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Assimilation, differentiation, and thickening during formation of arc crust in space and time: The Jurassic Bonanza arc, Vancouver Island, Canada

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1 Assimilation, differentiation and thickening during formation of

2 arc crust in space and time: the Jurassic Bonanza arc, Vancouver

3 Island, Canada

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9

10 **ABSTRACT**

11   Continental arcs and island arcs, eventually accreted to continental margins, are thought

12 to have been the locus of continental growth since at least the Proterozoic eon. The Jurassic

13 Bonanza arc, part of the Wrangellia terrane on Vancouver Island, British Columbia, exposes the

14 stratigraphy of an island arc emplaced between 203 and 164 Ma on a thick pre-existing substrate

15 of non-continental origin. We measured the bulk major and trace element geochemistry, Rb-Sr

16 and Sm-Nd isotope compositions of 18 plutonic samples to establish if differentiation involved

17 contamination of the Bonanza arc magmas by the pre-Jurassic basement rocks. The $^{87}Sr/^{88}Sr$ and

18 $^{143}Nd/^{144}Nd$ isotope ratios of the plutonic rocks at 180 Ma vary from 0.70253 – 0.7066 and

19 0.512594 – 0.512717, respectively. Assimilation-Fractional Crystallization modeling using trace

20 element concentration and Nd and Sr isotope ratios indicate that contamination by a Devonian

21 island arc in the Wrangellia basement is less than 10%. Rare earth element modeling indicates

22 that the observed geochemistry of Bonanza arc rocks represents two lineages, each defined by

23   two-stages of fractionation that implicate removal of garnet, varying in modal proportion up to

24   15%. Garnet-bearing cumulate rocks have not been reported from the Bonanza arc, but their

25   inference is consistent with our crustal thickness estimates from geological mapping and

26   geobarometry indicating that the arc grew to at least 23 km total thickness. The inference of

27   garnet-bearing cumulate rocks in the Bonanaza arc is a previously unsuspected similarity with

28   the coeval Talkeetna arc (Alaska), where garnet-bearing cumulate rocks have been described.

29   Geochronological data from the Bonanza arc shows a continuum in plutonic ages from 164 to

30   203 Ma whereas the volcanic rocks show a bimodal age distribution over the same span of time

31   with modes at 171 and 198 Ma. We argue that the bimodal volcanic age distribution is likely due

32   to sampling or preservation bias. East-west separation of regions of young and old volcanism

33   could be produced by roll-back of a west-dipping slab, fore-arc erosion by an east-dipping slab,

34   or juxtaposition of two arcs along arc-parallel strike-slip faults.

35

36   **INTRODUCTION**

37   The continental crust is thought to be broadly andesitic in composition and its lower

38   density compared to the underlying mantle has resulted in its preservation over geologic time

39   (Taylor, 1977; Rudnick, 1995; Rudnick and Gao, 2014). Today, andesites that are similar in

40   composition to the bulk continental crust are formed in convergent margin settings (Arculus and

41   Johnson, 1978) leading to the hypothesis that continental crust is being produced at island arcs

42   and continental arcs (Condie, 1989; Rudnick, 1995). As oceanic plates subduct, island arcs

43   formed thereupon are accreted to the margins of overriding continents (e.g. Condie, 1990). Such

44   tectonic accretion has exposed the complete stratigraphy of some ancient arcs allowing their bulk

45   chemistry to be assessed – for example, the Talkeetna arc in Alaska (DeBari and Sleep, 1991)

46 and the Kohistan arc in Pakistan (Jagoutz and Schmidt, 2012). On the basis of these mass-

47 balanced average compositions it is generally accepted that the bulk chemistry of arcs, and

48 therefore their parental melt, is basaltic (DeBari and Sleep, 1991) and that arcs are refined to the

49 andesitic character of the continental crust by some subsequent process. Various hypotheses have

50 been presented to produce andesitic crust at convergent margins, including assimilation by the

51 primary arc magma of pre-existing continental crust (e.g. Hildreth and Moorbath, 1988; Annen et

52 al., 2006), melting of the subducting slab (Defant and Drummond, 1990; Kelemen et al., 2014),

53 andesite magma formation by mantle melting fluxed by subduction-related fluids (Rapp et al.,

54 1999; Grove et al., 2002), garnet fractionation (Macpherson, 2008) or granite formation by

55 amphibole biotite gabbro fractionation from medium to high-K basalt (Sisson et al., 2005).

56 Density sorting by relamination of subducted sediments at the base of the continental crust

57 (Hacker et al., 2011) and delamination or erosion of dense mafic lower crust (Bird, 1979; von

58 Huene and Scholl, 1991; Kay and Mahlburg-Kay, 1991) can further refine the bulk composition

59 of arcs and is thought to be why the Kohistan arc has an andesitic bulk composition (Jagoutz and

60 Schmidt, 2012). Delamination of the dense lower crust may also result in the formation of the

61 Continental Moho (Jagoutz and Behn, 2013).

62 As an arc thickens with time, post-segregation magma differentiation may proceed at

63 progressively deeper levels. The effect of higher-pressure fractionation is observed in arc

64 volcanic rocks as a progressive decrease in Yb, Fe and Cu content with increasing crustal

65 thickness (Jagoutz, 2010; Chiaradia, 2013). Jagoutz (2010) attributes Yb depletion to the

66 stabilization of garnet, in which Yb is highly compatible, in the fractionating assemblage as the

67 crust thickens. Chiaradia (2013) attributed the decrease in Fe and Cu to the early crystallization

68 of magnetite in magmas under higher pressure resulting in the crystallization of sulfides (Jenner

69 et al., 2010), thus decreasing the amount of Fe and Cu in the liquid.

70   A thickening arc may also provide greater opportunity for assimilation of pre-existing

71 crust by the arc magmas at virtually all levels of the arc. The signature for assimilation using

72 radiogenic isotopes is quite notable in continental arcs, but lesser so in oceanic arcs because pre-

73 existing, isotopically evolved crustal material is typically absent or less voluminous in oceanic

74 crust (Hildreth and Moorbath, 1988). The Jurassic Bonanza arc on Vancouver Island is unique in

75 that it is traditionally interpreted as an island arc, yet formed upon a Devonian–Triassic arc-

76 oceanic plateau-carbonate succession – in other words a pre-existing crust that was formed in the

77 oceanic realm. The Bonanza arc thus provides a snapshot of the evolution of an island arc being

78 built on thick non-continental crust. In the present study we report new whole rock major and

79 trace element geochemistry plus Sr and Nd isotopic compositions for samples collected from a

80 comprehensive geographic area of Bonanza arc plutonic rocks on Vancouver Island. We

81 examine the Sr and Nd isotopic variations of the Bonanza arc samples, including previously

82 published data, to determine the degree of crustal contamination. Using major and trace element

83 compositions of Bonanza arc samples we model the likely fractionating assemblages that could

84 produce the observed geochemical variations and compare these predictions with constraints

85 from field mapping. Finally, we examine published zircon U-Pb and hornblede Ar-Ar

86 geochronological data for the Bonanza arc to examine how the arc may have evolved in space

87 and time.

88

89 **REGIONAL GEOLOGY**

90   The Bonanza arc was emplaced between 203 and 164 Ma, as an island arc on a substrate

91   comprising the Devonian Sicker arc, the carbonates of the Buttle Lake Group, the Triassic

92   Karmutsen plateau basalt, Quatsino carbonates and the late Triassic clastic Parson Bay formation

93   (Fig. 1a, b). Deltaic and marine conglomerates, sandstones, siltstone and shale of the Cretaceous

94   Nanaimo Group (Muller, 1977) overlie the Bonanza arc rocks. The Bonanza arc is

95   geochronologically correlative to the Jurassic Talkeetna arc in Alaska (DeBari et al., 1999) but

96   there are some important distinctions. In contrast to the Bonanza arc, the basement of the

97   Talkeetna arc is not exposed and the latter arc may have developed directly on oceanic crust

98   (DeBari and Sleep, 1991). Additionally, garnet-bearing cumulate rocks are present in the

99   Talkeetna arc section but not in the Bonanza arc (DeBari et al., 1999).

100   The Bonanza arc has traditionally been divided into a volcanic unit and two plutonic

101   units, namely the Island Plutonic Suite and Westcoast Complex (Fig. 1; Muller, 1977). The

102   volcanic unit comprises flows, breccias and tuffs of basalt, andesite, dacite and rhyolite. The

103   Island Plutonic Suite is made up of plutons of quartz diorite, granodiorite, quartz monzonite and

104   tonalite, which are in sharp contact with the Bonanza volcanic unit and the older Karmutsen

105   Formation. Geobarometry indicates a restricted and generally uniform depth of equilibration of 2

106   – 10 km for the Island Plutonic Suite (Canil et al., 2010). The Westcoast Complex is composed

107   of hornblendites and gabbroic to granodioritic rocks occasionally in contact with rocks of the

108   Devonian Sicker arc (DeBari et al., 1999). The Westcoast Complex shows equilibration depths

109   of 10 – 17 km using Al-in-hornblende geobarometry, but those results have high uncertainty

110   (Canil et al., 2010). Amphibole-bearing ultramafic cumulate rocks occur as schlieren and layers

111   in intermediate plutonic units of the Bonanza arc near Port Renfrew and Tahsis (Fig. 1 -

112   Larocque, 2008; Fecova, 2009; Larocque and Canil, 2010). Al-in-hornblende barometry

113   (Larocque and Canil, 2010) indicates that the ultramafic rocks from the Port Renfrew area

114   equilibrated at depths of 15 – 25 km, again with high uncertainty.

115   The Island Plutonic Suite has traditionally been described as being unfoliated and more

116   felsic than the Westcoast Complex (Muller, 1977). However, this distinction has proven difficult

117   to apply in the field and can be imprecise as both units can overlap considerably in bulk

118   chemistry (Canil et al., 2013). Hereafter we avoid confusion and refer to samples of the Island

119   Plutonic Suite and Westcoast Complex collectively as the Bonanza arc intrusive rocks.

120

121   **METHODS**

122   We analyzed a suite of 18 Bonanza arc intrusive rocks sampled across Vancouver Island

123   (Fig. 1). After trimming off weathered surfaces with a diamond saw, samples were crushed into

124   cm-sized fragments in a steel jaw crusher and ground to a fine powder in an agate ball mill.

125   Major and trace element abundances (Table 1) were determined using Inductively Coupled

126   Plasma Optical Emission Spectrometry (ICP-OES) and Inductively Coupled Plasma Mass

127   Spectrometry (ICP-MS), respectively, at Activation Laboratories Ltd. (Ancaster, Ontario,

128   Canada). Analytical results for certified reference materials were within 3% of the certified

129   values for all elements, except V, Cu, Ce, Pr, Ho, Er, Tm and Nb (within 8%). The Rb-Sr and

130   Sm-Nd isotopic ratios of the 18 samples and two additional samples (JL06-054 and DC06-047

131   from Larocque and Canil, 2010; Fig. 1c) were measured at the Radiogenic Isotope Facility at the

132   University of Alberta, Edmonton, Canada (Table 2). Aliquots of powdered samples were

133   dissolved and spiked, followed by chromatographic separation of Rb, Sr, Sm and Nd using ion

134   exchange columns. The isotopic ratios of Sr, Sm and Nd in each sample was determined by multi

135   collector ICP-MS. Rubidium isotopic composition was determined using Thermal Ionization

136 Mass Spectrometry. Specific details of Rb, Sr, Sm and Nd separation and analytical procedures

137 can be found in Creaser et al. (1997, 2004).

138 Whole rock chemical and isotopic analyses from this study were combined with data

139 from all previous work (Larocque, 2008; Larocque and Canil, 2010; Fecova, 2009; Paulson,

140 2010; DeBari et al., 1999; Andrew et al., 1991; Isachsen, 1987; Samson et al., 1990). The

141 geochronological database that we use was compiled from all available zircon U-Pb and igneous

142 hornblende Ar-Ar ages (Isachsen, 1987; DeBari et al. 1999; Breitsprecher and Mortensen, 2004;

143 Fecova, 2009; Nixon, 2011a-e; Canil et al., 2012).

144

145 **RESULTS**

146 The concentration of SiO_2 in the Bonanza arc samples analyzed in the present study

147 varies from 46.7 to 73.8 wt.% and is negatively correlated with FeO^T, MgO and CaO (Fig. 2) but

148 is positively correlated with Na_2O and K_2O. All newly analyzed samples in this study are within

149 the range of variation of Bonanza arc intrusive and volcanic rocks analyzed in previous work

150 (Fig. 2). Across all the Bonanza arc rocks, P_2O_5, Al_2O_3 and TiO_2 show an inflection from

151 positive to negative correlation at ~50 wt.% SiO_2 (Fig. 2). Compared to the intrusive rocks, the

152 volcanic samples show generally lower SiO_2 concentration (<60 wt.%). The Bonanza arc

153 samples show similar ranges of major element concentrations as the Talkeetna and Kohistan

154 rocks (Fig. 2).

155 All samples, except JL06-114, are similarly enriched in the large ion lithophile elements

156 (Rb, Ba, K, Pb and Sr) relative to MORB and show sharply negative Nb, Ta and Ti anomalies

157 (Fig. 3a). Chondrite-normalized (Fig. 3b) REE patterns for the samples in this study all show

158 light REE (La to Sm) enrichment relative to the middle and heavy REE (Eu to Lu). The intrusive

159 rocks, except JL06-114, overlap the volcanic rocks in all trace element abundances (Fig. 3).

160 Sample JL06-114 is a layered gabbro (Larocque, 2008) and has major and trace element

161 concentrations, similar to the cumulate rocks from Port Renfrew (Fig. 2; Larocque and Canil,

162 2010). Compared to rocks from the Talkeetna and Kohistan arcs, the Bonanza arc rocks show

163 restricted range of trace element abundances (Fig. 3c, d).

164 The samples we analyzed (Fig. 1c) show a wide range in present-day Sr isotope ratios

165 (Table 2): $^{87}Rb/^{86}Sr$ from 0.0146 to 4.2833, and present day $^{87}Sr/^{88}Sr$ from 0.70365 to 0.71386.

166 The Sr isotope ratios of samples in this study are within the range of those reported in previous

167 work (Isachsen, 1987; Samson et al.; 1990; Andrew et al., 1991) except for JL06-034 and JL06-

168 054, which are granites with higher Sr isotope ratios. Present day $^{147}Sm/^{144}Nd$ varies from 0.1048

169 to 0.1758 and present day $^{143}Nd/^{144}Nd$ varies from 0.512744 to 0.512898 in the samples we

170 analyzed, within the range reported in previous studies.

171 Our compilation of geochronological data shows that the Bonanza arc intrusive rocks

172 have ages between 164 and 203 Ma (Fig. 1b). The ages for volcanic rocks have an overall range

173 similar to that of the intrusive rocks but show a distinctly bimodal age distribution with peaks at

174 171 and 198 Ma. We note that intrusive rocks that have been dated are geographically

175 widespread across Vancouver Island, whereas the volcanic ages come mostly from samples

176 collected on northern Vancouver Island (Fig. 1a).

177

178 **DISCUSSION**

179 The effect of crustal thickness on the chemistry of arc magmas has a long history of

180 study. In a classic paper, Miyashiro (1974) observed that as arc thickness increases, island arc

181 volcanic rock series shift from tholeiitic to calc-alkaline. In a compilation of data from >50 arc

182   volcanoes, Mantle and Collins (2008) observed that trace elements ratios such as Ce/Y, La/Yb

183   and Zr/Y increase in erupted volcanic rocks as depth to the Moho increases for those arcs.

184   Jagoutz (2010) compiled data from 12 arcs and highlighted a decrease in Yb concentration in arc

185   rocks as crustal thickness increased. He postulated that this trend was due to the fractionation of

186   garnet, a phase in which Yb is highly compatible, and was causally related to arc thickness, as

187   garnet is only stable on the liquidus of arc magmas at depths greater than 24 km (0.8 GPa).

188   Contrary to Jagoutz (2010), Mantle and Collins (2008) indicated that the HREE concentration,

189   using Y as a proxy, did not decrease with arc thickness. Chiaradia (2013) compiled data from 23

190   Quaternary volcanic arcs and observed that the Fe and Cu content of arc volcanic series are on

191   average lower in thick arcs than in thin arcs and attributed this to the early fractionation of

192   magnetite and sulfides beneath thick arcs.

193   We test whether chemical changes observed in the Bonanza arc rocks can be attributed to

194   changing fractionating conditions in the arc. In particular, the combined thickness of the

195   Bonanza arc and its substrate may have exceeded 24 km over the ~45 Myr history of the arc

196   leading to the stabilization of garnet as a fractionating phase in the lower crust (Müntener and

197   Ulmer, 2006), thus affecting the chemistry of the magmas that ascended to higher levels. We first

198   test if assimilation of older crustal material occurred and affected the trace element chemistry of

199   the Bonanza arc rocks and then compare the effect of different modelled fractionating

200   assemblages on the liquid REE concentration. Finally, we examine the spatial distribution and

201   timing of magmatism in the Bonanza arc to determine how the arc might have evolved with time.

202

203   **Assimilation of pre-existing crust in Wrangellia**

204   During their ascent through the crust, the Bonanza arc magmas may have assimilated pre-

205   existing crust of the Wrangellia terrane, thus obscuring the chemical signature of primary

206   processes (e.g. fractional crystallization) that controlled the chemistry of magmas in the arc. To

207   assess the extent of assimilation that the Bonanza arc magmas experienced, we examine the

208        $^{87}Sr/^{86}Sr_{180\ Ma}$ and $\varepsilon Nd_{180\ Ma}$ of the samples analyzed in this study (Table 2) and reported in the

209   literature. The effect of fluid alteration on Rb and Sr by post-emplacement metamorphism is

210   minor as <10% secondary minerals by mode are observed in the Bonanza arc rocks (Larocque

211   and Canil, 2010). We also minimized the geochemical effect of weathering by removing

212   weathered surfaces and fractures from samples with a diamond saw prior to crushing and

213   pulverizing the samples for analysis.

214   Assimilation of older, more evolved crustal material by a mantle-derived magma

215   increases $^{87}Sr/^{86}Sr_{initial}$, lowers $\varepsilon Nd_{initial}$ and increases the concentration of Sr and Nd, both

216   incompatible elements, in the melt. The combined effect of increasing concentration and

217   changing isotopic ratios caused by assimilation produces a positive correlation between

218        $^{87}Sr/^{86}Sr_{initial}$ and Sr concentration, and a negative correlation between $\varepsilon Nd_{initial}$ and Nd

219   concentration. The Bonanza arc data show no correlation between isotopic ratios of Sr and Nd as

220   element concentration increases (Fig. 4). We argue that this indicates that there has been little

221   assimilation of older crustal material by Bonanza arc magmas.

222   To more quantitatively assess the degree of assimilation experienced by the Bonanza arc

223   magmas, we performed assimilation-fractional crystallization (AFC) calculations (DePaolo,

224   1981). We use a primary, uncontaminated melt with Nd and Sr concentration and isotopic ratios

225   similar to basalt extracted from the Depleted Mantle at 180 Ma (Workman and Hart, 2005; White

226   and Klein, 2014). We used two different contaminants in the AFC model calculations (Fig. 4):

227   the average of all the Devonian Sicker arc data (grey circle, solid lines) and the most isotopically

228   evolved Sicker arc sample (black circle, dashed lines). The latter provides the greatest isotopic

229   difference between melt and contaminant thereby indicating the minimum degree of

230   contamination. As liquid compositions will change with contamination, we avoid uncertainties

231   arising from resulting variations in mineral-liquid partition coefficients (D) by displaying the

232   results of the AFC models (Fig. 4) for a range of D values from very incompatible (D = 0.05) to

233   neutral (D = 1.00). Although important to assess, we do not consider a Karmutsen Formation

234   contaminant in the AFC models as those rocks have similar Nd and Sr concentration and isotopic

235   ratios as the Bonanza arc samples (Fig. 4) and AFC calculations would not yield a detectable

236   signal.

237   AFC calculations using the average Sicker arc contaminant indicate that a contaminant-

238   melt ratio between 0.07 and 0.15 is sufficient to explain all the Sr variation that we observe in the

239   Bonanza arc (solid lines; Fig. 4a–c). A model using the most isotopically evolved Sicker arc

240   sample (dashed lines; Fig. 4a–c) yields a maximum contaminant-melt ratio of 0.07. The AFC

241   calculation results for Nd (Fig. 4d–f) are equivocal in the case of both average and extreme

242   Sicker arc contaminants, indicating contaminant-melt ratios between 0.07 and 0.30.

243   Eight Bonanza arc rocks that plot to the left of the D = 1.00 curve using the extreme

244   Sicker arc contaminant in Figures 4d–f have lower Nd concentration than expected from the

245   AFC model. Five of these samples are mafic/ultramafic cumulates and low Nd concentration is

246   expected for such rocks. Although the precise reason that the remaining three samples (two

247   granodiorites, one monzodiorite) have low Nd concentrations is unclear, it is possible that those

248   magmas had accumulated early-formed phases with low Nd concentration.

249   On the basis of our AFC models we argue that Bonanza arc magmas have undergone

250   minimal assimilation (contaminant-melt ratio <0.10) of Devonian Sicker arc material.

251   Assimilation of Karmutsen Formation rocks by Bonanza arc magmas would not be detectable by

252   the Rb-Sr and Sm-Nd isotopic systems due to the similarity in isotopic ratios between these

253   suites (Fig. 4). However the similarity of the major and trace element geochemistry, Nd and Sr

254   isotopic ratios between the Bonanza arc and the uncontaminated Talkeetna arc (Fig. 2, 3 and 4),

255   emplaced directly on the oceanic lithosphere (DeBari and Sleep, 1991), suggests that

256   contamination by any pre-existing material, including the Karmutsen Formation, must have been

257   minimal.

258

259   **Amphibole or garnet fractionation?**

260   The Bonanza arc was active for ~40 Myr (Fig. 1b), during which time the arc may have

261   thickened and the pressure of magmatic differentiation could have increased to above 0.8 GPa

262   (24 km), where garnet becomes a stable liquidus phase in hydrous basaltic systems relevant for

263   arc magmas (Müntener and Ulmer, 2006). Garnet strongly partitions the HREE (Table 3) and

264   fractionation of large proportions of garnet will result in decreasing concentration of these

265   elements in the remaining liquid as magma evolution progresses. Accordingly, Jagoutz (2010)

266   ascribed Yb depletion in felsic rocks from arcs >24 km thick to garnet fractionation in the lower

267   crust of those arcs.

268   We observe two sample populations on the basis of Yb and SiO_2 concentrations in the

269   Bonanza arc rocks (Fig. 5): one population increases in Yb concentration with increasing SiO_2,

270   whereas the other has low Yb concentration at high SiO_2 content, here referred to as the 'normal

271   Yb' and 'low Yb' groups, respectively. These Yb groups are most evident in the intrusive rock

272 suite and less clearly observed in the Bonanza volcanic suite which have generally SiO_2

273 <60wt.% (Fig. 5). The range of Yb and SiO_2 variation in the Talkeetna and Kohistan arcs (Fig. 5;

274 Kelemen et al., 2014; Jagoutz and Schmidt, 2012) show a positive correlation of Yb with SiO_2

275 that changes to a negative correlation at SiO_2 >65 wt.%. The Talkeetna and Kohistan arc sections

276 include garnet-bearing cumulate rocks (DeBari and Coleman 1989; Hacker et al., 2008; Jagoutz

277 et al., 2007) corroborating the assertion made by Jagoutz (2010) that rocks with low Yb and high

278 SiO_2 record the effect of fractionating garnet during magma evolution. Thus, it is possible that

279 felsic arc rocks with low Yb can be used to infer garnet fractionation and a minimum arc

280 thickness of 24 km. No garnet-bearing cumulate rocks have been reported from the Bonanza arc,

281 however amphibole is a commonly observed cumulate phase and is implicated in the evolution

282 of the Bonanza arc magmas (Larocque and Canil, 2010).

283   Ytterbium partitions into amphibole increasingly strongly (i.e. D_{Yb} increases) as a liquid

284 evolves to higher SiO_2 content (Fig. 6), implying that amphibole fractionation alone can

285 conceivably produce low to intermediate silica liquids enriched in Yb and in felsic liquids

286 depleted in Yb. In order to determine whether amphibole or garnet fractionation is responsible

287 for the 'low Yb' Bonanza arc rocks, we examine Dy and Yb variation as these elements partition

288 differently depending on whether amphibole or garnet is fractionating. In basaltic to andesitic

289 liquids, D_{Yb} for garnet varies from 3.55 to 23.5 and D_{Yb} for hornblende varies from 0.68 to 1.15

290 (Table 3). Over the same range of liquid compositions, D_{Dy} for garnet changes from 1.43 to 9.50

291 and D_{Dy} for amphibole increases from 1.06 to 1.77. Regardless of liquid composition, D_{Dy}/D_{Yb} is

292 0.40 for garnet and 1.54 for amphibole (Fig. 6).

293   Dysprosium is strongly positively correlated with Yb in the Bonanza arc rocks (Fig. 7a).

294 The volcanic rocks and the 'normal Yb' intrusive rocks lie along regression lines with slopes of

295　~1.6 and the 'low Yb' intrusive rocks lie on a shallower slope of 1.45 (Fig. 7a). The similarity in

296　Dy/Yb slope of the Bonanza arc sample array to the D_{Dy}/D_{Yb} of amphibole (1.5) and implies that

297　amphibole strongly controlled Dy and Yb variation in these rocks. The small differences between

298　the slopes and amphibole D_{Dy}/D_{Yb} likely indicate the effect of co-crystallizing phases – for

299　example olivine (D_{Dy}/D_{Yb} = 0.04; Adam and Green, 2006), orthopyroxene (D_{Dy}/D_{Yb} = 0.3;

300　Bédard, 2006) and garnet (D_{Dy}/D_{Yb} = 0.4).

301　　　　To quantitatively determine the cause of the observed Dy and Yb variation, we have

302　modeled the Rayleigh fractionation of amphibole- and garnet-bearing assemblages from a

303　primitive parent liquid (Fig. 7b), followed by fractionation of gabbroic assemblages from

304　intermediate liquids (Fig. 7c). We assume a parent liquid composition (Table 4) similar to a

305　primitive basalt sample from the Bonanza arc (sample JL06-027, Mg# = 0.67; Table 2;

306　Larocque, 2008). Partition coefficients and cumulate phase proportions appropriate for basaltic

307　and andesitic liquids are provided in Tables 3 and 4. We selected the most suitable

308　experimentally determined values of D_{Dy} and D_{Yb} for clinopyroxene, garnet and olivine from the

309　literature and comprehensive parameterizations of D for plagioclase, orthopyroxene, titanite and

310　apatite (Bédard, 2006; 2007; Prowatke and Klemme, 2006, 2007). As no suitable experimental

311　determinations were available for D_{La} in garnet in andesitic liquids we used a phenocryst-matrix

312　determination (Irving and Frey, 1978). The modes of the amphibole-bearing cumulate

313　assemblages used in the models (Table 4) are based on those observed in Bonanza arc cumulate

314　rocks (Larocque and Canil, 2010). Modes for the garnet-bearing cumulate assemblage are based

315　on mass balance calculations using silica variation diagrams for CaO and Al_2O_3 for the Bonanza

316　arc rocks (i.e. ~13% garnet; Fig. 2) and similar assemblages from the Talkeetna and Kohistan

317　arcs (20 – 50 % garnet; DeBari and Coleman, 1989; Jagoutz, 2010).

318   The variation in Dy and Yb concentration of the 'normal Yb' intrusive rocks is best fit by

319   removal of a hornblende-olivine orthopyroxenite assemblage (Path A on Fig. 7b) from the parent

320   basalt. Fractionation of a garnet gabbro with 13% garnet from the parent basalt produces a liquid

321   with increasing Yb and Dy (Path B on Fig. 7b) that fits the variation of the Bonanza arc volcanic

322   rocks at low degrees of fractionation (i.e. fraction of liquid remaining, $F > 0.4$). Removal of

323   garnet gabbros similar to those observed in the Talkeetna and Kohistan arcs ($20 - 50\%$ garnet)

324   produces liquids that evolve to higher Dy and lower Yb on paths that are subhorziontal to

325   subvertical.

326   To account for shifts in element partitioning with changing liquid composition, we have

327   modeled a second fractionation stage involving the removal of plagioclase- and garnet-bearing

328   cumulate assemblages from intermediate liquids on Paths A and B (Table 4, Fig. 7c). Plagioclase

329   cumulate assemblages are based on observed modes in similar rocks form the Bonanza arc,

330   whereas garnet gabbros have similar modal mineralogies as in the primitive liquid models. Mass

331   balance calculations suggest around 1% each of titanite and apatite are responsible for the

332   inflections in the TiO_2 and P_2O_5 silica variation diagrams (Fig. 2). These trace phases are

333   important because their high D_{REE} can substantially impact the trace element budget of a liquid:

334    $D_{Dy} = 25$ and $D_{Yb} = 10$ for titanite; $D_{Dy} = 12$ and $D_{Yb} = 6$ for apatite (Prowatke and Klemme,

335   2005, 2006). Although fractionation of magnetite and/or ilmenite is another possible cause for

336   the inflection in the TiO_2–SiO_2 variation diagram (Fig. 2), we do not consider Fe-Ti oxides in our

337   models as they are of low abundance in the Bonanza arc rocks ($< 3\%$; Larocque and Canil, 2010)

338   and, given the very low D_{REE} of these oxides (Nielsen et al., 1992), have negligible effect on Dy

339   and Yb concentrations in the fractionating assemblages we consider.

340   The intermediate liquid composition used to model the further evolution of the Bonanza

341   arc intrusive rocks ('Intermediate liquid 1', Table 4, Fig. 7c) is similar to the liquid produced at

342   60% fractionation of a hornblende-olivine orthopyroxenite from the basaltic parental liquid (F =

343   0.4 on Path A, Fig. 7b). The range of Dy and Yb in the 'normal Yb' intrusions is best modeled as

344   the liquid produced by removal of a clinopyroxene-rich gabbro (Table 4) from 'Intermediate

345   Liquid 1' (Path C, Fig. 7c). Removal of an apatite-titanite-garnet-hornblende gabbro assemblage

346   (Table 4) from 'Intermediate Liquid 1' produces liquids similar in composition to the 'low Yb'

347   samples (Path D on Fig. 7c). The Bonanza arc volcanic rock compositions are described by the

348   removal of a gabbro with 13% garnet from a basaltic parent liquid (Path B, Fig. 7b) followed, at

349   F = 0.4 ('Intermediate liquid 2', Table 4), by removal of a clinopyroxene-rich gabbro from the

350   resulting intermediate liquid (Path E, Fig. 7c). Removal of garnet gabbro with 20 – 50% garnet

351   from Intermediate Liquids 1 and 2 (Fig. 7c) causes the resulting liquids to evolve to lower Yb

352   and Dy along shallow positive slopes that do not describe the composition of the 'low Yb'

353   intrusive rocks.

354   With consideration of La, the volcanic rocks and the intrusive rocks show strikingly

355   different trends (Fig. 8a, b) compared to their subparallel trends in Figure 7. Originating from a

356   cluster centered around $(Dy/Yb)_N = 1.2$ and $(La/Dy)_N = 1.7$, the intrusive rocks describe a

357   negative trend to high $(Dy/Yb)_N$, whereas the volcanic rocks form a positive trend to high

358    $(Dy/Yb)_N$. The results of models incorporating La, extremely incompatible in garnet ($D_{La} =$

359    $0.0034 – 0.07$) and only moderately incompatible in amphibole ($D_{La} = 0.12 – 0.1675$; Table 4)

360   are shown in Figure 8. The distribution of the 'normal Yb' and 'low Yb' intrusive suites in

361   Figure 8a is generally described by the fractionation trends produced by removal of a

362   hornblende-olivine orthopyroxenite from the parent basaltic liquid followed by removal of

363 apatite-titanite-garnet-hornblende gabbro (Path A and D, Fig. 8a) from 'Intermediate liquid 1'

364 (Table 4), as was discussed above in relation to Figure 7b and c. The removal of a

365 clinopyroxene-rich gabbro from 'Intermediate Liquid 1' produces liquids that are slightly lower

366 in $(Dy/Yb)_N$ than the main array formed by the intrusive suite (Path C, Fig. 8a). Although some

367 of the low $(Dy/Yb)_N$ volcanic rocks are fit by the same models as the intrusive rocks (Fig. 8b),

368 the high $(Dy/Yb)_N$ ratios of other volcanic samples necessitates a different fractionating

369 assemblage. We find that removal of a garnet gabbro assemblage with 13% garnet from a

370 basaltic parent liquid followed by removal of a clinopyroxene gabbro assemblage from

371 'Intermediate liquid 2' (Table 4; Paths B and E, Fig. 8) generally describes the distribution of the

372 majority of the Bonanza arc volcanic data in Figure 8b.

373   Although their La, Dy and Yb variation require garnet fractionation, the Bonanza arc

374 volcanic rocks do not show the Yb depletion at high SiO_2 (Fig. 5) associated with garnet

375 fractionation (e.g. Jagoutz, 2010). We argue that this is due to the relatively small proportion of

376 garnet $(1 - 13\%)$ that is removed, combined with the low partition coefficients for Yb in the

377 other fractionating phases (plagioclase, clinopyroxene and amphibole; Table 3), resulting in a

378 low bulk partition coefficient of Yb in the fractionating assemblage.

379   The models we present indicate that fractionation of hornblende-olivine orthopyroxenite

380 from a primitive liquid followed by the fractionation of clinopyroxene gabbro and apatite-

381 titanite-garnet-hornblende gabbro from a resulting intermediate liquid (Paths A, C and D in Fig.

382 7 and 8) can reproduce the La, Dy and Yb variation of the Bonanza arc intrusive rocks, including

383 the felsic 'low Yb' intrusive suite. The volcanic rocks of the Bonanza arc indicate fractionation

384 of ~13% garnet from a primitive liquid followed by fractionation of clinopyroxene gabbro from

385 an intermediate liquid (Paths B and E in Fig. 7 and 8). The poor fit between the models and the

386   data in Figure 8 may be due to several simplifications inherent in modeling magma evolution as

387   a pure liquid produced by only two discrete stages of Rayleigh fractional crystallization. For

388   example, amphibole accumulation observed in some Bonanza arc volcanic rocks (Nixon et al.,

389   2011a, b) implies that they are not pure liquids. Such accumulation moves the whole rock

390   composition to lower $(La/Dy)_N$ but higher $(Dy/Yb)_N$, shown schematically on Figure 8a, due to

391   the higher D_{Dy} compared to D_{La} and D_{Yb} of amphibole (Table 3). Futhermore, the high D_{Dy} and

392   D_{Yb} of apatite and titanite (Table 3) mean that small variations in the amount of these minerals in

393   the fractionating assemblage can affect the liquid composition considerably. For example,

394   increasing the amount of titanite or apatite fractionating would shift the liquid evolutions lines to

395   lower $(Dy/Yb)_N$ while only slightly increasing $(La/Yb)_N$, as shown schematically in Figure 8a.

396   The imperfect fit between the models and data could also be due to the choice of partition

397   coefficients, although we attempted to minimize this effect by using comprehensive

398   parameterizations and suitable experimental determinations of this parameter. The continuous

399   change in liquid composition during evolution means that no single value for partition coefficient

400   can perfectly model the evolution of liquid composition and some mismatch between predictions

401   and observations is inevitable. The distribution of Bonanza arc rock analyses in Figures 7 and 8

402   could also be produced by fractionation of similar assemblages from different parent liquid

403   compositions. The likely range of starting compositions are shown on Figure 8, similar to MORB

404   (Jenner and O'Neill, 2012).

405   Another process by which low Yb, high SiO_2 rocks may be formed is partial melting of

406   amphibolite to leave a garnet-bearing residue at the base of the crust (Zhang et al., 2013). This

407   process presupposes a crust that is thick enough that garnet is stable (>24 km depth; Müntener

408   and Ulmer, 2006; Zhang et al., 2013) and is consistent with our assertion that the Bonanza arc

409   was thick enough to allow garnet to be a stable phase in the lower crust.

410

411   *Alternate modeling approaches*

412   Other approaches are able to overcome the aforementioned shortcomings of modeling

413   using partition coefficients. For example, a subtractive modeling, based on the incremental

414   removal of chemical compositions of observed cumulate rocks from that of a parental liquid

415   causing the remaining liquid to evolve away from the cumulate composition, was used to

416   determine the petrogenesis of the Kohistan arc (Jagoutz, 2010). Larocque and Canil (2010) also

417   used a subtractive model to describe the major element composition of the Bonanza arc rocks in

418   terms of the removal of olivine, amphibole and/or clinopyroxene from a primitive parental

419   liquid.

420   Using the method described by Jagoutz (2010), we modeled the removal of an olivine-

421   bearing cumulate assemblage followed by the removal of a plagioclase-bearing assemblage, each

422   modeled as the average of similar assemblages observed in the Bonanza arc, from the same

423   basaltic parent liquid used in the above models (sample JL06-027; Larocque, 2008). This model

424   (Fig. 9) predicts the increasing Yb concentrations of the Bonanza arc rocks up to 60 – 65 wt.%

425   SiO_2. However, the compositions of observed cumulate rocks in the Bonanza arc are insufficient

426   to reproduce the 'low Yb' samples (Fig. 9). A cumulate rock composition with high Yb and low

427   SiO_2 is required, but no such cumulate rocks are observed in the Bonanza arc suite.

428   A cumulate assemblage containing garnet, hornblende and trace phases like titanite and

429   apatite would have high Yb and relatively low SiO_2 concentration, potentially similar to the

430   garnet-bearing ultramafic rocks of the Kohistan arc (Fig. 9; Jagoutz and Schmidt, 2012).

431   Fractionation of such an assemblage from the modeled liquid would efficiently drive the

432   remaining liquid to low Yb and high SiO_2 compositions, similar to the spread of data in Figure 9.

433   The requisite garnet-bearing assemblages are not observed in the Bonanza arc, but are similar

434   those used in REE modeling presented above (Fig. 7 and 8). The absence of a garnet-bearing

435   cumulate assemblage in the Bonanza arc section maybe due to its high density compared with

436   the sub-arc mantle, resulting in the foundering of these rocks (Kay and Mahlburg-Kay, 1991;

437   Jagoutz and Schmidt, 2012).

438

439   *Comparison to other arcs*

440   The chemical composition of Bonanza arc rocks overlaps that of rocks from the

441   Talkeetna and Kohistan arcs in major element concentration (Fig. 2) and trace element

442   abundance (Fig. 3). The Talkeetna and Kohistan arc data show much greater range and scatter in

443    $(La/Dy)_N$ and $(Dy/Yb)_N$ than do the Bonanza arc data (Fig. 8c). We have not attempted to fit our

444   models to the Talkeetna and Kohistan arc data but we note that the data for those arcs are not

445   incompatible with our models (Fig. 7d, 8c). Although not shown, we note that the hornblende

446   gabbro fractionation model that Jagoutz (2010) presents for the Kohistan arc is similar in

447   trajectory to our hornblende olivine orthopyroxenite model (Path A; Fig. 7, 8). Similar to our

448   conculsions, Jagoutz (2010) also noted the importance of a garnet-bearing fractionating

449   assemblage in the petrogenesis of low Yb Kohistan arc granitoids, however no data were

450   available to compare that garnet fractionation model to ours. The array of very low $(La/Dy)_N$

451   samples, with variable $(Dy/Yb)_N$, from the Talkeetna and Kohistan arc (Fig. 8c) has no

452   equivalent in the Bonanza arc and likely represents the garnet-bearing cumulate rocks known

453   from the former arcs (DeBari and Coleman, 1989; Jagoutz, 2010) but not in the Bonanza arc.

454 The inference of garnet-bearing cumulate rocks in the petrogenesis of the Bonanza arc is

455 significant as it provides a previously unknown similarity with the coeval Talkeetna arc (DeBari

456 et al., 1999).

457

458 **Constraints on the thickness of the Bonanza arc**

459   Our fractionation models imply that garnet was a fractionating phase in the Bonanza arc

460 and implies that the lower crust extended to depths at which garnet was stable. The crust on

461 which the Bonanza arc was emplaced consists of at least 3 km of Devonian Sicker arc rocks

462 (Muller et al. 1977) overlain by 6 km of Triassic Karmutsen basalts, inferred to have an equally

463 thick gabbroic complement, possibly residing in the lower crust of Wrangellia (Greene et al.,

464 2009). Thus, the total thickness of the substrate on which the Bonanza arc formed was at least 15

465 km. Because garnet is only stable at greater than 24 km depth (i.e. 0.8 GPa; Müntener and

466 Ulmer, 2006), the possibility of garnet fractionation in controlling the evolution of the Bonanza

467 arc magmas as modelled above depends critically on whether the combined thickness of the

468 Bonanza arc and the pre-Jurassic crust reached or exceeded this thickness.

469   A previous estimate of the total thickness of the Bonanza arc and its substrate of ~ 24 km

470 was based primarily on hornblende thermobarometry of felsic intrusive rocks and less so on

471 barometry of the mafic and ultramafic plutonic rocks in the Bonanza arc section (Canil et al.,

472 2010). Here we attempt to make simple, first-order estimates of the total thickness of the

473 Bonanza arc and pre-Jurassic crust using constraints from geological mapping combined with

474 amphibole thermobarometry. Figure 10 shows the widths of all the Bonanza arc units along a

475 line perpendicular to the NW-SE strike of the Bonanza arc on Saanich Peninsula, southern

476 Vancouver Island. This region was chosen for this exercise because it is relatively free of

477 faulting that might otherwise distort the thicknesses of these units (Fig. 1, 10). Using

478 geobarometry, Canil et al. (2010) determined that the Island Plutonic Suite was 5 – 8 km thick.

479 Assuming this thickness range is accurate, the dip required to produce the observed outcrop

480 length of the Island Plutonic Suite exposed on Saanich Peninsula (~11 km; Fig. 10) varies from

481 28 – 48°, which overlaps the range of dips for foliations (35 – 65°) of intrusive rocks observed in

482 the field (Larocque and Canil, 2010). Assuming dips of 28 – 48° for Bonanza intrusive (i.e. the

483 Island Plutonic Suite and the Westcoast Crystalline Complex) and volcanic units, the observed

484 outcrop lengths (Fig. 10) prescribe a total true thicknesses of 11 – 18.4 km for the arc. Applying

485 an alternate amphibole barometer (Ridolfi et al., 2009) to the data of Canil et al. (2010) gives a

486 maximum thickness of only 3.5 km for the Island Plutonic Suite, requiring a dip of only 20° to

487 explain the measured outcrop lengths in Figure 10, and resulting in an total true thickness of the

488 Bonanza arc of only 8 km.

489   Using our lowest estimate of the thickness of the Bonanza arc (8 km), the minimum

490 combined thickness of the Bonanza arc and pre-existing crust is 23 km. The base of the crust in

491 this case is slightly shallower than the minimum required for garnet to be a stable liquidus phase

492 in arc magmas (Müntener and Ulmer, 2006). Our maximum likely thickness estimate for the

493 Bonanza arc (~18 km) combined with the pre-existing crust gives a total thickness of

494 approximately 33 kilometers and implies that the base of the crust was within the stability zone

495 of garnet. This maximum estimate is similar to the seismically determined depth to the present-

496 day Moho beneath Vancouver Island (35 km; Clowes et al., 1987).

497   There are large differences in the results of the amphibole barometers used by Canil et al.

498 (2010) and Ridolfi et al. (2009). As noted by Canil et al. (2010) the pressures they report for

499 some samples are maxima due to the plagioclase composition (>An_{35}) and the absence of K-

500   feldspar in some samples (Anderson and Smith, 1995). Ridolfi et al. (2009) similarly caution that

501   errors for their pressure estimates may be as high as 25% for magnesiohorneblende and

502   tschermakitic pargasite, the most common amphiboles in the Bonanza arc intrusive rocks

503   (Larocque, 2008). The mismatch between these barometric pressure estimates underscores the

504   importance of using barometers that are suitable for the species of amphibole and the coexisting

505   mineral assemblage present in a sample.

506

507   **Timing and spatial distribution of magmatism in the Bonanza arc**

508   The intrusive Bonanaza arc rocks, sampled from exposures across Vancouver Island,

509   show a continuous range of ages from 163 to 200 Ma, with a peak at 172 Ma (Fig. 1b). The

510   distinctly bimodal volcanic age distribution may indicate that volcanism occurred as two separate

511   pulses within one arc, at 198 and 171 Ma, with an intervening quiescent period of ~10 Myr.

512   Another interpretation, linking the distinct spatial separation of regions exposing young and old

513   volcanic rocks on northern Vancouver Island (Fig. 1a), is that what is presently called the

514   Bonanza arc was actually two geographically separate arcs that were active within ~10 Myr of

515   one another. In this interpretation, the two separate arcs are juxtaposed in the present day by

516   movement along arc-parallel strike slip faults.

517   The intrusive rock age distribution (n = 63, peak at 172 Ma) is skewed toward younger

518   ages, as expected from the greater preservation potential for younger rocks compared to older

519   ones. Contrary to the expectation that older rocks are less likely to be preserved than younger

520   ones, the volcanic rock age distribution (n = 31) shows that older ages are better represented than

521   younger ages in our compilation (Fig. 1b). Thus, we argue that the bimodal age distribution of

522   the Bonanza arc volcanic rocks is not a true representation of their ages and is an artefact of

523 intensive sampling of those rocks in a limited geographic region compared to the geographically

524 comprehensive sampling of intrusive rocks (Fig. 1a). We also cannot rule out preservation bias in

525 producing the bimodal volcanic age distribution as the trace of the Holberg Fault, running

526 through Holberg Inlet (Fig. 1a), bisects the main region of measured volcanic ages.

527 The geographic distribution of the ages of Bonanza arc volcanic rocks on northern

528 Vancouver Island is sharply divided with young (i.e. ~171 Ma) and old (i.e. ~198 Ma) ages

529 northeast and southwest, respectively, of the trace of the Holberg Fault. The observed eastward-

530 younging of the rocks can be produced by: 1) subduction in the west (present coordinates) of an

531 east-dipping slab combined with forearc erosion; or 2) subduction in the east of a west-dipping

532 slab that is 'rolling-back' (e.g. Gvitrzman and Nur, 1999). We are unable to distinguish between

533 the possibilities of slab rollback or forearc erosion as Jurassic forearc assemblages, which would

534 constrain subduction polarity have not been found on Vancouver Island (Canil et al., 2012). On

535 the other hand, little is known about the timing and sense of displacement along the steeply

536 dipping Holberg Fault (Nixon et al., 2011a, b) but it may be a major strike-slip structure that

537 juxtaposed younger and older arc segments, thus increasing the width of the present exposure of

538 the Bonanza arc. A test of that idea, and how the Holberg Fault links with other major structures

539 that dissect the Bonanza arc, (Fig. 1) requires further investigation.

540

541 **CONCLUSIONS**

542 We have determined that <10% assimilation of pre-existing crust (Sicker arc material) is

543 required to explain the variations observed in Sr and Nd isotopes in rocks of the Bonanza arc.

544 Although comparisons of Bonanza arc geochemistry with that of the uncontaminated Talkeetna

545 arc are favourable, we are unable to conclusively rule out contamination of the former by the

546 isotopically similar Karmutsen Formation. The intrusive rocks of the Bonanza arc have high

547 $(La/Dy)_N$ and low $(Dy/Yb)_N$, whereas both ratios are high in the volcanic rocks. Thus, two

548 separate fractionation models are required to predict the REE chemistry of the Bonanza arc

549 rocks: one model (garnet gabbro fractionation followed by clinopyroxene gabbro fractionation)

550 describes the chemistry of the majority of volcanic rocks and some intrusive rocks; another

551 model (hornblende-olivine orthopyroxenite fractionation, followed by apatite-titanite-garnet-

552 hornblende gabbro fractionation) describes the chemistry of the majority of intrusive rocks and

553 some volcanic rocks. Both lineages implicate garnet as a fractionating phase, which is significant

554 as garnet-bearing cumulate rocks have not been described in the Bonanza arc and are a

555 previously unknown similarity with the coeval Talkeetna arc. Our estimates for the thickness of

556 the Bonanza arc and the pre-existing crust indicate that the base of the crust was likely deeper

557 than the 24 km (0.8 GPa) minimum limit for garnet stability, thereby supporting the garnet

558 fractionation models we have presented. Garnet-bearing rocks are not described in the Bonanza

559 arc and may have been lost by foundering into the comparatively buoyant underlying mantle

560 (e.g. Kay and Mahlburg-Kay, 1991).

561   The Bonanza arc volcanic rocks show a bimodal age distribution due to sampling bias,

562 yet show an abrupt change to younger ages to the north of the Holberg Fault, on northern

563 Vancouver Island. This spatial distribution is either due to movement of the magmatic front with

564 time by fore-arc erosion or slab rollback during subduction, or the juxtaposition of separate arcs

565 by strike-slip motion on the Holberg Fault. Our geochronological compilation indicates that the

566 Bonanza arc was active from 203 to 164 Ma during which time the arc may have thickened

567 enough that the composition of later magmas was affected by garnet fractionation whereas

568 earlier magmas were not. The conclusive test of such spatio-temporal magmatic evolution

569 depends critically on the comparison of geochemical and geochronological data, however the

570 number of samples for which both data are presently available is too meager to draw such

571 conclusions. Expanding this dataset could provide unique insights into the evolution of a

572 thickening arc and presents a potentially fruitful avenue for future work.

573

581

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789   **FIGURE CAPTIONS**

790   Figure 1. a) Geological map of Vancouver Island, showing the units of the Jurassic Bonanza arc

791   and the pre-Jurassic crust and the locations and ages of the intrusive and volcanic Bonanza arc

792   rocks that have been dated in other studies (zircon U-Pb and hornblende Ar-Ar). The black

793   rectangle shows the location of Figure 10. b) The distribution of Bonanza arc ages plotted as a

794   Kernel Density Estimate (Vermeesch, 2012). c) The locations of Bonanza arc samples with

795   measured Rb-Sr and Sm-Nd isotopic ratios from this study and others.

796

797   Figure 2. Silica variation diagrams showing the variation of major elements in Bonanza arc

798   samples analyzed in this study and previous work. Also shown are fields for the Talkeetna and

799   Kohistan arc data (Kelemen et al., 2014; Jagoutz and Schmidt, 2012).

800

801   Figure 3. a) N-MORB normalized (Sun and McDonough, 1989) trace element profiles for

802   samples analyzed in the present study (thick black lines) and those from the literature, grouped as

803   volcanic, intrusive or cumulate rocks. b) Chondrite normalized (McDonough and Sun, 1995)

804   REE profiles for Bonanza arc samples, as in Figure 3a. c) Fields for the N-MORB normalized

805   trace element profiles and d) chondrite normalized REE profiles for the Talkeetna and Kohistan

806   arcs (Kelemen et al., 2014; Jagoutz and Schmidt, 2012) and all Bonanza arc data, including

807   samples analyzed in the present study.

808

809   Figure 4. Assimilation-fractional crystallization (AFC) models for a melt from the Depleted

810   Mantle and two possible contaminants: the average of the available Sicker arc data (solid lines)

811   and an extreme sample from the Sicker arc (dashed lines). Three melt-contaminant ratios (r) are

812   presented for Sr and Nd AFC models: a, d) r = 0.07; b, e) r = 0.15; c, f) r = 0.30. Curves have

813   been calculated for different values of partition coefficient (D) for Sr and Nd, ranging from very

814   incompatible (D = 0.05) to neutral (D = 1). At low D values, curves for the two contaminants are

815   very similar and only the solid curve has been shown for clarity. The legend for all panels is split

816   between panels a, b and c.

817

818   Figure 5. Yb concentration as a function of SiO_2 in the Bonanza arc rocks. On the basis of this

819   plot, the intrusive suite is divided into 'low Yb' and 'normal Yb' groups. Also shown are fields

820   for the Talkeetna and Kohistan arc data (Kelemen et al., 2014; Jagoutz and Schmidt, 2012).

821

822   Figure 6. Amphibole-liquid partition coefficients for Dy and Yb (D_{Dy}, D_{Yb}) and D_{Dy}/D_{Yb} as a

823   function of SiO_2 in the liquid. Data from Tiepolo et al., (2007).

824

825   Figure 7. Dy and Yb variation in the Bonanza arc rocks. a) Regression lines and their equations

826   fitted through the volcanic, 'normal Yb' and 'low Yb' intrusive rock groups. b) Liquid evolution

827   models for fractionation of different mineral assemblages from a basaltic parent melt. c) Liquid

828   evolution models for fractionation of different mineral assemblages from an intermediate liquid.

829   At low degrees of fractionation, there is little to no separation between the liquids of garnet

830   gabbros with 20 – 50% garnet. d) Data for the Talkeetna and Kohistan arcs (Kelemen et al.,

831   2014; Jagoutz and Schmidt, 2012) and a composite of liquid evolution paths A – E from panels b

832   and c, with arrows to indicate direction of liquid evolution. Partition coefficients used in the

833   models are provided in Table 3 and phase proportions for each assemblage and the compositions

834   of the parent liquid and two intermediate liquids are provided in Table 4. Legend is split across

835   panels a, b and d. Abbreviations: ap = apatite, cm = cumulate, cpx = clinopyroxene, gb = gabbro,

836   gt = garnet, hbl = hornblende, ol = olivine, opx = orthopyroxene, tt = titanite.

837

838   Figure 8. Chondrite-normalized (McDonough and Sun, 1995) La/Dy and Dy/Yb variation of the

839   Bonanza arc rocks for a) the intrusive rocks, b) the volcanic rocks and c) the Talkeetna and

840   Kohistan arc rocks (Kelemen et al., 2014; Jagoutz and Schmidt, 2012). The results of selected

841   fractionation models are shown. Abbreviations as per Figure 7.

842

843   Figure 9. Plot showing the subtractive fractionation model of the Yb-SiO_2 variation in a liquid

844   produced by removal of 25% of the average Bonanza arc olivine cumulate rock (Yb = 0.6 ppm,

845   SiO_2 = 41.2 wt.%) followed by removal of the average primitive Bonanza arc plagioclase

846   cumulate (Yb = 1.3 ppm, SiO_2 = 43.2 wt.%). The range of compositions of garnet-bearing mafic

847   rocks from the Kohistan arc (Jagoutz and Schmidt, 2012) is also shown. Abbreviations as per

848   Figure 7.

849

850   Figure 10. Mapped lengths of the Bonanza arc units on a line perpendicular to the NW-SE

851   regional strike of the Bonanaza arc, along a relatively unfaulted section on southern Vancouver

852   Island.