1   Revision 1   Word Count: 9316

2   **Revisiting the genesis of the adakite-like granitoids in collisional**

3   **zones: water-fluxed melting of intermediate to felsic rocks with**

4   **dilution by low Sr/Y phases**

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25   **ABSTRACT**

26   High Sr/Y granitoids in continental settings are sometimes erroneously regarded as

27   the products derived from partial melting of thickened/delaminated mafic lower curst

28   under relatively higher pressures (> 1.5 GPa) in a collisional orogenic setting. In fact,

29   multiple magmatic processes in the trans-crustal magma system such as recycling of

30   antecrysts, crustal assimilation, and fractional crystallization can create or modify

31   primary 'adakitic' signature. As a result, the generation of adakitic magmas in

32   continental settings remains controversial from a bulk-rock perspective. Here, we

33   address the origin of adakitic plutonic rocks through geochemical and textural

34   characterization of rock-forming minerals in the pyroxene-bearing, Zhuyuan

35   granodiorite (West Qinling, China). The Zhuyuan granodiorite formed in a post-

36   collisional setting, and primarily consists of resorbed orthopyroxene, three types of

37   clinopyroxene, amphibole, two types of plagioclases, K-feldspar, biotite, and quartz.

38   Type-1 Cpx has high X_{Mg} (70.0–81.7). Type-2 Cpx displays normal zoning and

39   decreasing X_{Mg} (80.9 to 71.5) from the core to rim. Type-3 Cpx is reversely zoned,

40   where the rims have higher X_{Mg} (75.5–86.9), Ni, Cr, suggesting a recharge event.

41   Orthopyroxene has high Ni and Cr contents, as well as high X_{Mg} (80.9–82.8), indicative

42   of antecrysts that grew in mafic magma reservoirs. The injection of magmas from

43   different sources is supported by sieve-textured plagioclase and crystal size

44   distributions of non-poikilitic amphibole. Finally, non-sieve textured plagioclase,

45   biotite, K-feldspar, and quartz are late-crystallized phases, indicative of an orthocrystic

46   origin. The melts in equilibrium with these orthocrysts display significantly higher Sr/Y

47   values than the magma batches that crystallized other mafic phases (i.e., amphibole,

48   clinopyroxene, and orthopyroxene). Thus, we propose that the system involved an

49   initial high-Sr/Y melts in equilibrium with the orthocryst assemblage were generated

50   by water-fluxed melting of intermediate to felsic sources. The addition of low Sr/Y non-

51   orthocrysts (e.g., amphibole and pyroxene) and associated melt diluted the original

52   'adakitic signal' in the magma reservoir, and drove the bulk composition to more mafic

53   values. Consequently, the Zhuyuan pyroxene-bearing granodiorite represents a mixture

54   of crystals with diverse origins and distinct magma batches of various compositions

55   (from felsic to mafic compositions). Our study emphasizes that the origin of adakitic

56   granitoids cannot be clearly deciphered without the geochemical analysis of the

57   constituent minerals. We also suggest that Sr/Y values in plutons should be cautiously

58   used in paleo-crustal thicknesses estimates in collisional settings because of possible

59   open system scenarios like we document here.

60   **Keywords:** Adakitic rock, antecryst, dilution, pyroxene-bearing granodiorite, water-

61   fluxed melting

62

63   **INTRODUCTION**

64   The term "adakite" was originally defined as high-Mg andesites produced by partial

65   melting of subducted oceanic crust (Kay, 1978; Defant and Drummond, 1990).

66   Geochemically, adakites are characterized by elevated Sr contents (> 400 ppm), high

67   Sr/Y and La/Yb values, but depleted Y (< 18 ppm) and HREE (e.g., Yb < 1.8 ppm)

68   (Defant and Drummond, 1990). A number of mechanisms have been proposed for the

69   origin of adakitic magmas based on whole-rock geochemical compositions (Ma et al.,

70   2015; Shen et al., 2021 and references therein). For example, primary magmas with

71   adakitic affinity may be generated by partial melting of various sources under various

72   pressures (e.g., delaminated lower crust, thickened lower crust, mantle wedge peridotite

73   metasomatized by slab melts, intermediate to felsic source rocks with initially high Sr,

74   low Y and Yb; Calmus, 2003; Moyen et al. 2009; Ma et al., 2015; Ji et al., 2018; Ou et

75   al., 2017; Yu et al., 2015; Zhan et al., 2020). On the other hand, magma processes (e.g.,

76   fractional crystallization, crystal accumulation and/or magma mixing) may produce or

77   modify 'adakitic' felsic melts (e.g., Chen et al., 2016; Guo et al., 2007). For example,

78   amphibole fractionation prior to plagioclase saturation would lead to the enrichment of

79   Sr and depletion of Y in derivative melts (Moyen, 2009; Nandedkhar et al., 2016). As

80   such, the origin of adakites has been controversial and this issue warrants further

81   reevaluation via comprehensive mineral-scale geochemical investigation (Castillo,

82   2012; Castillo et al., 1999).

83   Moreover, previous mechanisms for the generation of adakitic magmas are largely

84   based on experiments and modeling using a simple rock source or a melt-dominated

85 closed system (e.g., Martin et al., 2005; Stern and Kilian, 1996); however, recent crystal

86 population studies regarding trans-crustal magma-mush reservoirs have challenged the

87 suppositions necessary to generate adakitic magmas especially in plutonic arc crust

88 (e.g., Paterson et al., 2016; Graham et al., 2020; Brackman & Schwartz, 2022). For

89 example, some workers argue that felsic magma reservoirs likely comprise multiple

90 generations of crystals (e.g., orthocrysts, antecrysts, peritectic crystals, or xenocrysts;

91 Bach et al., 2012; Miller et al., 2007; Clemens and Stevens, 2012) of contrasting origins

92 (Jerram et al., 2018; Miller et al., 2007), which are entrained by different batches of

93 both interstitial melts and volatile phases (i.e., a system of melt stored in a framework

94 of crystals, referred to as crystal mush; Cashman et al., 2017; Collins et al., 2020;

95 Wieser et al., 2020). In some cases, original adakitic signals (i.e., high Sr/Y and La/Yb

96 values) could be diluted by the addition of non-orthocrysts characterized by low Sr/Y

97 values (e.g., Macpherson et al., 2006), and as a consequence, geochemical trends

98 defined by the whole-rock compositions could deviate from the liquid line of descent

99 of the host magma due to the addition of various proportions of non-orthocrysts.

100 One approach to characterize these complex geochemical signals is to study the

101 composition of individual minerals such as plagioclase, pyroxenes, titanite, zircon, and

102 apatite which have become widely used as petrogenetic tools in supplementing or even

103 replacing conventional bulk-rock analyses. For instance, Hollings et al. (2020) used

104 early-crystallized apatite to show that the 'adakite signal' of the equilibrium melt had

105 not been influenced by subsequent amphibole-dominated fractional crystallization. In

106   this regard, geochemical signatures of constituent minerals that witnessed different

107   stages of the geochemical evolution history and/or various sources may provide new

108   perspectives for further constraining mechanisms of adakites generation.

109   Here, we explore the Late Triassic post-collisional granodiorite pluton in the

110   Zhuyuan area, West Qinling which has complex mineral assemblages and show

111   remarkably whole-rock high Sr/Y properties，a diagnostic imprint of adakitic rocks.

112   This makes it a valuable target for exploring the contribution of different generations

113   of minerals to the nature of adakitic granitoids. In this study, we have classified several

114   types of amphiboles, plagioclase and pyroxenes in the Zhuyuan pluton. Multiple lines

115   of evidence support open-system processes including pluton construction from multiple

116   generations of antecrysts and magma batches in a felsic magma reservoir at shallow

117   crustal depths. Furthermore, we argue that water-fluxed melting of intermediate to

118   felsic sources controls the development of high Sr/Y interstitial melts of the studied

119   pluton and it has no tectonic indication for thickened/delaminated mafic lower curst

120   even though emplacement during post-collisional settings.

121

122   **SAMPLE DESCRIPTIONS**

123   The Zhuyuan pluton investigated in this study intruded Devonian strata (the

124   Wangjiaba, Weijiamu, and Yuchiba Formation) in the eastern part of the West Qinling

125   Orogenic Belt (Fig. 1b and 2). All 17 samples are classified as granodiorites (Fig. DR1;

126   Streckeisen, 1976). They display a medium- to fine-grained texture (Fig. 3a–3b). Rock-

127   forming minerals include quartz (Qtz: ~20 vol%), plagioclase (Pl: 40–45 vol%), K-

128   feldspar (Kfs: 15–20 vol%), biotite (Bt: ~5 vol%), amphibole (Amp: 5–10 vol%),

129   clinopyroxene (Cpx: ~5 vol%), and orthopyroxene (Opx: <2 vol%). Accessory minerals

130   are apatite, zircon, titanite, and magnetite.

131   Two types of Pl crystals are identified. One is clear without resorbed cores or

132   oscillatory zoning; it occurs as phenocrysts or microlites in the groundmass, and

133   generally exhibits polysynthetic twinning (Fig. 3b). The other type commonly displays

134   oscillatory zoning with patchy- or sieve-textured cores surrounded by clear rims (Fig.

135   3c–3d). The sieve texture (Fig. 3c) indicates disequilibrium or resorption and thus

136   implies a xenocrystic (Xu et al., 1999) or antecrystic origin (Jerram and Martin, 2008)

137   for the cores. Kfs is anhedral and generally measure less than 1 mm (Fig. 3b).

138   Pyroxenes display poikilitic textures (Fig. 3e–3i), are anhedral to subhedral, and have

139   sizes of 0.05–1 mm in length. All Cpx and Opx with ragged margins are enclosed by

140   Amp, reflecting the formation of Amp at the expense of pyroxene (Fig. 3e–3i). Based

141   on back-scattered electron (BSE) images and geochemical characteristics, we identify

142   three types of Cpx: unzoned (Type-1 Cpx), normally zoned (Type-2 Cpx), and reversely

143   zoned (Type-3 Cpx) crystals. In BSE images, both Type-2 and Type-3 Cpx (Fig. 3g)

144   show zoning with core–rim textures, while Opx does not display zoning (Fig. 3i).

145   Amp is one of the principal mineral phases in the Zhuyuan granodiorites that

146   occasionally forms aggregates. Amps are euhedral to subhedral, with sizes of 0.01–2.5

147   mm in diameter, have distinct brown to pale green pleochroism, and do not display

148   zoning in BSE images (Fig. 3g). Some Amps display poikilitic textures with Bt (Fig.

149   3c). According to the texture and particle sizes, we divided them into two types (Type-

150   1 Amp and Type-2 Amp). Type-1 Amp grows along pyroxene grain boundaries and

151   forms a poikilitic texture with pyroxene. Their size is greater than 0.3 mm. Type-2 Amp

152   does not show poikilitic textures with pyroxene and has smaller grain sizes (0.01–0.4

153   mm). Most Amps occur as corroded grains and do not display equilibrium grain

154   boundary textures where they are in contact with Pl and they generally exhibit lobate

155   textures (Fig. 3g–3i). This observation suggests that Amp and Pl do not exist in the

156   same equilibrium mineral assemblage. Subhedral to anhedral Bts are khaki to brown,

157   with a length of less than 1 mm. Bts usually occurs as interstitial phases associated with

158   Kfs and Qtz.

159

160   **RESULTS**

161   **Mineral element compositions**

162   Representative in-situ major- and trace-element data of Opx, Cpx, Amp, Bt, Pl, and

163   Kfs from the Zhuyuan granodiorites are listed in Tables DR3–DR4 and shown in Fig.

164   4 to 6. In order to ensure the reliability of the data, we only use trace element

165   concentrations higher than 0.1 ppm (generally 5 greater than times the detection limit)

166   for interpretations and calculations. Chemical formulae for Bt and Pl were calculated

167   with the AX software (Holland and Blundy, 1994). For pyroxene, we use the Geokit

168   software (Lu, 2005), and for Amp we use the method proposed by Li et al. (2020a).

169   To determine trace-element distributions in mineral phases, several mineral grains

170   were selected for LA-ICP-MS element mapping. A total of 51 elements were mapped

171   for these minerals, and Fig. 7–9 display the elements of interest (i.e., Al, Sr, Y, REE,

172   Cr, and Ni) and important parameters (Sr/Y and X_{Mg} values). Fig. 7 and Fig. 9 present

173   compositional profiles across core-rim interfaces, and Tables DR4 contain the

174   corresponding data.

175   **Clinopyroxene** shows a large range of SiO_2 (50.0–54.1 wt.%) and MgO (12.4–17.1

176   wt.%) contents, high X_{Mg} ($Mg/[Mg + Fe^{2+}] \times 100$) of 70.0–86.9, and variable ΣREEs

177   (37.8–245 ppm), Cr (145–5821 ppm), and Ni (56.2–346 ppm) abundances (Tables 1

178   and DR4). All are classified as diopside or augite (Fig. 4a). Several grains exhibit

179   compositional zonation (Fig. 5). By observing BSE images and geochemical data, we

180   identified three types of Cpx (Fig. 5): unzoned, normally zoned, and reversely zoned.

181   Unzoned Cpxs (Type-1 Cpx) are subhedral to anhedral and compositionally are

182   diopside and augite (Fig. 4a). We further divide them (Type-1A and Type-1B) based

183   on their FeO^T contents, X_{Mg} values, and chondrite-normalized REE patterns, and both

184   subtypes may occur in a single thin section. Type-1A Cpx is characterized by high X_{Mg}

185   (72.6–81.7; Fig. 5a), variable FeO^T (6.63–9.69 wt.%), and low ΣREEs (54.3–75.0 ppm;

186   Tables DR3–DR4). They have chondrite normalized REE distribution patterns with

187   negative slopes and moderately negative Eu anomalies (Eu/Eu* = 0.54–0.68) (Fig. 6a).

188   The primitive mantle-normalized trace element patterns (Fig. 6b) show depletions in

189   Sr, P, Nb, Ta, Zr, Hf, and Ti, and enrichments in Pr, Nd, and Sm.

190   Type-1B Cpx has higher FeO^T (9.67–11.0 wt.%), Cr (551–1033 ppm), Ni (185–187

191   ppm), and ΣREEs (135–189 ppm) but slightly lower X_{Mg} (70.0–76.5; Fig. 5b, Table 1)

192   than Type-1A Cpx. In addition, the Type-1B Cpx exhibit moderately negative Eu

193   anomalies (Eu/Eu* = 0.41–0.43, Fig. 6a). The primitive mantle-normalized trace

194   element patterns (Fig. 6b) of both sub-types are similar.

195   Normally zoned Cpx is subhedral, with slightly darker cores and brighter rims (Fig.

196   5c–5d). The cores exhibit high X_{Mg} (76.1–80.9; Fig. 5d, Table 1) and Cr contents

197   (1210–1377 ppm) but low ΣREEs (53.7–60.9 ppm). Their chondrite-normalized REEs

198   (Fig. 6c) display weakly negative Eu anomalies (Eu/Eu* = 0.73–0.78). The Type-2 Cpx

199   cores show significant depletions in HFSEs (e.g., Nb, Ta, Zr, Hf, and Ti), K, and P and

200   enrichments in Pb and Nd (Fig. 6d). In comparison with the Type-2 Cpx cores, their

201   rims have slightly higher FeO^T (8.75–9.92 wt.%) and ΣREEs (139–245 ppm), but lower

202   MgO (12.4–14.6 wt.%) contents and X_{Mg} (71.5–76.2). In addition, the Type-2 Cpx rims

203   have much stronger negative Eu anomalies (Eu/Eu* = 0.32–0.46, Fig. 6c) and larger

204   ranges of the Nb, Ta, and K concentrations (Fig. 6d).

205   Reversely zoned Cpx (Type-3 Cpx) is subhedral with brighter cores and darker rims

206   in BSE images (Fig. 5e–5f). The bright cores contain 14.3–16.0 wt.% of MgO with X_{Mg}

207   of 74.3–83.2, are classified as diopside and augite with Wo = 41.8–46.5 mol% (Fig.

208   4a), have slight negative Eu anomalies (Eu/Eu* = 0.82–0.97; Fig. 6e). As revealed by

209   primitive mantle-normalized trace element patterns, rims of the Type-3 Cpx show

210   depletions in HFSEs (e.g., Nb, Ta, Zr, Hf, and Ti), Ba, K, and P but enrichments in Nd,

211   Th, and Pb (Fig. 6f). By contrast, the dark rims contain slightly more MgO (14.6–17.1

212   wt.%) with X_{Mg} of 75.5–86.9 (Fig. 5f, Table 1), are augite with a lower Wo content

213   (42.1–44.1mol%). The BSE darker rims show similar primitive mantle-normalized

214   trace element patterns as the bright cores (Fig. 6e), but significantly higher Cr (3480–

215   5821 ppm) and Ni (244–346 ppm) contents.

216   One Type-3 Cpx from sample ZY17-4 was selected for LA-ICP-MS element

217   mapping. The Cr and Ni concentrations are higher in the rim than in the core (Fig.7),

218   likely reflecting a mafic magma recharge event. Element data of the corresponding

219   cross-section (Profile A) are provided in Table DR4. The Cr contents are lower in the

220   core (530–1500 ppm), but higher in the rim (2315–10375 ppm), which also applies to

221   Th and Sr, resulting in higher Sr/Y values in the rim (core: 4.45–9.49, rim: 5.85–18.5;

222   Table DR4).

223   **Orthopyroxene** are classified as enstatite (Fig. 4a) with a compositional range of

224     $Wo_{2.02-2.58}En_{78.9-80.9}Fs_{17.1-19.0}$. They have high Cr (1854–2261 ppm) and Ni (591–837

225   ppm) concentrations, high X_{Mg} of 80.9–82.8, and low abundances of Al_2O_3 (1.76–2.86

226   wt.%), TiO_2 (0.09–0.18 wt.%), and CaO (1.01–1.30 wt.%; Xie et al., 2023), and very

227   low ΣREEs (0.73–2.82 ppm; Table DR4).

228   On a LA-ICP-MS element map of one representative Opx of sample ZY17-15 (Fig.

229   8), the crystal shows a ubiquitous enrichment of Cr and Ni. Notably, the Sr/Y values

230   increase significantly along the cleavage, cracks, and edges of this crystal, probably

231   reflecting the influence of late-stage magmatic/hydrothermal activity.

232   **Amphibole.** Using the amphibole nomenclature and classification schemes of Leake

233   et al. (1997) and Li et al. (2020a), all the analyzed Amps are calcic ($Ca_B \geq 1.5$ atoms per

234   formula unit, $(Na + K)_A < 0.5$ atoms per formula unit) and are classified as

235   magnesiohornblende (Fig. 4b). There are no obvious compositional differences

236   between larger (Type-1 Amp) and smaller (Type-2 Amp) Amps (Table DR3–DR4).

237   They feature variable SiO_2 (46.5–51.0 wt.%), Cr (77–1038 ppm), and Ni (103–205

238   ppm) contents, moderately high X_{Mg} (63.1–74.6), and limited ranges in Al_2O_3 (4.22–

239   6.14 wt.%), TiO_2 (0.48–1.21 wt.%), and total alkalis ($Na_2O + K_2O$: 1.11–1.79 wt.%).

240   The Amps show high $\sum REEs$ (303–712 ppm), pronounced negative Eu anomalies

241   (Eu/Eu* = 0.14–0.29) and obvious depletion of HREE relative to LREE (Fig. 6g). They

242   are depleted in Ba, Sr, and Zr, but enriched in Nd and Sm (Fig. 6h).

243   LA-ICP-MS element mapping of one magnesiohornblende (Type-2 Amp) abutting

244   Opx (Fig. 8) confirms the compositional features (e.g., relatively high X_{Mg} and low

245   Sr/Y) of the single spot in-situ analysis.

246   **Biotite** exhibit relatively consistent Al^{IV} values (1.13 a.p.f.u. to 1.32 a.p.f.u.) and

247   contain high FeO^T (19.1–20.6 wt.%) and Al_2O_3 (12.7–14.6 wt.%) and moderate MgO

248   (11.1–14.3 wt.%); X_{Mg} are 54.4–61.5 (Table 1). According to the classification of

249   Foster (1960), the Bts are within the compositional range of magnesian biotite (Fig. 4c).

250   Nachit et al. (2005) discriminate magmatic or primary biotite from secondary or re-

251   equilibrated primary biotite in a $10 \times TiO_2$–FeO*(= FeO + MnO)–MgO ternary diagram

252   (Fig. 4d). On this diagram, all analyzed Bts plot in the primary biotite field. The trace

253   element compositions of the Bts vary slightly (Table DR4): they have low abundances

254   of Sr (1.74–6.74 ppm), relatively low concentrations of Y (0.15–0.33 ppm), with high

255   values of Sr/Y (17.5–43.8), relatively low ∑REEs (ranging from 0.30 to 4.12 ppm),

256   relatively high contents of Rb (317–601 ppm), Ba (471–6055 ppm), Nb (27.5–53.7

257   ppm), and Ni (191–283 ppm), but low abundances of Ta (1.00–4.79 ppm) and Hf (0.12–

258   0.28 ppm).

259   One Bt from sample ZY17-4 was selected for LA-ICP-MS element mapping (Fig. 9)

260   and acquisition of one cross-section (Profile B; Table DR4). The core of this Bt features

261   lower Sr, Cu, and Pb concentrations than the rim. The entire Bt shows high Sr/Y values

262   (7.32–174), relatively high X_{Mg} values (52.1–60.1), and high abundances of Ni (307–

263   459 ppm), Ba (2840–6438 ppm), and Rb (191–382 ppm). All these characteristics are

264   similar to those of the Bts described above based on single spot in-situ analysis.

265   **Plagioclase** are mainly classified as oligoclase–andesine and subordinately as

266   labradorite (Fig. 4e), with anorthite contents (An) of 14.9–51.6 mol-% (Tables 1 and

267   DR3–DR4). We identify two distinct Pl populations: sieve-textured Pl cores (Type-1

268   Pl) with rim overgrowths (Fig. 5g), and unreacted Pls devoid of sieve textures (Type-2

269   Pl, Fig. 5h). The sieve-textured Pl cores (Type-1 Pl) exhibit higher An (32.9–51.6

270   mol-%) and Rb contents (10.4–318 ppm) than their overgrowth rims (Type-2 Pl; 15.6–

271   29.4 mol-% and 0.92 ppm, respectively; Table 1). Type-2 Pls are homogeneous in

272   composition, and contain low An (14.9–26.9 mol-%) and Rb (0.31–4.28 ppm; Table 1).

273   The composition of the sieve-textured Pl rims is similar to that of the Type-2 Pl, we

274   therefore propose both of them grew at the same time. In other words, we consider the

275   rims on Type-1 grains as part of the same geochemical group (Type-2 Pl). Both types

276   of Pls have variable ∑REEs abundances (12.8–45.3 ppm), high Sr (865–1519) ppm but

277   extremely low Y contents (0.10–0.22 ppm), and high Sr/Y (4254–14513) (Table 1).

278   LA-ICP-MS element mapping of several Pl inclusions within the Amp featured in

279   Fig. 8 shows that Pls have high Sr contents (~ 66.9–1860 ppm) and high Sr/Y (~ 25.3

280   to 62600) and Sr/Rb (~ 17.0 to 66200) values, similar to Type-2 Pls and sieve-textured

281   Pl rims described above. This indicates that the appearance of these Pls included by

282   Amp might be the result of the sectioning-effect (Pls protruding into Amp from the top

283   or bottom of the thin section), and these Pls do not crystallize earlier than hornblende.

284   The similar sectioning-effect also occur between Amp and pyroxene (Fig. 7).

285   It should be noted that HREE are sometimes close to or below the detection limits in

286   Pl, and the extremely high Sr/Y values of some Pl crystals are not accurate.

287   **K-feldspars** are sanidine, and their orthoclase (Or) contents range from 72.4 to 95.8

288   mol-% (Table DR3). They display very high positive Eu anomalies (Eu/Eu* > 4.01,

289   Tables 1 and DR4), high concentrations of Rb (197–338 ppm), Ba (1077–5925 ppm),

290   and Sr (535–1029 ppm), low contents of Y (≤ 0.1 ppm, the Y contents of several crystals

291   are below the detection limit), with correspondingly extremely high Sr/Y values (>

292   5345; Table 1).

293

294   **Crystal size distribution (CSD)**

295   We analyzed a 354 mm^2 area across two thin sections and observed 2246 Amp with

296   non-poikilitic textures covering an area of 41.4 mm^2 (see Table DR5 for CSD analysis

297   data of these Amps). The crystal sizes range from 0.01 mm to 0.4 mm (Fig. 10a–10b).

298   On a plot of the logarithm of the crystal population density (ln(n)) versus size (L) (Fig.

299   10c–10d), the CSDs of both samples exhibit a significant change in slope, from a

300   shallow gradient in the larger crystals to a steeper gradient in the smaller crystals. As

301   shown in Fig. 10 the Amp CSD may be separated into at least two groups, and the

302   regression curve equations of different groups of Amp CSDs are given in the figure.

303   Linear CSD curves generally indicate that the crystal population densities are primarily

304   controlled by crystal nucleation and growth, whereas kinked CSDs are usually

305   explained by the mixing of different crystal generations (Burney et al., 2020; Higgins,

306   1996; Morgan et al., 2007; Wang et al., 2019; Yang et al., 2010).

307

308   **DISCUSSION**

309   A key problem in interpreting adakitic rocks in continental settings is that felsic

310   magmatic rocks commonly represent an assembly of interstitial melts and several

311   crystal populations with different origins (Namur et al., 2020 and references therein).

312   In the case of the Zhuyuan granodiorites, we also hypothesize that their high-Sr/Y signal

313   could be derived from multiple batches of magmas within an open magmatic system.

314   We combine whole-rock geochemical characteristics with in-situ mineral compositions

315   to highlight the potential role of magma mixing in the formation of the Zhuyuan

316   granodiorites. The relevant discussion is provided in the "Supplementary Materials".

317   Furthermore, in subsequent discussions, we focus on the origin and evolutionary

318   process of the high-Sr/Y signature of the Zhuyuan granodiorites.

319

320   **Crystal–melt equilibria**

321   Assuming that the minerals were in equilibrium with the corresponding host melts

322   during crystallization, the geochemical compositions of the parental magmas may be

323   estimated with compositionally appropriate mineral-melt partition coefficients (K_D;

324   Table DR6). Based on petrographic observations (Fig. 3), we have determined the

325   complex mineral associations of the Zhuyuan granodiorites, which is mainly composed

326   of 11 kinds of minerals, including three types of Cpxs, Opx, two types of Amps, two

327   types of Pls, Bt, Kfs and Qtz. Because there is no difference in compositional

328   characteristics and crystallization conditions between the Type 1 Amp and Type-2 Amp

329   (Tables DR3–DR4), we consider them to have formed in the same trans-crustal

330   magmatic system. In addition, Bt, Kfs, and Qtz are the interstitial minerals, and are the

331   most easily identifiable late-stage crystalline mineral phases, which could have possibly

332   formed in the same magmatic environment. Thus, we provisionally define eight magma

333   environments (A, B, C, D, E, F, G, and H) in which different types of minerals

334   crystallized (Table 2). Based on the mineralogical characteristics, we initially classified

335   the magmatic environments into four subtypes: A-D, E, F-G, and H. In the following,

336   these magma environments could be identical, similar, or distinct. We will further

337   discuss the significance of these below in Section 'Crystal cargoes in the magmatic

338   plumbing system'

339   1. Environments A, B, C, and D: the parental magmas, in which the various types of

340   pyroxenes crystallized

341   We use the Fe–Mg exchange coefficient ($K_D(Fe–Mg)^{Cpx–liq}$) value of 0.27 ± 0.03 to

342   calculate the Mg# of melts in equilibrium with Cpxs (Pichavant and Macdonald, 2007;

343   Putirka, 2008; Sisson and Grove, 1993). Considering the high X_{Mg} of pyroxenes in this

344   study, we use partition coefficients between pyroxene and basaltic melts to calculate

345   trace-element compositions of the melt in equilibrium with the pyroxene (Bédard, 2001;

346   Elkins et al., 2008). Calculated trace-element concentrations of melts in equilibrium

347   with pyroxenes are listed in Tables 2 and DR6.

348   The calculated equilibrium melts (Environment A) of the Type-1 Cpx have a wide

349   range of Mg# (39.5–55.5) and values of Type-1A (39.5–47.7) and Type-1B Cpx (42.7–

350   55.5) overlap. Melts in equilibrium with Type-1A Cpx exhibit moderately negative Eu

351   anomalies (Eu/Eu* = 0.54–0.68; Fig. 11a), relatively high Ce/Pb values (83.6 on

352   average), and low Sr/Y values (4.52–7.27) (Fig. 12). Type-1B Cpx equilibrium melts

353   have more pronounced negative Eu anomalies (Eu/Eu* = 0.41–0.43), comparable

354   Ce/Pb values (78.8–156), and lower Sr/Y values (1.97–2.57). Type-1A and Type-1B

355   Cpx equilibrium melts show similar chondrite-normalized rare earth element

356   distribution patterns.

357   The melts (Environment B) in equilibrium with Type-2 Cpx have Mg# of 41.3 to

358   54.2. The melts in equilibrium with Type-2 Cpx cores display slight to moderate Eu

359   anomalies (Eu/Eu* = 0.72–0.77; Fig. 11b) and low Sr/Y (11.3–12.2) but high Ce/Pb

360   values (15.5 on average). Compared with the cores, the melts in equilibrium with Type-

361   2 Cpx rims exhibit more significant negative Eu anomalies (Eu/Eu* = 0.32–0.46),

362   higher ∑REE contents and Ce/Pb values (41.2–133), but lower values of Sr/Y (1.97–

363   3.93).

364   The melts (Environment C) in equilibrium with Type-3 Cpx span a large range of

365   Mg#. The melts in equilibrium with Type-3 Cpx core have Mg# of 44.7–58.1, high

366   Ce/Pb (23.9–55.7) and Sr/Y (17.0–47.6) values, and slight to negligible negative Eu

367   anomalies (Eu/Eu* = 0.82–0.96; Fig. 11c). Compared with the cores, the melts in

368   equilibrium with Type-3 Cpx rim have on average higher Mg# (48.4–65.0), high Sr/Y

369   (37.6–42.4, Fig. 12a) and Ce/Pb values (12.1 on average, Fig. 12b), and negative Eu

370   anomalies (Eu/Eu* = 0.85–1.02). The melts (Environment D) in equilibrium with Opx

371   have high Mg# of 56.8–59.9 (Kd = 0.31; Price et al., 2012), high mean Ce/Pb values of

372   11.4 (Fig. 12b), but moderate Sr/Y values (11.7–21.8).

373   2. Environment E: the parental magmas in which two types of Amps crystallized

374   Amp–liquid partition coefficients for trace elements were calculated using mineral

375   composition model proposed by Humphreys et al. (2019) and Shimizu et al. (2017).

376   The melts in equilibrium with Amp (Tables 2 and DR6) feature low Mg# (21.7–34.6),

377   negative Eu anomalies (Eu/Eu* = 0.13–0.29; Fig. 11d), and relatively low Sr/Y (4.13–

378   21.6), and medium Ce/Pb values (8.92 on average).

379   3. Environments F and G: the parental magmas in which both sieve-textured and clear

380   Pl crystallized

381   The partition coefficients of Sr between plagioclase and silicate melts depends on the

382   chemical composition of plagioclase (Bindeman et al., 1998). Plagioclase–silicate melt

383   partition coefficients for Sr, Rb and REE were calculated using mineral composition

384   model proposed by Sun et al. (2017). Partition coefficients for Y and Ba are from Nash

385   (1985). The melts (Environment F) in equilibrium with Type-1 Pl have relatively high

386   Sr/Y (218–315) and Sr/Ba values (0.4–1.27), low Sr/Rb (0.2–6.81) and Ce/Pb (3.18–

387   5.59), and positive Eu anomalies (Eu/Eu* = 5.44–8.16; Table 2). By contrast, the melts

388   in equilibrium with Type-2 Pl (Environment G) display lower Ce/Pb (1.55–2.27),

389   higher Sr/Rb (26.4–252) and Sr/Ba values (0.99–1.67), the same high Sr/Y values

390   (96.5–375), and more obvious positive Eu anomalies (Eu/Eu* = 4.85–25.4).

391   4. Environment H: the parental magmas in which Bt, Kfs, and Qtz crystallized

392   Bt and Kfs mainly appear as interstitial minerals, which are the products of late-stage

393   melt. Therefore, we select the partition coefficients of trace elements for melts in

394   equilibrium with Bt and Kfs refer to studies on silicic magmas (Nash, 1985; Sun et al.,

395   2017; Schnetzler and Philpotts 1970; Ewart and Griffin 1994). The Y content in the

396   analyzed Kfs samples is all lower than 0.1 ppm. Here, we assume 0.1 ppm Y to calculate

397   the Y content of equilibrium melt. The actual content will be much lower than the

398   calculated value, but this does not affect the subsequent discussion. The melts in

399   equilibrium with Bt have high Sr/Y (49.5–124) but low Ce/Pb values (0.01–0.07; Table

400   2). The melts in equilibrium with Kfs are characterized by high Sr/Y values (>> 29),

401   low Ce/Pb values (0.05–0.84) and variable Eu contents (0.35–1.47 ppm; Table 2).

402

403   **Crystallization Conditions**

404   The temperature and pressure of the magma reservoir is essential for our

405   understanding of the origin of different minerals (Blundy & Cashman, 2008).

406   Experimental petrology studies have shown that the Cpx and Amp are sensitive to

407   temperature and pressure during crystallization. Thus, thermobarometers based on

408   compositions of Cpx or Amp are commonly used to estimate the physical conditions of

409   magma reservoirs (e.g., Higgins et al., 2022, Neave et al., 2019, Neave & Putirka, 2017,

410   Putirka, 2016, Putirka, 2008). We chose the thermometer (Eq. 32d in Putirka et al.,

411   2008) and the barometer (Eq. 32a in Putirka et al., 2008) based on Cpx compositions

412   only to estimate the crystallization temperatures and pressures. The thermobarometer

413   we used produces one standard error of estimate (1se) of ±58 °C and ±0.31 GPa,

414   respectively (Putirka et al., 2008). Due to the poikilitic textures and the irregular

415   corrosion boundary between pyroxene and Amp, the thermochemical reactions at/near

416   the pyroxene-Amp boundary is significant. It may lead to a large error in conditions

417   with the pyroxene compositions close to the reaction boundary, so we only selected the

418   spot analyses away from the boundary for the corresponding calculation (Table 3).

419   The estimate temperature based on Type-1, Type-2 and Type-3 Cpx range from

420   1150°C to 1191°C, 1130°C to 1192°C and 1173°C to 1211°C, respectively. Estimated

421   pressures vary from 0.48 to 0.75 GPa, 0.4 to 0.84 GPa and 0.38 to 0.61 GPa,

422   respectively. These values correspond to crystallization depths of 18.1–28.4 km, 15.3–

423   31.7 km and 14.2–23.0 km, respectively, indicating that Type-1 and Type-2 Cpx

424   crystallized in magma reservoirs at approximately similar depths, while the Type-3 Cpx

425   formed at shallower crustal levels.

426   In addition, we use the single-phase Amp thermobarometer in Higgins et al. (2022)

427   for determining the crystallization conditions of both types of Amps in this study, which

428   is calibrated using random forest machine learning. The random forest machine learning

429   algorithm can recover subtle non-linear relationships between phase compositions,

430   pressure, and temperature (Higgins et al., 2022). Therefore, this approach is superior

431   for retrieving the physical conditions of Amp formation in open magmatic systems. The

432   temperatures calculated from Amp compositions of the Zhuyuan granodiorites range

433   from 744 ± 38 °C to 814 ± 54 °C. The pressure of Amp crystallization varies from 0.2

434   ± 0.02 GPa to 0.35 ± 0.18 GPa, corresponding crystallization depth ranges from 7.64

435   to 13.4 km. The specific calculation results are listed in Tables 2 and DR3.

436   The Ti-in-zircon thermometer has become an accurate and precise monitor of both

437   igneous and metamorphic thermal history (Bloch et al., 2022, Fu et al., 2008, Schiller

438   & Finger, 2019, Watson et al., 2006). Apparent temperatures for zircon crystallization

439   for the Zhuyuan granodiorites were calculated using the Ti-in-zircon thermometer

440   (Watson et al., 2006). We estimated the apparent peak temperature for the zircons from

441   the Zhuyuan granodiorites (Xie et al., 2023), ranging from 721°C to 787°C (30 zircons;

442   Table DR2). In addition, some of higher apparent temperatures range from 893°C to

443   989°C (3 zircons).

444   The zircons from the Zhuyuan granodiorite show obvious negative Eu anomalies

445   (0.01–0.64, Table DR2; Xie et al., 2023), indicating that they crystallized later than

446   plagioclase or contemporaneously with plagioclase. Considering that Type-2 Pl belongs

447   to the late-stage mineral assemblage, it is reasonable to assume that the crystallization

448   temperatures of Type-2 Pl are close to, or overlapping with, those of zircons. The water

449   contents of the magma (Table DR3), from which the Type-2 Pl crystallized, are

450   calculated using the plagioclase–liquid hygrometer of Waters and Lange (2015), for

451   which the impact of the pressure is negligible but the effect of the temperature is

452   significant (Lange et al., 2009; Waters and Lange, 2015). We have used the whole-rock

453   compositions of our samples as proxies for the primitive melt compositions. However,

454   the hygrometer we employed is insensitive to variations in liquid compositions, and is

455   thus well suited for our samples that have undergone an open-system crustal evolution.

456   Assuming the maximum apparent temperatures for zircon crystallization, we calculate

457   magmatic water contents ranging from 6.12–6.46 wt.% based on rims of Pl with sieve

458   texture and values ranging from 6.11–6.50 wt.% for the Type-2 Pl. Assuming the

459   minimum zircon crystallization temperatures yield values of 7.99–8.34 wt.% for rims

460   of Pl with sieve textures, and 7.99–8.38 wt.% for Type-2 Pl. Consequently, we conclude

461   that the high Sr/Y magma reservoir was hydrous (H_2O contents > 4 wt.%; Patiño Douce,

462   1999; Collins et al., 2020) when late-stage Pl (Type-2 Pl) crystallized.

463

464   **Crystal cargoes in the magmatic plumbing system**

465   Based on the crystallization conditions of different minerals in the Zhuyan pluton

466   and the compositions of equilibrium melts, we attempted to construct an open magmatic

467   plumbing system model, which is illustrated in Fig. 13. The melts in equilibrium with

468   both Type-1 Cpx and Type-2 Cpx (Environments A and B) are likely indicative of

469   extensive fractional crystallization resulting in a large range of Ni and Cr contents. In

470   support this interpretation, we note that Amps were formed at the expense of Cpx likely

471   in a peritectic reaction relationship (Fig. 3 and 5), and we speculate that both Type-1

472   Cpx and Type-2 Cpx are "antecrysts" that crystallized from separate mafic to

473   intermediate magma batches. Our geobarometry data indicate that both Type-1 Cpx and

474   Type-2 Cpx formed at depths of 15.3–31.7 km (Tables 3 and DR3); whereas crystal–

475   melt equilibria (Environments C) indicate that the Type-3 Cpx cores are also likely

476   antecrysts characterized by a more primitive rim overgrowth that was in disequilibrium

477   with the host magmas. High Cr and Ni concentrations and X_{Mg} in the Type-3 Cpx rims

478   indicate the overgrowth is the result of mafic magma replenishment (Fig. 5f and Fig.

479   7). The estimated depths where Type-3 Cpx crystallized vary from 14.2 km to 23.0 km

480   (Table 3). The relic Opx with a resorbed boundary is also defined by high Ni and Cr

481   contents, and also indicative of an antecryst origin (Environments D). The overgrowth

482   of relic Opx by Apm implies Opx entered a hydrous magma reservoir.

483   The estimated crystallization depths, at which Amps crystallized, vary from 7.6 km

484   to 13.4 km (Table 3). There is no statistical overlap in terms of crystallization depths

485   between Amps and pyroxenes, indicating that they may have crystallized at different

486   magma reservoirs in the crust, and pyroxenes were overgrown by Amps in a magma

487   reservoir at shallow crustal levels. The lobate boundary between Amp and Pl (Fig. 3e),

488   and the corroded grains of Amp (Fig. 3g) indicate that there is a reactive relationship

489   between Amp and Pl. In addition, some Amps display poikilitic textures with Bts (Fig.

490   3c), indicating that they crystallized from different melts. Considering the low Sr/Y

491   values and relatively high Ce/Pb values of the melts in equilibrium with both large and

492   small Amps, it is likely that these Amps crystallized from other magma reservoirs that

493   are compositionally different from the environments that crystallized the Type-2 Pl,

494   Kfs, and Bt. Therefore, we tend to consider Amps as antecrysts.

495   The sieve-textured Pl core (Type-1 Pl) is likely an antecryst due to its resorbed and

496   most calcic nature, and its equilibrium melt (Environments F) has lower Sr/Rb and

497   Sr/Ba values and higher Ce/Pb values in comparison with melt in equilibrium with the

498   Type-1 Pl rim.

499   We speculate that Environments G, and H that crystallized Type-2 Pl, Bt, Kfs and

500   Qtz are similar due to similar Eu/Eu*, Sr/Y and Ce/Pb values (Figs. 11–12; Tables 1–

501   2). Furthermore, their petrography exhibits the characteristics of paragenetic mineral

502   assemblages (Fig. 3). Thus, these four (Type-2 Pl, Bt, Kfs and Qtz) are reasonably

503   interpreted as orthocrysts which crystallized during the late stage of magma evolution,

504   which is also consistent with the petrographic observations (Fig. 3, Table 1).

505   Melts in equilibrium with pyroxenes collectively display low Sr/Y values, and it is

506   unlikely that these melts developed adakitic signatures through crystal fractionation.

507   Although hornblende fractionation may drive magmas toward high Sr/Y values

508   (Castillo et al., 1999), in this case, we would expect that the melts in equilibrium with

509   the Amps would also gradually evolve towards higher Sr/Y values. Contrary to

510   prediction, all melts in equilibrium with large (Type-1) and small (Type-2) Amps

511   collectively have low Sr/Y values (4.13 to 21.6). From a whole-rock perspective, a

512   negative correlation between $(Dy/Yb)_N$ and $(La/Yb)_N$ is expected for Amp-dominant

513   fractional crystallization (Davidson et al., 2007; He et al., 2011). However, the two

514   ratios show a slight positive correlation for the Zhuyuan granodiorites (grey dashed line

515   with arrowhead in Fig. DR2a).

516   In summary, we identify several different magma batches (environments). Three

517   types of Cpxs and Opx are antecrysts from mafic melts with low Sr/Y but high Ce/Pb

518   values. The different groups of Amp testify to the presence of more than two different

519   melts with low Sr/Y and medium Ce/Pb values. It is difficult to determine whether these

520   Amps have genetic connections with the pyroxenes through fractional crystallization.

521   Meanwhile, the antecrystic Type-1 Pl cores likely crystallized in melt with a more calcic

522   composition than Type-2 Pl. Finally, the late-stage orthocrysts including the Type-2 Pl,

523   Bt, Kfs, and Qtz were probably derived from an intermediate to felsic source with high

524   Sr/Y properties.

525

526   **High Sr/Y melts produced by anatexis of intermediate–felsic rocks under water-**

527   **fluxed condition**

528   Experimental studies show that the fluid-absent breakdown of micas from the

529   intermediate–felsic protoliths may produce melts with low Sr/Rb and Sr/Ba, and

530   notable negative Eu anomalies (Harris et al., 1993; Weinberg and Hasalová, 2015; Zhou

531   et al., 2020). This is consistent with the presence of Kfs as a coexisting peritectic phase

532   in melts generated by muscovite and/or biotite dehydration melting (Harris et al., 1993).

533   In comparison, water-fluxed melting of intermediate–felsic rocks (e.g., diorite,

534   granodiorite, etc.) at mid-crustal levels (0.6–1.2 GPa) will generate felsic magmas with

535   high Sr/Y (Reichardt and Weinberg, 2012; Zhan et al., 2020). Water-fluxed melting

536   (Amp + Pl + Qtz + vapour = melt), where preferential feldspar consumption over micas

537   may leave an Amp-rich residue in the source, leads to felsic melts expected to have

538   positive Eu anomalies, low Rb contents, and high Sr/Rb and Sr/Ba values (Harris et al.,

539   1993; Reichardt and Weinberg, 2012). Simultaneously, these felsic melts may display

540   high Al_2O_3 (> 16 wt.%), low $Fe_2O_3^T$ (< 4.5 wt.%) and elevated Sr concentrations, while

541   exhibiting HREE depletions (Beard and Lofgren 1991; Frost et al. 2016; Zhang et al.,

542   2021).

543   We hypothesize that the resorbed, sieve-textured Pl (Type-1 Pl) core with a relatively

544   high Rb content (10.4–318 ppm) indicates an antecrystic origin (Table 1). By contrast,

545   the high Sr/Y melts in equilibrium with the Type-2 Pl display low Rb contents, high

546   Sr/Rb and Sr/Ba values, and positive Eu anomalies, suggesting that the high Sr/Y melts

547   in equilibrium with them likely formed due to partial melting of intermediate to felsic

548   rocks under water-fluxed conditions. This inference is consistent with the finding that

549   Type-2 Pl crystallized under water-rich conditions (see Section 'Crystallization

550   Conditions'). Therefore, the high-water contents of the melts in equilibrium with the

551   Type-2 Pl most likely resulted from the anatexis of intermediate–felsic rocks under

552   water-fluxed conditions.

553   Although the whole-rock composition is a mixture of multiple batches of magmas,

554   the late-stage mineral assemblage still dominates the whole-rock compositions because

555   the volume percentage of the rim of Type-1 Pl, Type-2 Pl + Bt + Kfs + Qtz is greater

556   than 75%. Therefore, the whole-rock compositions reflect the first-order characteristics

557   of late-stage melting despite the presence of antecrysts which functions to dilute the

558   high-Sr/Y bulk rock composition. In addition, whole-rock compositions display high

559   Al_2O_3 (15.64–17.32 wt.%) and low $Fe_2O_3^T$ (3.71–5.28 wt.%), and show pronounced

560   HREE depletions $((La/Yb)_N = 15–21)$. Meanwhile, we note that the addition of

561   antecrystic mafic minerals resulted in higher concentrations of $Fe_2O_3^T$ and decreased

562   Al_2O_3 in whole-rock compositions. Accordingly, the late-stage felsic melt typically has

563   higher Al_2O_3, but lower $Fe_2O_3^T$ contents. However, melts produced by water-flux

564   melting of intermediate to felsic rocks under 0.6–1.2 GPa are generally characterized

565   by high Al_2O_3 (> 16 wt.%) and low $Fe_2O_3^T$ (< 4.5 wt.%) (Beard & Lofgren, 1991, Frost

566   et al., 2016), which coincide with late-stage melt compositions of the Zhuyuan

567   granodiorites.

568   Moreover, the low Rb and high Sr contents of the melts in equilibrium with the Type-

569   2 Pl also argues against an extensive fractionation process, thus ruling out the possibility

570   that the high-water content is caused by the high degrees of fractional crystallization

571   (Wang et al., 2017). Accordingly, we conclude that the late-stage orthocryst assemblage

572   represents the near-primary high-Sr/Y composition derived from water-fluxed melting

573   of intermediate to felsic source rocks. Meanwhile, the high Sr/Y signal of felsic melts

574   was diluted by magma recharge, leading to more mafic compositions in the bulk.

575

576   **Modeling for source rock compositions**

577   To further elucidate the dilution of the high Sr/Y properties of late-stage felsic melt

578   by antecrysts with low Sr/Y values, and to identify the possible sources of these late-

579   stage melts, we carried out simple quantitative simulations. We assume sample ZY17-

580   8 (Opx free) to represent a melt composition that is least affected by the low-Sr/Y

581   antecrysts, given that it is one of the samples with the highest SiO_2 contents (67.16

582   wt.%) and relatively low Mg# value (50; Table DR2; Xie et al., 2023). The proportion

583   of various rock-forming minerals in the sample is estimated using mass balance

584   calculations (Li et al., 2020b). The calculated results (Table DR7) are in good

585   agreement with the petrographic observations. We estimate the interstitial magma

586   compositions (i.e., the 'undiluted melt') by removing the mass of antecrysts. After

587   deducting the intermediate-mafic antecrysts, the remaining bulk composition shows

588   high SiO_2 content (70.33 wt.%), low Mg# value (31.4), and significantly increased Sr

589   content (555 ppm) and Sr/Y value (132). By comparing the whole-rock Sr/Y value

590   (36.3) of sample ZY17-8, we confirm that the adaktic signals of the high-Sr/Y melts

591   are significantly weakened by the incorporation of intermediate-mafic antecrysts. Thus,

592   antecryst entrainment is crucial for understanding the geochemical diversity of granitic

593   magmas with an adakitic signature, and whole-rock compositions of granitoids

594   probably deviate remarkably the original melt compositions (Werts et al., 2020).

595   To quantitatively simulate the nature of the source rock, we assumed that the high

596   Sr/Y 'undiluted melt' calculated based on sample ZY17-8 with the highest Zr/Hf value

597   is the near-primary melt derived from partial melting of intermediate–felsic source rock.

598   When the residual solid phase and melt fraction (i.e., the degree of partial melting) can

599   be reasonably constrained, the trace element compositions of the source rock can be

600   calculated from known melt compositions using the batch melting model of Shaw

601   (1970):

$$C_0^i = C_L^i * (D_{Bulk}^i + F * (1 - D_{Bulk}^i))$$

603   where C_0^i and C_L^i represent the concentration of element i in the source rock and melt,

604   respectively; F is the melt fraction of source rock; and D_{Bulk}^i is the bulk partition

605   coefficient of element i, which is the sum of the partition coefficient (D) for each

606   mineral multiplied by the weight percentage of corresponding mineral in the residual

607   solid phase ($D_{Bulk}^{i}=D_{S}^{i}*W_{S}$).

608   We compared the major elements of the undiluted melt with that of experimental

609   melts derived from the partial melting of a range of crustal protoliths compiled by Gao

610   et al. (2016), Weinberg and Hasalová (2015), and Zhan et al. (2020). To find the best

611   matching experimental melt compositions, the sum of square of the deviations of each

612   major element oxides between experimental melts and undiluted melt was calculated.

613   Based on the discussion above regarding water-fluxed melting, only the melting

614   experiments of intermediate–felsic source rocks under water-presence conditions are

615   considered here. We report the four best matching experimental melts (the sum of

616   squared of the deviations is less than 10), and the corresponding partial melting

617   pressures, melt fractions, and proportion of residual solid phases (Experiments 1–4 in

618   Table DR7).

619   We also explore the trace element composition of the source rocks (e.g., REE, Sr,

620   and Y) of undiluted melt (inferred from sample ZY17-8) using compositionally

621   appropriate mineral partition coefficients (Table DR7) and the batch melting equation.

622   The calculated trace element compositions under different melting conditions

623   corresponding to the four experiments are listed in Table DR7 and are plotted in Fig.

624   14. The modeling results show that different source rocks may have different

625   implications for constraining the derivation of high Sr/Y granites.

626   We find that the calculated trace elements of intermediate-felsic sources

627   corresponding to different melting conditions are characterized by significant positive

628   Eu anomalies (1.66-3.96), indicating that the plagioclase accumulation in the source

629   rocks is particularly important for melting to produce high Sr/Y melt. This is consistent

630   with the interpretations proposed by Shi et al. (2022) and Wang et al. (2022). In addition,

631   we find the following results:

632   (1) In the experimental runs under high pressure conditions (Exp 1, 800°C, 1.5 GPa,

633   5 wt% H_2O; Koester et al., 2002), the partial melting degree of source rocks is relatively

634   low (21%). The calculated source rock shows a low Sr/Y value (21.9), which is mainly

635   due to the fact that the source rock contains a considerable proportion of garnet (Grt)

636   and Amp. Therefore, for Exp 1 to produce the high Sr/Y melt, it is necessary to have a

637   significant amount of residual Y-rich minerals dominated by Grt in the source.

638   (2) In the experimental runs under moderate pressure conditions (Exp 2, 850°C, 1

639   GPa, 2 wt% H_2O; García-Arias et al., 2012), the partial melting degree of source rocks

640   is relatively high (61%), with minor Grt in the residues (< 1 wt%). Our modeling result

641   for source rock exhibits a relatively high Sr/Y value (98.9), which is most likely due to

642   the high abundance of feldspar but low abundance of Grt in the source. Moreover, the

643   high Sr/Y signal of the partial melt is mainly attributed to significant melting of feldspar

644   in the source rocks, releasing large amounts of Sr into the melt.

645   (3) In the moderate-low pressure melting experiment of Grt-bearing metasedimen-

646   tary gneiss (Exp 3, 800°C, 0.7 GPa, 5.1 wt% H_2O; Ward et al., 2008), the degree of

647   partial melting in the source rocks is relatively high (67%). Feldspar is absent in the

648   residues, but some Y-rich minerals (Grt + Amp) are retained. In addition, the calculated

649   source rock shows the least obvious positive Eu anomaly (Eu/Eu* = 1.66) and have

650   much lower Sr content (183 ppm) and Sr/Y value (12.6). These results indicate that the

651   high Sr/Y signal of the partial melt requires concurrent feldspar melting and retention

652   of an Y-rich mineral in the residue.

653   (4) In the low-pressure melting experiment of biotite tonalite (Exp 4, 690°C, 0.599

654   GPa, H_2O-satuated; Watkins et al., 2007), the moderate degree of partial melting (32%)

655   produces a melt with major elements comparable to undiluted melt of sample ZY17-8.

656   The calculated trace elements of this biotite tonalite (source rock) is characterized by

657   strongly fractionated REE patterns (Fig. 14), strong positive Eu anomalies and high

658    $(La/Yb)_N$ (265) and Sr/Y (191) values. Furthermore, Y-rich minerals are absent in the

659   residues of Exp 4, and some feldspar is present. Therefore, the high Sr/Y signal of the

660   partial melt corresponding to Exp 4 is completely inherited from the source rock, mainly

661   through the melting of large amounts of feldspar under water-saturated condition.

662   In summary, for intermediate-felsic sources, water-present to water-saturated partial

663   melting at high to low pressures (corresponding to 0.599 GPa to 1.5 GPa) may produce

664   the high Sr/Y and $(La/Yb)_N$ signatures of the Zhuyuan granodiorites. We also note that

665   high Sr/Y and $(La/Yb)_N$ values are produced even when the source rock contains no or

666   very little Y-rich minerals (Grt + Amp). However, when Y-rich minerals are enriched in

667   source rocks, high-Sr/Y melts may also be produced by melting a large amount of feld-

668   spar while retaining considerable amounts of Y-rich minerals in the sources. Thus, we

669   suggest that the Zhuyuan high-Sr/Y melts were produced under various pressure con-

670   ditions, and not limited to high pressures (> 1.5 GPa). Previous studies have also con-

671   firmed that felsic melt with adakitic signatures can be generated at much lower pres-

672   sures (0.6–1.2 GPa, e.g., Zhan et al., 2020). Accordingly, high Sr/Y adakitic granites

673   cannot be directly used to infer the thickness of the continental crust when the source

674   is a felsic to intermediate protolith melted under water-fluxed conditions.

675

676   **IMPLICATIONS**

677   Our study highlights that the adakitic signatures in plutonic rocks are not only

678   significantly influenced by the stability (e.g., high pressure conditions) and modal

679   abundance of source residual minerals (Moyen, 2009), but also by the variations in

680   source lithology and water content (Johnson et al., 2017; Ma et al., 2015; Pourteau et

681   al., 2020). For example, magmas with adakitic affinity can be generated by water-fluxed

682   melting of intermediate to felsic rocks under various pressures (Moyen, 2009). In

683   addition, antecryst recycling processes in granitic magma systems are common (Barnes

684   et al., 2019; Oppenheim et al. 2021). Injection by diverse magma batches with various

685   types of non-orthocrysts could significantly obscure the evolutionary path of the

686   primary magmas. Our study clearly reveals that the high Sr/Y signal of primary adakitic

687   melts can be diluted by the addition of non-orthocrysts or other batches of melts with

688   low Sr/Y values. From this perspective, estimates of paleo-crustal thickness based on

689   whole-rock granitic compositions (Profeta et al., 2015; Hu et al., 2017) should be

690   considered with caution due to the possibility of open-system behavior that may have

691   affected original melt compositions.

692

ACKNOWLEDGEMENTS AND FUNDING

704

REFERENCES CITED

706   Bach, P., Smith, I.E.M. and Malpas, J.G. (2012) The Origin of Garnets in Andesitic

707   Rocks from the Northland Arc, New Zealand, and their Implication for Sub-arc

708   Processes. Journal of Petrology, 53, 1169–1195.

709   Barnes, C.G., Werts, K., Memeti, V. and Ardill, K. (2019) Most Granitoid Rocks are

710   Cumulates: Deductions from Hornblende Compositions and Zircon Saturation.

711   Journal of Petrology, 60, 2227–2240.

712   Beard, J.S. and Lofgren, G.E. (1991) Dehydration melting and water-saturated melting

713   of basaltic and andesitic greenstones and amphibolites at 1, 3, and 6. 9 kb. Journal

714   of Petrology, 32, 365–401.

715   Bédard, J.H. (2001) Parental magmas of the Nain Plutonic Suite anorthosites and mafic

716   cumulates: a trace element modelling approach. Contributions to Mineralogy and

717   Petrology, 141, 747–771.

718   Bindeman, I.N., Davis, A.M. and Drake, M.J. (1998) Ion microprobe study of

719   plagioclase-basalt partition experiments at natural concentration levels of trace

720   elements. Geochimica et Cosmochimica Acta, 62, 1175–1193.

721   Bloch, E.M., Jollands, M.C., Tollan, P., Plane, F., Bouvier, A.S., Hervig, R., Berry, A.J.,

722   Zaubitzer, C., Escrig, S., Müntener, O., Ibañez-Mejia, M., Alleon, J., Meibom, A.,

723   Baumgartner, L.P., Marin-Carbonne, J. and Newville, M. (2022) Diffusion

724   anisotropy of Ti in zircon and implications for Ti-in-zircon thermometry. Earth and

725   Planetary Science Letters, 578, 117317.

726   Blundy, J. and Cashman, K. (2008) Petrologic Reconstruction of Magmatic System

727   Variables and Processes. Reviews in Mineralogy and Geochemistry, 69, 179–239.

728   Brackman, A.J. and Schwartz, J.J. (2022) The formation of high-Sr/Y plutons in

729   cordilleran-arc crust by crystal accumulation and melt loss. Geosphere, 18, 370–

730   393.

731   Burney, D., Peate, D.W., Riishuus, M.S. and Ukstins, I.A. (2020) Reconstructing the

732   plumbing system of an off-rift primitive alkaline tuya (Vatnafell, Iceland) using

733   geothermobarometry and CSDs. Journal of Volcanology and Geothermal

734   Research, 399, 106914.

735   Calmus, T., Aguillon-Robles, A., Maury, R.C., Bellon, H., Benoit, M., Cotten, J.,

736   Bourgois, J. and Michaud, F. (2003) Spatial and temporal evolution of basalts and

737   magnesian andesites (bajaites) from Baja California, Mexico: the role of slab

738   melts. Lithos, 66, 77–105.

739   Cashman, K.V., Sparks, R.S. and Blundy, J.D. (2017) Vertically extensive and unstable

740   magmatic systems: A unified view of igneous processes. Science, 355, eaag3055.

741   Castillo, P.R. (2012) Adakite petrogenesis. Lithos, 134, 304–316.

742   Castillo, P.R., Janney, P.E. and Solidum, R.U. (1999) Petrology and geochemistry of

743   Camiguin Island, southern Philippines: insights to the source of adakites and other

744   lavas in a complex arc setting. Contributions to Mineralogy and Petrology, 134,

745   33–51.

746   Chen, S., Niu, Y., Li, J., Sun, W., Zhang, Y., Hu, Y. and Shao, F. (2016) Syn-collisional

747   adakitic granodiorites formed by fractional crystallization: Insights from their

748   enclosed mafic magmatic enclaves (MMEs) in the Qumushan pluton, North Qilian

749   Orogen at the northern margin of the Tibetan Plateau. Lithos, 248, 455–468.

750   Clemens, J.D. and Stevens, G. (2012) What controls chemical variation in granitic

751   magmas? Lithos, 134, 317–329.

752   Collins, W.J., Murphy, J.B., Johnson, T.E. and Huang, H. (2020) Critical role of water

753   in the formation of continental crust. Nature Geoscience, 13, 331–338.

754   Davidson, J., Turner, S., Handley, H., Macpherson, C. and Dosseto, A. (2007)

755   Amphibole "sponge" in arc crust? Geology, 35, 787–790.

756   Defant, M.J. and Drummond, M.S. (1990) Derivation of some modern arc magmas by

757   melting of young subducted lithosphere. Nature, 347, 662–665.

758   Elkins, L.J., Gaetani, G.A. and Sims, K.W.W. (2008) Partitioning of U and Th during

759   garnet pyroxenite partial melting: Constraints on the source of alkaline ocean

760   island basalts. Earth and Planetary Science Letters, 265, 270–286.

761   Ewart, A. and Griffin, W.L. (1994) Application of Proton-Microprobe Data to Trace-

762   Element Partitioning in Volcanic-Rocks. Chemical Geology, 117, 251–224.

763   Foster, M.D. (1960) Interpretation of the Composition of Trioctahedral Micas, United

764   States Geological Survey Professional Paper, 354, 1–49.

765   Frost, C.D., Swapp, S.M., Frost, B.R., Finley-Blasi, L. and Fitz-Gerald, D.B. (2016)

766   Leucogranites of the Teton Range, Wyoming: A record of Archean collisional

767   orogeny. Geochimica et Cosmochimica Acta, 185, 528–549.

768   Fu, B., Page, F.Z., Cavosie, A.J., Fournelle, J., Kita, N.T., Lackey, J.S., Wilde, S.A. and

769   Valley, J.W. (2008) Ti-in-zircon thermometry: applications and limitations.

770   Contributions to Mineralogy and Petrology, 156, 197–215.

771   Gao, P., Zheng, Y.F. and Zhao, Z.F. (2016) Experimental melts from crustal rocks: A

772   lithochemical constraint on granite petrogenesis. Lithos, 266-267, 133–157.

773   García-Arias, M., Corretgé, L.G. and Castro, A. (2012) Trace element behavior during

774   partial melting of Iberian orthogneisses: An experimental study. Chemical

775   Geology, 292, 1–17.

776 Graham, B., Dunning, G. and Leitch, A. (2020) Magma Mushes of the Fogo Island

777   Batholith: a Study of Magmatic Processes at Multiple Scales. Journal of Petrology,

778   61, egaa097.

779 Guo, F., Nakamuru, E., Fan, W., Kobayoshi, K. and Li, C. (2007) Generation of

780   Palaeocene Adakitic Andesites by Magma Mixing; Yanji Area, NE China. Journal

781   of Petrology, 48, 661–692.

782 Harris, N., Massey, J. and Iner, S. (1993) The role of fluids in the formation of High

783   Himalayan leucogranites. Geological Society, London, Special Publications, 74,

784   391.

785 He, Y., Li, S., Hoefs, J., Huang, F., Liu, S.-A. and Hou, Z. (2011) Post-collisional

786   granitoids from the Dabie orogen: New evidence for partial melting of a thickened

787   continental crust. Geochimica et Cosmochimica Acta, 75, 3815–3838.

788 Higgins, M.D. (1996) Crystal size distributions and other quantitative textural

789   measurements in lavas and tuff from Egmont volcano (Mt. Taranaki), New

790   Zealand. Bulletin of Volcanology, 58, 194–204.

791 Higgins, O., Sheldrake, T. and Caricchi, L. (2022) Machine learning thermobarometry

792   and chemometry using amphibole and clinopyroxene: a window into the roots of

793   an arc volcano (Mount Liamuiga, Saint Kitts). Contributions to Mineralogy and

794   Petrology, 177, 1–22.

795   Hofmann, A.W., Jochum, K.P., Seufert, M. and White, W.M. (1986) Nb and Pb in

796   oceanic basalts: new constraints on mantle evolution. Earth and Planetary Science

797   Letters, 33–45.

798   Holland, T. and Blundy, J. (1994) Non-ideal interactions in calcic amphiboles and their

799   bearing on amphibole–plagioclase thermometry. Contributions to Mineralogy and

800   Petrology, 116, 433–447.

801   Hollings, P., Sievwright, R.H., Buret, Y., Wilkinson, J.J., Loader, M.A. and Nathwani,

802   C.L. (2020) Multi-stage arc magma evolution recorded by apatite in volcanic

803   rocks. Geology, 48, 323–327.

804   Hu, F., Ducea, M.N., Liu, S. and Chapman, J.B. (2017) Quantifying Crustal Thickness

805   in Continental Collisional Belts: Global Perspective and a Geologic Application.

806   Scientific Reports, 7, 7058.

807   Hu, J., Li, X., Xu, J., Mo, X., Wang, F., Yu, H., Shan, W., Xing, H., Huang, X. and

808   Dong, G. (2019) Generation of coeval metaluminous and muscovite-bearing

809   peraluminous granitoids in the same composite pluton in West Qinling, NE Tibetan

810   Plateau. Lithos, 344, 374–392.

811   Humphreys, M.C.S., Cooper, G.F., Zhang, J., Loewen, M., Kent, A.J.R., Macpherson,

812   C.G. and Davidson, J.P. (2019) Unravelling the complexity of magma plumbing

813   at Mount St. Helens: a new trace element partitioning scheme for amphibole.

814   Contributions to Mineralogy and Petrology, 174, 1–15.

815   Jerram, D.A., Dobson, K.J., Morgan, D.J. and Pankhurst, M.J. (2018) The Petrogenesis

816   of Magmatic Systems: Using Igneous Textures to Understand Magmatic

817   Processes, Volcanic and Igneous Plumbing Systems, Elsevier, 191–229.

818 Jerram, D.A. and Martin, V.M. (2008) Understanding crystal populations and their

819   significance through the magma plumbing system. Geological Society, London,

820   Special Publications, 304, 133–148.

821 Ji, Z., Ge, W., Yang, H., Tian, D., Chen, H. and Zhang, Y. (2018) Late Carboniferous–

822   Early Permian high- and low-Sr/Y granitoids of the Xing'an Block, northeastern

823   China: Implications for the late Paleozoic tectonic evolution of the eastern Central

824   Asian Orogenic Belt. Lithos, 322, 179–196.

825 Johnson, T.E., Brown, M., Gardiner, N.J., Kirkland, C.L. and Smithies, R.H. (2017)

826   Earth's first stable continents did not form by subduction. Nature, 543, 239–242.

827 Kay, R. and Kay, S. (1993) Delamination and magmatism. Tectonophysics, 219, 177–

828   189.

829 Kay, R.W. (1978) Aleutian magnesian andesites: Melts from subducted Pacific ocean

830   crust. Journal of Volcanology and Geothermal Research, 4, 117–132.

831 Koester, E., Pawley, A.R., Fernandes, L.A.D., Porcher, C.C. and Soliani, J.R.E. (2002)

832   Experimental melting of cordierite gneiss and the petrogenesis of syntranscurrent

833   peralumnious granites in southern Brazil. Journal of Petrology, 1595–1616.

834 Lange, R.A., Frey, H.M. and Hector, J. (2009) A thermodynamic model for the

835   plagioclase–liquid hygreometer/thermometer. American Mineralogist, 94, 494–

836   506.

837   Leake, B.E., Woolley, A.R. and Birch, W.D. (1997) Nomenclature of Amphiboles:

838   Report of the Subcommittee on Amphiboles of the International Mineralogical

839   Association Commission on New Minerals and Mineral Names. Mineralogical

840   Magazine, 61, 295–321.

841   Li, X., Mo, X., Huang, X., Dong, G., Yu, X., Luo, M. and Liu, Y. (2015) U–Pb zircon

842   geochronology, geochemical and Sr–Nd–Hf isotopic compositions of the Early

843   Indosinian Tongren Pluton in West Qinling: Petrogenesis and geodynamic

844   implications. Journal of Asian Earth Sciences, 97, 38–50.

845   Li, X., Zhang, C., Almeev, R.R. and Holtz, F. (2020a) GeoBalance: An Excel VBA

846   program for mass balance calculation in geosciences. Geochemistry, 80, 125629.

847   Li, X., Zhang, C., Behrens, H. and Holtz, F. (2020b) Calculating amphibole formula

848   from electron microprobe analysis data using a machine learning method based on

849   principal components regression. Lithos, 362–363.

850   Lu, Y. (2005) GeoKit-A geochemical toolkit for Microsoft Excel. Geochimica, 35, 459–

851   464 (in Chinese with English abstract).

852   Luo, B., Zhang, H. and Lü, X. (2012) U–Pb zircon dating, geochemical and Sr–Nd–Hf

853   isotopic compositions of Early Indosinian intrusive rocks in West Qinling, central

854   China: petrogenesis and tectonic implications. Contributions to Mineralogy and

855   Petrology, 164, 551–569.

856   Ma, Q., Zheng, J.P., Xu, Y.G., Griffin, W.L. and Zhang, R.S. (2015) Are continental

857   "adakites" derived from thickened or foundered lower crust? Earth and Planetary

858   Science Letters, 419, 125–133.

859   Macpherson, C.G., Dreher, S.T. and Thirlwall, M.F. (2006) Adakites without slab

860   melting: High pressure differentiation of island arc magma, Mindanao, the

861   Philippines. Earth and Planetary Science Letters, 243, 581–593.

862   Marsh, B.D. (1988) Crystal size distribution (CSD) in rocks and the kinetics and

863   dynamics of crystallization. Contributions to Mineralogy Petrology, 99, 277–291.

864   Martin, H., Smithies, R.H., Rapp, R., Moyen, J.F. and Champion, D. (2005) An

865   overview of adakite, tonalite–trondhjemite–granodiorite (TTG), and sanukitoid:

866   relationships and some implications for crustal evolution. Lithos, 79, 1–24.

867   Miller, J.S., Matzel, J.E.P., Miller, C.F., Burgess, S.D. and Miller, R.B. (2007) Zircon

868   growth and recycling during the assembly of large, composite arc plutons. Journal

869   of Volcanology and Geothermal Research, 167, 282–299.

870   Morgan, D.J., Jerram, D.A., Chertkoff, D.G., Davidson, J.P., Pearson, D.G., Kronz, A.

871   and Nowell, G.M. (2007) Combining CSD and isotopic microanalysis: Magma

872   supply and mixing processes at Stromboli Volcano, Aeolian Islands, Italy. Earth

873   and Planetary Science Letters, 260, 419–431.

874   Morimoto, N., Fabries, J., Ferguson, A.K., Ginzburg, I.V., Ross, M., Seifert, F.A.,

875   Zussman, J., Aoki, K. and Gottardi, G. (1988) Nomenclature of Pyroxenes.

876   Mineralogical Magazine, 52, 535–550.

877   Moyen, J.-F. (2009) High Sr/Y and La/Yb ratios: The meaning of the "adakitic

878   signature". Lithos, 112, 556–574.

879   Nachit, H., Ibhi, A., Abia, E.H. and Ben Ohoud, M. (2005) Discrimination between

880   primary magmatic biotites, reequilibrated biotites and neoformed biotites.

881   Comptes Rendus Geoscience, 337, 1415–1420.

882   Namur, O., Montalbano, S., Bolle, O. and Vander Auwera, J. (2020) Petrology of the

883   April 2015 Eruption of Calbuco Volcano, Southern Chile. Journal of Petrology, 61,

884   egaa084.

885   Nandedkar, R. H., Hürlimann, N., Ulmer, P. & Müntener, O. (2016) Amphibole-melt

886   trace element partitioning of fractionating calc-alkaline magmas in the lower crust:

887   an experimental study. Contributions to Mineralogy and Petrology, 171, 1–25.

888   Nash, P.W. (1985) Partition coefficients for trace elements in silicic magmas.

889   Geochimica et Cosmochimica Acta, 49, 2309–2322.

890   Neave, D.A., Bali, E., Guðfinnsson, G.H., Halldórsson, S.A., Kahl, M., Schmidt, A.-S.

891   and Holtz, F. (2019) Clinopyroxene–Liquid Equilibria and Geothermobarometry

892   in Natural and Experimental Tholeiites: the 2014–2015 Holuhraun Eruption,

893   Iceland. Journal of Petrology, 60, 1653–1680.

894   Neave, D.A. and Putirka, K.D. (2017) A new clinopyroxene-liquid barometer, and

895   implications for magma storage pressures under Icelandic rift zones. American

896   Mineralogist, 102, 777–794.

897   Oppenheim, L. F., Memeti, V., Barnes, C. G., Chambers, M., Krause, J., & Esposito, R.

898   (2021) Feldspar recycling across magma mush bodies during the voluminous Half

899   Dome and Cathedral Peak stages of the Tuolumne intrusive complex, Yosemite

900   National Park, California, USA. Geosphere, 17(2), 322-351.

901   Ou, Q., Wang, Q., Wyman, D.A., Zhang, H., Yang, J., Zeng, J., Hao, L., Chen, Y., Liang,

902   H. and Qi, Y. (2017) Eocene adakitic porphyries in the central-northern Qiangtang

903   Block, central Tibet: Partial melting of thickened lower crust and implications for

904   initial surface uplifting of the plateau. Journal of Geophysical Research: Solid

905   Earth, 122, 1025–1053.

906   Paterson, S., Memeti, V., Mundil, R. and Žák, J. (2016) Repeated, multiscale, magmatic

907   erosion and recycling in an upper-crustal pluton: Implications for magma chamber

908   dynamics and magma volume estimates. American Mineralogist, 101, 2176–2198.

909   Patiño Douce, A.E. (1999) What do experiments tell us about the relative contributions

910   of crust and mantle to the origin of granitic magmas? Geological Society, London,

911   Special Publications, 168, 55–75.

912   Pichavant, M. and Macdonald, R. (2007) Crystallization of primitive basaltic magmas

913   at crustal pressures and genesis of the calc-alkaline igneous suite: experimental

914   evidence from St Vincent, Lesser Antilles arc. Contributions to Mineralogy and

915   Petrology, 154, 535–558.

916   Pourteau, A., Doucet, L.S., Blereau, E.R., Volante, S., Johnson, T.E., Collins, W.J., Li,

917   Z.-X. and Champion, D.C. (2020) TTG generation by fluid-fluxed crustal melting:

918   Direct evidence from the Proterozoic Georgetown Inlier, NE Australia. Earth and

919   Planetary Science Letters, 550, 116548.

920   Price, R.C., Gamble, J.A., Smith, I.E.M., Maas, R., Waight, T., Stewart, R.B. and

921   Woodhead, J. (2012) The Anatomy of an Andesite Volcano: a Time–Stratigraphic

922   Study of Andesite Petrogenesis and Crustal Evolution at Ruapehu Volcano, New

923   Zealand. Journal of Petrology, 53, 2139–2189.

924 Profeta, L., Ducea, M.N., Chapman, J.B., Paterson, S.R., Gonzales, S.M., Kirsch, M.,

925   Petrescu, L. and DeCelles, P.G. (2015) Quantifying crustal thickness over time in

926   magmatic arcs. Scientific Reports, 5, 17786.

927 Putirka, K. (2016) Amphibole thermometers and barometers for igneous systems and

928   some implications for eruption mechanisms of felsic magmas at arc volcanoes.

929   American Mineralogist, 101, 841–858.

930 Putirka, K.D. (2008) Thermometers and Barometers for Volcanic Systems. Reviews in

931   Mineralogy and Geochemistry, 69, 61–120.

932 Reichardt, H. and Weinberg, R.F. (2012) Hornblende Chemistry in Meta- and Diatexites

933   and its Retention in the Source of Leucogranites: an Example from the Karakoram

934   Shear Zone, NW India. Journal of Petrology, 53, 1287–1318.

935 Schiller, D. and Finger, F. (2019) Application of Ti-in-zircon thermometry to granite

936   studies: problems and possible solutions. Contributions to Mineralogy and

937   Petrology, 174, 1–16.

938 Schnetzler, C.C. and Philpotts, J.A. (1970) Partition coefficients of rare-earth elements

939   between igneous matrix material and rock-forming mineral phenocrysts; II.

940   Geochimica et Cosmochimica Acta, 34, 331–340.

941 Shaw, D.M. (1970) Trace element fractionation during anatexis. Geochimica et

942   Cosmochimica Acta, 34, 237–243.

943   Shen, Y., Zheng, Y.-C., Hou, Z.-Q., Zhang, A.-P., Huizenga, J.M., Wang, Z.-X. and

944   Wang, L. (2021) Petrology of the Machangqing Complex in Southeastern Tibet:

945   Implications for the Genesis of Potassium-rich Adakite-like Intrusions in

946   Collisional Zones. Journal of Petrology, 62, egab066.

947   Shi, H., Xia, Y., Xu, X., Zhu, J. and He, J. (2022) Crystal-melt separation of the

948   Cretaceous volcanic-plutonic complex in SE China: High Sr/Y rocks generated by

949   plagioclase accumulation. Lithos, 106848.

950   Shimizu, K., Liang, Y., Sun, C., Jackson, C.R.M. and Saal, A.E. (2017) Parameterized

951   lattice strain models for REE partitioning between amphibole and silicate melt.

952   American Mineralogist, 102, 2254–2267.

953   Sims, K.W.W. and DePaolo, D.J. (1997) Inferences about mantle magma sources from

954   incompatible element concentration ratios in oceanic basalts. Geochimica et

955   Cosmochimica Acta, 61, 765–784.

956   Sisson, T.W. and Grove, T.L. (1993) Experimental investigations of the role of H2O in

957   calc-alkaline differentiation and subduction zone magmatism. Contributions to

958   Mineralogy and Petrology, 113, 143–166.

959   Smith, J.V. (1974) Feldspar Minerals. Volume 1. Crystal Structure and Physical

960   Properties. Berlin: Springer, 625.

961   Stern, C.R. and Kilian, R. (1996) Role of the subducted slab, mantle wedge and

962   continental crust in the generation of adakites from the Andean Austral Volcanic

963   Zone. Contributions to Mineralogy and Petrology, 123, 263–281.

964 Streckeisen, A.L. (1976) Classification of the common igneous rocks by means of their

965   chemical composition: A provisional attempt. Neues Jahrbuch für Mineralogie,

966   Monatshefte, 1, 1–15.

967 Sun, C., Graff, M. and Liang, Y. (2017) Trace element partitioning between plagioclase

968   and silicate melt: The importance of temperature and plagioclase composition,

969   with implications for terrestrial and lunar magmatism. Geochimica et

970   Cosmochimica Acta, 206, 273–295.

971 Sun, S.S. and McDonough, W.F. (1989) Chemical and isotopic systematics of oceanic

972   basalts: implications for mantle composition and processes. Geological Society,

973   London, Special Publications, 42, 313–345.

974 Wang, D., Liu, J., Carranza, E.J.M., Zhai, D., Wang, Y., Zhen, S., Wang, J., Wang, J.,

975   Liu, Z. and Zhang, F. (2019) Formation and evolution of snowball quartz

976   phenocrysts in the Dongping porphyritic granite, Hebei Province, China: Insights

977   from fluid inclusions, cathodoluminescence, trace elements, and crystal size

978   distribution study. Lithos, 340, 239–254.

979 Wang, L.J., Guo, J.H., Yin, C. and Peng, P. (2017) Petrogenesis of ca. 1.95 Ga meta-

980   leucogranites from the Jining Complex in the Khondalite Belt, North China

981   Craton: Water-fluxed melting of metasedimentary rocks. Precambrian Research,

982   303, 355–371.

983 Wang, P., Zhao, G., Liu, Q., Yao, J., Han, Y. and Li, J. (2022) Effect of source

984   compositions on adakitic features: A case study from the Buya granite, in western

985   Kunlun, NW China. American Journal of Science, 322, 828–850.

986   Ward, R., Stevens, G. and Kisters, A. (2008) Fluid and deformation induced partial

987   melting and melt volumes in low-temperature granulite-facies metasediments,

988   Damara Belt, Namibia. Lithos, 105, 253–271.

989   Waters, L.E. and Lange, R.A. (2015) An updated calibration of the plagioclase-liquid

990   hygrometer-thermometer applicable to basalts through rhyolites. American

991   Mineralogist, 100, 2172–2184.

992   Watkins, J.M., Clemens, J.D. and Treloar, P.J. (2007) Archaean TTGs as sources of

993   younger granitic magmas: melting of sodic metatonalites at 0.6–1.2 GPa.

994   Contributions to Mineralogy and Petrology, 154, 91–110.

995   Watson, E.B., Wark, D.A. and Thomas, J.B. (2006) Crystallization thermometers for

996   zircon and rutile. Contributions to Mineralogy and Petrology, 151, 413–433.

997   Weinberg, R.F. and Hasalová, P. (2015) Water-fluxed melting of the continental crust:

998   A review. Lithos, 212, 158–188.

999   Werts, K., Barnes, C.G., Memeti, V., Ratschbacher, B., Williams, D. and Paterson, S.R.

1000   (2020) Hornblende as a tool for assessing mineral–melt equilibrium and

1001   recognition of crystal accumulation. American Mineralogist, 105, 77–91.

1002   Wieser, P.E., Jenner, F., Edmonds, M., Maclennan, J. and Kunz, B.E. (2020)

1003   Chalcophile elements track the fate of sulfur at Kīlauea Volcano, Hawai'i.

1004   Geochimica et Cosmochimica Acta, 282, 245–275.

1005   Xie, Y. H., Li, X. W., Mo, X. X., Dong, G. C., Sun, Y. Q. & Shan, W. (2023) The effects

1006   of the source composition on the origin of orthopyroxene-bearing adakitic

1007   granitoid in West Qinling, Central China. Geoscience Frontiers, 14(3), 101554.

1008   Xing, H., Li, X., Xu, J., Mo, X., Shan, W., Yu, H., Hu, J., Huang, X. and Dong, G.

1009   (2020) The genesis of felsic magmatism during the closure of the Northeastern

1010   Paleo-Tethys Ocean: Evidence from the Heri batholith in West Qinling, China.

1011   Gondwana Research, 84, 38–51.

1012   Xu, X., Dong, C., Li, W. and Zhou, X. (1999) Late Mesozoic intrusive complexes in

1013   the coastal area of Fujian, SE China: the significance of the gabbro-diorite–granite

1014   association. Lithos, 46, 299–315.

1015   Yang, Z.F., Luo, Z.H. and Lu, X.X. (2010) Quantitative textural analysis of igneous

1016   rocks and the kinetics and dynamics of magma solidification processes. Earth

1017   Science Frontiers, 17, 246–266.

1018   Yu, S., Zhang, J., Qin, H., Sun, D., Zhao, X., Cong, F. and Li, Y. (2015) Petrogenesis of

1019   the early Paleozoic low-Mg and high-Mg adakitic rocks in the North Qilian

1020   orogenic belt, NW China: Implications for transition from crustal thickening to

1021   extension thinning. Journal of Asian Earth Sciences, 107, 122–139.

1022   Zeng, L., Zhang, K., Tang, X., Zhang, Y. and Li, Z. (2018) Mid-Permian rifting in

1023   Central China: Record of geochronology, geochemistry and Sr–Nd–Hf isotopes of

1024   bimodal magmatism on NE Qinghai–Tibetan Plateau. Gondwana Research, 57,

1025   77–89.

1026   Zhan, Q.Y., Zhu, D.C., Wang, Q., Weinberg, R.F., Xie, J.C., Li, S.M., Zhang, L.L. and

1027   Zhao, Z.D. (2020) Source and pressure effects in the genesis of the Late Triassic

1028   high Sr/Y granites from the Songpan-Ganzi Fold Belt, eastern Tibetan Plateau.

1029   Lithos, 368, 105584.

1030   Zhang, Y.Z., Wang, X.L., Li, J.Y., He, Z.Y., Zhang, F.F., Chen, X., Wang, S., Du, D.H.,

1031   Huang, Y. and Jiang, C.H. (2021) Oligocene Leucogranites of the Gangdese

1032   Batholith, Southern Tibet: Fractional Crystallization of Felsic Melts from Juvenile

1033   Lower Crust. Journal of Petrology, 62, egab076.

1034   Zheng, J.P., Griffin, W.L., Sun, M., O'Reilly, S.Y., Zhang, H.F., Zhou, H.W., Xiao, L.,

1035   Tang, H.Y. and Zhang, Z.H. (2010) Tectonic affinity of the west Qinling terrane

1036   (central China): North China or Yangtze? Tectonics, 29.

1037   Zhou, J., Wang, Q., Wyman, D.A. and Zhao, Z. (2020) Petrologic reconstruction of the

1038   Tieshan magma plumbing system: Implications for the genesis of magmatic-

1039   hydrothermal ore deposits within originally water-poor magmatic systems. Journal

1040   of Petrology, 61, egaa056.

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1043 **Figure and Table Captions**

1044 **Fig. 1**. (a) Simplified geological map of China, showing the major tectonic units

1045 (after Zheng et al., 2010). (b) Geological map of the West Qinling Orogenic Belt,

1046 showing the distribution of Early Mesozoic granitoids (after Hu et al., 2019; Li et al.,

1047 2015; Luo et al., 2012; Xing et al., 2020; Zeng et al., 2018). Data sources for the zircon

1048 U–Pb ages are given in Table DR1. Place names: WQ, West Qinling; SG, Songpan–

1049 Garzê Terrane; QD, Qaidam; QL, Qilian Terrane; NQ, North Qinling; YB, Yangtze

1050 Block; NCB, North China Block; SCS, South China Sea; QT, Qiangtang Terrane; LT,

1051 Lhasa Terrane; CB, Cathaysia Block.

1052 **Fig. 2**. The geological sketch map of the Zhuyuan pluton

1053 **Fig. 3**. Representative field and microstructural photographs of the Zhuyuan pluton.

1054 (a) Photograph of the Zhuyuan granodiorites; (b) Plagioclases with polysynthetic

1055 twinning; (c) A plagioclase phenocryst with a sieve texture; (d) A plagioclase

1056 phenocryst with oscillatory zoning; (e) A clinopyroxene crystal enclosed by amphibole;

1057 (f) A clinopyroxene crystal enclosed by amphibole and biotite; (g) A clinopyroxene

1058 crystal with clear core–rim texture; (h) An orthopyroxene crystal enclosed by

1059 amphibole; (i) An unzoned orthopyroxene (black outline) mantled by amphibole.

1060 Mineral abbreviations: Cpx, clinopyroxene; Opx, orthopyroxene; Amp, amphibole; Bt,

1061 biotite; Pl, plagioclase; Kf, K-feldspar; Qtz, quartz.

1062 **Fig. 4**. Classification diagrams for rock-forming minerals from the granodiorites of

1063 the Zhuyuan pluton. (a) Wo–En–Fs ternary diagram for pyroxenes (after Morimoto et

1064 al., 1988); (b) $Mg/(Mg + Fe^{2+})$ versus Si diagram for amphiboles (after Leake et al.,

1065   1997); (c) Ternary Mg–(Fe^{2+} + Mn)–(Al^{VI} + Fe^{3+} + Ti) (apfu) diagram for biotite (after

1066   Foster, 1960); (d) Ternary 10 × TiO$_2$–(FeO^T + MnO)–MgO (wt.%) diagram for biotite

1067   (after Nachit et al., 2005); (e) Or–Ab–An ternary diagram for feldspars (after Smith,

1068   1974). Abbreviation: Cpx, clinopyroxene; Opx, orthopyroxene; Abbreviation: Ab,

1069   albite; Or, orthoclase; An, anorthite; Pl, plagioclase; Amp, amphibole; Bt, biotite; Kf,

1070   K-feldspar.

1071   **Fig. 5**. Back scattered electron images and X$_{Mg}$ and An contents for selected

1072   clinopyroxenes and plagioclases, respectively. (a) and (b) Optically unzoned

1073   clinopyroxenes (ZY17-11-2 and ZY17-13-2); (c) and (d) A normally zoned

1074   clinopyroxene and the core–rim profile of its X$_{Mg}$ (ZY17-4-3); (e) and (f) A reversely

1075   zoned clinopyroxene and the core–rim profile of its X$_{Mg}$ (ZY17-4-2); (g) A plagioclase

1076   crystal with a sieve texture (ZY17-4-1); (h) A plagioclase crystal without sieve texture

1077   (ZY17-6-1). Mineral abbreviations: Cpx, clinopyroxene; Opx, orthopyroxene; Pl,

1078   plagioclase; Amp, amphibole; Bt, biotite.

1079   **Fig. 6**. (a, c, e, g) Chondrite-normalized REE patterns and (b, d, f, h) primitive

1080   mantle-normalized trace element patterns for clinopyroxene and amphibole from the

1081   Zhuyuan pluton. The normalization values are from Sun and McDonough (1989).

1082   **Fig. 7**. Back scattered electron image and LA-ICP-MS maps of representative

1083   elements and important parameters for a reversely zoned clinopyroxene from sample

1084   ZY17-4. All LA-ICP-MS maps show probability density abundances to accentuate

1085   distribution characteristics. LA-ICP-MS data of Profile A extracted parallel to line A–

1086   B are listed in Table DR4.

1087   **Fig. 8**. Back scattered electron image and LA-ICP-MS maps of representative

1088   elements and important parameters for an orthopyroxene + amphibole assemblage from

1089   sample ZY17-15. All LA-ICP-MS maps show probability density abundances to

1090   accentuate distribution characteristics.

1091   **Fig. 9**. Back scattered electron image and LA-ICP-MS maps of representative

1092   elements and important parameters for a biotite from sample ZY17-4. All LA-ICP-MS

1093   maps show probability density abundances to accentuate distribution characteristics.

1094   LA-ICP-MS data of Profile B extracted parallel to line C–D are listed in Table DR4.

1095   **Fig. 10**. (a) and (b) Amphiboles outlined in photomicrographs of samples ZY17-1

1096   and ZY17-11, respectively; (c) and (d) The CSD diagrams of ln(n) versus size of

1097   amphibole for samples ZY17-1and ZY17-11, respectively, where 'n' represents the

1098   number of grains. Slope and intercept definitions are as follows: Slope = -1/Gt;

1099   Intercept = I/G, where nucleation rates (I) and crystal residence reservoir (t) were

1100   calculated by assuming a constant crystal growth rate (G; Marsh, 1988).

1101   **Fig. 11**. Chondrite-normalized REE distribution patterns for melts in equilibrium

1102   with (a) unzoned clinopyroxenes (Type-1 Cpx); (b) normally zoned clinopyroxenes

1103   (Type-2 Cpx); (c) reversely zoned clinopyroxenes (Type-3 Cpx); (d) amphiboles

1104   (Amp); The normalization values are from Sun and McDonough (1989).

1105   **Fig. 12**. Sr/Y values of different minerals versus the Sr/Y values of the melts in

1106   equilibrium with them (a), and the melts with Sr/Y values higher than 30 are considered

1107   to have high Sr/Y signature; Ce/Pb values of different minerals versus the Ce/Pb values

1108   of the melts in equilibrium with them (b). The Ce/Pb value of mantle derived melt is

1109   generally greater than 9, while that of shell derived melt is usually less than 4 (Hofmann

1110   et al., 1986; Sims and DePaolo, 1997).

1111   **Fig. 13**. Schematic diagram showing the hypothetical magma conduit system used

1112   by magmas that formed the Zhuyuan adakitic granodiorites and the various possible

1113   mineral crystallization environments. See text for a detailed discussion.

1114   **Fig.14.** Chondrite normalized REE patterns of calculated intermediate felsic sources

1115   (color lines) of the high Sr/Y undiluted melt of the Zhuyuan granodiorites under

1116   different conditions. Each color line corresponds to different experiments listed in

1117   Table DR7. The source rocks corresponding to Exp 1 to 4 are garnet-bearing semi-

1118   pelitic metasedimentary gneiss, orthogneiss, garnet-bearing metasedimentary gneiss

1119   and biotite tonalite

1120

1121   **Table.1.** The important parameters of rock-forming minerals of the Zhuyuan

1122   granodiorites

1123   **Table 2.** The important parameters of the melts in equailibrium with rock-forming

1124   minerals from the Zhuyuan granodiorites

1125   **Table 3.** Crystallization conditions of amphibole and clinopyroxene from the

1126   Zhuyuan granodiorites

1127

1128   **Electronic Supplementary materials**

1129   **Supplementary Table DR1.** Compilation of previously published zircon U–Pb ages

1130   of the Triassic igneous activity in the Western Qinling Orogen

1131   **Supplementary Table DR2.** Compilation of whole-rock geochemical data and Ti-

1132   in zircon thermometer data for the Zhuyuan granodiorites

1133   **Supplementary Table DR3.** Electron microprobe analysis results of rock-forming

1134   minerals from the Zhuyuan granodiorites and standard materials of the Astimex series

1135   **Supplementary Table DR4.** LA–ICP–MS results of rock-forming minerals from

1136   the Zhuyuan granodiorites and standard materials

1137   **Supplementary Table DR5.** Textual parameters of amphlibole in the samples from

1138   the Zhuyuan pluton in West Qinling

1139   **Supplementary Table DR6.** Calculated compositions of the melts in equilibrium

1140   with rock-forming minerals from the Zhuyuan granodiorites and the partition

1141   coefficients used

1142   **Supplementary Table DR7.** Modeled compositions of the "undiluted melts" and

1143   source rocks

1144

1145   **Supplementary Figure DR1.** Classification diagrams for the granodiorites from the

1146   Zhuyuan pluton. (a) Q–A–P diagram (after Streckeisen, 1976); I–Quartzolite; II–

1147   Quartz-rich granitoid; III–Alkali-feldspar granite; IV–Syenogranite; V–Monzogranite;

1148   VI–Granodiorite; VII–Tonalite; VIII–Alkali-feldspar quartz syenite; IX–Quartz

1149   syenite; X–Quartz monzonite; XI–Quartz monzodiorite/monzogabbro; XII–Quartz

1150   diorite/Quartz gabbro; XIII–Alkali-feldspar syenite; XIV–Syenite; XV–Monzonite;

1151   XVI–Monzodiorite/Monzogabbro; XVII–Diorite/Gabbro.

1152   **Supplementary Figure DR2.** (a) $(Dy/Yb)_N$ versus $(La/Yb)_N$ diagram (after He et al.,

1153   2011) for adakite-like rocks from the Zhuyuan pluton. (b) La/Sm versus La/Nb diagram

1154   for adakitic rocks from the Zhuyuan pluton.

1155

1156   **Other Supplementary Materials**

1157   Description of **GEOLOGICAL SETTING**

1158   Description of **ANALYTICAL METHODS**

1159   Description of the **RESULTS** of **"Whole-rock major and trace element**

1160   **geochemistry"**

1161   **DISCUSSION** on **"The critical role of magma mixing and antecryst recycling"**

Table.1. The important parameters of rock-forming minerals of the Zhuyuan granodiorites

Mineral	X_{Mg}	An/Or	Sr (ppm)	Y (ppm)	Rb (ppm)	Sr/Y	∑REE (ppm)	Texture	Type
Type-1A Cpx	72.6–81.7	—	34.4–45.5	20.1–24.4	2.69	1.41–2.26	54.3–75.0	poikilitic texture,	antecrysts
Type-1B Cpx	70.0–76.5	—	32.8–38.2	43.3–53.3	0.90–2.03	0.61–0.80	135–189	non-zoned	antecrysts
Type-2 Cpx core	76.1–80.9	—	50.9–52.2	13.8–14.5	0.20–0.36	3.51–3.79	53.7–60.9	poikilitic texture,	antecrysts
Type-2 Cpx rim	71.5–76.2	—	29.3–42.7	29.7–47.7	0.91–2.62	0.61–1.22	139–245	normally zoned	antecrysts
Type-3 Cpx core	74.3–83.2	—	43.1–127	7.57–8.96	0.31–11.7	5.30–14.8	51.0–68.6	poikilitic texture,	antecrysts
Type-3 Cpx rim	75.5–86.9	—	82.5–91.9	6.27–7.57	0.24–0.55	11.7–13.2	37.8–46.6	reversely zoned	antecrysts
Orthopyroxene	80.9–82.8	—	0.29–0.84	1.29–3.77	0.10–0.22	0.45–0.65	0.72–2.82	poikilitic texture	antecrysts
Amphibole	63.1–74.6	—	17.0–29.8	58.2–141	1.54–1.94	0.15–0.33	303–693	disequilibrium boundary texture	antecrysts
Type-1 Pl	—	An: 32.9–51.6	965–1519	0.14–0.21	10.4–318	6002–9768	12.8–45.3	sieve texture	antecrysts
Type-2 Pl	—	An: 14.9–29.4	865–1494	0.10–0.22	0.31–4.28	4254–14513	15.3–36.2	non-sieve texture	orthocrysts
Biotite	54.4–61.5	—	1.74–6.74	0.15–0.33	317–601	17.5–43.8	0.30–4.12	interstitial mineral	orthocrysts
K-feldspar	—	Or: 72.4–95.8	535–1029	< 0.1	197–338	> 5345	1.47–16.1	interstitial mineral	orthocrysts

Table 2. The important parameters of the melts in equailibrium with rock-forming minerals from the Zhuyuan granodiorites

Equilibrium melt	Mg#	Cr (ppm)	Ni (ppm)	Eu/Eu*	Sr/Y	Sr/Rb	Sr/Ba	Ce/Pb	Environment
Type-1A Cpx	39.5–47.7	46.5–71.2	28.1–46.0	0.54–0.68	4.52–7.27	—	—	42.5–125	A
Type-1B Cpx	42.7–55.5	145–272	92.4–93.5	0.41–0.43	1.97–2.57	—	—	78.8–156	
Type-2 Cpx core	47.2–54.2	318–362	31.9–33.3	0.72–0.77	11.3–12.2	—	—	11.6–19.4	B
Type-2 Cpx rim	41.3–47.3	101–460	34.6–67.7	0.32–0.46	1.97–3.93	—	—	41.2–133	
Type-3 Cpx core	44.7–58.1	38.2–244	45.8–85.1	0.82–0.96	17.0–47.6	—	—	23.9–55.7	C
Type-3 Cpx rim	48.4–65.0	916–1532	122–173	0.85–1.02	37.6–42.4	—	—	5.07–25.5	
Orthopyroxene	56.8–59.9	976–1190	169–239	—	11.7–21.8	—	—	~11.4	D
Amphibole	21.7–34.6	—	—	0.13–0.29	4.13–21.6	—	—	4.4–18.9	E
Type-1 Pl	—	—	—	15.9–23.3	218–315	0.20–6.81	0.40–1.27	3.18–5.59	F
Type-2 Pl	—	—	—	14.6–67.4	96.5–376	26.4–252	0.99–1.67	1.55–2.27	G
Biotite	—	—	—	—	49.5–124	—	—	0.01–0.07	H
K-feldspar	—	—	—	—	>>29	—	—	0.05–0.84	

Table 3. Crystallization conditions of amphibole and clinopyroxene from the Zhuyuan granodiorites

Mineral	Temperature °C	Pressure GPa	Depth km
Type-1 Cpx	1150–1191	0.48–0.75	18.1–28.4
Type-2 Cpx	1130–1192	0.40–0.84	15.3–31.7
Type-3 Cpx	1173–1211	0.38–0.61	14.2–23.0
Amphibole	744–814	0.20–0.35	7.64–13.4
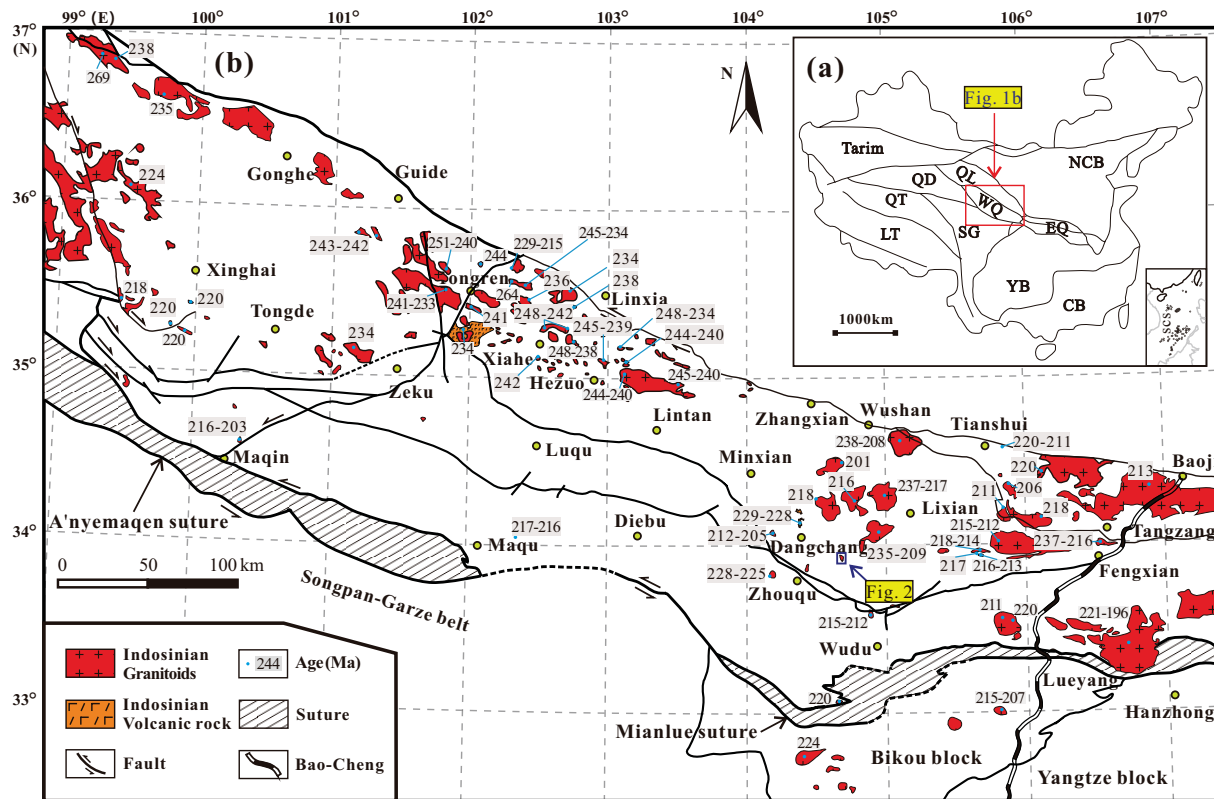
Figure 1
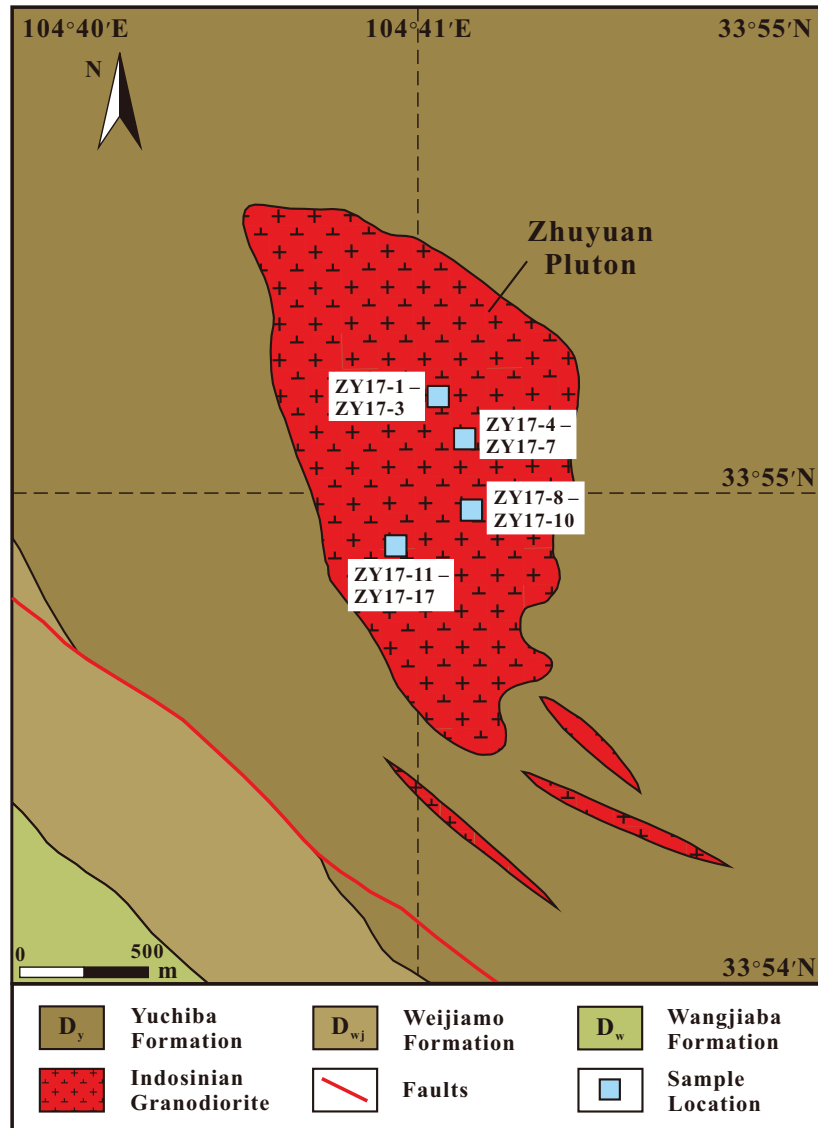
Figure 2
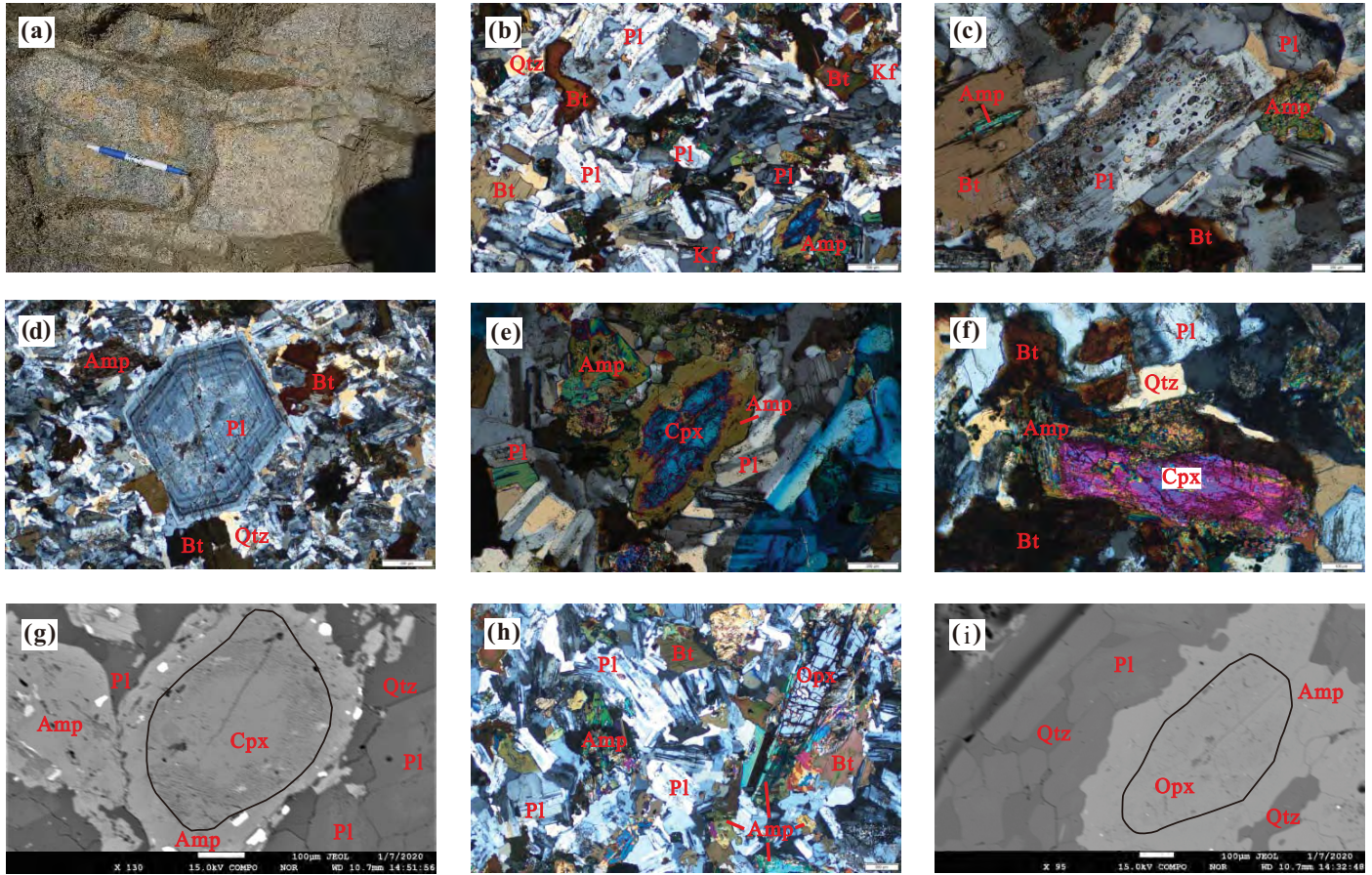
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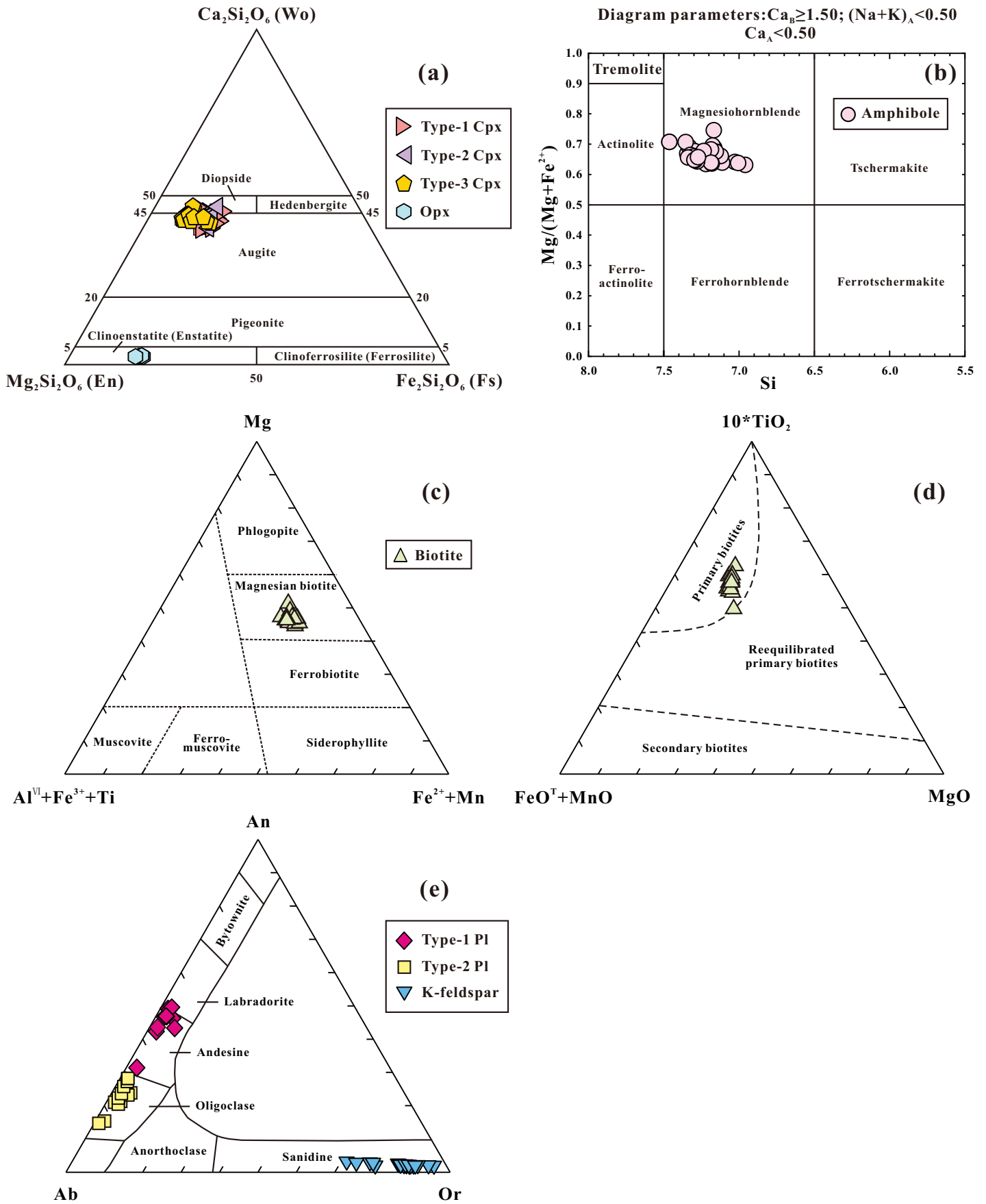
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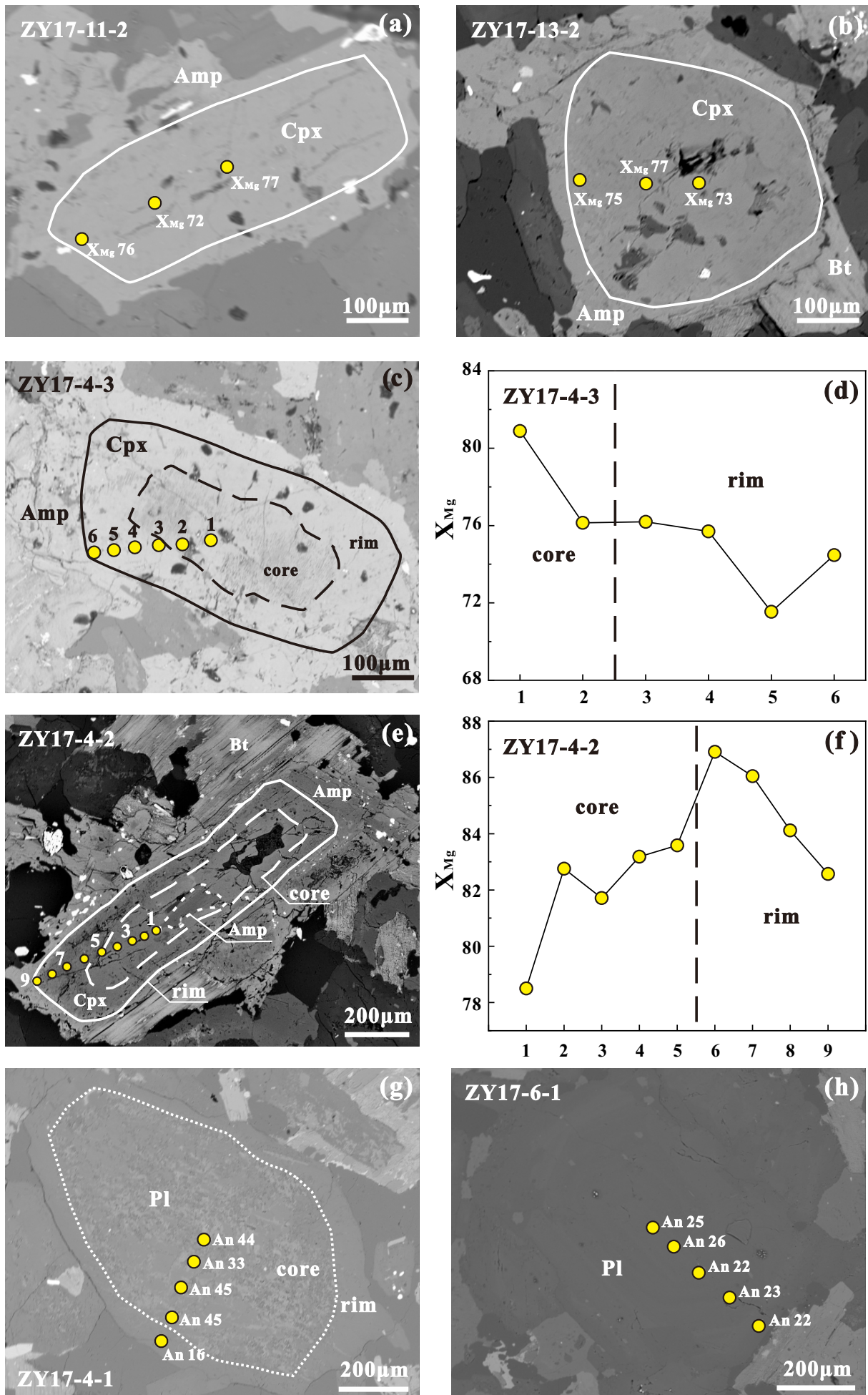
Figure 5

Always consult and cite the final, published document. See http:/www.minsocam.org or GeoscienceWorld
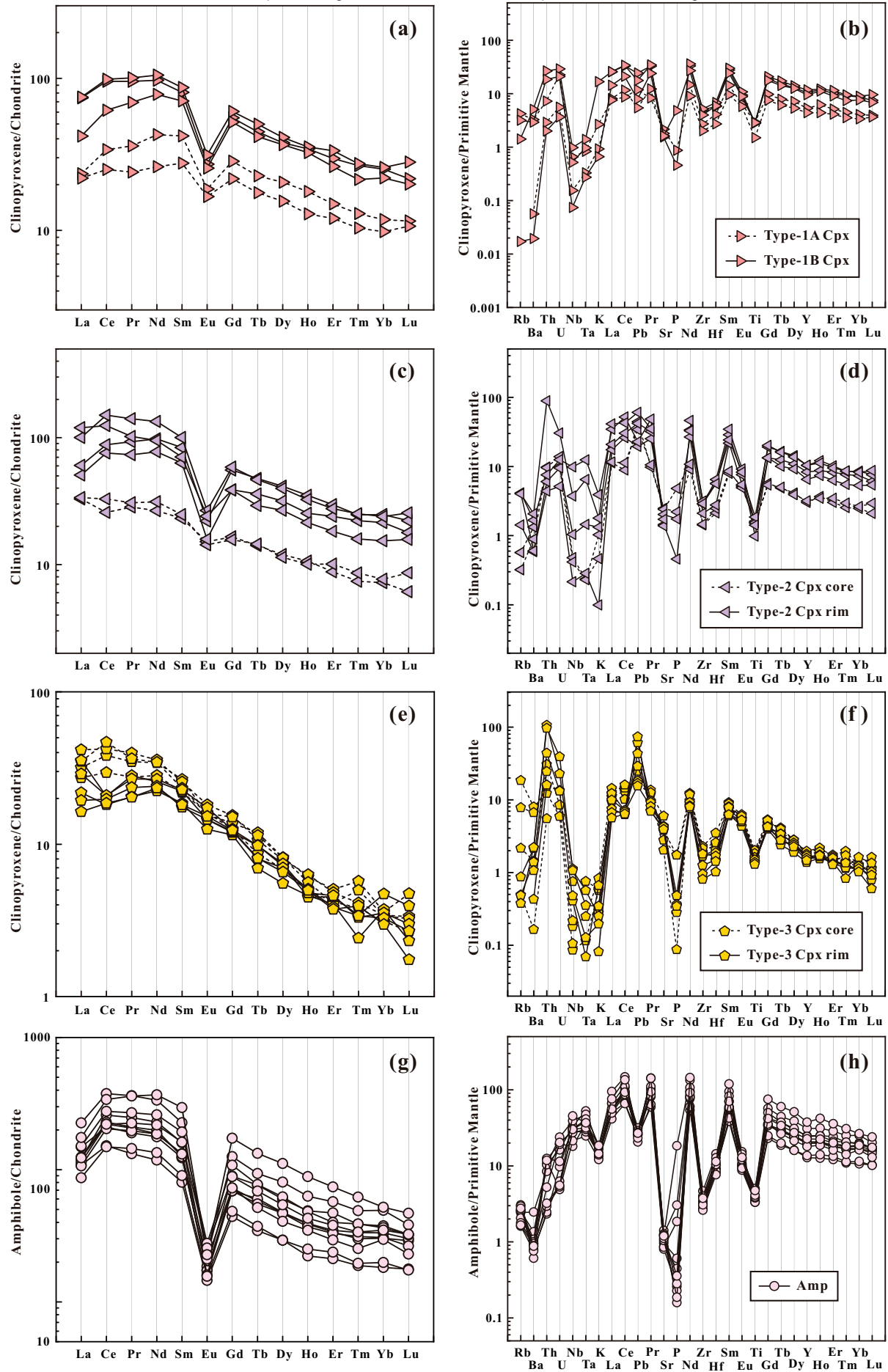
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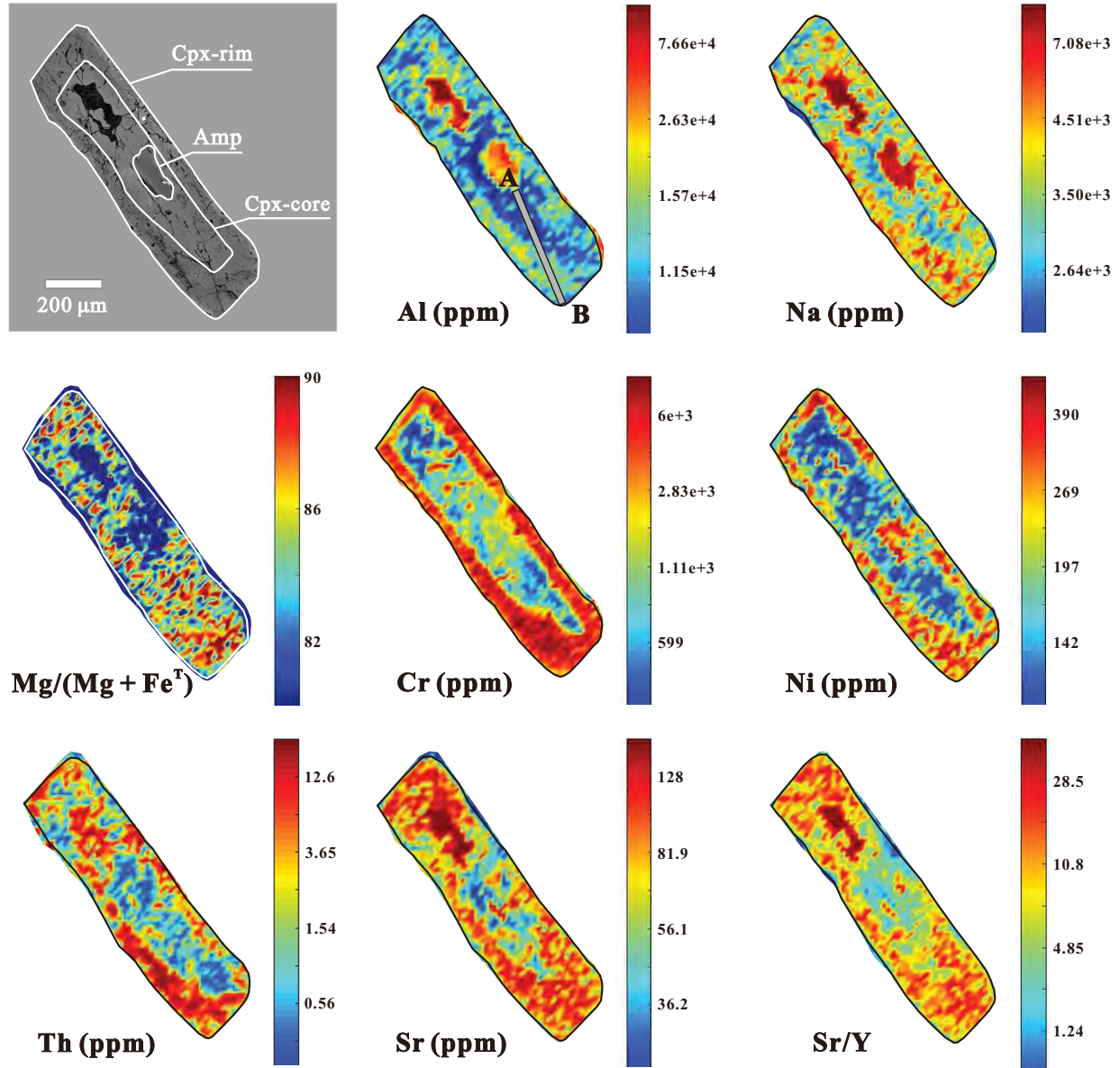
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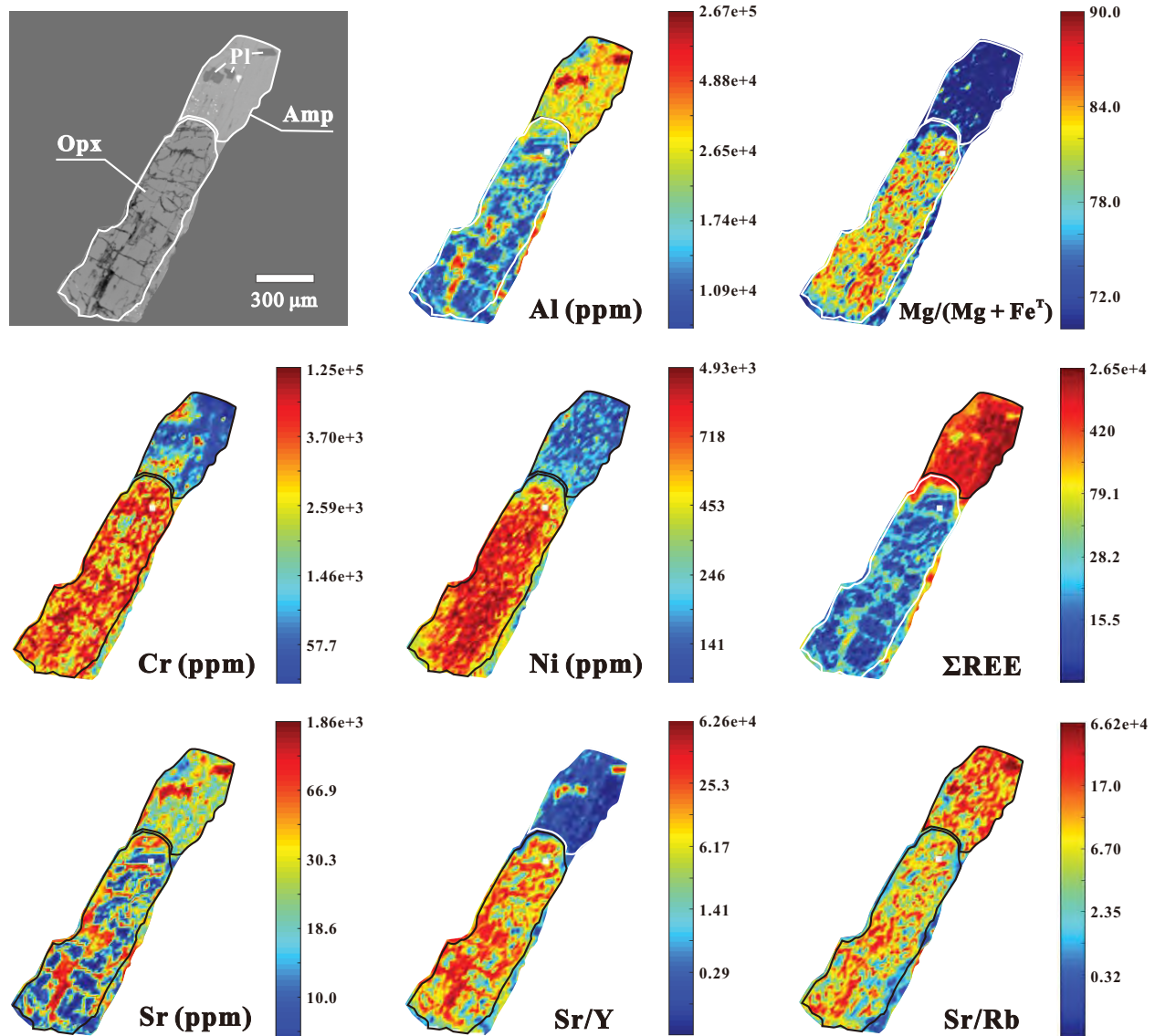
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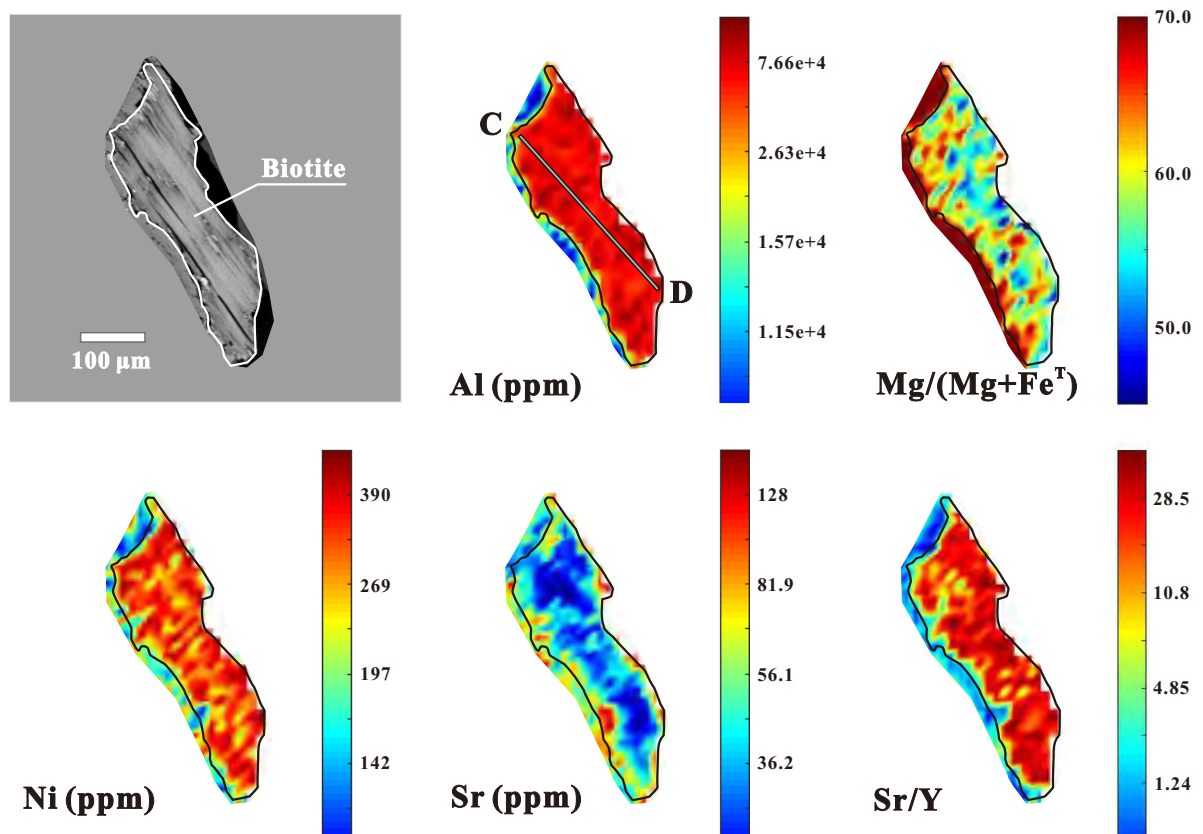
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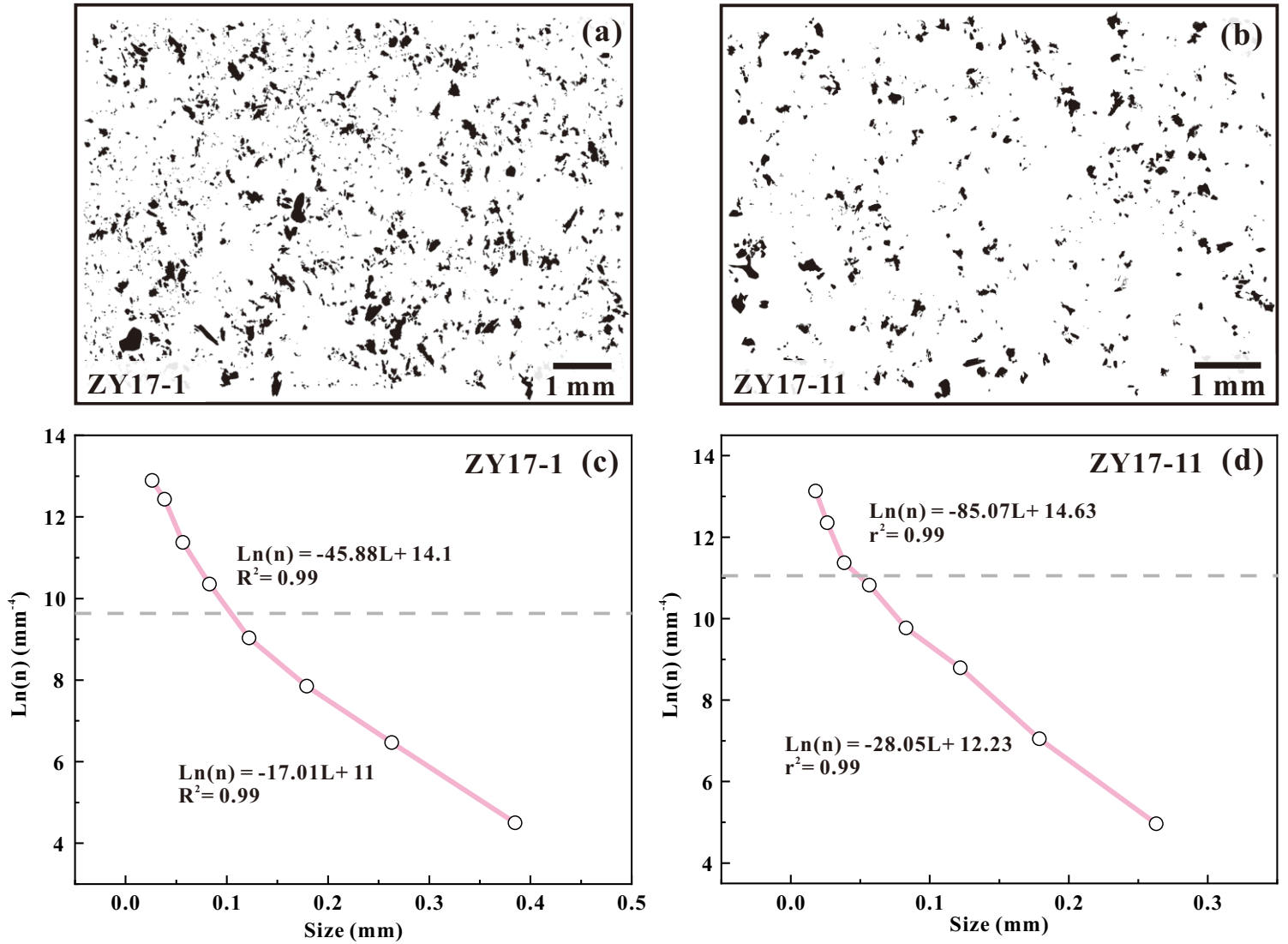
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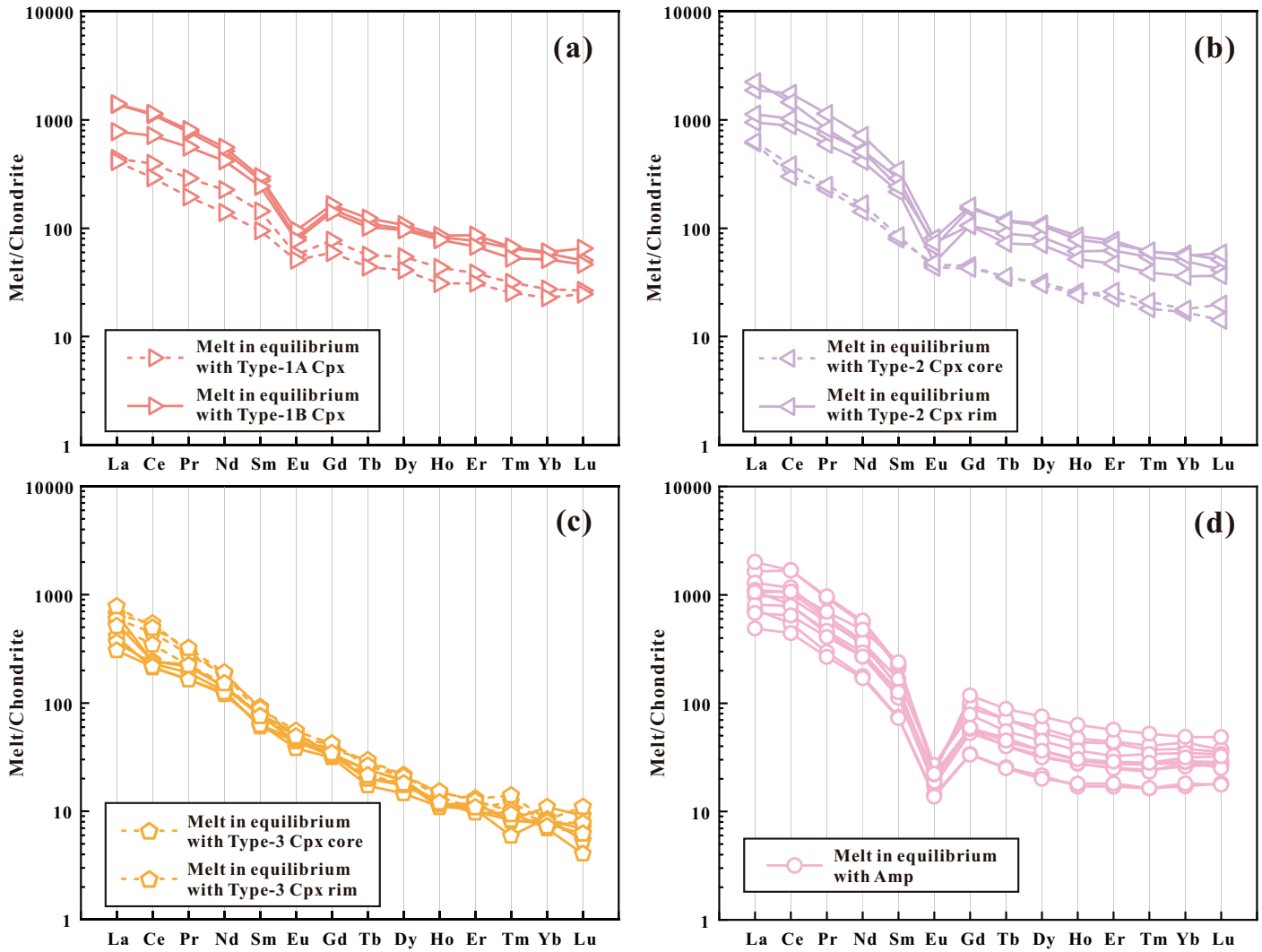
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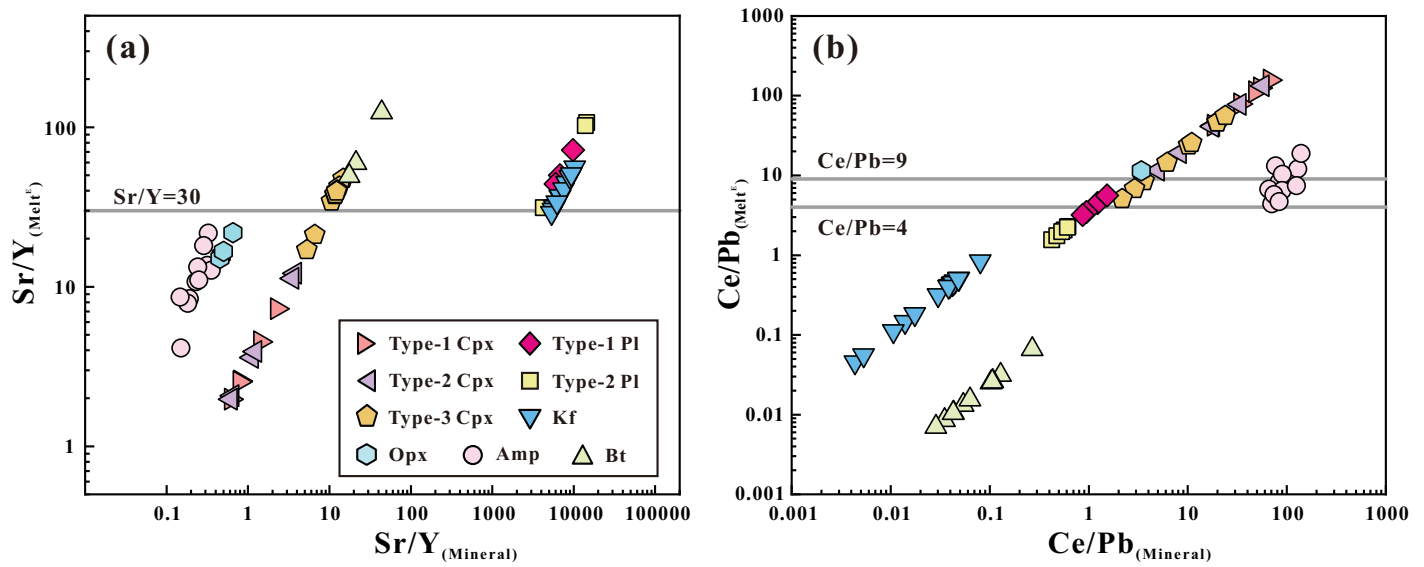
Figure 12

Figure 13

Figure 14