

1 **Post-collisional Pan-African granitoids and rare metal**
2 **pegmatites in western Nigeria: age, petrogenesis, and the**
3 **‘pegmatite conundrum’**

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13 **Abstract**

14 The Minna area of western Nigeria lies within a Pan-African orogenic belt that
15 extends along the margin of the West African Craton, from Algeria southwards
16 through Nigeria, Benin and Ghana, and into the Borborema Province of Brazil. This
17 belt is characterised by voluminous post-collisional granitoid plutons that are well
18 exposed around the city of Minna. In this paper we present new information about
19 their age and petrogenesis.

20 The Pan-African plutons around Minna can be divided into two main groups: a group
21 of largely peraluminous biotite-muscovite granites that show varying levels of
22 deformation in late Pan-African shear zones; and a younger group of relatively
23 undeformed, predominantly metaluminous hornblende granitoids. Pegmatites,
24 including both barren and rare-metal types, occur at the margins of some of the
25 plutons.

26 New U-Pb zircon dating presented here, in combination with published data, indicates
27 an early phase of magmatism at c. 790-760 Ma in the Minna area. This magmatism
28 could be related either to continental rifting, or to subduction around the margins of
29 an existing continent. The peraluminous biotite-muscovite granites were intruded at

30 c. 650-600 Ma during regional shearing in the orogenic belt, and are likely to have
31 formed largely by crustal melting. Subsequent emplacement of metaluminous
32 granitoids at c. 590 Ma indicates the onset of post-orogenic extension in this area,
33 with a contribution from mantle-derived magmas. The rare-metal pegmatites represent
34 the youngest intrusions in this area and thus are likely to have formed in a separate
35 magmatic episode, post-dating granite intrusion.

36 **Keywords**

37 Nigeria; Pan-African granite; post-collisional; rare-metal pegmatite; critical metals

38 **1. Introduction**

39 A network of Pan-African orogenic belts, formed during the Neoproterozoic to
40 Cambrian amalgamation of Gondwana, extends across the African continent and into
41 the Brasiliano orogen of South America (Black and Liégeois, 1993; Castaing et al.,
42 1994; de Wit et al., 2008; Jacobs and Thomas, 2004; Stern, 1994). These belts are
43 typically composed of Archaean and Proterozoic rocks that were reworked by
44 Neoproterozoic to Cambrian orogenesis, together with a variable proportion of
45 juvenile material. Many of the belts are characterised by extensive post-collisional
46 granitoid plutons (Black and Liégeois, 1993; Küster and Harms, 1998). These plutons
47 are typically potassic and their parental magmas are likely to be derived from mixed
48 mantle and crustal sources (Black and Liégeois, 1993; Bonin, 2004; Küster and
49 Harms, 1998; Liégeois et al., 1998). They thus represent major additions to the upper
50 crust during amalgamation of Gondwana.

51 Alkaline igneous plutons, including those in post-collisional settings, are increasingly
52 of interest as potential sources of 'critical metals' used in a range of advanced
53 technologies. These critical metals include the Rare Earth Elements (REE), niobium
54 and tantalum, which are commonly enriched in alkaline magmas. The increase in
55 demand for these metals makes a reappraisal of the controls on magmatism and the
56 potential for mineralisation worthwhile.

57 In West Africa, the Pan-African Dahomeyide orogenic belt separates the Archaean to
58 Mesoproterozoic West African and Congo cratons, and is exposed in an area known
59 as the Benin-Nigeria Shield (Ajibade and Wright, 1989). Northwards, this belt
60 continues into the Hoggar Massif of Algeria; southwards, prior to Atlantic opening, it

61 was connected to the Borborema Province of north-east Brazil (Arthaud et al., 2008;
62 Caby, 1989; Castaing et al., 1994; Dada, 2008; de Wit et al., 2008; Neves, 2003).

63 In Nigeria, the Dahomeyide orogenic belt has been divided into eastern and western
64 terranes separated by a major north-south lineament that has been recognised from
65 remote sensing, but not studied in detail (Ajibade et al., 1987; Ananaba and Ajakaiye,
66 1987; Ferré et al., 1996; Fitches et al., 1985; Woakes et al., 1987) (Figure 1). The
67 basement of the western terrane is dominated by Archaean migmatitic gneisses, with
68 Proterozoic schist belts composed of low-metamorphic grade, highly deformed,
69 metasedimentary and metavolcanic rocks (Ajibade et al., 1987; Arthaud et al., 2008;
70 Bruguier et al., 1994; Dada, 2008; Fitches et al., 1985). The eastern terrane is
71 characterised by high-grade (high-temperature amphibolite to granulite-facies),
72 migmatitic metamorphic rocks that have Palaeoproterozoic protoliths but were
73 migmatised during the Neoproterozoic (Ajibade et al., 1987; Ferré et al., 1996; Ferré
74 et al., 2002). Proterozoic schist belts are not recognised in the eastern terrane. Both
75 terranes are cut by a number of NNE–SSW-trending ductile shear zones that are tens
76 to hundreds of kilometres in length, and can be correlated with similar shear zones in
77 the Borborema Province in Brazil (Caby, 1989; Ferré et al., 2002).

78 Neoproterozoic magmatism at c. 780–770 Ma has been recorded in volcano-
79 sedimentary sequences of the Borborema Province. This has been interpreted as
80 related either to active subduction around continental margins, or to rifting (Arthaud
81 et al., 2008; Fetter et al., 2003). Magmatism of this age has been recorded by
82 relatively imprecise Rb-Sr dating in western Nigeria (Fitches et al., 1985).

83 The Nigerian basement is intruded by many Pan-African syn- to post-collisional
84 plutons, which are more voluminous in the eastern terrane than the west, and which
85 are known as the Older Granites. In eastern Nigeria, two suites of Older Granite
86 plutonism have been recognised; an earlier (c. 640–600 Ma) suite of peraluminous
87 biotite-muscovite granites, and a later (c. 600–580 Ma) suite of trans-alkaline
88 hornblende-biotite granitoids (Ferré et al., 1998; Ferré et al., 2002). Emplacement of
89 the later group was typically controlled by regional NE–SW shear zones (Ferré et al.,
90 1995). The Older Granites of the western terrane were considered to be I-type
91 granitoids by Fitches et al. (1985) but have not previously been subdivided into suites.
92 Hornblende-biotite granites from the western terrane have been dated at c. 630–580
93 Ma, similar to those in eastern Nigeria (Key et al., 2012; Tubosun et al., 1984).

94 Within the eastern terrane, a suite of Mesozoic alkaline plutons emplaced in an intra-
95 plate setting are known as the Younger Granites (Bowden, 1970). Mesozoic plutons
96 have not been recognised in the western terrane.

97 Similar groups of Neoproterozoic granites have been recognised in the Borborema
98 Province, where granitoid intrusions, including some S-type granites, were emplaced
99 prior to or during the early stages of collision at c. 630–610 Ma. This was followed by
100 emplacement of late-tectonic plutons, typically intruded into major shear zones, at
101 590–570 Ma (Arthaud et al., 2008; Bueno et al., 2009; Fetter et al., 2003; Neves et al.,
102 2008). Contemporaneous granitoid plutons are also found in the Pan-African belts to
103 the west and north of Nigeria. Westwards, in Ghana, Togo, and Benin, the overall
104 period of granitoid magmatism lasted from c. 660–550 Ma (Kalsbeek et al., 2012) and
105 alkaline plutons were emplaced at c. 590 Ma (Nude et al., 2009). To the north, in the
106 Hoggar Massif of Algeria, alkaline post-collisional magmatism continued until c. 530
107 Ma (Caby, 2003)

108 The post-collisional granites in Nigeria are associated with rare metal (tin-tantalum)
109 granitic pegmatites, some of which have been artisanally mined (Adetunji and Ocan,
110 2010; Garba, 2003; Kinnaird, 1984; Kuster, 1990; Matheis and Caen-Vachette, 1983;
111 Melcher et al., 2013; Okunlola, 2005; Woakes et al., 1987). The rare metal pegmatites
112 occur in a distinct belt that extends SW–NE from Ife to Jos, and appears to cut across
113 the boundary between the eastern and western Nigerian terranes, although the
114 individual pegmatite intrusions are oriented north-south (Kinnaird, 1984; Matheis and
115 Caen-Vachette, 1983; Woakes et al., 1987). Individual pegmatites vary in length from
116 10 m to over 2 km, and can be up to 200 m wide (Adetunji and Ocan, 2010).

117 Pegmatites of this type are typically associated with peraluminous or S-type granites
118 (Cerny et al., 2012) and in western Nigeria the pegmatites are most commonly found
119 close to the margins of peraluminous granite plutons. However, dating indicates that
120 the pegmatites were emplaced at 560–450 Ma (Matheis and Caen-Vachette, 1983;
121 Melcher et al., 2013), rather younger than the few previous dates for western Nigeria
122 granites (Tubosun et al., 1984). The origin of these pegmatites is thus uncertain,
123 although the peraluminous plutons with which they are associated have not previously
124 been targeted for dating. Similar pegmatites occur in the Borborema Province, where
125 they are extensively mined for tantalum (Beurlen et al., 2008). As well as the tantalum

126 potential, gold deposits are known in the Nigerian schist belts, but their formation
127 may pre-date the Pan-African orogeny (Dada, 2008).

128 Recent British Geological Survey (BGS) – Nigerian Geological Survey Agency
129 (NGSA) geochemical mapping in the western Nigeria terrane (Key et al., 2012;
130 Lapworth et al., 2012) has highlighted areas of enrichment in some critical metals,
131 such as the Rare Earth Elements (REE), niobium and tantalum, around the Older
132 Granite intrusions. This paper presents a more detailed study of these granitoids to
133 investigate their age relationships, petrogenesis and potential for critical metal
134 enrichment.

135

136 **2. Geology of the study area**

137 The area chosen for this study extends north-west from Abuja, the federal capital of
138 Nigeria, and is centred on the city of Minna (Figure 2). This area lies within the
139 western Nigeria terrane, and is a lush and well-vegetated part of Nigeria, made up of
140 low rolling hills with rockier whalebacks forming on the Older Granites (Figure 3a).
141 The basement comprises Archaean migmatitic gneisses with areas of Proterozoic
142 schist and metavolcanic rocks (Ferré et al., 1996). The migmatitic gneisses in the
143 study area are highly deformed, with the melanosome dominated by biotite and more
144 than one phase of pegmatitic, quartzofeldspathic leucosome. The metavolcanic and
145 metasedimentary rocks have been metamorphosed at greenschist to amphibolite
146 facies.

147 The basement rocks are transected by a number of broadly north-south to NNE-SSW
148 shear zones, the widest of which is defined by the outcrops of mylonites along the
149 Zungeru River to the north-west of Minna (Figure 2). The rocks within this several-
150 km wide Zungeru shear zone are intensely deformed, with a strong, steeply dipping,
151 mylonitic foliation and a near-horizontal lineation (Fitches et al., 1985). They have a
152 range of protoliths, including amphibolite and quartzofeldspathic rocks; the Older
153 Granites are also intensely deformed in this shear zone (Figure 3b). A second major
154 shear zone can be traced over a distance of around 100 km from the town of Kaduna
155 SSW through Sarkin Pawa. It is marked by a zone at least several hundred metres
156 wide in which the Older Granites and the country rocks are intensely foliated.

157 The Older Granites form between 30 and 40% of the outcrop area in the western
158 Nigeria terrane (Fitches et al., 1985), and crop out extensively in the Minna area.
159 They range from batholiths up to tens of km across to much smaller bodies (Figure 2).
160 Previous work has indicated that syn-tectonic plutons are typically elongate parallel to
161 the main regional NNE trend, whereas late-tectonic bodies tend to be rounded in
162 shape (Ferré et al., 1998). There has been little or no previous detailed study of the
163 plutons around Minna.

164 The Older Granites in the Minna area show a wide range of compositions, from
165 diorite through monzonite and granodiorite to voluminous granite and rare syenite.
166 They are typically coarse-grained, and many examples contain large (1 cm or more)
167 white or pink tabular feldspars. Xenoliths of country rock are common at pluton
168 margins. Later, cross-cutting sheets of aplitic and pegmatitic granite are also common.
169 Three granite samples from the plutons north of Minna have previously been dated
170 (by LA-ICPMS for U-Pb on zircons) at c. 606–616 Ma. All three samples were taken
171 close to the major Zungeru and Sarkin Pawa shear zones (Key et al., 2012). A U-Pb
172 age of 635 Ma has also been reported for a syn-tectonic granitoid from Sarkin Pawa
173 (Dada, 2008).

174 Some of the plutons are elongate in a NNE-SSW trend, parallel to the major shear
175 zones, and appear to have been emplaced during movement on those shear zones.
176 These plutons show a gradation in deformation state. Some have a magmatic fabric
177 defined by elongate tabular feldspars, but have not been-affected by solid state
178 deformation. This magmatic fabric can grade into a moderate deformation fabric in
179 which biotite plates and ribbons of quartz are aligned and xenoliths, where seen, are
180 foliation-parallel. The most deformed granitoids have a pervasive fabric in which a
181 gneissose banding has begun to develop, feldspars have been deformed and elongated,
182 and all minerals define the tectonic foliation. Excellent examples of all these fabrics
183 can be seen in the Tegina Pluton north-west of Minna, which lies within the Zungeru
184 shear zone (Figure 2, 3b). This pluton consists of foliated biotite granite and
185 granodiorite with some late pegmatite sheets.

186 Other plutons are not elongated parallel to the regional trend and their margins cross-
187 cut the main fabric in their country rocks, although an intense deformation fabric is
188 still developed where the granites are cut by localised shear zones. A particular
189 example of this is the major Minna Batholith centred on the city of Minna. It

190 comprises coarse-grained biotite-muscovite granite that is largely structureless or has
191 a weak magmatic foliation, although numerous discrete, metre- to decametre-scale
192 shear zones (typically with a NNE-SSW foliation) are present. Enclaves of biotite-rich
193 country rock are common at the margins of the Minna Batholith.

194 Numerous smaller plutons of biotite-muscovite granite and granodiorite are found in
195 the area around Sarkin Pawa north-east of Minna. These are commonly quite
196 complex, with outcrops showing several magmatic phases from diorite through
197 granodiorite to granite. In some areas these different phases have sharp but lobate
198 contacts indicating magma mingling, whereas in others they have gradational contacts
199 suggesting localised magma mixing. Late veins and sheets of pegmatite, aplite and
200 leucogranite are abundant (Figure 3c). The granites and granodiorites are locally
201 strongly foliated, particularly in the main Sarkin Pawa shear zone.

202 The Abuja Batholith forms a large mass that is not elongated parallel to regional shear
203 zones. This batholith largely comprises pink, coarse-grained, alkali feldspar-rich
204 hornblende-biotite granite with many enclaves and larger bodies of more mafic
205 monzonitic to dioritic composition (Figure 3d). At some localities, the enclaves are
206 rounded and have clear reaction rims with the granite but no evidence of chilling,
207 indicating largely coeval magmatism. Biotite-muscovite leucogranites occur at the
208 margins of the batholith; these have not been studied in detail, but may represent
209 partially melted country rock as suggested for similar plutons in eastern Nigeria (Ferré
210 et al., 1998).

211 Mineralised pegmatites are associated with the Older Granite plutons in Nigeria, and
212 existing Rb-Sr dates suggest that the pegmatites in central Nigeria were emplaced at c.
213 555 Ma (Matheis and Caen-Vachette, 1983). These pegmatites form sheets, typically
214 up to 1-2 m wide, cutting both basement rocks and the Pan-African granitoid plutons.
215 In some areas, much larger pegmatitic bodies up to 200 m wide have been recognised
216 (Adetunji and Ocan, 2003). The pegmatite suite can be divided into 'barren' and 'rare
217 metal' suites (Garba, 2003). The rare metal pegmatites comprise quartz, K-feldspar,
218 plagioclase, muscovite, biotite, and tourmaline with varying amounts of beryl,
219 lepidolite, spodumene, garnet, apatite and accessory minerals including columbite –
220 tantalite, tapiolite, wodginite, microlite, ilmenite and cassiterite (Melcher et al., 2013;
221 Wright, 1970). Crystals can vary up to 5 cm in size. The accessory minerals are
222 worked for tantalum by artisanal miners. The barren pegmatites comprise quartz, K-

223 feldspar, plagioclase, muscovite and biotite, but lack the accessory minerals that
224 concentrate rare metals. Both barren and rare metal pegmatites are found in the Minna
225 area, typically close to the biotite-muscovite granite plutons.

226

227 **3. Petrography of the granitoids**

228 The Older Granites in the study area share a number of petrological features; they are
229 typically coarse-grained, and primary magmatic crystal shapes are rare; textures range
230 from granoblastic and equigranular, to strongly foliated with aligned mafic minerals
231 and quartz ribbons. However, each of the named batholiths in the study area (Figure
232 2) is characterised by slightly different mineralogy and petrology.

233 The Minna Batholith is largely composed of coarse-grained leucogranites, generally
234 with c. 10% mafic minerals. Large (up to 1 cm), subhedral plates of heavily sericitised
235 microcline and plagioclase, zoned in some samples, are set in a matrix of
236 recrystallized pools of quartz with smaller feldspar crystals. The main mafic minerals
237 are biotite and muscovite, with primary epidote or zoisite and garnet in a few samples.
238 Cross-cutting aplites and pegmatites have similar mineralogy but vary in grain size.
239 Where these granitoids are sheared, a foliation is defined by aligned flakes of biotite
240 and muscovite, and ribbons of recrystallized quartz (Figure 4a). Larger epidote
241 crystals are undeformed, and wrapped by the foliation.

242 The Tegna Pluton shows significant variation in deformation state. It is formed of
243 coarse-grained biotite granite, granodiorite and diorite, with 10–30% mafic minerals.
244 Large subhedral feldspar (microcline and/or plagioclase) plates have very ragged,
245 recrystallized rims, and quartz is also recrystallized to granoblastic textures, forming
246 distinct elongate ribbons in more sheared samples. Biotite is the main mafic mineral,
247 with hornblende and garnet also being present in the more mafic granodiorite (Figure
248 4b). Biotite flakes are aligned and define the foliation in sheared samples. One sample
249 contains euhedral, zoned allanite crystals up to 2 mm across associated with clusters
250 of biotite.

251 Plutons around Sarkin Pawa are largely made up of leucogranite with numerous shear
252 zones. Large plates of microcline (2–10 mm across) are common in a matrix of
253 recrystallized quartz with alkali feldspar and plagioclase. Mafic minerals are generally
254 less than 15% of the rock; biotite is the main mafic mineral and muscovite is also

255 present in most samples. Hornblende, garnet, titanite, and zircon all occur in some
256 samples. Samples from shear zones have a foliation defined by elongate micas and
257 pools of recrystallized quartz, typically wrapping around rounded plates of
258 microcline. Late leucogranite and pegmatitic granite sheets are common in this area.
259 A leucogranite sheet cross-cutting foliated granitoids close to Sarkin Pawa village
260 contains hornblende and euhedral, zoned allanites up to 0.5 mm across (Figure 4c).
261 Rare-metal pegmatites occur close to the pluton margins around Sarkin Pawa, cutting
262 both the granites and the country rocks; some have granite-like mineralogy and
263 contain large tourmaline crystals, whereas other examples are composed almost
264 entirely of quartz and lithium mica. Tantalite is a notable accessory mineral in these
265 pegmatites.

266 The Abuja Batholith is dominated by biotite-amphibole granitoids; hornblende is the
267 predominant amphibole, but more sodic compositions are also present. Feldspars in
268 these rocks, most typically microcline, can form large crystals (up to 2 cm) and these
269 commonly have very irregular, recrystallized rims. More mafic monzonitic to
270 monzodioritic compositions, with up to 40% mafic minerals, were found particularly
271 at a locality in the north of the batholith. Some samples from this locality include
272 remnant orthopyroxene, which shows two stages of hydration and alteration, firstly to
273 cummingtonite and then to hornblende (Figure 4d). The orthopyroxene-bearing
274 compositions correspond to the hypersthene-quartz monzodiorites (also described as
275 charnockites) of eastern Nigeria (Ferré et al., 1998). Accessory minerals found
276 throughout the Abuja Batholith include titanite, apatite, zircon and opaque oxides.

277

278 **4. Analytical methods**

279 *4.1 Whole-rock geochemistry*

280 The samples comprised 2–3 kg of carefully selected representative rock chips.
281 Preparation and analysis of the samples was carried out by Acme Analytical
282 Laboratories Ltd, Vancouver. 1 kg of material was crushed before a 250 g split was
283 taken for analysis. Samples were analysed for 11 major oxides by ICP-ES and 34
284 trace elements by ICP-MS, following a lithium borate fusion and dilute acid digestion
285 of a 0.2 g sample to give total abundances. Due to the interest in metallogenesis, the
286 samples were also analysed for 14 metallic elements by ICP-MS following a hot aqua

287 regia digestion of 0.5 g samples. Duplicate analyses were within $\pm 2\%$ of each other
288 for major elements and key trace elements. Data for blanks were below detection
289 limits; data for international standard SO-18 were consistent with accepted values.
290 Data are presented in Table 1; data for elements that were consistently below
291 detection limit have not been included, and these include many of the metallic
292 elements analysed following the aqua regia digestion.

293

294 *4.2 U-Pb Geochronology*

295 Zircon crystals from four samples were dated by Laser Ablation Inductively Coupled
296 Plasma Mass Spectrometry (LA-ICP-MS) using a New Wave Research 193ss Nd-
297 YAG laser ablation system coupled to a Nu Instruments Attom single collector ICP-
298 MS. The full analytical method is described in Thomas et al. (2013). Zircons were
299 analysed in an epoxy mount after heavy mineral separation, and were imaged with
300 cathodoluminescence to characterise growth zones. Laser ablation parameters include
301 a 25 μm spot size, 2.5 j/cm^2 fluence, 30 second ablation time, 15 second washout
302 time, and 60 second background measurement prior to each ~ 20 analyses. A standard
303 sample bracketing routine was used to normalise Pb/U and Pb/Pb ratios using the
304 zircon reference material 91500. Secondary zircon reference materials (GJ-1 and
305 Plesovice) were analysed during the session to check accuracy and precision, both of
306 which are $<3\%$ 2σ . The full analytical results are provided in the online
307 supplementary files. All final crystallisation ages are $^{206}\text{Pb}/^{238}\text{U}$ ages, and include two
308 uncertainties written as $\pm x/y$, whereby x is the 2σ uncertainty after propagation of
309 measurement and session-based uncertainties, and y is the 2σ total uncertainty after
310 propagation of systematic uncertainties. The latter should always be referred to for
311 age comparison and compilation.

312

313 **5. Geochemistry of the granitoids**

314 Forty-five whole-rock samples from the Minna, Abuja, Tegna and Sarkin Pawa
315 intrusions were analysed for major, trace and rare earth elements (Table 1). The
316 majority of samples are granite *sensu stricto* with $\text{SiO}_2 > 70$ wt% (Figure 5a) with
317 rarer monzonite, granodiorite and syenite. Three samples from within the Abuja
318 Batholith have $\text{SiO}_2 < 60$ wt% and plot in the monzonite field on a total alkali-silica

319 diagram. In general the Abuja Batholith samples appear to follow a more alkaline
320 evolution trend than samples from the other intrusions, with higher total alkalis (Na_2O
321 + K_2O) at lower SiO_2 contents. Samples from the Abuja Batholith also fall within the
322 high-K field on a K_2O vs SiO_2 plot (Figure 5b); samples from the Minna Batholith
323 largely fall in the medium-K field, and samples from other plutons spread across the
324 boundary between high and medium-K fields. MgO is generally low (< 2wt% in
325 almost all samples) but total FeO + Fe_2O_3 is more variable. Samples from the Abuja
326 Batholith, and some from the Sarkin Pawa plutons, are typically metaluminous;
327 samples from the Minna Batholith, the Tegna Pluton, and most of the Sarkin Pawa
328 plutons, are typically peraluminous (Figure 6). Figure 6 shows that the samples from
329 the Abuja Batholith overlap with the fields for the later trans-alkaline granitoid suite
330 in eastern Nigeria (Ferré et al., 1998). However, the samples from the other western
331 Nigeria plutons extend to significantly more peraluminous compositions.
332 Geochemical data for the peraluminous plutons of eastern Nigeria are not available
333 for comparison.

334

335 The different intrusive complexes are clearly distinguished on well-established granite
336 discrimination diagrams (Figure 7). On the Y vs Nb plot (Pearce et al., 1984), all
337 samples from the Minna Batholith and Tegna plutons, as well as most Sarkin Pawa
338 samples, plot within the field of volcanic arc and syn-collisional granites. Samples
339 from the Abuja Batholith and some Sarkin Pawa plutons extend into the Within-Plate
340 Granite field. Similarly, on the Ga/Al vs Zr discrimination plot (Whalen et al., 1987),
341 the Minna and Tegna samples fall largely within the I-, S- and M-type field, whereas
342 most of the Abuja Batholith samples lie within the A-type field. Samples from Sarkin
343 Pawa extend across both fields. The samples from the Abuja Batholith typically
344 overlap with the trans-alkaline granites and quartz-monzonites of eastern Nigeria
345 (Ferré et al., 1998). Post-collisional granitoids are generally known to extend across
346 more than one field in these diagrams (Pearce, 1996), reflecting the involvement of
347 several different sources in their formation, including mixing of mantle and crustal
348 sources.

349

350 On the plot of SiO_2 vs Fe^* (Frost et al., 2001), samples from the Abuja Batholith fall
351 entirely within the A-type or ferroan granite field, and samples from the other plutons
352 fall entirely within the post-collisional granite field, although there is considerable

353 overlap (Figure 8). Samples from the Minna Batholith and Sarkin Pawa plutons
354 extend across the boundary between the ferroan and magnesian fields, indicating
355 contributions from more than one source component.

356 Post-collisional granitoids throughout the Pan-African orogenic belts are typically
357 characterised by similar geochemical features, including relatively high contents of
358 the large-ion lithophile elements (LILE), negative Nb-Ta, Sr and Ti anomalies, and
359 relative enrichment in the light REE (LREE) (Goodenough et al., 2010; Küster and
360 Harms, 1998). Spider diagrams for representative granite samples from the western
361 Nigeria plutons show many of these features (Figure 9). All the granites have minor
362 relative enrichment in the LILE such as Rb, Ba and K; relative depletions in Ta, Nb
363 and Ti; and enrichment of the LREE over the heavy REE (HREE). The most
364 fractionated granitoids are typically more strongly enriched in the LREE over HREE
365 and have negative Sr and Eu anomalies; a notable example of this is sample
366 NG/11/12, a late leucogranite sheet from the Sarkin Pawa area.

367

368 Granite, granodiorite and monzonite samples from the Abuja Batholith typically show
369 the least fractionated patterns and have higher contents of Nb, Ta, Zr, Hf and the
370 HREE relative to samples from the other areas. However, it is notable that the more
371 silica-rich granitic rocks from the Abuja Batholith actually have lower contents of
372 many incompatible elements (including Nb, Ta, Zr, Hf, and the MREE and HREE)
373 than the more mafic monzonitic rocks (Figure 9b). This suggests that the granitic and
374 monzonitic compositions cannot be related by simple fractional crystallisation, which
375 would enhance incompatible element contents in the most evolved magmas, and that
376 they are likely to represent mixing of two magmatic components. The results of a
377 simple mixing calculation, using the spreadsheet of Ersoy and Helvacı (2009), are
378 presented in Figure 10a. The most mafic (monzonitic) component of the Abuja
379 Batholith is represented by sample NG/11/45, and local crustal material is represented
380 by sample NG/11/16, a bulk sample of western Nigeria Archaean migmatitic gneiss. It
381 is evident that mixing with local crustal material has the potential to explain many of
382 the observed geochemical patterns in the Abuja Batholith. However, it is important to
383 note that NG/11/16 is a single sample and does not fully represent the variation of
384 compositions in the local crust.

385

386 In general, the geochemical patterns of the Abuja Batholith are similar to those of the
387 trans-alkaline plutons from Eastern Nigeria (Ferré et al., 1998) and from other Pan-
388 African suites such as the Maevarano suite of Madagascar (Goodenough et al., 2010)
389 (Figure 10b). However, samples of peraluminous granite from the Minna Batholith
390 are generally characterised by lower contents of most incompatible elements than
391 samples from the Abuja Batholith. These geochemical patterns, particularly low
392 contents of Hf, Zr, Ta and Nb, cannot be explained by simple melting of the local
393 Archaean gneisses. Petrography shows that the Minna Batholith samples are
394 characterised by large plates of feldspar in a felsic matrix; such textures are unlikely
395 to represent magmatic compositions, and thus it is difficult to derive source
396 compositions from the whole-rock geochemistry. However, the peraluminous nature
397 of these granitoids indicates a likely derivation from sedimentary sources, potentially
398 those represented by the Proterozoic schist belts.

399

400 Total REE contents (TREE) vary up to 915 ppm (in fractionated leucogranite sheets
401 from Sarkin Pawa) and are dominated by the LREE, with the highest TREE contents
402 found in allanite-bearing samples. It is notable that TREE contents show a weak
403 negative correlation with SiO₂, with some of the most evolved granitic rocks showing
404 the lowest total REE contents.

405

406 Late pegmatites are found across the Minna area and have been recognised in spatial
407 association with the Minna, Teginia and Sarkin Pawa plutons, both cutting the granite
408 plutons and intruded around their margins. Of these, true rare-metal pegmatites have
409 only been found by this study in association with the Sarkin Pawa plutons. All these
410 late pegmatites have variable trace element patterns but are typically strongly
411 fractionated. They are enriched in Rb, K, U, Nb and Ta relative to the granitoids, but
412 typically show notable depletions in Ba, the REE, Hf and Zr (Figure 9). All have
413 negative Ti anomalies, but Eu and Sr are more variable. The pegmatites are also
414 characterised by notably higher Ta/Nb and Hf/Zr ratios than the granites; this is
415 characteristic of highly evolved magmas of this type (Linnen, 1998). The rare metal
416 pegmatites from the Sarkin Pawa area also have elevated Be, Cs, Sn and W contents
417 (Table 1) and in this respect they are generally typical of the LCT (Li-Cs-Ta) family
418 of pegmatites (Cerny and Ercit, 2005; Cerny et al., 2012). Similar whole-rock
419 geochemical patterns for rare metal pegmatites and their host granites are known from

420 other areas of post-collisional magmatism, such as the Altai mountains of China (Zhu
421 et al., 2006), but there are very few published whole-rock geochemical data for
422 pegmatites from the Pan-African orogenic belts.

423 **6. Geochronology of the granitoids**

424 Four samples of the plutonic rocks were collected for U-Pb dating by LA-ICPMS
425 (Table 2). Sample NG/11/12 was collected from an allanite-bearing leucogranite sheet
426 cross-cutting foliated granitoids in the Sarkin Pawa area, and represents the youngest
427 magmatism in that area. Sample NG/11/25 is a strongly foliated granodiorite from the
428 outer part of the Minna Batholith, and NG/11/35 is a garnetiferous biotite-muscovite
429 granite also from the Minna Batholith. Sample NG/11/49 is a biotite granite from the
430 Abuja Batholith.

431 *6.1 Zircon Description and Interpretation*

432 **NG/11/12**

433 Zircon in this sample comprises largely prismatic grains with length/width ratios of 1
434 to 4, showing complex oscillatory zoning, typically with darker inner zones and
435 brighter outer zones under cathodoluminescence (CL) (Figure 11a). Unconformities in
436 the zoning are observed in some grains (less than a third of the total population).
437 Altered zoning in the form of convolutions of the oscillatory zones is also seen in
438 some grains. Metamorphic rims are not apparent, but some of the outer zones are thin
439 with embayments into the inner zones. The population looks consistent and would be
440 expected to give one, or at most two main ages.

441 **NG/11/25**

442 This sample contains prismatic zircon grains with length/width ratios of 1 to 2 and
443 complex oscillatory zoning, typically with one or two unconformities per grain
444 (Figure 11b). Some grains (less than a third of the population) have fuzzy or
445 convoluted inner zones. The inner zones typically appear darker under
446 cathodoluminescence, and the outer zones appear brighter. Embayments or
447 metamorphic rims are not apparent. Two or more magmatic growth periods may be
448 recorded by this zircon population.

449 **NG/11/35**

450 Zircon grains in this sample are prismatic with length/width ratios of 1 to 3 (Figure
451 11c). They show complex oscillatory zoning, typically with darker outer zones under

452 CL. Most grains exhibit unconformities between outer and inner zones. Many grains
453 (c. two-thirds of the population) exhibit alteration of the inner zones, generally in the
454 form of convolution of zoning and/or a granular texture. Many outer zones have
455 embayment, but no thin metamorphic rims are apparent. The population is probably
456 comprised of at least two growth phases; alteration of the inner zones may be younger
457 than zircon crystallisation, or part of the youngest growth phase.

458 **NG/11/49**

459 This sample contains prismatic zircon grains with length/width ratios of 2 to 4 (Figure
460 11d). Complex oscillatory zoning is ubiquitous. Darker outer zones around brighter
461 inner zones are most common, but brighter outer zones also exist. Unconformities
462 across zoning are present in some grains (less than a quarter of the population). Some
463 convolution of zoning occurs on the outer zone of some grains, but this is typically
464 associated with inclusions within the zircons. No metamorphic rims are apparent.
465 Crystallisation probably occurred during one main magmatic episode, but discordant
466 inner zones suggest the possibility of inherited zircon cores.

467 *6. 2 Results*

468 **NG/11/12**

469 62 analyses were made from 54 grains, 8 of these were rejected due to high common
470 Pb component (>600 cps Pb^{204}). The data cluster around 590 Ma (Figure 12a). One
471 concordant grain at ~ 1008 Ma ($^{207}\text{Pb}/^{206}\text{Pb}$ age) indicates some inheritance; this
472 analysis was from a core of a grain. The data spread towards slightly older ages along
473 Concordia. These may represent a slightly older inherited component, or mixing with
474 distinctly older zones (e.g. ~ 1000 Ma); the latter is not supported by the CL imagery.
475 The data also spread towards discordant analyses with older $^{207}\text{Pb}/^{206}\text{Pb}$ ages, these
476 probably result from small amounts of common lead and/or mixing with inherited
477 components. For the age calculation, discordant ($>10\%$) analyses were excluded, as
478 were distinctly older concordant analyses. The youngest analysis pertains to an outer
479 zone of a grain that has an embayment to the inner zone, this was also excluded from
480 the age calculation. The remaining 41 analyses give a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age
481 of $590 \pm 3/13$ Ma (MSWD = 1.8).

482 **NG/11/25**

483 50 analyses were made from 46 zircon grains, and these cluster around 780–760 Ma
484 (Figure 12b). One concordant grain at 830 Ma ($^{206}\text{Pb}/^{238}\text{U}$ age), indicates inheritance

485 of a slightly older component. Three discordant (>10%) analyses are likely affected
486 by common lead, and/or mixing with an inherited component. The rest of the
487 population spreads along concordia slightly, and exhibits some minor reverse
488 discordance. The CL imagery resolved discordant zoning that indicates the likelihood
489 of crystallisation during more than one phase. The data are split into inner and outer
490 zones, although this includes some subjectivity since some grains do not have obvious
491 boundaries between zones. Excluding one analysis with a high degree of reverse
492 discordance, 19 outer zone analyses give a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of $764 \pm$
493 $6/18$ Ma (MSWD = 1.7). The remaining 26 inner zone analyses overlap in age with a
494 weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of $774 \pm 7/19$ Ma (MSWD = 3.9) but spread to much
495 older ages. The age given by the outer zones is interpreted as representing final
496 crystallisation of the unit.

497 **NG/11/35**

498 46 analyses were made from 38 zircon grains, and 4 of these were rejected due to high
499 common Pb (>600 cps Pb^{204}). One inherited grain is distinctly older than the main
500 populations at ~2100 Ma. The rest of the data spread from ~820 to 620 Ma (Figure
501 12c), and include a range of analyses that extend to older $^{207}\text{Pb}/^{206}\text{Pb}$ ages, probably
502 related to minor common Pb content. After exclusion of discordant (>10%) data, the
503 analyses fall into two broad populations. The data have been divided into inner and
504 outer zones based on the CL imagery. Nine of the ten inner zones form a population
505 which gives a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of $793 \pm 12/21$ Ma (MSWD = 2.9).
506 Twelve of the thirteen outer zones form a population which gives a weighted mean
507 $^{206}\text{Pb}/^{238}\text{U}$ age of $653 \pm 12/19$ Ma (MSWD = 6.3). These two populations both have a
508 high MSWD, which indicates that they do not represent single populations, probably
509 because the analyses represent a small amount of mixing between different age zones.
510 The youngest phase of crystallisation of this unit is interpreted to be ca. 653 Ma, and
511 an earlier crystallisation is recorded at ca. 793 Ma.

512 **NG/11/49**

513 Forty analyses were made from 30 zircon grains, and of these only one corresponds
514 to a distinctly older inherited grain, dated at ca. 1180 Ma ($^{207}\text{Pb}/^{206}\text{Pb}$). The rest of the
515 analyses cluster around an age of ~590 Ma (Figure 1
516 2d). Several analyses spread to slightly older $^{207}\text{Pb}/^{206}\text{Pb}$ ages, probably related to a
517 minor common lead content. Three analyses are slightly older than the main
518 population in terms of $^{207}\text{Pb}/^{206}\text{Pb}$ age; one of these is slightly normally discordant

519 and dated at 639 Ma ($^{206}\text{Pb}/^{238}\text{U}$ age), and two are reversely discordant and dated at
520 620 Ma ($^{206}\text{Pb}/^{238}\text{U}$ age). These older analyses indicate the possibility of a slightly
521 older inherited component, but do not particularly relate to separate internal zones that
522 are apparent from the CL imagery. The remaining 30 analyses define a single
523 population with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of $588 \pm 3/13$ Ma (MSWD = 1.07).
524 This is interpreted as dating crystallisation of this unit.

525

526 **7. Discussion**

527 Field, petrological and geochemical data for Pan-African granitoids in the Minna area
528 clearly indicate that the granitoid plutons can be divided into two broad groupings.
529 The Minna Batholith, the Tegina Pluton and plutons around Sarkin Pawa comprise
530 biotite-muscovite granites, locally containing garnet and epidote, which typically have
531 peraluminous compositions. They show evidence of having been emplaced into an
532 active tectonic regime characterised by major NNE-SSW shear zones. The second
533 grouping comprises the metaluminous hornblende granitoids of the Abuja Batholith
534 and late intrusive sheets in the Sarkin Pawa area. These intrusions are more alkaline,
535 and contain a greater mafic magmatic component than the earlier biotite granites,
536 varying from syenodiorites to leucogranites. In general they have higher contents of
537 Nb, Zr and Hf than the biotite granites, but this study has found no evidence for
538 significant critical metal enrichments. A third group of intrusions, the late pegmatites,
539 is found throughout much of the area and discussed separately from the major plutons.

540 The age data from this study, together with published ages of Key et al. (2012),
541 indicate that the Older Granite magmatism in the Minna area spanned a considerable
542 amount of time. The Minna Batholith clearly contains evidence for an early phase of
543 magmatism at c. 790–760 Ma. Because one sample (NG/11/25) has a single
544 population of zircons of this age, this is highly unlikely to represent an inheritance
545 age, and is considered to date crystallisation of the unit. The sample was taken from
546 an outcrop apparently within the Minna Batholith, but may represent a large screen of
547 older crust that has been incorporated within the batholith, but not assimilated. Ages
548 of c. 790–740 Ma have previously been obtained by relatively imprecise Rb-Sr dating
549 of Nigerian Older Granites from the area north of Minna (Fitches et al., 1985), and
550 magmatic ages of 800–770 Ma are found in the Borborema Province (Arthaud et al.,

551 2008). The tectonic setting of the Brazilian magmatism is debated, and may be related
552 to continental rifting, or to subduction at an active continental margin (Arthaud et al.,
553 2008; de Araujo et al., 2012; Fetter et al., 2003). It is evident that Nigeria was affected
554 by a contemporaneous magmatic event. However, only the single dated sample can be
555 clearly attributed to this event in Nigeria. Identification and study of individual
556 intrusions formed at this time would be needed in order to identify the tectonic
557 setting.

558 The sites of earlier Neoproterozoic magmatism were subsequently exploited by later
559 peraluminous magmas at c. 650 Ma, as demonstrated by the two age populations in
560 sample NG/11/35. These earlier, biotite-muscovite peraluminous granites are likely to
561 have had a significant source component of sedimentary material. However, a lack of
562 published isotopic data means that the source of this sedimentary material remains in
563 doubt; one potential source lies in the schist belts of the western Nigeria terrane. The
564 magmas are thought to have formed by crustal melting associated with high-
565 temperature metamorphism and crustal thickening following the peak of the main
566 Pan-African collision (Ferré et al., 2002).

567 Biotite granites continued to be emplaced in the region between c. 635 and 600 Ma
568 (Dada, 2008; Key et al., 2012), and in many areas these were affected by intense
569 ductile shearing, acquiring strong syn- to post-magmatic foliations.

570 Subsequently, metaluminous hornblende granitoids were emplaced at c. 590 Ma,
571 forming the Abuja Batholith as well as later leucogranite sheets in the Sarkin Pawa
572 area (samples NG/11/12 and NG/11/49). Relatively mafic monzonitic to
573 monzodioritic lithologies are present as enclaves and larger masses within the Abuja
574 Batholith. In contrast with the earlier peraluminous granites, the metaluminous
575 granitoids, monzonites and monzodiorites have alkaline affinities, and show many
576 geochemical features akin to A-type granitoids. However, the presence of negative
577 Nb-Ta anomalies is not typical of A-type granitoids, but can be attributed either to
578 melting of a lithospheric mantle source that has been enriched by earlier subduction,
579 or to contamination by continental crust.

580 Recent geochemical and isotopic studies of coeval metaluminous hornblende-biotite
581 granitoids in eastern Nigeria show that initial ϵ_{Nd} ranges from -5 to -16, and initial
582 $^{87}\text{Sr}/^{86}\text{Sr}$ ranges from 0.70617 to 0.71015 (Dada et al., 1995; Ferré et al., 1998). These

583 data have been interpreted to indicate that the source of the granitoid magmas was
584 largely in the continental crust, with limited contribution from the mantle (Dada et al.,
585 1995). The more mafic components of the suite in eastern Nigeria are highly potassic
586 quartz monzonites such as those in the Bauchi pluton (although the best available
587 dates place these at c. 640 Ma (Dada and Respaut, 1989; Oyawoye, 1961)). Isotopic
588 data for these monzonites show a trend towards more mantle-like compositions with
589 initial ϵ_{Nd} from -4 to -8 (Dada et al., 1995). Strongly alkaline c. 590 Ma intrusions
590 sourced from mantle-derived magmas have also been recognised in the Dahomeyide
591 belt in Ghana (Nude et al., 2009). Geochemical evidence in both eastern (Ferré et al.,
592 1998) and western Nigeria (this study) indicates that the metaluminous granitoids
593 were not formed by direct fractional crystallisation of the more mafic monzonitic and
594 monzodioritic magmatic component. Instead, the composition of the granitoids can be
595 largely explained by mixing between melts of the local Archaean meta-igneous crust,
596 and a more mafic mantle-derived magma. Overall, the geochemical data for the
597 metaluminous plutons of western Nigeria fit with the hypothesis proposed for similar
598 plutons in eastern Nigeria, namely a fractionated mantle-derived magma that has
599 mixed with magmas derived by melting of igneous material in the continental crust
600 (Dada et al., 1995; Ferré et al., 1998).

601 The final magmatic event in the area was the intrusion of barren and rare-metal
602 pegmatites, which have been dated at 560–450 Ma (Matheis and Caen-Vachette,
603 1983; Melcher et al., 2013). Late pegmatites are spatially associated with most of the
604 Older Granite plutons, but the dating indicates that they post-date the Older Granites,
605 and are not directly genetically related to them, as originally suggested by Matheis
606 (1987). This is difficult to reconcile with the geochemical evidence presented here,
607 which shows that the pegmatites formed from very highly evolved magmas. These
608 pegmatites have affinities with the LCT pegmatite family, which is typically
609 considered to comprise the most highly fractionated parts of S-type or peraluminous
610 granitic suites formed during crustal thickening (Cerny et al., 2012). However, in
611 western Nigeria the dating presented here indicates that the Older Granites evolved
612 with time away from a sedimentary source towards an increased contribution from a
613 mantle or lower crustal source. The origin of the pegmatites thus remains uncertain.

614 The Borborema Province in Brazil also contains rare-metal pegmatites emplaced at
615 515–509 Ma (Baumgartner et al., 2006); as with the Nigerian pegmatites, these have

616 been artisanally mined for Nb and Ta. The Borborema Province pegmatites are also
617 associated with granites, and as in Nigeria, the pegmatites appear to be distinctly
618 younger than the granites. This ‘pegmatite conundrum’ has been recognised in post-
619 collisional settings elsewhere in the world (e.g. the Altai Mountains (Zhu et al.,
620 2006)). Rare-metal pegmatites are typically considered to crystallise from highly
621 fractionated magmas, representing the latest intrusion stage in a granitic province
622 (Cerny et al., 2012). However, in many areas, they appear to post-date the associated
623 granitoid plutons by a significant period of time, and potentially represent a separate
624 intrusive event. Pegmatites such as those in western Nigeria are an important part of
625 the global tantalum resource, yet their genesis remains poorly understood, and further
626 work is needed to understand the source of these unusual magmas.

627 **8. Conclusions**

628 Pan-African-Brasiliano orogenic belts extending around the West African Craton
629 contain abundant post-collisional granitoids, which are recognised throughout West
630 Africa and Brazil. The Minna area of western Nigeria provides good exposures of all
631 elements of this magmatic province.

632 The earliest magmatism, at 790–760 Ma, is recorded by zircon cores and zones of
633 intensely deformed granodiorite within the Minna Batholith. Magmatism of this age is
634 known in the Borborema Province of Brazil, and has also been recognised by Rb-Sr
635 dating in Nigeria. It may be related to Neoproterozoic subduction around the margins
636 of the West African Craton, but more work is needed to fully characterise this
637 magmatic episode.

638 Large volumes of peraluminous biotite granite were produced during crustal
639 thickening at 600–650 Ma in western Nigeria. Emplacement of these plutons was
640 focused along large-scale crustal shear zones and many of the plutons are intensely
641 foliated. These granites typically have peraluminous characteristics and were largely
642 derived by melting of local crust.

643 Later, post-tectonic metaluminous magmas (hornblende diorites, granodiorites and
644 granites) were emplaced in an extensional post-collisional setting at c. 590 Ma. The
645 association of mafic (dioritic) and felsic magmas, emplaced contemporaneously, and
646 the more alkaline, LILE-enriched nature of those magmas, indicates both mantle-
647 derived and crustally-derived magmatic components. Thus, initial post-collisional

648 melting in this orogenic belt was focused in the thickened upper to middle crust, with
649 the mantle-derived component increasing over time.

650 The last magmatic event in western Nigeria was the emplacement of LCT-type
651 pegmatites, some of which are enriched in rare metals such as tantalum. On the basis
652 of current evidence, these pegmatites were emplaced at c. 560–450 Ma, and
653 significantly post-date the peraluminous granitoid plutons. These pegmatites thus
654 cannot be highly evolved melts derived from a fertile, S-type, parental granite as is
655 normally considered for LCT pegmatites. The origin of such rare-metal pegmatites
656 thus presents an unsolved conundrum.

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663 **Figures**

664 Figure 1: Simplified map of the geology of Nigeria, after Ferré et al. (1996) and Key
665 et al. (2012). Box indicates the area shown in Figure 2.

666 Figure 2: Simplified map of the geology of the Minna area, after Key et al. (2012).

667 Figure 3: a) Granite whaleback hill in the Teginia Pluton, illustrating the typical
668 scenery of the field area; b) Foliated granitoid demonstrating strong solid-state
669 deformation, Teginia Pluton; c) Coarse-grained porphyritic granitoid cut by late
670 granite pegmatite, Sarkin Pawa area; d) Outcrop showing mingling, mixing and
671 localised shearing of dioritic and granitic magmas in the Abuja Batholith.

672 Figure 4: Photomicrographs of thin sections from Nigerian Older Granites, viewed in
673 plane polarised light. a) Sheared granitoid from the Minna Batholith, with a foliation
674 defined by aligned biotites (Bt) and recrystallised quartz (Qz) ribbons, and highly
675 altered feldspar (Fsp); b) Granodiorite from the Teginia Pluton, containing biotite (Bt),
676 hornblende (Hbl) and garnet (Grt); c) Late stage hornblende (Hbl)-biotite (Bt) granite
677 sheet from the Sarkin Pawa area with large, high-relief, yellowish allanite (Aln)
678 crystals (Aln); d) Monzonite from the Abuja Batholith containing altered
679 orthopyroxene (Opx) typically rimmed by hornblende (Hbl).

680 Figure 5: a) Plot of total alkalis versus silica for all analysed samples from Nigerian
681 Older Granites, divided by pluton. Fields from Gillespie and Styles (1999). Dashed
682 line represents boundary between alkalic rocks above and subalkalic rocks below
683 (Miyashiro, 1974); b): Plot of K_2O vs SiO_2 for all samples, with fields from Le Maitre
684 (2002).

685 Figure 6: Shand Index plot for all analysed samples. A/NK = molar ($Al_2O_3/(Na_2O +$
686 $K_2O)$); A/CNK = molar ($Al_2O_3/(CaO + Na_2O + K_2O)$). Fields for trans-alkaline
687 plutons from Eastern Nigeria (Ferré et al., 1998) given for comparison.

688 Figure 7: Granite discrimination diagrams for all analysed samples. a) Nb vs Y plot
689 after Pearce et al. (1984); b) Zr vs Ga/Al plot after Whalen et al. (1987). Fields for
690 trans-alkaline plutons from Eastern Nigeria (Ferré et al., 1998) given for comparison.

691 Figure 8: Plot of SiO_2 vs $\text{FeO}^{\text{tot}}/(\text{FeO}^{\text{tot}}+\text{MgO})$ for all analysed samples, with fields
692 for A-type and post-collisional granitoids from Frost et al. (2001)

693 Figure 9: Primitive mantle-normalised trace element plots for selected samples from
694 the different plutons within the study area. Normalising factors from McDonough and
695 Sun (1995).

696 Figure 10a): Primitive mantle-normalised trace element plots for samples from the
697 Abuja Batholith, with grey lines showing the calculated compositions achieved by
698 mixing Abuja Batholith monzonite (NG/11/48) with local Archaean crust; b)
699 Primitive mantle-normalised trace element plots for representative samples from the
700 Minna Batholith and Abuja Batholith (this study), the Rahama Granite of Eastern
701 Nigeria (Ferré et al., 1998), and the comparable Maevarano suite of Madagascar
702 (Goodenough et al., 2010). Normalising factors from McDonough and Sun (1995).

703 Figure 11: Cathodoluminescence images for representative zircon crystals from the
704 four geochronology samples

705 Figure 12: Zircon concordia plots for the four dated samples. a) NG/11/12; b)
706 NG/11/25; c) NG/11/35; d) NG/11/49. Analyses in black are those used for age
707 calculations; those in grey were rejected due to discordance or mixed age.

708 Tables

709 Table 1: Whole-rock geochemical data for all analysed samples

710 Table 2 (online supplementary data): U-Pb data for the four dated samples.

711 Discordance = $(1 - ((206\text{Pb}/238\text{U}) / (207\text{Pb}/206\text{Pb}))) * 100$. Concentrations in ppm are
712 based on normalisation to 91500, based on 14.8ppm Pb, 30ppm Th and 81.2ppm U.
713 ^{204}Pb , ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th and ^{235}U in counts per second. ^{204}Pb is after
714 subtraction of ^{204}Hg based on measurement of ^{202}Hg . Osci = oscillatory zoning.
715 Analyses in black are those used for age calculations.

716

717 References

- 718 Adetunji, A., Ocan, O.O., 2010. Characterization and Mineralization Potentials of
719 Granitic Pegmatites of Komu area, Southwestern Nigeria. *Resource Geology* 60, 87-
720 97.
- 721 Ajibade, A.C., Woakes, M., Rahaman, M.A., 1987. Proterozoic crustal development
722 in the Pan-African regime of Nigeria, in: Kroner, A. (Ed.), *Proterozoic Lithospheric*
723 *Evolution* AGU, Washington DC.
- 724 Ajibade, A.C., Wright, J.B., 1989. The Togo-Benin-Nigeria Shield: evidence of
725 crustal aggregation in the Pan-African belt. *Tectonophysics* 165, 125-129.
- 726 Ananaba, S.E., Ajakaiye, D.E., 1987. Evidence of tectonic control of mineralization in
727 Nigeria from lineament density analysis. A Landsat study. *International Journal of*
728 *Remote Sensing* 8, 1445-1452.
- 729 Arthaud, M.H., Caby, R., Fuck, R.A., Dantas, E.L., Parente, C.V., 2008. Geology of
730 the northern Borborema Province, NE Brazil, and its correlation with Nigeria, NW
731 Africa, in: Pankhurst, R.J., Trouw, R.A.J., Brito Neves, B.B., De Wit, M.J. (Eds.),

732 West Gondwana: Pre-Cenozoic Correlations across the South Atlantic Region.
733 Geological Society, London, Special Publication 294, pp. 49-67.

734 Baumgartner, R., Romer, R.L., Moritz, R., Sallet, R., Chiaradia, M., 2006. Columbite-
735 tantalite bearing granitic pegmatites from the Serido Belt, Northeastern Brazil:
736 Genetic constraints from U-Pb dating and Pb isotopes. *The Canadian Mineralogist* 44,
737 69-86.

738 Beurlen, H., da Silva, M.R.R., Thomas, R., Soares, D.R., Olivier, P., 2008. Nb-Ta-
739 (Ti-Sn) oxide mineral chemistry as tracer of rare-element granitic pegmatite
740 fractionation in the Borborema Province, Northeastern Brazil. *Mineralium Deposita*
741 43, 207-228.

742 Black, R., Liégeois, J.P., 1993. Cratons, mobile belts, alkaline rocks and continental
743 lithospheric mantle; the Pan-African testimony. *Journal of the Geological Society of*
744 *London* 150, 89-98.

745 Bonin, B., 2004. Do coeval mafic and felsic magmas in post-collisional to within-
746 plate regimes necessarily imply two contrasting, mantle and crustal, sources? A
747 review. *Lithos* 78, 1-24.

748 Bowden, P., 1970. Origin of the younger granites of northern Nigeria. *Contributions*
749 *to Mineralogy and Petrology* 25, 153-162.

750 Bruguier, O., Dada, S.S., Lancelot, J.R., 1994. Early Archaean component (> 3.5 Ga)
751 within a 3.05 Ga orthogneiss from northern Nigeria: U-Pb zircon evidence. *Earth and*
752 *Planetary Science Letters* 125, 89-103.

753 Bueno, J.F., Oliveira, E.P., McNaughton, N.J., Laux, J.H., 2009. U-Pb dating of
754 granites in the Neoproterozoic Sergipano Belt, NE Brazil: Implications for the timing
755 and duration of continental collision and extrusion tectonics in the Borborema
756 Province. *Gondwana Research* 15, 86-97.

757 Caby, R., 1989. Precambrian terranes of Benin-Nigeria and northeast Brazil and the
758 Late Proterozoic south Atlantic fit, in: Dallmeyer, R.D. (Ed.), *Terranes in the Circum-*
759 *Atlantic Palaeozoic Orogens*. Geological Society of America Special Paper 230, pp.
760 145-158.

761 Caby, R., 2003. Terrane assembly and geodynamic evolution of central-western
762 Hoggar: a synthesis. *Journal of African Earth Sciences* 37, 133-159.

763 Castaing, C., Feybesse, J.L., Thieblemont, D., Triboulet, C., Chevremont, P., 1994.
764 Palaeogeographical reconstructions of the Pan-African/ Brasiliano orogen: closure of
765 an oceanic domain or intracontinental convergence between major blocks?
766 *Precambrian Research* 69, 327-344.

767 Cerny, P., Ercit, T.S., 2005. The Classification of Granitic Pegmatites Revisited. *The*
768 *Canadian Mineralogist* 43, 2005-2026.

769 Cerny, P., London, D., Novak, M., 2012. Granitic Pegmatites as Reflections of Their
770 Sources. *Elements* 8, 289-294.

771 Dada, S.S., 2008. Proterozoic evolution of the Nigeria-Borborema province, in:
772 Pankhurst, R.J., Trouw, R.A.J., Brito Neves, B.B., de Wit, M.J. (Eds.), *West*
773 *Gondwana: Pre-Cenozoic Correlations across the South Atlantic Region*. Geological
774 *Society of London Special Publication* 294
775 pp. 121-136.

776 Dada, S.S., Briquieu, L., Harms, U., Lancelot, J.R., Matheis, G., 1995. Charnockitic
777 and monzonitic Pan-African series from north-central Nigeria: Trace-element and Nd,
778 Sr, Pb isotope constraints on their petrogenesis. *Chemical Geology* 124, 233-252.

779 Dada, S.S., Respaut, J.P., 1989. La monzonite à fayalite de Bauchi (bauchite),
780 nouveau témoin d'un magmatisme syntectonique pan-africain au nord du Nigeria.
781 *Comptes Rendus Academie Science de Paris* 309, 887-892.

782 de Araujo, C.E.G., Cordani, U.G., Basei, M.A.S., Castro, N.A., Sato, K., Sproesser,
783 W.M., 2012. U–Pb detrital zircon provenance of metasedimentary rocks from the
784 Ceará Central and Médio Coreau Domains, Borborema Province, NE-Brazil: Tectonic
785 implications for a long-lived Neoproterozoic active continental margin. *Precambrian*
786 *Research* 206-207, 36-51.

787 de Wit, M.J., Stankiewicz, J., Reeves, C., 2008. Restoring Pan-African-Brasiliano
788 connections: more Gondwana control, less Trans-Atlantic corruption in: Pankhurst,
789 R.J., Trouw, R.A.J., Brito Neves, B.B., De Wit, M.J. (Eds.), *Pre-Cenozoic*
790 *Correlations Across the South Atlantic Region*. The Geological Society, London, pp.
791 399-412.

792 Ersoy, Y., Helvacı, C., 2009. FC–AFC–FCA and mixing modeler: A Microsoft Excel
793 spreadsheet program for modeling geochemical differentiation of magma by crystal
794 fractionation, crustal assimilation and mixing. *Computers and Geosciences* 36, 383-
795 390.

796 Ferré, E.C., Caby, R., Peucat, J.J., Capdevila, R., Monie, P., 1998. Pan-African, post-
797 collisional, ferro-potassic granite and quartz-monzonite plutons of Eastern Nigeria.
798 *Lithos* 45, 225-279.

799 Ferré, E.C., Deleris, J., Bouchez, J.-L., Lar, A.U., Peucat, J.-J., 1996. The Pan-African
800 reactivation of Eburnean and Archaean provinces in Nigeria: structural and isotopic
801 data. *Journal of the Geological Society of London* 153, 719-728.

802 Ferré, E.C., Gleizes, G., Bouchez, J.-L., 1995. Internal fabric and strike-slip
803 emplacement of the Pan-African granite of Solli Hills, northern Nigeria. *Tectonics* 14,
804 1205-1219.

805 Ferré, E.C., Gleizes, G., Caby, R., 2002. Obliquely convergent tectonics and granite
806 emplacement in the Trans-Saharan belt of Eastern Nigeria: a synthesis. *Precambrian*
807 *Research* 114, 199-219.

808 Fetter, A.H., dos Santos, T.J.S., Van Schmus, W.R., Hackspacher, P.C., Brito Neves,
809 B.B., Arthaud, M.H., Neto, J.A.N., Wernick, E., 2003. Evidence for Neoproterozoic
810 Continental Arc Magmatism in the Santa Quitéria Batholith of Ceará State, NW
811 Borborema Province, NE Brazil: Implications for the Assembly of West Gondwana.
812 *Gondwana Research* 6, 265-273.

813 Fitches, W.R., Ajibade, A.C., Egbuniwe, I.G., Holt, R.W., Wright, J.B., 1985. Late
814 Proterozoic schist belts and plutonism in NW Nigeria. *Journal of the Geological*
815 *Society of London* 142, 319-337.

816 Frost, B.R., Barnes, C.G., Collins, W.J., Arculus, R.J., Ellis, D.J., Frost, C.D., 2001.
817 A Geochemical Classification for Granitic Rocks. *Journal of Petrology* 42, 2033-
818 2048.

819 Garba, I., 2003. Geochemical discrimination of newly discovered rare-metal bearing
820 and barren pegmatites in the Pan-African (600 ± 150 Ma) basement of northern
821 Nigeria. *Applied Earth Science (Trans. Inst. Min. Metall. B)* 112, 287-292.

822 Gillespie, M.R., Styles, M.T., 1999. *Rock Classification Scheme Volume 1,*
823 *Classification of Igneous Rocks*, British Geological Survey Research Report (2nd
824 ed.). British Geological Survey, Keyworth, Nottingham.

825 Goodenough, K.M., Thomas, R.J., De Waele, B., Key, R.M., Schofield, D.I., Bauer,
826 W., Tucker, R.D., Rafahatelo, J.-M., Rabarimanana, M., Ralison, A.V.,
827 Randriamananjara, T., 2010. Post-collisional magmatism in the central East African
828 Orogen: The Maevarano Suite of north Madagascar. *Lithos* 116, 18-34.

829 Jacobs, J., Thomas, R.J., 2004. Himalayan-type indenter-escape tectonics model for
830 the southern part of the late Neoproterozoic-early Palaeozoic East African-Antarctic
831 orogen. *Geology* 32, 721-724.

832 Kalsbeek, F., Affaton, P., Ekwueme, B., Frei, R., Thrane, K., 2012. Geochronology of
833 granitoid and metasedimentary rocks from Togo and Benin, West Africa:
834 Comparisons with NE Brazil. *Precambrian Research* 196-197, 218-233.
835 Key, R.M., Johnson, C.C., Horstwood, M.S.A., Lapworth, D.J., Knights, K.V., Kemp,
836 S.J., Watts, M.J., Gillespie, M., Adekanmi, M.A., Arisekola, T.M., 2012.
837 Investigating high zircon concentrations in the fine fraction of stream sediments
838 draining the Pan-African Dahomeyan Terrane in Nigeria. *Applied Geochemistry* 27,
839 1525-1539.
840 Kinnaird, J.A., 1984. Contrasting styles of Sn-Nb-Ta-Zn mineralization in Nigeria.
841 *Journal of African Earth Sciences* 2, 81-90.
842 Kuster, D., 1990. Rare-metal pegmatites of Wamba, central Nigeria - their formation
843 in relationship to late Pan-African granites. *Mineralium Deposita* 25, 25-33.
844 Küster, D., Harms, U., 1998. Post-collisional potassic granitoids from the southern
845 and northwestern parts of the Late Neoproterozoic East African Orogen: a review.
846 *Lithos* 45, 177-195.
847 Lapworth, D.J., Knights, K.V., Key, R.M., Johnson, C.C., Ayoade, E., Adekanmi,
848 M.A., Arisekola, T.M., Okunlola, O.A., Backman, B., Eklund, M., Everett, P.A.,
849 Lister, R.T., Ridgway, J., Watts, M.J., Kemp, S.J., Pitfield, P.E.J., 2012. Geochemical
850 mapping using stream sediments in west-central Nigeria: Implications for
851 environmental studies and mineral exploration in West Africa. *Applied Geochemistry*
852 27, 1035-1052.
853 Le Maitre, R.W., 2002. *Igneous Rocks: A classification and glossary of terms.*
854 *Recommendations of the IUGS Subcommittee on the Systematics of Igneous Rocks.*
855 Cambridge University Press.
856 Liégeois, J.P., Navez, J., Hertogen, J., Black, R., 1998. Contrasting origin of post-
857 collisional high-K calc-alkaline and shoshonitic versus alkaline and peralkaline
858 granitoids. The use of sliding normalization. *Lithos* 45, 1-28.
859 Linnen, R.L., 1998. The Solubility of Nb-Ta-Zr-Hf-W in Granitic Melts with Li and
860 Li + F: Constraints for Mineralization in Rare Metal Granites and Pegmatites.
861 *Economic Geology* 93, 1013-1025.
862 Matheis, G., 1987. Nigerian rare-metal pegmatites and their lithological framework.
863 *Geological Journal* 22, 271-291.
864 Matheis, G., Caen-Vachette, M., 1983. Rb-Sr isotopic study of rare-metal bearing and
865 barren pegmatites in the Pan-African reactivation zone of Nigeria *Journal of African*
866 *Earth Sciences* 1, 35-40.
867 McDonough, W.F., Sun, S.-s., 1995. The Composition of the Earth. *Chemical*
868 *Geology* 120, 223-253.
869 Melcher, F., Graupner, T., Gabler, H.-E., Sitnikova, M., Henjes-Kunst, F., Oberthur,
870 T., Gerdes, A., Dewaele, S., 2013. Tantalum- (niobium-tin) mineralisation in African
871 pegmatites and rare metal granites: Constraints from Ta-Nb oxide mineralogy,
872 geochemistry and U-Pb geochronology. *Ore Geology Reviews*.
873 <http://dx.doi.org/10.1016/j.oregeorev.2013.09.003>
874 Miyashiro, A., 1974. Volcanic rock series in island arcs and active continental
875 margins *American Journal of Science* 274, 321-355.
876 Neves, S.P., 2003. Proterozoic history of the Borborema province (NE Brazil):
877 Correlations with neighboring cratons and Pan-African belts and implications for the
878 evolution of western Gondwana. *Tectonics* 22. 10.1029/2001TC001352
879 Neves, S.P., Bruguier, O., Bosch, D., da Saliva, J.M.R., Mariano, G., 2008. U-Pb
880 ages of plutonic and metaplutonic rocks in southern Borborema Province (NE Brazil):

881 Timing of Brasiliano deformation and magmatism. *Journal of South American Earth*
882 *Sciences* 25, 285-297.

883 Nude, P.M., Shervais, J.W., Attoh, K., Vetter, S.K., Barton, C., 2009. Petrology and
884 geochemistry of nepheline syenite and related carbonate-rich rocks in the Pan-African
885 Dahomeyide orogen, southeastern Ghana, West Africa. *Journal of African Earth*
886 *Sciences* 55, 147-157.

887 Okunlola, O.A., 2005. Metallogeny of Tantalum-Niobium Mineralization of
888 Precambrian pegmatites of Nigeria. *Mineral Wealth* 137, 38-50.

889 Oyawoye, M.O., 1961. On an Occurrence of Fayalite Quartz-Monzonite in the
890 Basement Complex around Bauchi, Northern Nigeria. *Geological Magazine* 98, 473-
891 482.

892 Pearce, J.A., 1996. Sources and settings of granitic rocks. *Episodes* 19, 120-125.

893 Pearce, J.A., Harris, N.B.W., Tindle, A.G., 1984. Trace element discrimination
894 diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology* 25,
895 956-983.

896 Stern, R.J., 1994. Arc Assembly and continental collision in the Neoproterozoic East
897 African orogeny - implications for the consolidation of Gondwana. *Annual Reviews*
898 *of Earth and Planetary Sciences* 22, 319-351.

899 Thomas, R.J., Roberts, N.M.W., Jacobs, J., Bushid, A.M., Horstwood, M.S.A.,
900 Mruma, A., 2013. Structural and geochronological constraints on the evolution of the
901 eastern margin of the Tanzania Craton in the Mpwapwa area, central Tanzania.
902 *Precambrian Research* 224, 671-689.

903 Tubosun, I.A., Lancelot, J.R., Rahaman, M.A., Ocan, O.O., 1984. U-Pb Pan-African
904 ages of two charnockite-granite associations from Southwestern Nigeria.
905 *Contributions to Mineralogy and Petrology* 88, 188-195.

906 Whalen, J.B., Currie, K.L., Chappell, B.W., 1987. A-type granites: geochemical
907 characteristics, discrimination and petrogenesis. *Contributions to Mineralogy and*
908 *Petrology* 95, 407-419.

909 Woakes, M., Rahaman, M.A., Ajibade, A.C., 1987. Some metallogenic features of
910 the Nigerian Basement. *Journal of African Earth Sciences* 6, 655-664.

911 Wright, J.B., 1970. Controls of Mineralization in the Older and Younger Tin Fields of
912 Nigeria. *Economic Geology* 65, 945-951.

913 Zhu, Y.-F., Zeng, Y., Gu, L., 2006. Geochemistry of the rare metal-bearing pegmatite
914 No. 3 vein and related granites in the Keketuohai region, Altay Mountains, northwest
915 China. *Journal of Asian Earth Sciences* 27, 61-77.

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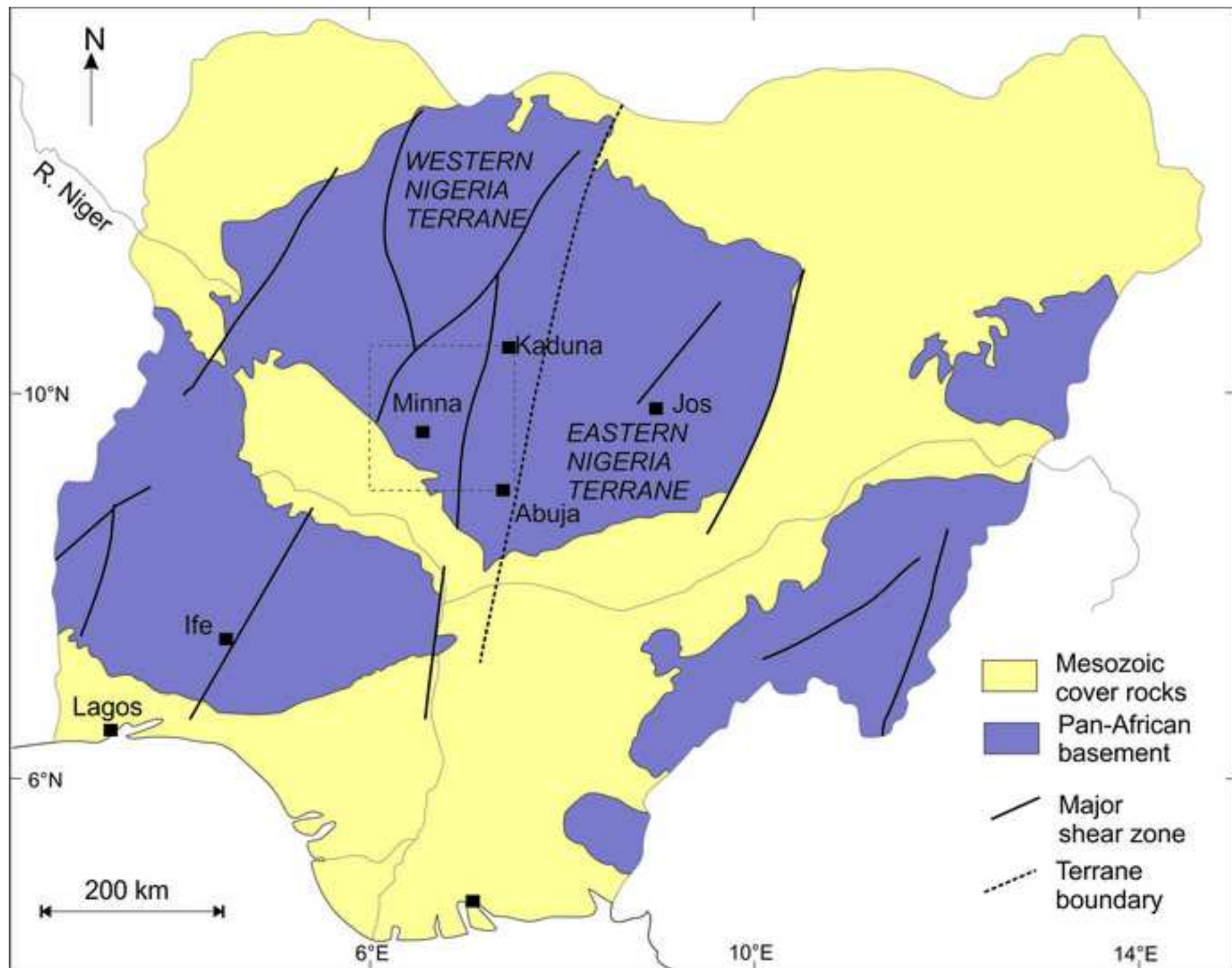


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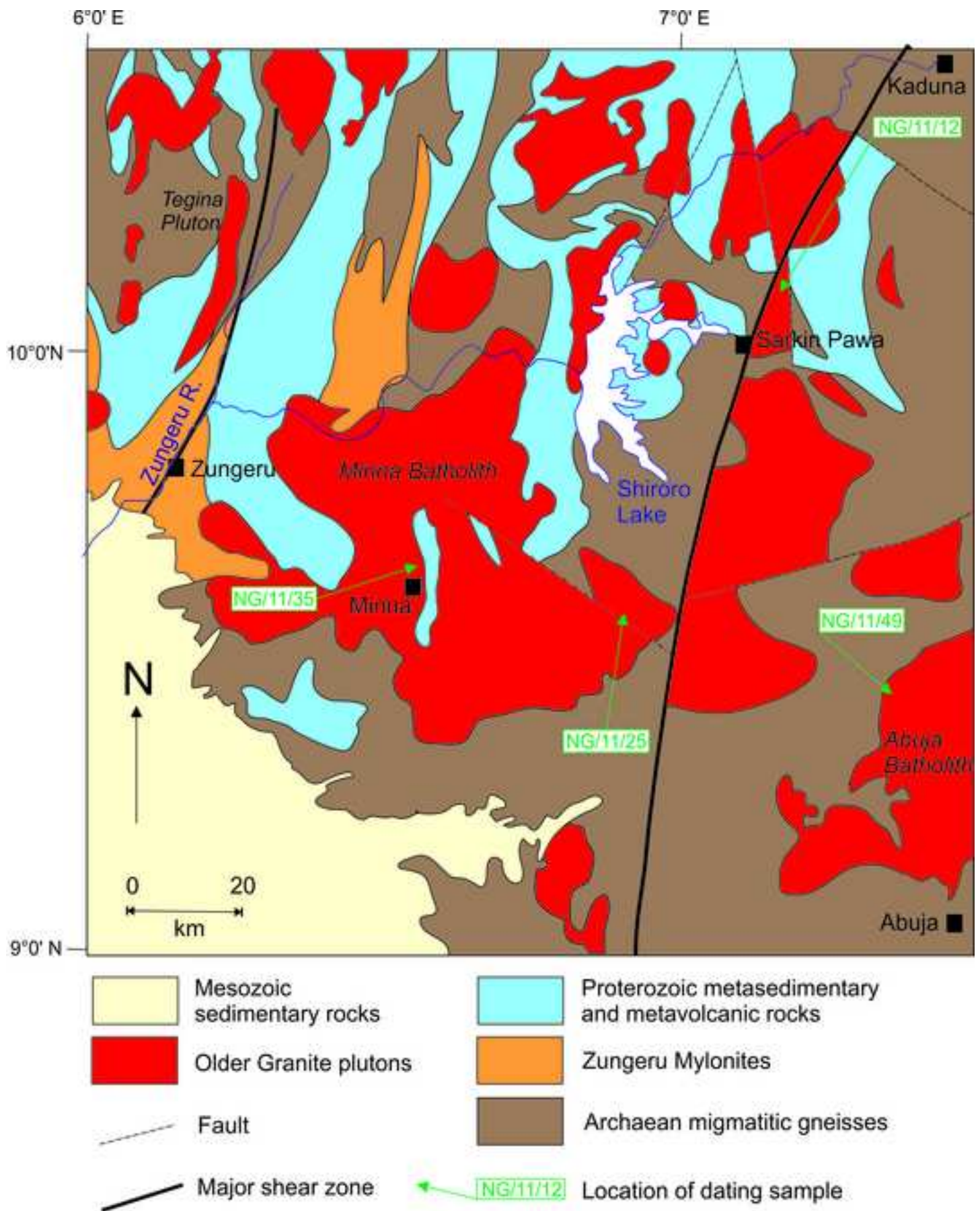


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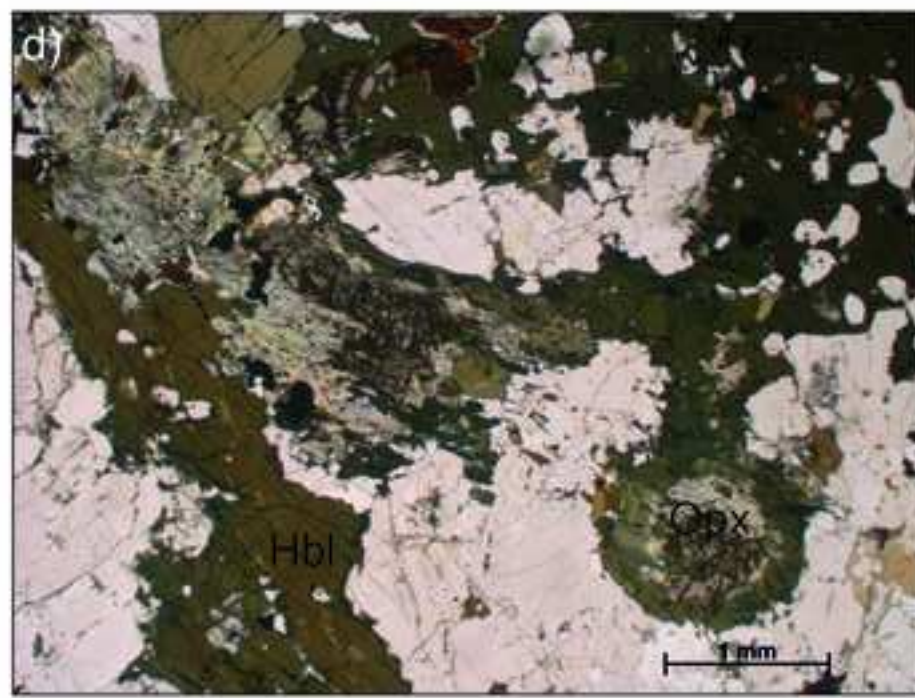
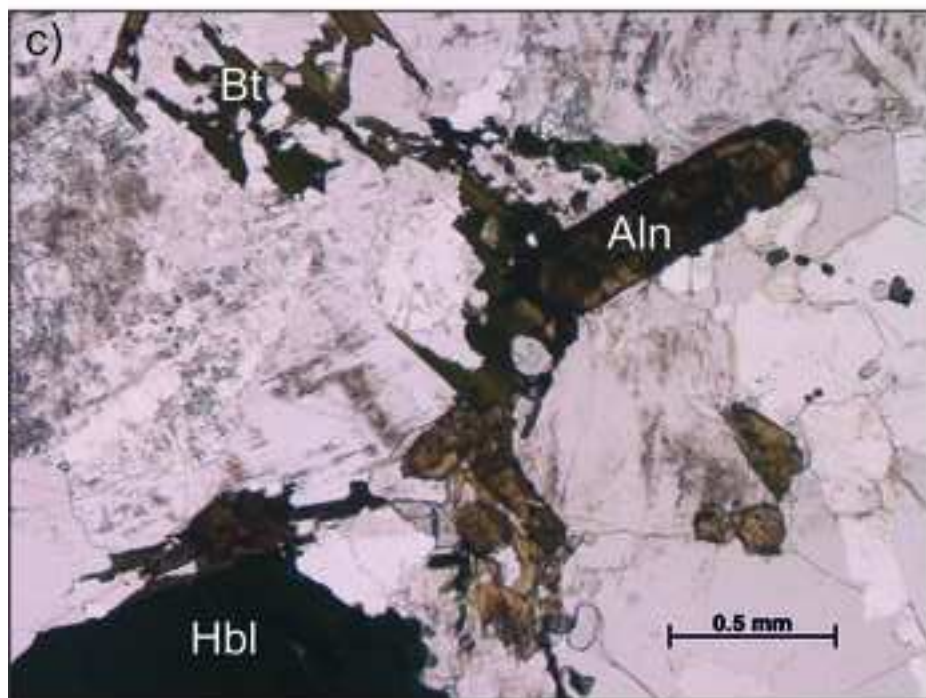
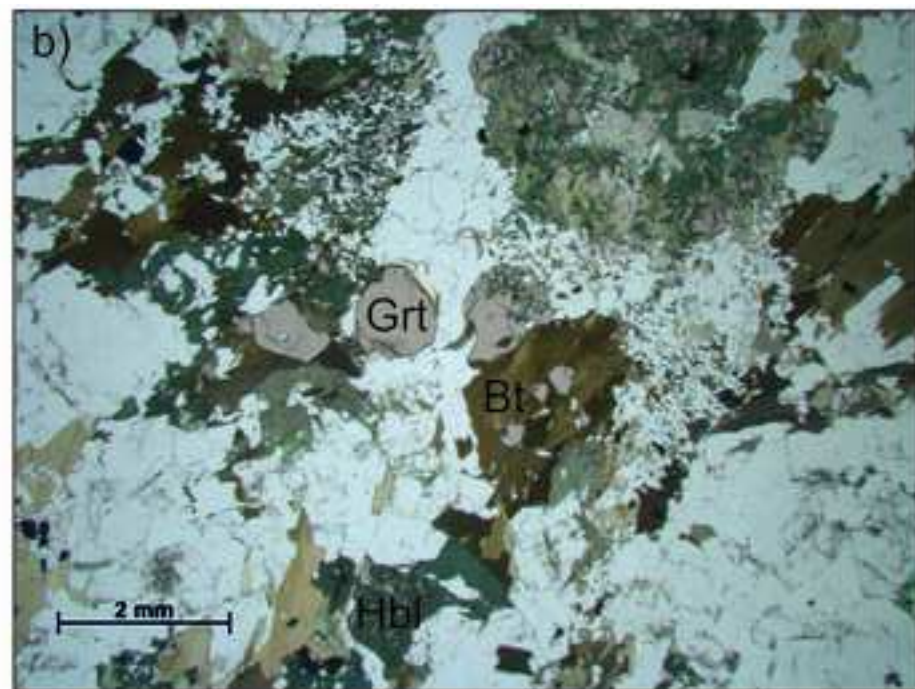
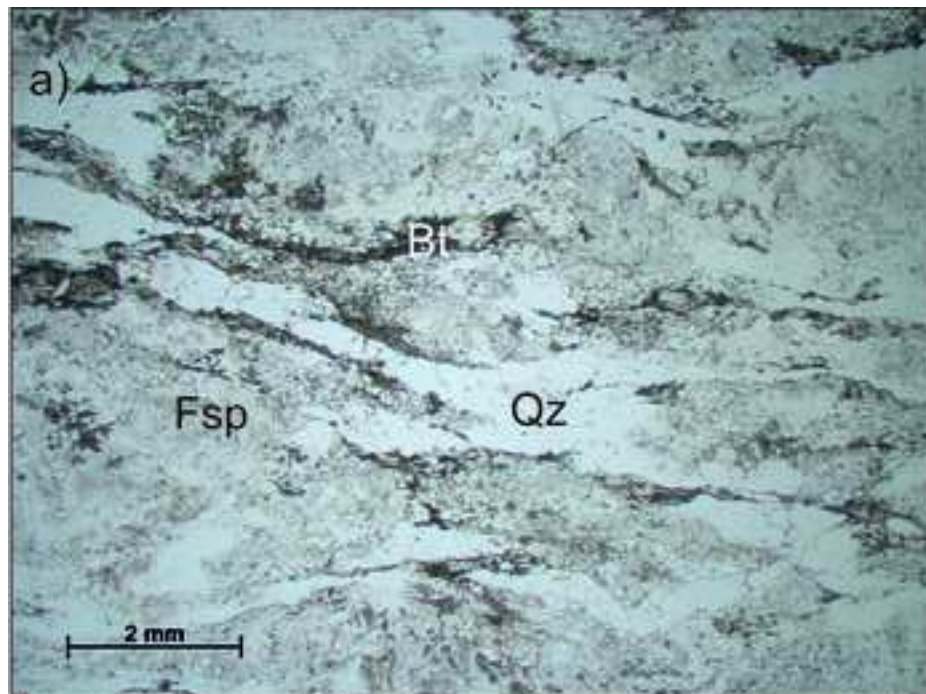
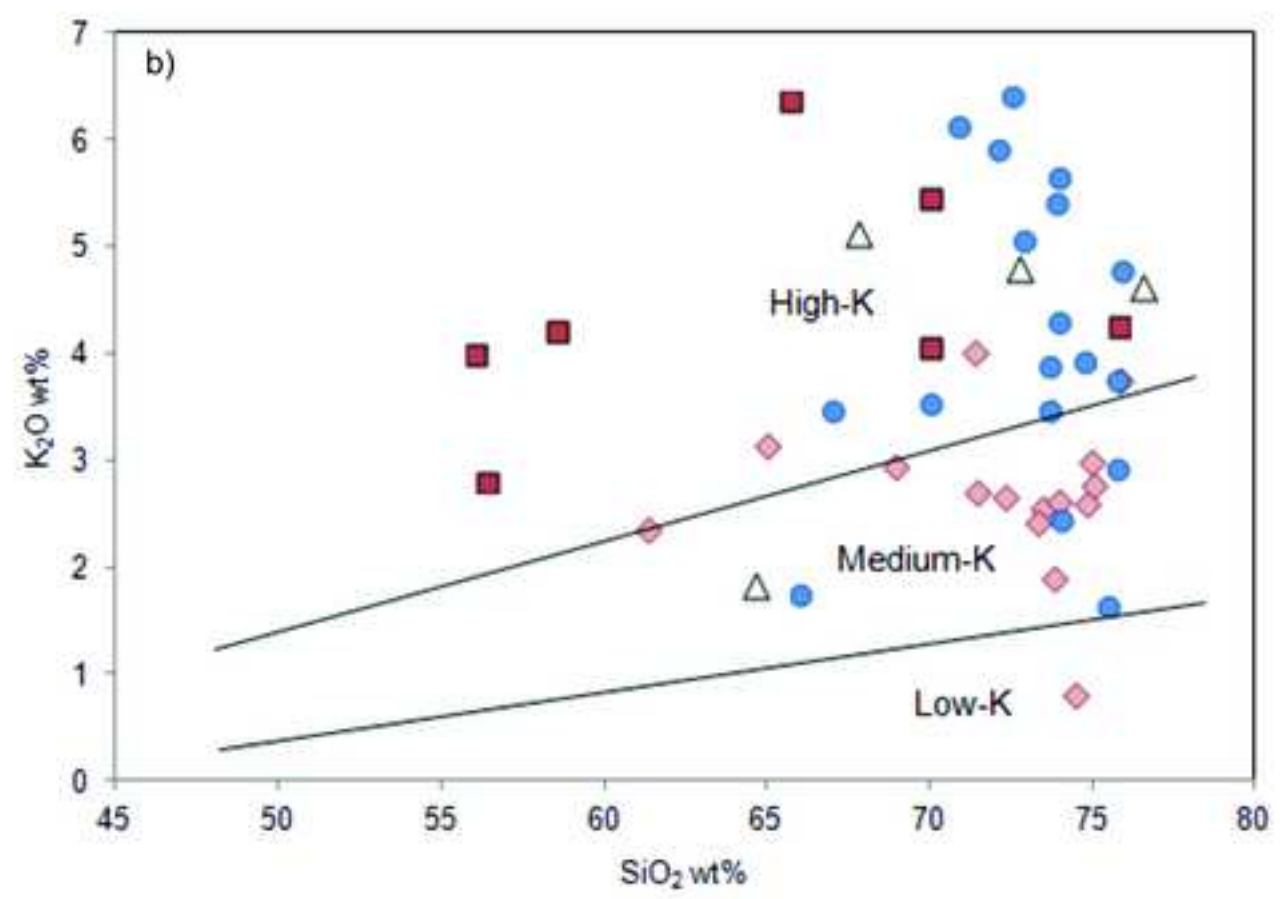
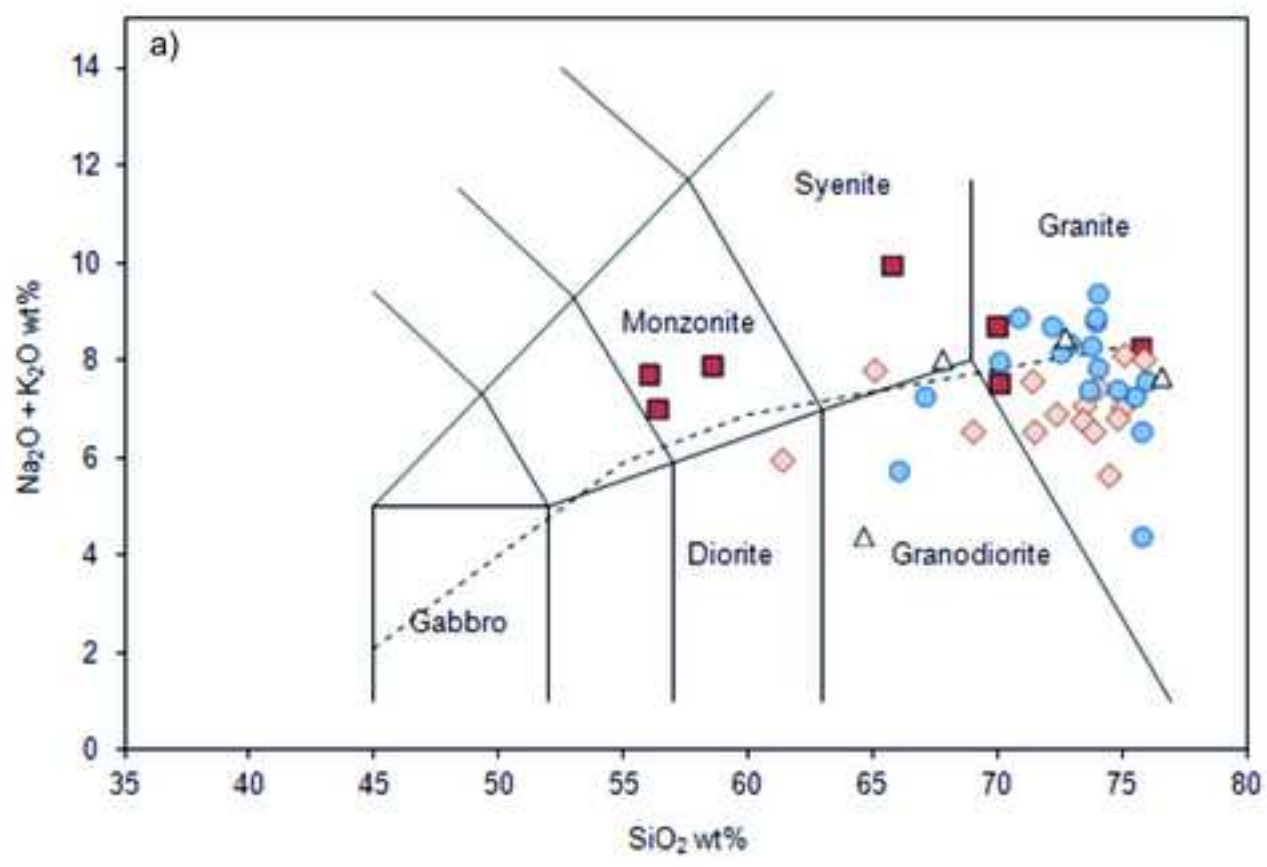


Figure 5

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■ Abuja ◆ Minna ● Sarkin Pawa △ Tegina

Figure 6
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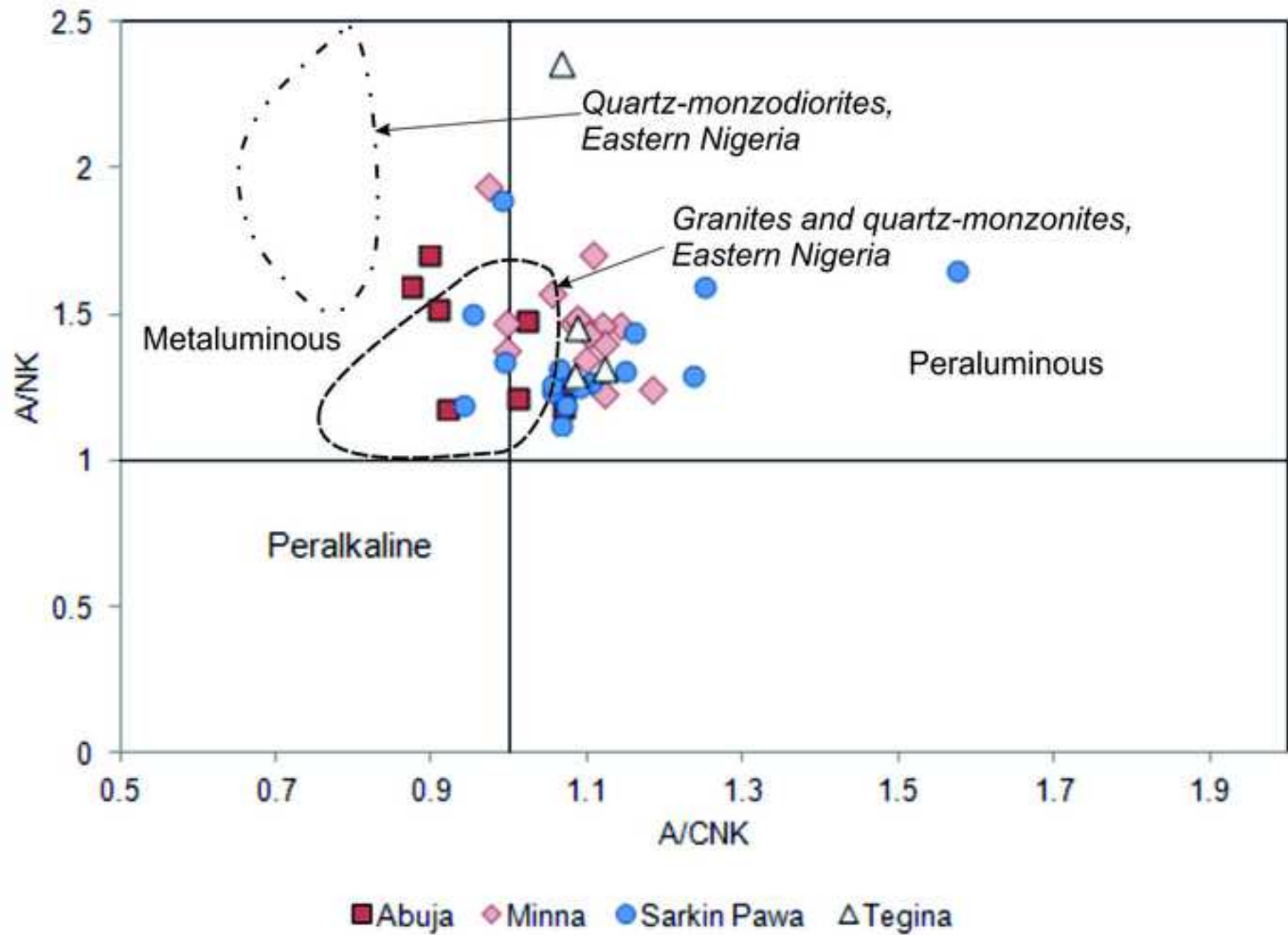


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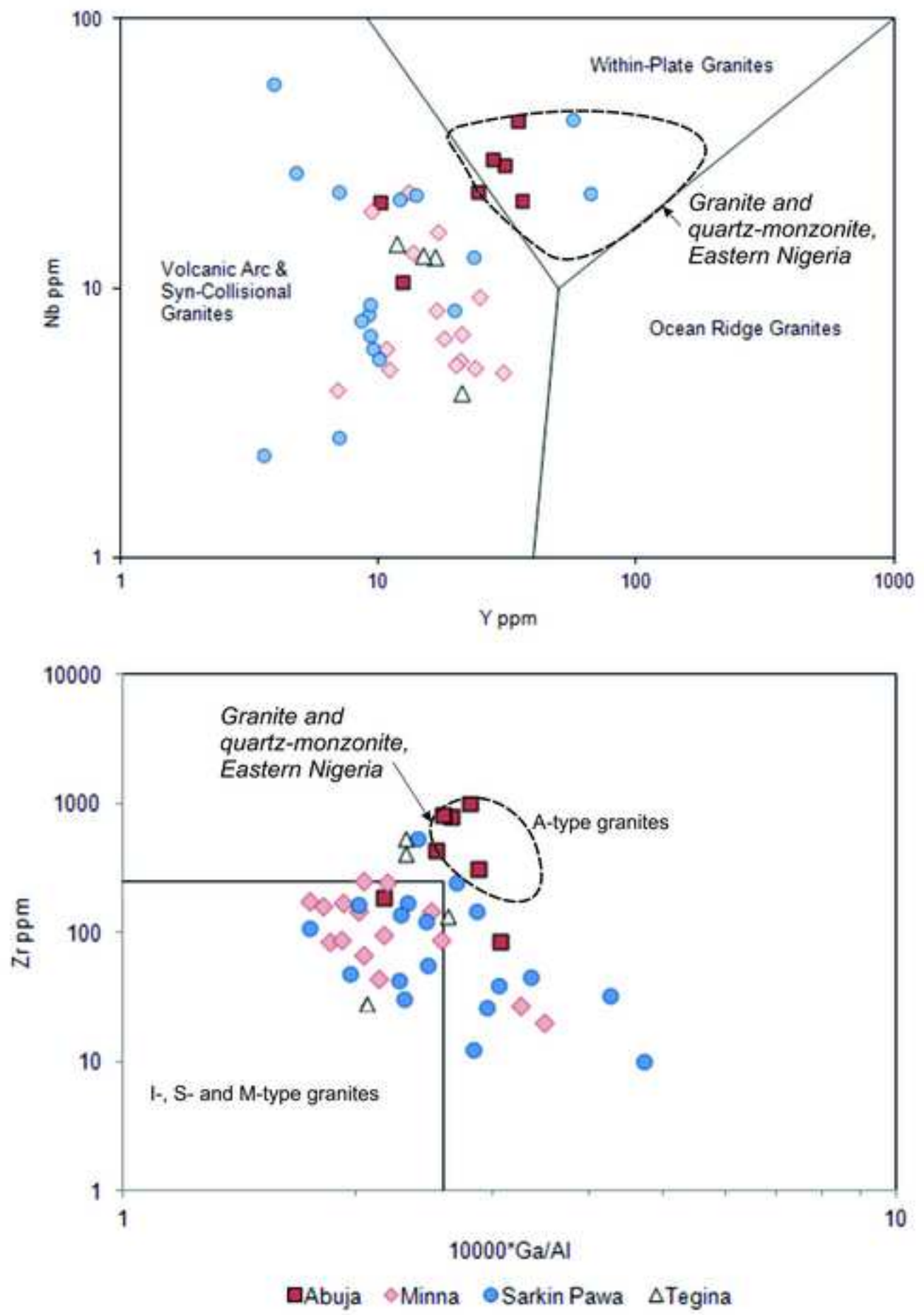


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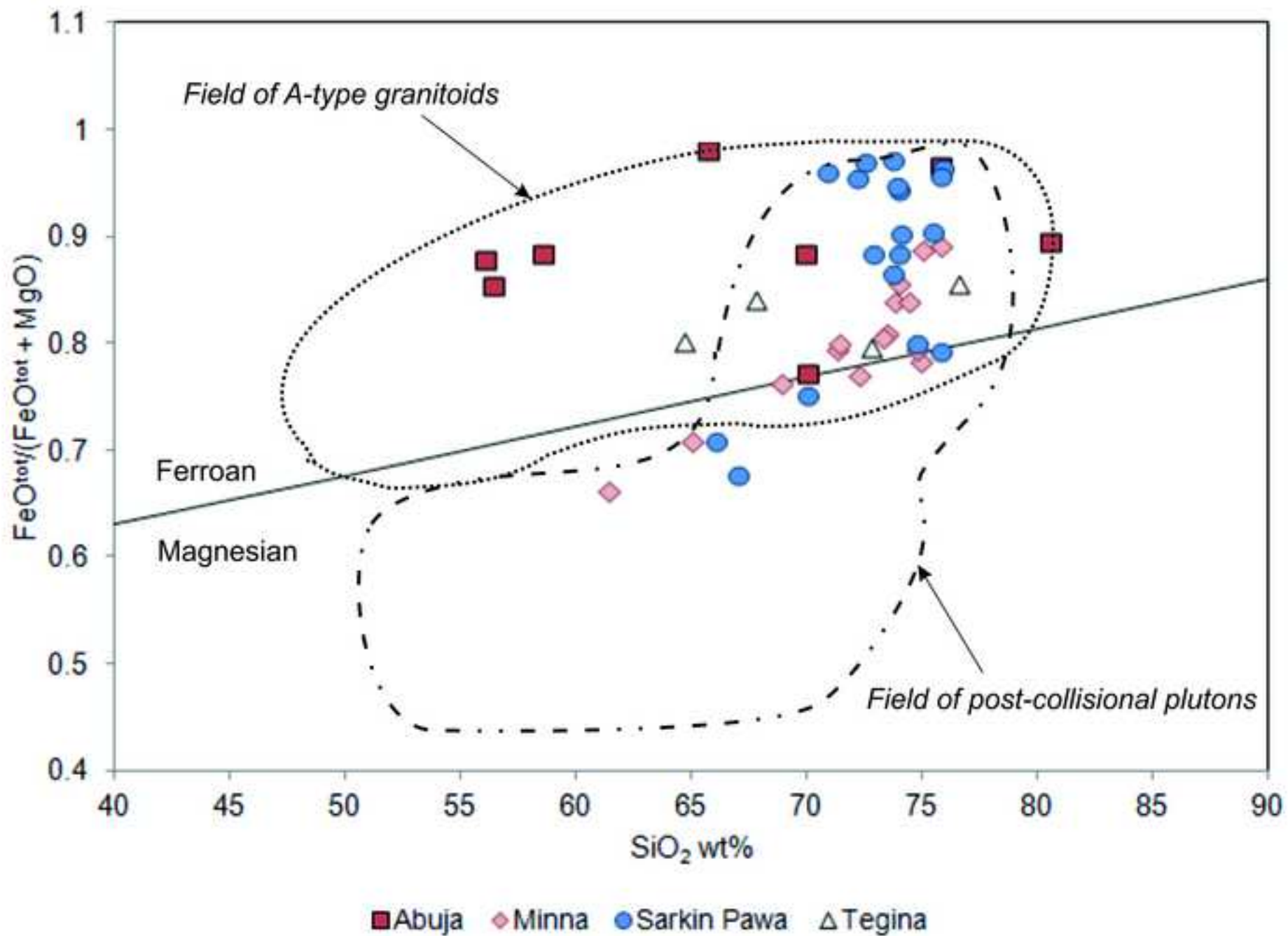


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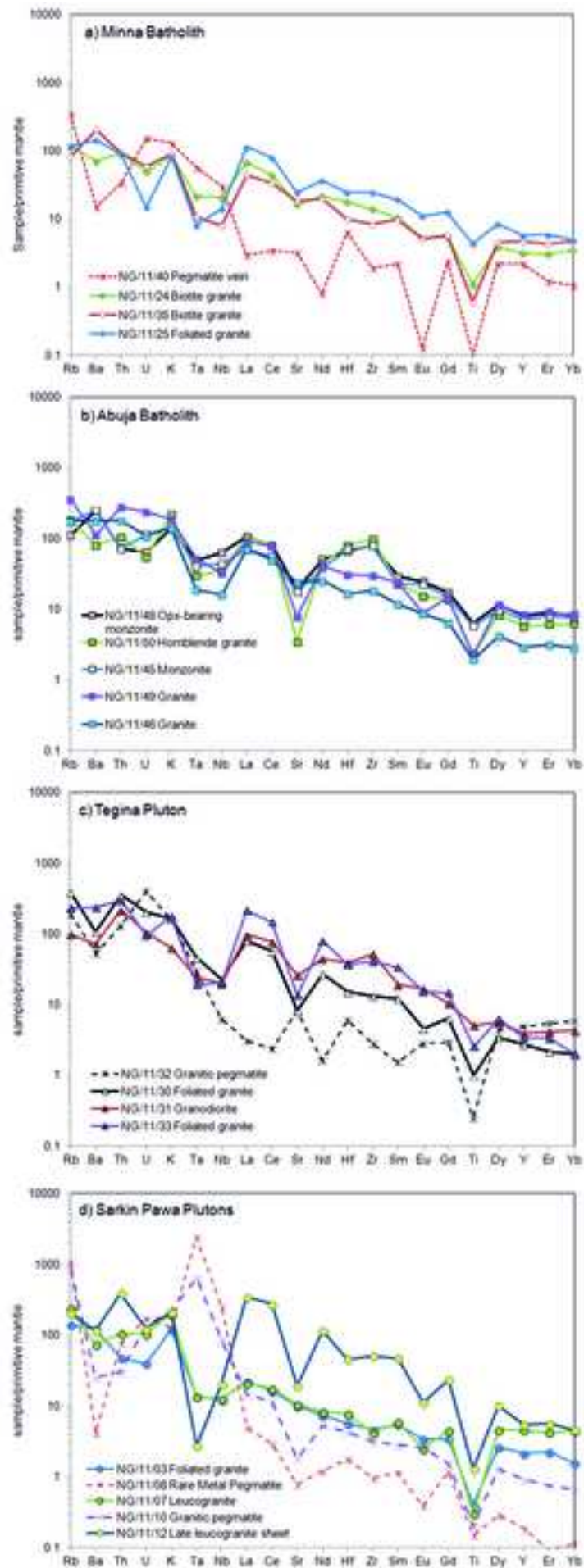


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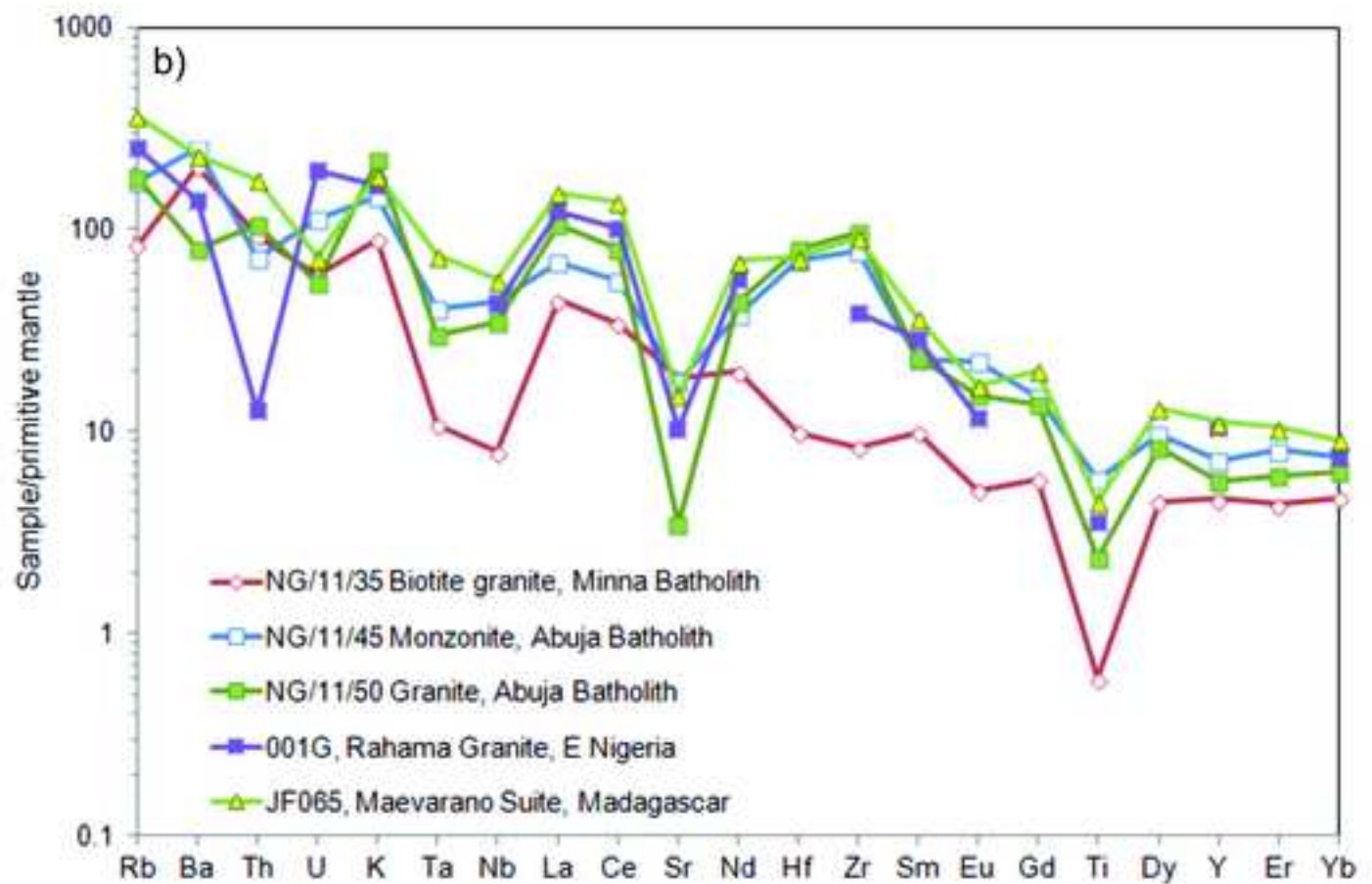
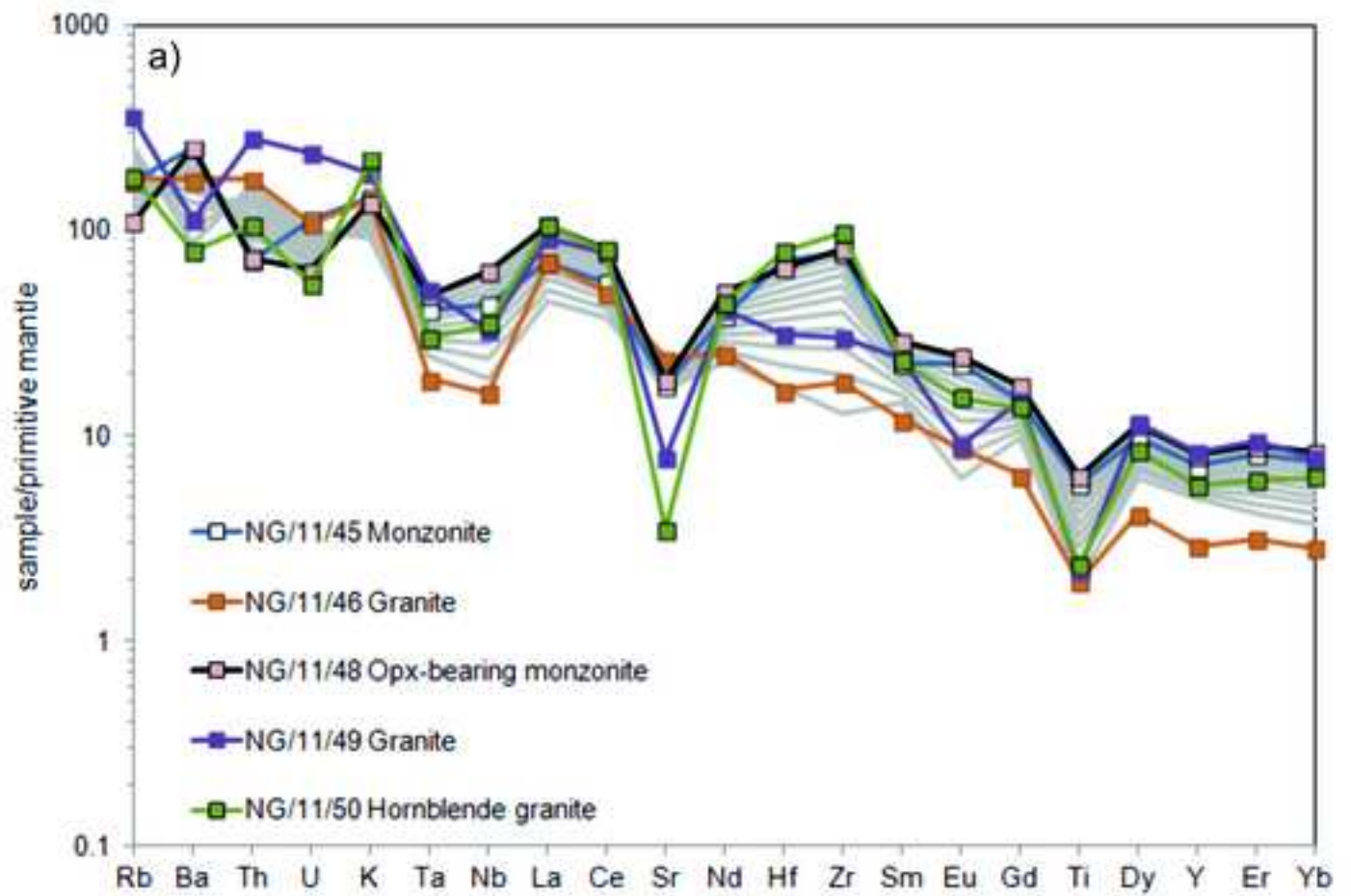


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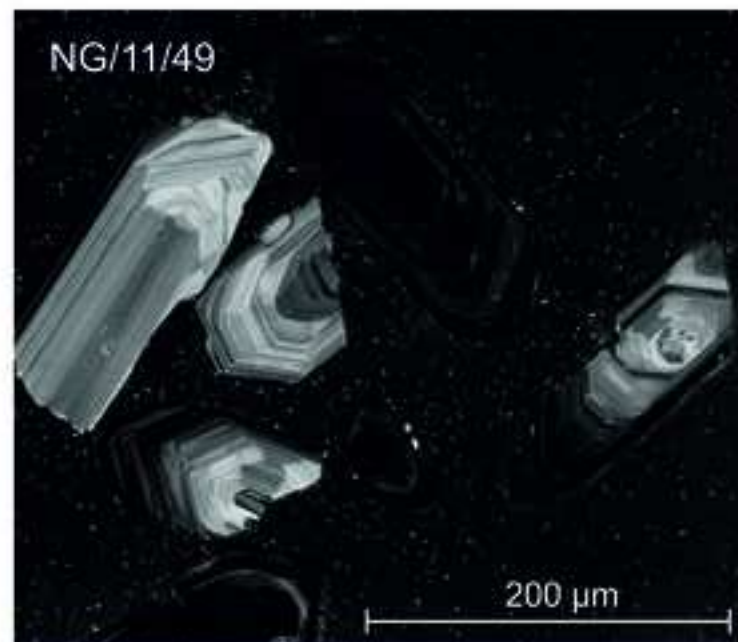
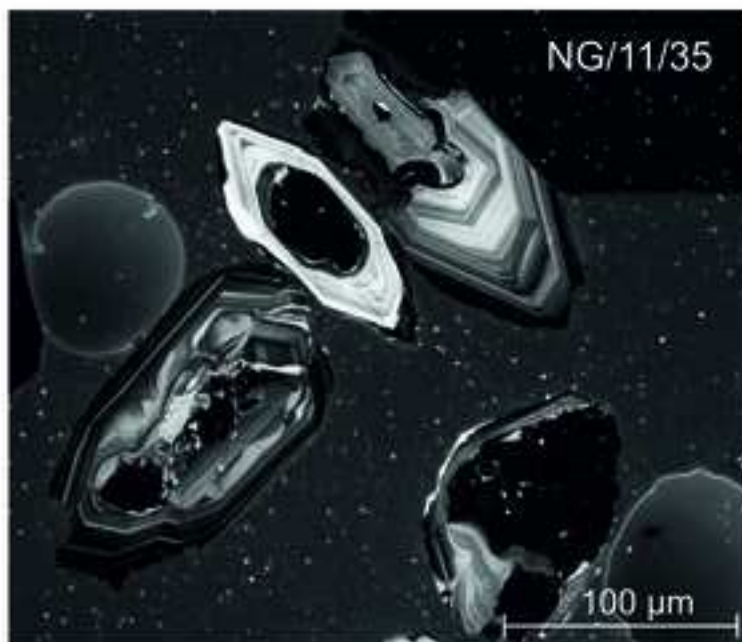
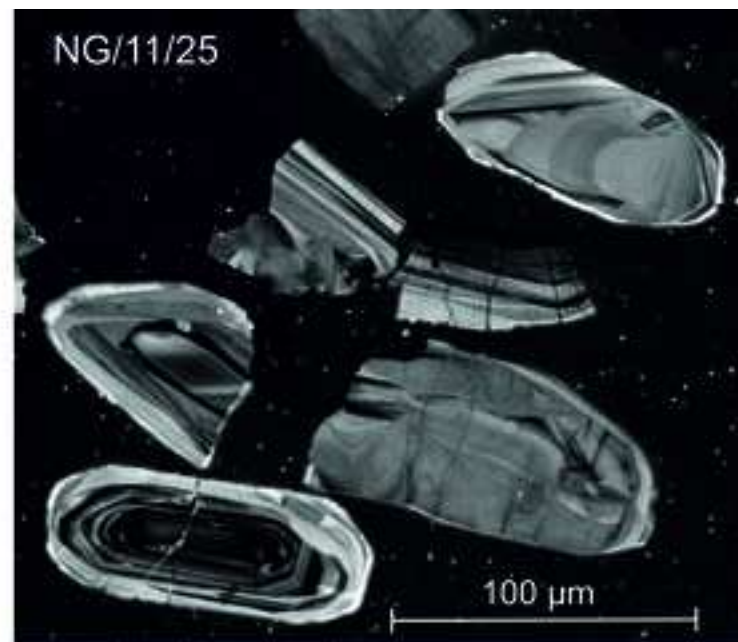
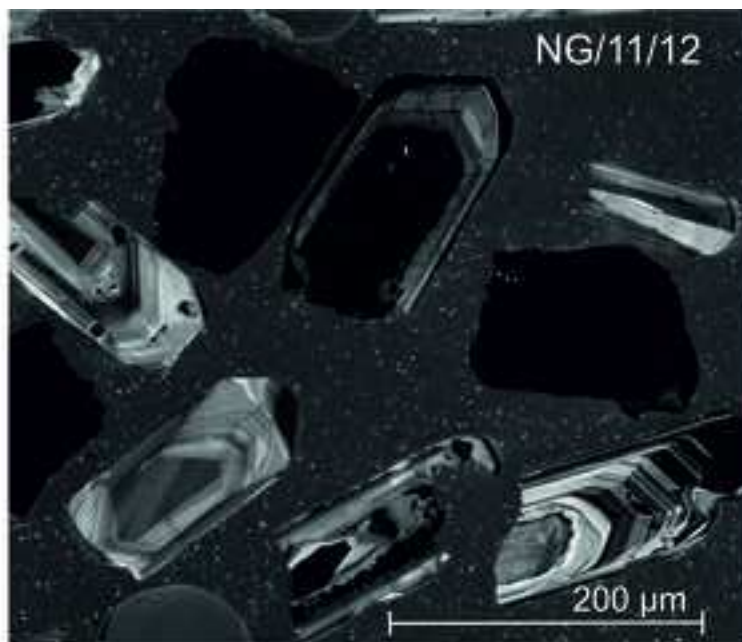


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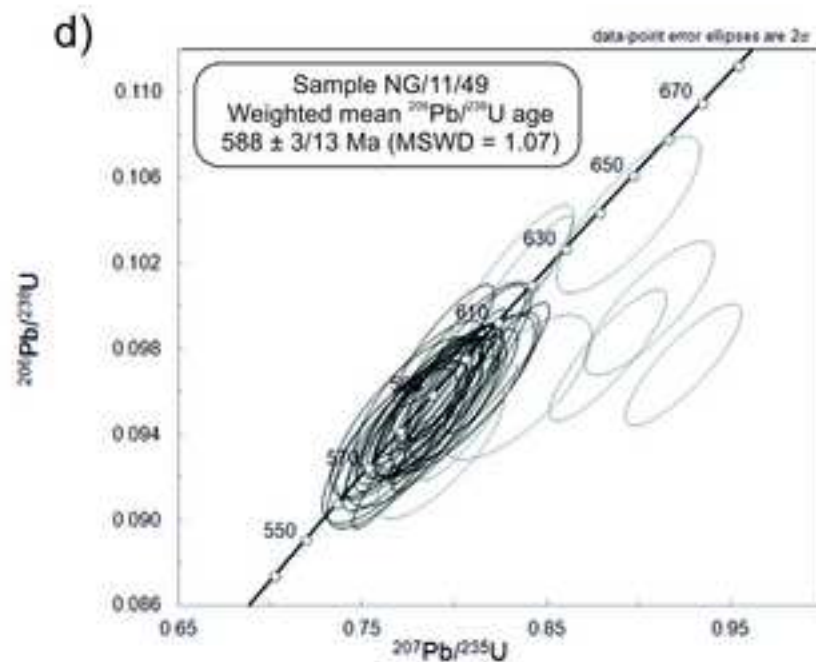
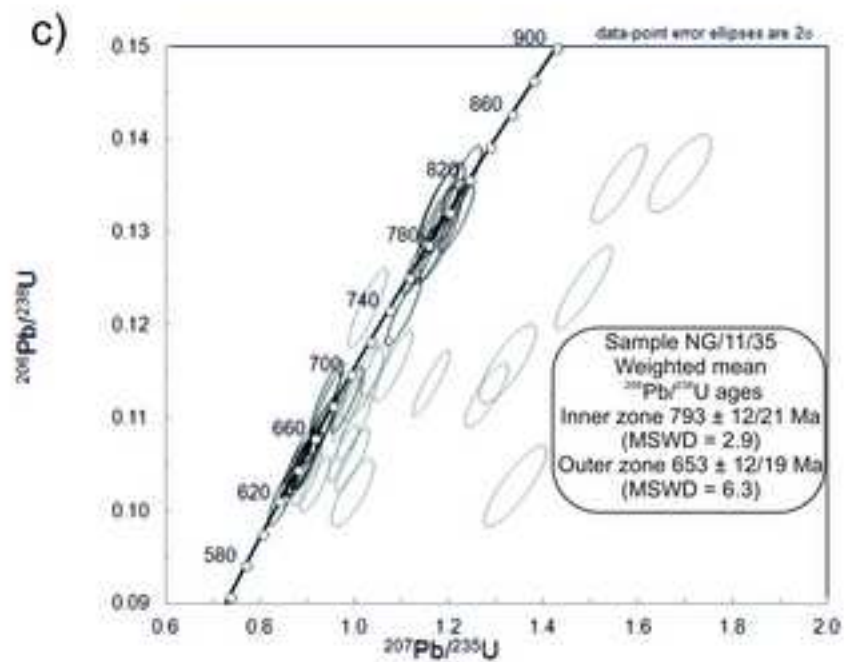
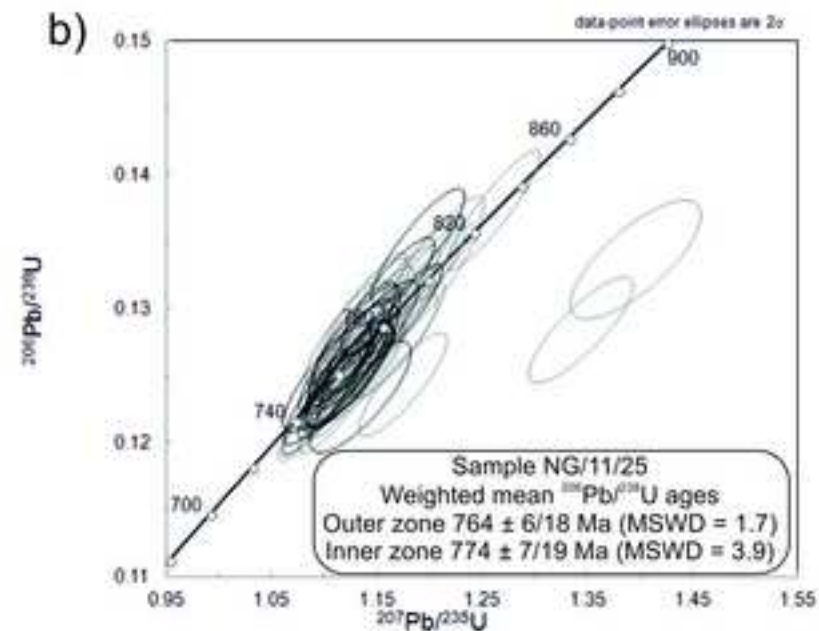
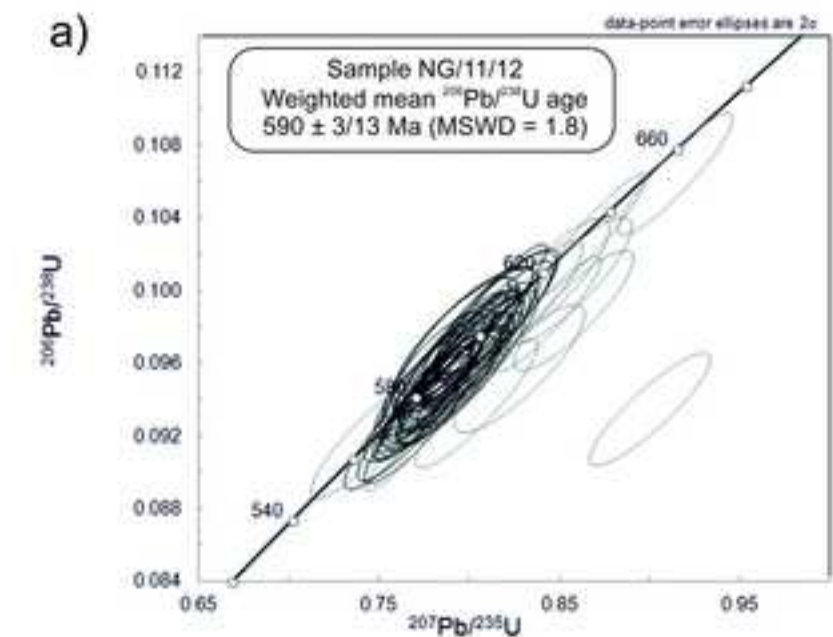


Table 1

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Sample	Rock type	Intrusion	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO
			%	%	%	%	%
NG/11/1	Granite	Sarkin Pawa area	75.89	12.55	2.21	0.07	0.83
NG/11/2	Aplite	Sarkin Pawa area	73.68	15.01	1.15	0.03	0.34
NG/11/3	Granite	Sarkin Pawa area	73.65	14.81	1.44	0.2	1.38
NG/11/4	Diorite	Sarkin Pawa area	66.02	16.2	4.24	1.56	4.3
NG/11/5	Pegmatite	Sarkin Pawa area	75.44	14.56	0.97	0.09	0.9
NG/11/6	Pegmatite	Sarkin Pawa area	74	14.45	0.94	0.09	1.16
NG/11/7	Granite	Sarkin Pawa area	73.91	14.35	0.95	0.11	0.99
NG/11/8	Pegmatite	Sarkin Pawa area	75.73	16.08	1.25	0.05	0.01
NG/11/9	Granite	Sarkin Pawa area	72.87	14.02	2.22	0.26	1.15
NG/11/10	Pegmatite	Sarkin Pawa area	72.5	16.38	1.09	0.03	0.29
NG/11/11	Granite	Sarkin Pawa area	72.1	14.07	2.6	0.11	1.26
NG/11/12	Granite	Sarkin Pawa area	70.84	13.42	3.8	0.14	1.66
NG/11/13	Granite	Sarkin Pawa area	70.02	15.13	2.29	0.68	2.22
NG/11/14	Pegmatite	Sarkin Pawa area	73.94	14.74	0.76	0.04	0.44
NG/11/15	Granite	Sarkin Pawa area	66.99	15.12	3.86	1.65	3.21
NG/11/16	Gneiss	Country rock	71.12	14.47	3.09	0.82	2.01
NG/11/17	Granite	Sarkin Pawa area	73.87	13.94	1.82	0.09	0.74
NG/11/18	Granite	Sarkin Pawa area	74.74	13.28	1.47	0.33	1.35
NG/11/19	Granite	Sarkin Pawa area	75.74	14.69	0.73	0.17	1.42
NG/11/20	Gneiss	Country rock	53.92	19.23	7.02	3.04	4.95
NG/11/21	Granite	Minna Batholith	73.48	15.12	1.2	0.25	1.63
NG/11/22	Granodiorite	Minna Batholith	68.94	15.7	3.13	0.87	2.76
NG/11/23	Granite	Minna Batholith	71.36	15.2	1.82	0.42	2.09
NG/11/24	Granite	Minna Batholith	73.33	14.49	2.05	0.44	1.73
NG/11/25	Granodiorite	Minna Batholith	61.36	16.59	5.9	2.68	4.7
NG/11/26	Granite	Minna Batholith	74.93	14.09	1.01	0.25	1.41
NG/11/27	Granite	Minna Batholith	64.99	16.46	4.15	1.52	2.99
NG/11/28	Amphibolite	Country rock	48.4	17.76	8.37	6.06	10.71
NG/11/29	Mylonite	Country rock	72.39	14.26	2.89	0.58	2.51
NG/11/30	Granite	Tegina Granite	72.73	14.59	1.43	0.33	1.21
NG/11/31	Diorite	Tegina Granite	64.66	14.79	7.76	1.73	4.16
NG/11/32	Pegmatite	Tegina Granite	76.55	13.27	0.46	0.07	0.95
NG/11/33	Granodiorite	Tegina Granite	67.78	15.13	4.49	0.76	1.93
NG/11/34	Granite	Minna Batholith	73.83	14.48	1.65	0.28	1.92
NG/11/35	Granite	Minna Batholith	74.78	14.1	1.22	0.28	1.65
NG/11/36	Granite	Minna Batholith	74.44	13.24	2.98	0.51	1.83
NG/11/37	Amphibolite	Country rock	52.21	13.36	11.97	3.89	8.75
NG/11/38	Granite	Minna Batholith	73.95	14.69	1	0.15	1.38
NG/11/39	Aplite	Minna Batholith	75.04	14.61	0.54	0.06	0.66
NG/11/40	Pegmatite	Minna Batholith	75.84	13.96	0.65	0.07	0.36
NG/11/41	Granite	Minna Batholith	72.29	13.72	2.87	0.76	2.14
NG/11/42	Granite	Minna Batholith	71.41	14.79	2.57	0.57	2.58
NG/11/43	Leucogranite	Abuja batholith	75.76	13.34	0.98	0.03	0.67
NG/11/44	Pegmatite	Abuja batholith	80.49	10.06	0.96	0.1	0.94
NG/11/45	Diorite	Abuja batholith	58.51	16.18	9.78	1.13	3.95
NG/11/46	Granodiorite	Abuja batholith	70.01	15.05	2.73	0.72	2.53
NG/11/47	Diorite	Abuja batholith	56.34	17.05	10.14	1.53	4.97
NG/11/48	Diorite	Abuja batholith	56.03	16.72	10.42	1.28	4.76

