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# West Africa in Rodinia: High quality paleomagnetic pole from the ~860 Ma Manso dyke swarm (Ghana)

**Paul Yves Jean Antonio**<sup>1,2,\*</sup>, Lenka Baratoux<sup>2</sup>, Ricardo I. F. Trindade<sup>1</sup>, Sonia Rousse<sup>2</sup>, Ayite Anani<sup>3</sup>, Cristiano Lana<sup>4</sup>, Mélina Macouin<sup>2</sup>, Adu E.W. K.<sup>5</sup>, Caroline Sanchez<sup>6</sup>, Marco A. L. Silva<sup>4</sup>, Anne-Sophie Firmin<sup>2</sup>, Carmen I. Martinez-Dopico<sup>7</sup>, Arnaud Proietti<sup>8</sup>, Prince Ofori Amponsah<sup>5</sup>, Patrick Asamoah Sakyi<sup>5</sup>

1. Universidade de São Paulo (USP), Instituto de Astronomia, Geofísica e Ciências Atmosféricas (IAG), Rua do Matão, 1226, Cidade Universitária, 05508-090 São Paulo – SP, Brazil.
2. Université Paul Sabatier (UPS) - Toulouse III, Observatoire Midi-Pyrénées (OMP), Géosciences Environnement Toulouse (GET), 14 Avenue Edouard Belin 31400 Toulouse – France.
3. Ghana Geological Survey Authority, 6, 7th Avenue West Ridge, Box M80, Accra – Ghana.
4. Universidade Federal de Ouro Preto (UFOP), Applied Isotope Research Group, Departamento de Geologia, Escola de Minas, Rua Diogo de Vasconcelos, 122, 35400-000 Ouro Preto – MG, Brazil.
5. Department of Earth Science, School of Physical and Mathematical Sciences, University of Ghana, P.O. Box LG 58, Legon-Accra, Ghana.
6. GEOPS, Université Paris-Sud, CNRS, Université Paris-Saclay, Rue du Belvédère, Bât. 504, 91405Orsay, France.
7. INGEIS- Instituto de Geocronología y Geología Isotópica. Av. Int. Güiraldes, Ciudad Universitaria, Ciudad Autónoma de Buenos Aires – Argentina.
8. Centre de Microcaractérisation Raimond Castaing, 3 Rue Caroline Aigle, 31400 Toulouse – France

\* **E-mail address:** [paulantonio0931@gmail.com](mailto:paulantonio0931@gmail.com)

## HIGHLIGHTS

- **Primary origin for the ~860 Ma Manso dyke magnetic remanence confirmed by high magnetic stability and a baked contact test**
- **High-latitude position for West Africa between 915 and 860 Ma.**
- **The new ~860 Ma high-quality paleomagnetic pole for West Africa constrains its position in Rodinia.**
- **Paleomagnetically viable long-lived WABAMGO configuration (West Africa-Baltica-Amazonia-Congo) between ~1200 and 800 Ma.**
- **Closure of Nuna's ocean led to the collision of WABAMGO with Laurentia forming Rodinia.**



36 **ABSTRACT**

1  
2 37 The paleogeography of the Meso-Neoproterozoic Rodinia supercontinent remains  
3  
4 38 debated partly because many stable cratons still lack reliable paleomagnetic data for this period.  
5  
6 39 A new geochronological and paleomagnetic study was conducted on the NNW-trending Manso  
7  
8 40 dyke swarm of southern West Africa (Ghana) to clarify the position of this unconstrained  
9  
10 41 continent in Rodinia. Two U-Pb apatite ages of  $857.2 \pm 8.5$  Ma and  $855 \pm 16$  Ma agree with  
11  
12 42 one previous baddeleyite age, indicating a  $\sim 860$  Ma emplacement age for the Manso dykes. A  
13  
14 43 characteristic remanent magnetization (ChRM) was isolated by stable single to pseudo-single  
15  
16 44 domain (SD-PSD) magnetite. Well constrained site mean directions obtained for 13 dykes lead  
17  
18 45 to a mean direction for the Manso dyke swarm of  $D_m = 181.9^\circ$ ,  $I_m = -77.2^\circ$  ( $N = 13$ ,  $\alpha_{95} = 7.6^\circ$ ,  
19  
20 46  $k = 30.6$ ), yielding a paleomagnetic pole at  $177.6^\circ\text{E}$ ,  $28.3^\circ\text{S}$ , ( $A_{95} = 12.7^\circ$   $K = 11.6$ ). Two  
21  
22 47 clusters of opposite inclination pass a reversal test (C-class) and the primary origin is supported  
23  
24 48 by a positive baked contact test, satisfying all the seven R-criteria to provide the first West  
25  
26 49 African Tonian key paleomagnetic pole. This key pole indicates a polar latitude for the West  
27  
28 50 Africa craton was during the emplacement of the  $\sim 860$  Manso dykes. A compilation of reliable  
29  
30 51 paleomagnetic poles for West Africa, Baltica, Amazonia and Congo-São Francisco cratons  
31  
32 52 suggests that these cratons were together between  $\sim 1200$  and  $800$  Ma in a long-lived  
33  
34 53 WABAMGO configuration. We suggest that the collision of this block with Laurentia along  
35  
36 54 the Grenvillian-Sunsás orogens closed the external Nuna Ocean and formed Rodinia by  
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38 55 extroversion.  
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49 56 **Keywords:** West Africa, Neoproterozoic, Tonian, Rodinia, paleomagnetism.  
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## 58 1. INTRODUCTION

1  
2  
3 59 The Earth's geodynamics at the Mesoproterozoic–Neoproterozoic transition was  
4  
5 60 marked by the making and unmaking of the Rodinia supercontinent, which duration and  
6  
7  
8 61 configuration are still subject of debate ([Condie, 2002](#); [Dalziel, 1997](#); [Evans, 2009](#); [Hoffman,](#)  
9  
10 62 [1991](#); [Li et al., 2013](#); [Li et al., 2008](#); [Meert, 2001](#); [Meert and Torsvik, 2003](#); [Merdith et al.,](#)  
11  
12 63 [2017](#); [Moore, 1991](#); [Pisarevsky et al., 2003](#); [Sears and Price, 1978](#); [Wen et al., 2018](#); [Wingate](#)  
14  
15 64 [et al., 2002](#)). In all models, Laurentia is considered as the central piece of Rodinia, surrounded  
16  
17 65 by passive margins during the late Neoproterozoic, in a similar way to the place occupied by  
18  
19  
20 66 the African plate during the Phanerozoic ([Bond et al., 1984](#); [Hoffman, 1991](#)). Regarding the  
21  
22 67 paleomagnetic database for Rodinia, Laurentia has a substantial number of reliable  
23  
24  
25 68 paleomagnetic poles between ~1270 and 1000 Ma, but the ~1000–800 Ma interval lack of high-  
26  
27 69 quality data ([Evans, 2009](#)). Around Laurentia, the models place Baltica along the northeastern  
28  
29  
30 70 coast of Laurentia/Greenland in the northern hemisphere or, as an alternative, in an inverted  
31  
32 71 position ([Hartz and Torsvik, 2002](#)). Siberia is considered to be close to Laurentia but its relative  
33  
34  
35 72 orientation and distance are debated ([Li et al., 2008](#); [Piper, 2007](#); [Pisarevsky and Natapov, 2003](#);  
36  
37 73 [Sears and Price, 1978](#); [Sears and Price, 2000](#)). The most reported position for Siberia is facing  
38  
39  
40 74 the (present-day) northwest margin of Laurentia ([Dalziel, 1997](#); [Hoffman, 1991](#); [Li et al., 2008](#);  
41  
42 75 [Pisarevsky and Natapov, 2003](#)). But an alternative position in the southern hemisphere near the  
43  
44 76 North China craton was also proposed ([Evans, 2009](#)). Considered as neighbors in most  
45  
46  
47 77 supercontinents (Columbia, Rodinia and Pangea), these three cratons are defined as the “strange  
48  
49 78 attractors” by [Meert \(2014\)](#). The Amazonia, West Africa and Rio de la Plata cratons are  
50  
51  
52 79 unconstrained by palaeomagnetic data during the ~1000–700 Ma interval, but they are usually  
53  
54 80 placed in proximity to western Laurentia ([Evans, 2009](#)). Coherence between these blocks but  
55  
56  
57 81 with slight differences in orientation in different reconstructions led [Meert \(2014\)](#) to call them  
58  
59 82 the “spiritual interlopers”. Note that at the peak of Rodinia continental assembly at ~950–850  
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61  
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83 Ma, only four continents (Baltica, São Francisco, North China, and Siberia) exhibit robust  
84 paleomagnetic data ([Merdith et al., 2017](#)). This emphasizes the still scarce paleomagnetic  
85 database for Rodinia event in its "golden age".

86 The peak of continental Rodinia assembly precedes a drastic change in paleolatitude  
87 from a high-latitude for the Rodinian landmasses to a low-latitude paleogeography, which  
88 occurred at ~800 Ma, before its breakup at ~750 Ma ([Li et al., 2008](#)). This rotation began after  
89 the emplacement of a large superplume beneath the polar landmasses at ~840 Ma, triggering  
90 large magmatism and rifting ([Li et al., 2003](#)). Recently, some authors argued that these events  
91 can be better explained by a Tonian inertial interchange true polar wander (IITPW), but its  
92 amplitude, characteristics (single shift or TPW oscillations), and duration are debated ([Jing et](#)  
93 [al., 2019](#); [Li et al., 2004](#); [Maloof et al., 2006](#); [Niu et al., 2016](#); [Swanson-Hysell et al., 2012](#)).  
94 From an environmental point of view, no glacial deposits were observed in the landmasses  
95 during the polar position of Rodinia at ~950–850 Ma ([Li et al., 2013](#)), but more constrained are  
96 needed since climatic models depends strongly on the Tonian (1000–720 Ma) paleogeography  
97 ([Donnadieu et al., 2004](#)). The ~812–790 Ma interval is characterized by the Neoproterozoic  
98 Bitter Springs Anomaly (BSA), a large negative  $\delta^{13}\text{C}$  excursion which can be associated with  
99 some indicators of increasing oxygenation of the ocean and atmosphere during the radiation of  
100 early eukaryotes ([Swanson-Hysell et al., 2015b](#)).

101 Therefore, a precise and reliable Tonian paleogeography is crucial to understand the  
102 impact of the Rodinia supercontinent and the magmatic events it encompasses on the Earth's  
103 system. In this contribution, we performed a detailed paleomagnetic study on the ~860 Ma  
104 Manso dyke swarm ([Baratoux et al., 2019](#)) associated with new U-Pb apatite dating to obtain  
105 the first Tonian key pole for West Africa. Our first well constrained West Africa key  
106 paleomagnetic pole allows us to propose the existence of a long-lived WABAMGO

107 juxtaposition between West Africa, Baltica, Amazonia and Congo-São Francisco cratons,  
108 which collision with Laurentia led to the Apex of Rodinia supercontinent.

109

## 110 2. GEOLOGICAL SETTING

111 The West African Craton is composed of two Proterozoic Shields (Reguibat Shield in  
112 the north and Leo-Man Shield in the south) stabilized at about ~2 Ga, and separated by the  
113 Upper Proterozoic–Paleozoic sedimentary Taoudeni Basin ([Black et al., 1979](#)) (**Fig. 1**). The  
114 Ghanaian Paleoproterozoic domain (within the Baoulé-Mossi domain) is composed of an  
115 association of granitoids and five northeastern trending greenstone belts (Bole-Nagandi, Bui,  
116 Sefwi, Ashanti, and Kibi-Winneba belts from west to east, respectively) ([Feybesse et al., 2006](#))  
117 (**Fig. 1**). These greenstones and the associated sedimentary basins were deformed during the  
118 ~2100–2000 Ma Eburnean Orogeny ([Bonhomme, 1962](#)). These two Proterozoic Shields  
119 underlie Meso-Neoproterozoic Basins ([Affaton et al., 1991](#)). The older sediments of the Volta  
120 basin (Lower Voltaian) in southern Ghana were deposited at ~1000 Ma. The southeastern limit  
121 of the Volta basin is bordered by the development of the Dahomeyide belt, the southern  
122 extension of the Pan-African belts ([Affaton et al., 1991](#)) (**Fig. 1**). These Neoproterozoic events  
123 have strongly affected the northern West African Craton, where the sedimentary sequences and  
124 dykes are folded and deformed along shear zones in the Anti-Atlas Orogen (**Fig. 1**) ([Samson et  
125 al., 2004](#)), while the Leo-Man Shield in turn remained stable.

126 Twenty-six distinct dyke swarms were identified in the West African Craton by  
127 aeromagnetic mapping according to their orientation ([Jessell et al., 2015](#)). In the Leo-Man  
128 Shield, Paleoproterozoic–Mesoproterozoic dykes are represented by the ~1790 Ma Libiri  
129 swarm, the ~1790 Korsimoro swarm, and the ~1520 Essakane swarm ([Baratoux et al., 2019](#)).  
130 Paleomagnetic poles from greenstone rocks and Paleo- to Mesoproterozoic dykes were

131 previously reported by [Piper and Lomax \(1973\)](#). Two Neoproterozoic dyke swarms from Ghana  
132 were recently dated by U-Pb baddeleyite at  $915 \pm 7$  Ma for the N070° Oda dyke swarm, and  
133  $867 \pm 16$  Ma for the N355° Manso dyke swarm ([Baratoux et al., 2019](#)) (**Fig. 1**). A younger  
134 generation of basaltic dykes was also recognized in the northeastern part of Ghana/southern  
135 Burkina Faso with an U-Pb baddeleyite age of  $198 \pm 16$  Ma (Houde dyke swarm) and was  
136 related to the Central Atlantic Magmatic Province (CAMP) ([Baratoux et al., 2019](#)).

137 In this study, we sampled the ~860 Ma NNW-trending Manso dykes and one dyke  
138 (GH07) of the ~915 ENE- trending Oda dyke swarm (**Fig. 1**). The Manso dykes have mainly a  
139 NNW-direction conjugated to a NNE-direction for some branches of the dyke swarm, and are  
140 ~50–100 m to the geophysical signature but their contact with the host rock was not observed  
141 in the field. They are fresh, coarse to medium-grained dolerites composed mainly of plagioclase  
142 and clinopyroxene (augite) with Fe-Ti oxides. Rare orthopyroxene, altered olivine, baddeleyite,  
143 and sulfide were also observed ([Baratoux et al., 2019](#)). Fine-grained lamprophyre dykes  
144 containing micas and some titanite occur in the Ahafo mine. These Neoproterozoic dykes are  
145 undeformed, and they crosscut the Paleoproterozoic basement and Paleoproterozoic regional  
146 tectonic structures.

## 147 **FIGURE 1**

### 148 **3. METHODS**

#### 149 **3.1. Sampling**

150 Due to the dense vegetation and the occurrence of a thick ( up to ~30m) laterite cover, the  
151 outcrops of mafic dykes in Ghana are restricted to the rivers, isolated blocks (**Fig. 2A, B**), and  
152 fresh outcrops from mine pits. In March 2019 we sampled 121 oriented cylindrical cores using  
153 a portable gasoline-powered rock drill, as well as eight hand-samples in the Ahafo mine pit  
154 (Newmont Company), for a total of 16 sites. According to the field orientation, 15 dykes are

155 from the ~860 Ma NNW-trending Manso dyke swarm and one dyke (GH07) is from the ~915  
156 Ma E-trending Oda dyke swarm ([Antonio et al., 2019](#); [Baratoux et al., 2019](#)). The number of  
157 samples by site (5-8) were restricted essentially due to agreement with local communities and  
158 the mining company. Both cores and hand-samples were oriented using solar and magnetic  
159 compasses, and no declination difference was observed. The 16 sites sampled cover a vast  
160 geographical area (~41,500 km<sup>2</sup>) from the capital Accra in southeast Ghana to Sunyani in the  
161 northwest via Cape Coast in the south ([Fig. 1](#) & site coordinates provided in [Table 1](#)).

### 162 **3.2. Geochronology**

163 Two samples (GH05 and GH16) were selected for U-Pb geochronology on apatite. Apatite  
164 separation was performed in the Géosciences Environnement Toulouse (GET, France)  
165 laboratory. Hand-samples were crushed and sieved to collect the mineral fraction below 400  
166 µm. The low-density minerals and clay fraction were removed using a Wilfley table. Heavy  
167 minerals were then isolated using heavy liquids (tetrabromoethane and diiodomethane, with  
168 respective densities of 2.967 and 3.325 g/cm<sup>3</sup>). Magnetic minerals were consequently removed  
169 with a Franz magnetic separator. Finally, the apatite grains were handpicked using a binocular  
170 microscope before being mounted into epoxy puck and polished. U-Pb data were acquired at  
171 the Isotopic Geochemistry Laboratory in Federal University of Ouro Preto (UFOP, Brazil) using  
172 a 193 nm HeLEX Photon Machine coupled with a ThermoScientific Neptune Plus Multicollector  
173 (LA-MC-ICP-MS). A beam spot size of 85 µm was used with beam energy densities of 6 J/cm<sup>2</sup>  
174 <sup>2</sup>, and a 6-Hz repetition rate. During apatite U-Pb measurement sequences, the 91500 zircon  
175 ([Wiedenbeck et al., 1995](#)) was used as a primary reference standard, while the Durango apatite  
176 ([McDowell et al., 2005](#)), the 401 apatite ([Thompson et al., 2016](#)), and the Madagascar apatite  
177 ([Thomson et al., 2012](#)) were used as secondary reference material in order to correct for matrix  
178 match effects as well as to constrain and verify the corrections accuracy and reproducibility.  
179 Data reduction and correction was carried out with the SATURN package of the laboratory of

180 Ouro Preto. Apatite U-Pb ages of the studied samples are reported as isochron ages calculated  
181 as lower-intercepts on a Terra-Wasserburg Concordia diagram using the Isoplot 4.15 software  
182 ([Fig. 2](#)) ([Ludwig, 2009](#)). The grains analyzed from each sample are igneous co-genetic apatites.  
183 Initial common Pb value was anchored to a  $^{207}\text{Pb}/^{206}\text{Pb}$  value of 0.898 ([Stacey and Kramers,](#)  
184 [1975](#)) according to the U-Pb baddeleyite (ID-TIMS) crystallization age of  $867\pm 16$  Ma  
185 ([Baratoux et al., 2019](#)). All the apatite isotopic data, at  $2\sigma$  level, are reported in the  
186 **supplementary material 1**. Additional information on the analytical conditions, and the Terra-  
187 Wasserburg Concordia diagrams of reference materials, are provided in the **supplementary**  
188 **material 2**.

### 189 3.3. Paleomagnetism

190 Oriented blocks were drilled in Geosciences Montpellier (France). Preparation of  
191 standard specimens (2.2 cm height) and alternating field (AF) demagnetization for a pilot study  
192 were carried out at the GET (Toulouse, France) using a JR5-A spinner magnetometer and a  
193 LDA-3 AF demagnetizer (AGICO) in a MMLFC shielded room design to reduce the effect of  
194 ambient magnetic field ( $<200$  nT). For the remaining samples the characteristic remanent  
195 magnetization (ChRM) was isolated by stepwise AF and thermal demagnetization performed  
196 in a magnetically shielded room with ambient field  $<500$  nT at the Laboratorio de  
197 Paleomagnetismo of the University of São Paulo (USPMag, Brazil). An AF pre-treatment until  
198 10 mT was performed before thermal demagnetization, to eliminate an eventual low-coercivity,  
199 viscous component. AF and thermal demagnetizations were performed using a vertical 2G-  
200 Enterprises<sup>TM</sup> DC-SQUID magnetometer with a RAPID automatic sample changer ([Kirschvink](#)  
201 [et al., 2008](#)). Stepwise thermal demagnetization of  $50^\circ\text{C}$  (until  $500^\circ\text{C}$ ) and  $20^\circ\text{C}$  (until  $700^\circ\text{C}$ )  
202 were carried out using a TD-48 furnace device. Only principal component analysis (PCA)  
203 ([Kirschvink, 1980](#)) was used to determine the remanence directions using orthogonal vector  
204 diagrams ([Zijderveld, 1967](#)). Site mean directions and paleomagnetic poles were calculated by



205 Fisher's (1953) statistics using the PALEOMAC package ([Cogné, 2003](#)). Paleogeographic  
206 reconstructions were performed using the GPlates software ([Müller et al., 2018](#)). Magnetic  
207 mineralogy was investigated under optical microscopy and using a Scanning Electron  
208 Microscopy (SEM JEOL JSM 7100F TTLS LV – EDS/EBSD) at the Centre de Micro  
209 Caractérisation Raimond Castaing (Toulouse, France). High-temperature thermomagnetic  
210 curves (susceptibility versus temperature) were conducted at the Toulouse, France) in an argon  
211 atmosphere using a CS-3 apparatus coupled to the KLY-3 Kappabridge (AGICO, Brno, Czech  
212 Republic). In addition, hysteresis loops, isothermal remanent magnetization (IRM) and first-  
213 order reversal curve (FORC) for selected samples were performed at the LABGeo, Instituto  
214 Oceanográfico, University of São Paulo (Brazil) using a MicroMag-VSM, Model 3900  
215 (Princeton Measurements Corporation). FORC diagrams were processed using the Forcot  
216 software ([Berndt and Chang, 2019](#)).

217

## 218 4. RESULTS

### 219 4.1. Geochronology

220 The GH05 site is situated near Cape Coast, between the towns of Yamoransa and Biriwa  
221 (southern Ghana) (Fig 1). It is a 20-50m wide dyke disintegrated into several blocks of coarse-  
222 grained relatively fresh dolerite, with ~0.5 cm of weathering crust (**Fig. 2A**). The second dated  
223 site GH16 is located within the Bechem city (SE of Sunyani) (Fig.1). Multiple blocks of metric  
224 size (*in situ*) were observed in an open area (**Fig. 2B**). The dyke is a coarse-grained dolerite  
225 showing a fresh doleritic texture (*i.e.* intergranular subophitic).

226 Apatites from the doleritic samples (GH05 and GH16) exhibit a nearly perfect euhedral  
227 prism shape (**Fig. 2C, D**) with grain size ranging between 90 and 300  $\mu\text{m}$ . The isotopic data  
228 obtained for the GH05 dolerite sample displays variable proportions of common Pb with



229  $^{207}\text{Pb}/^{206}\text{Pb}$  values varying between 0.32 and 0.53. The anchored lower intercept age for this  
230 sample is  $857.2 \pm 8.5$  Ma with a MSWD of 2.2 using 17 apatites (**Fig. 2C**). Sample GH16  
231 (dolerite dyke) displays variable proportions of common Pb with  $^{207}\text{Pb}/^{206}\text{Pb}$  values between  
232 0.45 and 0.64. Data for this sample define an anchored lower intercept age of  $855 \pm 16$  Ma with  
233 a MSWD of 2.4 using 13 apatites (**Fig. 2D**). The unanchored plots give identical ages for GH05  
234 and GH16 respectively within the error of  $841 \pm 31$  Ma (MSWD = 2.2) and  $833 \pm 66$  Ma  
235 (MSWD = 2.5), respectively, but the anchored ages were preferred following [Chew et al.](#)  
236 ([2011](#)).

## FIGURE 2

### Supplementary material 1

### Supplementary material 2

## 4.2. Paleomagnetic results

241 Natural remanent magnetization (NRM) values for the dolerite dykes vary between  $\sim 0.1$   
242 and  $9.8 \text{ A}\cdot\text{m}^{-1}$ . Samples showing scattered NRM directions and higher intensity values of 270–  
243  $555 \text{ A}\cdot\text{m}^{-1}$  (*e.g.* GH07A, B) were discarded, most probably due to lightning effects.

244 An extremely stable magnetic component was reached for the NNW-trending Manso  
245 dolerite dykes after removing a secondary/viscous component. Linear behavior is generally  
246 observed with two well-defined segments in the Zijdeveld plots with a “high  
247 coercivity/temperature component” revealed above AF values of 17 mT (**Fig. 3A, E, and F**) and  
248 temperature values range of  $\sim 540\text{--}580^\circ\text{C}$  (**Fig. 3B, C, and D**). These unblocking temperatures  
249 ( $T_{\text{ub}}$ ) point toward magnetite as the main carrier of the high-temperature component. Calculated  
250 by PCA analysis, a characteristic remanent magnetization (ChRM) is revealed for a first cluster  
251 (A+) of five sites showing a northern direction with a positive inclination (**Fig. 3A, B**). A second

252 cluster (A-) is composed of eight sites with a ChRM of southern direction with a steep negative  
253 inclination (**Fig. 3C, D, and E**).

254 A total of 165 specimens (13 sites) was used to calculate the Manso pole using the high  
255 coercivity-temperature component (**Fig. 4A**). Using the sites with positive inclinations ( $D_m =$   
256  $16.6^\circ$ ,  $I_m = 76.7^\circ$ ,  $n = 5$ ,  $k = 21$ ) and the sites with negative inclinations ( $D_m = 172.8^\circ$ ,  $I_m = -$   
257  $77^\circ$ ,  $n = 8$ ,  $k = 37.1$ ), the Manso dyke swarm passes a reversal test with a critical gamma of  
258  $16.2^\circ$  and a difference of  $5.4^\circ$  between normal and reverse axes (reversal test of C-class)  
259 ([McFadden and McElhinny, 1990](#)). 163 specimens show a secondary component with low  
260 inclination (**Fig. 4B**), and the subsequent secondary site-mean direction is  $D_m = 345.5^\circ$ ,  $I_m = -$   
261  $1.4^\circ$  ( $\alpha_{95} = 21.1^\circ$ ,  $k = 4.8$ ) (**Fig. 4C**). The Manso pole (13 sites) was calculated using the 5 sites  
262 of positive inclinations and the 8 sites of negative inclinations (**Fig. 4C**) giving a site mean  
263 direction of  $D_m = 181.9^\circ$ ,  $I_m = -77.2^\circ$  ( $\alpha_{95} = 7.6^\circ$ ,  $k = 30.6$ ), yielding to a paleomagnetic pole  
264 located at  $28.3^\circ\text{S}$  and  $177.6^\circ\text{E}$  ( $A_{95} = 12.7^\circ$   $K = 11.6$ ) (**Table 1; Fig. 4C, D**)

265 An iterative cutoff of  $37.6^\circ$  was determined using the 13 sites with no site exclusion  
266 ([Vandamme, 1994](#)), yielding a VGP dispersion (S-value) of  $23.8^\circ$  (**Fig. 4D**). High dispersion is  
267 expected for results with high inclination values as suggested by paleosecular models of  
268 latitudinal dependence of S (*e.g.* Model-G from [McFadden et al. \(1988\)](#)). The  $A_{95}$  for the  
269 Manso pole is equal to  $12.7^\circ$  which is comprised within the  $A_{95}$  envelope ( $4.3^\circ$ – $16.3^\circ$ ) of  
270 [Deenen et al. \(2011\)](#) (see **Fig. 4D**). Altogether, these characteristics suggest that our sampling  
271 of the Manso dolerite dykes average the paleosecular variation.

272 Though based on a single site (GH07), a stable ChRM of steep negative inclination and  
273 southwestern direction was obtained for the  $\sim 915$  Ma E-trending Oda dyke, similar to the A-  
274 cluster of the Manso dykes (**Fig. 3F**) providing a VGP at  $21^\circ\text{S}$  and  $222.3^\circ\text{E}$ .

275

276

**FIGURE 3**1  
2

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**FIGURE 4**

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**TABLE 1**

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**4.3. Baked contact test**

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Due to the weathering cover, host rocks could only be sampled in the Ahafo mining pit (Newmont Company) in the Sefwi Belt (**Fig. 5**), to attempt a baked contact test (BCT). **Fig. 5A** shows the sampled outcrop where two undeformed lamprophyre dykes (GH11 as illustrated in **Fig. 5B**, and GH12) are cutting the granodiorite host rock deformed during the ~2000 Ma Eburnean orogeny ([Feybesse et al., 2006](#)). Two oriented blocks (OB3 and OB4) were collected for the GH12 dyke (**Fig. 5A**). To attest the primary origin of the magnetization carried by the dyke GH12, we sampled one oriented block (OB6) within the baked zone into a two- branched dyke. The oriented blocks OB7 and OB8 were sampled at ~1 m and ~30 m respectively from the GH12 dyke. Thermal demagnetizations revealed a high unblocking temperature interval ( $T_{ub}$ ) of 520–620°C and high stability for the ChRM of the baked host rock at the contact (OB6) with a site-mean of  $D_m = 117.9^\circ$  and  $I_m = 80.3^\circ$  ( $\alpha_{95} = 4.9^\circ$ ,  $k = 112.8$ ) (**Table 1**; **Fig. 5C, D**). The host rock at the contact shows the same ChRM direction of the GH12 dyke ( $D_m = 87.9^\circ$   $I_m = 86.8^\circ$ ,  $\alpha_{95} = 4^\circ$ ,  $k = 100.2$ ) (**Table 1**; **Fig. 5C, D**). The secondary components are close to the present field with a northwestern direction and a low inclination for the dyke and the host rock. At ~1 m from the dyke, the OB7 block shows a significantly different behavior where thermal and AF demagnetizations reveal a more unstable magnetization (**Fig. 5C**), nevertheless magnetic vectors were defined for this block with two specimens providing a direction close to the dyke's direction and two specimens showing a western direction with low positive inclination (**Fig. 5C**). This western direction was also disclosed for the oriented block collected at ~30 m from the contact (OB8). Differently from the OB7 block, specimens from the OB8

300 block are well-clustered ( $D_m = 291.3^\circ$ ,  $I_m = 31^\circ$ ,  $\alpha_{95} = 7.6^\circ$ ,  $k = 46.7$ ) with a stable ChRM until  
301  $\sim 500^\circ\text{C}$ . This baked contact test can be considered as positive and attests to the primary origin  
302 of the extremely stable ChRM disclosed in the Manso dykes.

## FIGURE 5

### 4.4. Magnetic mineralogy

305 Most opaque phases show composite texture of ilmenite-magnetite and probably  
306 titanomagnetite ([Haggerty, 1991](#)). **Fig. 6A** shows a representative magnetite with ilmenite  
307 lamellae in a coarse-grained dolerite dyke (GH16). Intergrowth textures with ilmenite  
308 exsolutions are generally related to a stable thermoremanent magnetization (TRM) which  
309 supports our interpretation of the paleomagnetic results ([Evans and Wayman, 1974](#)). **Fig. 6B**  
310 shows three thermomagnetic curves, two for the Manso (GH08 and GH14) and one for the Oda  
311 dyke (GH07). The sample GH08A shows a curve with a reversible behavior between the  
312 heating and cooling steps whereas the cooling curve for samples GH14B3 and GH07B3 are not  
313 perfectly reversible. All samples show a Curie temperature ( $T_c$ ) at about  $560\text{--}580^\circ\text{C}$ , and a  
314 Hopkinson peak for GH08 and GH14 just below  $T_c$  ([Dunlop, 1974](#)), characteristic of fine-  
315 grained pure magnetite. The Day plot (**Fig. 6C**) and FORC diagrams (**Fig. 6D**) indicate domain  
316 states mainly in the stable single-domain (SD) to pseudo-single domain (PSD) fields. Values of  
317  $M_r/M_s$  higher than 0.10, and the strong proportion of 60–40 % of single domains magnetite in  
318 the Day plot are consistent with the narrow unblocking temperatures above  $540^\circ\text{C}$ . FORC  
319 diagram of sample GH08H1 is typical of the PSD behavior ([Roberts et al., 2014](#)), with SD-like  
320 magnetite dominance of the magnetic assemblage as shown by the peak value of  $\sim 25$  mT with  
321 closed contours on the  $H_u = 0$  axis (**Fig. 6D**). Conversely, the GH03M1 sample show a strong  
322 proportion of multi-domain (MD) grains mixed with SD grains as suggested by a large  
323 coercivity distribution on the  $H_u$  axis. This SD/MD behavior is also confirmed by the position

324 of GH03M1 in the [Dunlop \(2002\)](#) mixing curves of the Day plot (**Fig. 6D**). GH15 sample fall  
325 in the MD field of the Day diagram which suggests a strong proportion of MD-like magnetite  
326 in the magnetic assemblage, consistent with the strong decay of ~50% of its NRM at 10 mT  
327 during AF pre-treatment (**Fig. 3B**). The host rocks fall into the PSD domain for samples at the  
328 contact, whereas samples far from the contact fall into the MD field of the Day plot (**Fig. 6C**),  
329 suggesting a less stable behavior for these rocks. This further confirms that the host rock at the  
330 contact was mineralogically affected and re-heated during the dyke's intrusion.

## 331 **FIGURE 6**

### 332 **5. DISCUSSION**

#### 333 **1.1. Reliability of the Manso paleomagnetic pole (R-criteria)**

334 The Manso paleomagnetic pole was calculated with 13 sites of NNW- trending mafic dykes  
335 in Ghana and satisfies all seven criteria of the revised “R” reliability index ([Meert et al., 2020](#)).  
336 **(R1)** The Manso dyke swarm is well-dated by multi-method radiometric dating with one U-Pb  
337 baddeleyite (ID-TIMS) age of  $867 \pm 16$  Ma ( $^{207}\text{Pb}/^{206}\text{Pb}$  weighted mean age) (GH08) ([Baratoux](#)  
338 [et al., 2019](#)) and two identical (within error) U-Pb apatite ages of  $857.2 \pm 8.5$  Ma (GH05) and  
339  $855 \pm 16$  Ma (GH16) (**Fig. 2**). Given that the U-Pb apatite system ([Chew and Spikings, 2015](#))  
340 has a lower closure temperature ( $550\text{--}350^\circ\text{C}$ ) than the U-Pb baddeleyite system ( $700\text{--}1100^\circ\text{C}$ )  
341 ([Heaman and LeCheminant, 2001](#)), these identical ages within error suggest the U-Pb apatite  
342 system recorded the age of crystallization. Using the U-Pb baddeleyite  $^{207}\text{Pb}/^{206}\text{Pb}$  weighted  
343 mean age of  $867 \pm 16$  Ma (*or the Concordia age:  $855 \pm 10$  Ma*) ([Baratoux et al., 2019](#)) combined  
344 with the two new U-Pb apatite ages, a mean age of  $858.6 \pm 6.7$  ( $856.1 \pm 6$ ) Ma can be calculated  
345 for the emplacement of the NNW-trending Manso dyke swarm. **(R2)** ChRM directions were  
346 isolated on 13 sites (165 specimens) by thermal and AF demagnetizations and no difference  
347 was observed between the two demagnetization methods. Moreover, all vectors were well-  
348 defined by stable linear segments reaching the origin (**Fig. 3**), and analyzed by PCA analysis

349 using Zijderveld plots and equal-area projections ([Kirschvink, 1978](#); [Zijderveld, 1967](#)). Our  
350 new Manso pole is characterized by a value of precision K of 11.6, above the lower limit of 10  
351 proposed by ([Meert et al., 2020](#)). In addition, the A95 of 12.7° is comprised within the [Deenen  
et al. \(2011\)](#)'s interval (4.3°–16.3°) showing that the pole averages the paleosecular variation  
(**Fig. 4D**). No VGPs were excluded by the iterative cutoff of [Vandamme \(1994\)](#). (**R3**) The  
magnetic properties of these mafic dykes confirm their remanent magnetization is carried by a  
magnetic assemblage dominated by SD-like magnetite (**Fig. 6**). (**R4**) A positive baked contact  
test for the GH12 dyke confirms the remanence is primary. In addition, a primary origin is also  
suggested by the narrow and high unblocking temperatures ( $T_{ub}$ ) (540–580°C) of the Manso  
dykes which are above those of the undisturbed U-Pb apatite system (550–350°C). (**R5**) These  
undeformed dykes were sampled in a vast geographic area in Ghana considered as stable and  
without evidence of deformation related to the Pan-African belts or younger tectonic events.  
Moreover, geochronological and paleomagnetic results of distant sites (*e.g.* between GH05 and  
GH16, which are 233 km apart from each other) support a strong regional consistency in our  
results. The younger events in the area were associated with the magmatic activity of the Central  
Atlantic Magmatic Province (CAMP) and the Atlantic rifting between Africa and South  
America ([Baratoux et al., 2019](#)). These events produced a low-temperature regional influence  
of <120°C ([Fernie et al., 2018](#)), not sufficient to affect the primary magnetization of the dykes.  
This is consistent with the secondary component calculated for most of dykes with a  
corresponding pole located at 73.1°N, 244.8°E (**Table 1**), similar to the CAMP pole of 73°N,  
244.7°E obtained for West Africa ([Palencia-Ortas et al., 2011](#)) (**Fig. 4B**). (**R6**) The Manso pole  
passes a reversal test ([McFadden and McElhinny, 1990](#)) with 5 sites of positive inclination and  
8 sites of negative inclination. (**R7**) The A95 envelope of Manso pole overlaps the robust B2  
group (R = 6) of [Robert et al. \(2017\)](#) for volcanic units of ~550–530 Ma sampled in the Anti-  
Atlas mountains, north of the West African Craton. Nevertheless, [Meert et al. \(2020\)](#) underline

1 374 that comparison to younger poles should be discarded if the younger poles come from an  
2 375 orogenic belt, which is the case with the B2 pole, calculated from units folded during the  
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4 376 Carboniferous–Permian Hercynian (or Variscan) orogeny ([Robert et al., 2017](#)). Therefore, a  
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7 377 remagnetization of the Manso dykes seems improbable because no evidence of deformation has  
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9 378 been documented in the study area, and our large spatial sampling discard any localized tectonic  
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11 379 rotations. Thus, we can consider that the Manso pole fulfills all the R7 criteria of [Meert et al.](#)  
12  
13 [\(2020\)](#). The ~860 Ma Manso paleomagnetic pole can thus be considered as a high-quality key  
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15 380 pole and can serve as the first Neoproterozoic reference for the paleogeography of West Africa  
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17 381 during Rodinia.  
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## 22 383 **1.2. Testing the existence of the long-lived WABAMGO configuration in Rodinia**

24 384 The Grenville, Sveconorwegian, and Sunsás orogens are typically used to reflect the  
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27 385 collision between Laurentia, Baltica and Amazonia between ~1200 and 1000 Ma assembling  
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29 386 the Rodinia supercontinent ([Hoffman, 1991](#)). This combination between these cratons is nearly  
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31 387 identical in several Rodinia reconstructions but was questioned by [Meert and Torsvik \(2003\)](#),  
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33 388 and more recently by [Evans \(2009\)](#) using an updated paleomagnetic database. Recently, [Martin](#)  
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35 [et al. \(2020\)](#) re-evaluated the isotopic signature of the long-lived Paleo– to Mesoproterozoic  
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37 389 accretionary orogens along the margins of Laurentia, Baltica, Amazonia, and Kalahari. In their  
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39 390 model, the core of Rodinia is defined by the Laurentia-Baltica-Azononia-Kalahari connection  
40  
41 391 finally sutured during the Stenian. In the Rodinian reconstructions, West Africa is still  
42  
43 392 associated with the Amazonia Craton but without paleomagnetic constrains ([D'Agrella-Filho](#)  
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45 [et al., 2016](#)), we can use our new paleomagnetic results to test if a long-lasting connection is  
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47 393 paleomagnetically viable between Amazonia, West Africa and the paleomagnetically well-  
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49 394 constrained Baltica and Laurentia block.  
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57 397 A long-lived connection is usually proposed for Baltica and Laurentia between ~1760 Ma  
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59 398 and ~1270 Ma ([Salminen et al., 2014](#)). A large distance is observed across the APW path of  
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399 Baltica between the mean 1265 Ma pole (BA1) ([Pesonen et al., 2003](#)), the Salla diabase VGP  
400 (BA2) and the 1100-1050 Ma poles (BA3, BA4) (**Table 2**; **Fig. 7A**) ([Mertanen et al., 1996](#);  
401 [Pesonen et al., 2003](#)) and suggests fast drifting at that time. A similar trajectory is observed for  
402 Laurentia with the Logan loop and the ~1105-1080 Ma Keweenawan track (LA1-LA2)  
403 ([Swanson-Hysell et al., 2019](#)). Between ~1050 and 900 Ma the APW path of Laurentia was  
404 defined as the Grenville loop and the same interval in Baltica was defined as the  
405 Sveconorwegian loop, but its shape and motion are debated ([Elming et al., 2014](#); [Gong et al.,](#)  
406 [2018](#)). The best attempts to adjust the Grenville and Sveconorwegian loops are along an Euler  
407 pole of 75.8°N, 264.2°E, -59.2° ([Pisarevsky et al., 2003](#)), or in a tighter fit of 81.5°N, 250°E, -  
408 50° ([Evans, 2009](#)). However, Baltica rotated ~70° clockwise in relation to Laurentia between  
409 the ~1800–1200 Ma NENA (Northern Europe-North America) configuration ([Gower et al.,](#)  
410 [1990](#)) and the ~1050–800 Ma Rodinia configuration ([Salminen et al., 2009](#)). If these  
411 reconstructions hold true, they imply a single Laurentia-Baltica block between ~1050 and 800  
412 Ma. Key 951-935 Ma mean poles for Baltica (BA6) confirmed this clockwise motion, but a  
413 more complex shape for the APW path is proposed considering the ~971 Ma VGP of Blekinge-  
414 Dalarna dykes (Group. B) (BA5) (**Fig. 7A**) ([Gong et al., 2018](#)). A late Sveconorwegian group  
415 of poles (936–850 Ma) obtained for the Rogaland Igneous Complex (RIC) and the ~860 Ma  
416 Hunnedalen dykes with a stable remanence of same polarity suggest a stable position for Baltica  
417 at high latitude (BA7-BA11) ([Walderhaug et al., 1999](#)). The primary remanence of this group  
418 is supported by an inverse contact test with the ~635 Ma Egersund dyke swarm ([Walderhaug](#)  
419 [et al., 2007](#)).

420 West Africa is always associated with the Amazonia Craton in the Paleo-Mesoproterozoic  
421 reconstructions but in a different position from the Gondwana link ([Onstott and Hargraves,](#)  
422 [1981](#)). These cratons were juxtaposed with the Baltica in the **S**outh **A**merica **B**altica (**SAMBA**)  
423 connection with the possibility of a long-lived connection between ~1800 and 800 Ma



424 ([Johansson, 2009](#)). An alternative reconstruction, using geological considerations, was  
425 proposed with Kalahari-Congo, São Francisco and India in the Umerkondia supercraton at ~1110  
426 Ma ([Choudhary et al., 2019](#)). Using the paleomagnetic poles of the ~1199 Ma Nova Floresta  
427 formation (AM1) ([D'Agrella-Filho et al., 2008](#)) and ~1149 Ma Fortuna formation (AM2)  
428 ([Tohver et al., 2002](#)) (**Fig. 7A**), a strike-slip migration of Amazonia along the Laurentia at  
429 ~1200–1150 Ma was initially proposed. But, a preliminary ~1110 Ma paleomagnetic pole for  
430 the well-dated Rincon del Tigre Complex (AM3) ([Teixeira et al., 2015](#)) supports a moderate to  
431 low latitude for Amazonia at that time ([Patroni, 2015](#)), which is incompatible with the model  
432 of oblique collision proposed by [Tohver et al. \(2002\)](#). These AM3 pole for Amazonia supports  
433 the model of [Evans \(2013\)](#) suggesting a clockwise rotation of the Amazonia and Baltica to  
434 collide with Laurentia. For West Africa, paleomagnetic results were obtained from the  
435 Mesoproterozoic units of the Adrar (NW- West Africa, Mauritania) ([Morris and Carmichael,  
436 1978](#); [Perrin et al., 1988](#); [Perrin and Prévot, 1988](#)). [Rooney et al. \(2010\)](#) obtained a new Re-Os  
437 age of ~1105 Ma for the Atar group previously estimated at 890–775 Ma. Based on the  
438 similarity with younger directions some authors have suggested some remagnetization effects  
439 ([Perrin and Prévot, 1988](#); [Tohver et al., 2006](#)), but without further evidence that the primary  
440 origin for their remanence cannot be ruled out. The characteristic component for those rocks is  
441 carried by hematite and was revealed at high temperatures (>590°C). If the magnetization is  
442 primary this allows to define a new Mesoproterozoic age of ~1105 Ma for the I9 pole (WA1)  
443 calculated by [Perrin and Prévot \(1988\)](#) coeval to the ~1110 Ma Rincon del Tigre pole (AM3)  
444 from the Amazonia Craton ([Patroni, 2015](#)) (**Fig. 7A**). No data are available to define the APW  
445 path for the Amazonia Craton in Early Neoproterozoic times, but our new ~860 Ma Manso pole  
446 satisfies a maximum R-criteria to be considered as an anchor point for paleogeographic  
447 reconstructions (**Fig.7A**; R = 7, **this study**).

448 The Mesoproterozoic APW path for the Congo-São Francisco Craton is defined by the well-  
1  
2 449 dated Late Kibaran pole (C1) at ~1236 Ma ([Meert et al., 1994b](#)). A large shift is observed  
3  
4 450 between the ~1110 Ma pole from the Huile-Epembe dykes ([Salminen et al., 2018](#)) and the ~925  
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6 451 Ma poles from the São Francisco dykes (Salvador, Ilhéus, Oliveira) ([Fig. 7A](#)) [D'Agrella-Filho](#)  
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8  
9 452 [et al. \(1990\)](#); ([D'Agrella-Filho et al., 2004](#); [Evans et al., 2016](#)). The Congo-São Francisco  
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11 453 Craton is usually associated with the Rodinia supercontinent ([Merdith et al., 2017](#)), or in a  
12  
13 454 different view connected with the African blocks ([D'Agrella-Filho and Cordani, 2017](#)).

17 455 Similarities in length and shape of the APW paths for Baltica, Amazonia, West Africa, and  
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19 456 São Francisco-Congo cratons allow us to build a Master APW path between ~1200 and 850 Ma  
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21 457 for these continental units ([Fig. 7A](#)). This Master APW path suggests that these blocks were  
22  
23 458 nearby between ~1200 and 850 Ma, forming a single continental entity. This large continental  
24  
25 459 unit, hereafter referred to **WABAMGO** (**W**est **A**frica-**B**altica-**A**mazonia-**C**ongo) is represented  
26  
27 460 in [Fig. 7B](#). Geological domains, LIPs comparisons, and paleomagnetic data between Baltica,  
28  
29 461 Amazonia, and West Africa support a strong connection between these continents since the  
30  
31 462 Paleoproterozoic using the SAMBA model ([Baratoux et al., 2019](#); [D'Agrella-Filho et al., 2016](#);  
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33 463 [Terentiev and Santosh, 2020](#)). Our model supports the presence of a long-lived accretionary  
34  
35 464 margin during the Mesoproterozoic times in the western part of Amazonia ([Sadowski and](#)  
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37 465 [Bettencourt, 1996](#)). The orientation of West Africa in relation to Amazonia in the SAMBA  
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39 466 model is paleomagnetically viable from ~2100 Ma until ~1400 Ma ([D'Agrella-Filho et al.,](#)  
40  
41 467 [2016](#)), but a later reorientation is necessary to fit with the classical ~550 Ma Gondwana  
42  
43 468 configuration. In the WABAMGO configuration, the West Africa-Amazonia connection is  
44  
45 469 close to this late Neoproterozoic configuration, suggesting this reorientation could have  
46  
47 470 occurred between ~1400 and 1200 Ma, during the breakup of the Columbia supercontinent. The  
48  
49 471 Sunsás and Sveconorwegian orogens can be correlated between Amazonia and Baltica in this  
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51 472 model ([Fig. 7B](#)). A large Early Tonian mafic magmatism is observed in the São Francisco  
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473 craton spanning from ~925 Ma to 850 Ma ([Danderfer et al., 2009](#); [Moreira et al., 2020](#)). Similar  
474 records of Tonian age magmatism have been reported for the Congo with the Sembé Ouessou  
475 ([Vicat and Pouclet, 1995](#)), for Baltica with the ~850 Ma Hunnedalen dykes ([Walderhaug et al.,  
476 1999](#)), for Amazonia with the ~809 Ma Makinet (ex-Tampok) dykes ([Delor et al., 2003](#)), and  
477 also for West Africa with the ~860 Manso and ~915 Oda dykes in the south of the craton  
478 ([Baratoux et al., 2019](#)) and the ~880-850 Iguerda-Taïfast dykes in the Anti-Atlas ([Kouyaté et  
479 al., 2013](#)). An Early Tonian rifting is also documented for the northern part of the West African  
480 Craton with the volcanoclastic deposits of the ~883 Ma Tachdamt Fm ([Bouougri et al., 2020](#)).  
481 An Early Tonian rifting between the northern West Africa and the São Francisco is thus  
482 supported by the WABAMGO configuration (**Fig. 7B**). A rare “Grenvillian event” (~1000–920  
483 Ma) documented within the WABAMGO juxtaposition is the Cariris Velhos tectonic event,  
484 proving some continental reorganization and convergence at the edge of the mega block of the  
485 Borborema Province was followed by a Tonian rifting ([dos Santos et al., 2010](#); [Neves et al.,  
486 2020](#)).

487 Our model also supports a “Grenvillian” source for zircons in northern West Africa  
488 ([Bouougri et al., 2020](#); [Kalsbeek et al., 2008](#)) with the proximity of the Grenvillian orogens to  
489 the west such as Sunsás and Sveconorwegian and the associated small blocks (*e.g.* Oaxaquia,  
490 Maya), and the Cariri Velhos event to the east. Major shifts in the sedimentation on the West  
491 African Craton suggest a complete breakup of the WABAMGO from Baltica and São  
492 Francisco-Congo after ~800 Ma with the development of subduction zones in northern West  
493 Africa in the late Neoproterozoic ([Triantafyllou et al., 2016](#)). Following this model, the  
494 proximity of the Congo-São Francisco and West Africa may explain the large displacements  
495 along the major dextral Transbrasiliano lineament with the closure of the Pharusian Ocean  
496 during the assembly of Gondwana in late Neoproterozoic times. The proposed long-lived

497 WABAMGO juxtaposition is geologically and paleomagnetically viable between ~1200 and  
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2 498 800 Ma.  
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### 5 499 **1.3. Implications for the Rodinia assembly**

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8 500 Using our new Master APW path for the West Africa-Baltica-Amazonia-Congo block, the  
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11 501 reconstruction at ~1110 Ma shows that the assembly of Rodinia is dominated by the V-shape  
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13 502 closure of the external Nuna Ocean ([Li et al., 2019](#)), or Grenville Ocean, ([Sadowski and](#)  
14  
15 503 [Bettencourt, 1996](#)), between the northern Laurentian blocks and the southern WABAMGO  
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17 504 (**Fig. 8A**). This hypothesis of the closure of this Ocean by accretionary orogens was previously  
18  
19 505 suggested on geological grounds ([Cawood and Pisarevsky, 2017](#); [Martin et al., 2020](#)), but our  
20  
21 506 study add a paleomagnetic support. The Kalahari craton is positioned in **Fig. 8** along the  
22  
23 507 southern tip of Congo (pos-A) as in ([Salminen et al., 2018](#)) or in its inverted position (pos-B)  
24  
25 508 with the Natal-Namaqua orogen facing the coeval Grenville orogen in Laurentia, in both cases  
26  
27 509 constrained by the ~1109 Ma Umkondo pole (K1) ([Swanson-Hysell et al., 2015a](#)). In the  
28  
29 510 preferred position B, the Kalahari craton will collide with the southern coast of Laurentia after  
30  
31 511 the closure of the external Nuna Ocean (**Fig. 8B**). Nevertheless, the Kalahari position is poorly  
32  
33 512 constrained in Rodinia, and is beyond the scope of this contribution. The orientation of West  
34  
35 513 Africa in the WABAMGO configuration (pos-A, **Fig. 8B**) differs from the SAMBA model, in  
36  
37 514 which the western margin of West Africa is associated to the southern part of Baltica.  
38  
39 515 Nevertheless, our new proposed configuration requires new Tonian high-quality poles for the  
40  
41 516 unconstrained cratons, especially Amazonia, and new Mesoproterozoic poles for West Africa  
42  
43 517 to confirm the relative orientation between Amazonia and West Africa. Discarding the ~1105  
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45 518 Ma WA1 pole, a position closer to the SAMBA model ([Johansson, 2009](#)) is paleomagnetically  
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47 519 plausible for West Africa (pos-B, **Fig. 8B**).  
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58 520 For the final paleogeographic configuration at 925-850 Ma we can compare the position of  
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60 521 West Africa derived from the Manso paleomagnetic pole with the available record of Laurentia  
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522 and surrounding blocks (**Fig. 8C**). Three paleomagnetic poles are available for the northern  
523 blocks of Rodinia. Laurentia can be constrained by the basal units from the Little Dal Group,  
524 LA3 pole, which passes a fold test, and its age was recently constrained by high-quality  
525 correlations between 892 and 849 Ma ([Greenman et al., 2020](#); [van Acken et al., 2013](#)). One  
526 pole for the Tarim (T1) at ~880 Ma ([Wen et al., 2018](#)), and one pole for North China at ~895  
527 Ma (NC1) ([Fu et al., 2015](#)) complete the paleomagnetic database for the northern blocks of  
528 Rodinia. Our model implies that Rodinia was formed by extroversion ([Murphy and Nance,](#)  
529 [2003](#)), with the closure of an external Nuna Ocean between two large blocks, the southern  
530 WABAMGO and the northern Laurentian block. Rodinia was finally assembled by a large  
531 dextral motion of the Australia-Tarim blocks as suggested by [Wen et al. \(2018\)](#). The polar  
532 location of the WABAMGO at ~900 Ma, together with the low-mid latitudinal distribution of  
533 Laurentia and the blocks of North China, Tarim, Australia (?) confirms a pan-latitudinal rather  
534 than an equatorially distributed supercontinent as suggested by [Jing et al. \(2019\)](#).

535 **FIGURE 7**

536 **FIGURE 8**

537 **TABLE 2**

## 538 **6. CONCLUSIONS**

539 New U-Pb apatite ages of  $857.2 \pm 8.5$  Ma and  $855 \pm 16$  Ma agree with the previous  $867 \pm 16$   
540 Ma U-Pb baddeleyite age ([Baratoux et al., 2019](#)) confirming the extension of the Manso dyke  
541 swarm to the north of Ghana. A ~860 Ma Manso key pole ( $28.3^\circ\text{S}$ ,  $177.6^\circ\text{E}$ ,  $A95 = 12.7^\circ$ ,  $R =$   
542  $7$ ) was calculated and represent the first high-quality paleomagnetic data in Early Tonian for  
543 the West African craton. The remagnetization is considered as primary, passing a baked contact  
544 test and a reversal test. The paleomagnetic database for West Africa, Baltica, Amazonia, and  
545 the Congo-São Francisco cratons supports a long-lived continental unit between ~1200 and 800

1 546 Ma, the WABAMGO juxtaposition. During the late Mesoproterozoic-Early Neoproterozoic  
2 547 (~1200–900 Ma), the WABAMGO and the Laurentia were drifting southward. During this  
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4 548 migration, a clockwise rotation of the WABAMGO in relation to Laurentia closed the external  
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7 549 Nuna Ocean causing the Grenvillian collisions suturing the Rodinia supercontinent. Thus, this  
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10 550 model favors with paleomagnetic support the formation of the Rodinia supercontinent by  
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12 551 extroversion.

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51 566 (Amanfro, Domeabra, ...).

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568 **FIGURE AND TABLE CAPTIONS**

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3 569 **Fig. 1:** Inset: Location of the study area in the West African craton (WAC). Geological map of  
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5 570 the Neoproterozoic units of Ghana with sampling location for geochronology (red stars) and  
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8 571 paleomagnetism. \*: U-Pb baddeleyite age of GH08 =  $867 \pm 16$  Ma (Manso) and GH07 =  $915 \pm$   
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10 572  $7$  Ma (Oda) from [Baratoux et al. \(2019\)](#). \*\*: U-Pb apatite ages of GH05 =  $857.2 \pm 8.5$  Ma and  
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12  
13 573 GH16 =  $855 \pm 16$  Ma from **this study**.

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16 574 **Fig. 2: A and B:** Field photographs of the Manso dolerite dykes at GH05 and GH16 sites,  
17  
18 575 respectively. **C and D:** U-Pb Terra-Wasserburg diagrams for apatite dating of the Manso  
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21 576 dolerite dykes at GH05 (C) and GH16 (D) sites. The upper intercept is anchored to the initial  
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23 577 Pb/Pb ratio (0.898) that was calculated based on Pb model of [Stacey and Kramers \(1975\)](#) for an  
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25 578 emplacement age of  $\sim 867$  Ma ([Baratoux et al., 2019](#)). Unanchored ages are also illustrated (in  
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28 579 red).

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31 580 **Fig. 3:** Representative demagnetization plots of Neoproterozoic dykes for different geographic  
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33 581 sites in Ghana after AF and thermal demagnetizations. Equal-area stereonet (filled (open)  
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35 582 symbols represent positive inclination), Zijderveld plots (vertical/horizontal projections shown  
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38 583 by open/filled circles), and Magnetization intensity decay curves (M/M<sub>max</sub>) are indicated for  
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41 584 each example. Values of 75% of the NRM decay (in mT) and unblocking temperature spectra  
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43 585 are indicated for the AF and thermal demagnetization curves, respectively. NRM = natural  
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46 586 remanent magnetization. Numbers, T100 (A5), indicate thermal (AF) demagnetization step.

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49 587 **Fig. 4:** Sample and site mean directions for the Manso dykes. **A:** Specimen mean directions of  
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51 588 the high coercivity/temperature components (in green). **B:** Specimen mean directions of the low  
52  
53 589 coercivity/temperature components (in purple). **C:** Site mean directions for the Manso dykes  
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56 590 (in green), the secondary site mean directions is also indicated (in purple). Sites/specimens with  
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59 591 positive and negative inclinations are represented with filled (open) symbols represent



592 downward (upward) inclinations. Confidence circle ( $\alpha_{95}$ ) around the means are indicated. PDF  
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2 593 – Present dipolar geomagnetic field; PGF – Present geomagnetic field. **D**: Dispersion of site  
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4 594 mean virtual geomagnetic poles (VGPs) and paleomagnetic pole calculated for the Manso dykes  
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7 595 (**Table 1**) represented in a Schmidt projection. [Deenen et al. \(2011\)](#)'s A95 envelope ( $4.3^\circ$ –  
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9 596  $16.3^\circ$ ) and the iterative cutoff limit ( $37.6^\circ$ ) of [Vandamme \(1994\)](#) are indicated. \*: U-Pb  
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11 597 baddeleyite age of GH08 =  $867 \pm 16$  Ma (Manso) and GH07 =  $915 \pm 7$  Ma (Oda) from [Baratoux](#)  
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13 598 [et al. \(2019\)](#). \*\*: U-Pb apatite ages of GH05 =  $857.2 \pm 8.5$  Ma and GH16 =  $855 \pm 16$  Ma from  
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15 599 this study. Direction and VGP for the  $\sim 915$  Ma site (GH07) are indicated in grey, not considered  
16  
17 600 for the Manso pole.

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22 601 **Fig. 5:** Baked contact test for the GH12 dyke ( $\sim 1$  m in width). **A**: Geological sketch of the  
23  
24 602 outcrop with location of the sampled oriented blocks (star) of dykes (in green), and the host  
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26 603 rocks at contact (in red), at  $\sim 1$  m (in pink), and at  $\sim 30$  m (in blue) from the contact. **B**: Field  
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28 604 photograph of the GH11 lamprophyre dyke, 0.30 m wide, located in (A). **C**: Equal-area  
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30 605 stereonet (filled (open) symbols represent positive inclination) of site-mean directions for the  
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32 606 GH12 dyke (in green) and the subsequent host rocks at contact (in red), at  $\sim 1$  m (in pink), and  
33  
34 607  $\sim 30$  m (in blue) from the contact. Magnetization intensity decay curves ( $M/M_{max}$ ) are indicated.  
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36 608 **D**: Zijderveld plots for representative specimens after thermal demagnetization from the GH12  
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38 609 dyke (OB4A1), the host rock at contact (OB6A2b) and at  $\sim 30$  m (OB8E1).

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44 610 **Fig. 6:** **A**: SEM-BSE micrograph of titanomagnetite (Mag) with exsolutions of ilmenite (Ilm),  
45  
46 611 augite (Aug), plagioclase (Pl), spharelite (Sp), and apatite (Ap) for the GH16 dyke. **B**: Heating  
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48 612 (in red) and cooling (in blue) thermomagnetic curves for three samples (GH14B3, GH07B3,  
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50 613 and GH08A). **C**: Day plot for the Manso dykes and the host rocks with SP-MD mixture lines  
51  
52 614 indicating the single domain proportions. SD: single domain, PSD (or vortex state): pseudo-  
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54 615 single domain, MD: multidomain. **D**: First-order reversal curve (FORC) diagrams for the  
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616 GH08H1 and the GH03M1 specimens. SF is the smoothing factor used by the FORCOT  
617 software.

618 **Fig. 7: A:** The **WABAMGO** (**W**est **A**frica-**B**altica-**A**mazonia-**C**ongo) juxtaposition using  
619 Baltica as reference frame in present coordinates. Euler poles used in the Baltica reference  
620 frame for the different cratons in the WABAMGO configuration: West Africa (1.375°N,  
621 15.1585°E, -66.0819°), Amazonia (10.894°S, 369.8179°E, -89.4471°), Congo (52.32°S,  
622 158.71°E, -70.57°). The São Francisco craton is rotated to Congo using its pre-Mesozoic  
623 configuration (46.8°N, 329.4°E, 55°, ([McElhinny et al., 2003](#))). Kalahari is connected to the  
624 Congo craton (12.8°S, 19°E, -43.2°) according the configuration of [Salminen et al. \(2018\)](#).  
625 Present North is indicated for each craton by an arrow. ***Abbreviations for the ~1200–1000 Ma***  
626 ***Grenvillian orogens (in black):*** (1) Sveconorwegian orogen, (2) Sunsás orogen, (3) Cariris  
627 Velhos event, (4) Namaqua-Natal orogen. Tonia large igneous provinces (LIPs, in red) are  
628 indicated. **B:** Master apparent polar wander (APW) path for the WABAMGO between ~1200  
629 and 850 Ma. Paleomagnetic poles and used abbreviations are listed in the **Table 2**.

630 **Fig. 8: A:** Paleogeography reconstruction of the Rodinia assembly at ~1110 Ma showing the  
631 presence of the external Nuna Ocean (Grenville Ocean) between the WABAMGO (south  
632 Rodinia) and the Laurentia (north Rodinia). Two plausible positions are illustrated for the  
633 Kalahari craton with the [Salminen et al. \(2018\)](#) configuration (pos-A), and Kalahari placed in  
634 the west of Amazonia (pos-B) as paleolongitude is arbitrary. We followed the model of  
635 [Sadowski and Bettencourt \(1996\)](#) using a subduction towards Amazonia. **B:** Paleogeography  
636 reconstruction of the Rodinia at ~925–850 Ma. Cratons with paleomagnetic constraints (in  
637 colors) and cratons with no data (?) are indicated. Two positions of West Africa are illustrated  
638 with the position A in agreement with the WABAMGO configuration and the plausible position  
639 B according the uncertainty for the paleolongitude. The hypothesis of a dextral movements  
640 from [Wen et al. \(2018\)](#) is indicated for the northern cratons of Australia-Mawson-Tarim. **C:**

641 Paleomagnetic poles (north pole) used in the reconstruction at ~925–850 Ma (**B**). See **Table 2**  
642 for abbreviations and references.

643  
644 **Table 1:** S.lat, S.lon are the site latitude and longitude. n/N - number of specimens used in mean  
645 directions/number of analyzed specimens; Dec – Declination; Inc – Inclination; R – the  
646 resultant vector,  $\alpha_{95}$  ( $A_{95}$ ) is the radius of the 95% cone of confidence and k ( $K$ ) is the precision  
647 parameter - Fisher's statistical parameters ([Fisher, 1953](#)) for the mean directions (*mean virtual*  
648 *geomagnetic poles – VGPs*); P.Lat – pole latitude; P.Long – pole longitude. Values of mean  
649 sites directions are indicated in bold for the positive, negative, and combined polarities. \*: U-  
650 Pb baddeleyite age of GH08 =  $867 \pm 16$  Ma (Manso) and GH07 =  $915 \pm 7$  Ma (Oda) from  
651 [Baratoux et al. \(2019\)](#). \*\*: U-Pb apatite ages of GH05 =  $857.2 \pm 8.5$  Ma and GH16 =  $855 \pm 16$   
652 Ma from this study. †: Site with an attempted baked contact test (BCT).  $\gamma$  ( $\gamma_c$  = critical) is the  
653 angle calculated between the mean directions of reversed and normal polarities ([McFadden and](#)  
654 [McElhinny, 1990](#)).

655  
656 **Table 2:** Paleomagnetic database for the Rodinia. Code, Plat – pole latitude, Plon – Pole  
657 longitude, Age – nominal age,  $A_{95}$  confidence cones of the paleomagnetic poles used in the  
658 paleogeographical reconstructions. R-criteria from [Meert et al. \(2020\)](#). **References:** **Laurentia:**  
659 [1] [Park \(1981\)](#), [2] [Swanson-Hysell et al. \(2019\)](#), **Baltica:** [3] [Walderhaug et al. \(1999\)](#), [4]  
660 [Brown and McEnroe \(2004\)](#), [5] [Stearn and Piper \(1984\)](#), [6] [Walderhaug et al. \(2007\)](#), [7]  
661 [Brown and McEnroe \(2015\)](#), [8] [Gong et al. \(2018\)](#), [9] [Mertanen et al. \(1996\)](#), [10] [Pesonen et](#)  
662 [al. \(2003\)](#), [11] [Salminen et al. \(2009\)](#), **West Africa:** [12] **This study**, [13] [Perrin and Prévot](#)  
663 [\(1988\)](#), [14] [Rooney et al. \(2010\)](#), **Amazonia:** [15] [Patroni \(2015\)](#), [16] [Teixeira et al. \(2015\)](#)  
664 [17] [D'Agrella-Filho et al. \(2008\)](#), [18] [Tohver et al. \(2002\)](#), **Congo-São Francisco:** [19] [Evans](#)

665 [et al. \(2016\)](#), [20] [D'Agrella-Filho et al. \(2004\)](#), [21] [D'Agrella-Filho et al. \(1990\)](#), [22]

666 [Salminen et al. \(2018\)](#), [23] [Meert et al. \(1994a\)](#), **Kalahari:** [24] [Swanson-Hysell et al. \(2015a\)](#),

667 **North China:** [25] [Fu et al. \(2015\)](#), **Tarim:** [26] [Wen et al. \(2018\)](#).

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669 **S1:** Apatite U-Pb isotope data.

670 **S2:** Analytical conditions for apatite LA-ICP-MS dating.

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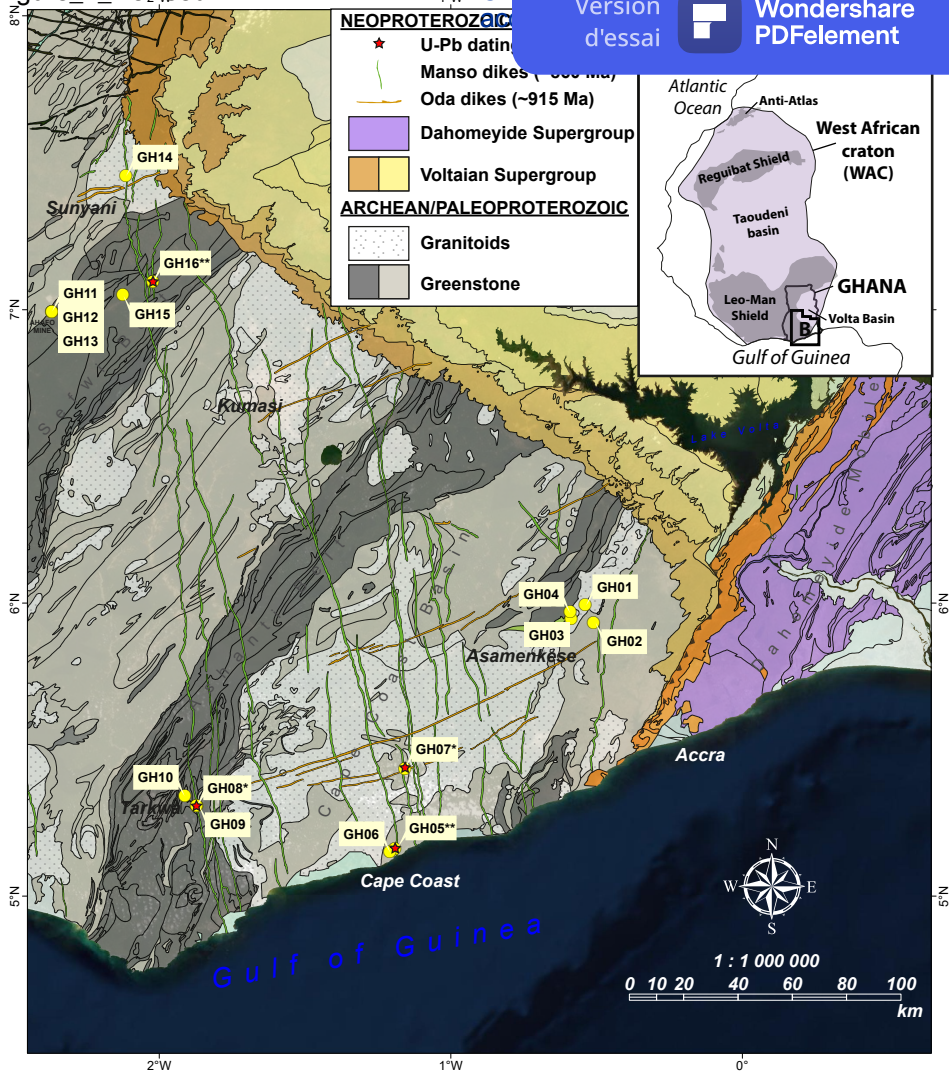
Figure\_1\_Revised

1°W

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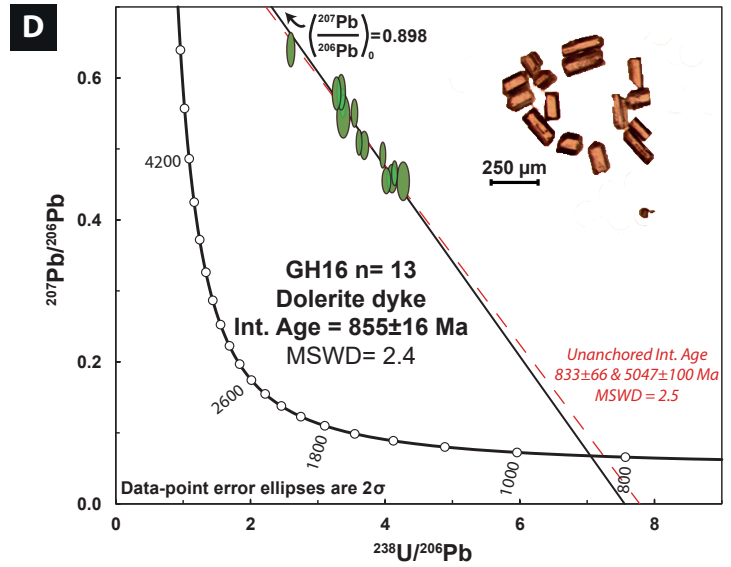
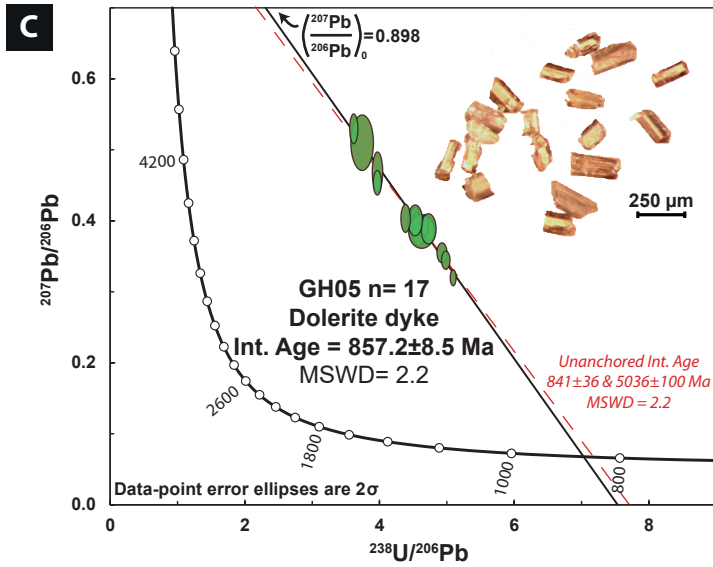


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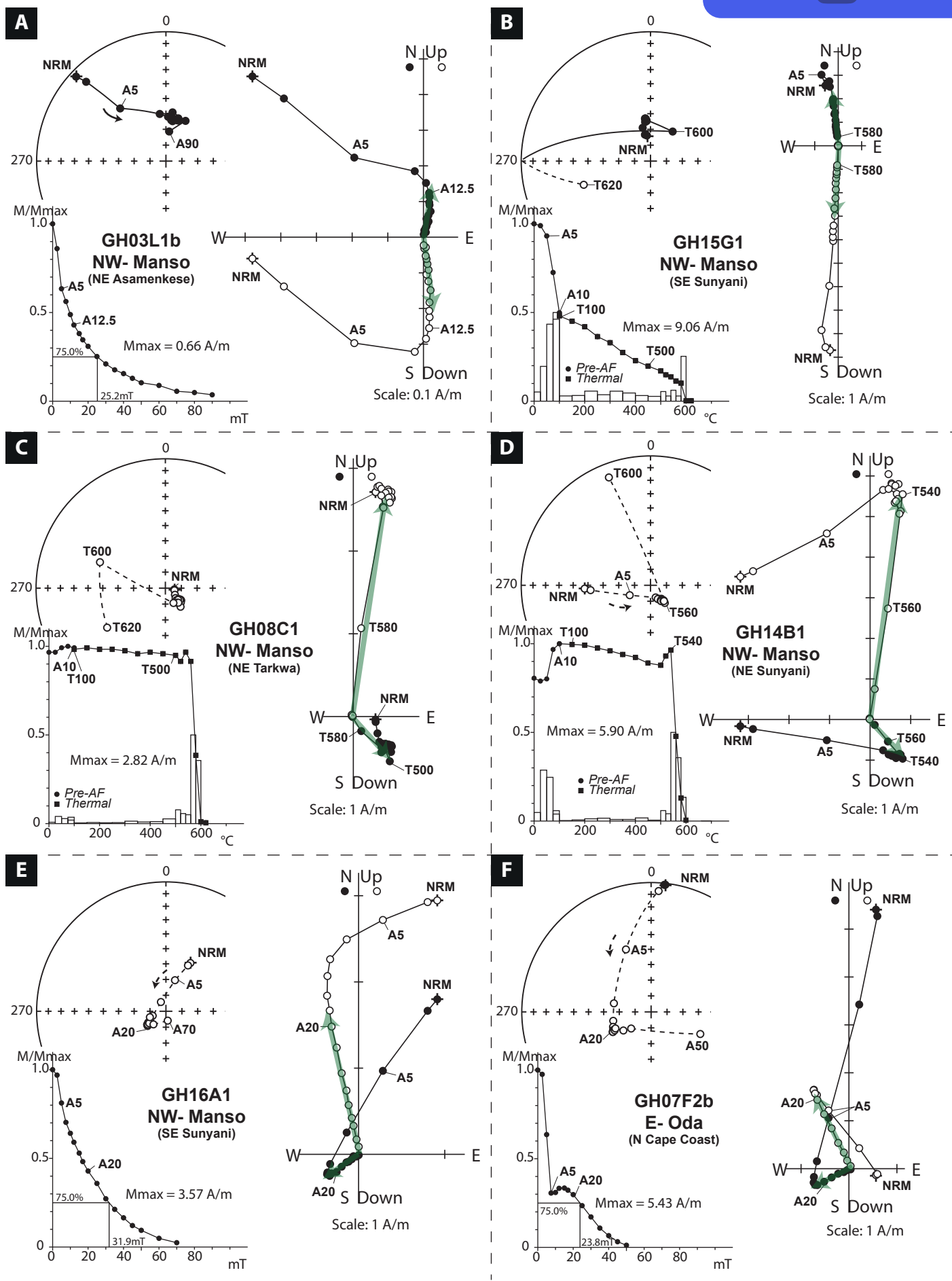


**Figure 1**

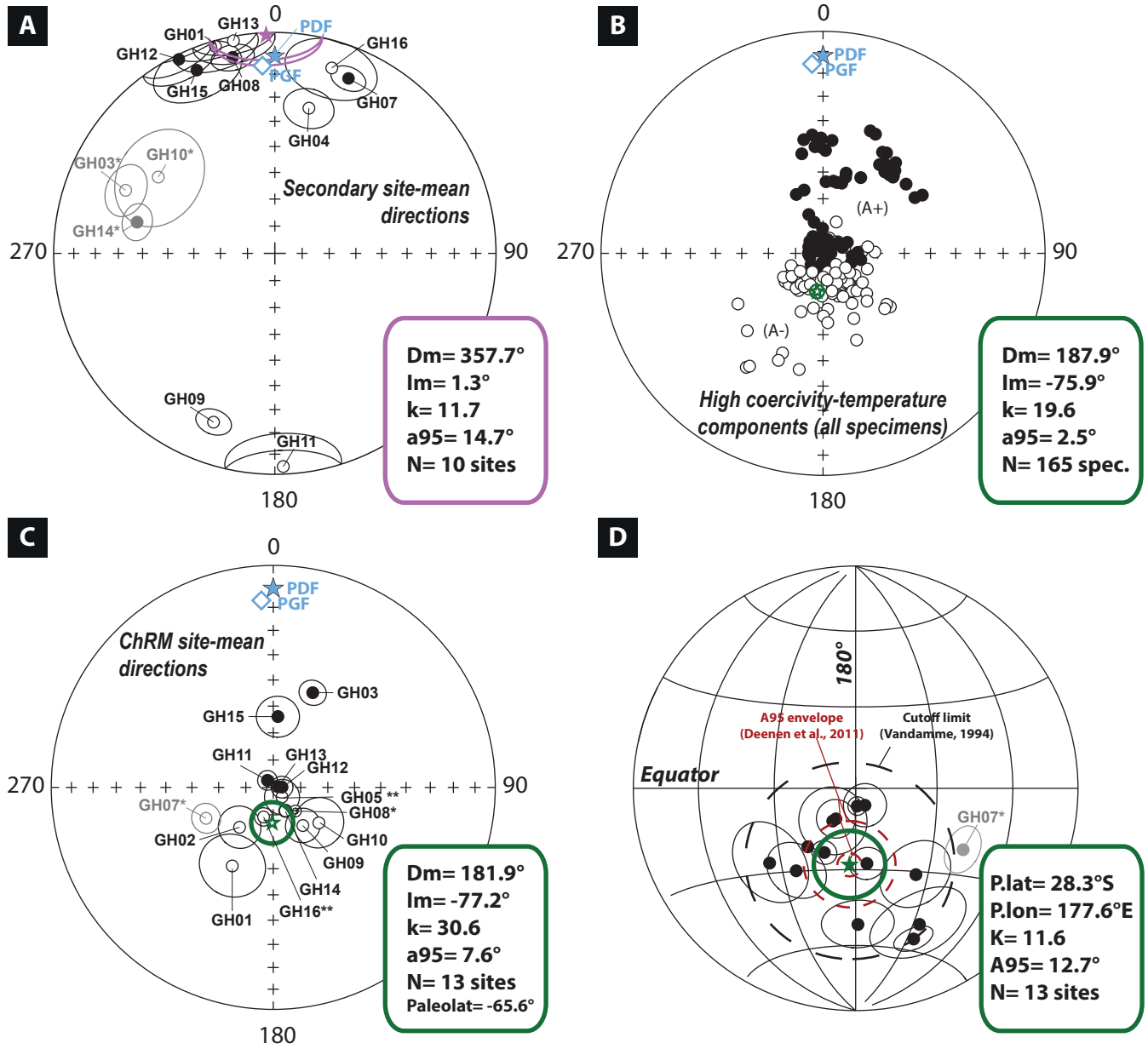




**Figure 2**

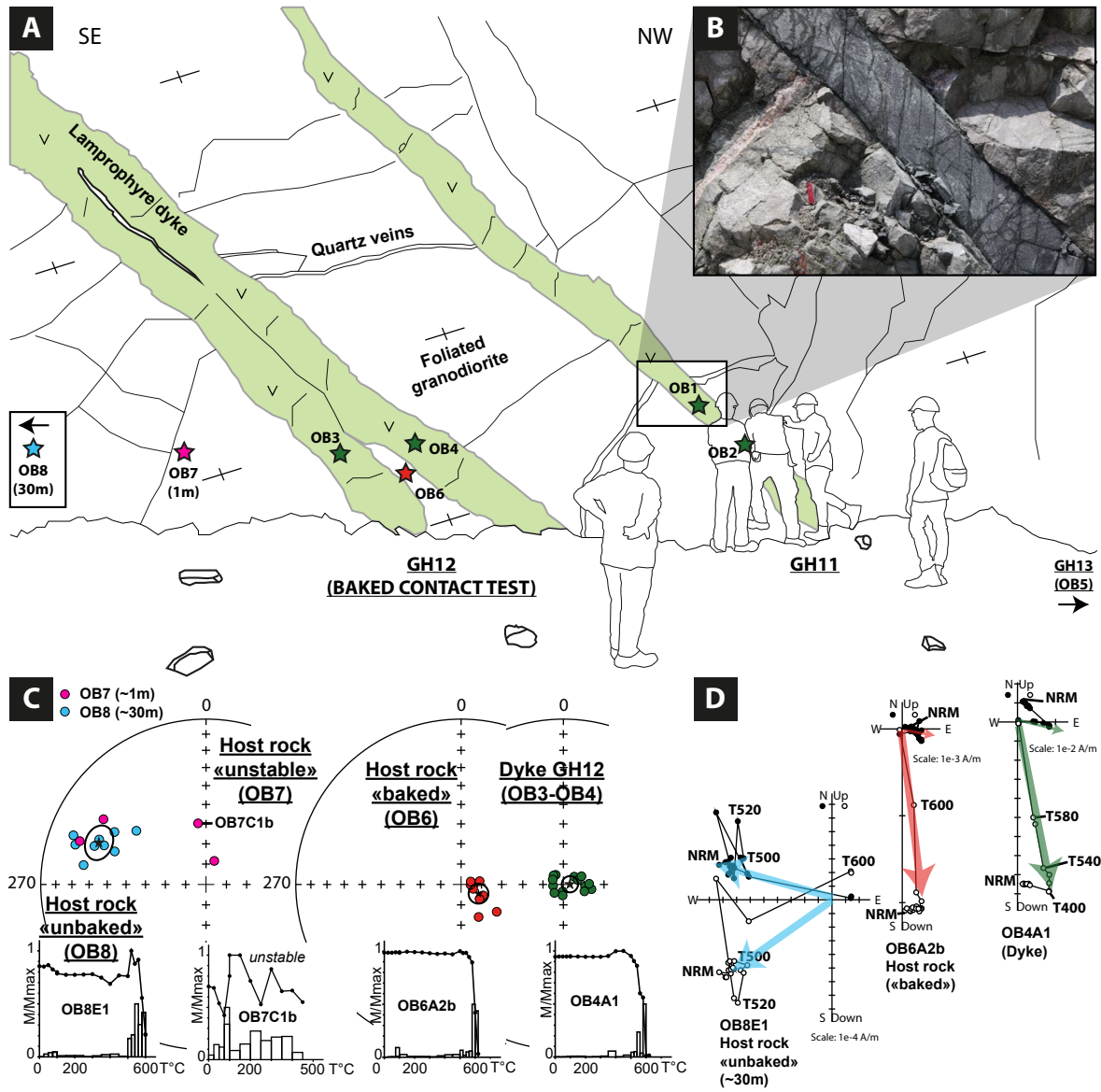


**Figure 3**

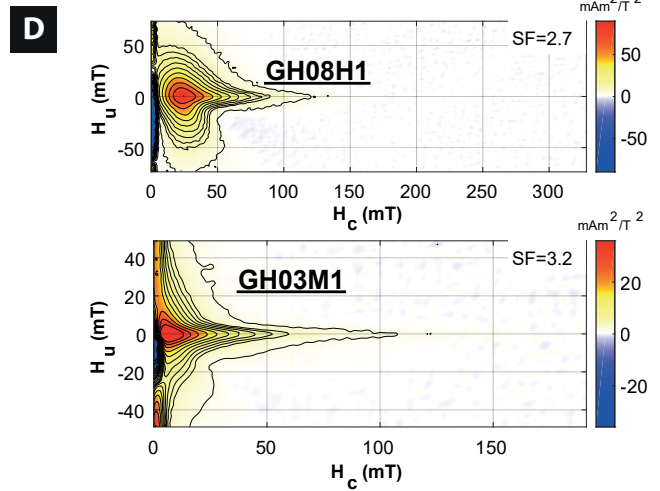
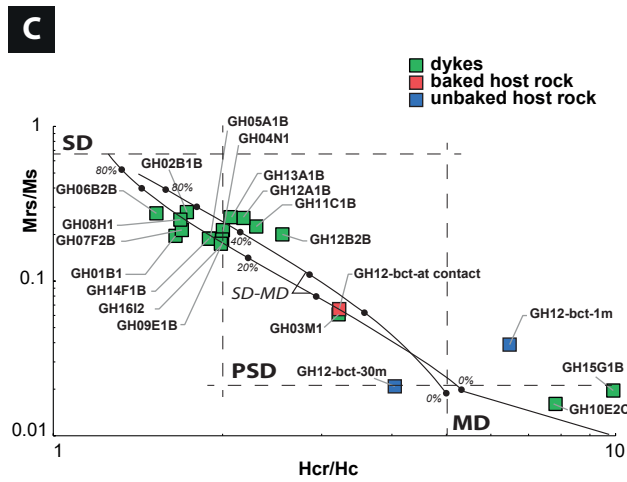
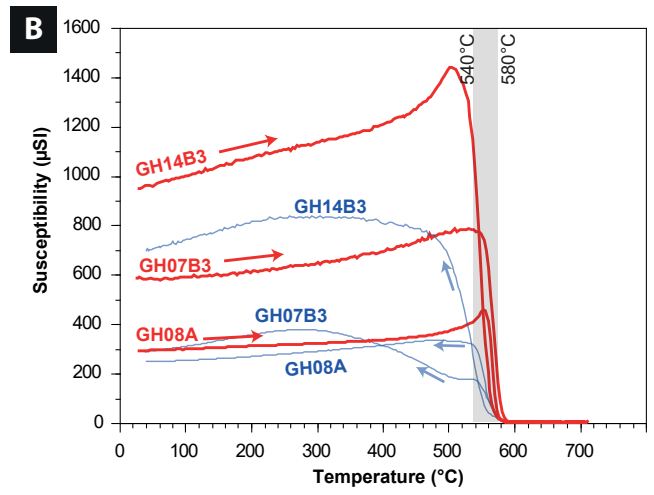
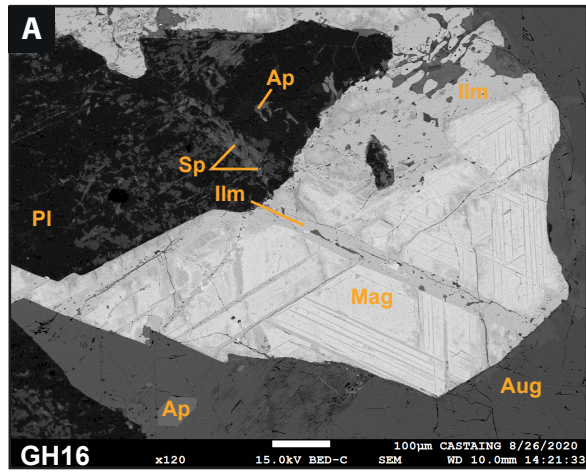


**Figure 4**

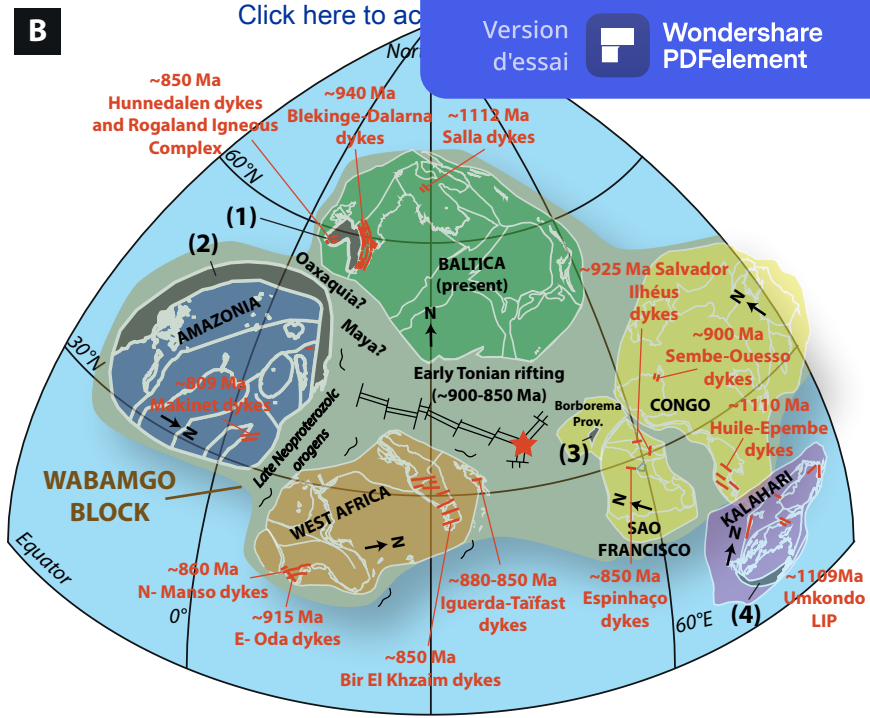
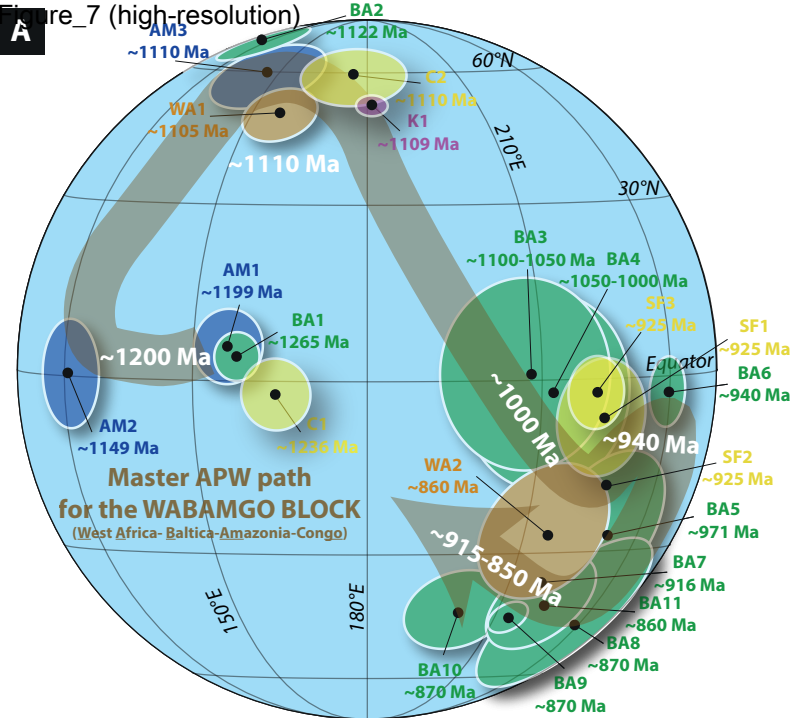




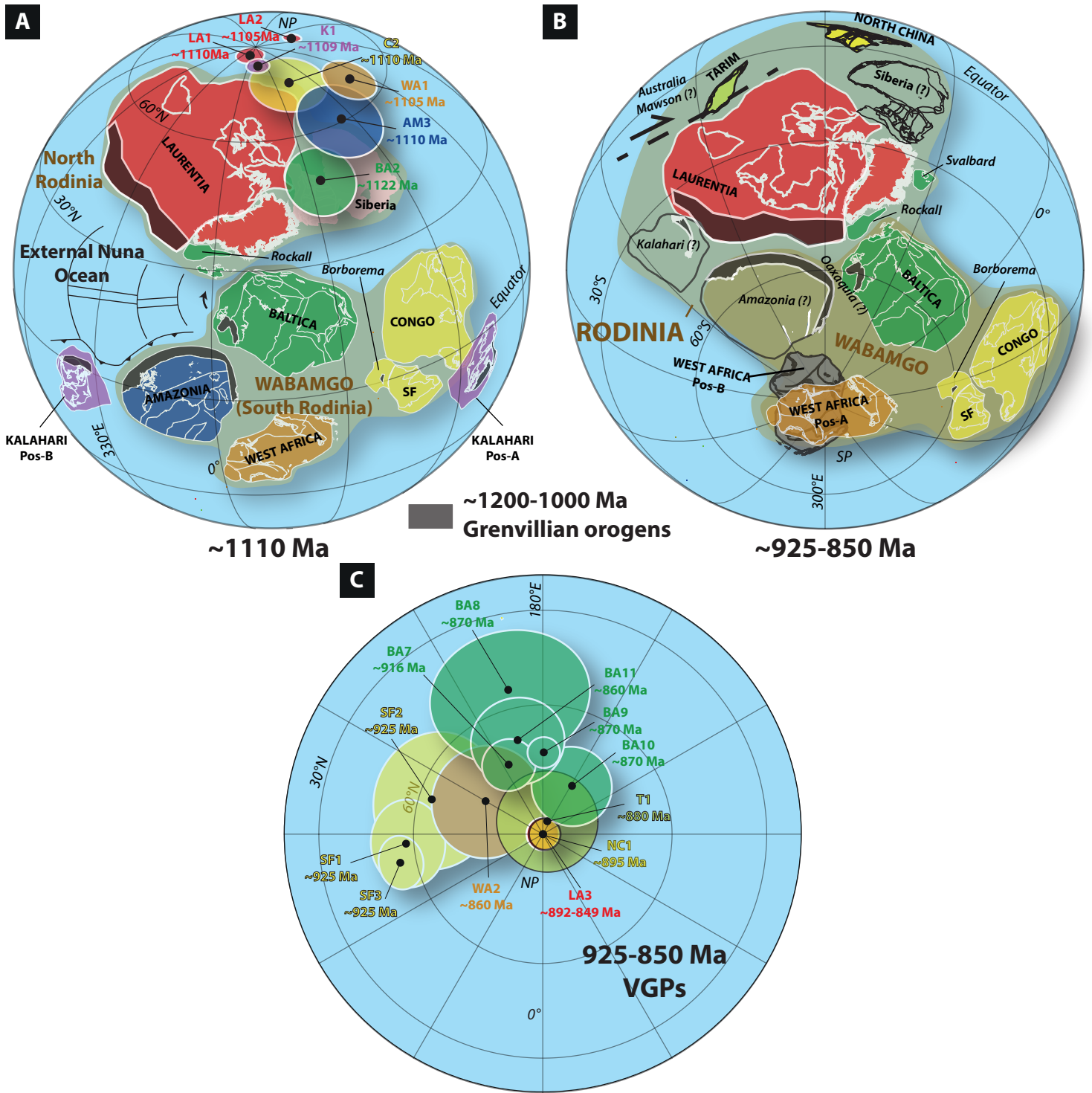
**Figure 5**



**Figure 6**



**Figure 7**



**Figure 8**