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## Weathering history and landscape evolution of Western Ghats (India) from $^{40}\text{Ar}/^{39}\text{Ar}$ dating of supergene K-Mn oxides

A. Jean, Anicet Beauvais, D. Chardon, Nicolas Olivier Arnaud, M. Jayananda, P.-E. E Mathe

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2                   **Weathering history and landscape evolution of Western Ghats**  
3                   **(India) from  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of supergene K-Mn oxides**  
4

5                   **A. Jean<sup>1</sup>, A. Beauvais<sup>1\*</sup>, D. Chardon<sup>2,3</sup>, N. Arnaud<sup>4</sup>, M. Jayananda<sup>5</sup> & P.E. Mathe<sup>1</sup>**  
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7

8                   <sup>1</sup> Aix-Marseille Univ, CNRS, IRD, INRA, Coll France, CEREGE, Aix-en-Provence, France

9                   <sup>2</sup> IRD and Département des Sciences de la Terre, Université Joseph Ki-Zerbo, Ouagadougou,  
10                   Burkina Faso

11                   <sup>3</sup> GET, Université de Toulouse, CNRS, IRD, UPS, CNES, F-31400 Toulouse, France

12                   <sup>4</sup> Université de Montpellier 2, Géosciences Montpellier, UMR CNRS 5243, 34095  
13                   Montpellier, France

14                   <sup>5</sup> Centre for Earth, Ocean and Atmospheric Sciences, University of Hyderabad, P.O. Central  
15                   Gachibowli, Hyderabad 500 046, India

16  
17  
18                   \* Correspondence: (beauvais@cerege.fr)  
19  
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## Abstract

Laterites preserved on both sides of the Western Ghats Escarpment of Peninsular India have formed by long-term lateritic weathering essentially after India-Seychelles continental break up following Deccan Traps emplacement (c. 63 Ma ago). Supergene manganese ores of the Western Ghats were formed on Late Archean manganese protores. Among Mn oxides composing the ores, cryptomelane (K-rich Mn oxide) was characterized and dated by  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology. Measured ages complement those previously obtained in other South-Indian manganese ores from the hinterland plateau (Bonnet et al., 2016) and further document three major weathering periods, c. 53-44 Ma, c. 39-22 Ma, and c. 14-10 Ma, the later being documented for the first time in India. These periods coincide with global paleoclimatic proxies and date the lateritic weathering of three successive paleolandscapes of the Western Ghats that evolved under slow denudation (c. 8 m/myr) over the last 44 Myr and were mostly incised during the Neogene (< 22 Ma). That indicates the Western Ghats are a relict of a South Indian plateau preserved at the headwaters of very long east-flowing river systems and above the Western Ghats escarpment. Topography and denudation history of this landscape do not require Neogene tilt of the Peninsula as recently proposed.

Keywords:  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology – Manganese oxides – Lateritic weathering – Cenozoic – Denudation – Indian Western Ghats

**Supplementary material:** [Full details of field and samples description, methodology, and analytical data including electron probe microanalyses of cryptomelane, and isotopic analyses and degassing spectra of irradiated cryptomelane grains] is available at

57 Lateritic regoliths of the continental inter-tropical belt have formed by supergene  
58 chemical weathering of rocks and landscape evolution under evolving tropical climates. Over  
59 long-time scale, weathering profiles accumulate clays (mainly kaolinite), and metal oxides  
60 (Al, Fe, or Mn oxy-hydroxides), which are mostly concentrated in lateritic duricrusts capping  
61 the profiles (Bárdossy and Aleva, 1990; Nahon, 1986; Thomas, 1994; Tardy, 1997). Lateritic  
62 weathering profiles (up to c.100 m thickness) are currently exposed on relict  
63 paleolandscapes over large cratonic areas of Africa, South America, Australia and India.  
64 Much work was done for dating weathering profiles on most continents of the tropical belt,  
65 using  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of K-rich Mn oxides (e.g., Vasconcelos, 1999; Vasconcelos et Conroy,  
66 2003; Beauvais *et al.*, 2008; Bonnet *et al.*, 2016; Deng *et al.*, 2016; Li *et al.*, 2007; Riffel *et*  
67 *al.*, 2015), or (U-Th)/He dating of iron oxy-hydroxides (e.g., Shuster *et al.*, 2005; Vasconcelos  
68 *et al.*, 2013; Monteiro *et al.*, 2018; Allard *et al.*, 2018). For instance, ages of cryptomelane  
69 formed *in situ* in lateritic regolith of West Africa and Brazil allowed calibrating continental  
70 denudation over geological time scales (Beauvais and Chardon, 2013; Vasconcelos and  
71 Carmo, 2018). But a reliable geochronological geomorphology is still often lacking to better  
72 calibrate the long-term erosion history of many areas of the tropical World that would allow  
73 linking lateritic weathering episodes, continental denudation and the evolving  
74 paleolandscapes, particularly on passive continental margins and their cratonic hinterlands  
75 (e.g., Bonnet *et al.*, 2016).

76 In Peninsular India, relicts of several generations of stepped lateritic paleolandscapes  
77 (termed paleosurfaces) were distinguished (e.g., Widdowson, 1997; Gunnell, 1998), but only  
78 recently characterized and dated by  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometry (Bonnet *et al.*, 2014; 2016; Beauvais  
79 *et al.*, 2016). Paleolandscape remnants preserved on either side of Western Ghats Escarpment  
80 (WGE) separating the coastal lowland plain from a continental-scale high plateau (i.e. the

81 Karnataka plateau; **Fig. 1b**), are most numerous upon the Western Ghats proper, i.e., the belt  
82 of high topography (800 m - 1500 m) running along the escarpment. These remnant  
83 landscapes are key paleotopographic markers of the denudation history of the Peninsula.  
84 Three major weathering periods, c. 53-45 Ma, c. 37-26 Ma and c. 26-19 Ma, and two discrete  
85 pulses, c. 9 and 2.5 Ma, were previously defined from  $^{40}\text{Ar}/^{39}\text{Ar}$  ages series of cryptomelane,  
86 which formed *in situ* in the lateritic profiles and supergene Mn-ore deposits on the highland  
87 plateau and coastal lowland plain (Bonnet *et al.*, 2016). These ages combined with regional  
88 geomorphological observations imply very slow denudation, c. 5-6 m/myr in the lowland and  
89 a maximum of c. 15 m/myr in the highland over the last 50 Myr (Beauvais *et al.*, 2016).

90 The present study focuses on  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of the cryptomelane-rich Mn ore deposits  
91 of North Kanara region in the Western Ghats, which have been loosely dated so far by  
92 Neogene palynostratigraphic record in their sedimentary overburden (Krishna Rao *et al.*,  
93 1989a). New data further document the major Cenozoic weathering periods previously  
94 identified upon the Karnataka plateau and in the coastal lowland (Bonnet *et al.*, 2016) and  
95 reveal for the first time a well-characterized Mid-Miocene (14-10 Ma) weathering period. All  
96 the ages obtained here establish the first geochronology of lateritic weathering in the North  
97 Kanara region and further document the evolution of Western Ghats landscapes that was  
98 previously outlined (e.g., Sethumadhav *et al.*, 2010). The geomorphological structuration of  
99 the Western Ghats into three major lateritic paleolandscapes and the new ages obtained imply  
100 a slow denudation regime varying between c. 4.5 and c. 12.5 m/myr over the last 44 Myr, and  
101 limited landscape dissection mostly in the Neogene. These results also document the  
102 persistence of a lateritic paleolandscape above the West-facing escarpment as a relict of an  
103 Eocene plateau in South India comparable to that of current Southern Africa.

## Geological and geomorphological setting of the Western Ghats

Lithologies of North Kanara region consist of Archean gneisses/granites and Late Archean (c. 2.6 Ga) supracrustals comprising greywackes, banded iron formations and quartzite with strips of cherts, phyllites, and shales, as well as some stromatolitic dolomites and limestones (Fig. 2a; Sawkar, 1980; Sethumadhav *et al.*, 2010). Greenschist facies metamorphism and moderate deformation affect the supracrustal sequence (Shivaprakash, 1983; Roy, 1981). Supracrustals of North Kanara constitute the northward extension of the Shimoga greenstone belt, and host many Mn supergene ore deposits (Sethumadhav *et al.*, 2010) as other belts of the Dharwar craton (e.g., Sandur and Chitradurga; **Figs. 1 and 2**) (e.g., Mohopatra *et al.*, 1996; Manikyamba *et al.*, 1997). Most of the North Kanara ore deposits developed upon phyllites/argillites and cherts forming three hilly structural strips trending NNW-SSE (**Fig. 2a**; Sawkar, 1980).

The Kali River drains the region, sourcing near Diggi east of the escarpment; it first flows eastward then south before turning and incising the escarpment westward (Fig. 2b). Relicts of three lateritic paleolandscapes have been distinguished and mapped on the basis of their regolith, morphology and topography (**Figs. 2b-c and 3**). The first and older one, noted S1, is mostly flat and carries Al-Fe rich laterites, mostly bauxitic, between altitudes of c. 770 m and c. 1000 m (**Figs. 2b-c and 3**). This S1 paleolandscape is equivalent to the S2 paleosurface described by Gunnell (1998). The second lateritic paleolandscape, noted S2, bears thick weathering profiles rich in kaolinite and iron oxy-hydroxides, which are often duricrusted by an Al-Fe rich duricrust (Bonnet *et al.*, 2016) between altitudes of c. 650 m and c. 930 m (**Figs. 2b-c and 3**). The lateritic weathering profile related to the S2 paleolandscape has been previously interpreted as resulting from the late geochemical epigenetic evolution of bauxites (Krishna Rao *et al.*, 1989b; see also Boulangé, 1986). The two paleolandscapes (S1-S2) form

129 a composite landscape, the S2 relicts being preserved mostly as gentle slopes under scarp-  
130 bounded S1 remnants that have undergone limited incision (a few tens of meters) but clear  
131 relief inversion before final installation of S2. The composite S1-S2 landscape can reach c.  
132 100 m of relief (**Figs. 2c and 3**). This paleolandscape is best preserved near the escarpment  
133 (Fig. 2b) and represents the westernmost relict of a more extended low relief and gently  
134 sloping S1-S2 paleolandscape on the Karnataka plateau, whose remnants have been also  
135 observed on the Chitradurga and Sandur greenstone belts at 900-1100 m elevation (**Fig. 1**; see  
136 Bonnet et al., 2016; Beauvais et al., 2016). The third paleolandscape, noted S3, consists of  
137 coalescent pediments between c. 750 and 500 m elevation (**Figs. 2c and 3**). The pediments  
138 are covered by clay-rich ferruginous soils (Gunnell and Bourgeon, 1997), which can be  
139 locally duricrusted. S3 surface once formed a pediplain resulting from the dissection of the  
140 composite S1/S2 landscape. The pediplain fossilizes the foot of steep, regolith-free slopes,  
141 150 to 250 m in amplitude, which formed by incision of the S1-S2 relict landscape (**Figs. 2c**  
142 **and 3**; Bonnet *et al.*, 2016; see also Chardon et al., 2018 and references therein). The S3  
143 pediplain therefore integrates relicts of the S1-S2 landscape. The pediplain is incised by about  
144 50 to 100 m (locally 300 m by the Kali River valley, **Figs 2b-c and 3**). The regolith  
145 underlying the S3 pediment surfaces hosts most of the Mn ore deposits at altitudes ranging  
146 from 520 to 650 m (**Fig. 2b and Tab. 1**). The S1-S3 landscape sequence in the Western Ghats  
147 is similar to that previously described on the Karnataka plateau (Bonnet et al., 2016).

## 148 **Materials and methods**

### 149 ***Sampling, characterization and collection of cryptomelane***

150  
151 Eleven samples of Mn-rich duricrusted ore were collected for their richness in  
152 cryptomelane on sections and benches of five-abandoned open mine workings of supergene

153 Mn ore deposits at Diggi, Terali, Nagari, Illva and Pradhani (**Figs. 2 and 4a**). Most of  
154 collected manganese ores show massive, botryoidally colloform-mineralized structures, or  
155 infiltration ore in lateritic iron duricrust rich in cryptomelane and other Mn oxides, as well as  
156 secondary goethite (**Figs. 4b-e**). Some samples also show the primary lithological banding of  
157 parent rocks and protosols.

158 The different operations for identifying, characterizing and sampling cryptomelane grains  
159 are summarized in the Figure 3 (see also Bonnet *et al.*, 2016). Cryptomelane and other Mn  
160 oxides were first identified on fully polished thin sections (200-300  $\mu\text{m}$ -thickness), which  
161 were observed under reflected light microscopy and analysed by X-ray micro-fluorescence,  $\mu$ -  
162 XR, (**Figs. 4d-e**). The  $\mu$ -XRF analysis allowed mapping Mn, K and Fe concentrations on the  
163 polished thin sections to identify the area the richest in cryptomelane. Cryptomelane was also  
164 analysed by Electron Probe Micro-Analysis (EPMA) in polished thin sections.

165 Additional small grains were extracted from the remaining Mn ore duricrust specimens  
166 for observation under a scanning electron microscope and characterization by X-ray  
167 diffraction (**Figs. 4f-g**). Cryptomelane grains of 0.5 to 2 mm in size were picked on thick  
168 counterparts (500  $\mu\text{m}$ -thickness) of each thin section where K and Mn are both present (**Fig.**  
169 **4e**). Fifty-one grains were selected and divided into two batches, one reduced to powder (c. 64  
170  $\mu\text{m}$  size fraction) and analysed by XRD (**Fig. 4f**), and the other one kept for dating.

### 171 ***Cryptomelane grain irradiation and $^{40}\text{Ar} / ^{39}\text{Ar}$ dating***

173 Cleaned and purified cryptomelane grains were conditioned in aluminium foil packets,  
174 and placed into an irradiation vessel including also the monitor VN-FCT-98 of Fish Canyon  
175 Tuff volcanic (U.S.A.) dated at  $28.172 \pm 0.028$  Ma (Rivera *et al.*, 2011) every ten grains.  
176 Isotopic analyses and dating were performed using the step-heating method of irradiated

177 grains with a CO<sub>2</sub> laser emitting in the infrared. Measured isotopic ratios were corrected for  
178 irradiation interferences and air contamination using the up-to-date mean <sup>40</sup>Ar/<sup>36</sup>Ar<sub>atm</sub> value of  
179 298.56 ± 0.31 (Lee *et al.*, 2006; Renne *et al.*, 2011).

180 Plateau ages are generally derived using several apparent ages integrated over continuous  
181 degassing steps overlapping at 2σ error level and integrating at least 70% <sup>39</sup>Ar released  
182 (Fleck, 1977; Maluski, 1985; McDougall and Harrison, 1988). A plateau age is still valid  
183 when it integrates 50 % to 70 % of <sup>39</sup>Ar released over at least three continuous degassing  
184 steps whose individual ages overlap in the 2σ error (e.g., Vasconcelos, 1999; Li and  
185 Vasconcelos, 2002; Vasconcelos and Conroy, 2003; Colin *et al.*, 2005; Li *et al.*, 2007; Feng  
186 and Vasconcelos, 2007; Vasconcelos *et al.*, 2013; Riffel *et al.*, 2015; Bonnet *et al.*, 2014;  
187 Deng *et al.*, 2016). When more than two degassing steps integrate only 40 to 50% of <sup>39</sup>Ar  
188 released in the 2σ level, a “pseudo-plateau” age was preferred (Vasconcelos *et al.*, 2013;  
189 Riffel *et al.*, 2015). When at least three consecutive reasonably flat steps do not strictly  
190 overlap in the 2σ level, a “forced” plateau was required to calculate an age weighted by error  
191 and the <sup>39</sup>Ar released for each degassing step (Vasconcelos *et al.*, 2013; Riffel *et al.*, 2015).

192 Picked cryptomelane are generally pure, but sometimes, hypogene contaminations  
193 (muscovite), mixed cryptomelane generations, or cryptomelane mixed with authigenic phases  
194 (e.g., todorokite ((Na,Ca,K)<sub>2</sub>(Mn<sup>4+</sup>,Mn<sup>3+</sup>)<sub>6</sub>O<sub>12</sub>•3-4.5(H<sub>2</sub>O)) result in very perturbed degassing  
195 spectra including analysis biases and dating errors. For such cases, although pseudo-plateau  
196 and forced plateau ages can be estimated, the <sup>36</sup>Ar/<sup>40</sup>Ar vs. <sup>39</sup>Ar/<sup>40</sup>Ar correlation diagrams  
197 may be required to derive age from best-fitted isochron with a mean square weighted  
198 deviation (MSWD) as close as possible to 1 (ideally less than 2.5; see Roddick *et al.*, 1980)  
199 and a <sup>40</sup>Ar/<sup>36</sup>Ar intercept as close as possible to the air value of 298.56 in the 2σ error level.

## Results and interpretations

### *Characterization and stoichiometric composition of cryptomelane*

All samples contain mostly cryptomelane (**Fig. 4d-f**), but iron oxy-hydroxides such as goethite and sometimes hematite were also identified, with other manganese oxy-hydroxides, i.e., lithiophorite ((Al, Li) Mn<sup>4+</sup>O<sub>2</sub>(OH)<sub>2</sub>), nsutite ( $\gamma$ -MnO<sub>2</sub>) (see **Figs. 4d-e**), and even pyrolusite ( $\beta$ -MnO<sub>2</sub>). Similar Mn oxides have been previously described in same Mn ore deposits of Western Ghats (Sethumadhav *et al.*, 2010). The relative richness in iron oxide such as goethite is linked to banded iron formations associated with phyllites/argillites. Quartz and muscovite were also determined as minor components.

The stoichiometric compositions of cryptomelane were calculated from EPMA and plotted in a ternary diagram (**Fig. 5**). Some microanalyses from Nagari Mn deposit samples have relatively high aluminium content owing to possible intergrowth with lithiophorite, or mixture with a primary mineral like muscovite inherited from parent phyllites and argillites (Bonnet *et al.*, 2016). Microanalyses from Pradhani samples show high Fe content up to 20 wt.%. Cryptomelane from Terali deposit can be Al-rich (**Fig. 5**) owing to relict muscovite. Cryptomelane from Diggi, Illva and some from Pradhani have less aluminous impurities (Al never exceeding 2.73 wt.%, **Fig. 5**).

### *Weathering geochronology of the Western Ghats*

Fifty-one cryptomelane grains collected in samples from five Mn ore deposits were analysed and dated, and thirty-eight have significant geological ages (**Tab. 1**). Synthetic results presented in the Table 1 allow distinguishing three family or groups of ages, Mid-Miocene (**Fig. 6**), Early Miocene – Late Eocene (**Fig. 7**), and Mid-Eocene (**Fig. 8**).

## Overview of $^{39}\text{Ar}$ release spectra

Fifteen grains have homogenous degassing spectra allowing calculation of plateau ages integrating 70 to 90 % of  $^{39}\text{Ar}$  released and thirteen with 50 to 70 % of  $^{39}\text{Ar}$  released (**Tab. 1**, **Figs. 6 and 8**). Many irradiated grains picked in the same sample have reproducible homogeneous degassing spectra. Seven spectra do not strictly respect the overlap upon the  $2\sigma$  error that requires calculation of acceptable age from forced plateaus and/or best-fitted isochrons in correlation diagrams (**Figs. 7 and 8 and Tab. 1**).

Three types of perturbed degassing spectra have been identified. Hump-shape degassing spectra, tagged HS (see **Figs. 7 and 8**) typify a mixture of at least two cryptomelane generations that only allow estimating the minimum age of the oldest phase and the maximum age of the youngest phase (Beauvais *et al.*, 2008). Saddle shape degassing spectra, tagged SS (**Fig. 7**) result from mixture of several supergene phases, or contamination by a hypogene mineral (Hautmann et Lippolt, 2000; Ruffet *et al.*, 1996; Vasconcelos *et al.*, 1995). Staircase-degassing spectra, tagged SD, suggest possibly a system opening, or a mixing of different cryptomelane generations with a disturbance at high energy, owing generally to a contamination by a hypogene phase (**Fig. 7**).

## Mid-Miocene cryptomelane ages

Most of the Mid-Miocene ages have been calculated for cryptomelane of samples collected in Diggi and Illva Mn ore deposits (**Figs. 6a-b**). Three grains, DIG-1A-T4 to T6, picked in the same thick section, have very similar degassing spectra allowing to derive reproducible plateau ages between c.11 and c.12 Ma integrating more than 70 % of  $^{39}\text{Ar}$  (**Fig. 6a**). Two other grains DIG-1B-T2 to T3 have a same age of c.13 Ma. The first one (DIG-1B-T2) is a “pure” cryptomelane grain, with a regular  $^{39}\text{Ar}$ -releasing spectrum allowing to

249 calculate a meaningful plateau age, based on 85 % <sup>39</sup>Ar released. The second one (DIG-1B-  
250 T3), picked in the same thick section, has a plateau like degassing spectrum with 79 % <sup>39</sup>Ar  
251 released confirming the reproducibility of plateau age calculation for the two grains (**Fig. 6a**).  
252 Grain DIG-1B-T4 is also a “pure” cryptomelane characterized by a regular degassing  
253 spectrum with 74 % <sup>39</sup>Ar released, providing a robust plateau age of c.12 Ma.  
254 One grain (ILV-1B-T4) has a homogeneous degassing spectrum providing plateau ages of c.  
255 13 Ma integrating more than 90 % <sup>39</sup>Ar released (**Fig. 6b**). Two others grains picked in  
256 botryoidal crystallizations from a same thick section (ILV-2C-T3 and -T4) also have  
257 reproducible homogenous degassing spectra with robust plateau ages of c.12 to c.13 Ma  
258 accounting for more than 80 % of <sup>39</sup>Ar released. Grain ILV-3C-T4 picked in allochthonous  
259 Mn ore sample has degassing spectra allowing calculation of a plateau age of c. 14 Ma  
260 integrating more than 60 % <sup>39</sup>Ar released (**Fig. 6b**). Two other grains picked in a same thick  
261 plate have reproducible degassing spectra providing plateau age of c. 12 Ma (ILV-6A-T2) and  
262 c. 10 Ma (ILV-6A-T3) both integrating c. 80 % of <sup>39</sup>Ar released.

#### 263 264 *Late Eocene to Early Miocene Cryptomelane ages*

265 This group (**Fig. 7**) comprises ages obtained for cryptomelane of samples from deposits  
266 of Terali and Pradhani. Two cryptomelane rich grains (TER-1A-T1, TER-1B-T3) have  
267 degassing spectrum with a slight hump-shape (**Fig. 7a**) suggesting mixture of two  
268 cryptomelane generations. Such spectra allow defining only forced plateau ages c. 29 and c.  
269 27.5 Ma, respectively, both accounting for at least 60% <sup>39</sup>Ar released.

270 One grain (PRA-1B-T1) is characterized by a staircase-degassing spectrum (**Fig. 7b**), which  
271 at best allows estimating poorly robust pseudo or forced plateau ages c. 25 Ma integrating 61  
272 % of <sup>39</sup>Ar released. Three cryptomelane grains (PRA-2A-T1, -T3 and -T5) have similar slight

273 staircase degassing spectra allowing to derive plateau ages of c. 24.5 Ma, c. 23.7 and c. 21.6,  
274 integrating 58 to 78-79 % of  $^{39}\text{Ar}$  released, respectively (**Fig. 7b**). The degassing spectra of  
275 the other four grains (PRA-2B-T1, -T4; PRA-3B-T1, and -T2) provide plateau and/or forced  
276 plateau ages varying from c. 23 Ma to c. 37.5 Ma (**Fig. 7 and Tab. 1**). Two grains (PRA-3B-  
277 T1 –T2) have reproducible “saddle shape” spectra (**Fig. 7b**) suggesting opened systems  
278 and/or supergene phase’s mixture with a hypogene phase at high energies. Nonetheless,  
279 plateau and forced plateau accounting for more than 50 % of  $^{39}\text{Ar}$  released, allow deriving  
280 ages c. 32.8 and c. 37.5 Ma (**Tab. 1**), which may be the less poorly estimated maximum ages.

#### 281 282 *Mid-Eocene cryptomelane ages*

283 Most of Mid-Eocene cryptomelane grains (**Fig. 8**) were picked in samples from the  
284 deposits of Nagari and Pradhani (**Tab. 1**). Two grains picked in the same thick section (NAG-  
285 3B-T1 and T2) have a more or less homogenous degassing, allowing calculation of plateau  
286 ages at c. 45 and c. 44 Ma, respectively (**Fig. 8a**). The  $^{39}\text{Ar}$  release spectrum of NAG-3B-T2  
287 shows a slight hump shape with three steps accounting for 78 % of  $^{39}\text{Ar}$  released and  
288 overlapping in  $2\sigma$  error, which provides a reliable plateau age. The last grain NAG-3B-T3 has  
289 a perturbed  $^{39}\text{Ar}$  release spectrum resulting from mixing of cryptomelane generations that  
290 only allows consideration of a forced plateau age c. 45 Ma accounting for more than 50 % of  
291  $^{39}\text{Ar}$  release (**Fig. 8a**). Grain PRA-1B-T3 has a pronounced hump-shape degassing spectrum  
292 typifying phases mixing that provide only a forced-plateau age of c. 45 Ma accounting for 50  
293 % of  $^{39}\text{Ar}$  released (**Fig. 8b**).

#### 294 295 *Summary and interpretation of the $^{40}\text{Ar}/^{39}\text{Ar}$ ages*

296 The three groups of ages (Table 1), c. 45-44 Ma, c. 37.5-22 Ma, and c. 14-10 Ma,  
297 complement ages obtained previously in other manganese ore deposits from the Karnataka

298 plateau (Sandur) and Western Ghats (Shimoga) south of the present study area that further  
299 document the weathering periods previously established by Bonnet *et al.* (2016): Eocene and  
300 Oligocene-Early Miocene, with a new period in Mid-Miocene. Altogether, the ages define  
301 three main weathering periods, c. 53 to c. 44 Ma (W1), c. 39 to c. 22 Ma (W2), and c. 14 to c.  
302 10 Ma (W3). Those periods mostly coincide with warm and humid climatic global trends  
303 (**Fig. 9**), which were potentially conducive to intense lateritic weathering in the Peninsula as  
304 well on most continents of the tropical belt (Retallack, 2010). Under such conditions, and  
305 especially during the two first periods W1 and W2, relatively fast deepening of weathering  
306 fronts (up to 10 m/myr; Boulangé *et al.*, 1997; see also Tardy and Roquin, 1992) allowed  
307 early segregation of aluminium, iron and manganese, controlled by their relative mobility  
308 (Eh- and pH-dependent) in weathering profiles and landscapes (Melfi and Pedro, 1974; Hem,  
309 1981; Beauvais *et al.*, 1987). Early weathering of parental minerals such as illite or muscovite  
310 into kaolinite or gibbsite released  $K^+$  ions required to form cryptomelane (Parc *et al.*, 1989).  
311 Like in West Africa (Beauvais *et al.*, 2008) or upon the Karnataka plateau (Bonnet *et al.*,  
312 2014, 2016), Al-Fe-Mn geochemical differentiations have resulted in early formation of  
313 manganese ore deposits including K-rich Mn oxides (cryptomelane) at depth in the profiles of  
314 the S1 bauxitic paleolandscape (**Fig. 10a**). Such a surface geochemical dynamics typifies the  
315 weathering regime of cratonic tropical regions, where slow base level lowering warranties  
316 coeval landscape incision/dissection and long lasting deepening of weathering fronts. A slight  
317 change in climatically driven surface erosional processes after c. 44 Ma (**Fig. 9**) allowed for  
318 the abandonment of a duricrust-capped paleosurface S1 and installation of the S2 surface  
319 without stripping the entire thickness of the S1 bauxitic weathering profile (**Fig. 10b**). A  
320 comparable scenario applies for the abandonment of S2 and installation of S3, even though S3  
321 has allochthonous clasts of older weathered material dispersed on its surface. Such a

322 punctuated erosion-weathering regime therefore allowed for the preservation of early-formed  
323 weathering materials including manganese ores rich in cryptomelane in the S1 profiles, as  
324 well as in those of S2 and S3 (**Fig. 10b-c**). Therefore, the weathering profiles of the youngest  
325 S3 surface were able to host and keep record of “the roots” of manganese-rich profiles formed  
326 during the S1 and S2 stages (**Fig. 10c**). The minimum age of weathering periods marks the  
327 stabilization of weathering fronts at each stage responding to the lowering of base levels  
328 resulting in landscape dissections and the abandonment of S1 at c. 44 Ma, S2 at c. 22 Ma, and  
329 S3 at c. 10 Ma (**Figs. 10a-c**). The time intervals between the age groups, i.e., 44-39 Ma, 22-14  
330 Ma, and 10-0 Ma (**Fig. 9**) document periods of subdued weathering under seasonally drier  
331 climatic conditions with correlative landscape dissection and evolution into three stepped  
332 lateritic paleolandscapes, S1 to S3 (**Figs. 2c and 3**; see also Beauvais and Chardon, 2013).  
333 Therefore, the Western Ghats have seen their early low-relief S1 landscape differentiated  
334 during three major denudation periods bounded by terminal ages of W1, W2, W3 and the  
335 present-day, i.e., 44-22 Ma, 22-10 Ma, and 10-0 Ma.

## 336

### 337 **Weathering and morphoclimatic history of the Western Ghats**

#### 338 *Early to Mid Eocene weathering period, W1 (53 - 44 Ma)*

339 The Eocene period documented here by four ages around 44-45 Ma attests to the  
340 minimum age boundary of this first weathering period (**Fig. 9**), which begun at least c. 53 Ma  
341 ago as documented further east at Sandur (Bonnet *et al.*, 2016). The Eocene is known as a  
342 period of bauxitization worldwide, particularly from cratonic domains of the inter-tropical  
343 belt (Prasad, 1983; Valeton, 1999; Retallack, 2010). This first weathering period of at least 9  
344 Myr coincided with the global Early Eocene climatic optimum (c. 50 Ma; **Fig. 9**), and  
345 occurred in Peninsular India less than c. 5 Myr after the Paleocene-Eocene Thermal

346 Maximum and the onset of Himalayan collision c. 55-57 Ma ago (Hu et al., 2016; Najman et  
347 al., 2010). During this period, India slowed its northward drift across the mostly equatorial  
348 inter-tropical zone (Tardy and Roquin, 1998; Kent and Muttoni, 2008; see Bonnet et al.,  
349 2016) and intense lateritic weathering, with segregation of aluminium from iron and  
350 manganese in thick, mostly bauxitic profiles, affected most of lithologies including the  
351 Deccan Traps (Bardossy and Aleva, 1990; Krishna Rao *et al.*, 1989b; Valetton, 1999).  
352 Remnants of such bauxitic paleolandscapes (S1) are distributed in the Western Ghats and  
353 locally preserved on the Karnataka plateau (Bonnet *et al.*, 2016). After 44 Ma, the S1 bauxitic  
354 paleolandscape was reworked (see Krishna Rao et al., 1989b) allowing the establishment of the  
355 S2 paleolandscape (**Figs. 2c, 3 and 10b**).

#### 356 357 *Late Eocene - Early Miocene weathering period, W2 (39 - 22 Ma)*

358 This long weathering period (c. 17 Myr) in the Western Ghats is documented by fifteen  
359 ages complementing those previously obtained in Sandur on the Karnataka plateau and in  
360 Shimoga (Western Ghats south of the Kanara district studied here) between 39 Ma and 23 Ma  
361 (Bonnet *et al.*, 2016). The oldest ages obtained in the Western Ghats (c. 37.5 Ma in the  
362 present study and c. 39 Ma in Shimoga) document that lateritic weathering might have been  
363 enhanced in South India by monsoon-like climatic regimes recently reported by authors  
364 (Dupont-Nivet *et al.*, 2008; Licht *et al.*, 2014). This weathering period occurred a few million  
365 years after the onset of global Mid-Eocene Climatic Optimum (c. 42 Ma; **Fig. 9**).

366 Late Eocene ages (c. 39 Ma) were obtained on cryptomelane in Shimoga Mn ore deposit  
367 upon the S2 paleosurface (Bonnet et al., 2016; **Fig. 9**) and on kaolinite from a relict truncated  
368 weathering profile from the southernmost Western Ghats in the upslope part of Kavery River  
369 drainage (see Mathian *et al.*, 2019). This means that both minerals formed simultaneously at

370 the onset of lateritization and morphogenesis of S2 paleolandscape (**Fig. 10b**). Old concordant  
371 ages obtained on the Karnataka plateau as well as in the Western Ghats belt are attributed to  
372 the S2 paleolandscape that evolved slowly during a long-lasting period (c. 17 Myr) of intense  
373 lateritic weathering, potentially under seasonally tropical humid climate.

374 The numerous ages between c. 30 and 23 Ma (**Tab. 2 and Fig. 9**) confirm those  
375 previously obtained in Sandur and Shimoga (**Fig. 1a**; Bonnet *et al.*, 2016) and document  
376 enhanced weathering of S2 paleolandscape at the Oligocene-Miocene transition. These ages  
377 bracket the global late Oligocene warming (LOW) at c. 26 Ma (**Fig. 9**), during which modern-  
378 like monsoon regimes might have installed on the Peninsula (Chatterjee *et al.*, 2013), with a  
379 western/eastern rainfall contrast comparable to the modern one. Therefore, more humidity  
380 supported intense lateritic weathering upon the Western Ghats and below the escarpment,  
381 while further aridity and landscape dissection prevailed in the interior plateau, e.g., Sandur  
382 where weathering was subdued from c. 26 Ma (**Fig. 8**; see also Bonnet *et al.*, 2016). The  
383 weathering period ended c. 22 Ma ago with the abandonment of paleolandscape S2 (**Fig.**  
384 **10b**). Afterwards, landscape dissection prevailed in the Western Ghats and the S3  
385 paleolandscape established (**Figs. 2c, 3 and 10c**).

#### 386 387 ***Mid-Miocene weathering period, W3 (14 - 10 Ma)***

388 The mid-Miocene weathering period W3 is relatively short (c. 4 myr) but well  
389 documented by eighteen ages in the Western Ghats, and coincided with the global Mid-  
390 Miocene Climatic Optimum (**Fig. 9**). The ages also agree with palynostratigraphy in the same  
391 Mn deposits (Krishna Rao *et al.*, 1989a), and document renewed lateritic weathering in the  
392 Western Ghats once the S3 pediplain landscape was established (**Figs. 2c, 3 and 10c**). After c.  
393 10 Ma, landscape dissection that formed the current incised valleys (**Fig. 2c**) would have been

394 coeval with apparently subdued weathering attested to by the lack of ages (**Fig. 9**). However,  
395 late Neogene ages (9 and 2.5 Ma) were previously recorded on cryptomelane in the coastal  
396 lowland (Bonnet et al., 2016) or further south (9, 3.5 and 1 Ma) on kaolinite in the Western  
397 Ghats (Mathian et al., 2019). Those weathering pulses date landsurface processes responses to  
398 Neogene monsoon regimes, which are particularly marked in the Western Ghats and the  
399 western lowland due to the orographic effect of the WGE (Bonnet *et al.*, 2016).

### 401 **Landscape evolution of the Western Ghats**

402 The well-preserved S1-S2 composite paleolandscape of Western Ghats has been mostly  
403 shaped by c. 18 Myr of cumulated chemical weathering (45 to 44 and 39 to 22 Ma; **Fig. 9**)  
404 and moderate denudation between 44 and 39 Ma (**Figs. 2c and 10a-b**). Most of the dissection  
405 of that landscape occurred from 22 to 14 Ma during which the S3 pediplain grew at its  
406 expenses (**Figs. 2c, 3 and 10c**). Then, after a short episode of weathering (4 Myr), the S3  
407 paleolandscape was finally dissected over the last 10 Myr. Therefore, after abandonment of  
408 S1 paleolandscape 44 Ma ago (**Fig. 10a**), the Western Ghats relief gradually increased up to  
409 350 m by punctuated base level falls (**Fig. 2c**), implying a maximal denudation rate of c. 8  
410 m/myr over the last 44 Myr. In detail, the maximum 350 m of relief production in Western  
411 Ghats may be divided into three steps correlated to the abandonment of each paleolandscape,  
412 S1 to S3 (**Figs. 2c, 3 and 10**). First, a maximum elevation difference of 100 m between S1  
413 (44 Ma) and S2 (22 Ma) implies a maximum denudation rate of 4.5 m/myr, which is mostly  
414 chemical (**Fig. 9**). Then, a maximum of 150 m elevation between S2 and S3 (**Figs. 2c, 3 and**  
415 **10b-c**) implies 12.5 m/myr of maximum denudation rate between 22 Ma and 10 Ma. Finally,  
416 the 100 m of maximum elevation difference between S3 and the current local base level in the  
417 upstream area of the Kali River drainage basin (**Figs. 2c and 3**) implies a river incision rate

418 that did not exceed 10 m/myr over the last 10 Myr. Locally, 300 m-deep gorges of the Kali  
419 River imply imply an incision rate of 30 m/myr.

420 The estimated denudation rates are similar to millennial-scale erosion rates derived from  
421  $^{10}\text{Be}$  cosmogenic radionuclides measurements (CRN) on the southern Karnataka plateau  
422 (Gunnell *et al.*, 2007), or slightly lower than  $^{10}\text{Be}$ -derived estimate (c. 15 m/myr) in river  
423 borne sediments from the same region (Mandal *et al.*, 2015). Although time scale (1 myr) and  
424 hypotheses of CRN methods complicate comparisons, altogether same order estimates  
425 derived from different time scales typify slow, steady state denudation regimes of landscapes  
426 mostly controlled by climate rather than by epeirogeny (Beauvais and Chardon, 2013).

427 Over the last 22 Myr, slow denudation (c. 11 m/myr) and dissection have preserved a  
428 Paleogene S1-S2 smooth paleolandscape over the Western Ghats (**Figs. 2b-c, 3 and 10b-c**).

429 This antique paleolandscape is the remnant of a South Indian plateau that once occupied most  
430 of the peninsula, comparable to the current Southern African Plateau (Partridge and Maud,  
431 1987; Burke and Gunnell, 2008). The great extension of the South Indian plateau is attested  
432 to, for instance, by the preservation of large areas of smooth bauxitic paleolandscapes at 900-  
433 1450 m elevation in the Eastern Ghats (Bardossy and Aleva, 1990; see also Subramanian and  
434 Mani, 1979) or by the Sandur relict of the S1-S2 paleolandscape more than 250 km inland the  
435 WGE (Bonnet *et al.*, 2016). The current E-W asymmetric and eastward sloping topographic  
436 profile of the Peninsula (e.g., Gunnell, 1998; Richards *et al.*, 2016) would be due to the  
437 regressive erosion of the plateau by the long east-flowing river systems that mostly preserved  
438 a plateau relict near their headwaters, right above the Western Ghats escarpment as well as  
439 residual patches such as the Eastern Ghats (Jean, 2019). The asymmetrically eroded plateau  
440 model proposed here is an alternative to the c. 20 Ma eastward tilt model of the Peninsula  
441 proposed by Richards *et al.* (2016) to explain the current eastward slope of Southern India.

442 Indeed, negligible Neogene denudation rates documented on either side of the WGE  
443 (Beauvais *et al.*, 2016; Bonnet *et al.*, 2016; present work) imply that the escarpment is at least  
444 50 Ma old and challenge the popular model of uplift and/or rejuvenation of the escarpment in  
445 the Neogene advocated by most authors (e.g., Radhakrishna, 1993; Widdowson and Gunnell,  
446 1999; Mandal *et al.*, 2017). Furthermore, combined geomorphology and Ar-Ar  
447 geochronology of the western coastal lateritic lowland of the Peninsula infers negligible uplift  
448 since c. 50 Ma (Beauvais *et al.*, 2016; Bonnet *et al.*, 2016). Therefore, geomorphological  
449 observations and denudation rates quantified by Ar-Ar geochronology preclude the eastward  
450 tilt model of Richard *et al.* (2016) that requires 30 to 100 m/myr of uplift - and thus  
451 rejuvenation - of the Western margin of the Peninsula since 23 Ma. Our results also imply that  
452 the largest volume of sediments produced from the dissection of the South Indian plateau was  
453 routed towards the eastern margin of the Peninsula.

## 454 **Conclusions**

455 The  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of cryptomelane from supergene manganese ores of the Western  
456 Ghats document three major weathering periods in South India: Early-Mid-Eocene (W1), Late  
457 Eocene-Early Miocene (W2) and Mid-Miocene (W3). These weathering periods coincide  
458 with known global and regional climatic proxies and alternated after c. 22 Ma with periods of  
459 subdued weathering during which landscape has been structured step by step into three  
460 composite lateritic paleolandscapes S1, S2 and S3. The minimum age of each weathering  
461 period determines the abandonment of each paleolandscape, i.e., S1 at 44 Ma, S2 at 22 Ma  
462 and S3 at 10 Ma, which bound three major periods of landscape denudation and shaping, i.e.,  
463 44-22 Ma, 22-10 Ma and 10-0 Ma. Maximum Cenozoic denudation rates in Western Ghats  
464 range from 4.5 to 12.5 m/myr, which confirms previous estimates in South India (Beauvais *et*  
465

466 *al.*, 2016). Our results document very long-term slow denudation of tropical cratonic  
467 mountains typified by the Western Ghats. That persistent topography is a relict of a South  
468 Indian lateritic plateau of Eocene age.

469  
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## 698 699 **FIGURES AND TABLE CAPTION**

700  
701 **Fig. 1. (a)** Simplified geology (adapted from Bonnet et al., 2016 based on Chardon et al.,  
702 2008) of the western part of Peninsular India, and **(b)** 30 m SRTM topography. Location of  
703 studied area (North Kanara region) is shown.

704  
705 **Fig. 2. (a)** Geological map of the study area in North Kanara region with the three  
706 morphogeological strips upon which Mn ore deposits formed; **(b)** Topo-geomorphologic map  
707 of the region showing the distribution area of remnants of three major landsurfaces, S1, S2,

708 and S3, with location of the studied/dated Mn ore deposits; (c) Synthetic geomorphological  
709 section across the study area in upstream Kali river drainage basin (section lines shown in Fig.  
710 2b). Vertical exaggeration = 4.

711  
712 **Fig. 3.** 3-D distribution of relicts of the three major lateritic landsurfaces of the Western Ghats  
713 landscape, S1, S2, and S3; (a) Google-Earth view showing the landscape geomorphology  
714 around the Terali Mn ore deposit, TER, (Image Landsat/Copernicus, Image©2018  
715 DigitalGlobe); (b) Geomorphological interpretation map of this image. The altitudes are those  
716 given by Google Earth (black dots).

717  
718 **Fig. 4.** Field characteristics and petrographic structures of sample DIG-1 collected in the  
719 Diggi Mn ore deposits. (a) Diggi open cast mine; (b) sample DIG-1 showing infiltration Mn  
720 ore in iron duricrust; (c) Polished thin section of sample DIG-1A; (d) microscopic observation  
721 of the polished thin section showing the colloform structure of infiltration Mn ore (C=  
722 cryptomelane; Li= lithiophorite; ns= nsutite G= goethite); (e) micro X-ray fluorescence  
723 analysis showing cryptomelane (C) and goethite (G) determined from a colour code, blue  
724 (Mn) and green (K), and iron in red; (f) Scanning Electron Microscopy (SEM) image of  
725 cryptomelane “needles”; (g) X-ray diffraction diagram of the sample powder.

726  
727 **Fig. 5.** Micro-chemical compositions of cryptomelane obtained by electron probe  
728 microanalyses (EPMA) distributed in a ternary diagram whose poles are Mn, 10 K and 10 Al.

729  
730 **Fig. 6.**  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectra of cryptomelane grains from Mn ore deposits of (a) Diggi and  
731 (b) Illva, with K/Ca (black) and Ar\* (grey) step curves. (SS = Saddle shape)

732  
733 **Fig. 7.**  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectra of cryptomelane grains from Mn ore deposits of (a) Terali, and  
734 (b) Pradhani, with K/Ca (black) and Ar\* (grey) step curves. (HS = Hump shape; SD = Stair  
735 case degassing; SS = Sadde shape)

736  
737 **Fig. 8.**  $^{40}\text{Ar}/^{39}\text{Ar}$  age spectra of cryptomelane grains from Mn ore deposits of (a) Nagari, and  
738 (b) Pradhani, with K/Ca (black) and Ar\* (grey) step curves. (HS = Hump shape)

739  
740 **Fig. 9.** Synthesis of the  $^{40}\text{Ar}/^{39}\text{Ar}$  ages results with individual ages probability curves  
741 accounting for results from this study and previous ones (Bonnet *et al.*, 2016). Each age  
742 probability curve accounts for 1/3 of the total signal integrating individual ages degassing at  
743 least 5%  $^{39}\text{Ar}$  from all the preferred calculated ages (table. 1) weighted by the error margin for  
744 the three sites ( $N_{\text{Sandur}} = 19$  ages,  $N_{\text{Shimoga}} = 10$  ages;  $N_{\text{This study}} = 38$  ages). The calculated ages  
745 are also plotted against the altitude. Altogether, the probability curves and the calculated ages  
746 document major weathering peaks and periods W1, W2 and W3 (vertical colour bands),  
747 which are compared to major trends of the global paleoclimatic curve (from Zachos *et al.*,  
748 2008). PETM = Paleocene-Eocene Thermal Maximum; EECO = Early Eocene Climatic  
749 Optimum; MECO = Mid-Eocene Climatic Optimum; EOC = Early Oligocene Cooling;  
750 LOW = Late Oligocene Warming; MMCO = Mid-Miocene Climatic Optimum. Ages in bold  
751 and arrowed are terminal ages of weathering periods W1 to W3.

752  
753 **Fig. 10.** Landscape and lateritic weathering dynamical evolution in Western Ghats of  
754 Peninsular India illustrating early cryptomelane-rich Mn ores formation at (a) the first  
755 bauxitic step S1 (red), and their preservation over the Cenozoic at each next landscape (b)

756 stage S2 (in blue), and (c) S3 pediment (in green). Coloured dashed lines represent successive  
757 weathering fronts of S1, S2 and S3 profiles. After 10 Ma, the S3 landscape is dissected.

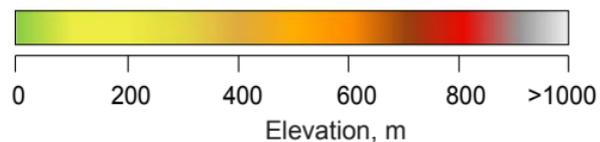
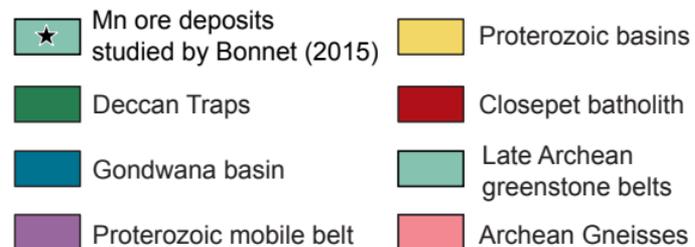
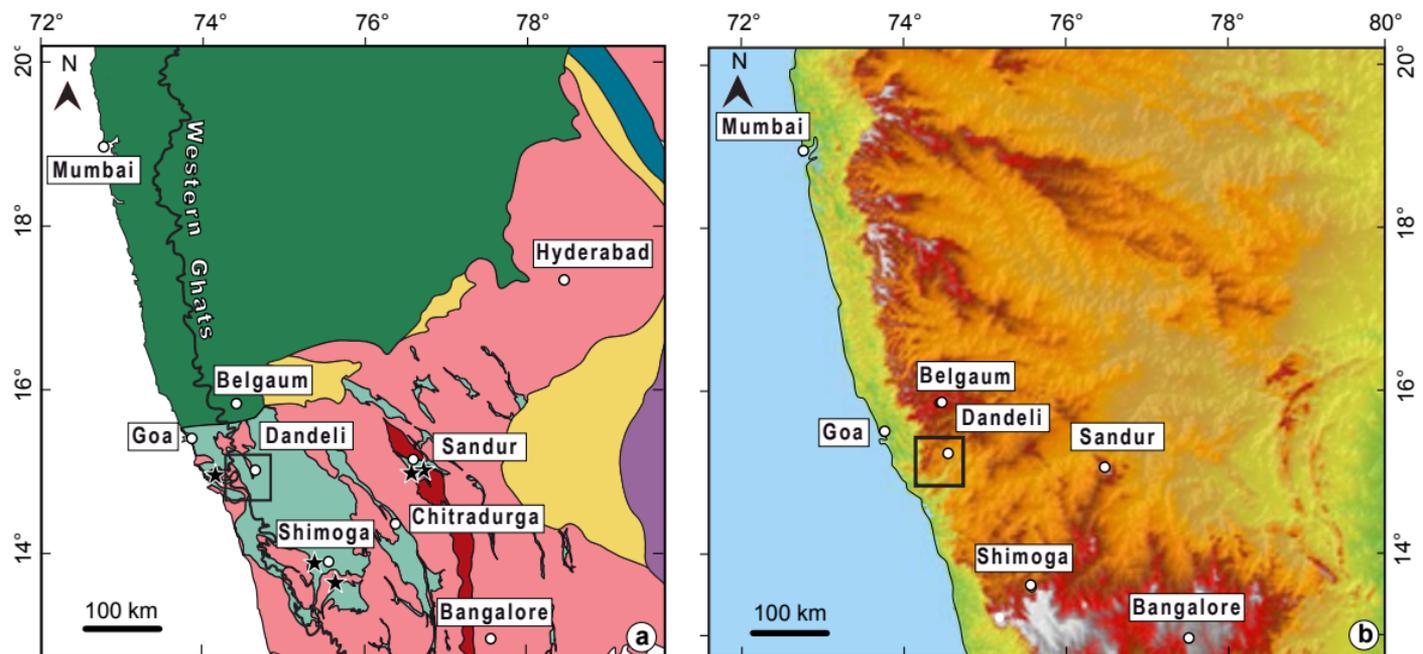
758  
759 **Table 1.** Synthesis of the  $^{40}\text{Ar}/^{39}\text{Ar}$  ages calculated from plateaus in  $^{39}\text{Ar}$  release spectra and  
760 isochrons, with the integrated and the preferred ages.

<b>A</b>												
Sample ID	Altitude (m)	<sup>39</sup> Ar release spectrum			Isochrone					Integrated Age	Preferred age	Comments
		Age ± 2σ, Ma	Step(s)	% <sup>39</sup> Ar	Age ± 2σ, Ma	<sup>40</sup> Ar/ <sup>36</sup> Ar	MSWD	Steps	% <sup>39</sup> Ar	Age ± 2σ, Ma	Age ± 2σ, Ma	
<b>DIGGI</b>												
DIG-1A-T4	623	12.3 ± 0.3	7-11	72	11.3 ± 0.5	318 ± 10	1.11	7-11	72	12.0 ± 0.3	<b>12.3 ± 0.3</b>	Plateau > 70 % <sup>39</sup> Ar
					11.1 ± 0.3	298 ± 4	0.13	5-6, 12-14	21			
DIG-1A-T5	623	11.6 ± 0.2	5-8	71	11.8 ± 0.2	289 ± 5	0.57	5-8	71	11.7 ± 0.5	<b>11.6 ± 0.2</b>	Plateau > 70 % <sup>39</sup> Ar
					11.6 ± 0.2	298 ± 3	1.32	1-4, 7-8	62			
DIG-1A-T6	623	12.3 ± 0.3	7-12	83	12.6 ± 0.2	284 ± 6	1.36	6-7, 9-10, 14-15, 17-18	58	12.4 ± 0.2	<b>12.3 ± 0.3</b>	Plateau > 70 % <sup>39</sup> Ar
DIG-1B-T2	623	13.3 ± 0.2	4-8	85	13.0 ± 0.7	302 ± 31	1.43	4, 6-8	61	13.3 ± 0.3	<b>13.3 ± 0.2</b>	Plateau > 70 % <sup>39</sup> Ar
DIG-1B-T3	623	13.3 ± 0.3	3-9	79	13.3 ± 0.4	296 ± 6	0.69	3-9	79	13.4 ± 0.5	<b>13.3 ± 0.3</b>	Plateau > 70 % <sup>39</sup> Ar
DIG-1B-T4	623	12.4 ± 0.2	9-13	74	12.4 ± 0.2	298 ± 3	1.19	2-3, 10-13	73	12.2 ± 0.5	<b>12.4 ± 0.2</b>	Plateau > 70 % <sup>39</sup> Ar
<b>TERALI</b>												
TER-1A-T1	644	28.7 ± 0.5	6-8	61	28.5 ± 0.4	289 ± 7	2.41	1-4, 6, 8-9	63	28.2 ± 0.5	<b>28.7 ± 0.5</b>	Min of oldest Forced plateau > 50 % <sup>39</sup> Ar
TER-1A-T2	644	32.3 ± 0.4	11-14	49	22.6 ± 0.6	289 ± 3	0.61	2-5, 7-8	10	31.5 ± 0.9	<b>32.3 ± 0.4</b>	Min of oldest Forced plateau < 50 % <sup>39</sup> Ar
TER-1B-T3	644	27.5 ± 0.3	6-8	73	27.8 ± 0.2	278 ± 4	2.88	1, 3, 6-7, 12	63	26.7 ± 1.2	<b>27.5 ± 0.3</b>	Min of oldest Plateau > 70 % <sup>39</sup> Ar
<b>B</b>												
Sample ID	Altitude (m)	<sup>39</sup> Ar release spectrum			Isochrone					Integrated Age	Preferred age	Comments
		Age ± 2σ, Ma	Step(s)	% <sup>39</sup> Ar	Age ± 2σ, Ma	<sup>40</sup> Ar/ <sup>36</sup> Ar	MSWD	Steps	% <sup>39</sup> Ar	Age ± 2σ, Ma	Age ± 2σ, Ma	
<b>NAGARI</b>												
NAG-1B-T2	520	32.0 ± 1.9	1-4	50	32.4 ± 2.0	293 ± 6	0.78	1-4, 7	52	38.0 ± 3.4	<b>32.4 ± 2.0</b>	Best fitted isochrone
		41.2 ± 1.4	5-7	50								
NAG-3A-T3	520	31.3 ± 0.1	9-11	24	31.6 ± 1.1	295 ± 2	2.07	3-4, 9-12	32	43.8 ± 4.5	<b>31.6 ± 1.1</b>	Best fitted isochrone
					50.3 ± 0.4	292 ± 1	1.1	1-2, 5, 7	42			
NAG-3B-T1	520	45.0 ± 1.0	7-11	53	40.6 ± 1.6	301 ± 4	0.5	2-6, 10-11	49	44.3 ± 1.3	<b>45.0 ± 1.0</b>	Plateau > 50 % <sup>39</sup> Ar
NAG-3B-T2	520	44.0 ± 0.9	4-6	78	44.3 ± 0.8	299 ± 4	1.74	2, 4-5	58	43.6 ± 1.3	<b>44.0 ± 0.9</b>	Min of oldest Plateau > 70 % <sup>39</sup> Ar
NAG-3B-T3	520	44.9 ± 3.6	8-10	52	35.3 ± 4.7	297 ± 16	0.25	7, 11-14	28	43.2 ± 2.9	<b>44.9 ± 3.6</b>	Forced plateau > 50 % <sup>39</sup> Ar
					46.4 ± 2.6	297 ± 5	1.88	5-6, 8-9	43			

TABLE. 1a-b

C	Sample ID	Altitude (m)	<sup>39</sup> Ar release spectrum			Isochrone				Integrated Age	Preferred age	Comments	
			Age ± 2σ, Ma	Step(s)	% <sup>39</sup> Ar	Age ± 2σ, Ma	<sup>40</sup> Ar/ <sup>36</sup> Ar	MSWD	Steps	% <sup>39</sup> Ar	Age ± 2σ, Ma		Age ± 2σ, Ma
<b>ILLVA</b>													
	ILV-1B-T4	524	12.7 ± 0.8	2-8	92	12.7 ± 0.9	296 ± 9	1.11	2-8	92	12.6 ± 0.8	<b>12.7 ± 0.8</b>	Plateau > 70 % <sup>39</sup> Ar
	ILV-1B-T5	524	12.3 ± 0.1	6-9	73	12.3 ± 0.1	298 ± 3	1.22	2, 7-9	57	12.3 ± 0.5	<b>12.3 ± 0.1</b>	Plateau > 70 % <sup>39</sup> Ar
	ILV-2C-T3	524	12.1 ± 1.3	1-9	100	12.1 ± 1.6	29 ± 40	0.14	1, 4-6, 8	82	12.1 ± 1.3	<b>12.1 ± 1.3</b>	Plateau > 70 % <sup>39</sup> Ar
	ILV-2C-T4	524	12.9 ± 0.3	7-9	70	12.9 ± 0.7	295 ± 48	0.46	6-9	85	12.9 ± 0.3	<b>12.9 ± 0.3</b>	Plateau > 70 % <sup>39</sup> Ar
	ILV-3A-T1	524	13.1 ± 0.4	6-7	63	13.2 ± 0.2	300 ± 7	2.7	5-6, 10-12	48	13.1 ± 0.2	<b>13.1 ± 0.4</b>	Forced plateau > 50%
	ILV-3A-T3	524	14.0 ± 0.7	6-10	76	14.0 ± 0.8	304 ± 79	0.4	7-9	66	14.1 ± 2.9	<b>14.0 ± 0.7</b>	Plateau > 70 % <sup>39</sup> Ar
	ILV-3C-T4	524	13.6 ± 0.3	1-6	65	13.5 ± 0.3	294 ± 16	1.14	3-6, 8	61	13.7 ± 0.4	<b>13.6 ± 0.3</b>	Plateau > 50 % <sup>39</sup> Ar
	ILV-6A-T1	524	11.3 ± 0.1	9-11	50	11.3 ± 0.1	293 ± 2	1.84	1-3, 4-5, 9-11	59	11.6 ± 0.7	<b>11.3 ± 0.1</b>	Best fitted isochrone
	ILV-6A-T2	524	11.6 ± 0.2	8-11	79	11.4 ± 0.1	296 ± 3	0.94	3, 7, 10-11, 14-15	42	11.6 ± 0.2	<b>11.6 ± 0.2</b>	Plateau > 70 % <sup>39</sup> Ar
	ILV-6A-T3	524	10.0 ± 0.2	7-9	84	10.1 ± 0.1	297 ± 6	0.45	1, 4, 6, 8-9	56	10.0 ± 0.2	<b>10.0 ± 0.2</b>	Plateau > 70 % <sup>39</sup> Ar
	ILV-6B-T1	524	11.0 ± 0.1	7-9	55	11.0 ± 0.1	289 ± 4	2.85	2-3, 7-9, 12	64	11.1 ± 0.2	<b>11.0 ± 0.1</b>	Pseudo-Plateau > 50 % <sup>39</sup> Ar
	ILV-6B-T2	524	14.4 ± 0.4	7-9	62	14.5 ± 0.1	292 ± 2	1.24	3-5, 7, 9	55	14.0 ± 1.0	<b>14.5 ± 0.1</b>	Best fitted isochrone
	ILV-6B-T3	524	12.0 ± 0.2	8-11	66	11.9 ± 0.2	310 ± 6	0.99	5, 8-11	69	12.8 ± 0.8	<b>12.0 ± 0.2</b>	Plateau > 50 % <sup>39</sup> Ar
<b>PRADHANI</b>													
	PRA-1B-T1	620	25.2 ± 0.2	5-6	61	-	-	-	-	-	25.2 ± 1.7	<b>25.2 ± 0.2</b>	Pseudo-Plateau > 50 % <sup>39</sup> Ar
	PRA-1B-T2	620	29.8 ± 0.4	8-10	48	24.2 ± 0.2	276 ± 3	1.21	2, 4-5	8	28.6 ± 4.2	<b>29.8 ± 0.4</b>	Forced plateau < 50 % <sup>39</sup> Ar
	PRA-1B-T3	620	45.4 ± 0.9	7-9	50	30.8 ± 1.7	277 ± 8	0.96	2-4, 12	18	43.8 ± 2.2	<b>45.4 ± 0.9</b>	Forced plateau ~ 50 % <sup>39</sup> Ar
						44.9 ± 0.6	289.5 ± 27	2.13	1, 7, 9, 11	40			
	PRA-2A-T1	620	24.5 ± 0.2	7-9	58	24.6 ± 0.2	252 ± 19	4.7	2, 7-9	60	24.5 ± 0.6	<b>24.5 ± 0.2</b>	Plateau > 50 % <sup>39</sup> Ar
	PRA-2A-T3	620	23.7 ± 0.2	10-16	78	23.7 ± 0.2	272 ± 28	0.44	1, 3, 10-14	61	23.7 ± 0.4	<b>23.7 ± 0.2</b>	Plateau > 70 % <sup>39</sup> Ar
	PRA-2A-T5	620	21.6 ± 0.1	9-15	79	21.6 ± 0.1	294 ± 9	1.07	1-2, 9-16	81	21.5 ± 0.3	<b>21.6 ± 0.1</b>	Plateau > 70 % <sup>39</sup> Ar
	PRA-2B-T1	620	27.8 ± 0.2	15-22	59	20.3 ± 1.1	294 ± 11	0.84	4, 7-11	11	27.5 ± 0.6	<b>27.8 ± 0.2</b>	Plateau > 50 % <sup>39</sup> Ar
	PRA-2B-T2	620	22.4 ± 0.2	12-15	47	19.9 ± 0.6	292 ± 20	1.05	2, 5-7	4	22.5 ± 0.4	<b>22.4 ± 0.2</b>	Forced plateau < 50 % <sup>39</sup> Ar
	PRA-2B-T4	620	23.4 ± 0.1	9-12	62	21.2 ± 0.5	291 ± 1	4.81	3-6	6	23.6 ± 0.7	<b>23.4 ± 0.1</b>	Plateau > 50 % <sup>39</sup> Ar
	PRA-3B-T1	620	32.8 ± 0.2	10-12	54	29.1 ± 0.7	277 ± 6	2.73	2-6	8	36.2 ± 4.3	<b>32.8 ± 0.2</b>	Plateau > 50 % <sup>39</sup> Ar
	PRA-3B-T2	620	37.5 ± 0.5	11-13	58	28.7 ± 0.8	277 ± 4	1.1	1-3, 6-7	6	41.6 ± 8.7	<b>37.5 ± 0.5</b>	Forced plateau > 50 % <sup>39</sup> Ar

TABLE. 1c



Study area (see Fig. 2)

FIGURE. 1 (Jean et al., 2019)

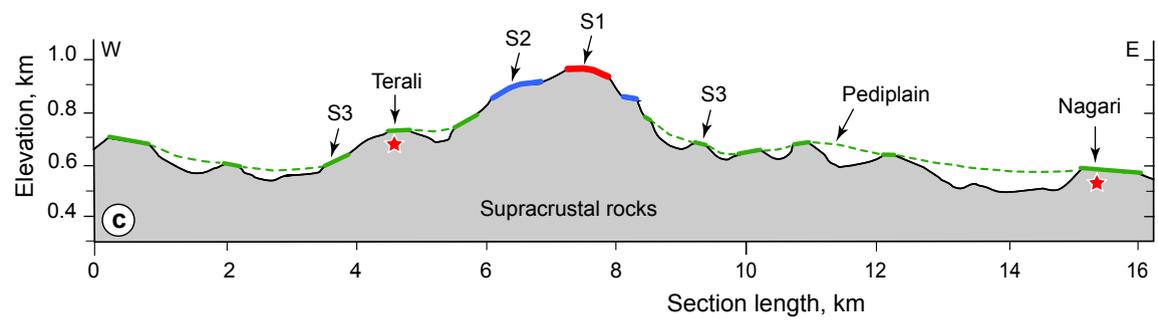
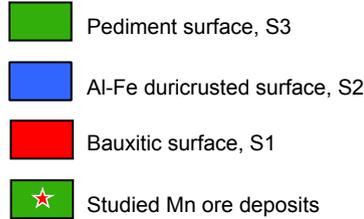
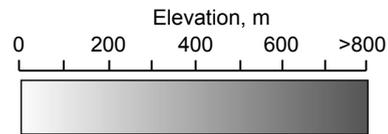
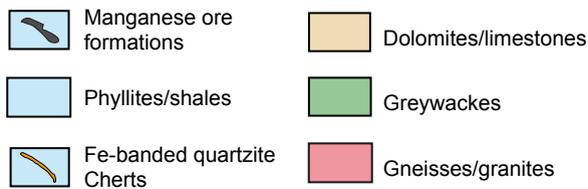
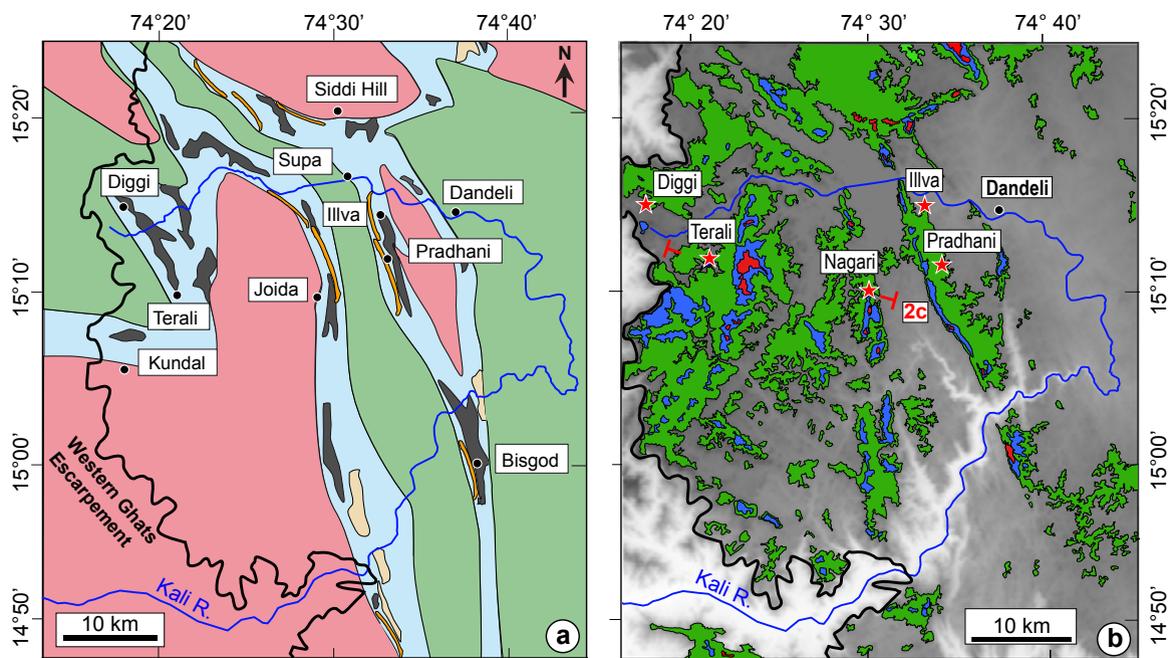
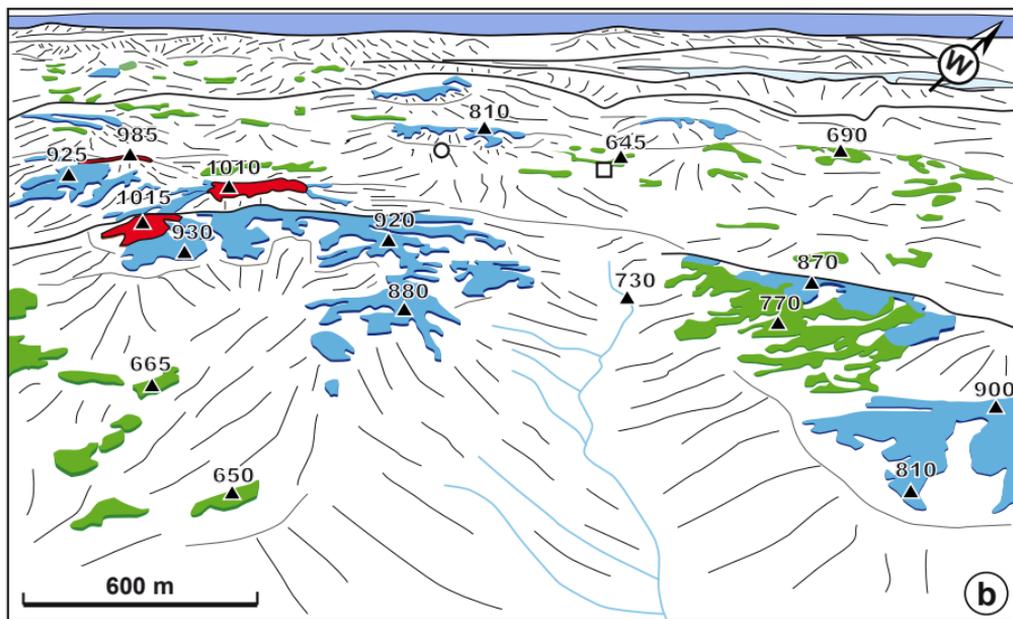


Figure. 2 (Jean et al., 2019)



■ S3 pediment surface

■ S2 Al-Fe duricrusted surface

■ S1 bauxitic surface

FIGURE. 3 (Jean et al., 2019)

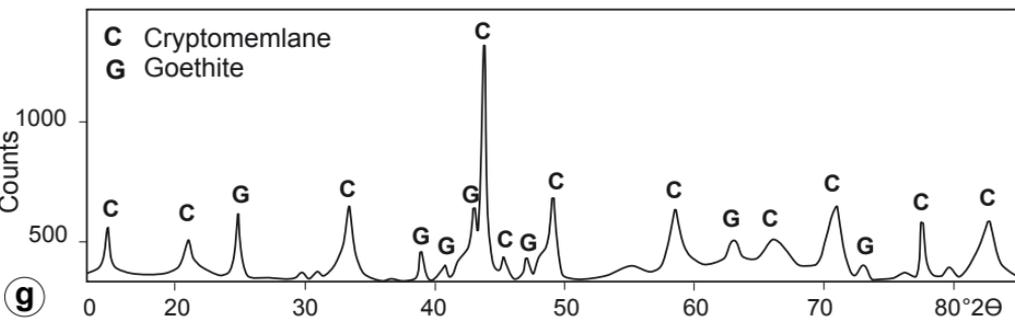
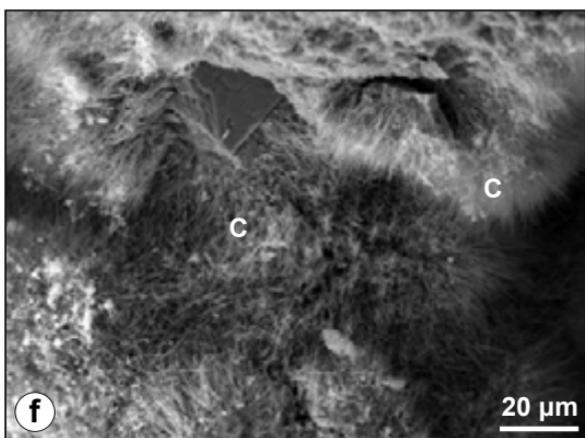
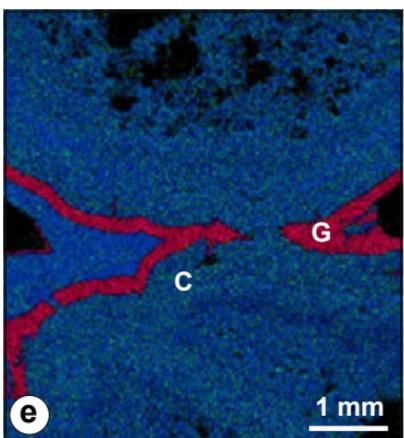
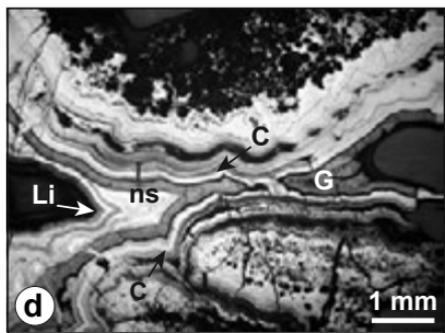
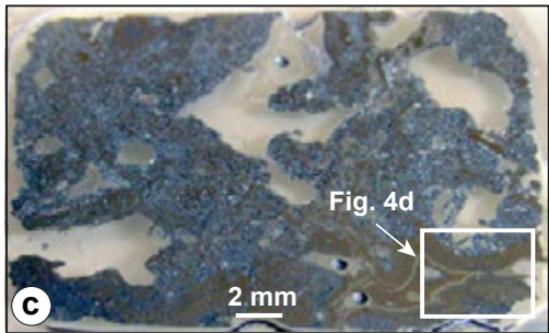


FIGURE. 4 (Jean et al., 2019)

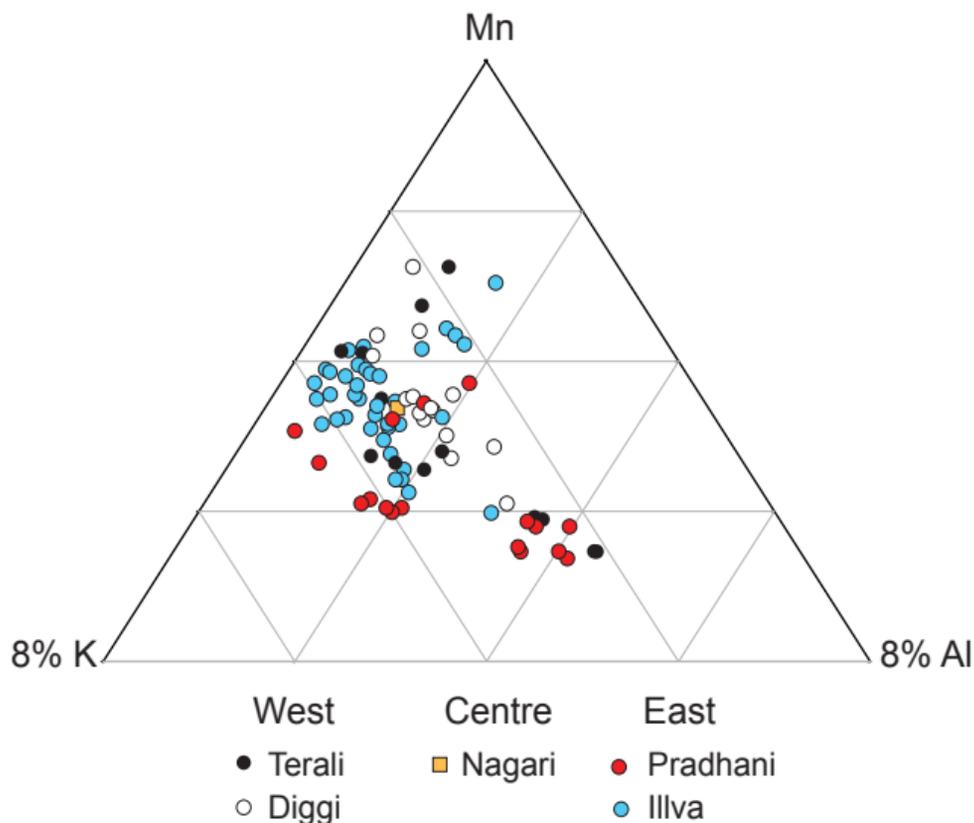


FIGURE. 5 (Jean et al., 2019)

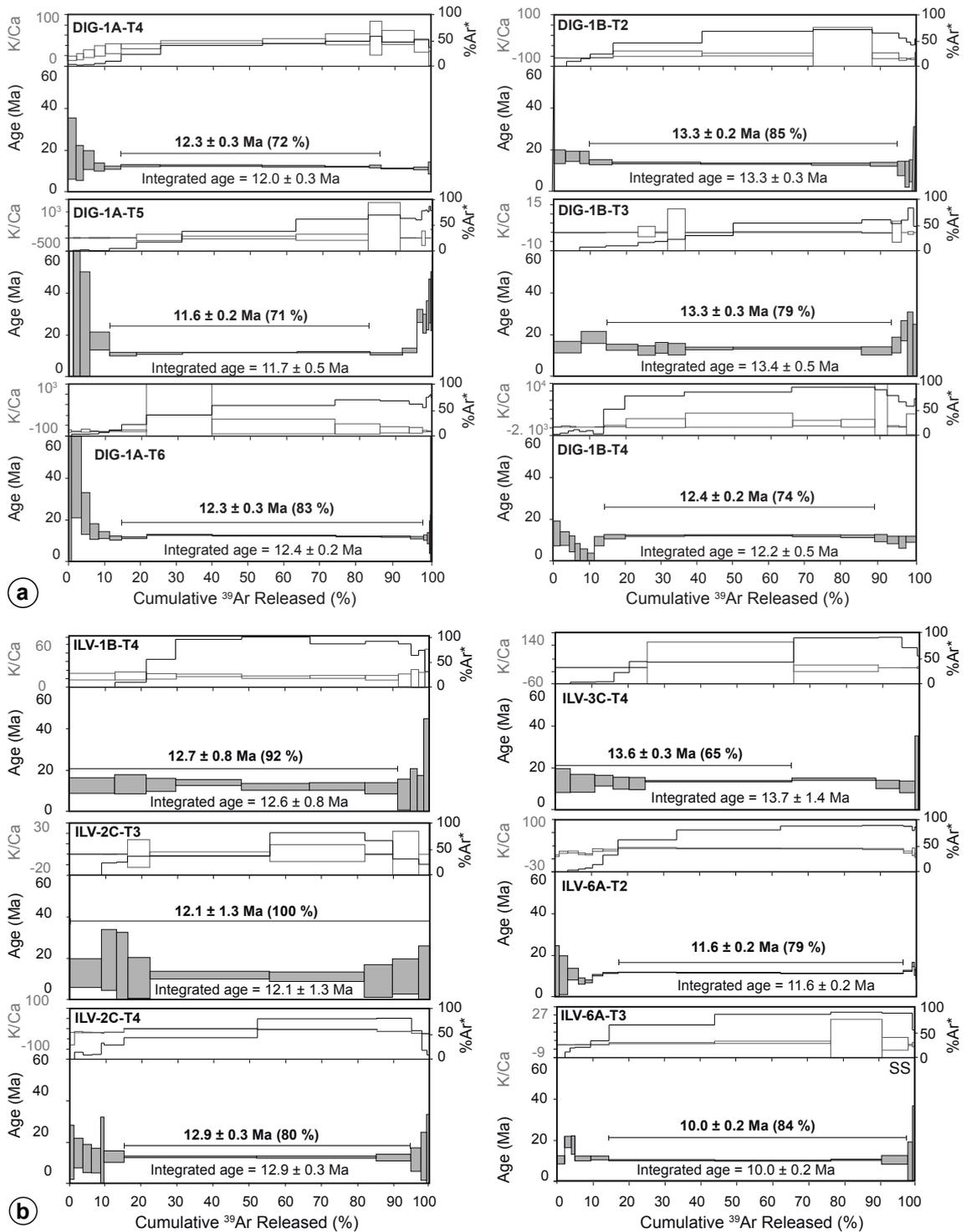


FIGURE. 6 (Jean et al., 2019)

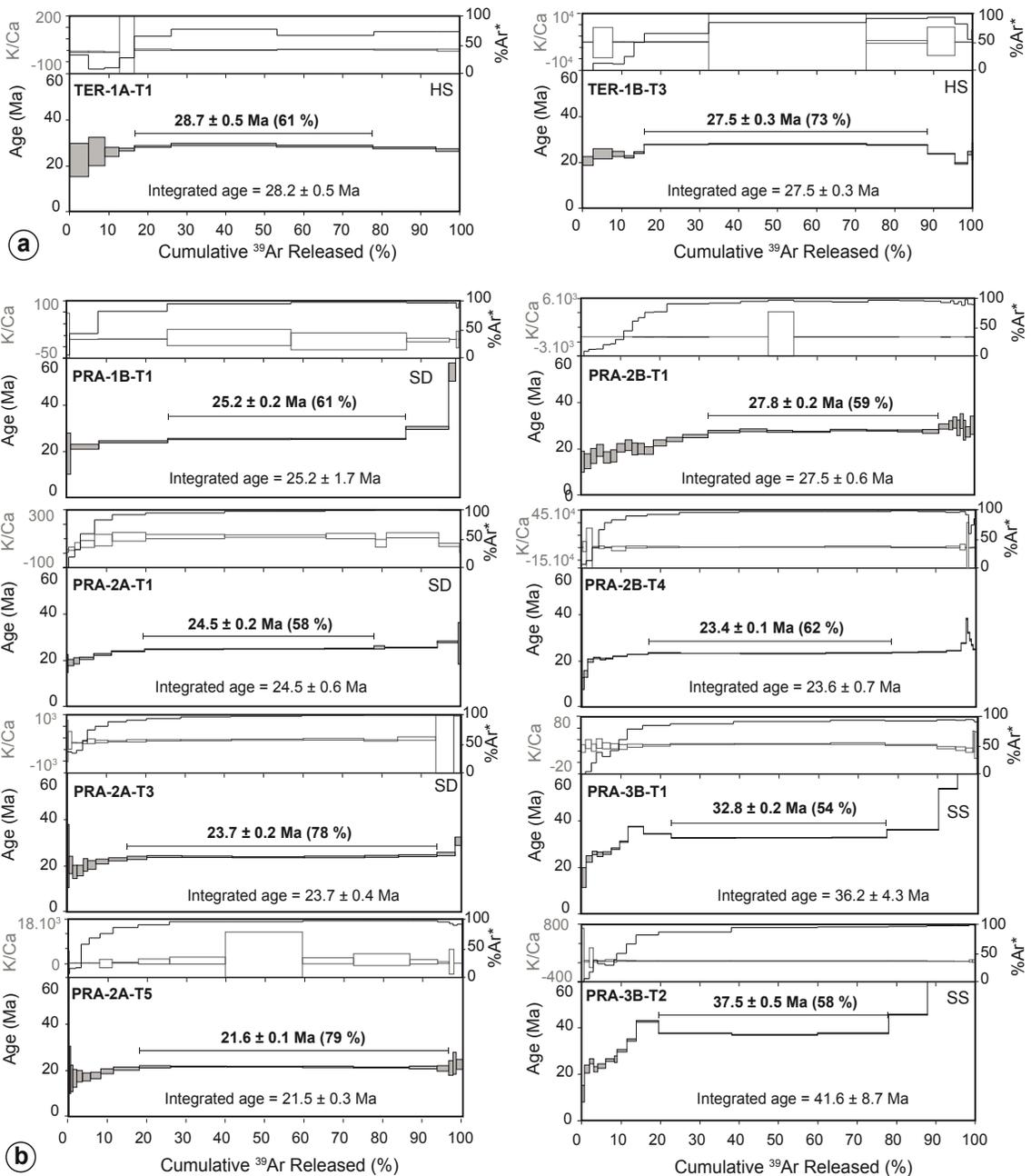


FIGURE. 7 (Jean et al., 2019)

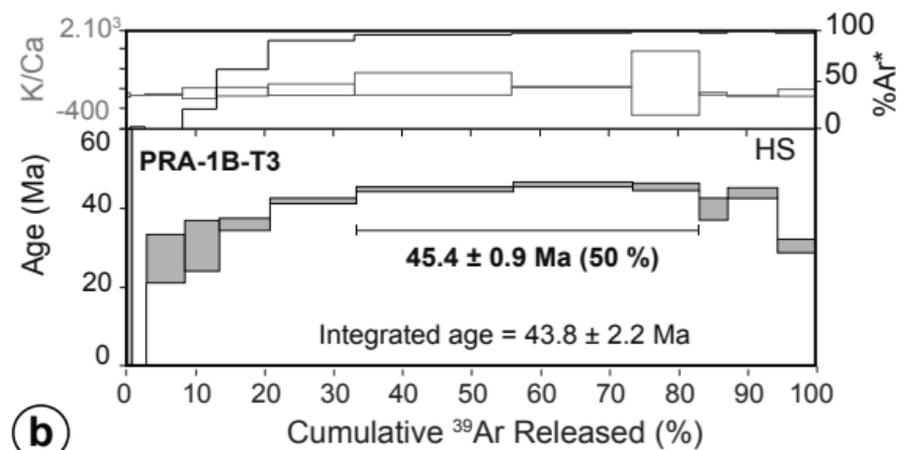
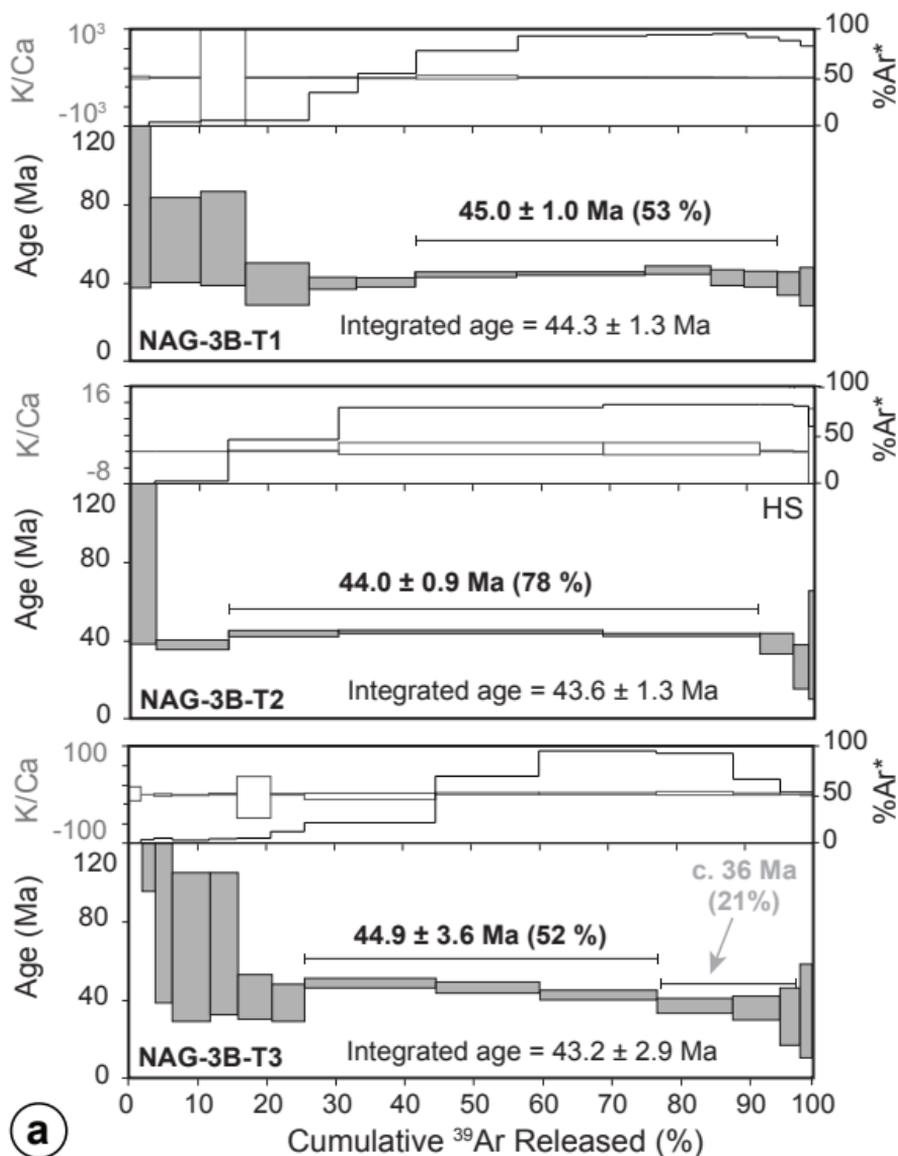


FIGURE. 8 (Jean et al., 2019)

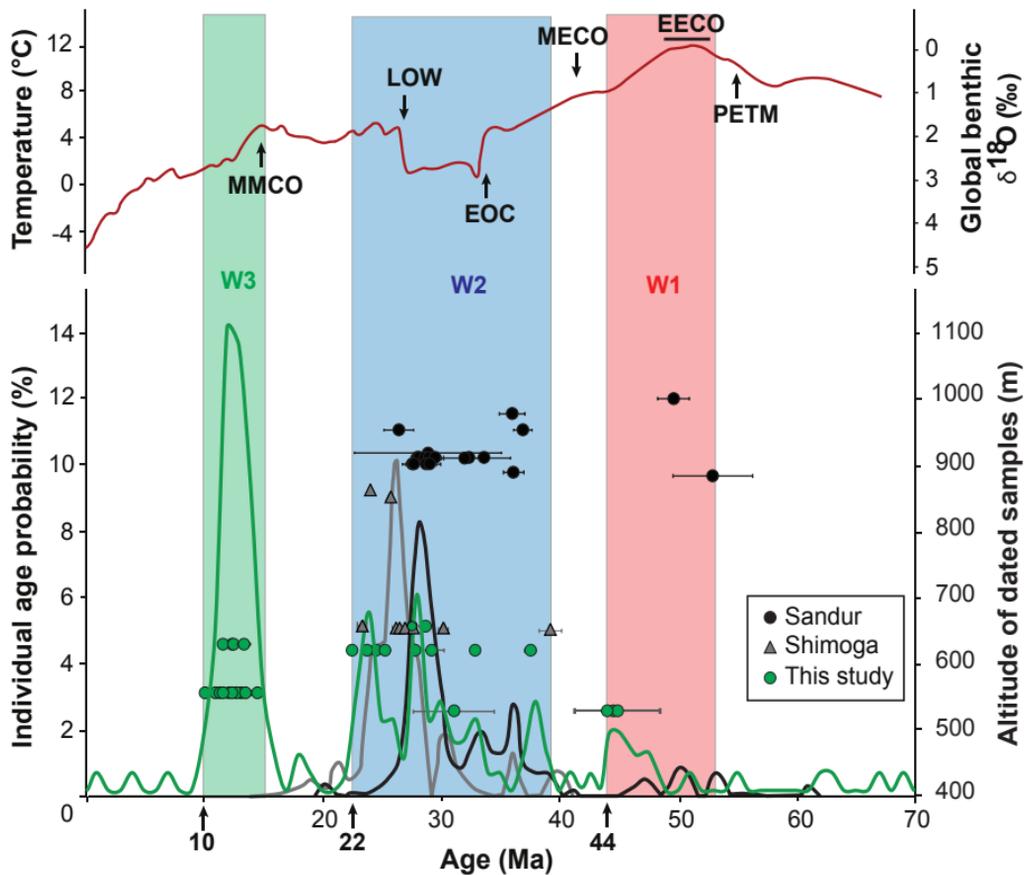


FIGURE. 9 (Jean et al., 2019)

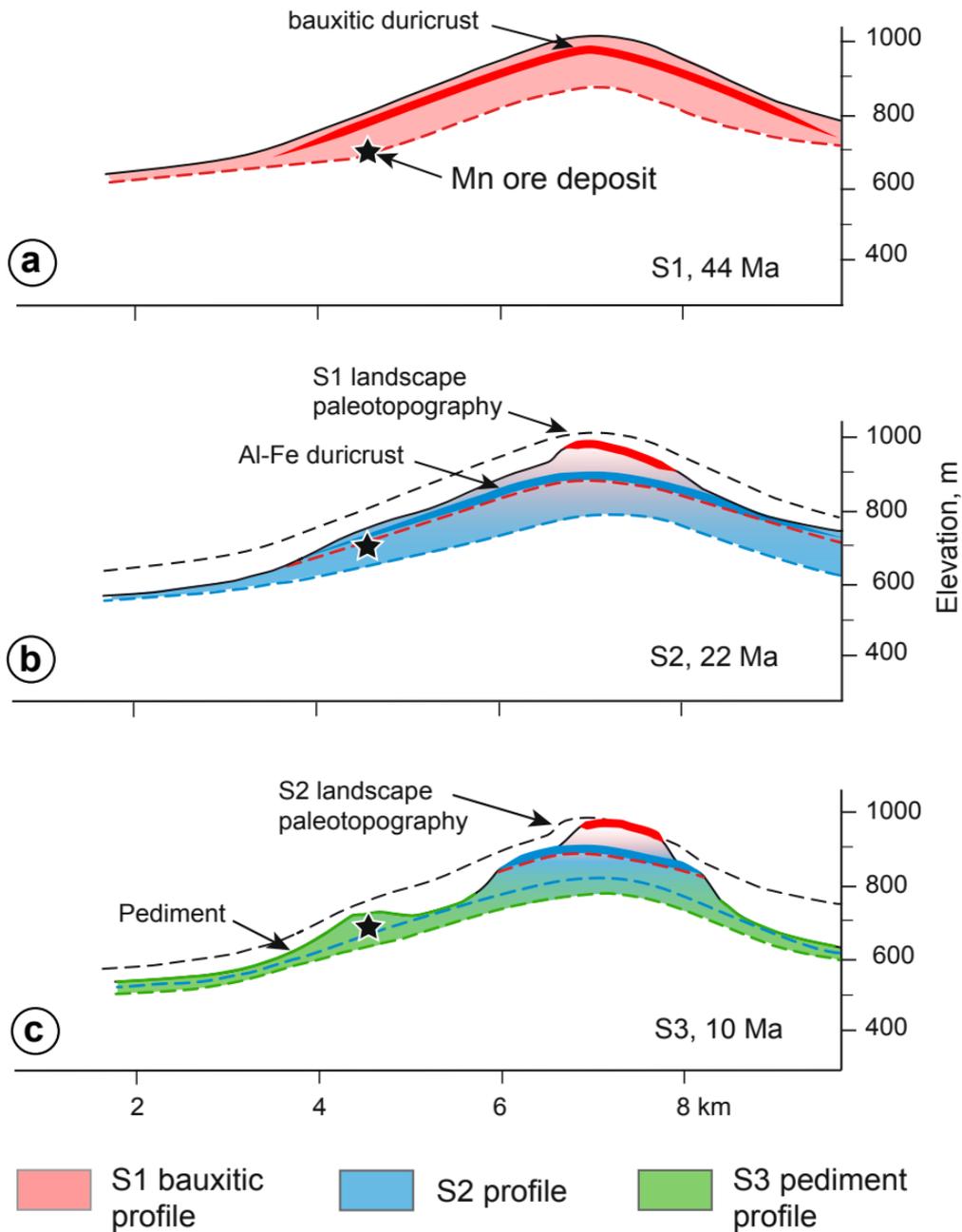


FIG. 10 (Jean et al., 2019)