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**Abstract:** Contamination of ascending mantle-derived magmas by the continental crust was investigated and modelled for a suite of volcanic rocks from the Bolivian Altiplano, Central Andes, using bulk geochemical compositions for mantle-derived and crustal end-members as dictated by traditional approaches. The assumption that the crustal contaminant in these open magmatic systems is a single composition was assessed through in-situ analysis of quenched anatectic melt trapped within its crustal source. Our results show for the first time significant chemical and Sr-isotopic disequilibrium between melt and source over centimetre length scales in a natural system. Sampled glass is rhyolitic and peraluminous in nature and enriched in LREE e.g. Ba, Rb and depleted in HREE e.g. Y and Yb. Analysis of the quenched anatectic melt for its  $^{87}\text{Sr}/^{86}\text{Sr}$  composition revealed isotopic heterogeneity ranging from 0.7166 to 0.7281. The isotopic disequilibrium between melt and source is understood to reflect the melting of minerals with different Rb/Sr (and therefore  $^{87}\text{Sr}/^{86}\text{Sr}$ ) more quickly than the isotopic composition can diffusively equilibrate between melt and minerals. Our results suggest that the mechanism of crustal anatexis produces contaminating melts which are geochemically heterogeneous both spatially and temporally. This highlights the need for detailed microscopic investigations coupled with petrogenetic modelling in order to develop a more robust characterisation and well constrained quantification of crustal contamination in open magmatic systems.

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1 Disequilibrium melting during crustal anatexis and implications for modelling open  
2 magmatic systems.

3

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5

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8

9

## 10 ABSTRACT

11 Contamination of ascending mantle-derived magmas by the continental crust was investigated and modelled  
12 for a suite of volcanic rocks from the Bolivian Altiplano, Central Andes, using bulk geochemical compositions  
13 for mantle-derived and crustal end-members as dictated by traditional approaches. The assumption that the  
14 crustal contaminant in these open magmatic systems is a single composition was assessed through *in-situ*  
15 analysis of quenched anatectic melt trapped within its crustal source. Our results show for the first time  
16 significant chemical and Sr-isotopic disequilibrium between melt and source over centimetre length scales in a  
17 natural system. Sampled glass is rhyolitic and peraluminous in nature and enriched in LREE e.g. Ba, Rb and  
18 depleted in HREE e.g. Y and Yb. Analysis of the quenched anatectic melt for its <sup>87</sup>Sr/<sup>86</sup>Sr composition revealed  
19 isotopic heterogeneity ranging from 0.7166 to 0.7281. The isotopic disequilibrium between melt and source is  
20 understood to reflect the melting of minerals with different Rb/Sr (and therefore <sup>87</sup>Sr/<sup>86</sup>Sr) more quickly than the  
21 isotopic composition can diffusively equilibrate between melt and minerals. Our results suggest that the  
22 mechanism of crustal anatexis produces contaminating melts which are geochemically heterogeneous both  
23 spatially and temporally. This highlights the need for detailed microscopic investigations coupled with  
24 petrogenetic modelling in order to develop a more robust characterisation and well constrained quantification of  
25 crustal contamination in open magmatic systems.

26

## 27 INTRODUCTION

28 During ascent towards the Earth's surface, primary basaltic magma sourced from the mantle has the potential  
29 to interact with overlying crustal rocks. This has been recognised since Bowen (1928) argued that assimilation

30 of foreign material into a magma body should be treated as an inevitable consequence of fractional  
31 crystallisation, with a positive feedback loop between the extraction of heat due to assimilation and the  
32 generation of latent heat of crystallisation as crystallisation is promoted by heat extraction and cooling (e.g.  
33 Kuritani et al., 2005). One of the key questions in understanding the origin of igneous rocks at convergent  
34 margins (e.g. The Andes) is the fraction and nature of the crustal and mantle reservoirs involved in their  
35 petrogenesis. The degree to which mantle and crustal reservoirs have contributed to the geochemical signatures  
36 of surface expressions of volcanism at continental arcs is frequently assessed through combined assimilation and  
37 fractional crystallisation models (e.g. Taylor, 1980; Spera and Bohron, 2001). However the nature of potential  
38 contaminants is rarely well constrained and the intricacies inherent to crustal anatexis and thus the nature of  
39 contaminating crustal melts is left unconsidered.

40 Partial melting redistributes trace elements as a function of their partition coefficients. Isotope ratios however  
41 are unaffected by this process and have therefore been implemented as tracers of geochemical reservoirs  
42 throughout the Earth. This so-called “fingerprinting” has been widely applied for decades (e.g. Allegre, 1982;  
43 Mamani et al., 2010). Sr isotopes are particularly useful at identifying the interaction between crustal and  
44 mantle sources as the mantle is relatively nonradiogenic (e.g.  $^{87}\text{Sr}/^{86}\text{Sr}$  of 0.703-0.704, Lucassen et al., 2006)  
45 whereas old, high Rb/Sr continental crust is radiogenic (e.g.  $^{87}\text{Sr}/^{86}\text{Sr}$  of 0.735, Taylor, 1980).

46 In order to investigate in detail the geochemical consequences of crustal anatexis and the subsequent  
47 implications for modelling contamination processes, the compositions of Central Andean crustal xenoliths and  
48 their host Early Pliocene lavas were investigated. These xenoliths provide new constraints to the composition of  
49 the Andean continental crust which contaminates ascending mantle-derived magmas. These xenoliths also  
50 preserve rare anatectic melts trapped as glass in their protoliths and it is the composition of this glass that offers  
51 a unique insight into the behaviour of the crust in open magmatic systems and which challenges our  
52 understanding of crustal anatexis and contamination of mantle-derived magmas.

53

## 54 SAMPLES

55 Geochemical signatures of crustal xenoliths and their host lavas erupted from monogenetic centres on the  
56 Bolivian Altiplano, Central Andes form the basis of this study (Fig. 1a, b). Both centres are small volume  
57 comprising of a few flows ( $\sim 0.04 \text{ km}^3$  at Quillacas,  $\sim 0.29 \text{ km}^3$  at Pampas Aullagas), compared with the typical  
58 CVZ composite volcanoes of  $>100 \text{ km}^3$ . Sampled lavas from flows at Quillacas (1.42 Ma,  $19^\circ\text{S}, 66^\circ\text{W}$ ) and  
59 Pampas Aullagas (1.89 Ma,  $19^\circ\text{S}, 67^\circ\text{W}$ ) are andesitic to dacitic and peraluminous ( $\text{Al}_2\text{O}_3 > \text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO}$ ;

60 15.6-17.1 > 9.4-11.8). They display seriate to porphyritic textures and contain up to 35 vol. % crystals in which  
61 phenocrysts, microlites and xenocrysts are present. These lavas preserve a disequilibrium mineral assemblage  
62 evidenced by plagioclase displaying sieve textures and oscillatory zoning along with crustal xenocrysts and  
63 aggregates of metamorphic minerals. The entrained xenolith lithologies vary from almost pure quartzite to  
64 garnet-mica schists with rare granulites and several igneous lithologies including diorites and microgranites.  
65 Minerals present include quartz, plagioclase, almandine garnet, biotite, sillimanite ± cordierite ± alkali feldspar  
66 ± kyanite ± oxide minerals with accessory epidote, hercynitic spinel, monazite and zircon. Whole rock analyses  
67 of sampled lavas clearly indicates crustal contamination has occurred during petrogenesis. This is demonstrated  
68 by their extreme Sr-isotopic diversity, ranging from 0.7091-0.7169 (Fig. 1c) and with  $^{87}\text{Sr}/^{86}\text{Sr}$  correlating with  
69 indices of differentiation such as  $\text{SiO}_2$  (Fig. 1d). The upper limit of this range is one of the most radiogenic  
70 compositions to be reported for Central Andean volcanic rocks to date. Lavas erupted at Pampas Aullagas alone  
71 record 43% of the observed Sr-isotopic diversity in volcanic rocks from the entire Central Andean region (12%  
72 at Quillacas).

73 Identification of extreme isotopic heterogeneity within a single volcanic eruptive unit requires a detailed  
74 multi-sampling approach in the field otherwise the complexities of an open magmatic system will be  
75 overlooked. The entrained crustal xenoliths display an even greater range of Sr-isotopic compositions ranging  
76 from 0.7105 to 0.7368. All sample compositions are provided in the supplementary information.

77

## 78 MODELLING CRUSTAL CONTAMINATION

79 Numerous formulations aimed at evaluating and constraining the geochemical evolution in open magmatic  
80 systems have been developed over the past few decades e.g. Briquet and Lancelot, 1979; Taylor, 1980; De  
81 Paolo, 1981; Aitchison and Forrest, 1994; Spera and Bohrsen, 2001. The objective of these models is to meet  
82 the necessity for material mass balance whilst accounting for observed geochemical trends. Although a  
83 powerful petrogenetic tool, use of these models is only justifiable if the end member compositions are known  
84 i.e. those of the parental mantle-melt and those of the crustal assimilate, and in many studies at least one of  
85 those is unknown. Additionally, rates of assimilation to fractional crystallisation ( $r$ ) and partition coefficients  
86 (e.g.  $D_{\text{Sr}}$ ) need to be well constrained. The contaminated nature of the Pampas Aullagas and Quillacas lavas  
87 were investigated using the EC(AFC) (Energy Constrained Assimilation and Fractional Crystallisation) model  
88 of Spera and Bohrsen, (2001). All sampled xenoliths are potential crustal lithologies with which ascending  
89 magmas may have interacted. Choosing a suitable parental magma composition is challenging as no true basalts

90 have erupted recently in the Central Andes. Modelling was therefore carried out using a range of oceanic  
91 sources along with an older Andean primitive magma represented by a Miocene sill (Chiar Kkollu) from 60km  
92 WNW of the field area (Davidson and de Silva, 1992). This basalt (45 wt. % SiO<sub>2</sub> and 9 wt. % MgO) is more  
93 primitive than any other lava in this region of the Central Andes. The <sup>87</sup>Sr/<sup>86</sup>Sr of the Chiar Kkollu basalt  
94 (0.7041) indicates relatively little assimilation of and contamination by the continental crust and its composition  
95 may be the closest representative of a parental melt that is currently known for the region. The results are  
96 presented in Fig. 1c but offer only a number of possible solutions that model the observed geochemical trends  
97 (see supplementary information for model input parameters). Large values of r (>0.6) were required to model  
98 the isotopically enriched nature of the lavas. These high values are plausible due to the fusible nature of the  
99 meta-pelitic crust and represent 35-50% crustal assimilation which is considerably higher than ~20% as  
100 previously estimated for volcanic rocks from the Central Andean arc (Davidson and de Silva, 1992; Aitchison et  
101 al., 1995).

102

### 103 CRUSTAL ANATEXIS

104 The modelling of crustal contamination assumes that acquisition of a crustal isotopic signature involves 1)  
105 mixing of the bulk Sr-isotopic composition of the source crustal rock into an ascending magma and 2) that the  
106 composition of this crustal component remains unchanged during concurrent anatexis and contamination.

107 The dominant mechanism of anatectic melt formation in the continental crust is the incongruent melting of  
108 hydrous silicates (e.g. biotite) leaving behind a less hydrous restitic assemblage (Stevens et al., 1997). The  
109 natural occurrence of preserved anatectic melt within sampled xenoliths offers a rare insight into the primary  
110 compositions of potential crustal contaminants as well as constraints on the initial composition of crustal melts  
111 produced during orogenesis. .

112 One sample (BC93PAX12) was chosen for an in-depth geochemical study. Data and details of analytical  
113 methods and standards run throughout the course of this study are provided in the supplementary information.  
114 The quenched glass is vesiculated, indicating that decompression occurred during and/or after melting (i.e. that  
115 melting occurred at depth rather than on eruption). Euhedral hercynitic spinel (<100µm) is present within the  
116 melt pools. The presence of this phase has previously been shown to be a common product of the incongruent  
117 breakdown of biotite (e.g. Cesare, 2000). All analysed glass is peraluminous in nature (1.77 < A.S.I < 3.00,  
118 average 2.08), potassic (up to 5.62 wt. %) and exhibits a restricted range of SiO<sub>2</sub> from 70 to 75 wt. %. The  
119 minimum temperature of melting is constrained to >800°C given the coexistence of quartz and hercynitic spinel



120 (Montel et al., 1986). Experiments have shown that crustal melting will typically begin at 780-830°C through  
121 the incongruent breakdown of biotite (controlled by Mg number, René et al., 2008) with total biotite breakdown  
122 at ~975°C (Stevens et al., 1997). Analysed glass shows enrichment in LREE (Ba, Rb, Fig. 2) and depletion in  
123 the HREE that is retained in residual garnet (Fig. 2). The significant Nb depletion recorded in the glass is  
124 inferred to represent the stability of anatase, a metastable TiO<sub>2</sub> polymorph which is present as acicular crystals  
125 (<200µm). The occurrence of anatase (as opposed to rutile, the more common form of TiO<sub>2</sub>) is consistent with  
126 the experimental observation that anatase forms under rapid cooling conditions (i.e. quenching) whereas rutile  
127 will crystallise under near-equilibrium solidification conditions (Li and Ishigaki, 2002).

128 Analysis of the Sr-isotopic composition of the quenched anatectic melt (Fig. 3a) reveals extreme variability  
129 over short length scales and significant isotopic disequilibrium between the melt and its source (Fig. 3b).  
130 Sampled glass ranges from 0.7164 to 0.7276 which is more radiogenic than any of the host lavas and associated  
131 groundmass glass. The lower end of this range is similar to that of the bulk source xenolith (0.7173). The higher  
132 ratios extend beyond any Sr-isotopic compositions recorded by Central Andean volcanic rocks. The crustal  
133 signature inferred from the Sr-isotopic composition of volcanic rocks at the surface provides little (if any)  
134 information about how it got there nor does it provide any information or constraints on the nature of the  
135 contaminant at depth. It is generally accepted that major and trace element abundances of melts from silicate  
136 rocks change as melting progresses. Isotope ratios, however, are generally taken to reflect those of the source  
137 rock, because it is understood that diffusive equilibrium at the high temperatures of melting is capable of  
138 “keeping up” with the melting process. Indeed much of our understanding of isotopically defined mantle  
139 reservoirs is predicated on this premise (Hofmann and Hart, 1978). However, if diffusion cannot keep pace with  
140 melting then isotopic compositions will vary with the contributions of Sr from the individual phases present  
141 within the source (Rushmer and Knesel, 2010). In a magmatic plumbing system where crustal xenoliths are  
142 entrained and assimilated in an ascending magma, isotopic disequilibrium melting is likely, and has been  
143 documented widely (Al-Rawi and Carmichael, 1967; Pushkar and Stoeser, 1975; Philpotts and Asher, 1993;  
144 Hammouda et al., 1994; Hammouda et al., 1996; Knesel and Davidson, 1996; Knesel and Davidson, 1999;  
145 Knesel and Davidson, 2002).

146 Old crustal rocks containing phases with variable Rb/Sr will be characterised by Sr isotopic heterogeneity (it  
147 is this heterogeneity relative to Rb/Sr which is the basis for Sr isochron dating). Melting will typically begin  
148 with preferential breakdown of high Rb/Sr hydrous phases such as biotite, producing an initial melt with a  
149 higher <sup>87</sup>Sr/<sup>86</sup>Sr than the bulk source. If melting progresses relatively rapidly (so that diffusive equilibration of

150  $^{87}\text{Sr}/^{86}\text{Sr}$  does not occur), additional phases contribute Sr with different  $^{87}\text{Sr}/^{86}\text{Sr}$  and the composition of the melt  
151 will change as shown schematically in Fig. 4. Feldspar, for instance, has a lower Rb/Sr and will consequently  
152 contribute less radiogenic Sr.

153 The Sr isotopic compositions of anatectic melts that contaminate ascending magmas is, therefore, governed by  
154 (1) the stoichiometry of melting reactions which controls the changing proportions of phases entering the melt;  
155 (2) the rates at which heating and melting occur which define the balance between melt production and the  
156 capacity to equilibrate diffusively; (3) the composition of phases consumed, which dictates, in conjunction with  
157 (1), the mass balance of Sr in the melt at any given time; (4) the grain size of phases which constrains the length  
158 scales of diffusive equilibration; and (5) the timescales of melt segregation (controlled by the permeability of the  
159 (molten) source rock and thus grain-scale distribution of the melts, Laporte, 1994). The majority of these  
160 factors are left unaccounted for in the current petrogenetic models.

161

## 162 IMPLICATIONS FOR MODELLING NATURAL SYSTEMS

163 The contaminated signatures of volcanic rocks can be reproduced by various model calculations (e.g. Fig. 1c)  
164 however it should be noted that these solutions are unlikely to provide a realistic quantification of  
165 contamination. In each model,  $r$  and  $D_{\text{Sr}}$  were assumed to remain constant although in reality they may change  
166 as differentiation progresses (Roberts and Clemens, 1995). When investigating the petrogenesis of a  
167 contaminated volcanic rock suite through AFC modelling the assumption that each erupted unit has interacted  
168 with 1) the same crustal lithology and 2) to the same degree, cannot be confidently made. This is demonstrated  
169 by the geochemically diverse nature of the crustal xenoliths entrained within lavas at Pampas Aullagas and  
170 Quillacas, although the sampled xenoliths are unlikely to represent the full extent of the compositional diversity  
171 that exists throughout the 70km thick Central Andean continental crust. It should therefore be unsurprising that  
172 erupted volcanic units exhibit highly variable, crustal derived radiogenic Sr-isotopic signatures. A multi-stage,  
173 multi-depth plumbing system is likely to exist at depth beneath the centres at Pampas Aullagas and Quillacas  
174 where ascending magmas interact with and are contaminated by numerous crustal lithologies as has previously  
175 been suggested for larger volcanic edifices (e.g. Davidson and Wilson, 1989).

176 Precise and accurate quantification of the contamination process demands knowledge and understanding of the  
177 behaviour of the systems components. The contaminated nature of a suite of volcanic rocks can in principle, be  
178 modelled using current petrogenetic models (e.g. Spera and Bohron, 2001) where the crustal component is  
179 constrained by the bulk composition of a sample from the (local) underlying basement and/or a partial melt

180 thereof. Our observations suggest that such approaches should be used with caution and with a thorough  
181 understanding of their limitations.

182 There is significant danger in aiming to identify a simple genetic linkage between Sr-isotopic signatures of  
183 contaminated volcanic rock suites and sampled (potential) crustal contaminants such as attempted in Fig. 1c and  
184 consistently in crustal contamination studies (e.g. Guzmán et al., 2011). As analysis of anatectic melt has  
185 shown, significant isotopic disequilibrium exists between product and protolith (Fig. 3b). This has important  
186 ramifications for current petrogenetic models which assume a constant isotopic composition for the contaminant  
187 (either as a bulk whole rock value or an equilibrium melt thereof). Not only is melting likely to be non modal  
188 but anatectic melts will be out of Sr-isotopic equilibrium with their source on the sub-mm scale. Furthermore,  
189 the degree of disequilibrium will be heterogeneous throughout the melt as the  $^{87}\text{Sr}/^{86}\text{Sr}$  compositions will be  
190 controlled by the relative proportions of the Rb/Sr phases melting at any given point (Fig. 4). The observation  
191 that disequilibrium melts can be produced by the incongruent breakdown of variable Rb/Sr phases within the  
192 crust supports the explanation regarding the origin of the observed Sr-isotopic disequilibrium between a magma  
193 and crystals in an open magmatic system where the composition of the magma from which the crystals are  
194 crystallising changes as anatexis proceeds (Duffield and Ruiz, 1998). Further complexity is added when the  
195 degree of this heterogeneity through time (i.e. as anatexis proceeds) is considered as a function of the rate of  
196 breakdown of these Rb/Sr-bearing phases. A crustal partial melt is not necessarily a simple equilibrium, modal  
197 melt, but may be heterogeneous in both space and time (with respect to Sr-isotopes). The process of  
198 contamination is complicated further if partial melts from numerous crustal lithologies are incorporated into the  
199 same differentiating magma body. These initially highly radiogenic melts are likely to be diluted by continuous  
200 melting of less radiogenic phases (Fig. 4). The continuation of anatexis though time acts to dilute the early  
201 radiogenically enriched melt phase. Further mixing with a less silica-rich melt (e.g. a recharging mantle-derived  
202 magma) may also act to dilute the enriched crustal signature. The observed signature is therefore an average of  
203 the entire contamination process and masks the detail and complexities involved in how a crustal signature is  
204 acquired.

205 Simplistically, the process of crustal contamination can be viewed as a simple and efficient binary mixing  
206 process whereby a new composition is generated as a result of the interaction of two geochemically distinct end  
207 members. In reality, the geochemical consequences of crustal anatexis are complex, the process of crustal  
208 anatexis is progressive and anatectic melts are not simple partial melts of a source.

209 *In-situ* analysis of anatectic melts associated with their crustal source reveals for the first time the absolute  
210 geochemical composition of natural contaminant melts and therefore the potential geochemical signatures that  
211 may be derived from them i.e. a relatively high  $^{87}\text{Sr}/^{86}\text{Sr}$  vs. a relatively low  $^{87}\text{Sr}/^{86}\text{Sr}$  contaminant as controlled  
212 by the Rb/Sr of the phases incongruently breaking down. This approach highlights the need for a greater  
213 appreciation of the complexities inherent to crustal anatexis and the geochemical consequences for modelling  
214 the contamination of volcanic rock suites. Hence existing models investigating the petrogenesis of open  
215 magmatic systems, combined with microanalysis of potential contaminants will lead to improved quantitative  
216 characterisation of the contaminant and the crusts' relative influence on the geochemical signature observed at  
217 the surface.

218 Undoubtedly AFC models are useful petrogenetic tools for investigating crustal contributions to mantle-  
219 derived magmas however our study highlights the importance of small-scale, microscopic studies in order to  
220 improve our understanding of the interaction and transfer between Earth's reservoirs.

221

222

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229 preparation on the ICPMS. Sarah Collins and Kathy Mather provided useful comments on earlier drafts of this  
230 manuscript.

231

232

## 233 FIGURE CAPTIONS

234

235 Figure 1

236 A. Location map of the Central Volcanic Zone (CVZ; 14°S to 28°S) of the Andean Cordillera, South America.  
237 The Northern (NVZ) and Southern (SVZ) Volcanic Zones are also shown (adapted from de Silva, 1989). The  
238 area of study is outlined.

239 B. Location of monogenetic mafic centres at Pampas Aullagas and Quillacas on the Bolivian Altiplano.

240 C. Graph showing the Sr-isotopic diversity exhibited by sampled lavas from a single volcanic centre. Modelled  
241 EC-AFC curves (after Spera and Bohrsen, 2001) for the contaminated nature of the lavas erupted at Pampas  
242 Aullagas and Quillacas are also shown. The Miocene basalt of Chiar Kkollu was used as a mantle end-member  
243 in all models ( $^{87}\text{Sr}/^{86}\text{Sr}$ : 0.7041; Sr: 945ppm) and nine sampled crustal xenoliths were used as potential crustal  
244 contaminants ( $^{87}\text{Sr}/^{86}\text{Sr}$  0.7105-0.7368; Sr: 19-416ppm). The initial path of the EC-AFC curves are flat which  
245 reflects the time the crust takes to rise from its initial temperature to its solidus. The end points of each curve  
246 depicts the point at which the temperature of the melt (in the magma body) is equal to the equilibration  
247 temperature (Spera and Bohrsen, 2001). Solutions presented are those which best modelled the data.  
248 Compositions of crustal end members and model parameters for each numbered curve (1-13) are provided in the  
249 supplementary information.

250 D. Graph showing the increase of  $^{87}\text{Sr}/^{86}\text{Sr}$  with increasing  $\text{SiO}_2$  as evidence for assimilation and fractional  
251 crystallisation during the petrogenesis of Pampas Aullagas and Quillacas lavas (symbols as in Fig. 1c).

252

253 Figure 2

254 Trace element composition of sampled glass normalised to bulk xenolith BC93PAX12. The pattern reflects the  
255 mineralogy of the source whereby elements which are compatible in phases present in the xenoliths and which  
256 haven't melted are depleted (e.g. Y in garnet) and those which correspond to biotite melting are enriched (e.g.  
257 the LREE). For discussion see text.

258

259 Figure 3

260 A. Sketch depicting quenched glass (black) and unmelted crystalline restite (white) of BC93PAX12. Restite  
261 constitutes quartz, biotite, plagioclase, garnet and minor opaque phases. The sampled areas are also highlighted  
262 and correspond to the sample numbers in Table 1.

263 B. Sr-isotopic disequilibrium between anatectic melt and bulk source. Glass compositions are age corrected for  
264 the Pliocene age of lava eruption.

265

266 Figure 4

267 Hypothetical evolution of the Sr-isotopic composition of an anatectic melt. Crustal anatexis has been shown to  
268 commence with biotite melting. During the time which this is the only phase breaking down, the  $^{87}\text{Sr}/^{86}\text{Sr}$

269 composition of the anatectic melt is controlled only by biotite (Bt, controlled by the Rb/Sr). As melting  
270 continues, other Rb/Sr bearing phases begin to melt and contribute to the  $^{87}\text{Sr}/^{86}\text{Sr}$  of the anatectic melt e.g.  
271 plagioclase (Plg) and alkali feldspar (Ksp). As the proportions of these phases change with time, so too does the  
272  $^{87}\text{Sr}/^{86}\text{Sr}$  of the contaminating crustal melt. Starting compositions of mineral phases are taken from Knesel and  
273 Davidson, 2002.

274

275 Table 1

276 Trace element and Sr-isotopic compositions of BC93PAX12 and sampled glass.  $^{87}\text{Sr}/^{86}\text{Sr}_i$  corrected for  
277 Pliocene ages of lava eruption. Elemental concentrations are given in ppm unless stated otherwise.

278

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350

351

352



Table 1  
 Width: 6.4275cm  
 Height: 4.8486cm

	whole rock	glass						
	BC93PAX12	1	2	3	4	5	6	bulk
<b>Ba</b>	138.4	357.1	563.6	520.5	1893.0	699.2	146.5	696.7
<b>Rb</b>	27.3	101.8	172.2	178.4	226.6	236.1	84.3	166.7
<b>Th</b>	7.3	2.2	2.2	2.5	4.7	3.8	4.6	3.3
<b>U</b>	1.4	0.8	1.4	1.3	2.0	1.6	2.2	1.5
<b>Nb</b>	17.1	4.0	1.5	1.5	4.0	2.6	4.6	3.0
<b>La</b>	22.4	9.0	10.8	10.7	21.0	15.0	14.9	13.6
<b>Ce</b>	46.0	20.7	30.4	29.9	49.6	37.4	66.8	39.1
<b>Sr</b>	18.5	34.7	56.3	32.3	107.2	37.1	37.2	50.8
<b>Nd</b>	22.8	12.2	15.4	16.3	26.9	21.4	18.0	18.4
<b>Sm</b>	4.7	2.9	3.9	4.0	6.2	5.3	3.5	4.3
<b>Zr</b>	32.8	54.9	112.1	103.8	135.2	119.1	89.7	102.5
<b>Hf</b>	1.1	1.2	2.9	2.6	3.2	2.9	2.2	2.5
<b>Ti</b>	0.3 (wt %)	0.3	0.3	0.3	0.5	0.4	0.3	0.3
<b>Tb</b>	0.8	0.4	-	0.5	0.9	-	0.5	0.6
<b>Y</b>	30.2	7.6	9.8	11.0	19.6	16.7	21.0	14.3
<b>Yb</b>	5.7	0.3	0.4	0.5	0.7	0.7	1.8	0.7
<sup>87</sup> Sr/ <sup>86</sup> Sr	0.7173	0.7176	0.7209	0.7252	0.7246	0.7281	0.7166	-
<sup>87</sup> Sr/ <sup>86</sup> Sn	-	0.7174	0.7207	0.7248	0.7244	0.7276	0.7164	0.7223

Fig. 1  
Width: 6.5161cm  
Height: 11.7837cm

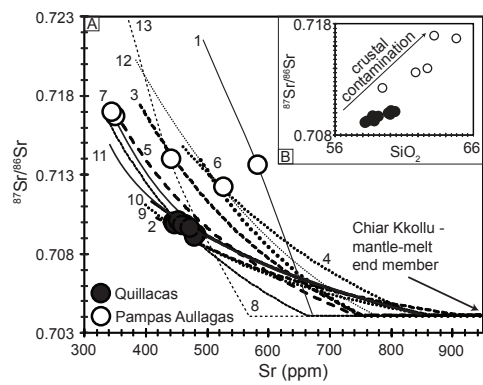


Fig. 2  
Width: 6.3796cm  
Height: 4.9200cm

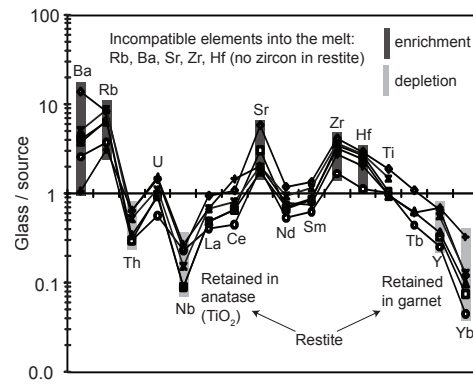


Fig. 3  
Width: 6.3975cm  
Height: 10.3717cm

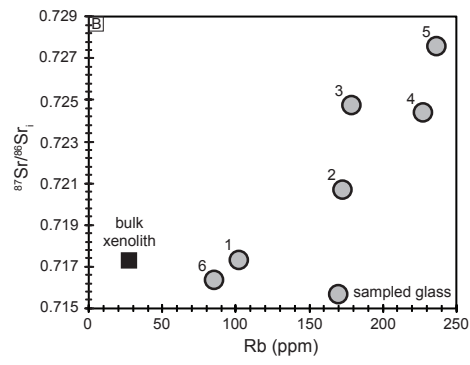
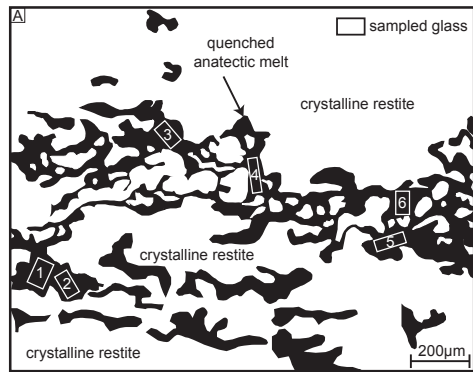
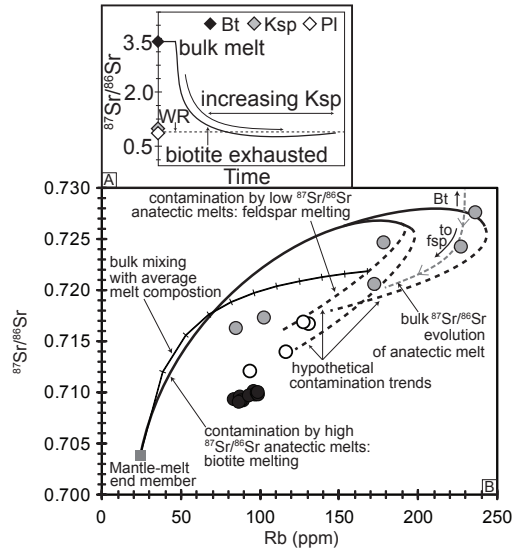


Fig. 4  
Width: 6.3975cm  
Height: 7.4923cm



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