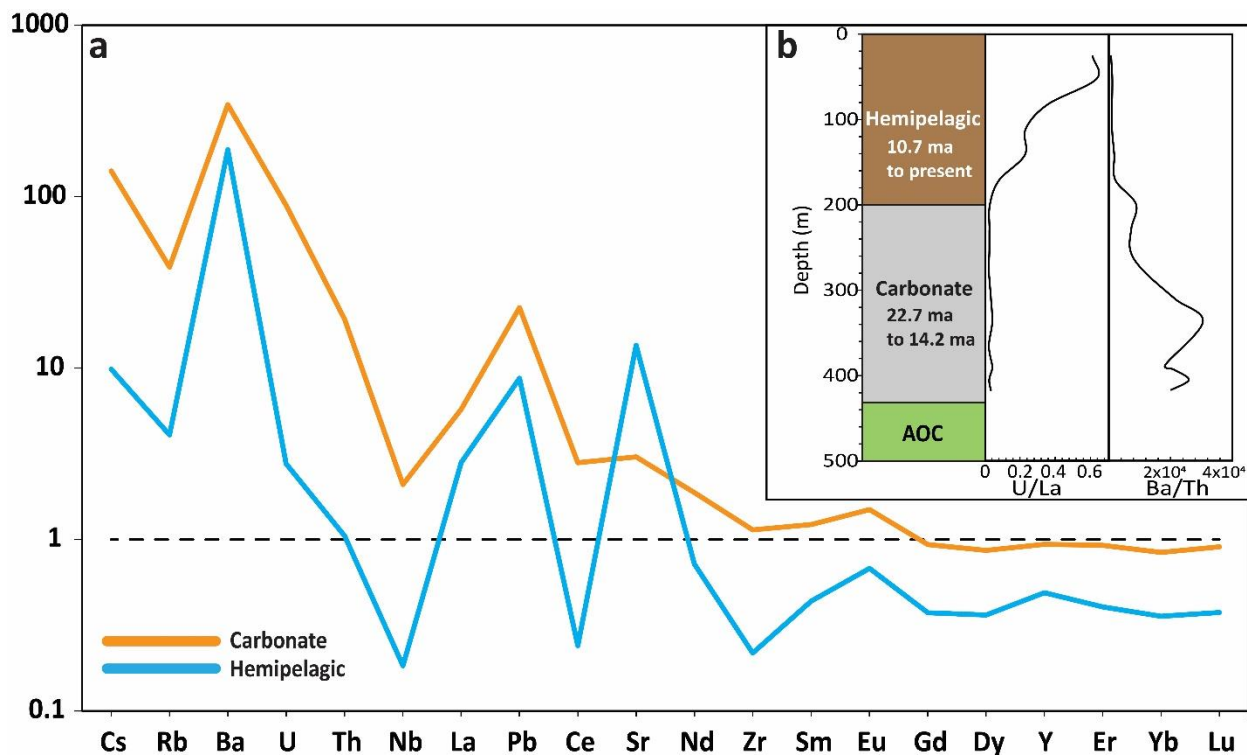
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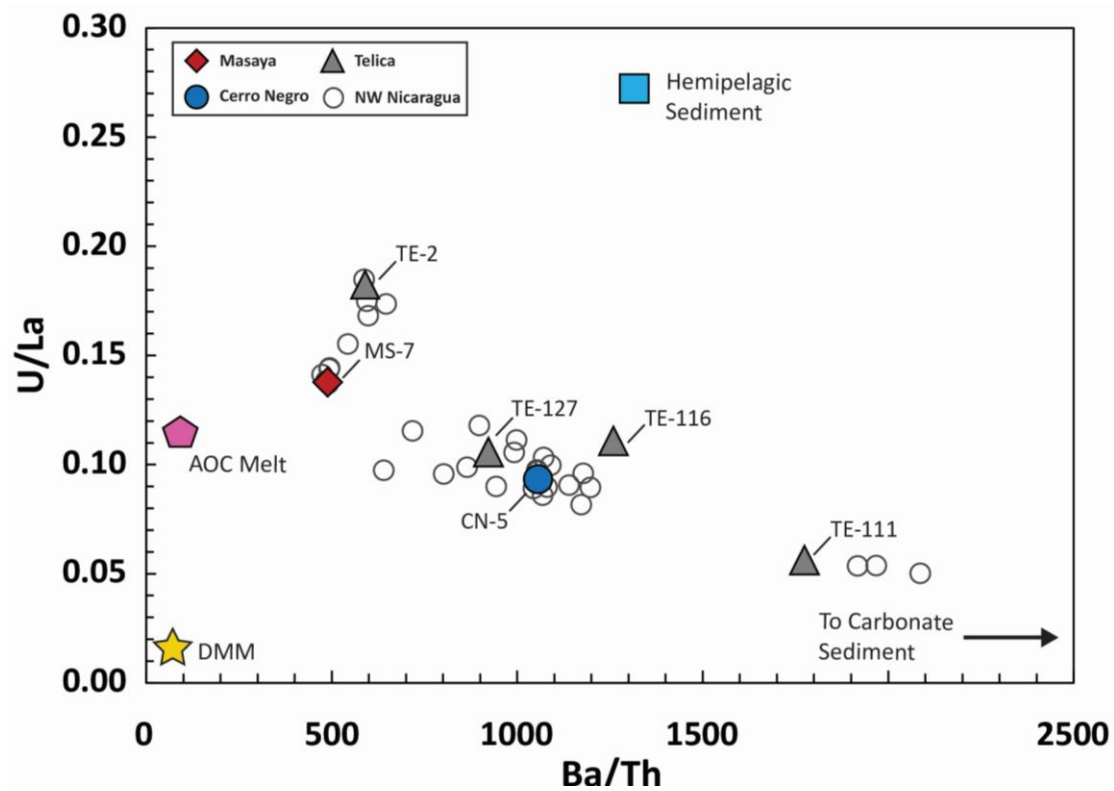
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664 **Figure 2. Compositional differences between average bulk hemipelagic and carbonate**
665 **sediments from DSDP Site 495. A** DMORB (black dotted line)⁶² normalized incompatible
666 element diagram highlighting the Bulk sediment compositions from ref 26. **B** General
667 stratigraphy of DSDP site 495 with U/La and Ba/Th ratios vs depth (see text for explanation).
A data point with an anomalously large Ba/Th value has been removed to preserve scale.

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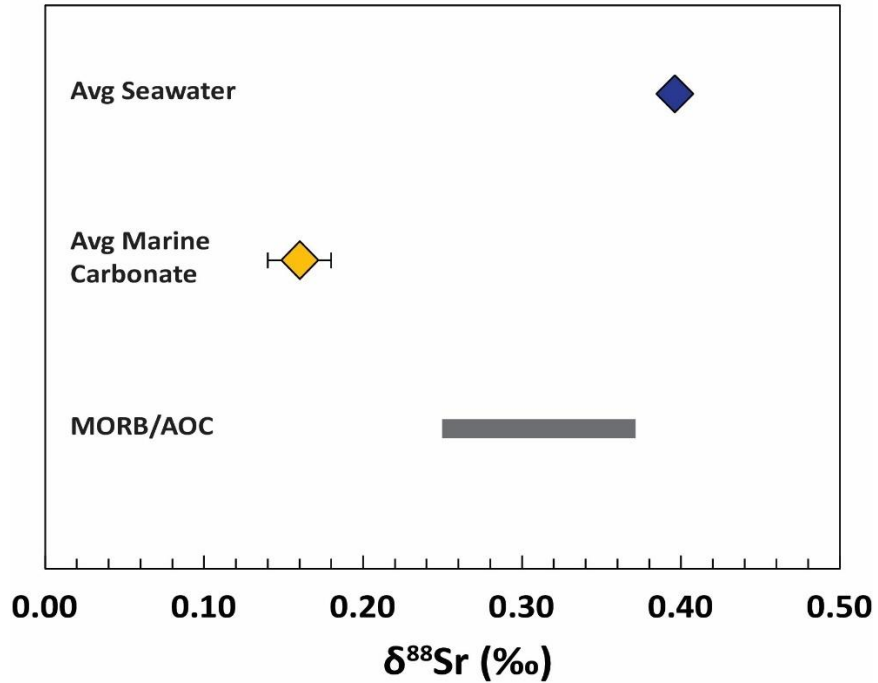
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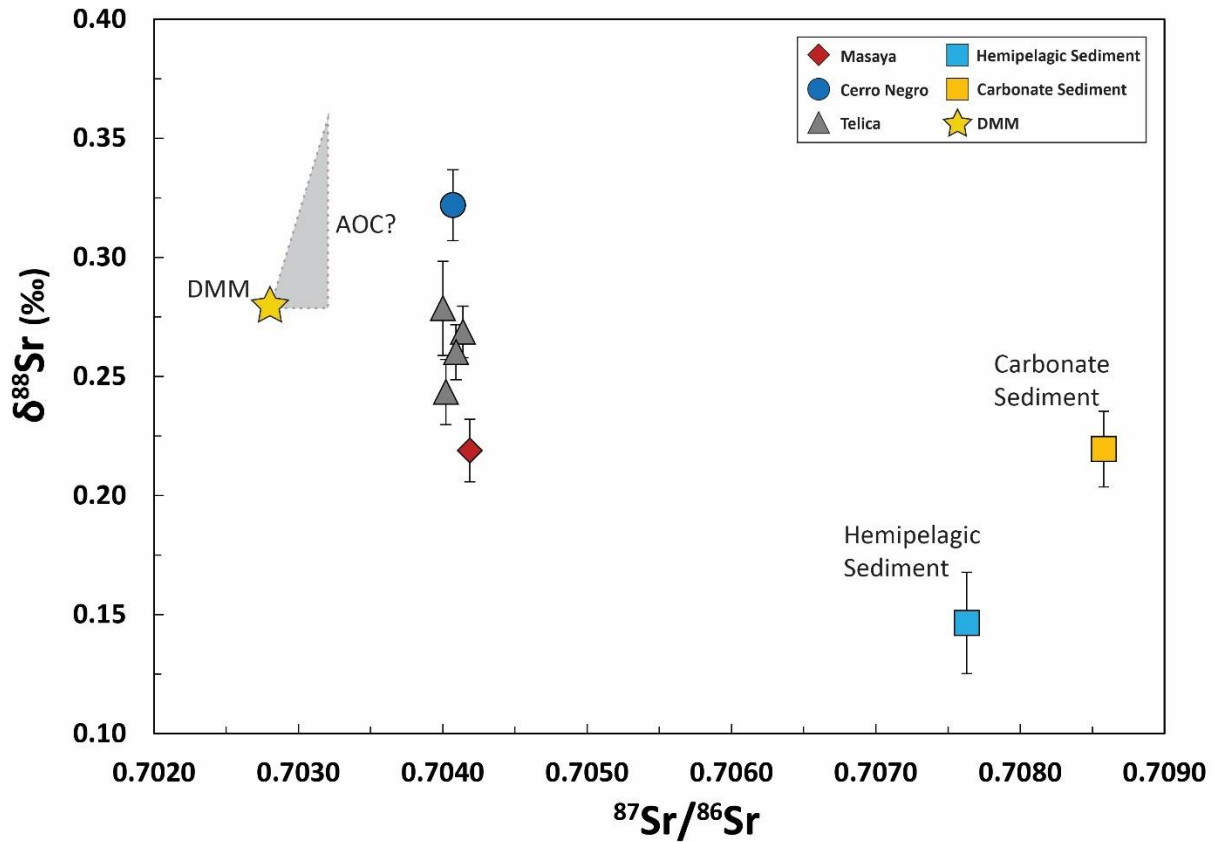
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Figure 3. U/La vs Ba/Th trace element ratios showing how variations in sediment flux and the relative proportion each Cocos plate sediment influence the overall geochemical variations in Nicaraguan arc lavas (open circles). The decreasing trend of the arc lavas indicate that U/La and Ba/Th are controlled by the sediments. Volcanoes selected for this study include: Telica (gray triangles, Cerro Negro (blue circle), and Masaya (red diamond). The Blue and yellow filled squares are bulk hemipelagic and carbonate sediment compositions from ref 26, respectively. Gold star is depleted MORB mantle (DMM) of ref 60. Pink pentagon is altered ocean crust (AOC) melt.



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673 **Figure 4. $\delta^{88}\text{Sr}$ of different geochemical reservoirs.** Fractionation of Sr isotopes during
 674 carbonate precipitation (yellow diamond) from seawater (blue diamond) produce an
 675 average carbonate $\delta^{88}\text{Sr}$ that is significantly lighter than the reported range of $\delta^{88}\text{Sr}$ for
 altered and unaltered MORB (grey bar). The original $\delta^{88}\text{Sr}$ of each component transferred to
 the arc should not undergo discernible fractionation during magma petrogenesis therefor
 highlighting the Sr stable isotope system's potential to serve as a tracer for subduction
 components. Average seawater and marine carbonate $\delta^{88}\text{Sr}$ from ref 47 and 48. Range of
 MORB/AOC $\delta^{88}\text{Sr}$ from ref 49 and 50.



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Figure 5. Three isotope plot showing Sr isotope systematics of measured Nicaraguan arc lavas and Cocos plate sediments from this study. Arc lava $^{87}\text{Sr}/^{86}\text{Sr}$ does not vary and falls

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closer to the un radiogenic slab components. Gray triangle is possible range of oceanic crustal component Sr isotope compositions based on measured and experimental $\delta^{88}\text{Sr}$ for

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altered and unaltered N-MORB . The upper bound of the array represents possible AOC component with a $\delta^{88}\text{Sr} \sim 0.37$. This value is from experimentally altered MORB from ref 50.

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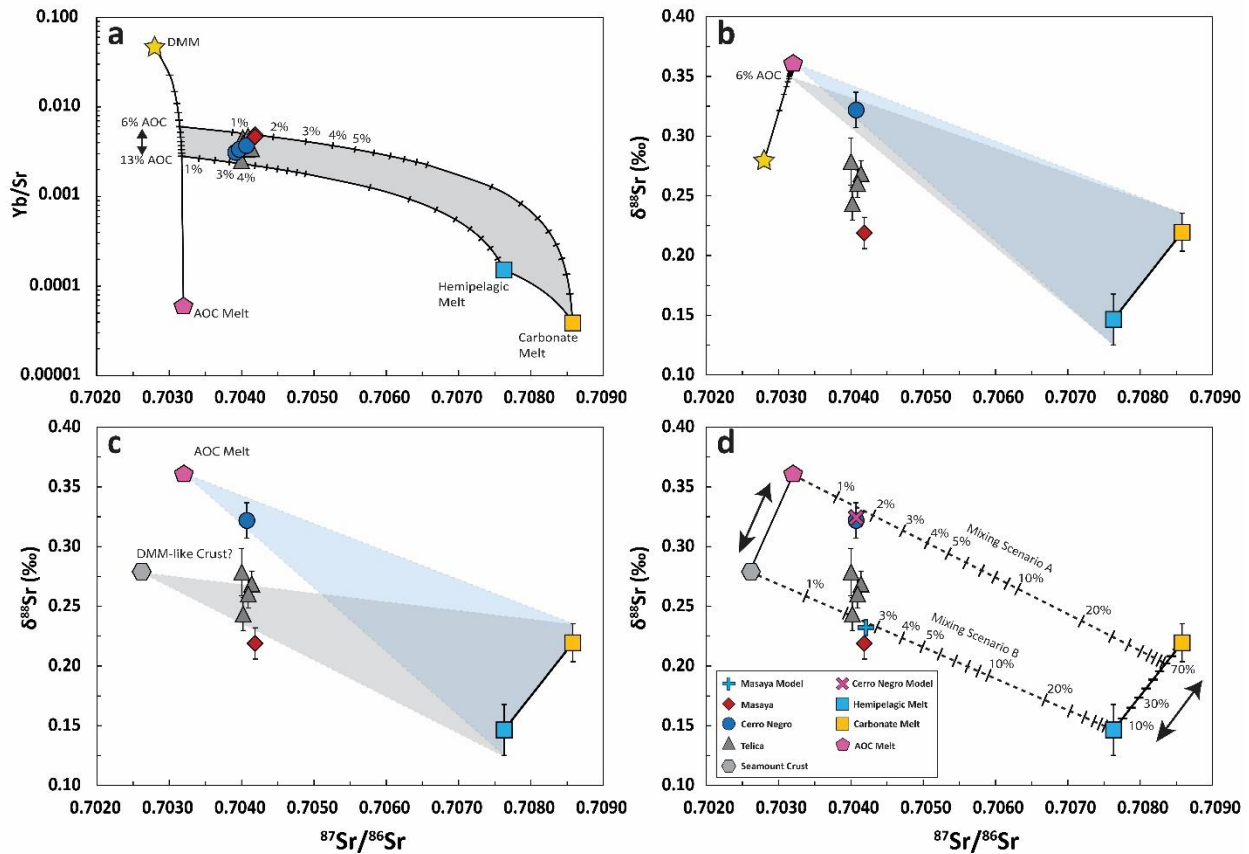
Gold star is ambient mantle Sr isotope composition (DMM). DMM Sr isotope values determined using average unaltered MORB $\delta^{88}\text{Sr}$ of $0.279 \pm 0.05\%$ from ref 49 and $^{87}\text{Sr}/^{86}\text{Sr}$

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of 0.7028 measured in back arc basalts from La Providencia Island that have negligible subduction related trace element signatures⁶¹.

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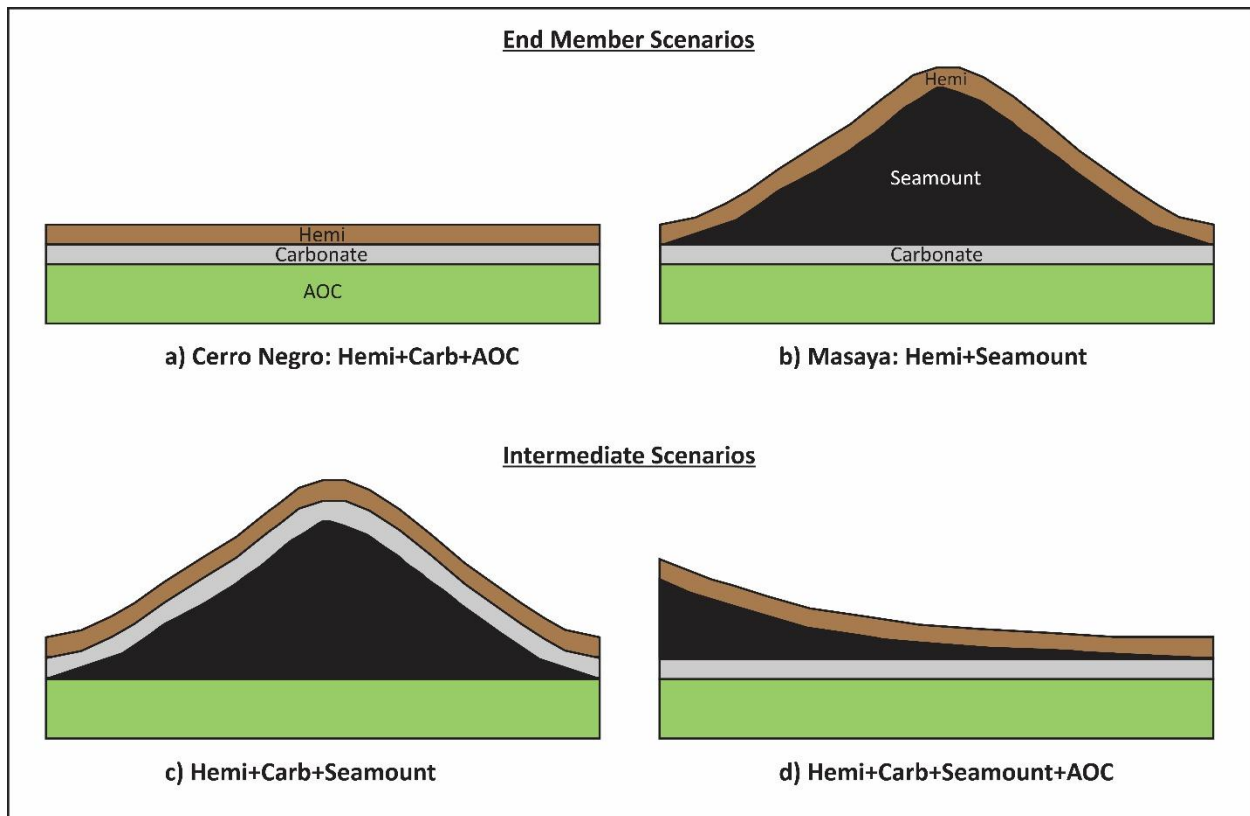
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Figure 6. Plots of $^{87}\text{Sr}/^{86}\text{Sr}$ vs trace element ratios and $\delta^{88}\text{Sr}$ for Nicaraguan arc basalts showing binary mixing models and quantitative forward model results for Masaya and Cerro Negro volcanoes. A Yb/Sr ratio mass balance to determine relative proportion of Sr contributed from each slab component. Even at very small amounts, the mass balance indicates AOC exerts the greatest control on Nicaraguan arc magma Sr content. **B** $\delta^{88}\text{Sr}$ further highlights how AOC dominates Sr contributions. **C** A second, DMM-like, low $\delta^{88}\text{Sr}$ unaltered ocean crust component can account for the low $\delta^{88}\text{Sr}$ Masaya end member lava. **D** Strontium isotope mixing and quantitative model results. Dashed lines are mixing lines for the Cerro Negro and Masaya mixing models, respectively.

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Figure 7. Conceptual models showing simplified slab surface of down going Cocos plate for several Nicaraguan subduction scenarios. A and B are end member scenarios for Cerro Negro and Masaya lavas, respectively. A reflects normal subduction in which a mixture of AOC and hemipelagic+carbonate sediments are added from the slab to the arc. In B large seamounts on the Cocos plate erupted after the carbonate crash effectively cap the carbonate sediments and underlying AOC. C and D represent intermediate scenarios in which various proportions of each component could reach the arc.

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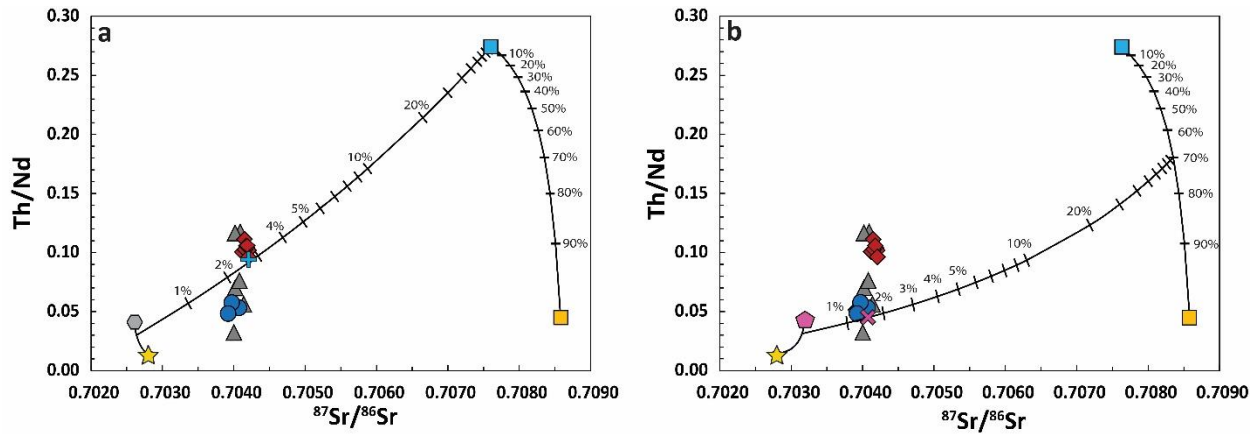
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701 **Figure 8. Plots of $^{87}\text{Sr}/^{86}\text{Sr}$ vs Th/Nd for Nicaraguan arc basalts showing mixing models and**
 702 **quantitative forward model results for Masaya and Cerro Negro volcanoes. A and B show**
 703 **Th/Nd ratio binary mixing and quantitative forward model results for Masaya and Cerro**
 704 **Negro end members respectively. These results are consistent with $\delta^{88}\text{Sr}$ constraints shown**
 705 **in Fig. 6 A-D. Symbols same as in Fig. 6. Solid hashed lines are binary mixing lines between**
 706 **ocean crust and sediment components.**

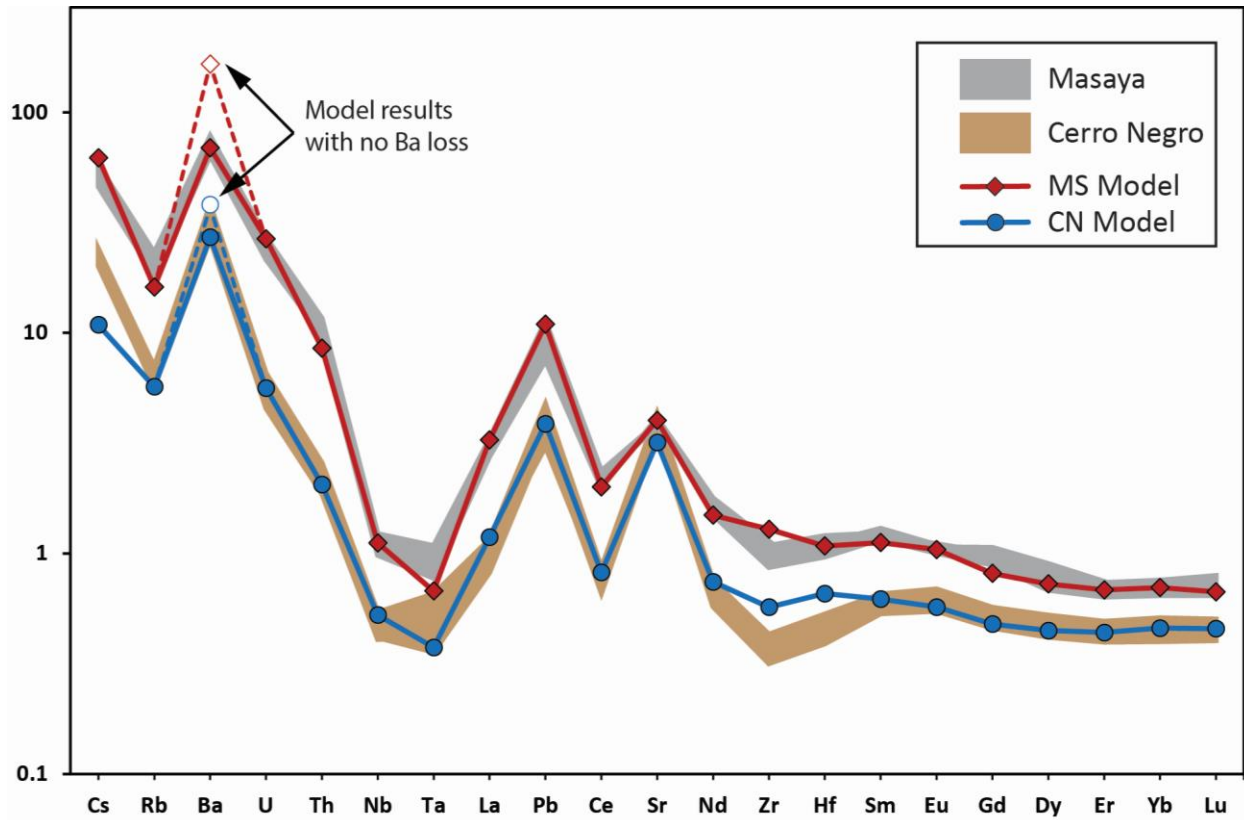
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Figure 9. DMORB normalized⁶² incompatible element diagram comparing modeled and measured trace element compositions for Cerro Negro and Masaya volcanoes. Shaded regions are the range of measured trace element compositions for Masaya and Cerro Negro volcanoes, respectively. Dotted lines with open symbols are model results that do consider Ba loss. Following the results of ref 46 a 60% loss of Ba from the sediments in the forearc can account for the Ba mismatch in the trace element abundance model. Nb and Ta are controlled by residual rutile and not a function of slab recycling. Similarly, Zr and Hf do not match for either model, but these values are dependent on our assumption of zircon solubility in the slab melts which is not well constrained. See Turner and Langmuir (2022b) for detailed explanation on how partition coefficients for Zr, Hf, Nb, and Ta are determined.

Table 1. Strontium isotope compositions and selected trace element ratios of Nicaraguan arc basalts, Cocos plate sediments, altered ocean crust, and reference standard JB-2. $\delta^{88}\text{Sr}$ values are reported relative to SRM-987. Complete trace element compositions of for arc lavas and sediments provided in the Online Supplement.

Sample ID	Name/description	$\delta^{88}\text{Sr}$	2SE	$^{87}\text{Sr}/^{86}\text{Sr}$	[Sr] ppm	Ba/Sr	Th/Nd
Arc Basalts							
CN-5	Cerro Negro	0.322	0.0149	0.704071	386.9	0.866	0.053
MS-7	Masaya	0.219	0.0131	0.704187	544.7	1.598	0.106
TE-2	Telica	0.260	0.016	0.70409	453.8	1.741	0.117
TE-116	Telica	0.269	0.024	0.70414	480.6	1.021	0.056
TE-127	Telica	0.243	0.014	0.70402	524.2	1.373	0.070
TE-111	Telica	0.279	0.020	0.70400	710.6	0.774	0.032
Sediments							
H(12R)-124m(a)	Hemipelagic	0.146	0.021	0.70758	336.2		
C(24R)-238m(a)	Carbonate	0.171	0.016	0.70881	1504.1		
C(37R)-362m(a)	Carbonate	0.219	0.016	0.70849	1		
Altered Ocean Crust							
801-MORB-11-220-FLO	ODP site 801 composite	0.247	0.008	0.70330			
801-MORB-11-220-VCL	ODP site 801 composite	0.263	0.014	0.70679			
Reference Standard							
JB-2		0.312	0.008	0.70375			

Trace element data for basalts from ref 56

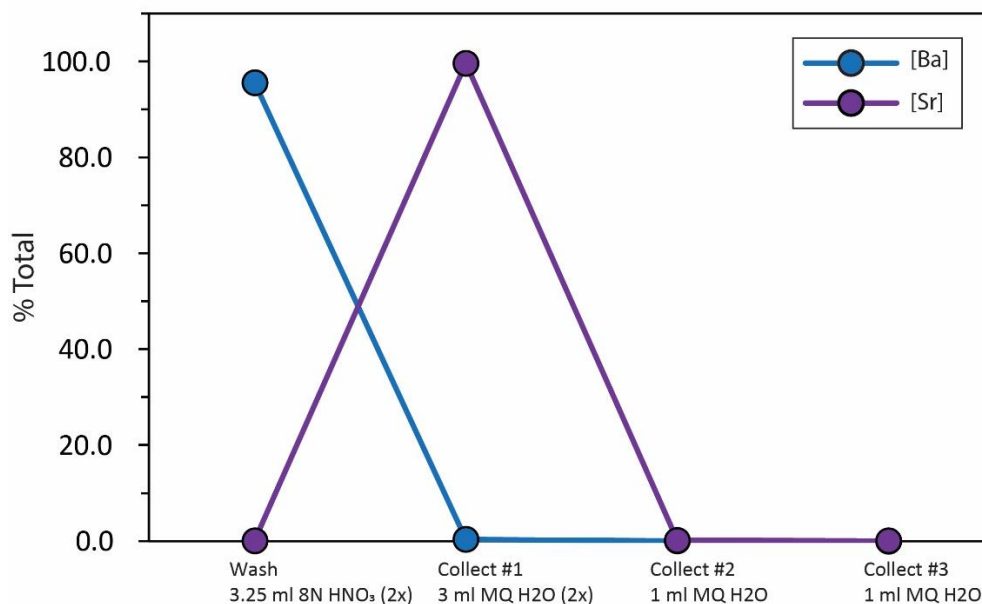
718 ***Supplementary Information for ‘Seamounts control subducted carbonate recycling in Central***
719 ***America – evidence from stable Sr isotopes’, by Alexander J. Hammerstrom, Rita Parai,***
720 ***Richard W. Carlson, and Stephen J. Turner***

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722 **Ion exchange chromatography and column chemistry calibration**

723 Spiked and un-spiked aliquots were prepared for each unknown sample. For spiked
724 samples, a mixed ^{87}Sr - ^{84}Sr solution was added to the aliquot prior to dissolution in order to
725 capture any mass-dependent fractionation during digestion or column chemistry. Strontium
726 was separated using Eichrom Sr Spec resin¹ in house-made Teflon microcolumns. Resin was
727 preconditioned by passing 3 ml of 8N Aristar Plus trace metal analysis grade HNO_3 through the
728 columns. Next, digested sample solutions were loaded into the columns and washed twice with
729 3.25 ml of 8N Aristar Plus trace metal analysis grade HNO_3 to elute matrix elements (the use of
730 8N HNO_3 as opposed to 3N HNO_3 was required to fully separate Sr from Ba). Following the
731 wash, purified Sr was collected by two elutions of 3 ml of Milli-Q H_2O (18.2 $\text{M}\Omega\cdot\text{cm}$) and
732 evaporated until dry, then redissolved in 10 μl of 8N Aristar Plus trace metal analysis grade
733 HNO_3 . The resulting solution was then dried down once more before a final dissolution in 10 μl
734 of 8N Aristar Plus trace metal analysis grade HNO_3 .

735 This column procedure was calibrated to enable efficient separation of Sr from Ba and
736 ensure complete recovery of Sr from our samples, some of which have very high Ba
737 concentrations. The column calibration was verified using a Perkin Elmer Nexion 350D
738 Quadrupole ICP-MS at UMass Amherst. Figure S1 shows the relative Ba and Sr concentrations
739 of eluate collected from the sample wash, and collection phases of our final column calibration

740 procedure using DSDP 495 sediment powder, which contains 2106 ppm Ba and 1444 ppm Sr.
741 The total Sr yield from the collection eluant is 99.9% of the total Sr in the added solution with a
742 negligible amount of Ba (~0.3% of the total Ba in solution passed through the column).



743 **Figure S1.** Sr and Ba concentrations of eluant collected from each step in our successful ion
exchange chromatography column chemistry calibration experiment. Samples were
measured via solution ICP-MS. Of the total Ba loaded into the column ~5% was lost during
the initial column loading step (not measured) and ~95% was eluted during the wash step
leaving 0.3% in the collection eluant.

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745 TIMS analysis and data reduction

746 Spiked and un-spiked aliquots were analyzed for each unknown sample. For each
747 analysis, 1ug of purified Sr was loaded onto degassed Re filaments along with a TaO₂ activator
748 and measured using a Thermo Finnigan Triton TIMS at the Carnegie Institution for Science Earth
749 and Planets Laboratory in Washington, D.C. ⁸⁵Rb was used to monitor for isobaric interference
750 from ⁸⁷Rb on ⁸⁷Sr. In-run ⁸⁵Rb/⁸⁶Sr ratios were < 1x10⁻⁵ and interference corrections to the
751 ⁸⁷Sr/⁸⁶Sr ratio were accordingly minimal. Data were acquired in 30 blocks of 20 cycles. The spike

752 composition was verified via measurements of variable mixtures of the spike solution and
753 SRM987 using ratios of 0:1,1:2, 1:2:,2:1,1:0. To calculate unknown Sr isotope compositions, an
754 exponential fractionation was assumed and spike:sample mixing proportion were left as
755 unknowns. This simple system of equations was then solved by minimizing least squares misfit
756 using MATLAB's fminsearch solver. Results for unknowns were then normalized to
757 fractionation-corrected SRM987 measurements (results of spiked-unspiked pairs) from the
758 same barrel.

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760 **$\delta^{88}\text{Sr}$ measurements of ODP 801c composite samples not representative of typical altered**
761 **ocean crust.**

762 The high- $\delta^{88}\text{Sr}$, low- $^{87}\text{Sr}/^{86}\text{Sr}$ end member required to account for the Cerro Negro
763 composition is consistent with altered ocean crust compositions inferred from², though the
764 range of available $\delta^{88}\text{Sr}$ measurements of actual AOC samples, which are all composite samples
765 from ODP 801c³, does not encompass the compositional range of AOC end members required
766 to account for the Central American arc data. The 801c site is probably not a good general
767 proxy for AOC, however, because the upper 100 m consists of off-axis lavas rather than typical
768 ocean crust. For example, Pockalny and Larson (2003) suggest that the presence of thick,
769 massive, and laterally extensive off-axis lava flows could seal the original fractured ocean crust
770 from seawater alteration. Moreover, crustal accretion models show that lava flows extending
771 ~2-4 km off-axis can influence crustal subsidence and cause crust to fracture less extensively,
772 decreasing the extent and depth of hydrothermal alteration⁴⁻⁶. The unique geology at site 801c
773 may thus explain the lack of heavy $\delta^{88}\text{Sr}$ compositions observed in most of the 801c composite

774 AOC powders. While additional measurements of AOC samples from other localities are needed
775 to further elucidate the variability of AOC $\delta^{88}\text{Sr}$, the experimental data and our new arc lava
776 $\delta^{88}\text{Sr}$ measurements suggest that typical altered oceanic crust may commonly have elevated
777 $\delta^{88}\text{Sr}$, and without this, there is no possible mixing solution capable of accounting for the
778 composition of Cerro Negro.

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Tables

Table S1. Quantitative forward model end member starting compositions and bulk partition coefficients.

	DMM and AOC melt compositions			Sediment melting partition coefficients, bulk sediment and modeled sediment melt compositions				
	¹ DMM	² AOC Melt (CN)	² AOC Melt (MS)	³ Bulk Carb	³ Bulk Hemi	² Sed D values	⁴ Sed Melt (CN)	⁴ Sed Melt (MS)
Rb	0.05	9.09	6.13	4.28	45.81	0.70	20.71	56.67
Cs	0.00	0.12	0.08	0.15	2.21	0.10	1.40	4.02
Sr	7.66	571.28	414.61	501.37	369.79	0.25	805.38	644.78
Ba	0.56	96.87	65.28	2145.48	2108.18	0.40	3353.39	3312.37
Ti	0.07	0.00	0.00	0.03	0.52	1.00	0.17	0.52
Nb	0.15	0.73	1.04	0.44	5.13	1.33	3.36	4.20
Ta	0.01	0.04	0.07	0.00	0.00	1.33	0.00	0.00
Zr	5.08	62.00	111.00	20.16	117.04	1.80	32.07	76.24
Hf	0.13	2.14	2.68	0.00	0.00	1.20	0.00	0.00
La	0.19	3.71	4.78	8.78	23.34	0.83	14.77	26.22
Ce	0.55	10.57	13.48	2.40	32.64	0.90	12.27	34.91
Nd	0.58	8.46	10.58	6.79	22.90	1.60	8.30	16.36
Sm	0.24	2.01	2.42	1.45	5.23	2.20	1.43	2.89
Eu	0.10	0.47	0.56	0.82	2.45	2.80	0.59	1.10
Gd	0.36	0.96	1.04	1.65	5.21	4.00	0.89	1.71
Dy	0.51	0.35	0.37	1.99	5.98	9.00	0.49	0.92
Er	0.35	0.10	0.10	1.40	3.84	16	0.19	0.34
Yb	0.37	0.06	0.06	1.18	3.40	50	0.05	0.10
Lu	0.06	0.01	0.01	0.19	0.53	75	0.01	0.01
Y	3.33	0.00	0.00	16.22	39.55	0.00	42.22	71.91
Sc	16.50	0.00	0.00	2.63	15.05	0.00	11.56	27.37
Pb	0.02	1.97	1.54	3.70	11.12	0.50	8.59	16.13
Th	0.01	0.37	0.44	0.16	3.35	0.60	1.50	4.49
U	0.00	0.33	0.33	0.15	3.54	0.40	1.83	5.56
δ⁸⁸Sr	0.279	0.36	0.279	0.22	0.15		0.20	0.15
⁸⁷Sr/⁸⁶Sr	0.7028	0.7032	0.7026	0.70858	0.70763		0.70835	0.70763

¹ Values from Workman and Hart (2005)

² AOC melt and sediment partition coefficients are determined in the model based on temperature input parameters following the methods described by Turner and Langmuir (2022b). Cerro Negro (CN) and Masaya (MS) AOC melt compositions correspond to “moderate” and “hot” values from Turner and Langmuir (2022b), respectively. Sediment partition coefficients correspond to “hot” values from Turner and Langmuir (2022b)

³ Values from Patino et al. (2000). Bulk hemipelagic sediment values are average composition of the bottom three hemipelagic layers recovered from DSDP 495 (see text for details).

⁴ Sed melts calculated using aggregate fractional melting equation, $Sed\ Melt = (D_{sed}/F_{sed}) * (1 - F_{sed})^{(1/D)}$, with a melt fraction of $F = 0.55$

Table S2. Input parameters and results for Cerro Negro and Masaya quantitative forward models.

Sample	Cerro Negro	Masaya
Input parameters		
P	1.9	1.9
F	0.22	0.15
%Carb	0.7	0
%Sed	0.0156	0.027
%AOC	0.09	0.075
Sed T (°C)	900	900
AOC T (°C)	850	900
Model Results		
Rb	5.99	16.94
Cs	0.17	0.96
Sr	352.96	444.70
Ba	310.65	789.35
Nb	1.26	2.68
Ta	0.06	0.11
Zr	52.80	119.17
Hf	1.52	2.49
La	3.70	10.20
Ce	8.21	20.06
Nd	7.03	14.11
Sm	2.06	3.71
Eu	0.69	1.26
Gd	2.12	3.59
Dy	2.45	3.99
Er	1.52	2.36
Yb	1.52	2.32
Lu	0.23	0.33
Y	18.37	39.89
Pb	1.65	4.65
Th	0.32	1.33
U	0.31	1.47
$\delta^{88}\text{Sr}$	0.324	0.237
$^{87}\text{Sr}/^{86}\text{Sr}$	0.7041	0.7042

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