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1 **Cenozoic lateritic weathering and erosion history of Peninsular India**
2 **from $^{40}\text{Ar}/^{39}\text{Ar}$ dating of supergene K-Mn oxides**

3
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24

25 **Abstract**

26 Since Deccan Traps extrusion ~ 65 Ma ago, thick weathering mantles have
27 developed over Peninsular India on both the western coastal lowland and adjacent
28 plateau separated by the Western Ghats Escarpment. Manganiferous lateritic profiles
29 formed by supergene weathering of Late Archean manganiferous protosols are exposed
30 on paleolandsurface remnants on both sides of the escarpment. Petrological and
31 geochemical characterizations of samples from those Mn lateritic profiles allowed
32 identifying cryptomelane (K-Mn oxide) dated by $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. The ages
33 obtained document major weathering periods, ca. 53-50 Ma, and ca. 37-23 Ma in the
34 highland, and ca. 47-45 Ma, ca. 24-19 Ma and discrete weathering pulses at ~ 9 Ma and
35 ~ 2.5 Ma in the lowland. Old ages of the highland (53-50 Ma) and the lowland (47-45
36 Ma) indicate synchronous lateritic weathering across the escarpment at a time the
37 peninsula started to drift across the equatorial belt. Intense weathering periods at ca. 53-
38 45 and ca. 37-23 Ma are interpreted to reflect the Early Eocene climatic optimum and
39 the onset of Asian monsoon regimes, respectively. The ages further indicate that most of
40 the dissection of the highland must have taken place after ~ 23 Ma, whereas the lowland
41 was weakly incised essentially after ~ 19 Ma. Our results also document divergent
42 erosion and weathering histories of the lowland and the highland after the Eocene,
43 suggesting installation of a dual climatic regime across the Western Ghats escarpment.

44
45 **Keywords:** $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology; Supergene Mn-oxides; Mn-ore deposits; Lateritic
46 weathering; Cenozoic; India

47

48

49 **1. Introduction**

50 Chemical rock weathering that results in the accumulation of metals such as Al,
51 Fe or Mn, and relative depletion of silica and base elements, produce lateritic regoliths
52 covering shields in the tropical belt. Weathering processes are intense under wet and
53 warm climate that characterizes most tropical forest's soil environments (Pedro, 1968;
54 Ollier, 1988; Nahon, 1991; Tardy, 1997). Metals are mostly retained in duricrusts
55 capping thick weathering profiles, which are, in turn, partly preserved from mechanical
56 erosion. Therefore, old lateritic weathering profiles several tens of meters thick may be
57 preserved on paleolandsurface remnants for several millions years (Bárdossy and Aleva,
58 1990; Thomas, 1994; Tardy and Roquin, 1998; Valeton, 1999; see also Beauvais and
59 Chardon, 2013).

60 Since Deccan Traps extrusion ~ 65 Ma ago, the surface of the Indian peninsula
61 was shaped by combined or alternating chemical weathering and mechanical erosion
62 processes that resulted in composite landscapes made of stepped lateritic
63 paleolandsurfaces remnants of various generations occurring on either side of the
64 Western Ghats Escarpment (WGE) (e.g., Widdowson, 1997; Gunnell, 1998). This
65 escarpment was carved both into Deccan Traps and Precambrian basement rocks and
66 separates a western lowland from a dissected hinterland also known as the Mysore
67 plateau (Radhakrishna, 1993; Gunnell, 1998; Widdowson and Gunnell, 1999).

68 Time constraints on the formation of South Indian laterites are still poorly
69 documented (Schmidt et al., 1983; Krishna Rao et al., 1989a) although Late Paleogene
70 $^{40}\text{Ar}/^{39}\text{Ar}$ ages of supergene K-Mn oxides have been recently obtained from the Sandur
71 Mn-ore deposit on the highland (Bonnet et al., 2014). Most south Indian Mn-ore
72 deposits result from supergene weathering of late Archean supracrustal rocks, either on

73 the highland in the Sandur and Shimoga areas (Krishna Rao et al., 1982; Mohapatra et
74 al., 1996), or in the lowland at the foot of the WGE (Dessai, 1985; Fig. 1). In both
75 contexts, Mn-ore deposits are hosted by lateritic weathering profiles underlying
76 remnants of several generations of paleosurfaces, which are preserved at variable
77 elevations (Fig. 2). All these Mn-ore deposits contain K-rich Mn oxides such as
78 cryptomelane [$K_x Mn_{8-x}^{IV} Mn_x^{III} O_{16}$], which is datable by $^{40}Ar/^{39}Ar$ geochronology.
79 Absolute dating of K-Mn oxides generally documents periods of intense lateritic
80 weathering controlled by specific paleoclimatic conditions and as such may be used to
81 reconstruct and quantify the long-term morphoclimatic evolution of tropical shield
82 surfaces (Beauvais et al., 2008; Beauvais and Chardon, 2013; Vasconcelos, 1999b;
83 Vasconcelos and Conroy, 2003). Here we report on $^{40}Ar/^{39}Ar$ geochronological data
84 series obtained on Peninsular India that bracket three Cenozoic weathering periods and
85 constrain the tempo of long-term South Indian morphogenesis. Our results also
86 document divergent erosion and weathering histories across the WGE suggesting
87 installation of a dual climatic regime on either side of the escarpment after the Eocene
88 warming period.

89

90 **2. Material and methods**

91 2.1. Geological and geomorphological setting

92 South Indian laterites have been discriminated in two groups: highland laterites on
93 the plateau and lowland laterites in the western coastal plain (e.g., Widdowson and Cox,
94 1996). Remnants of three main lateritic paleolandscapes are reported on the highland
95 and the remnants of a lateritic pediment have been described in the lowland
96 (Widdowson, 1997; Gunnell, 1998; Widdowson and Gunnell, 1999). Our field

97 observations indicate that each highland relict paleolandsurface has a specific regolith
98 covers. The relicts of the first, highest and oldest landsurface are capped by a
99 weathering profile topped by an Al-Fe duricrust (Figs. 2). This duricrust is commonly
100 economic-grade bauxite such as those preserved on the Deccan Traps (Valeton, 1999).
101 The bauxites are also preserved on the highest topographic massifs of the southern part
102 of the Peninsula (e.g., Londa, Bababudan, Shevaroy, Nilgiris and Palni hills; Figs. 1 and
103 2). Remnants of a second younger landsurface are found downslope Al-Fe duricrust
104 relicts. They are capped by weathering profiles topped by a Fe duricrust or by a Fe-Mn
105 duricrust if an underlying Mn-protore is present (Fig. 2). The third and last lateritic
106 paleolandsurface on the highland is a pediment, which is capped by reworked debris of
107 lateritic duricrusts (Fig. 2). The debris may be cemented to form a ferricrete, or a Fe-Mn
108 duricrust, if Mn ore debris are also included in the pediment sedimentary cover above a
109 Mn-protore (see below). Following weathering and abandonment of the pediment, the
110 lateritic covers of the highland have been essentially stripped and incised by rivers,
111 leaving only sparse relicts of the three paleolandsurfaces (Radhakrishna, 1993). The
112 lowland pediment is underlain by a weathering profile that locally hosts bauxite and Mn
113 ore pockets and is capped by a ferricrete, which may be a Fe-Mn duricrust above Mn-
114 protores (Beauvais et al., 2016).

115 Four Mn-ore deposits were visited and sampled on the highland and three in the
116 lowland (Fig. 1). Two actively operated Mn-ore deposits (Kappataswamy and
117 Channanghi KMK-E) were sampled in the highland Sandur massif (Figs. 1 and 2b; stars
118 1 and 2; Table 1). Lateritic Mn-ore deposits developed upon Late Archean protores
119 younger than 2651 ± 18 Ma, as constrained by SHRIMP U-Pb dating of their
120 stratigraphically underlying volcanics (Nutman et al., 1996). The protores include

121 phyllites, argillites, arenites and Fe-Mn stromatolitic carbonates that yielded a $2475 \pm$
122 65 Ma Pb-Pb isochron age (Chadwick et al., 1996; Russell et al., 1996). The open pits
123 are weathering profiles excavated into a remnant of the second paleolandsurface capped
124 by a Fe-Mn duricrust, at 1012-1015 m elevation (Figs. 2b; 3a and 3b). A remnant of the
125 first paleolandsurface dominates the deposit at ca. 1100 m elevation (Fig. 2b).

126 Highland samples were also collected closer to the WGE, in two abandoned mines
127 of the Shimoga area (Triveni and Kumsi Mn ore open pits; Figs. 1 and 2a, stars 3 and 4,
128 respectively, see also 3c-d and Table. 1). In these pits, the protore is a metavolcanic
129 rock belonging to the Shimoga greenstone belt (Rb-Sr isochron age of 2520 ± 62 Ma;
130 Bhaskar Rao et al., 1992). The protore also comprises Mn-phyllites, which weathered
131 during the Cenozoic as constrained by palynological analyses (Krishna Rao et al.,
132 1982). The Triveni Mn ore samples (Fig. 2a) have been collected at altitudes between
133 850 and 875 m (Table 1) in the Fe-Mn duricrust-capped weathering profile of the
134 second paleolandsurface (Fig. 2a). The Kumsi pit exposes a 21 m thick lateritic profile
135 of a relict of the pediment forming the third highland paleolandsurface (~ 710 m
136 altitude; Figs. 2a and 3d). The sampled profile consists in a ~ 6 m thick dismantled
137 lateritic duricrust hosting a ~ 2 m thick sedimentary layer mixing decimetric
138 ferruginous, manganiferous clasts and infracentimetric oolites (Fig. 3d) upon ~ 15 m of
139 massive Mn-ore.

140 The weathering profile of the lowland pediment developed upon greenstones
141 similar to those of the Shimoga belt (Dessai, 1985; Fig. 1) and were constrained by
142 paleomagnetism as “late Paleogene to Neogene” in age by Schmidt et al. (1983). The
143 elevation of the pediment varies from 200 m at the foot of the WGE to 50 m close to the
144 coastline (Fig. 2c). We collected samples in four pits excavated in the pediment capping

145 ferricrete (Caurem, star 5, Naveli 1 and Naveli 2, star 6, and Cudnem, star 7; Figs. 1 and
146 2c; see also Table. 1). Caurem, Naveli 1&2 and Cudnem pits have been excavated
147 where the ferricrete lies at 100 m, 140 m and 50 m elevation, respectively. In those pits,
148 the weathering profile is 25 to 100 m thick and the ferricrete is made of cemented
149 reworked lateritic clasts (Figs. 3e-f-g; Babu, 1981; Bonnet, 2015).

150

151 2.2. Samples preparation, characterization and analysis

152 Potassium-rich end-member of coronadite group (i.e., cryptomelane) from the
153 hollandite supergroup (Biagioni et al., 2013), is a common supergene Mn-oxide of the
154 lateritic Mn-ore deposits of southern India (e.g., Krishna Rao et al., 1982; Mohapatra et
155 al., 1996) which can be used for $^{40}\text{Ar}/^{39}\text{Ar}$ dating. The crystallographic system of this
156 mineral allows argon gas retentiveness in a tunnel-type crystal lattice, which is
157 characterized by a double chain of MnO_6 octahedra and K^+ cations in the large tunnel
158 lacuna to insure the electronic neutrality of the lattice (Turner and Buseck, 1979; Post
159 and Burnham, 1986). Tunnel oxides retained efficiently Ar and K and remain close in
160 supergene environmental conditions (Vasconcelos, 1999b; Vasconcelos et al., 1994),
161 leading to meaningful crystallization age of the minerals. However K-rich Mn-oxides
162 are usually mixed with other oxides, such as others Mn-oxides (e.g., pyrolusite,
163 lithiophorite) and Fe-oxides (hematite, goethite). Therefore, careful observations and
164 extraction techniques are required to ensure meaningful dating.

165 The method implemented to characterize and separate the K-rich Mn-oxides
166 grains from field samples is summarized in figure 4. Field samples were cut with a
167 circular saw (1.5 mm breadth) to get a section allowing accurate observations. A 200-
168 300 μm thick polished thin section and a symmetrical 500 μm thick slab were made

169 from each sawed fragment. Polished thin sections have been studied using reflected
170 light microscopy (Fig. 5a-g). We also used elemental cartography by X-ray micro-
171 fluorescence (μ -XRF) with a XGT7000 Horiba Jobin Yvon producing a high-intensity
172 beam with a 100 μ m spot size, Rh X-ray tube, accelerating voltage of 30 kV and current
173 of 1mA. Micro-XRF elemental maps of Fe, K and Mn are stacked together on a single
174 image using ImageJ software by assigning a distinct color to each elemental map (Figs.
175 4 and 6). The resulting images are helpful to locate K-rich phases on the slab. Electron
176 Probe Micro-chemical Analysis (EPMA) of minerals using a CAMECA SX-100
177 electron microprobe equipped with five wavelength-dispersive X-ray spectrometers
178 (WDS) provided the precise micro chemical composition of K-Mn oxides.

179 Grains were then separated from the slabs using a micro-drill under a large
180 magnifier (Fig. 4). Some of them were observed with a scanning electron microscope
181 (SEM, Fig. 5h), other were crushed to produce a powder sieved at 64 μ m, which was
182 analyzed by XRD using a Panalytical X'Pert Pro MPD with a Co K α X-ray source ($\lambda =$
183 1.79 \AA) operating at 40kV and 40 mA. The remaining grains were ultrasonically
184 cleaned in absolute ethanol, conditioned in aluminum foil packets and placed into a
185 irradiation vessel along with $^{40}\text{Ar}/^{39}\text{Ar}$ dating standard Taylor Creek Rhyolite sanidine 2
186 (TCRs-2) monitor, dated at 28.608 ± 0.033 Ma (Renne et al., 2011). Irradiation took
187 place in the TRIGA Mark-II reactor of Pavia University (Italy) during 50 hours. Prior
188 experiments have shown none or very little ^{39}Ar recoil from those grains.

189 Isotopic analyses were then performed on irradiated K-rich Mn-oxide separates
190 using either step heating degassing under a CO₂ laser probe coupled with an Argus VI
191 multicollection mass spectrometer (with 4 faradays for masses ^{40}Ar - ^{37}Ar and ion
192 counting on ^{36}Ar) or a step-wise heating procedure in a double vacuum Staudacher-type

193 furnace coupled with a VG3600 mass spectrometer using peak jumping and
194 Faraday/Daly analyzer as described by Arnaud et al. (2003). Mass discrimination of
195 machines and blank levels are followed daily. Isotopic ratios were corrected for
196 irradiation interferences and air contamination using a mean air value of 298.56 ± 0.31
197 (Lee et al., 2006; Renne et al., 2009).

198 Ages were statistically analyzed in three ways: ^{39}Ar release spectra, inverse
199 isochrons (Table. 2) and age's frequency or probability plots. Age spectra detail the
200 homogeneity of argon released and age stability throughout the degassing process, with
201 the prior assumption of atmospheric correction for inherited argon. When apparent ages
202 are integrated over continuous steps overlapping at the 2σ level and releasing at least
203 70% $^{39}\text{Ar}_K$, the derived plateau age is statistically robust and meaningful (e.g., Beauvais
204 et al., 2008). However, when plateau is derived from less than 70% of $^{39}\text{Ar}_K$ released
205 (e.g., Vasconcelos, 1999a; Li and Vasconcelos, 2002; Vasconcelos and Conroy, 2003;
206 Colin et al., 2005), the critical value of 50% $^{39}\text{Ar}_K$ released is accepted to calculate a
207 "plateau age" (e.g., Li et al., 2007; Feng and Vasconcelos, 2007; Vasconcelos et al.,
208 2013; Riffel et al., 2014; Bonnet et al., 2014; Deng et al., 2016) provided that it is
209 integrated over three or more continuous steps whose ages overlap at the 2σ level (Fleck
210 et al., 1977; Maluski, 1985; McDougall and Harrison, 1999). When more than two
211 apparent steps overlaps at the 2σ level but integrate only 40 to 50% of the $^{39}\text{Ar}_K$
212 released, "pseudo plateau" are defined and considered as acceptable and meaningful
213 (Vasconcelos et al., 2013; Riffel et al., 2014).

214 When those criteria are not satisfied but barely missed (ages do not strictly
215 overlap at the 2σ level) a "forced plateau" integrating more than two consecutive
216 reasonably flat steps is calculated with a weighed mean (weighed by the error and the

217 ^{39}Ar released in each step) (see Feng and Vasconcelos, 2007; Vasconcelos et al., 2013;
218 Riffel et al., 2014). The $^{36}\text{Ar}/^{40}\text{Ar}$ vs. $^{39}\text{Ar}/^{40}\text{Ar}$ correlation diagrams (also called inverse
219 isochrons) are also used to derive the best-fitted inverse isochron (Roddick et al., 1980)
220 allowing to estimate a statistically robust age. The inverse isochron approach also is
221 particularly useful to detect different contamination from various excess or inherited
222 argon reservoirs, which may result from atmospheric argon incorporated in the less
223 retentive site of the grain, or excess ^{40}Ar released from older K-bearing minerals. For
224 some authors (De Putter et al., 2015), best inverse isochrons exclude the first heating
225 steps, which are usually dominated by trapped atmospheric Ar in the less retentive
226 crystalline sites. These ages are derived from best-fitted inverse isochrons that should
227 have mean square weighted deviation (MSWD) as close as possible to 1 with regard to
228 the distribution of points and their absolute error, but this value is not a limitation to
229 derive an acceptable inverse isochron. Regressions are classically accepted as
230 significant when MSWD is less than 2.5 (Roddick et al., 1980), possibly around 1.
231 There is therefore a complicated trade-off between the number of points used, the
232 MSWD, and the use of the most radiogenic $^{40}\text{Ar}^*$ rich steps.

233

234 **3. Results and interpretations**

235 3.1. Petrological and geochemical characterization

236 Descriptions of samples and K-Mn oxide grains are compiled in the table 1. Two
237 main petrographic forms of manganese ore can be distinguished. Float (very porous) or
238 platy Mn-ores show the original banding of the siliceous phyllitic protore (Figs. 3a and
239 5a; Mishra, 1978; see also Bonnet et al., 2014). Mn-ore can also be massive podiform
240 and botryoidal filling micro porosities (Fig. 5b and Fig. 6a-b) and larger cavities, in

241 which geodes formed by successive overgrowth of colloidal microstructures (Fig. 5e-f
242 and Fig. 6a) becoming massive cryptocrystalline when cavities are totally filled (Fig.
243 5b-c). Colloidal overgrowth around nucleus (e.g. iron oxide, clasts) can also form
244 massive nodules where the initial protore structure is totally erased (Fig. 5d-e).

245 Cryptomelane EPMA data are plotted in a ternary diagram (Fig. 7; see also the
246 data repository DR1). Cryptomelane from Shimoga and Goa is enriched in aluminum
247 (Fig. 7). The differences in alumina result either from contrasted parent rocks
248 composition (e.g., carbonates without alumina vs. aluminous metavolcanic phyllites) or
249 possible intergrowth with lithiophorite (Fig. 5e-g and Fig. 6a) or even gibbsite (Fig. 5h).
250 These differences may also indicate a better maturation of Sandur's cryptomelane rich
251 ores (Fig. 6), which are devoid of aluminous impurities (e.g., Beauvais et al., 1987).

252

253 3.2. Deciphering the $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra

254 The different types of ^{39}Ar release spectra are shown in figures 8 and 9. Many
255 samples yielded a regular flat age spectrum (Fig. 8a). As explained above, plateau ages
256 are validated when at least three consecutive steps comprising up to 50% of total $^{39}\text{Ar}_K$
257 released overlap at the 2σ confidence level.

258 Degassing spectra may show evidence of negligible amount of ^{39}Ar , low % $^{40}\text{Ar}^*$
259 and large amount of atmospheric ^{40}Ar in the low energy degassing steps that generally
260 increases the 2σ error of the first apparent ages (Fig. 8a). Another issue is the
261 rejuvenated ages frequently observed at low temperature steps (Fig. 8b), which can be
262 the result of a loss of $^{40}\text{Ar}^*$ from less retentive and poorly crystallized sites (see
263 (Vasconcelos, 1999b). But most of the time the apparent ages progressively reach a
264 constant value at higher temperature steps allowing definition of a plateau, which is also

265 well supported by an inverse isochron (see Fig. 8b). Sixteen samples show such a
266 degassing spectrum integrating up to 90% of the total extracted signal, and excluding
267 only the very first steps with ages lower than the plateau. These well-defined plateaus
268 are used to calculate the absolute ages of the K-Mn oxides. Generally, both the ages
269 estimated from spectra and inverse isochrons are equivalent (Fig. 8a-b, Table. 2).
270 Therefore, we choose to present our ages only with ^{39}Ar release spectra that clearly
271 show a plateau, and with both spectra and inverse isochrons when no clear plateau is
272 identified. Plateau ages (70% $^{39}\text{Ar}_K$ released) and best-fitted inverse isochrons are
273 considered as first order ages and noted (A) in figures 10, 11 and 12.

274 Some age spectra do not allow calculating a standard age plateau according to the
275 definition of Fleck et al. (1977), but only a “forced-plateau” defined from ^{39}Ar release
276 spectra encompassing four steps releasing $\sim 70\%$ (Fig. 8c). In other release spectra, a
277 probable authigenic component ages the last steps, which result in an older intermediate
278 step with several little pseudo plateaus (10 to 30 % ^{39}Ar each) of similar ages (Fig. 8d).
279 In such cases, an estimated concordant pseudo-plateau age is often supported by a valid
280 inverse isochron age (Table. 2; see also Bonnet et al., 2014). This can be a valid
281 alternative when the total amount of integrated % $^{39}\text{Ar}_K$ is higher than 40% of the total
282 signal. But such a concordant pseudo-plateau age should also be certified by a well-
283 defined plateau age in another sample from the same weathering profile. Plateau ages
284 integrating less than 70% $^{39}\text{Ar}_K$ released, “Forced plateau”, “Pseudo plateau” and
285 “concordant pseudo plateau” ages are considered as second-order ages noted (B) in
286 figures 10, 11 and 12. Nevertheless, these ages are often validated by best-fitted inverse
287 isochrons (Table 2) and are meaningful of first order weathering events.

288 When the age spectra present an obviously convex hump shape (Fig. 9a) the
289 youngest and oldest apparent ages may result from a mixing between gases released
290 from two phases (e.g., Ruffet et al., 1996; Hautmann and Lippolt, 2000; Vasconcelos
291 and Conroy, 2003; Beauvais et al., 2008; De Putter et al., 2015). Possible argon loss
292 from less retentive intercrystalline site could also affect these degassing patterns (Fig.
293 9a). The statistical analysis of both the age spectrum and the inverse isochron may help
294 to estimate minimum and maximum ages of mixed phases (e.g., Bonnet et al., 2014). In
295 the case of sample TRI-3a the only possible inverse isochron yields a maximum
296 estimate of the youngest phase at ~ 11 Ma (Fig. 9a). However, this age is not validated
297 by a well-defined plateau age from another sample of the same deposit (Fig. 11), and
298 therefore noted (C). Most spectra with a hump-shape also show a plateau integrating at
299 least 50% of $^{39}\text{Ar}_K$ in the intermediate energy levels but the derived age is a minimum
300 estimate of the oldest phase (e.g., KUM-400, Fig. 11; see also NAV-3c and NAV-3b
301 Fig. 12). The plateaus included in these hump-shape spectra should be considered more
302 carefully and derived ages are noted (B), but acceptable inverse isochrons are derived
303 (Fig. 12, Table 2). Other hump shape spectra exhibit young apparent ages forming
304 “pseudo plateaus” in low and high energy levels with concordant ages, which bracket an
305 older plateau age in the intermediate energy level (e.g., CAU-1a, CAU-1c, CAU-3a,
306 CAU-2, Fig. 12, Fig. 12). The correlation diagrams for these samples point to possible
307 inverse isochrons estimating maximum and minimum age of the youngest and oldest
308 mixed-phases respectively (Fig. 12, Table 2). For example, the oldest phases with
309 minimum ages ~ 22 to ~ 24 Ma (Fig. 12) are probably contaminated by youngest phases
310 with maximum age ~ 19 to 20 Ma. These ages are noted as (B) and meaningful when
311 derived from best-fitted inverse isochrons and/or plateau integrating at least 50% $^{39}\text{Ar}_K$.

312 On another hand, the age difference between the youngest and oldest phases is larger
313 (e.g., KPA-2.5, Fig. 10; see also CAU-1b, Fig. 12), ages estimations are too speculative
314 and only the minimum age of the oldest phase can be estimated and noted with a (C) in
315 figures 10, 11 and 12 (see also Table 2). These ages are not meaningful.

316 Other samples show “saddle shape” spectra (Figs. 9b-c) with a progressive
317 decrease of the apparent ages in the intermediate energy steps and a very large increase
318 of the ages at highest energy steps. This complex type of spectra may result from
319 significant ^{39}Ar loss by recoil and/or contamination (Turner and Cadogan, 1974;
320 Vasconcelos, 1999b; Vasconcelos and Conroy, 2003). The high energy steps suggest a
321 hypogene contaminant (Vasconcelos et al., 1994; Ruffet et al., 1996; Li and
322 Vasconcelos, 2002; Bonnet et al., 2014), which can also age the other steps (e.g., Fig.
323 9c). Most of these spectra display overestimated ages, which are not reliable
324 (Vasconcelos and Conroy, 2003). Noted that no inverse isochron is derivable, the
325 correlation diagram showing at best a mixing of inherited contaminant and supergene
326 phase (Fig. 9c).

327 The Table 2 synthetize the results and shows 24 well defined plateaus ages (>
328 70% $^{39}\text{Ar}_K$) with one best-fitted inverse isochron age noted (A). In addition 18 ages
329 noted (B) are also derived either from “plateaus” and “forced plateaus” (at least 50%
330 $^{39}\text{Ar}_K$) or from “concordant pseudo plateaus” ages and best-fitted inverse isochrons. All
331 these ages are reliable and geologically significant and have been plotted against
332 altitude, and combined with individual age probability diagram (Fig. 13a) that enhances
333 most probable weathering age peaks (Vasconcelos, 1999b).

334

335 3.3. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of lateritic weathering in South India

336 Here we present 29 newly analyzed K-Mn oxide grains that are interpreted
337 together with grains studied by Bonnet et al. (2014) and Beauvais et al. (2016) (Table 2
338 and Fig. 13a). The total analysis of 46 Mn-oxide grains provides 40 age spectra with
339 significant geological meaning as “plateaus”, “forced-plateaus”, “pseudo plateau”
340 “concordant pseudo-plateaus” or “hump shape”. We present our results in three figures
341 grouping age spectra obtained from K-Mn oxide grains of the Sandur (Fig. 10),
342 Shimoga (Fig. 11) and Goa deposits (Fig. 12). All the ages are also presented in Table 2
343 including the best inverse isochron age estimates (See also data repository tables DR2
344 and DR3).

345

346 3.3.1. $^{40}\text{Ar}/^{39}\text{Ar}$ ages from highland Sandur Mn ore deposit

347 Among all the samples dated in the Sandur Mn ore deposit, 18 samples show
348 plateau ages noted (A). The ages range from ~ 26 Ma (KMK-3) to ~ 53 Ma (KPA-8)
349 (Fig. 10 and Table 2). Two age groups are distinguished: ~ 53 - 50 Ma and ~ 37 - 26 Ma
350 (Fig. 10). Two spectra have a “hump shape” resulting from mixed supergene phases
351 (Bonnet et al., 2014; Hautmann and Lippolt, 2000; Ruffet et al., 1996; Vasconcelos et
352 al., 1995). The spectrum of sample KPA-2.5 shows a maximum apparent age ~ 46 Ma
353 old, which is a minimum estimate of the oldest phase in the mixing. In sample KPA-
354 12a minimum age of ~ 34 Ma noted (C) for the oldest phase is coherent with plateau
355 ages (A) between ~ 37 Ma (KMK-3b) and ~ 32 Ma (KPA-11) (Fig. 10), which are
356 attributed to the second weathering period. Nine grains display plateau-ages between ~
357 26 and ~ 30 Ma. The high frequency of these ages is linked to the analysis of several
358 aliquots of samples KPA-10 (4 grains) and KPA-12a (6 grains), which yielded
359 reproducible plateaus, and also allowed quantifying the growth rate for these

360 cryptocrystalline colloidal structures. Grains KPA-12a1 and KPA-12a5 are separated by
361 12.2 ± 0.1 mm (Figs. 6 and 10) and the estimated growth rate of the massive
362 cryptocrystalline colloidal structure is 5.7 ± 3 mm. Ma⁻¹. A mean rate of 5.0 ± 4 mm.
363 Ma⁻¹ in botryoidal overgrowth microstructure was also estimated for sample KPA-10
364 between grains KPA-10a and KPA-10c (Figs. 6 and 10). These rates are comparable
365 with earlier growth rate estimates of 6.4 ± 1.2 mm. Ma⁻¹ (Vasconcelos et al., 1992) or 1
366 to 5 mm. Ma⁻¹ (Hénoque et al., 1998).

367

368 3.3.2. ⁴⁰Ar/³⁹Ar ages from highland Shimoga Mn ore deposits

369 The obtained ages are mostly comprised between ~ 30 and 24 Ma (Fig. 11).

370 However, one grain (KUM-400) displays a spectrum with a singular hump shape, which
371 results from a mixing of two phases (Figs. 11a-b). The “forced plateau” age at ~ 39 Ma
372 including 58% of the total amount of ³⁹Ar released is the minimum estimate of the
373 oldest phase and noted (B), which is also supported by the sole possible inverse
374 isochron with a MSWD value less than 2.5 (Fig. 11b). The correlation diagram does not
375 allow estimating an acceptable age for the youngest phase in this mixed grain (Table 2).

376 The considered grain was picked up from a lateritic clast reworked in the lateritic
377 pediment topping the Kumsi Mn-ore deposit (site 4 on Fig. 2a). The detrital nature of
378 this sample and its high porosity are attested by reflected light microscopy (Fig. 5d).
379 This suggests provenance from a lateritic Mn-duricrust previously exposed on a higher
380 landsurface, which was dissected and eroded allowing lateritic clasts transport and
381 deposition at lower elevations on the pediment in which the Kumsi pit is excavated.
382 Therefore, the Kumsi pediment must be younger than 39 Ma (minimum age of the
383 oldest phase in KUM-400) but older than 26 Ma (most common age of the youngest

384 phase in the same profile, Fig. 11a and Table 2). Sample TRI-3b (Fig. 11) shows a
385 middle spectrum portion with ages ranging from ~ 43 to ~ 48 Ma accounting for 70% of
386 the total ³⁹Ar released. An inherited phase seems to release gas especially at high energy
387 step heating, but when this phase started to degas at lower energy, the apparent ages at
388 intermediate heating steps are artificially aged that increases the apparent age up to ~ 48
389 Ma. The best age estimation of the supergene phase in this grain is most probably ~ 43
390 Ma but must be considered only as a maximum age estimate.

391 The release spectrum of samples KUM-3f and KUM-2 show weakly aged steps at
392 the beginning of the analysis, which possibly resulted from minor ³⁹Ar recoil (Turner
393 and Cadogan, 1974). However, the disturbance is very low and meaningful age at ~ 30
394 Ma (KUM-3f) and ~ 23 Ma (KUM-2) both by a pseudo plateau (Fig. 11a) and well-
395 constrained inverse isochrons (Fig. 11b; Table. 2). Several aliquots of samples TRI-3
396 and KUM-3a (Fig. 11) yield consistent plateau ages of 25.5 Ma and ~ 26-27.5 Ma,
397 respectively.

398

399 3.3.3. ⁴⁰Ar/³⁹Ar ages from lowland Goa Mn ore deposits

400 The cryptomelane ages from samples of the lowland Mn-ore deposits are
401 distributed in two main age groups. The first group comprises two-ages at ~ 47 and 45
402 Ma, obtained for two aliquots of sample NAV-3, which are probably minimum
403 estimates. The spectrum of NAV-3c allows integrating 60% of the total amount of ³⁹Ar
404 released overlapping at the 2σ error (Fleck et al., 1977) that yields a plateau age (A) of
405 47.0 ± 0.6 Ma, which is supported by the inverse isochron age (Table 2 and Fig. 12b).
406 Further evidence of early weathering around ~ 45 Ma (minimum age of NAV-3b) in the
407 lowland is supported by the spectrum and a possible inverse isochron (Fig. 12). The

408 spectrum of sample CAU-1b (Fig. 12) also shows a maximal apparent age at ~ 45 Ma,
409 which is a minimum age and should be noted (C). The old ages are systematically
410 obtained from samples collected in the deepest part of the weathering profile. Younger
411 ages between ~ 19 Ma and ~ 24 Ma (group 2) and discrete ages at ~ 8.7 Ma and 2.5 Ma
412 are also identified (Fig. 12). All these ages are supported by inverse isochron ages (see
413 Table. 2).

414 Sample CAU-2 shows a “hump shape” explained by the probable mixing of two
415 phases, with a minimum age of ~ 24.5 Ma for the oldest and a maximum estimate of ~
416 19 Ma for the youngest. The oldest estimate cannot be validated by inverse isochrons
417 (Fig. 12b, and Table 2). In three similar cases, secondary pseudo-plateaus at ~ 20 Ma
418 can be detected on either side of a plateau or a “forced plateau” (e.g., CAU-2). For
419 example, sample CAU-3a (Fig. 12) shows a plateau at ~ 24 Ma, which is a minimum
420 estimate flanked by small concordant pseudo-plateaus at ~ 19-20 Ma in low- and high-
421 energy steps accounting together for 32% ³⁹Ar degassed. Sample aliquots CAU-1a and
422 CAU-1c (Fig. 12) also show similar “hump shape” type spectra with a plateau age
423 flanked by concordant pseudo-plateau ages suggesting mixing of two phases of different
424 ages (Vasconcelos et al., 1995; Ruffet et al., 1996; Hautmann and Lippolt, 2000) but
425 close enough to be grouped in the same weathering period ca. 19 to ca. 24 Ma.
426 However, for these last three samples the difference between the oldest and the
427 youngest phase (20 Ma) is small enough to allow deriving three minimum plateaus ages
428 noted (B) at ~ 24 Ma associated with three concordant (B) maximum ages at ~ 20 Ma
429 (Fig. 12). The youngest ages ~ 20 Ma are rather well supported by reliable inverse
430 isochron ages (Table. 2, Fig. 12b).

431

432 3.3.4. Interpretation of the $^{40}\text{Ar}/^{39}\text{Ar}$ ages

433 The first- and second order (A and B) $^{40}\text{Ar}/^{39}\text{Ar}$ ages allow defining three main
434 lateritic weathering periods (W1, W2a and W2b) in South India (Fig. 13a). The first
435 weathering period W1 (ca. 53 to ca. 45 Ma) corresponds to intense chemical rock
436 weathering upon both the highland and the lowland. Intense (bauxitic) weathering of the
437 first paleolandsurface is interpreted as correlative to this weathering period (Bonnet et
438 al., 2014; Krishna Rao et al., 1989b). The second weathering period W2 from ca. 37 to
439 ca. 19 Ma may be divided in two stages, W2a (ca. 37-26 Ma) mostly in the highland
440 (Sandur, ca. 37-26 Ma and Shimoga, ca. 30-26 Ma) and W2b (ca. 26-19 Ma) only in the
441 western highland (Shimoga, ca. 26-23 Ma) and in the lowland (Goa, ca. 24-19 Ma). The
442 early stage (W2a) characterizes late Eocene to late Oligocene lateritic weathering of the
443 second highland paleolandsurface, as best recorded in the eastern part (Sandur), and
444 more discretely in Shimoga (e.g., ca. 30 Ma from KUM-3f, Fig. 11b). This weathering
445 period also led to maturation of the previously formed bauxitic weathering profiles (e.g.,
446 Krishna Rao et al., 1989b). After 26 Ma, the Sandur remnants of the two oldest
447 paleolandsurfaces do not seem to be longer subject to weathering, while the western
448 highland landscape (Shimoga) still weathered until ca. 23 Ma at the time the lowland
449 weathered too. Two later minor Late Neogene weathering pulses are also recorded in
450 the lowland (9 and 2.5 Ma).

451 The weathering periods would sign installation of wet and warm climate leading
452 to thick soil development under rainforest conditions over the peninsula, whereas the
453 time intervals between these weathering periods may be interpreted as episodes of
454 subdued chemical weathering and correlative higher mechanical erosion and landscape
455 dissections (e.g., Beauvais and Chardon, 2013). Such climate driven erosion processes

456 changes have resulted in the installation and preservation of the successive lateritic
457 paleolandsurfaces over South India. The first, bauxitic paleolandsurface, was essentially
458 shaped until a maximum age of ca. 45 Ma by intense weathering and only slightly
459 reworked and dissected after that time during the shaping, and later weathering of the
460 second landsurface between ca. 37 and ca. 26-23 Ma. Finally, abandonment / dissection
461 of the highland pediment after ca. 23 Ma indicates that the thick lateritic covers of
462 South India formed in the Eocene and Oligocene and that stripping of that material and
463 intense dissection of the peninsula essentially took place in the Neogene (i.e., after 23
464 Ma).

465

466 **4. Morphoclimatic implications of $^{40}\text{Ar}/^{39}\text{Ar}$ dating**

467 Periods of intense weathering have affected the highland landscapes during the
468 early Eocene, and from late Eocene to late Oligocene. By contrast, the lowland
469 weathered mostly during the early Eocene and the early Miocene (Fig. 13a). The
470 successive Eocene to early Miocene weathering periods documented by the present
471 study coincided with the northward migration of India across the humid equatorial belt
472 (Fig. 13b). Early Eocene bauxitic weathering also coincided with the Eocene climatic
473 optimum (Fig. 13c), at a time of relatively high atmospheric CO_2 (Pearson and Palmer,
474 2000), North Atlantic rifting (62 to 55 Ma) and the subduction of Tethysian carbonates
475 (Van der Voo et al., 1999).

476

477 4.1. Early Eocene lateritic weathering (ca. 53-45 Ma; W1)

478 The $^{40}\text{Ar}/^{39}\text{Ar}$ ages indicate that lateritic weathering started at least ~ 50 Ma ago
479 over the highland and ~ 47 Ma in the lowland (Figs. 10, 12 and 13a). Preserved laterites

480 as old as 47 Ma under the lowland pediment argue for Early Eocene installation and
481 stabilization of the Western Ghats Escarpment with a lateritic pediment on its piedmont
482 (Beauvais et al., 2016). The old ages (ca. 53 to ca. 45 Ma) also document synchronous
483 lateritic weathering in the lowland and the highland (Beauvais et al., 2016), when India
484 drifting slowed down at the onset of the collision with Asia ~ 50 Ma ago (e.g., Zhu et
485 al., 2005; Rowley and Currie, 2006). In the meantime, India also entered a latitudinal
486 range where water precipitation was higher than evaporation (Fig. 13b) propitious to the
487 development of equatorial and/or tropical warm and humid forest (Kent and Muttoni,
488 2008; see also Patriat and Achache, 1984; Manabe and Bryan, 1985; Tardy and Roquin,
489 1998; Chatterjee et al., 2013) that further enhanced lateritic weathering. At the time of
490 India-Asia collision, CO₂ degassing of pelagic carbonate into the atmosphere ceased
491 with the end of the North Tethys subduction (Caldeira, 1992) concomitantly with
492 intense continental (bauxitic) lateritic weathering worldwide (Prasad, 1983; Valetton,
493 1999; Retallack, 2010) and correlative offshore carbonate production (e.g., Chaubey et
494 al., 2002 for the West Indian margin). Bauxitic weathering was effectively documented
495 by ⁴⁰Ar/³⁹Ar cryptomelane ages throughout the tropical belt during the Eocene e.g.,
496 from 56 to 51 Ma in South America (Ruffet et al., 1996; Vasconcelos, 1999b;
497 Vasconcelos et al., 1994) and from 59 to 45 Ma in West Africa (Hénocque et al., 1998;
498 Colin et al., 2005; Beauvais et al., 2008). Combined together, all these concomitant
499 phenomena consumed high quantities of atmospheric CO₂ (Dessert et al., 2003) that
500 progressively cooled the climate once past the Eocene Climatic Optimum (Kent and
501 Muttoni, 2008, 2012; see also Zachos et al., 2001, 2008). In turn, progressive climate
502 cooling from Mid-Eocene onward (Fig. 13c) has favoured the dissection of early
503 Eocene bauxitic landscapes.

504

505 4.2. Late Eocene-late Oligocene weathering (ca. 37-26 Ma; W2a)

506 This first weathering stage of period W2 is marked mostly in the highland,
507 particularly by two prominent peaks at ~ 28 Ma and ~ 26 Ma in the Sandur massif and
508 the Shimoga area, respectively (Fig. 13a), and more speculatively in the lowland if we
509 consider that 24 Ma is a minimum age. This episode (37-26 Ma) is interpreted to reflect
510 the continental weathering response to the late Oligocene warming (Fig. 13c) at a time
511 of a marine transgression propitious to offshore carbonate production (Biswas, 1987).
512 Thickening of the proto-Himalaya since ~ 40 Ma (Aikman et al., 2008) resulted in the
513 installation of an orographic barrier (Molnar et al., 1993; Ramstein et al., 2005), which
514 redistributed the humid air masses southward (Dupont-Nivet et al., 2008). A monsoonal
515 regime installed at that time in Southern Asia (Licht et al., 2014) that could intensify
516 weathering processes on the Indian peninsula. Under such climatic conditions, the
517 lateritic weathering profiles underlying remnants of the first two paleolandsurfaces
518 became less well drained as a result of river incision, but did not become totally
519 inactive, as attested by younger dates in Sandur, e.g., ca. 37 to ca. 26 Ma (Figs. 10 and
520 13a). During this period, the early Eocene bauxites have still evolved on the highland
521 (Krishna Rao et al., 1989b; see also Bonnet et al., 2014) at least until global cooling by
522 ~ 34 Ma (Fig. 13c; Molnar and England, 1990; Zachos et al., 2001).

523 Early Oligocene cooling also coincided with a sea level fall (Chaubey et al.,
524 2002), and the installation of dryer climatic conditions (see Fig. 13c), which may have
525 resulted in the attenuation of the weathering intensity observed between 32 and 29 Ma
526 in the highland (Fig. 13a). The highland pediment may possibly have been formed in
527 this time interval, and subsequently weathered between 29 and 23 Ma. At that time, the

528 lowland landscape was also possibly rejuvenated, but previously formed lateritic
529 weathering mantles as old as ca. 47-45 Ma were preserved (Figs. 12 and 13a), attesting
530 to a very slow denudation regime of the pediment below the WGE (Beauvais et al.,
531 2016). The contrasted weathering record of the highland and the lowland after the Mid-
532 Eocene (Fig. 13a) suggests a spatial contrast in rainfall distribution on either side of the
533 WGE. This contrast was mostly controlled by dominant South-East moisture fluxes
534 during the late Eocene and the early Oligocene (Licht et al., 2014; Chen and Li, 2014)
535 before installation of modern monsoon regimes in the early Miocene (Clift et al., 2008),
536 which reactivated weathering preferentially in the lowland.

537

538 4.3. Late Oligocene-Early Miocene weathering (ca. 26-19 Ma; W2b)

539 This second stage of weathering period W2 is mostly marked in the western
540 highland and the lowland. Weathering in eastern highland lateritic profiles of the Sandur
541 massif definitively ceased at ca. 26 Ma (Bonnet et al., 2014), while the western part of
542 the highland adjacent to the WGE (Shimoga) possibly weathered until ca. 23 Ma (Fig.
543 13a). Therefore, the highland lateritic pediment carrying those profiles has been incised
544 essentially after 23 Ma at a rate < 5 m/m.y. (Figs. 2a-b). During highland incision,
545 lateritic weathering was reactivated on the lowland pediment with a peak activity at ~
546 19-21 Ma (Fig. 13a). Central Asia aridification started ~ 24 Ma ago (Sun et al., 2010).
547 Highland weathering mitigation after ~ 23 Ma may be due to such a change in climatic
548 regime, which increased the east-west wetness gradient over peninsular India and
549 signed the onset of modern-like monsoonal regimes (Clift et al., 2008; see also
550 Chatterjee et al., 2013).

551 The lack of reliable ages between ~ 19 Ma and 9 Ma (Fig. 13a) suggests that
552 weathering is not recorded or preserved in peninsular India during Mid-Miocene. After
553 the early Miocene (i.e., after ca. 16 Ma), a significant change has been however
554 observed in the clay content of sediments from the neighbouring Arabian Sea, wherein
555 illite became dominant compared to kaolinite and smectite (Phillips et al., 2014). This,
556 together with our results, indicates an attenuation of continental weathering and
557 suggests dominant landscape dissection of the highland. By contrast, the lowland
558 lateritic pediment was only slightly dissected after ~ 19 Ma (Beauvais et al., 2016). The
559 weathering pulses at ~ 9 Ma and ~ 2.5 Ma (Figs. 12 and 13a) may be linked to Late
560 Neogene intensification of the Asian monsoon in the sub region (Zhisheng et al., 2001),
561 which may have been driven by uplift of the Tibetan plateau (Molnar et al., 1993; see
562 also Clift et al., 2008).

563

564 **5. Conclusion**

565 The $^{40}\text{Ar}/^{39}\text{Ar}$ dating of supergene cryptomelane formed *in situ* in lateritic
566 weathering profiles of Peninsular India sheds light on the Cenozoic weathering and
567 erosion history of the subcontinent's surface. Cryptomelane ages document three major
568 periods of weathering, i.e., early Eocene (W1) both on the highland and the lowland, ~
569 late Eocene – late Oligocene (W2a), only in the highland, and early Miocene (W2b),
570 mostly in lowland. The $^{40}\text{Ar}/^{39}\text{Ar}$ age series suggest subdued relief production and
571 dominant weathering of the highland before ~ 23 Ma and its dissection and stripping
572 after that time, while the lowland weathered in the Early Eocene and Miocene before
573 being slightly incised after ~ 19 Ma. The oldest ages (53-45 Ma) indicate widespread
574 Eocene lateritic weathering in South India at the time of global Eocene climatic

575 optimum, when the peninsula crossed the equatorial belt. Our results also document the
576 installation of a dual climatic regime across the Western Ghats escarpment after the
577 Eocene climatic optimum, leading to divergent weathering and erosion patterns on both
578 sides of this topographic barrier. Hence, K-Mn oxides $^{40}\text{Ar}/^{39}\text{Ar}$ age series document the
579 tempo of South Indian morphogenesis, and as such may be viewed as a proxy for
580 erosion and climatically driven weathering over geological time scales.

581

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590

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867

868

869 **Figures and table caption**

870 **Figure 1.** Simplified geological map (adapted from Chardon et al., 2008) superimposed
871 to Gtopo 30 m showing the location of the Mn ore deposit pits (stars). Kappataswamy
872 pit (Star 1); Channanghi KMK-East pit (star 2); Triveni pit (star 3); Kumsi pit (star 4);
873 Caurem pit (star 5); Naveli 1 & 2 pits (star 6); Cudnem pit (star 7). Offshore bathymetry
874 is from ETOPO1 (1.8 km).

875

876 **Figure 2.** Synthetic topographic sections with major lateritic weathering surface relics.
877 **(a) (b)** sections located located in the figure 1. **(c)** Detailed section across the lowland
878 pediment. The stars and numbers are the sampled open pits located in the figure 1.

879

880 **Figure 3.** Sampled lateritic weathering profiles. **(a)** Kappataswamy, **(b)** Channanghi
881 KMK-E, **(c)** Triveni, **(d)** Kumsi, **(e)** Cudnem, **(f)** Caurem and **(g)** Naveli 1. White
882 crosses show the sampling spots. (See table 1 for GPS locations and ore sample types)

883

884 **Figure 4.** Synthetic sketch of the different steps of preparation, observation, sub-
885 sampling and characterization of cryptomelane grains before the isotopic dating.

886

887 **Figure 5.** Reflected-light photomicrographs of polished thin sections from samples
888 collected in Sandur **(a-b)** Shimoga **(c-d)** and Goa pits **(e-f-g)**, showing cryptomelane
889 (C), pyrolusite (P), the protore matrix (Pr), iron oxides (Fe), lithiophorite (L) and pores
890 (V). h) SEM image showing gibbsite crystals over cryptomelane needles. See the table 1
891 for samples description.

892

893 **Figure 6.** Procedure to separate cryptomelane grain aliquots from two sample slabs **(a-**
894 **b)** of the Sandur profile using from left to right the thin section, μ -XRF mapping
895 (yellow rectangle on section) and reflected-light photomicrography (pink rectangle on
896 section). The μ -XRF map yields the composite colored image with Mn in blue, Fe in
897 red and K in green. C = Cryptomelane; P = Pyrolusite; G = Goethite; H = Hematite. See
898 the table 1 for samples description

899

900 **Figure 7.** Electron probe microanalyses of cryptomelane on polished thin sections. The
901 three poles of the ternary diagram are initially Mn, 10 K and 10 Al. The black, grey and

902 white diamonds are samples from Sandur, Shimoga and Goa, respectively. See also the
903 data repository table DR1.

904

905 **Figure 8.** $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra of cryptomelane grains showing regular ages, with
906 K/Ca (black) and Ar^* (grey) step curves (left), and inverse isochron diagrams (right).
907 **(a)** Plateau age for Sandur's cryptomelane grain; **(b)** plateau age for Shimoga's
908 cryptomelane grain with small characteristic $^{40}\text{Ar}^*$ losses from less retentive and poorly
909 crystalline sites at the first step heating; **(c)** Forced-plateau age for Shimoga's sample
910 grain including four apparent ages forming a reasonably flat segment; **(d)** Concordant
911 pseudoplateaus ages for Sandur's cryptomelane grain included in the 2σ interval.
912 MSWD = mean square weighted deviation of the inverse isochron. See the table 1 for
913 sample description and the data repository DR2 and DR3.

914

915 **Figure 9.** Disturbed $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra of cryptomelane grains from Shimoga Mn
916 ore deposits with K/Ca (black) and Ar^* (grey) step curves (left), and inverse isochron
917 diagrams (right). **(a)** Hump shape spectrum that only allows estimation of maximum
918 and minimum ages of the mixed youngest and oldest phases, respectively. **(b)** Saddle
919 shape spectrum resulting from mixing between several phases (supergene or hypogene)
920 that lead to incorporation of excess $^{40}\text{Ar}^*$. **(c)** Case with an inherited hypogene
921 contaminant. In the first steps, only the supergene phase (~ 18 Ma) releases gas, the
922 inverse isochron diagram clearly showing the contamination with a hypogene phase
923 enriched in $^{40}\text{Ar}^*$. See the table 1 for sample description and the data repository tables
924 DR2 and DR3.

925

926 **Figure 10.** $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra of cryptomelane grains from Sandur Mn ore samples.
927 Sample ID with (F) when analyzed using a double vacuum Staudacher-type furnace
928 coupled with VG3600 mass spectrometer. Age quality is noted (A) for best quality first
929 order age, (B) for acceptable quality second order age, and (C) for lesser quality third
930 order age. See the table 1 for sample description, and the data repository table DR2.

931

932 **Figure 11.** (a) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra and (b) inverse isochron diagrams for
933 cryptomelane grains from Shimoga Mn ore samples. See the figure 10 for the analytical
934 system used, age quality explanation and the table 1 for sample description. See also the
935 data repository tables DR2 and DR3.

936

937 **Figure 12.** (a) $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra and (b) inverse isochron diagrams for
938 cryptomelane grains from Goa Mn ore samples. See the figure 10 for the analytical
939 system used, age quality explanation and the table 1 for sample description. See also the
940 data repository tables DR2 and DR3.

941

942 **Figure 13.** Synthesis of the $^{40}\text{Ar}/^{39}\text{Ar}$ ages results accounting for two-confidence order
943 (A) and (B) (see text and figure 9 for explanations). (a) Age probability curves
944 accounting for 1/3 of the total signal from all the validated ages weighted for the three
945 distinct areas ($N_{\text{Sandur}}=19$, $N_{\text{Shimoga}}=10$ and $N_{\text{Goa}}=10$) enhancing the major weathering
946 peaks that document the major weathering periods W1, W2a, and W2b (vertical colored
947 bands). The ages are also plotted against the altitude. (b) Paleo-latitude variation of
948 the southern boundary of the Deccan Traps across climatic zones defined by
949 evaporation (E) and precipitation (P) after Kent and Muttoni (2008). Note the main

950 weathering periods derived from the $^{40}\text{Ar}/^{39}\text{Ar}$ ages in (a) also correspond to the period
951 when peninsular India drift across the humid equatorial belt where $P > E$. (c) Global
952 benthic $\delta^{18}\text{O}$ curve from Zachos et al. (2008) and associated global deep ocean
953 temperature relative to actual $T^{\circ}\text{C}$. PETM = Paleocene-Eocene Thermal Maximum;
954 EECO = Early Eocene Climatic Optimum; MECM = Mid-Eocene Climatic Maximum;
955 EOC = Early Oligocene Cooling; LOW = Late Oligocene Warming; MMCM = Mid-
956 Miocene Climatic Maximum.

957

958 **Table 1.** Field characteristics of samples from Sandur, Shimoga and Goa Mn ore
959 deposits (Peninsular India) and description of cryptomelane grains extracted from these
960 samples. Other mineral species were also identified by reflected-light microscopy, XRD
961 and SEM.

962

963 **Table 2.** Synthesis of the $^{40}\text{Ar}/^{39}\text{Ar}$ ages presenting the plateau ages, the inverse
964 isochrons ages with their properties, and the integrated ages. The results in bold are
965 considered as the preferred ages. See the figure 10 for more information about the
966 analytical system used.

Figure 1
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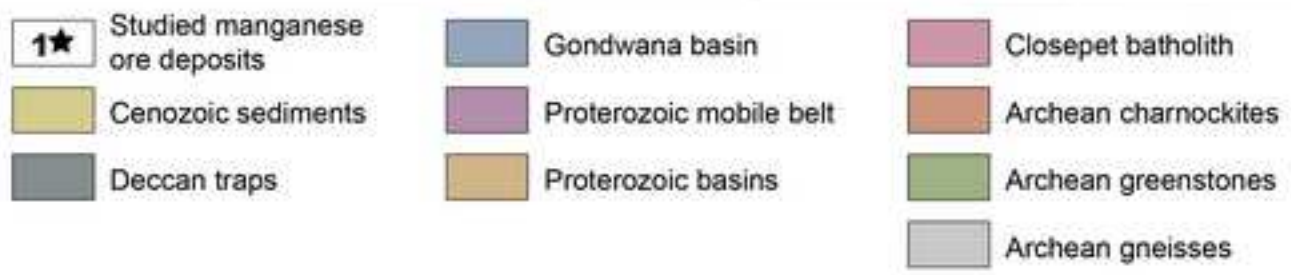
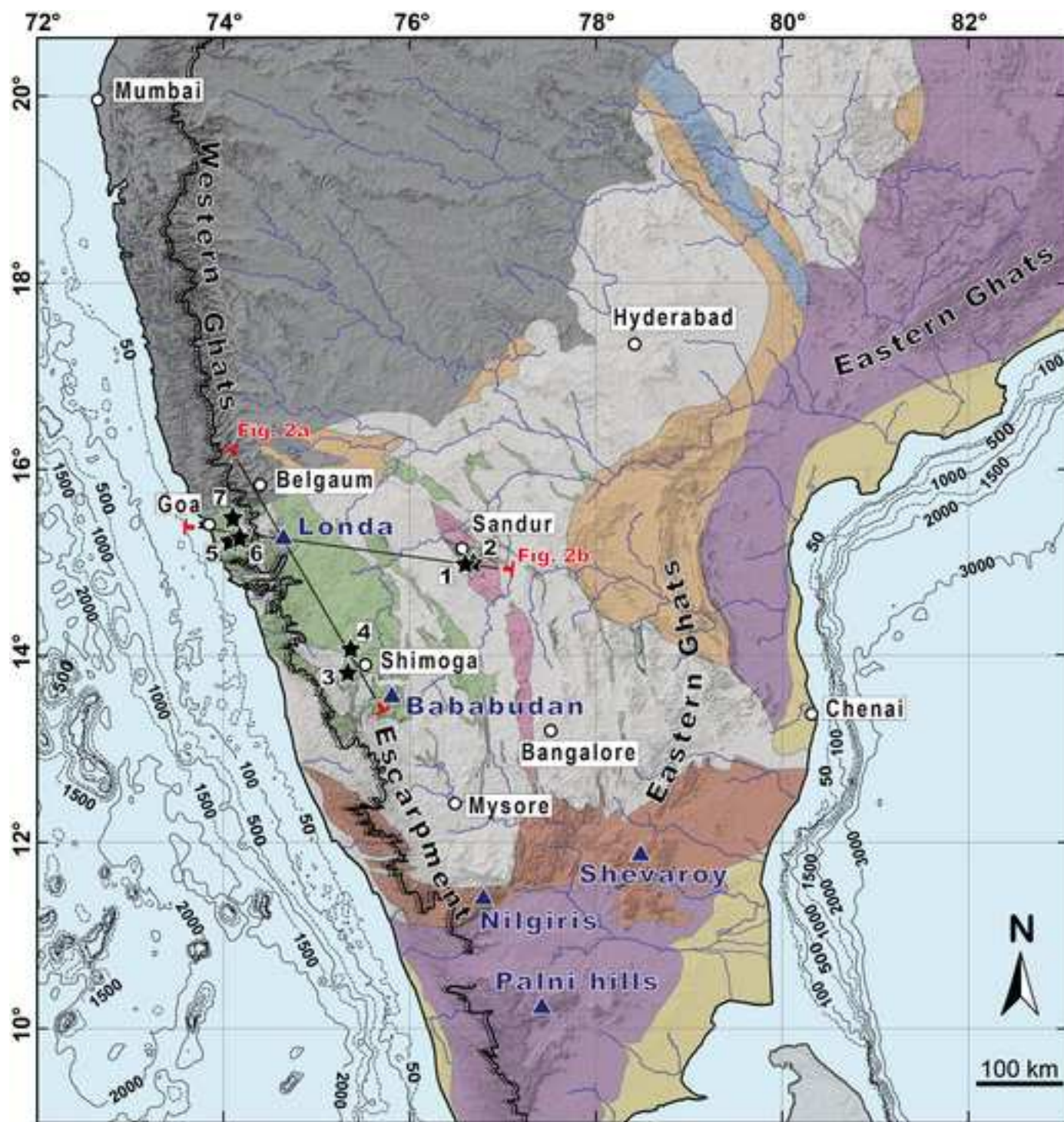


FIG. 1 (2 columns)

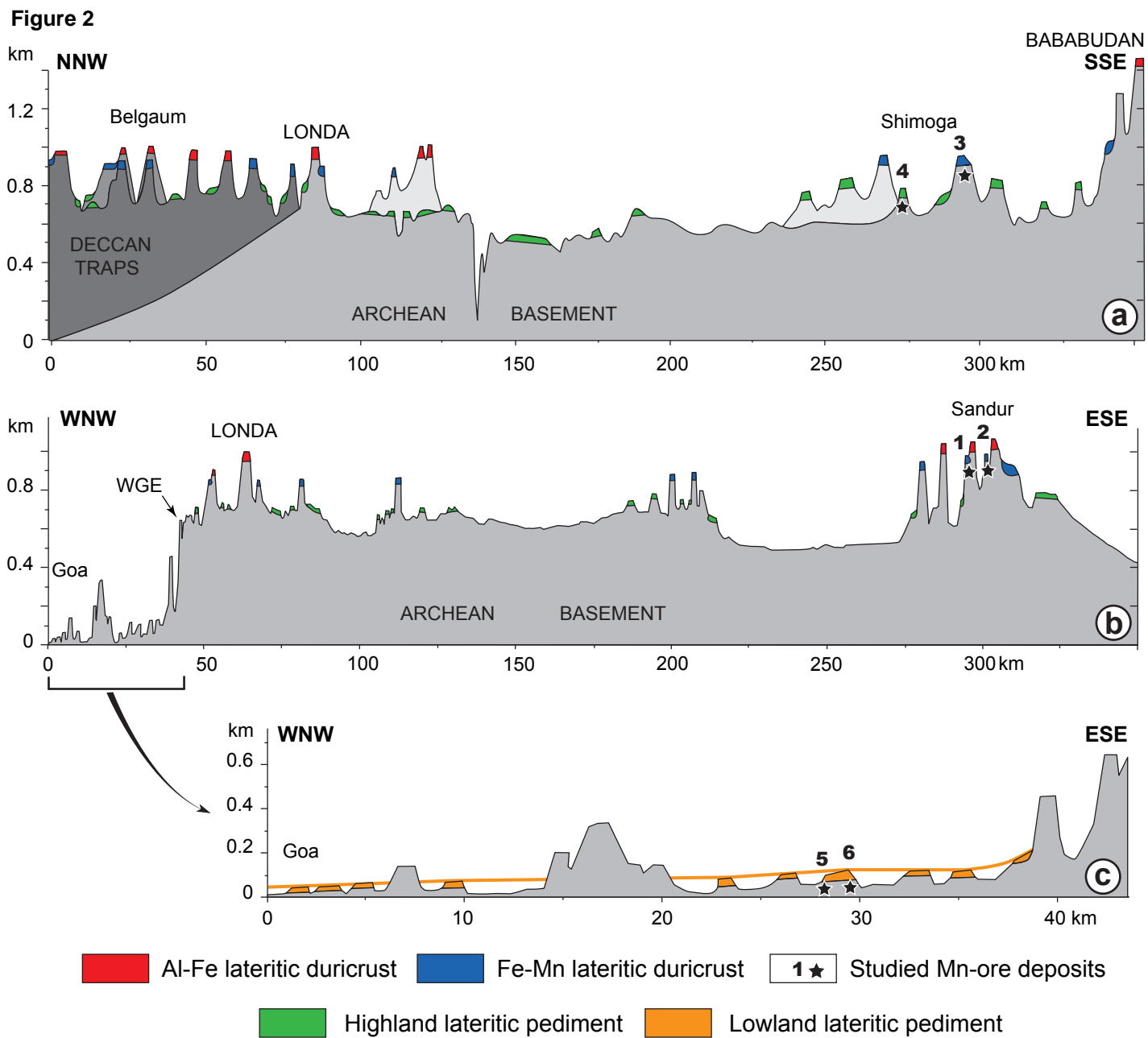


FIG.2 (2 columns)

Figure 3
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FIG. 3 (2 columns)

Figure 4

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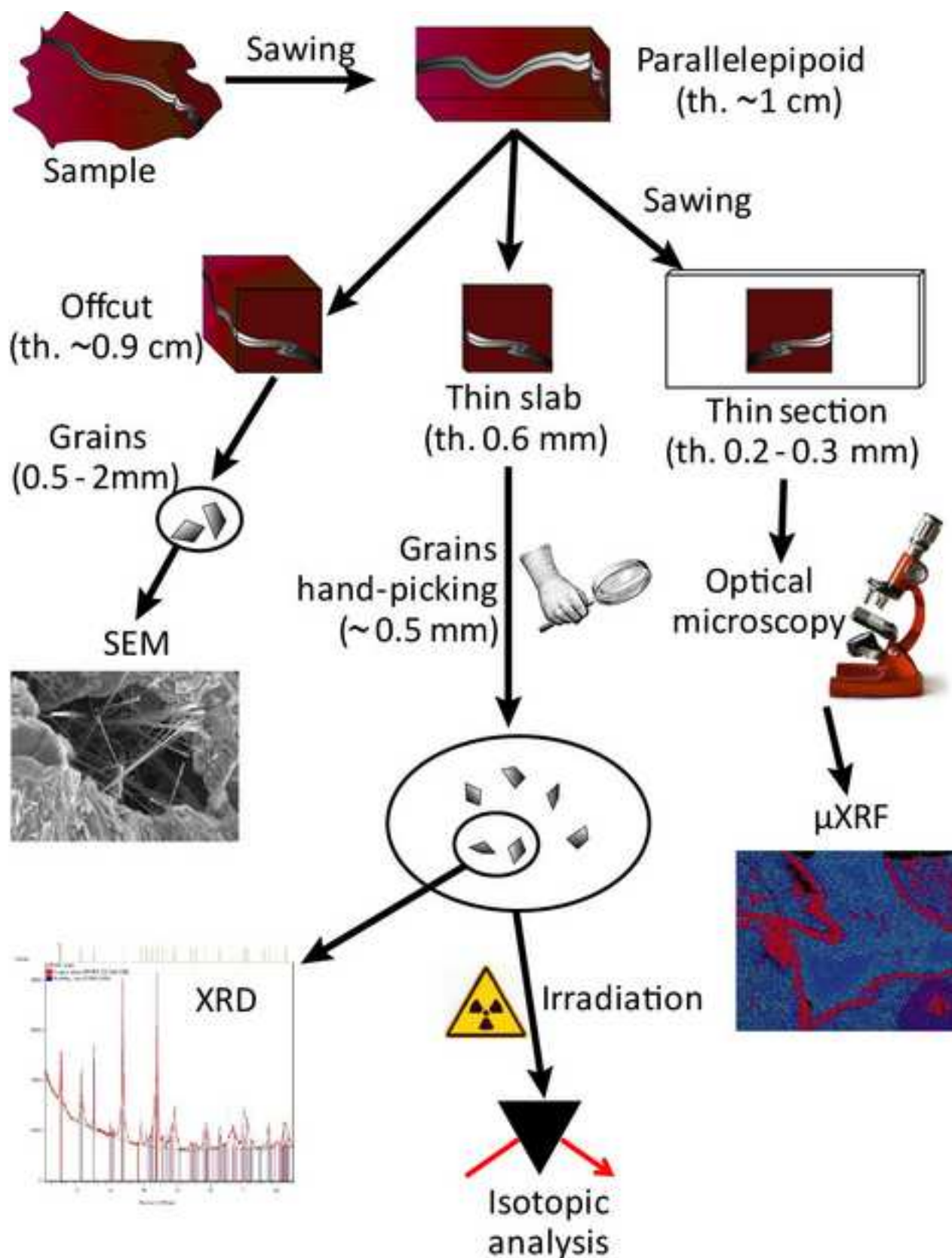


FIG. 4 (1 column)

Figure 5
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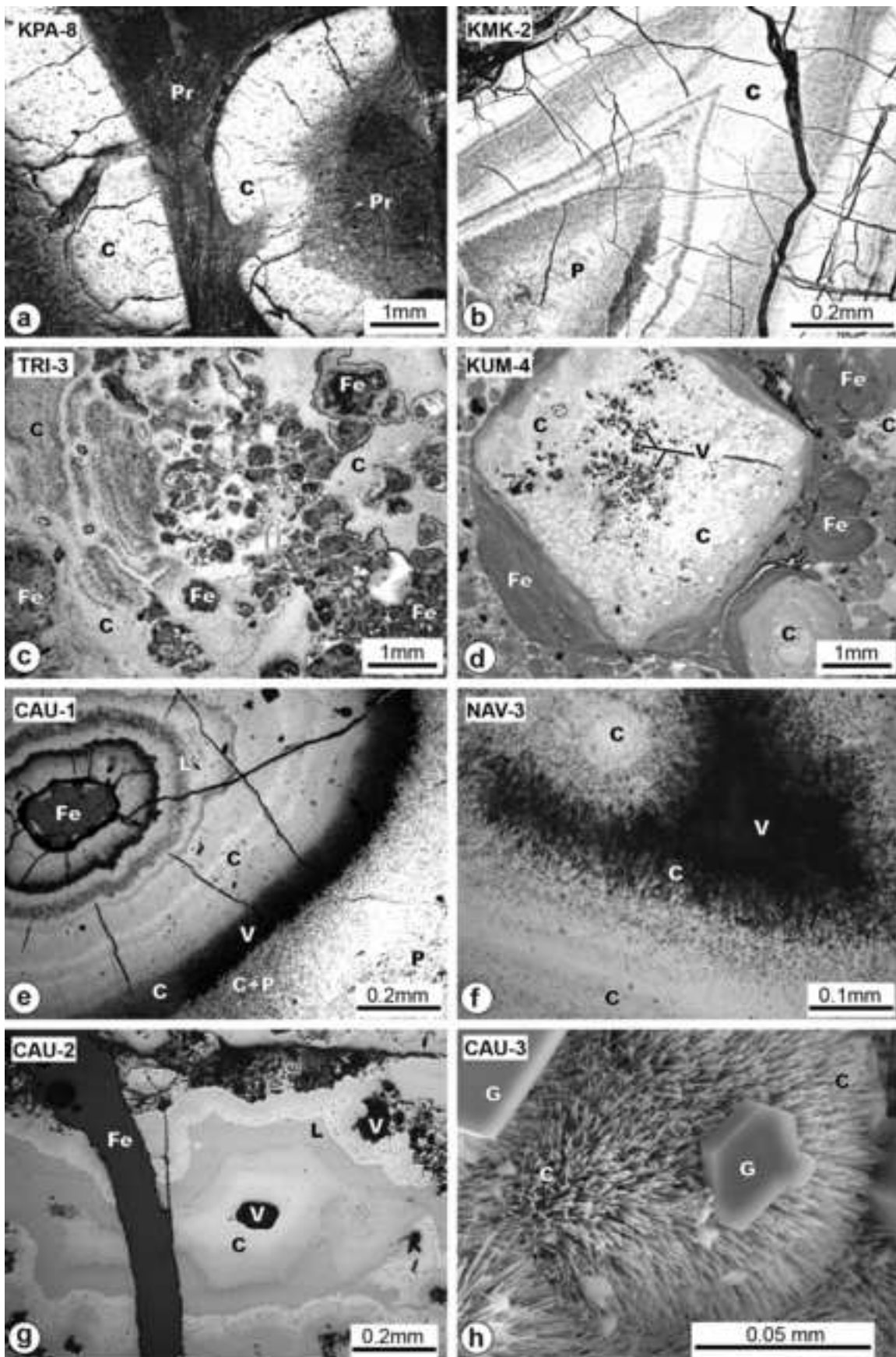


FIG. 5 (1.5 columns)

Figure 6
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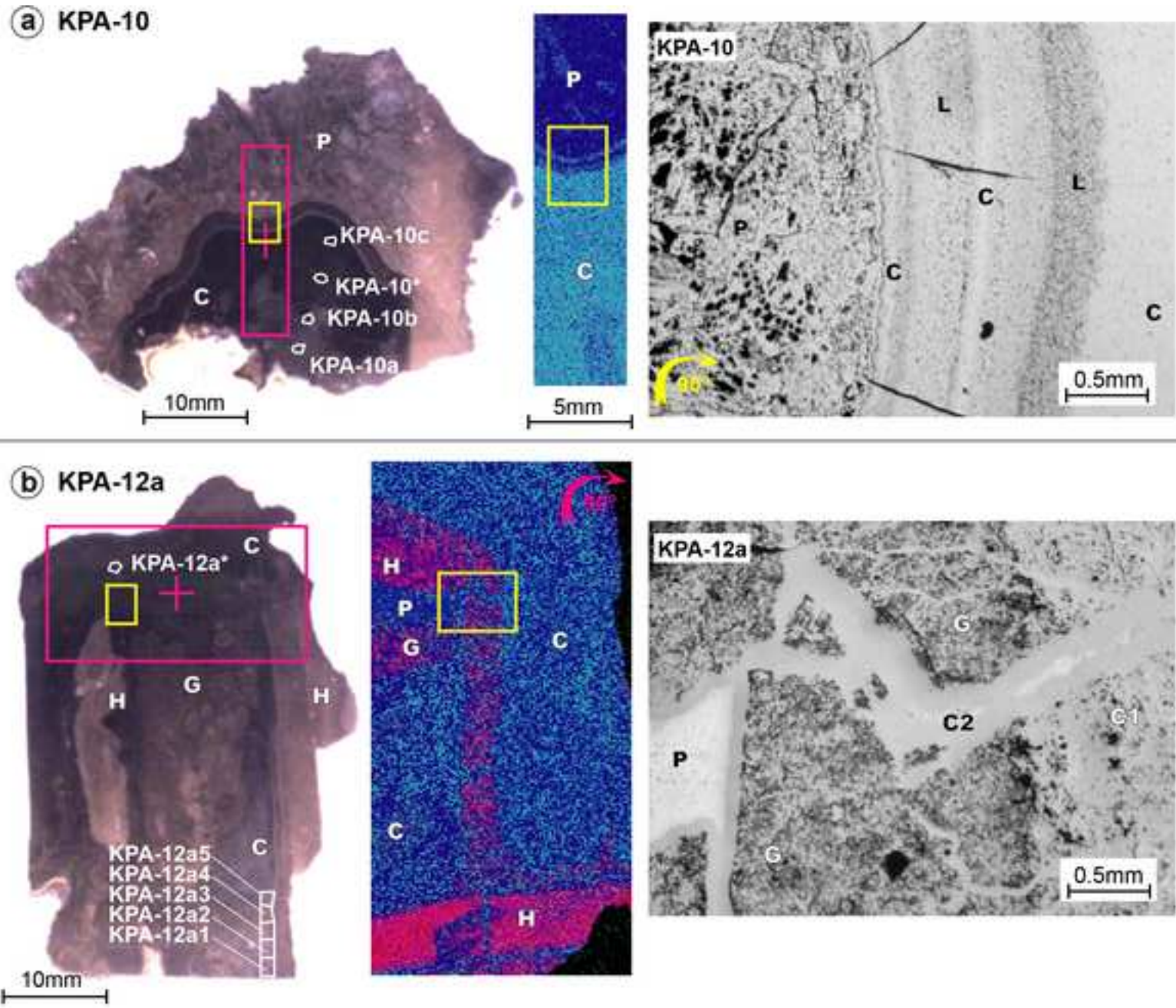


FIG. 6 (2 columns)

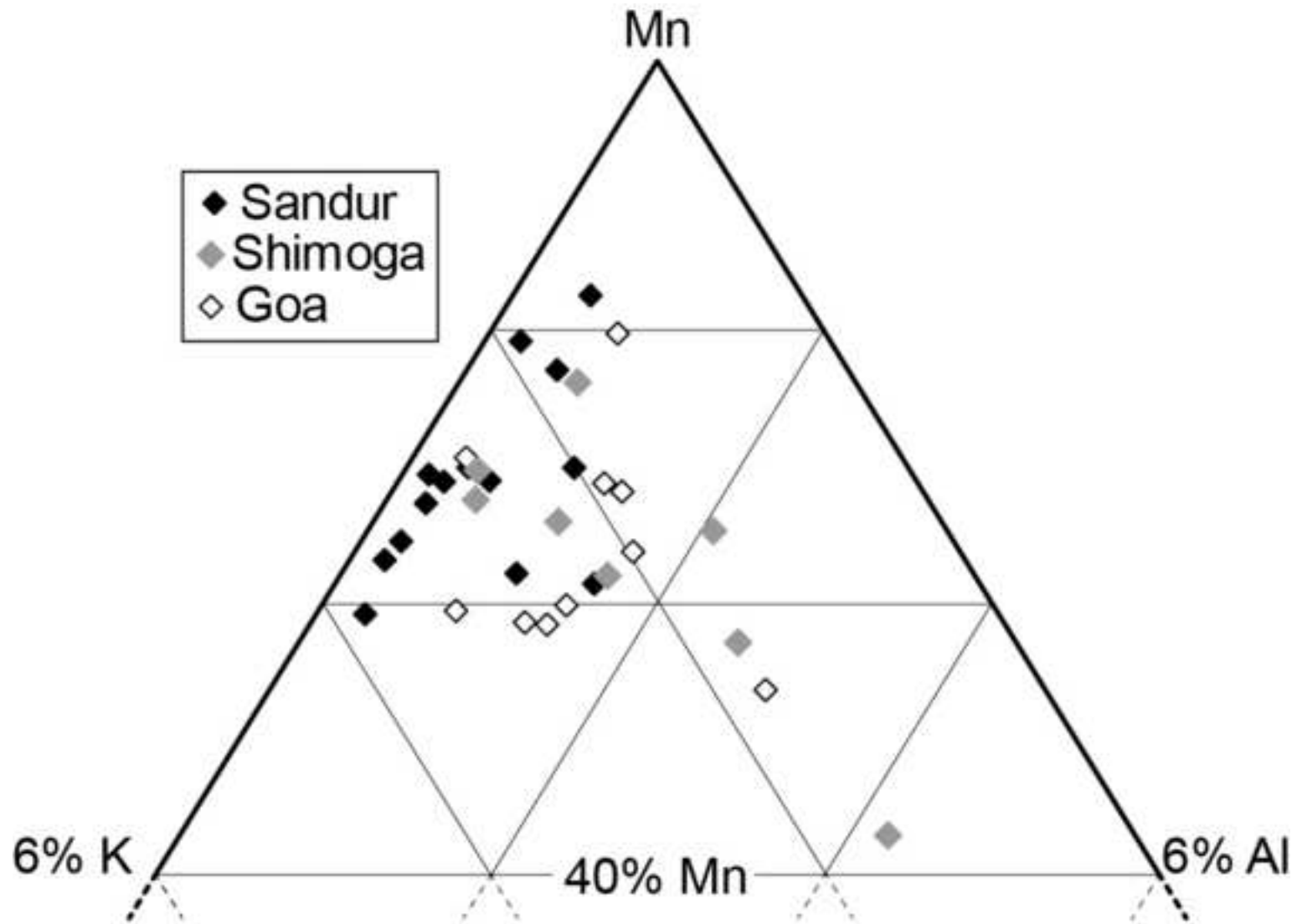


FIG. 7 (1 column)

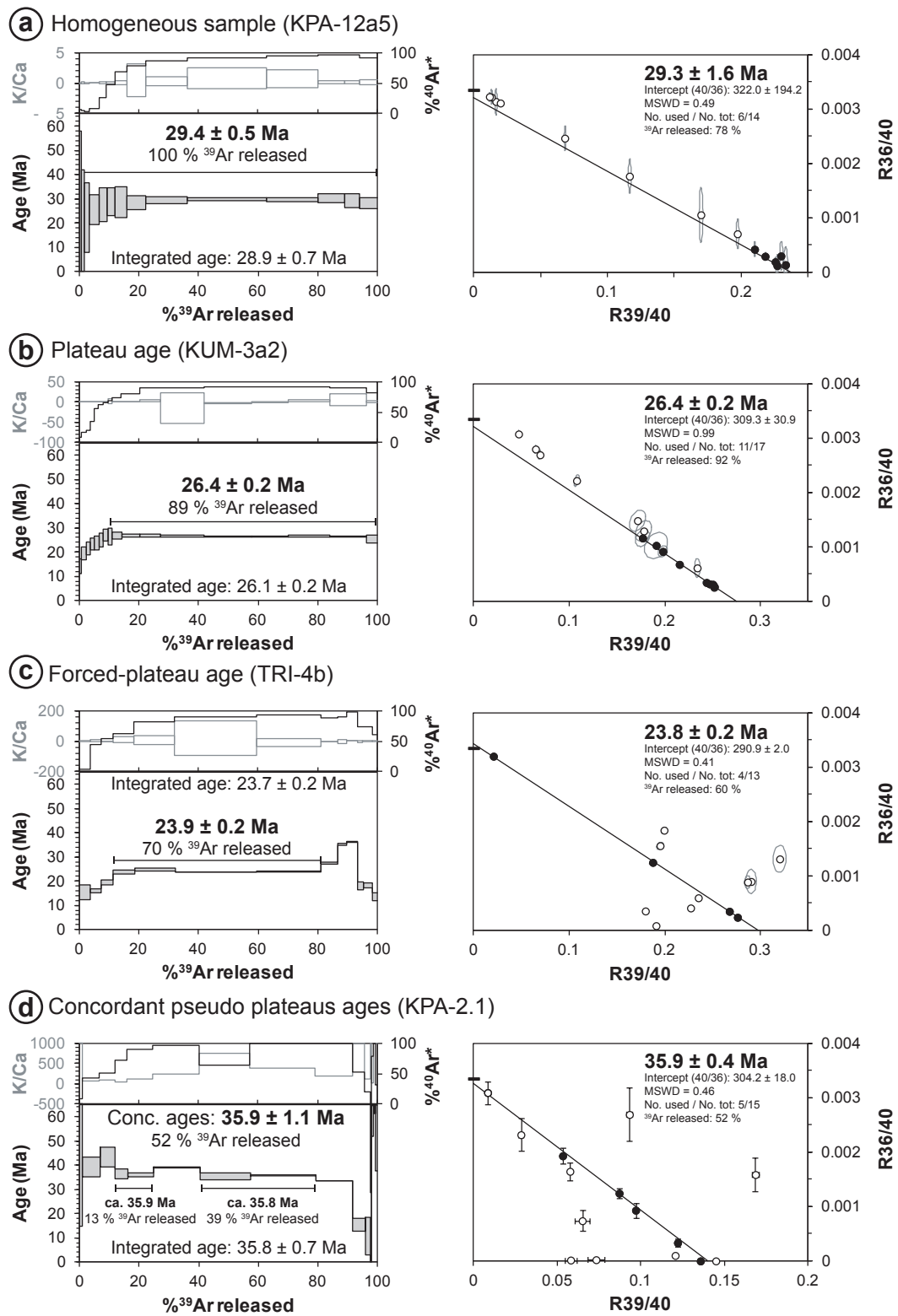


FIG. 8 (1.5 columns)

Figure 9

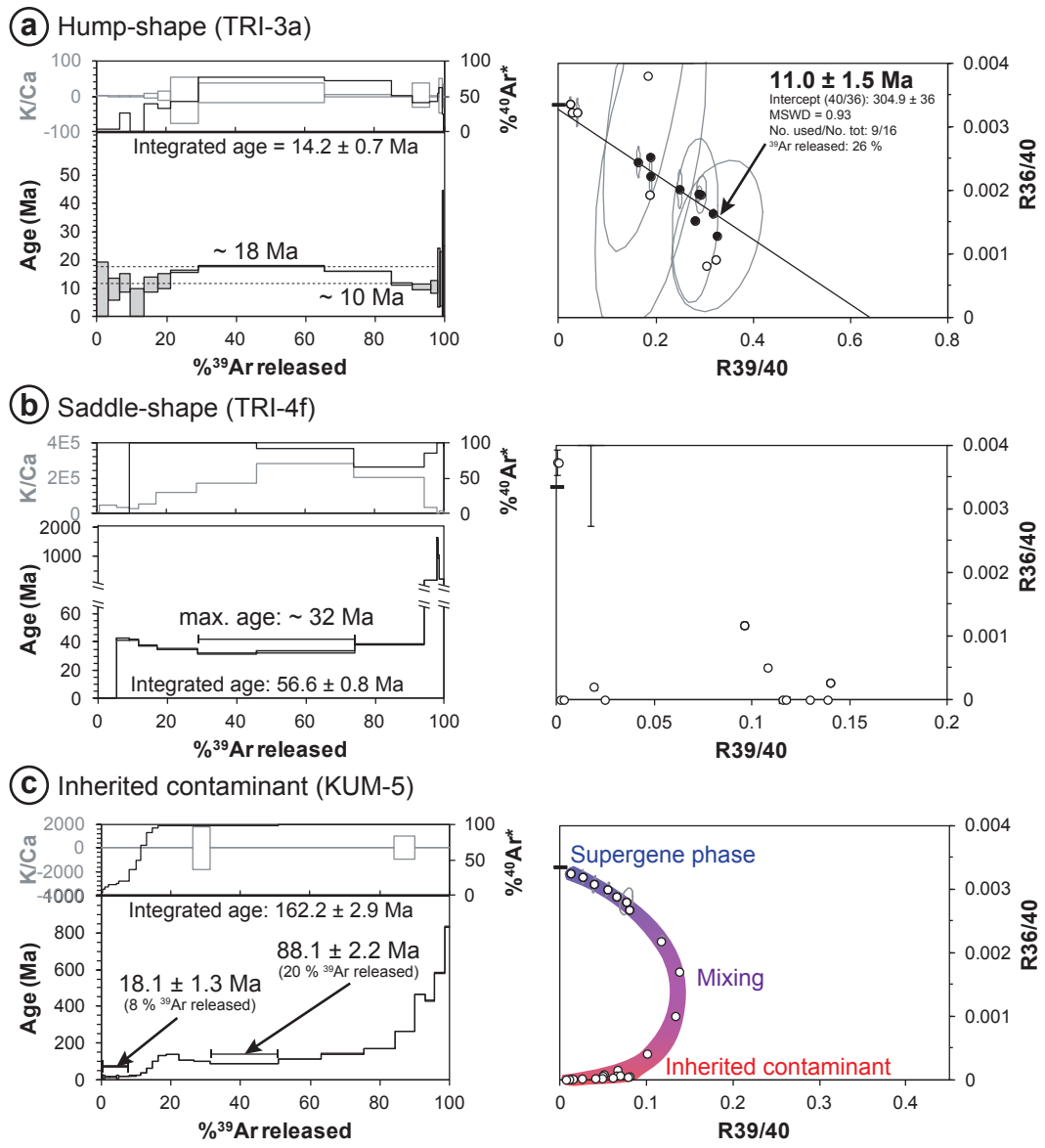


FIG. 9 (1.5 columns)

Figure 10

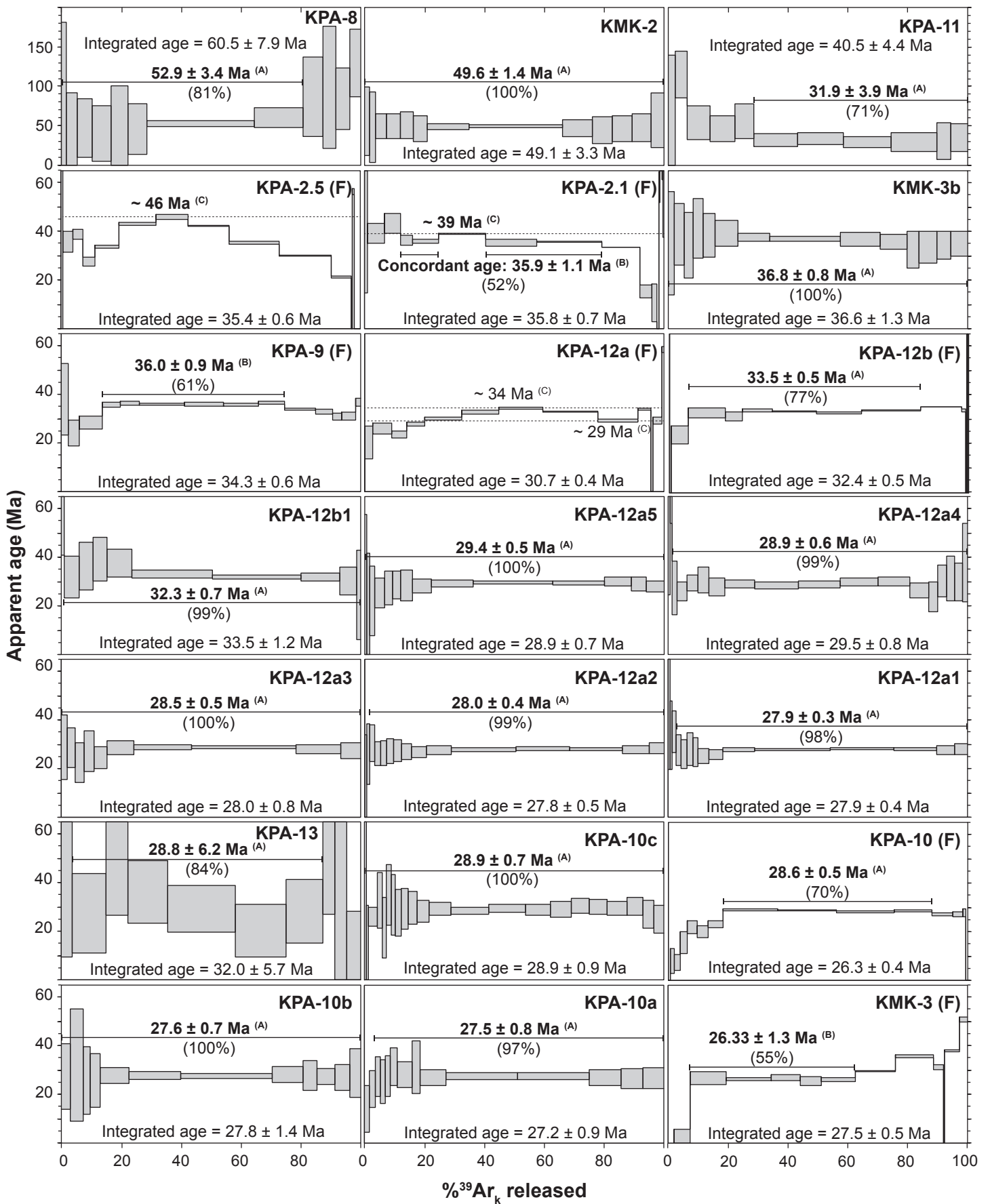


FIG. 10 (2 columns)

Figure 11

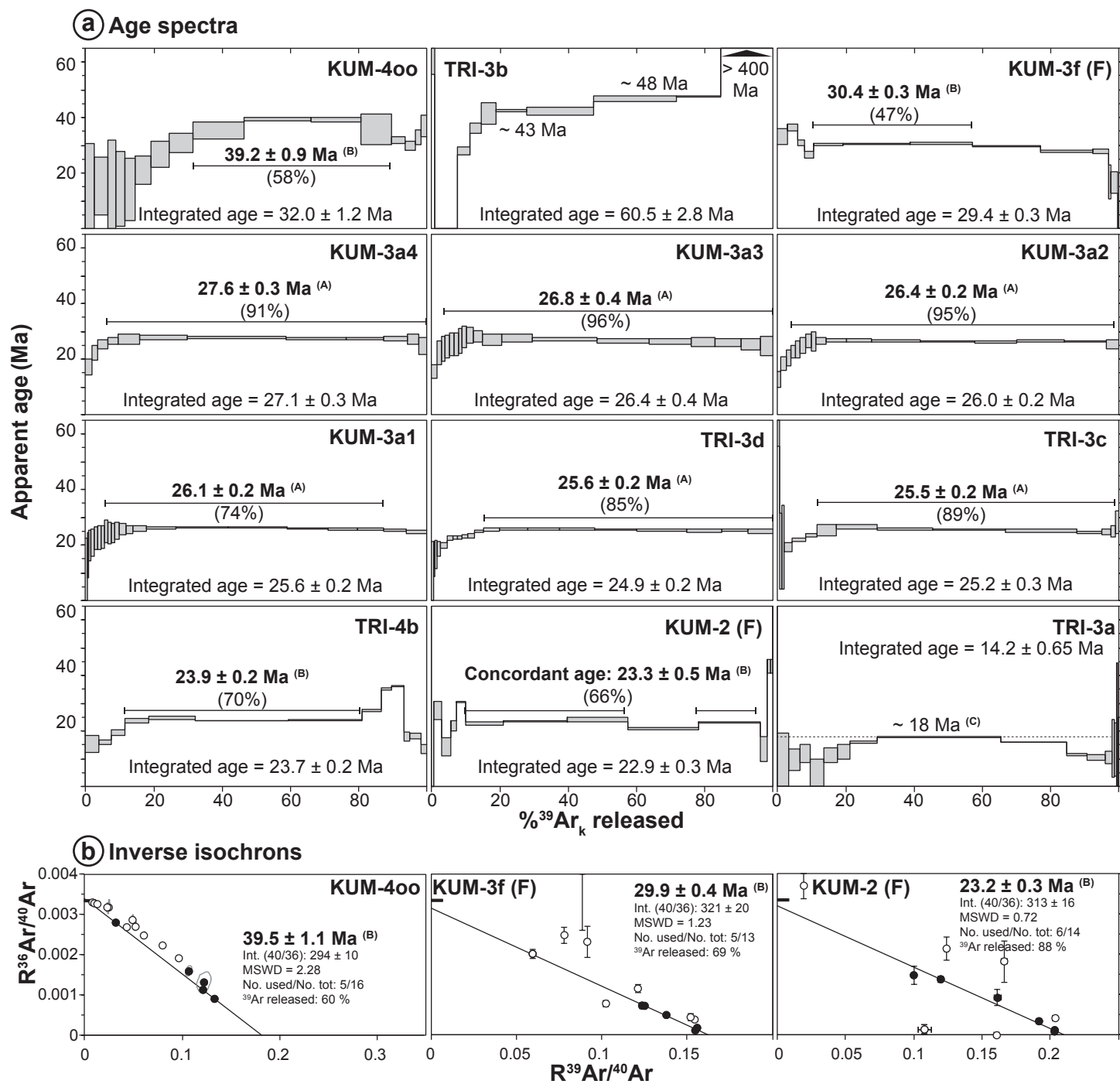


FIG. 11 (2 columns)

Figure 12

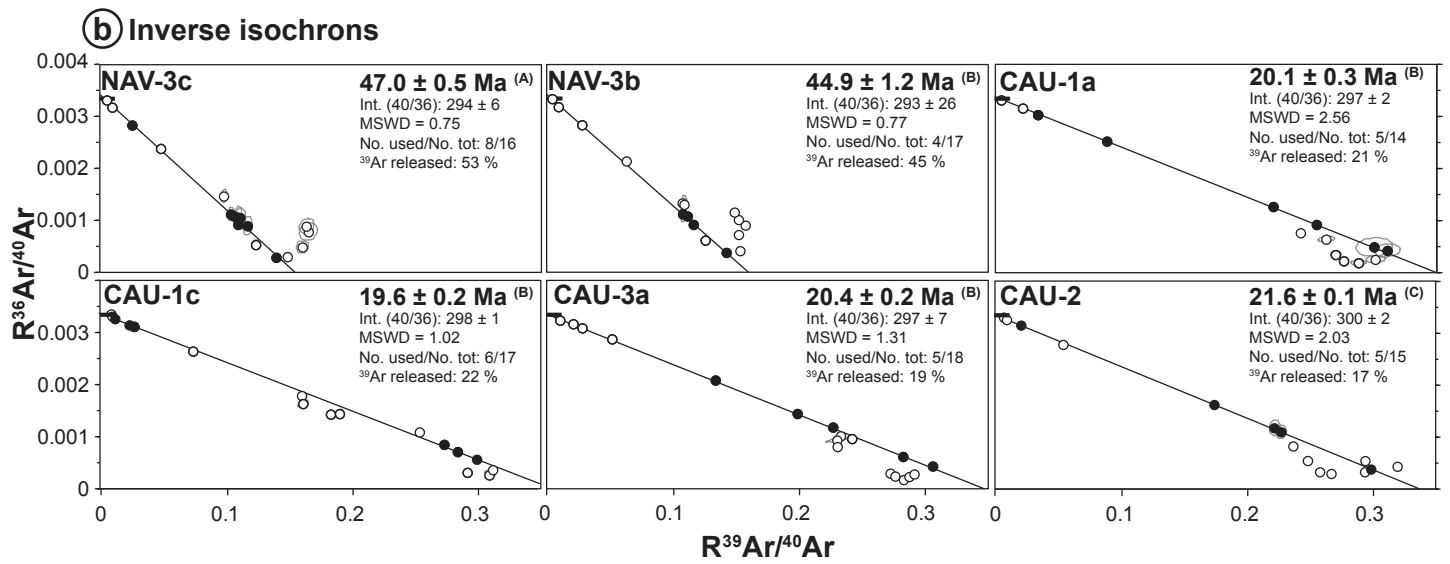
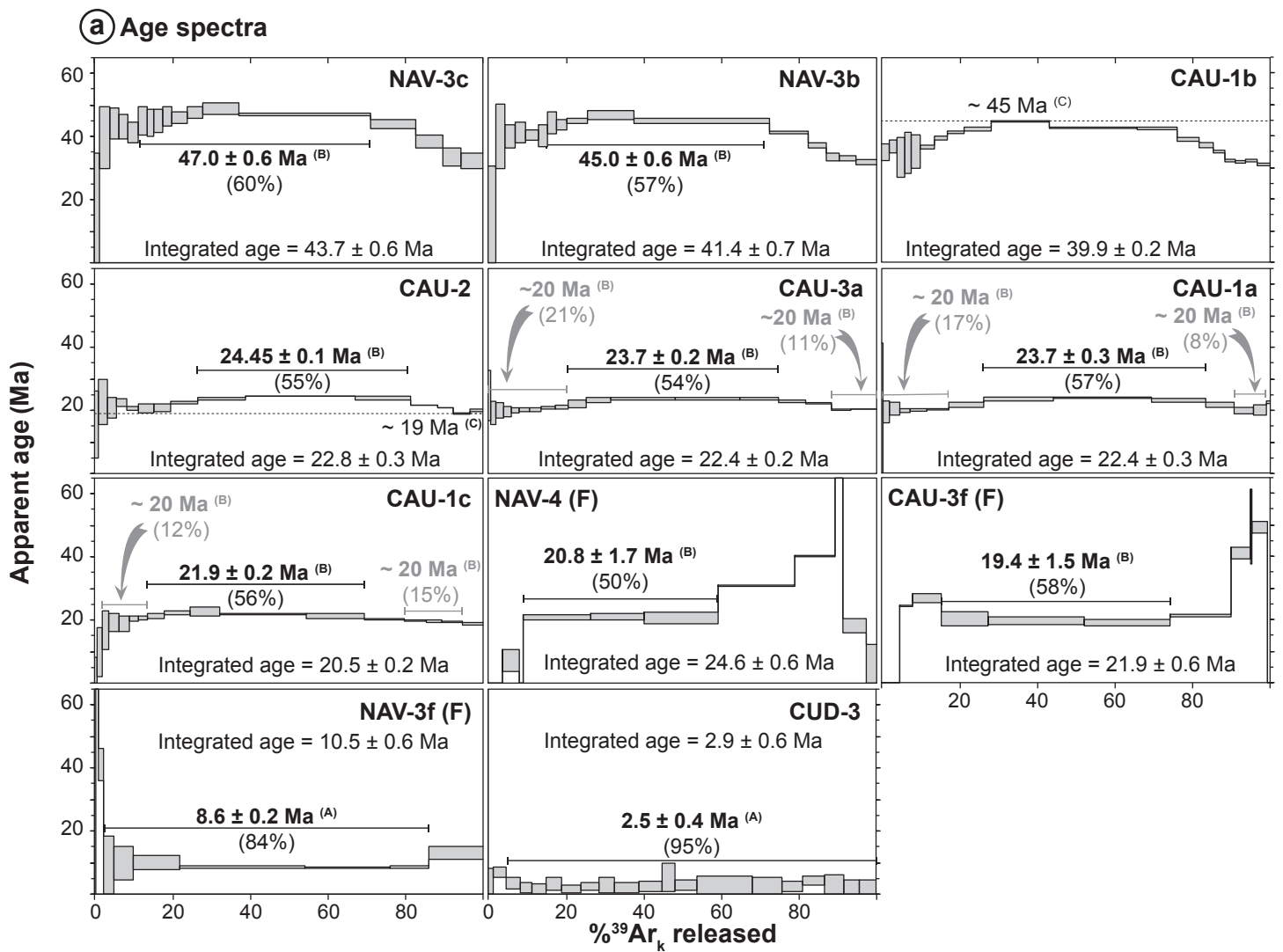


FIG. 12 (2 columns)

Figure 13

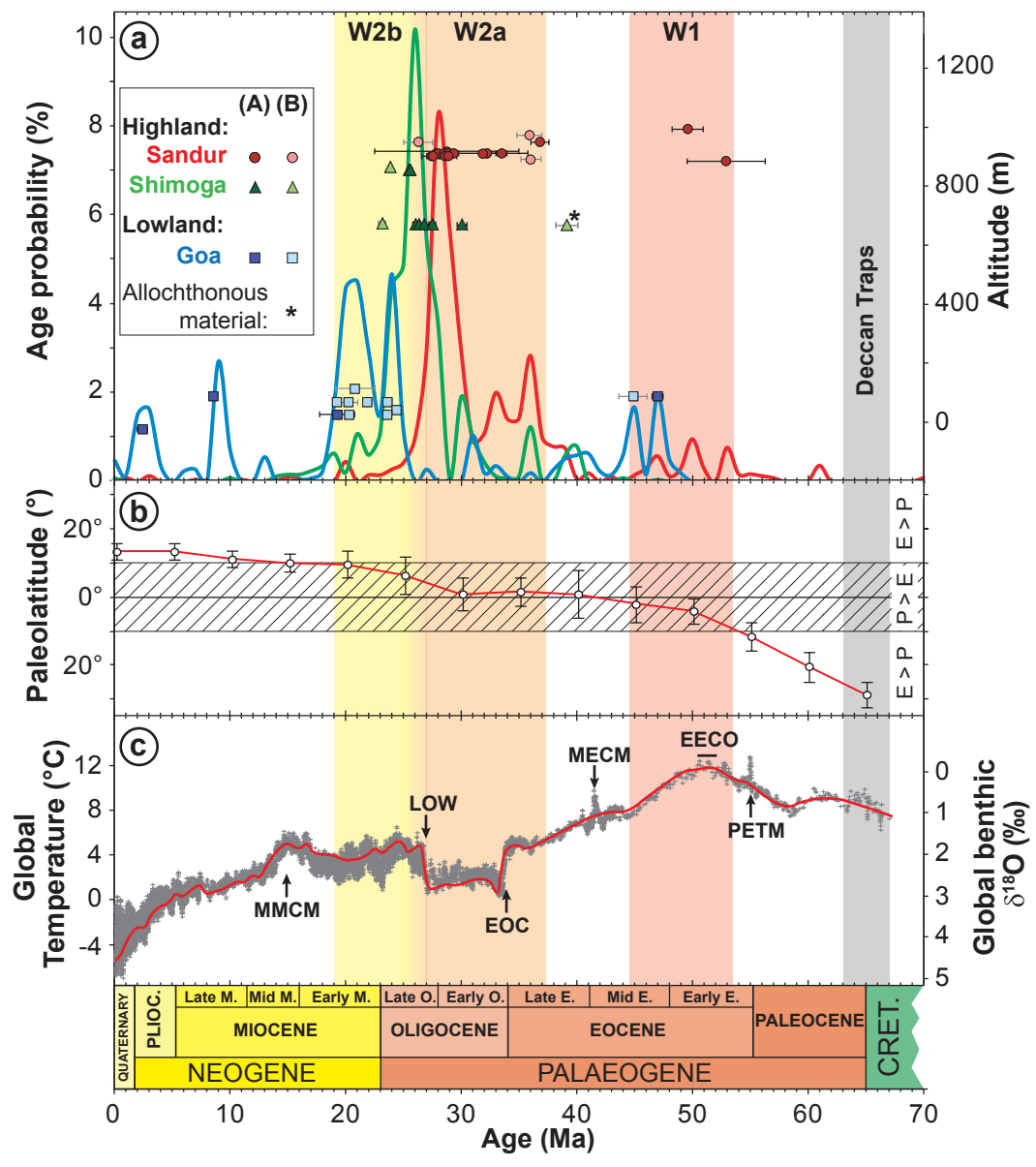


FIG. 13 (1.5 columns)

Table 1
[Click here to download Table: R2_Table. 1.xlsx](#)

| Location and mine | Sample ID | Depth ± 2m | Latitude N | Longitude E | Ore type | Mineral species observed | Grains ID | Cryptomelane crystallization type |
|---------------------|-----------|------------|-------------|-------------|--|---|---|--|
| Sandur | | | | | | | | |
| Kappataswamy | | | | | | | | |
| | KPA-2 | -140 | 14° 59' 59" | 76° 32' 42" | Massive Mn-ore with cavities ≤ 1cm | Cryptomelane, Goethite, Nsutite, Pyrolusite | KPA-2.1 KPA-2.5 | Internal band from colloidal overgrowth microstructure External band from colloidal overgrowth microstructure |
| | KPA-8 | -125 | 15° 0' 2" | 76° 32' 42" | Platy Mn-ore developed from siliceous protore | Cryptomelane, Pyrolusite, Lithiophorite | KPA-8 | Botryoidal |
| | KPA-9 | -123 | 15° 0' 1" | 76° 32' 38" | Platy Mn-ore developed from siliceous protore | Cryptomelane, Quartz, Pyrolusite, | KPA-9 | Massive cryptocrystalline domain |
| | KPA-10 | -111 | 15° 0' 1" | 76° 32' 38" | Massive Mn-ore with cavities > 1cm | Cryptomelane, Pyrolusite, Goethite, Hematite | KPA-10a KPA-10b KPA-10 KPA-10c | Internal band from geodic overgrowth microstructure 1st intermediate band from geodic overgrowth microstructure 2nd intermediate band from geodic overgrowth microstructure External band from geodic overgrowth microstructure |
| | KPA-11 | -103 | 15° 0' 1" | 76° 32' 38" | Platy Mn-ore developed from siliceous protore | Cryptomelane, Pyrolusite, Goethite, | KPA-11 | Cryptocrystalline plasma filling a microfracture |
| | KPA-12a | -102 | 15° 0' 1" | 76° 32' 38" | Platy Mn-ore with pods | Cryptomelane, Goethite, Hematite | KPA-12a KPA-12a1 KPA-12a2 KPA-12a3 KPA-12a4 KPA-12a5 | Cryptocrystalline domain filling a microfracture Massive cryptocrystalline domain Massive cryptocrystalline domain Massive cryptocrystalline domain Massive cryptocrystalline domain Massive cryptocrystalline domain |
| | KPA-12b | -102 | 15° 0' 1" | 76° 32' 38" | Platy Mn-ore with pods | Cryptomelane, Pyrolusite | KPA-12b | Massive cryptocrystalline domain |
| | KPA-13 | -96 | 15° 0' 1" | 76° 32' 37" | Platy Mn-ore developed from siliceous protore | Cryptomelane, Birnessite, Hematite | KPA-12b2 KPA-13 | Massive cryptocrystalline domain Veins of cryptocrystalline plasma |
| Channanghi KMK-East | | | | | | | | |
| | KMK-2 | -37 | 14° 59' 48" | 76° 34' 37" | Massive Mn-ore with cavities > 1cm | Cryptomelane, Pyrolusite, Lithiophorite | KMK-2 | Colloidal overgrowth microstructure |
| | KMK-3 | -60 | 14° 59' 46" | 76° 34' 38" | Massive Mn-ore with cavities > 1cm | Cryptomelane, Nsutite, Lithiophorite | KMK-3 KMK-3b | External band from colloidal overgrowth microstructure Internal band from colloidal overgrowth microstructure |
| Shimoga | | | | | | | | |
| Triveni | | | | | | | | |
| | TRI-3 | -18 | 13° 53' 50" | 75° 24' 46" | Massive developed from Banded Hematite Quartzite | Cryptomelane, Goethite, Birnessite | TRI-3a TRI-3b TRI-3c TRI-3d | Massive cryptocrystalline domain Massive cryptocrystalline domain Massive cryptocrystalline domain Massive cryptocrystalline domain |
| | TRI-4 | -8 | 13° 53' 46" | 75° 24' 43" | Massive developed from Banded Hematite Quartzite | Cryptomelane, Pyrolusite, Lithiophorite | TRI-4b TRI-4f | Massive cryptocrystalline domain Massive cryptocrystalline domain |
| Kumsi | | | | | | | | |
| | KUM-2 | -15 | 14° 6' 11" | 75° 24' 15" | Massive developed from Banded Hematite Quartzite | Cryptomelane, Goethite, hematite | KUM-2 | Massive cryptocrystalline domain |
| | KUM-3 | -18 | 14° 6' 11" | 75° 24' 14" | Massive developed from Banded Hematite Quartzite | Cryptomelane, Pyrolusite, Hematite | KUM-3a1 KUM-3a2 KUM-3a3 KUM-3a4 KUM-3f | Massive cryptocrystalline domain Massive cryptocrystalline domain Massive cryptocrystalline domain Massive cryptocrystalline domain Massive cryptocrystalline domain |
| | KUM-4 | -20 | 14° 6' 10" | 75° 24' 15" | Brecchia with manganiferous clasts and ferruginous oolites | Cryptomelane, Hollandite, Hematite | KUM-4o | Clast initially from massive cryptocrystalline domain |
| | KUM-5 | -21 | 14° 6' 11" | 75° 23' 55" | Massive developed from Banded Hematite Quartzite | Cryptomelane, Lithiophorite, Goethite, Kaolinite | KUM-5 | Veins of cryptocrystalline plasma |
| Goa | | | | | | | | |
| Caurem | | | | | | | | |
| | CAU-1 | -32 | 15° 7' 2" | 74° 8' 40" | Clastic with ferruginous and manganiferous clasts | Cryptomelane, Pyrolusite, Goethite, Lithiophorite, Hematite | CAU-1a CAU-1b CAU-1c | Colloidal overgrowth microstructure Colloidal overgrowth microstructure Colloidal overgrowth microstructure |
| | CAU-2 | -39 | 15° 7' 3" | 74° 8' 40" | Fe-oxides with Mn-rich veins filled by percolation | Cryptomelane, Hematite, Lithiophorite, Kaolinite | CAU-2 | Porous domains with visible needles |
| | CAU-3 | -55 | 15° 7' 3" | 74° 8' 39" | Clastic with ferruginous and manganiferous clasts | Cryptomelane, Hollandite, Goethite, Gibbsite | CAU-3a CAU-3f | Internal band from colloidal overgrowth microstructure External band from colloidal overgrowth microstructure |
| Naveli | | | | | | | | |
| | NAV-3 | -56 | 15° 7' 55" | 74° 9' 50" | Manganiferous lens included in saprolite | Cryptomelane, Nsutite | NAV-3b NAV-3c NAV-3f | Massive cryptocrystalline domain Massive cryptocrystalline domain Cryptocrystalline plasma filling a microfracture |
| | NAV-4 | -27 | 15° 8' 7" | 74° 9' 32" | Accumulation of manganese in plurimetric lenses | Cryptomelane, Goethite | NAV4 | Massive cryptocrystalline domain |
| Cudnem | | | | | | | | |
| | CUD-3 | -74 | 15° 32' 35" | 74° 2' 3" | Brecchia with manganiferous clasts and ferruginous oolites | Cryptomelane, Hollandite, Hematite | CUD-3 | Massive cryptocrystalline domain |

| Sample | | | ³⁹ Ar release spectrum | | | | Inverse isochron | | | | Integrated | Preferred age | | | | |
|----------------|--------------------------|----------|-----------------------------------|------------|--------------------|-------|------------------|------------------------|------|-----------------------------|--------------------|---------------|------------|------------|-------|---|
| Location | ID | Alt. (m) | Age, Ma | Step(s) | % ³⁹ Ar | Order | Age, Ma | 40Ar/36Ar _i | MSWD | Steps | % ³⁹ Ar | Order | Age, Ma | Ma | Order | Comments |
| SANDUR | | | | | | | | | | | | | | | | |
| 2 | KMK-2 ^a | 996 | 49.6 ± 1.4 | 1-13 | 100 | A | 49.8 ± 2.8 | 285 ± 201 | 0.11 | 4-10 | 69 | B | 49.1 ± 3.3 | 49.6 ± 1.3 | A | Plateau > 70% ³⁹ Ar _K |
| 2 | KMK-3b | 952 | 36.8 ± 0.8 | 1-15 | 100 | A | 36.8 ± 1.2 | 425 ± 643 | 0.62 | 3, 6-11 | 72 | B | 36.6 ± 1.3 | 36.8 ± 0.8 | A | Plateau > 70% ³⁹ Ar _K |
| 2 | KMK-3 (F) ¹ | 952 | 26.3 ± 1.3 | 3-7 | 55 | B | 25.9 ± 0.8 | 305 ± 29 | 0.17 | 3-7 | 55 | B | 27.5 ± 0.5 | 26.3 ± 1.3 | B | Plateau > 50% ³⁹ Ar _K |
| 1 | KPA-13 | 919 | 28.8 ± 6.2 | 2-7 | 84 | A | 27.6 ± 6.7 | 314 ± 293 | 1.19 | 2, 4-7 | 77 | B | 32.0 ± 5.7 | 28.8 ± 6.2 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-12b (F) ¹ | 913 | 33.5 ± 0.5 | 3-8 | 77 | A | 33.6 ± 0.4 | 292 ± 4 | 0.94 | 3-8, 10 | 78 | C | 32.4 ± 0.5 | 33.5 ± 0.5 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-12b1 | 913 | 32.3 ± 0.7 | 2-11 | 99 | A | 32.1 ± 0.8 | 343 ± 64 | 1.12 | 3-10 | 94 | A | 33.5 ± 1.2 | 32.3 ± 0.7 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-12a (F) ¹ | 913 | 34.3 ± 0.3 | 8 | 14 | C | 28.7 ± 0.6 | 336 ± 24 | 0.86 | 5-7, 10, 13 | 47 | C | 30.7 ± 0.4 | 34.3 ± 0.3 | C | Min. of oldest |
| | | | 28.6 ± 0.9 | 5 | 6 | C | | | | | | | | 28.6 ± 0.9 | C | Max. of youngest |
| 1 | KPA-12a1 | 913 | 27.9 ± 0.3 | 4-15 | 98 | A | 27.9 ± 0.3 | 297 ± 14 | 1.05 | 4-15 | 98 | A | 27.9 ± 0.4 | 27.9 ± 0.3 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-12a2 | 913 | 28.0 ± 0.4 | 3-15 | 99 | A | 28.1 ± 0.4 | 299 ± 8 | 0.70 | 3-6, 9, 11-13 | 70 | A | 27.8 ± 0.5 | 28.0 ± 0.4 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-12a3 | 913 | 28.5 ± 0.5 | 1-10 | 100 | A | 28.6 ± 0.5 | 292 ± 17 | 0.99 | 2-9 | 92 | A | 28.0 ± 0.8 | 28.5 ± 0.5 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-12a4 | 913 | 28.9 ± 0.6 | 3-18 | 99 | A | 28.9 ± 0.7 | 312 ± 57 | 1.02 | 5-18 | 94 | A | 29.5 ± 0.8 | 28.9 ± 0.6 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-12a5 | 913 | 29.4 ± 0.5 | 1-14 | 100 | A | 29.3 ± 1.6 | 322 ± 194 | 0.49 | 9-14 | 78 | A | 28.9 ± 0.7 | 29.4 ± 0.5 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-11v | 912 | 31.9 ± 3.9 | 6-11 | 71 | A | 31.3 ± 5.3 | 380 ± 94 | 0.33 | 3, 5-9 | 75 | B | 40.5 ± 4.4 | 31.9 ± 3.9 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-10a | 904 | 27.5 ± 0.8 | 3-14 | 97 | A | 27.6 ± 1.1 | 296 ± 855 | 0.43 | 4, 6-8, 10-11, 13 | 67 | B | 27.2 ± 0.9 | 27.5 ± 0.8 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-10b | 904 | 27.6 ± 0.7 | 1-12 | 100 | A | 27.6 ± 0.8 | 299 ± 370 | 0.06 | 5-12 | 87 | B | 27.8 ± 1.4 | 27.6 ± 0.7 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-10 (F) ¹ | 904 | 28.6 ± 0.5 | 8-12 | 70 | A | 28.8 ± 0.6 | 301 ± 38 | 0.83 | 8-9, 11, 13-14 | 54 | A | 26.3 ± 0.4 | 28.6 ± 0.5 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-10c | 904 | 28.9 ± 0.7 | 1-22 | 100 | A | 28.9 ± 1.1 | 294 ± 262 | 0.96 | 5, 10, 13-14, 17, 19, 21-22 | 49 | A | 28.9 ± 0.9 | 28.9 ± 0.7 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-9 (F) ¹ | 892 | 36.0 ± 0.9 | 4-9 | 61 | B | 36.2 ± 0.5 | 293 ± 23 | 0.37 | 4, 6, 8-9, 14 | 43 | B | 34.3 ± 0.6 | 36.0 ± 0.9 | B | Plateau > 50% ³⁹ Ar _K |
| 1 | KPA-8 ^a | 887 | 52.9 ± 3.4 | 1-8 | 81 | A | 52.1 ± 4.9 | 339 ± 133 | 0.89 | 4-9 | 77 | A | 60.5 ± 7.9 | 52.9 ± 3.4 | A | Plateau > 70% ³⁹ Ar _K |
| 1 | KPA-2.5 (F) ¹ | 875 | 46.0 ± 1.1 | 7 | 11 | C | 35.1 ± 0.7 | 299 ± 12 | 2.29 | 1-3, 5, 9 | 32 | NGS | 35.4 ± 0.6 | 46.0 ± 1.1 | C | Min. of oldest |
| | | | 21.2 ± 0.4 | 11 | 6 | NGS | | | | | | | | | | |
| 1 | KPA-2.1 (F) ¹ | 875 | 35.9 ± 1.1 | 4-5, 7-8 | 52 | B | 35.9 ± 0.4 | 304 ± 18 | 0.46 | 4-5, 7-8, 14 | 52 | B | 35.8 ± 0.7 | 35.9 ± 1.1 | B | Best fitted inverse isochrone |
| | | | 39.1 ± 0.3 | 6 | 16 | C | | | | | | | | | | |
| SHIMOGA | | | | | | | | | | | | | | | | |
| 3 | TRI-4b | 867 | 23.9 ± 0.2 | 4-7 | 70 | B | 23.8 ± 0.2 | 291 ± 2 | 0.41 | 1, 4, 6-7 | 60 | C | 23.7 ± 0.2 | 23.9 ± 0.2 | B | Forced-plateau |
| 3 | TRI-3a | 857 | 17.8 ± 0.2 | 8 | 36 | C | 11.0 ± 1.5 | 306 ± 36 | 0.93 | 3, 5-6, 10-15 | 26 | C | 14.2 ± 0.7 | 17.8 ± 0.2 | C | Min. of oldest |
| | | | 10.4 ± 1.0 | 11-12 | 5 | C | | | | | | | | 10.4 ± 1.0 | C | Max. of youngest |
| 3 | TRI-3b | 857 | 42.6 ± 0.3 | 5-7 | 33 | C | 42.6 ± 2.0 | 297 ± 232 | 0.36 | 5-7 | 33 | NGS | 60.5 ± 2.8 | 42.6 ± 0.3 | C | Max. age |
| 3 | TRI-3c | 857 | 25.5 ± 0.2 | 7-14 | 89 | A | 25.5 ± 0.5 | 353 ± 100 | 1.01 | 7-10, 14 | 57 | A | 25.2 ± 0.3 | 25.5 ± 0.2 | A | Plateau > 70% ³⁹ Ar _K |
| 3 | TRI-3d | 857 | 25.7 ± 0.2 | 12-20 | 87 | A | 25.5 ± 0.4 | 281 ± 89 | 1.86 | 11-12, 15-20 | 70 | B | 24.9 ± 0.2 | 25.7 ± 0.2 | A | Plateau > 70% ³⁹ Ar _K |
| 4 | KUM-2 (F) | 675 | 23.3 ± 0.5 | 6-8, 10 | 66 | B | 23.3 ± 0.3 | 307 ± 16 | 0.65 | 4, 6-8, 10 | 67 | B | 22.9 ± 0.3 | 23.2 ± 0.3 | B | Best fitted inverse isochrone |
| 4 | KUM-3a1 | 672 | 26.1 ± 0.2 | 8-20 | 74 | A | 25.2 ± 0.7 | 296 ± 17 | 0.92 | 6-14, 22 | 20 | B | 25.6 ± 0.2 | 26.1 ± 0.2 | A | Plateau > 70% ³⁹ Ar _K |
| 4 | KUM-3a2 | 672 | 26.4 ± 0.2 | 5-17 | 95 | A | 26.4 ± 0.3 | 303 ± 28 | 1.02 | 7-16 | 93 | A | 26.0 ± 0.2 | 26.4 ± 0.2 | A | Plateau > 70% ³⁹ Ar _K |
| 4 | KUM-3a3 | 672 | 26.8 ± 0.4 | 4-19 | 96 | A | 26.9 ± 0.5 | 294 ± 18 | 1.11 | 3-19 | 97 | A | 26.4 ± 0.4 | 26.9 ± 0.4 | A | Plateau > 70% ³⁹ Ar _K |
| 4 | KUM-3a4 | 672 | 27.6 ± 0.3 | 4-11 | 91 | A | 27.7 ± 0.5 | 293 ± 36 | 0.94 | 5-9 | 78 | A | 27.1 ± 0.3 | 27.6 ± 0.3 | A | Plateau > 70% ³⁹ Ar _K |
| 4 | KUM-3f (F) | 672 | 30.4 ± 0.4 | 5-7 | 47 | NGS | 29.9 ± 0.4 | 321 ± 20 | 1.23 | 3, 5-8 | 69 | NGS | 29.4 ± 0.3 | None | None | ⁴⁰ Ar ⁺ recoil |
| 4 | KUM-4oo | 670 | 39.2 ± 0.9 | 9-12 | 58 | B | 40.1 ± 4.4 | 284 ± 79 | 1.56 | 10-12 | 43 | B | 32.0 ± 1.2 | 39.2 ± 0.9 | B | Forced-plateau |
| | | | 24.0 ± 3.0 | 1-7 | 24 | C | 26.6 ± 5.3 | 293 ± 6 | 1.37 | 4-7 | 16 | C | | | | |
| GOA | | | | | | | | | | | | | | | | |
| 6 | NAV-4 (F) ² | 113 | 20.8 ± 1.7 | 6-8 | 54 | B | 20.7 ± 0.9 | 296 ± 25 | 0.41 | 4, 6-8, 13 | 56 | B | 24.6 ± 0.6 | 20.8 ± 1.7 | B | Plateau > 50% ³⁹ Ar _K |
| 6 | NAV-3b ² | 88 | 45.0 ± 0.7 | 7-11 | 57 | B | 44.9 ± 1.2 | 293 ± 26 | 0.77 | 7-9, 11 | 45 | B | 41.4 ± 0.7 | 44.9 ± 1.2 | B | Plateau > 50% ³⁹ Ar _K |
| 6 | NAV-3c ² | 88 | 47.0 ± 0.6 | 6-13 | 60 | B | 47.0 ± 0.5 | 294 ± 6 | 0.75 | 3, 6-11, 13 | 53 | A | 43.7 ± 0.6 | 47.0 ± 0.5 | A | Best fitted inverse isochrone |
| 6 | NAV-3f (F) ² | 88 | 8.6 ± 0.2 | 4-9 | 84 | A | 8.6 ± 0.6 | 309 ± 94 | 0.55 | 4-9 | 84 | B | 10.5 ± 0.6 | 8.6 ± 0.2 | A | Plateau > 70% ³⁹ Ar _K |
| 5 | CAU-1a ^a | 68 | 23.7 ± 0.3 | 8-10 | 57 | B | 23.7 ± 0.3 | 293 ± 3 | 1.99 | 3, 8-10 | 59 | C | 22.4 ± 0.3 | 23.7 ± 0.3 | B | Plateau > 50% ³⁹ Ar _K |
| | | | 20.1 ± 0.2 | 1-6, 12-13 | 26 | B | 20.3 ± 0.8 | 293 ± 25 | 0.45 | 5-6, 12 | 15 | B | | 20.3 ± 0.8 | B | Concordant pseudo-plateau |
| 5 | CAU-1b | 68 | 44.7 ± 0.2 | 10 | 15 | C | 35.2 ± 0.8 | 294 ± 42 | 0.81 | 3-6, 15 | 13 | NGS | 39.9 ± 0.2 | 44.7 ± 0.2 | C | Min. of oldest |
| | | | 31.2 ± 0.4 | 19 | 15 | C | | | | | | | | 31.2 ± 0.4 | C | Max. of youngest |
| 5 | CAU-1c ² | 68 | 21.9 ± 0.2 | 8-12 | 57 | B | 22.0 ± 0.3 | 299 ± 11 | 1.77 | 8-11 | 41 | B | 20.5 ± 0.3 | 21.9 ± 0.2 | B | Plateau > 50% ³⁹ Ar _K |
| | | | 19.7 ± 0.2 | 3-7, 14-16 | 27 | B | 19.6 ± 0.2 | 298 ± 1 | 1.02 | 3-5, 14-16 | 22 | B | | 19.3 ± 0.2 | B | Concordant pseudo-plateau |
| 5 | CAU-2 | 41 | 24.5 ± 0.1 | 9-11 | 55 | B | 24.0 ± 0.2 | 294 ± 3 | 0.92 | 4, 9, 11 | 29 | NGS | 22.8 ± 0.3 | 24.5 ± 0.1 | B | Forced-plateau |
| | | | 19.2 ± 0.2 | 13 | 4 | C | 21.6 ± 0.1 | 297 ± 2 | 2.56 | 3, 5-7, 12 | 21 | C | | 20.2 ± 0.3 | C | Max. of youngest |
| 5 | CAU-3a ² | 25 | 23.7 ± 0.2 | 10-14 | 54 | B | 23.7 ± 0.2 | 292 ± 2 | 1.82 | 3-4, 11-14 | 49 | C | 22.4 ± 0.2 | 23.7 ± 0.2 | B | Plateau > 50% ³⁹ Ar _K |
| | | | 20.4 ± 0.2 | 1-8, 17-18 | 29 | B | 20.4 ± 0.2 | 297 ± 7 | 1.31 | 5-7, 17-18 | 19 | B | | 20.4 ± 0.2 | B | Concordant pseudo-plateau |
| 5 | CAU-3f (F) ² | 25 | 19.4 ± 1.5 | 4-6 | 58 | A | 20.2 ± 0.4 | 284 ± 18 | 0.05 | 4-6 | 58 | C | 21.9 ± 0.6 | 19.4 ± 1.5 | A | Plateau > 50% ³⁹ Ar _K |
| 7 | CUD-3 | -24 | 2.5 ± 0.4 | 3-20 | 95 | A | 2.1 ± 0.6 | 305 ± 11 | 0.18 | 3-20 | 95 | B | 2.9 ± 0.6 | 2.5 ± 0.4 | A | Plateau > 70% ³⁹ Ar _K |

(^a) recalculated after Bonnet et al., 2014; (²) recalculated after Beauvais et al, 2016

Locations: 1 = Kappataswamy pit; 2 = Channanghi KMK-East pit; 3 Triveni Pit; 4 = Kumsi pit; 5 = Caurem pit; 6 = Naveli pits; 7 Cudnem pit (See also Fig. 1)

Refer to Fig. 1 for localities numbers

A = 1st order age; B = 2nd order age; C = 3rd order age; NGS = No Geological Significance

TABLE 2

Data Repository 1 EPMA

[Click here to download Background dataset for online publication only: Revised_DR1.xlsx](#)

Data Repository 2 ArArCalc

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