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1 ***Structure of the Paleoproterozoic Kédougou-Kéniéba Inlier (Senegal-Mali) deduced from***  
2 ***gravity and aeromagnetic data.***

3

4 Mahamadou Diallo<sup>a,b</sup>, Lenka Baratoux<sup>a</sup>, Grégory Dufréchoy<sup>a</sup>, Mark Walter Jessell<sup>a,c</sup>, Olivier  
5 Vanderhaeghe<sup>a</sup>, Saïdou Ly<sup>b</sup>, David Baratoux<sup>a</sup>

6

7 <sup>a</sup> Géosciences Environnement Toulouse, IRD, UPS, CNRS 14 Avenue Edouard Belin, 31400 Toulouse, France

8 <sup>b</sup> Département de Géologie, Ecole Nationale d'Ingénieurs Abderhamane Baba Touré (ENI-ABT), 410, Av. Van  
9 Vollenhoven, BP 242, Bamako, Mali

10 <sup>c</sup> Centre for Exploration Targeting, The University of Western Australia, 35 Stirling Highway, Crawley, WA  
11 6009, Australia

12

13 Corresponding author: M. Diallo: mahamadou.diallo@mesrs.ml

14

15 ***Abstract***

16 The Kédougou-Kéniéba Inlier (KKI) corresponds to a window through Paleoproterozoic  
17 terranes of the West African Craton (WAC). This study presents, first of all, an interpretation  
18 of a regional Bouguer gravity map (14°W-9°W, 11°N-16°N) of the KKI and then introduces a  
19 new litho-structural map of the Malian part of the KKI using aeromagnetic data (12°0'W-  
20 10°80'W, 12°0'N-14°50'N). The KKI is limited to the west by a negative gravity anomaly  
21 forming a 30-100 km wide corridor, oriented N-S to NNE-SSW, and correlated to the  
22 Variscan Mauritanides orogenic belt. West of this belt, the Mesozoic to Cenozoic sedimentary  
23 deposits are marked by the highest positive anomaly of the region, attributed either to the  
24 presence of mafic rocks at intermediate to deep crustal levels or to a shallower Moho depth.  
25 Within the KKI, moderately positive to negative anomalies are correlated with exposed  
26 plutonic and mafic to intermediate metavolcanic rocks. Gravity data also reveal (i) two north-  
27 west trending lineaments attributed to crustal-scale shear zones, (ii) three north-east trending  
28 lineaments marked by gravity anomalies sub-parallel to the known Bissau–Kidira–Kayes  
29 Fault Zone, and named Kayes, Kédougou-Kéniéba, and South Shear Zones, respectively, (iii)  
30 and the extension to the south of the known Mauritanides Belt Thrust.

31 The local aeromagnetic map of the Malian part of the KKI discriminates the Mako  
32 metavolcanic belt with granitic intrusions in the west characterized by heterogeneous  
33 anomalies, from the Kofi metasedimentary series delineated by magnetic lows in the east.  
34 ESE-WNW to ENE-WSW-trending alternation of magnetic anomalies in the metavolcanic  
35 and metasedimentary rocks are attributed to pervasive structures associated with ductile

36 deformation. The Senegalo-Malian Shear Zone is marked at the regional scale by deflection  
37 of the geophysical lineaments but is not expressed by any offset of identified structures or  
38 lithological contacts.

39

40 Keywords: Airborne Magnetics; Gravity; Paleoproterozoic; West Africa; Mali; Structural  
41 Evolution

42

## 43 **1. Introduction**

44 Aeromagnetic and gravity data are a critical source of information for regional and local  
45 geology mapping and resource exploration, especially in zones of poor outcrop conditions  
46 owing to vegetation, soil and/or thick lateritic cover (*e.g.*, [Hansen, 2001](#); [Boyd and Isles,](#)  
47 [2007](#)). These data are useful at all stages of regional litho-structural mapping and mineral  
48 exploration programs. Gravity data provide an integrated response to density variations of  
49 rocks within the crust and down to the upper mantle, produced by structural and lithological  
50 contrasts at regional and local scales. This information is complementary to that obtained  
51 from aeromagnetic data, which provide better resolution of near surface when compared to  
52 gravity data. Together, these data can be used to identify lithological units, faults and their  
53 prolongation as major crustal shear zones ([Gunn, 1997](#); [Nabighian et al., 2005](#); [Dufréchou et](#)  
54 [al., 2014](#); [Aitken et al., 2016](#); [Jessell et al., 2016](#)). The structural features are defined as linear  
55 gravity or magnetic expressions caused by geological discontinuities at surface or at depth.

56 The structural geophysics approach (*e.g.*, [Gunn et al., 1997](#); [Crafford and Brauch, 2002](#); [Boyd](#)  
57 [and Isles, 2007](#); [Ranganai et al., 2008](#)) utilizes the analysis of gravity and magnetic fields to  
58 interpret variations in mass and susceptibility that reflects the causative body characteristics.  
59 Transformations of potential field (gravity and magnetic) data enhance geophysical anomalies  
60 that are related to the observed field ([Gunn, 1975](#)). Interpretation of the geophysical  
61 anomalies offers the chance to explore, at the regional and local scale, the sub-surface  
62 distribution of geological properties ([Gunn et al., 1997](#)). Recognition of shear zones, deep-  
63 seated and second-order faults can be very important for mineral exploration, as these  
64 structures are widely regarded as the primary plumbing systems for migration of magmas and  
65 mineralizing fluids from the mantle or deep crust leading to deposit formation in the upper  
66 crust (*e.g.*, [McCuaig and Kerrich, 1998](#); [Crafford and Brauch, 2002](#); [Dufréchou et al., 2015](#)).  
67 Primary difficulties in gravity and magnetic data interpretation are to discriminate the

68 contribution to the geophysical field from sources located at different depths. It should be also  
69 noted that the interpretation of geophysical anomalies based on potential field data is  
70 intrinsically ambiguous as densities or susceptibilities are not uniquely related to rock type  
71 (*e.g.*, Emerson, 1990; Schön, 1996; Clark, 1997). Thereby, geological information becomes  
72 essential to constrain gravity and magnetic data interpretation.

73 This study focuses on the Kédougou-Kéniéba Inlier (KKI) and Kayes Inlier (KI), which  
74 comprises terranes affected by the Eburnean orogeny and overlain by Mesoproterozoic to  
75 Cenozoic sediments. These inliers are situated across southern Mauritania, eastern Senegal,  
76 northern Guinea and western Mali. Outcrop conditions are poor in the KKI/KI and crystalline  
77 basement rocks are widely masked by the lateritic cover and younger Quaternary deposits.

78 Previous studies have concentrated on geochemical, geochronological and structural analysis  
79 in the Senegalese part of the KKI (Bassot and Caen-Vachette, 1983; Bassot, 1987; Milési et  
80 al., 1989; Ledru et al., 1991; Dia et al., 1997; N'diaye et al., 1997; Gueye et al., 2007; 2008;  
81 Dabo and Aifa, 2010; 2011; Diene et al., 2012; 2015 and Diatta et al., 2017). Most of the  
82 Malian part of the KKI studies focused on mineralization at mining property-scale (Fouillac et  
83 al., 1993; Dommang et al., 1993; Lawrence et al., 2013a, b; Hein et al., 2015; Lambert-Smith  
84 et al., 2016a, b; Masurel et al., 2017a, b, c).

85 To complement the understanding of the Paleoproterozoic KKI and in order to fill gaps  
86 between sparse field observations, this paper presents an original analysis of gravity data at  
87 the regional scale and of the magnetic data at the scale of the Malian part of the KKI. These  
88 analyses are compared to published geological data in order to (i) place the KKI in its regional  
89 context, and (ii) decipher the main lithological units and structures of the KKI. The extension  
90 and internal structure of the KKI have been studied in detail with an emphasis on the  
91 structural framework and cross-cutting relationship between gravity and magnetic patterns  
92 related to regional tectonics. The shape and position of the lithology and structure of the KKI  
93 were better defined and several new major structures were identified and incorporated into the  
94 new interpretative map of the Malian part of the KKI.

## 95 **2. Geological context and tectonic history of the KKI**

### 96 ***2.1 Geological context***

97 The regional gravity data analyzed in this study (Figs 1a and 2a) covers an area of 300,000  
98 km<sup>2</sup> (14°W-9°W, 11°N-16°N) and straddles four countries: southern Mauritania, eastern  
99 Senegal, northern Guinea and western Mali. To the south, the Kenema-Man domain

100 represents an Archean cratonic nucleus locally reworked during the Eburnean orogeny  
101 (Kouamelan et al., 1997). The Kédougou-Kéniéba Inlier (KKI) and Kayes Inlier (KI)  
102 correspond to windows through Mesoproterozoic to Neoproterozoic sediments of the  
103 intracratonic Taoudeni basin exposing the Paleoproterozoic basement. The KKI is bounded to  
104 the west by a polyphase mobile zone of the Variscan Mauritanides orogenic belt (Dia, 1988;  
105 Villeneuve, 2008) and from the south-east to north-east by the late Proterozoic to Paleozoic  
106 intracratonic Taoudeni basin (Fig. 2a).

107 The KKI is made of metavolcanic and metasedimentary rocks deformed and metamorphosed  
108 during the Eburnean orogeny (Bonhomme, 1962). It is subdivided into two metavolcanic belts  
109 (Mako and Falémé belts) and two metasedimentary series (Dialé-Daléma and Kofi series)  
110 (Bassot, 1987; Hirdes and Davis, 2002) (Fig. 1b). In the western part of the KKI, the NNE-  
111 SSW to N-S trending 20-40 km wide Mako belt (Fig. 1b) is characterized by a thick sequence  
112 of tholeiitic basalts, locally displaying pillow lavas, basaltic, gabbroic and ultramafic rocks of  
113 tholeiitic affinity as well as calc-alkaline basalts and andesites (Dia et al., 1997; Hirdes and  
114 Davis, 2002; Dioh et al., 2006; N'gom et al., 2009). The eastern margin of the Mako belt is in  
115 tectonic contact with the Dialé-Daléma series along the Main Transcurrent Zone (MTZ; Ledru  
116 et al., 1991). The Dialé-Daléma series is characterized by metasedimentary rocks with minor  
117 intercalations of metavolcanic rocks (Bassot, 1987; Dia, 1988; Hirdes and Davis, 2002; Gueye  
118 et al., 2008). It is intruded by several plutons, among these is the Saraya batholith (Pons et al.,  
119 1992) (Fig. 1b). The Falémé belt (Hirdes and Davis, 2002), east of the Dialé-Daléma series,  
120 consists of metapyroclastites, metarhyolites, metaandesites, minor metabasalts,  
121 metasedimentary rocks and syntectonic granitoids (Fig. 1b). The Kofi series is separated from  
122 the Falémé belt by the Senegalo-Malian Shear Zone (Bassot and Dommaget, 1986; Ledru et  
123 al., 1991; Lawrence, 2010). The Kofi series consists of detrital metasedimentary rocks,  
124 metacarbonate rocks and breccias (Lawrence et al., 2013a, Lambert-Smith, 2014; Masurel et  
125 al., 2017c) (Fig. 1b). It is intruded by monzodiorites, monzogranites and post-  
126 Paleoproterozoic mafic dykes (Baratoux et al., 2019).

## 127 ***2.2 Tectonic framework***

128 The studied area covered by the gravity data, comprises the western edge of the West African  
129 Craton (WAC). It is cross-cut by the Mauritanides Belt Thrust to the west, and the Bissau-  
130 Kidira-Kayes Fault Zone (BKKF) in the north of the KKI, which cross-cuts the Mauritanides  
131 Belt (Villeneuve, 2008; Fig. 2a).

132 Three phases of deformation have affected the KKI during the Paleoproterozoic (Milési et al.,  
133 1989; Ledru et al., 1991; Dabo and Aïfa, 2011; Diene et al., 2012; Masurel et al., 2017a;  
134 Diatta et al., 2017). The D1 phase caused crustal thickening as a consequence of NE-SW to  
135 ENE-WSW horizontal shortening (Milési et al., 1989; Masurel et al., 2017c). The D1 phase is  
136 synchronous with the intrusion of large Tonalite-Trondhjemite-Granodiorite (TTG) batholiths  
137 within the Mako belt (Gueye et al., 2008; Diene et al., 2012). Contrariwise, Ledru et al.  
138 (1991) propose that the D1 has just affected the metasedimentary rocks of the Dialé-Daléma  
139 series and not those of the Mako belt. They infer an anteriority of the metasedimentary  
140 formations compared to the metavolcanic formations. However, the more recent  
141 geochronological data (Theveniaut et al., 2010) suggest that the Mako belt is older compared  
142 to the Dialé-Daléma series and therefore should have at least partially registered the D1  
143 deformation event. The D2 phase is characterized by large N-S strike-slip faults and shear  
144 zones (Diene et al., 2012; Masurel et al., 2017c) and marks a change in tectonic style from  
145 collisional to transcurrent deformation (Dabo and Aïfa, 2010; Diene et al., 2012). The D3  
146 phase is characterized by the reactivation of early structures and the activation of ductile-  
147 brittle N-S to NE-SW trending sinistral shear zones accommodating NNW-SSE horizontal  
148 shortening (Diene et al., 2012; Lawrence et al., 2013b, Dabo et al., 2016; Masurel et al.,  
149 2017c). The Senegalo-Malian Shear Zone (SMSZ) is considered to be related to the D3 event  
150 (Bassot and Dommaget, 1986; Lawrence et al., 2013a), which consists of alternating low and  
151 high strain domains localized along lithological contacts between igneous and sedimentary  
152 rocks.

153 The subsidence of the large intra-cratonic Taoudeni basin forming a depression in the center  
154 of the WAC started in the Mesoproterozoic (Deynoux, 1971; Trompette, 1973) and continued  
155 until the mid-Paleozoic. The WAC was later deformed by the Pan-African and Hercynian  
156 orogenies as a consequence of a succession of collision and accretion events (Villeneuve et  
157 al., 1990).

### 158 **3. Gravity data and interpretation**

#### 159 ***3.1 Gravity data sets and processing***

160 The data from 3823 gravimetric stations were extracted from the Bureau Gravimétrique  
161 International (BGI) database (<http://bgi.obs-mip.fr/>) covering a larger area around the Malian  
162 part of the KKI (Fig. 1a and Fig. 2b). The gravimetric stations have variable spacing up to 6  
163 km in the northern part of the studied zone and up to 20 km in its southern part (Fig. 2b).  
164 These gravity data were used to calculate a Bouguer gravity map with a 5 km cell size, over

165 an area extending from 14°W to 9°W and from 11°N to 16°N (~542 km x 555 km). This area  
166 encompasses a region extending from southern Mauritania to northern Guinea and eastern  
167 Senegal to western Mali (Figs 1a and 2b).

168 The interpolation of gravity data was achieved using a minimum curvature algorithm (Briggs,  
169 1974). Three sequential corrections, known as free-air, Bouguer and terrain correction have  
170 been made for the compensation of height and topographic effects. In this study, we have only  
171 applied the terrain correction as the free-air and Bouguer corrections were part of the BGI  
172 data-base. The terrain correction is the gravitational attraction, at the gravity station, of all the  
173 hills above the Bouguer slab and all the valleys occupied by the slab. It is obtained by  
174 determining the mass of the hills and the mass deficiencies of the valleys using topographic  
175 information. The topographic data used have an accuracy of 30m/pixel (Fig. 3b). The gravity  
176 measurement is influenced by the relief in the vicinity of a given measurement, in particular  
177 in the presence of rough topography. The terrain correction is made by calculating the  
178 regional terrain correction using a coarse regional Digital Elevation Model (at 90 m in our  
179 case) combined to a more finely sampled local DEM model covering the study area (at 30 m)  
180 (Fig. 3). The correction is applied to the entire Bouguer map, which includes both the flat  
181 Paleoproterozoic domain of the KKI and mountainous regions, such as the Meso to  
182 Neoproterozoic domains, including the Mauritanides Belt, the Northern Guinea and the  
183 Taoudeni Basin. The effect of the correction can be observed by comparing Figure 3a (before  
184 correction) and Figure 3c (after correction).

185 The process consists of creating a grid for the regional terrain correction (Fig. 3). We use in  
186 this process a crustal density value of  $2.67 \text{ g.cm}^{-3}$ , acknowledging that the resulting Bouguer  
187 anomaly is affected by this approximation (Flis et al., 1998). The grid is then used to calculate  
188 the detailed corrections at each gravity station with the appropriate module in the Geosoft  
189 Oasis Montaj software.

190 The obtained complete Bouguer anomaly map (Fig. 3c) provides information about mass  
191 distribution (variations in density) in the crust and in the upper mantle. As these density  
192 variations may be related to lithology, the Bouguer anomaly map allows for the identification  
193 of contacts between litho-tectonic domains (e.g., Nabighian et al., 2005; Ranganai et al.,  
194 2008; Dufrechou and Harris, 2013; Dufrechou et al., 2014; Aitken et al., 2016). The first  
195 vertical derivative (1VD) and upward continuation (Fig. 4b and 4c) were calculated from  
196 gravity data in order to improve the definition of lithological boundaries and highlight deeper  
197 structures, respectively.

198 In order to determine the depth extent of structures mapped from the Bouguer gravity map  
199 and its first vertical derivative, multi-scale edge detection, called gravity worms (Archibald et  
200 al., 1999; Hornby et al., 1999; Holden et al., 2000; Horowitz et al., 2000) was produced (Fig.  
201 5), using the Intrepid Geophysics software. This calculation is a wavelet transformation  
202 defining the positions of gradients at successive upward continued heights (Archibald et al.,  
203 1999; Holden et al., 2000). In this study, the gravity worm map (Fig. 5) was processed using  
204 seven steps of upward continuation from 7 to 58 km. The gravity worms represent  
205 discontinuities at all scales from local-scale shown by high-frequency features at lower levels  
206 of upward continuation to regional-scale, low-frequency features detected at higher levels of  
207 upward continuation. Dip direction can be inferred for sub-surface geological contacts (e.g.,  
208 lithological contact, faults and shear zones) based on the gravity worms map (Holden et al.,  
209 2000). Notably, the height levels of upward continuation may be related to the source depth.  
210 The upward continuation height is approximately twice the source depth of an idealized  
211 source geometry (e.g., intrusions, faults, dykes) (e.g., Archibald et al., 1999; Holden et al.,  
212 2000). Regional-scale structures are given names in the following text. Local-scale and near  
213 surface structures visible in the gravity worms map, which were not interpreted as regional-  
214 scale structures, were given numbers (Fig. 5) in order to refer to them in the following text.

### 215 ***3.2 Gravity patterns analysis: interpretation of regional geology***

216 During the gravity data analysis, consideration was given to the KKI with the purpose to set  
217 its limit within the regional setting in relationship to its current surface extent. The Bouguer  
218 gravity anomalies range from about -30 to 50 mGal (Fig. 2b). The KKI is located between the  
219 Mauritanides Belt (Variscan Orogeny) to the west and the Neoproterozoic to Paleozoic  
220 Taoudeni basin to the east and south (Fig. 2). To the extreme west of the KKI, the Mesozoic-  
221 Cenozoic Senegalo-Mauritanian sedimentary basins (MCB; Fig. 2) are expressed by positive  
222 gravity anomalies (15 mGal to 51 mGal). This domain of positive anomalies extends further  
223 south and encompasses the Paleozoic sedimentary formations (Pa; Fig. 2b). The gravity  
224 worms (Fig. 5) mark well the eastern margin of the MCB along the contact with the  
225 Mauritanides Belt. Contiguous to the western side of the KKI, the fold-and-thrust  
226 Mauritanides Belt is characterized by positive gravity anomalies to the north (10 mGal to 35  
227 mGal) and by pronounced negative gravity anomalies to the south (-4 mGal to -27 mGal). In  
228 the center and east of the studied area, the gravity anomalies are moderately positive (ca. 1 to  
229 15 mGal) to negative (ca. -8 mGal to -27 mGal) and display a complex spatial pattern. This  
230 zone correlates with the Paleoproterozoic KKI and the Taoudeni Basin displaying similar



231 gravity anomalies, which continue on both sides of the mapped KKI-Taoudeni boundary  
232 (KKI, KI, MNeP; Fig. 2b). This KKI-Taoudeni contact is no longer marked by any gravity  
233 lineament as seen in the gravity worms map (Fig. 5). The KKI-KI Paleoproterozoic  
234 metavolcanic/metasedimentary and plutonic rocks are associated either with positive or  
235 negative anomalies (10 mGal to -27 mGal; Fig. 2b). Commonly, the shape of a worm sheet in  
236 multiscale edge results from sharp discontinuities or interfaces between contrasting rock  
237 materials such as intrusive contact and highlights geological features (Holden et al. 2000).  
238 Indeed, a synthetic spherical worm sheet body is designed to represent a pluton intrusion type  
239 (Holden et al., 2000). A potential pluton at 15–20 km depth is inferred from an elongated  
240 rounded gravity worms (#1; Fig. 5b). This inferred intrusion is over a positive gravity  
241 anomaly suggesting a mafic intrusion elongated in a NNE-trending direction sub-parallel to  
242 the high level of the upward continuation of the West Mauritanides Thrust (WMT, Fig. 5b).  
243 Two previously undefined gravity worms features are depicted from gravity worms map (#2,  
244 #3; Fig. 5b). The worm #2 is marked by curved and large (up to 250 km) multi-scale edge  
245 detected all the way up to the 57 km upward continuation. The worm #2 shows a steep contact  
246 with a dip towards the NE in the south and towards the N in the north (#2; Fig. 5b). The worm  
247 #3 is a flat and curved SW-trending geological feature limited to the north by the KKSZ and  
248 to the south by the SSZ (#3; Fig. 4b). The gravity data (Figs 4b and 7c) shows several small  
249 regions with slightly negative gravity anomalies over the KKI corresponding to known  
250 granitic plutons (e.g., Pons et al., 1992; N'diaye et al., 1997; Masurel et al., 2017c), such as  
251 Saraya, Gamaye, Moussala and Yatia (Ga, Mo, Yt; Fig. 7c). Several positive gravity  
252 anomalies up to ca. 10 mGal located in the KKI are correlated to mafic and ultramafic rocks  
253 (Fig. 7c).

254 The Mesoproterozoic to Neoproterozoic sedimentary units (MNeP) and associated plutons are  
255 characterized by contrasted gravity anomalies. The lithologies do not appear to be correlated  
256 with gravity anomalies in these units. These MNeP rocks occupy a large part of the analysed  
257 Bouguer map from the south to the east and northeast. Positive anomalies (1 mGal to 10  
258 mGal) associated to the MNeP formations are interpreted as cropping out and buried mafic  
259 sills dated at  $200 \pm 3$  Ma (Baratoux et al., 2019), while negative anomalies (-19 mGal to -27  
260 mGal) are probably related to granitoid plutons and covering sediments (Fig. 2b). In  
261 summary, the studied area comprises two domains: (i) the western domain characterized by a  
262 positive gravity anomaly and (ii) the eastern domain characterized by heterogeneous patterns  
263 of positive and negative gravity anomalies.

### 264 *3.3 Structural analysis from gravity data*

265 The gravity data delineate straight or curved lineaments portrayed from (i) apparent alignment  
266 of gravity gradients; and (ii) offset of gravity anomalies across lineaments. These  
267 discontinuities are interpreted as an expression of faults and shear zones. The area comprises  
268 contrasted density domains affected by the Eburnean and Variscan Orogenies, and gravity  
269 data are expected to be useful in this context to reveal regional-scale faults and shear zones.  
270 The map of lineaments from gravity data proposed here must be considered as defining deep  
271 or broad deformation corridors rather than single and discrete faults at the surface.

272 Based on the gravity expression of the Mauritanides Belt Thrust (MbT) and the Bissau–  
273 Kidira–Kayes Fault Zone (BKKF), several new lineaments are identified from gravity maps  
274 (Fig. 4). The Mauritanides Belt Thrust may be extended to the south. A new sub-parallel  
275 lineament was drawn to the west of the southern part of the MbT, which is marked by a  
276 gravity lineament along the contact between contrasted gravity anomalies (positive gravity  
277 anomaly to the west and negative gravity anomaly to the east). This new structure, parallel to  
278 the MbT, corresponds to the southern continuation of mapped thrust zones that mark the  
279 western border of the MCB. We interpret this lineament as a thrust zone comparable to the  
280 MbT (WMT; Fig. 4 and Tab. 1) and name it the West Mauritanides Thrust (WMT). The  
281 WMT is well defined in gravity worms map (Fig. 5) where it sits at the contact between the  
282 MCB and the Mauritanides Belt. It is marked by a deep steep gravity worm discontinuity (Fig.  
283 5).

284 Three new gravity lineaments, with characteristics similar to the Bissau–Kidira–Kayes Fault  
285 Zone (BKKFZ), are identified. These identified lineaments are considered as deep crust  
286 lineaments and are thereby interpreted as shear zones. The gravity lineaments sub-parallel to  
287 the BKKFZ are named the Kayes Shear Zone, the Kédougou–Kéniéba Shear Zone and the  
288 South Shear Zone (KSZ, KKSZ, SSZ; Figs 4, 5 and Tab. 1). The KSZ, in the north of the  
289 BKKF, marks a contact between a positive gravity anomaly in the south and a negative  
290 gravity anomaly in the north (KSZ; Fig. 4). The KSZ indicates a dip towards the SE, as shown  
291 by gravity worms (Fig. 5a). The KKSZ is associated with truncation of gravity anomalies and  
292 is the only gravity structure which cross-cuts the Malian Paleoproterozoic KKI (KKSZ; Figs 4  
293 and 9). It is well defined in the first vertical derivative of the complete Bouguer gravity  
294 anomaly (Fig. 4b). The KKSZ marks the northern limit of a flat and curved SW dipping  
295 gravity worm (#3; Fig. 5b) as well as the northern limit of the long and steep, curved gravity  
296 worm (#2; Fig. 5b). The gravity worms indicate a steep dip towards the SE for the KKSZ. The

297 SSZ marks a contact between positive and negative gravity anomalies in its southern segment  
298 and shows truncation of positive gravity anomalies in its northern segment (SSZ; Fig. 4). In  
299 gravity worms, the southern part of the SSZ appears as the limit of the flat and curved SW  
300 dipping gravity worm (#3; Fig. 5b).

301 The analysis of gravity data allows the recognition of new NW-SE trending crustal-scale  
302 shear zones, which cross-cut the Mesoproterozoic to Neoproterozoic rocks and are visible in  
303 all gravity maps (Fig. 4). To the north of the studied area, the North Crustal Shear Zone  
304 (NCSZ) is characterized by contrasted gravity anomalies and by the truncation of gravity  
305 anomalies (NCSZ; Fig. 4 and Tab. 1). In gravity worms, the NCSZ is marked by the  
306 truncation and deflection of the worm (#2; Fig. 5a). To the south, a new gravity lineament  
307 sub-parallel to the NCSZ is portrayed and designated as the South Crustal Shear Zone (SCSZ;  
308 Fig. 4c and Tab. 1). The SCSZ is delineated by the truncation of positive gravity anomalies  
309 and by the contact between positive and negative gravity anomalies (SCSZ; Fig. 4). The  
310 SCSZ is only seen in gravity worms at its northern part as steep SW dipping structure (Fig.  
311 5b). The upward continuation map to 20 km depth from the Bouguer gravity, provides  
312 information about deep regional-scale features (Fig. 4c). The gravity lineaments identified in  
313 the previous paragraphs (WMT, NCSZ, SCSZ, KSZ and SSZ, Fig. 4c) are also portrayed in  
314 the upward continued map (Fig. 3c). It should be noted that the KKSZ is less apparent;  
315 although it is confirmed by the worm #2 to be deep in its northern part (KKSZ; Fig. 4c).

316 The conjugate NE and NW-trending gravity worms (#4; Fig. 5b) are sub-parallel to the deep  
317 NCSZ and KKSZ structures, respectively. However, these gravity worms are near the surface  
318 as they are related to a low continuation value ( $< 25$  km). The steep NE-trending gravity  
319 worms #5 and #6 do not correspond to any previously mapped structures. These lineaments  
320 (#5, #6; Fig. 5b) are considered as near-surface structures, as they are associated to a low  
321 continuation value ( $< 20$  km). Both of these features have an indicated dip towards SE. The  
322 worm #6 passes through the Sadiola gold deposit and can be correlated to the deep expression  
323 of the NNE-trending thrust zone oblique to the Sadiola Shear Zone (Masurel et al., 2017a).  
324 The worm #7 is close to the deep NCSZ lineament (#7; Fig. 5b) and is interpreted to represent  
325 a regional gravity lineament that marks the southern limit of the steep and curved gravity  
326 worm #2 (#7; Fig. 5b). The worm #7 indicates a dip towards the NE. Three N-trending worms  
327 are portrayed from gravity worms map (#8, #9, #10; Fig. 5b). The worm #8 is steep with a dip  
328 towards the W and the worm #9 is less steep with a dip towards the W. The worm #10 is  
329 deeper than the worm #9 with a dip towards the W. The worms #8 and #9 are related to low

330 continuation values (< 25 km), whilst the worm #10 is related to high continuation values (up  
331 to 50 km).

332 The Senegalo-Malian Shear Zone (SMSZ) and the Main Transcurrent Zone (MTZ) are  
333 regional shear zones described in the KKI (Bassot and Dommange, 1986; Ledru et al., 1991)  
334 (Fig. 1b). They do not show evidence of truncation of gravity anomalies. However, the SMSZ  
335 marks the limit between the highly negative gravity anomaly of the Gamaye pluton (Ga; Fig.  
336 7c) and the Falémé belt (K; Fig. 7c) in the south. The SMSZ seem to divide the F and G  
337 gravity anomalies (F, G; Fig. 7c) and to limit a few other gravity features as well (J; Fig. 7c).

## 338 4. Magnetic data

### 339 4.1 Magnetic data sets and processing

340 The aeromagnetic data used in this study (Figs 1b and 6) come from two main aeromagnetic  
341 surveys which were flown covering the Malian part of the KKI (High - Sense  
342 Geophysics/Aerodat Ltd, 1996, 1997; Kevron Pty Ltd, 2001). Their characteristics are  
343 summarized in Table 2.

344 Total Magnetic Intensity (TMI) data were reduced to the equator (RTE; Fig. 6a). The  
345 reduction to the pole (RTP) is less stable at the low magnetic latitudes than the reduction to  
346 the equator (RTE), which behaves well in low magnetic latitudes (Leu, 1982; Macleod et al.,  
347 1993). Several data transforms/derivatives were applied to the RTE in order to emphasize  
348 geological boundaries and major structures (Fig. 6).

349 The first vertical derivative (1VD; Fig. 6b) is used to delineate short wavelength features  
350 (Gunn et al., 1997; Milligan and Gunn, 1997). Thus, the 1VD map gives a sharper picture of  
351 the near-surface litho-structural features than the TMI (Verduzco et al., 2004) and was used to  
352 derive the structural framework of the studied area.

353 The absolute value of the analytic signal (AS; Fig. 6c) corresponds to the square root of the  
354 squared sum of the vertical and of the two horizontal derivatives of the magnetic field (Roest  
355 et al., 1992). The AS highlights the outlines of magnetic rock units and is effective for  
356 delineating geological boundaries. The AS resolves close-spaced bodies' relationship and is  
357 particularly useful for analyzing data from equatorial regions (McLeod et al., 1993).

358 The upward continuation transforms the data to attenuate near-surface features as if the  
359 measurements were made at a different height above the source (Milligan and Gunn, 1997)  
360 and highlight deeper structures masked by short wavelength anomalies (Jacobsen, 1987;

361 Lyngsie et al., 2006). The upward continuation is used to highlight magnetic and gravity  
362 anomalies (Figs 4c and 8b) associated with a pattern at 2.5 km and 20 km depth, respectively.  
363 The tilt derivative (Fig. 6d) is the arctangent of the ratio of the first vertical derivative and of  
364 the modulus of the total horizontal derivative (Miller and Singh 1994). For vertical magnetic  
365 bodies, the tilt derivative is positive over the source and negative outside of it. Because the tilt  
366 angle is based on a ratio, it responds well to both shallow and deep sources. The tilt images  
367 are used to trace the dolerite dyke swarm of the Malian part of the KKI (Fig. 9c).

#### 368 ***4.2 Gravity and magnetic patterns: interpretation of the geology of the Malian KKI***

369 The magnetic grain in the aeromagnetic data (Fig. 6) is interpreted to reflect deformed  
370 magnetic horizons. At the regional scale, these magnetic horizons correspond to three zones  
371 with distinct magnetic responses, which are correlated to the different litho-tectonic series  
372 forming the Malian part of the KKI (Figs 6 and 7b) (Hirdes and Davis, 2002; Villeneuve,  
373 2008; Masurel et al., 2017c). The nomenclature used in this section refers only to the  
374 subdivision of magnetic signatures (Fig. 7b), namely, the west magnetic high (WMH), the  
375 east magnetic low (EML), the Finman magnetic signature (FP), the Taoudéni magnetic  
376 signature (Ta), and the south sill magnetic signature (Sd). The patterns of these magnetic  
377 domains and their response in gravity data, as shown in Figures 5 and 6c, are further  
378 discussed below.

379 The west magnetic high (WMH) encompasses the Mako belt (including the Finman pluton)  
380 and part of the Falémé belt and the Dialé-Daléma series. The east magnetic low (EML)  
381 corresponds to the Kofi series with internal dolerite sills (Sd; Fig. 6b). The Taoudeni magnetic  
382 signature (Ta) is related to Mesoproterozoic formation (Fig. 7b).

383 The Mako belt is characterized by heterogeneous magnetic signatures with ovoid to elongate  
384 high and low anomalies in the RTE image (Fig. 6a). Prominent sub-circular or ovoid-shaped  
385 lower magnetic anomalies of the analytic signal (A, C and D; Fig. 7a) correlate with granitic-  
386 dioritic plutons. Several pluri-kilometer-wide, elongate, and locally curved high anomalies are  
387 attributed to the presence of basaltic to andesitic rocks (E, F and H; Fig. 7a). The NNE-SSW  
388 ovoid-shaped moderately magnetic body in the center of the Mako belt corresponds to a calc-  
389 alkaline, amphibole-bearing pluton (C; Fig. 7a) dated at ca. 2140 Ma (Masurel et al., 2017c)  
390 and known as the Finman plutonic complex. It appears in the complete Bouguer anomaly map  
391 as negative anomalies without a defined form (C; Fig. 7c). In the AS map, a high magnetic  
392 anomaly is depicted in the WMH (F; Fig. 7a), which shows a circular shape in the RTE (F;  
393 Fig. 6a). This high magnetic anomaly F show a positive gravity anomaly in the Bouguer

394 anomaly map (F; Fig. 7c). In gravity anomaly map, the F anomaly continues in the EML  
395 domains with a smooth texture (G; Fig. 7c). In the analytic signal map, the G anomaly (G,  
396 Fig. 7a) does not appear under the metasedimentary rocks of the Kofi series, but corresponds  
397 to the continuation of the F gravity anomaly under the Kofi series (F, G; Fig. 7a). The F and G  
398 anomalies are described as part of the Mako metavolcanic to meta-andesitic rocks.

399 The Dialé-Daléma series within the WMH is composed of clastic metasedimentary rocks with  
400 intercalated alkali pyroclastic flows (Bassot, 1987; Hirdes and Davis, 2002) (Fig. 1b), which  
401 are less magnetized than the Mako belt (Fig. 6a). The Dialé-Daléma series is characterized by  
402 a smooth magnetic texture with low magnetic anomalies. The series contains a folded high  
403 magnetic anomaly attributed to meta-andesites and meta-pyroclastic rocks (Mf; Figs 7a and  
404 10). The Dialé-Daléma series is intruded in its Senegalese part by the Saraya granitoid  
405 complex (Sa; Fig. 7c; Pons et al., 1992), which shows large negative gravity anomaly in its  
406 northern side and positive gravity anomaly to its extreme southern side. The KKSZ marks the  
407 limit between the two gravity anomalies of the Saraya batholith (Fig. 7c). The northern  
408 extension of the Saraya batholith is known as the Moussala granodiorite (N'diaye et al., 1997)  
409 (Mo; Figs 6a and 7a, 7c). The Moussala granodiorite is well defined in gravity data with a  
410 prominent low anomaly. It has an elongated shape with a long axis trending NNE-SSW (Mo;  
411 Fig. 7c). The Moussala pluton is expressed by a low magnetic anomaly (Mo; Fig. 6a). The  
412 gravity data show at the eastern side of the Saraya batholith negative anomalies that are  
413 attributed to the presence of granitoids similar to the ones of the Saraya batholith beneath the  
414 Dialé-Daléma series (L; Fig. 7c).

415 The Falémé belt (J, K; Figs 6a and 7a) shows higher magnetization than the Dialé-Daléma  
416 series (Figs 1b and 7a), although its intensity and texture are variable. In the center-west of  
417 magnetic data (J; Fig. 6a), the Falémé belt presents high magnetic anomalies, which  
418 correspond to an orthogneiss cross-cut by an ESE-WNW trending mafic dyke (J; Fig. 7a). The  
419 southern portion of the Falémé belt expresses intermediate to high magnetic anomalies that  
420 are associated to diorite and amphibole granodiorite elongated in the N-S direction with calc-  
421 alkaline metavolcanoclastic rocks of the Boboti suite (Lambert-Smith et al., 2016b) (K; Fig.  
422 7a). In gravity data, the (J) and (K) anomalies of Falémé belt are associated with positive  
423 gravity anomalies (J, K; Fig. 7c).

424 The east magnetic low (EML) of the analytic signal map corresponding to the Kofi series is  
425 marked by a low magnetic response with a smooth texture (Fig. 7b). The Kofi series is made  
426 of metasedimentary rocks alternating with calc-alkaline volcanic flows and pyroclastics (Fig.  
427 1b; Masurel et al., 2017c). The metasedimentary components are weakly magnetized, and the

428 igneous rocks give rise to moderate to high anomalies. The Yatia granite is the best example,  
429 which is marked by an ovoid-shape high magnetic anomaly with an E-W trending long axis  
430 (Yt; Fig. 6b and 7a) and a negative gravity anomaly (Yt; Fig. 7c). It is cross-cut by mafic  
431 dykes (Fig. 9a). In the south, the Gamaye granitic pluton (*e.g.*, N'diaye et al., 1997) does not  
432 appear in magnetic data and presents a textural appearance similar to the host  
433 metasedimentary rocks (Ga, Figs 6a and 7a). However, the Gamaye pluton is well-defined in  
434 gravity data with a negative gravity anomaly 40 km long and 15 km wide (Ga; Fig. 7c). A  
435 high amplitude magnetic anomaly is defined in the south of the Kofi series (Sd; Fig. 7a). This  
436 high magnetic anomaly corresponds to outcrops of NNE-SSW trending elongate doleritic sills  
437 (Sd; Fig. 7c).

438 The Mesoproterozoic cover of the Taoudeni basin (Ta) is associated with alternating high and  
439 low magnetic anomalies (Ta; Figs. 6 and 7). The sedimentary rocks correlate with low  
440 magnetic anomalies, and mafic sills correspond to high magnetic anomalies.

#### 441 ***4.3 Structural analysis from magnetic data***

442 The structural analysis is based on the first vertical derivative of the RTE map (Fig. 6b). The  
443 juxtaposition of sub-parallel and contrasting elongate magnetic horizons is categorized as  
444 lithological contacts or shear zones parallel to lithological units (Fig. 8 and Tab. 3). Long and  
445 deflected or dragged lineaments marking pronounced magnetic contrasts that can locally run  
446 parallel or cross-cut magnetic units on the enhanced derivative maps are interpreted as shear  
447 zones. Faults are characterized as straight and short offsets or abrupt truncations of magnetic  
448 horizons on the enhanced derivative maps.

##### 449 ***4.3.1 Foliation, folds and shear zones***

450 The lineament frequency depends on the magnetization of the analyzed domain and is higher  
451 in the metavolcanic rocks than in the metasedimentary rocks. This is especially the case of the  
452 metavolcanic Mako belt, which corresponds to the Western Magnetic High (WMH; Figs 7  
453 and 8a). The most prominent lineaments are marked by alternating high and low anomalies  
454 interpreted to correspond to major magnetic lineaments. The metavolcanic Mako belt is  
455 characterized by generally high-strained, deflected and heterogeneously sheared magnetic  
456 units (Figs 6b and 8a). These magnetic features portray an early ductile deformation episode,  
457 with WNW-ESE to NW-SE trending direction. It is noteworthy that such structures have not  
458 been mentioned in previous work. The repetition of these lineaments and curved patterns of  
459 linear magnetic anomalies are attributed to isoclinal folds. This is well illustrated in the first

460 vertical derivative map (Fig. 7b and Fig. 8a). In the entire West Magnetic High domain, folds  
461 display NW-SE, N-S, NE-SW and E-W axial traces (Fig. 8a and Tab. 3).

462 This early ductile fabric is cross-cut by N-S to NE-SW trending lineaments. The curvature of  
463 the WNW-ESE to NW-SE lineaments in the vicinity of the N-S to NE-SW trending  
464 lineaments suggests that the latter correspond to shear zones with an apparent dextral  
465 component (Tab. 3). These shear zones are regionally represented by the Main Transcurrent  
466 Zone (MTZ; Ledru et al., 1991) and the Senegalo-Malian Shear Zone (SMSZ; Basot and  
467 Dommaget, 1986). These later networks of ductile shear zones variably transposed the  
468 earlier deformation event with a regional reorientation of early lineaments from SW to NE  
469 and N within that frame. The MTZ is marked by a sharp and anastomosed network of  
470 lineaments cross-cutting E-W oriented magnetic units showing an apparent right-lateral offset  
471 of magnetic marker horizons (Fig. 8a and Tab. 3). The SMSZ corresponds to a N-S trending,  
472 long, and slightly curved lineament that follows the abrupt magnetic contact on the first  
473 vertical derivative map marking the limit between two contrasted magnetic domains (Fig. 8a  
474 and Tab. 3). The trace of the SMSZ marks the transition between a western domain  
475 characterized by the alternation of contrasted high and low magnetic anomalies associated  
476 with the Mako belt and Dialé-Daléma series and an eastern domain characterized by a more  
477 homogeneous magnetic signature corresponding to the Kofi series (Fig. 8b and Tab. 3). The  
478 WNW-ESE to NW-SE trending lineaments do not appear to be cross-cut by or dragged along  
479 the mapped trace of the SMSZ.

480 Comparing the metavolcanic belts of the Mako belt to the west and the metasedimentary  
481 rocks of the Kofi series to the east, we have shown that the aeromagnetic signatures of these  
482 two domains are different and none of the earliest E-W to WNW-ESE trending shear zones  
483 interpreted within the Mako belt are present within the Kofi series.

#### 484 4.3.2 *Faults*

485 Several lineaments oriented ca. NW-SE to NNW–SSE, NNE–SSW to NE-SW, and E-W are  
486 identified from magnetic data and are interpreted as faults. They are marked by linear  
487 magnetic lows or highs or cross-cut and mark abrupt terminations of magnetic units (Fig. 8a  
488 and Tab. 3). The density of faults is variable throughout the studied area. They are related to  
489 bedrock structures as they show the intersection of metasediment units in the south of Kofi  
490 series (EML) and the truncation of meta-andesite and metavolcano-sedimentary rocks in the  
491 Mako belt (Tab. 3 ; Figs 8b and 10). The dominant faults in the Mako belt are NNE-SSW to



492 NE-SW trending, and they mainly show evidence of dextral movement. In contrast, the E-W  
493 interpreted fault in the Kofi series shows a dextral movement (Tab. 3; Fig. 10).

#### 494 4.3.3 Dyke swarms

495 The tilt derivative highlights vertically dipping magnetic sources and is particularly useful to  
496 map dolerite dykes (Fig. 9a). Indeed, the tilt derivative map shows sublinear relatively narrow  
497 magnetic lows that delineate the two main groups of dyke swarms described in the KKI (Fig.  
498 9b, 9c) (Théveniaut et al., 2010; Baratoux et al., 2019), namely (i) the  $1764 \pm 4$  Ma Kédougou  
499 N035° trending dolerite dyke swarm; and (ii) the  $1521 \pm 3$  Ma Sambarabougou N90° trending  
500 dolerite dyke swarm. These dykes, posterior to all Paleoproterozoic formations, are  
501 predominant in the Birimian domain (Jessell et al., 2015).

## 502 5. Discussion

### 503 5.1 Strengths and weaknesses of the different datasets

504 The integration of the available gravity and magnetic data with existing geological map (Fig.  
505 1.b) proved to be useful for litho-structural mapping of the KKI (Fig. 10). As an example,  
506 illustrating the value of combining gravimetric and airborne magnetic data, the Gamaye  
507 granitic pluton does not appear in magnetics (Ga, Fig. 7a) but is well-defined in gravity data  
508 with a low gravity response of 40 km long and 15 km wide (Ga; Fig. 7c). Also, the dolerite  
509 sill in the south of Kofi series shows broad and well defined high magnetic anomaly (Sd, Fig.  
510 7a, 7b); whilst, it does not show a gravity signature (Sd; Fig. 7c).

511 The variations in data resolution is a difficulty that may be turned into advantages to decipher  
512 the crustal structure when the data are analysed together in an integrated approach. Indeed,  
513 gravity data (Fig. 2b) is gridded at 5 km resolution (6 km spaced data points in the north and  
514 up to 20 km in the south) whereas the magnetic data (Fig. 6a) is gridded at 100 m resolution  
515 (200 m spaced lines). As a consequence, magnetic data is more suited for the near-surface as  
516 they capture better high-frequency features associated with near-surface structures and  
517 exposed lithologies (Fig. 10) and gravity is most useful to decipher deep structures, especially  
518 in the basement (Fig. 4).

519 Interpretations of correlations between geology and gravity remain locally uncertain. At some  
520 places, the gravity anomalies cannot be explained by surface geology. For instance, the  
521 highest density which is expressed as positive gravity anomaly over the sedimentary basins  
522 (Paleozoic to Mesozoic in age) in the western part of the analyzed extent of the gravity data  
523 (MCB; Fig. 2b) may reflect a large volume of dense material in the deep crust (mafic rocks)

524 (*e.g.*, Gunn, 1997; Karner et al., 2005; Gao et al., 2017). This is inferred to compressed  
525 magma developed beneath the rifted area at the depocenters or edges of the Taoudeni  
526 sedimentary basin and/or may correspond to the uplifting of the Moho to the sub-surface  
527 giving high positive gravity anomalies over sedimentary basin. A strongly negative gravity  
528 anomaly is defined in the south of the Hercynian Mauritanides Belt, and this anomaly is  
529 difficult to understand considering the presence of mafic rocks (dense) at the surface  
530 (Villeneuve, 2008).

531 In summary, the detailed analysis of gravity and magnetic data, combined with geological  
532 information, has led to a revised litho-structural map of the Malian part of the KKI (Fig. 10)  
533 showing new or improved litho-structural information compared to the previously published  
534 map of the KKI (*e.g.*, Fig. 1b; Gueye et al., 2008; Lawrence et al., 2013a; Masurel et al.,  
535 2017c).

## 536 *5.2 Litho-tectonic features interpreted from gravity and magnetic data analyses*

537 The geophysical data presented in this paper compared to the known geology of the studied  
538 area provide new constraints on the lithological units and structures at the scale of the KKI  
539 and surrounding areas (gravity data) and at the scale of the Malian part of the KKI (combined  
540 gravity and magnetic datasets) (Figs 4, 8 and 9). This integrated approach of gravity and  
541 magnetic data confirmed previously recognized geological structures and led to several  
542 findings in the area of the Malian part of the KKI.

543 The Mauritanides Belt Thrust (MbT), as defined by geological data, is subdivided into three  
544 distinct segments. The north-western segment is marked by a limit between the highest  
545 density domain in the west and a high density domain in the east that corresponds to a positive  
546 gravity anomaly and coincides with the contact between the Senegalo-Mauritanian  
547 sedimentary basin and the Mauritanides Belt (MCB, Mb; Fig. 2). The north-eastern segment  
548 is not marked by a limit between contrasted gravity anomalies but is evidenced by offsets of  
549 negative gravity anomalies (Fig. 2b). The south-western segment is, however, not clearly  
550 delineated and cannot be traced in gravity maps.

551 The NE-SW trending Bissau–Kidira–Kayes Fault Zone (BKKF; Fig 2b) is well characterized  
552 in gravity data by the offset of the positive anomaly (10 mGal to 51 mGal) in its southern part  
553 where it shows truncation of the western domain. In its northern part, the BKKF marks the  
554 southern limit of the Kayes Inlier and the truncation of positive gravity anomaly (Fig. 3). The  
555 BKKF is not marked by any multi-scale edge detection in upward continued heights (Fig. 5a).  
556 Accordingly, the BKKF could be a sub-surface structure rather than a deep one. Other curved

557 faults mapped by Villeneuve (2008) (Cf; Fig. 2a) do not correlate with gravity contrasts. The  
558 curved shapes of these faults from geological data suggest that they correspond to flat  
559 structures, which may not produce signatures in the gravity signal. The Bissau – Kidira –  
560 Kayes Fault zone permits interpretation of three other shear zones parallel to it, namely the  
561 Kayes Shear Zone, the Kédougou-Kéniéba Shear Zone and the South Shear Zone (KSZ,  
562 KKSZ and SSZ; Fig. 4). Only the KKSZ cross-cuts the magnetic data investigation area. The  
563 KKSZ runs through the Loulo district (Fig. 8) which is defined as world a class orogenic gold  
564 deposit (Dommange et al., 1993; Lawrence et al., 2013a, b). However it is not expressed in  
565 magnetic data (Fig. 8) suggesting that this shear zone is a deep gravity lineament.

566 In Figures 7c and 8b, the pronounced gravity and magnetic patterns continue over the mapped  
567 KKI limit indicating a lateral continuation of the KKI greenstone belt under late Proterozoic  
568 to Paleozoic cover (Ta; Figs 7c and 8b) in the east. This is evidenced through the entire  
569 magnetic data from west to east as well as through gravity anomalies (F, G; Fig. 7c). On the  
570 other hand, the magnetic anomaly G does not appear in the RTE (Fig. 5a) as it is covered by  
571 magnetically quiet metasedimentary rocks, whilst this anomaly is well expressed in gravity  
572 data (G, Fig. 5c) and in the upward continued map (Fig. 8b). The occurrence of the KKI in  
573 this part of the WAC and its geophysical pattern continuation outside of its mapped limit  
574 suggests a continuity of the Paleoproterozoic basement underneath the sedimentary Taoudeni  
575 sequence from south to north. In contrast, the marked positive gravity anomaly to the west of  
576 the Mauritanides, interpreted as a step in the Moho, suggests that it represents the former  
577 western margin of the Paleoproterozoic KKI. These interpretations confirm previous models  
578 based on the interpretation of tomographic data (e.g., Begg et al., 2009, Priestley et al., 2008,  
579 Jessell et al., 2016). In gravity map (Fig. 7c), the SMSZ and the MTZ are not characterized by  
580 gravity contrasts and thus may correspond to sub-surface structures or may mark a limit  
581 between contrasted geological domains as suggested from magnetic data.

582 Gravity data also highlight some lineaments that are not correlated to any identified surface  
583 structures yet. Two of these lineaments cross-cut the Paleoproterozoic KKI (SCSZ, KKSZ;  
584 Fig. 3) and only the KKSZ extends to the Malian part (Fig. 8a). Geological contacts exposed  
585 at the surface and magnetic horizons are not offset by these faults (Figs 4d and 8a). Most of  
586 the interpreted gravity lineaments are highlighted in gravity worms map (Fig. 4) and their  
587 depth, as well as their dip direction, were deduced from the upward continued gravity worms  
588 generated from continuation levels of 7.7 km to 57.7 km. These lineaments can be classified  
589 into two main groups: the NW-SE-trending lineaments and the NE-SW-trending lineaments.

590 The movement along these lineaments cannot be inferred from the gravity data. However,

591 from the gravity worms map, the worms #9 and #10 seem to be sinistrally offset along the  
592 SCSZ structure (Fig. 5). Accordingly, the SCSZ can be considered as a sinistral fault or shear  
593 zone as well the other NW-SE-trending lineaments, which are sub-parallel to the SCSZ. An  
594 important question is raised about the interpreted gravity lineaments origin. It is observed that  
595 these large structures do not offset the surface structures and stratigraphy. It is therefore  
596 speculated here that these lineaments are crustal-scale to lithospheric shear zones which might  
597 have formed before the final Paleoproterozoic assembly and could, therefore, correspond to  
598 earlier Eburnean or even pre-Eburnean structures or may have reactivated an Archean sub-  
599 crustal lineament (*e.g.*, [Egal et al., 2002](#); [Dufréchou and Harris, 2013](#); [Dufréchou et al., 2014](#)).  
600 Even though the origin of these lineaments is not defined, they could potentially have  
601 important implications for the structural and metallogenic evolution of the region (*e.g.*,  
602 [Kohanpour et al., 2018](#)), as the relationship between deep-seated gravity gradients and  
603 location of large deposits has been validated ([Hobbs et al., 2000](#); [Archibald et al., 2001](#);  
604 [Dufréchou et al., 2011](#)). In the gravity worms map, the gold deposits in the region occur in  
605 association with relatively shallow worms (#6, #7 and #8; Fig. 5). We note that these gravity  
606 worms are connected to the deepest worms in the study area (Fig. 5). These deep lineaments  
607 may potentially represent deep conduct through which, could offer connectivity from the  
608 mantle to the crust, and thus, characterize relatively shallow structural traps as shown by the  
609 gravity worms map (Fig. 5).

### 610 ***5.3 Implications for litho-tectonic evolution of the KKI***

611 The previous tectonic model proposed for the KKI by Ledru et al. (1991) was based on the  
612 recognition of a polyphase structure for the Dialé-Daléma series with refolded folds that  
613 contrasts with the simple structure of the Mako belt characterized by a single NE-SW trending  
614 foliation. The polyphase structure of the Dialé-Daléma series is interpreted to record the  
615 succession of a D1 event followed by a D2 event, whereas the deformation of the Mako belt is  
616 ascribed to the D2 event. This proposition is contradicted by recent geochronological data in  
617 the KKI ([Delor et al., 2010a, b](#); [Théveniaut et al., 2010](#)) dating magmatism of the Mako belt  
618 at ~2.2 Ga and deposition of the protolith of the metasedimentary formation of the Dialé-  
619 Daléma series after ca. 2165 Ma ([Hirdes and Davis, 2002](#)).

620 The gravity and magnetic lineaments provide new constraints for the reconstruction of the  
621 lithotectonic-evolution of the studied area, which updates and partly contradicts the model  
622 proposed by Ledru et al. (1991) but is coherent with the geochronological data obtained by  
623 Delor et al. (2010a, b) and Théveniaut et al. (2010). Indeed, magnetic data presented above

624 show that the Mako belt, as the Dialé-Daléma series, are characterized by previously  
625 unrecognized WNW-ESE to NW-SE trending magnetic lineaments locally underlining  
626 isoclinal folds (Figs 6b and 8b). These lineaments are interpreted to represent an early phase  
627 of ductile deformation. Accordingly, we consider that the metavolcanic Mako belt has  
628 recorded the earliest increments of the local Paleoproterozoic tectonic event, as it is the case  
629 for the Dialé-Daléma series.

630 The lineaments attributed to this early D1 fabric are cross-cut by N-S to NE-SW trending  
631 lineaments, which we associate to transposition into D2 high-strain zones. The absence of E-  
632 W to WNW-ESE lineaments in the Kofi series, suggests either total transposition of the early  
633 fabric during D2 or that the protoliths of the Kofi series were deposited after D1. The  
634 transposition of E-W to WNW-ESE structures is particularly well expressed along the Main  
635 Transcurrent Zone (MTZ; Ledru et al., 1991) dominated by N-S to NE-SW lineaments (Fig.  
636 8a and Tab. 3). However, the geometric relationships between E-W to WNW-ESE structures  
637 and N-S to NE-SW structures do not show large offset as in the case of a regional transcurrent  
638 displacement. The Senegalo-Malian Shear Zone (SMSZ; Basot and Dommange, 1986) marks  
639 the boundary between a western magnetic domain characterized by highly contrasted  
640 magnetic anomalies and an eastern magnetic domain characterized by more homogeneous  
641 quiet magnetic signatures. The SMSZ is not associated with any horizontal offset of magnetic  
642 units and identified structures. Based on these considerations, we propose that the MTZ and  
643 SMSZ correspond to high-strain zones. The regional pattern of the Malian part of the KKI  
644 shows a reorientation of lineaments from the SW toward the N to NE, which either underlines  
645 the shape of former crustal blocks and/or suggests a strain gradient at this scale.

## 646 **6. Conclusions**

647 We have shown that the combination of gravity and magnetic data, leads to several significant  
648 findings complementing previously published work. The litho-tectonic map of the KKI was  
649 derived from this combination and new major structures were identified and incorporated in  
650 the Malian part of the KKI interpretative map (Fig. 10).

651 Gravity and magnetic analyses have shown that the KKI extends to the east underneath the  
652 Taoudeni basin but not to the west, where it is limited by the Mauritanides Belt. The eastward  
653 extension of the KKI was deduced from the continuation of anomalies with similar orientation  
654 and characteristics from both sides of the KKI-Taoudeni basin boundary.

655 Gravity anomaly map analysis led to several findings of new structures. The NW-trending  
656 North Crustal Shear Zone (NCSZ) and the South Crustal Shear Zone (SCSZ) are the most

657 significant and are identified for the first time in the area. The Kédougou-Kéniéba Shear Zone  
658 (KKSZ), the Kayes Shear Zone (KSZ) and the South Shear Zone (SSZ) with NE-SW trend  
659 (Fig. 3) were also defined from gravity data (Fig. 4). The nature and significance of these  
660 structures have not been identified yet, but it should be mentioned that the Loulo with Gara  
661 and Yatea gold deposits (Figs 1b and 4) district is located close to the KKSZ.

662 Magnetic data covering the Malian KKI allow elaborating a new interpretative litho-structural  
663 map based on the geophysical features of the area (Fig. 10). Previously mapped ductile  
664 fabrics, shear zones, faults, dykes, felsic and mafic intrusions that were identified by  
665 geological mapping alone, are now extended, specified, and more precisely defined based on  
666 magnetic and gravity analysis. Mostly, three main generations of ductile structures are  
667 identified from magnetics with WNW-ESE to NW-SE, N-S to NNE-SSW and NE-SW and  
668 three fault trends with NW-SE, N-S to NE-SW and E-W. The earliest WNW-ESE to NW-SE  
669 lineaments-structures are transposed in the later N-S to NE-SW trending lineaments-  
670 structures. The analysis of magnetic data shows that the MTZ is characterized by sharp  
671 anastomosed magnetic lineaments cross-cutting early WNW-ESE to NW-SE lineaments  
672 without significant horizontal offset. Similarly, the SMSZ marks a limit between the  
673 contrasted magnetic domain of metavolcanic rocks and the quiet magnetic domain of  
674 metasedimentary rocks but does not show any horizontal offset of the magnetic units. These  
675 analyses of the MTZ and SMSZ question the importance of these shear zones as regional  
676 transcurrent tectonic structures.

677 Several NE-SW and E-W trending dolerite dykes cutting-across the KKI greenstone belt have  
678 been revealed, dated previously at ca. 1764 and 1520 Ma (Baratoux et al., 2019). The  
679 directions of these sparsely outcropping dolerite dykes have been deduced from this study.  
680 Therefore, the concomitance of dyke direction with fault and shear directions in the KKI (Fig.  
681 9), highlighted from magnetic dyke mapping, suggests that the mafic magmas follow pre-  
682 existing zones of weakness.

683 This study illustrates the value of undertaking a combined analysis of gravity and magnetic  
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1037 **Figure Captions**

1038

1039 **Figure 1:** (a) - Geologic map of the West African craton (modified after [Masurel et al., 2017c](#); [Boher et al., 1992](#)). (b) - Geologic map of the Kédougou-Kéniéba inlier (1:250,000  
1040 scale, modified after [Gueye et al., 2007](#); [Lawrence et al., 2013a](#)). The Falémé River forms the  
1041 international border with Senegal to the west and Mali to the east and north. *Abbreviation:*  
1042 *KKI* = Kédougou-Kéniéba Inlier; *KMD* = Kénéma-Man Domain; *BMD* = Baoulé-Mossi  
1043 Domain; *Sa* = Saraya Pluton; *Yt* = Yatea Pluton; *Ga* = Gamaye Pluton.  
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1046 **Figure 2:** (a): Previously existing litho-structural map covering the gravity data (modified  
1047 after [Villeneuve, 2008](#)). (b): The gravity data distribution (grey dots) and the resulting  
1048 complete grid. The heavy dashed lines indicate structural interpretation while fine lines  
1049 indicate main lithological domains inferred from (a). *Abbreviation:* MbT = Mauritanide Belt  
1050 Thrust; BKKF = Bissau–Kidira–Kayes Fault Zone; KI = Kayes Inlier; KKI = Kédougou-  
1051 Kéniéba Inlier; KM = Kénéma-Man domain.

1052

1053 **Figure 3:** (a): Bouguer gravity map before applying terrain correction. (b): Local-scale  
1054 topographic data used in the calculation of the terrain correction. (c): Complete Bouguer map  
1055 after applying the terrain correction.

1056

1057 **Figure 4:** Bouguer gravity maps and lineament interpretations. (a) to (c): Most prominent  
1058 gravity lineaments interpreted from gravity data and superposed upon a- complete Bouguer  
1059 gravity grid; b- its first vertical derivative and c- its upward continued map at 20 km depth;  
1060 (d) Structural interpreted map from gravity on geological map in Fig.2a. Known structures  
1061 modified from Villeneuve, (2008) are represented in black lines and new structural  
1062 interpretation are represented in blue dashed lines. *Abbreviation:* KSZ: Kayes Shear Zone;  
1063 KKSZ: Kédougou-Kéniéba Shear Zone; SSZ: South Shear Zone; NCSZ = North Crustal  
1064 Shear Zone; SCSZ = North Crustal Shear Zone

1065

1066 **Figure 5:** Upward continuation gravity worms (rainbow coloured lines) from ~7 km upward  
1067 continuation in green to ~57 km upward continuation in red with (a) on the greyscale

1068 complete Bouguer gravity map with interpreted gravity lineaments in Fig. 3 and gold deposits  
1069 in the region; (b) on the litho-tectonic map from Villeneuve, (2008) and gold deposited in the  
1070 region. Distribution of gold deposits in the gravity worm image shows that gold deposits are  
1071 located in or near lower-order structures. Acronyms 1 to 10 are referred to geological features  
1072 discussed in the text.

1073

1074 **Figure 6:** Presentation of magnetic data. (a) - Image of the reduced to equator total magnetic  
1075 intensity; (b): Image of the first vertical derivative of the RTE magnetic field (c) Image of the  
1076 analytic signal of the RTE magnetic field. (d) Tilt derivative of the RTE aeromagnetic map.

1077

1078 **Figure 7:** (a) Image of the analytic signal of the RTE magnetic field with abbreviations of  
1079 units/features; (b) Lithological interpretation defined from the analytic signal map and based  
1080 on the definition of magnetic responses. The different families of color are magnetically  
1081 distinct subdivisions of the inlier in two part; (c): Zoom of KKI zone with structural  
1082 interpretation from first vertical derivative gravity data. Abbreviation: A to L = Acronyms of  
1083 magnetic and gravity anomalies; MTZ = Main Transcurrent Zone; SMSZ = Senegal-Malian  
1084 Shear Zone; KKSZ = Kédougou-Kéniéba Shear Zone; NCSZ = North Crustal Shear Zone; Ga  
1085 = Gamaye monzogranite; Sa = Saraya granitoids; Yt = Yatea monzogranite; Mo = Moussala  
1086 granodiorite; Ta: Mesoproterozoic to Paleozoic Taoudeni basin; Sd: Doleritic sill intrusion.

1087

1088 **Figure 8:** (a): Most prominent magnetic lineaments from and superposed upon a greyscale  
1089 image of the first vertical derivative of the RTE magnetic field and lineament interpretations  
1090 with lineaments inferred from gravity. (b): Magnetic lineaments interpreted from the  
1091 enhanced first vertical derivative of the RTE magnetic field superposed on upward continued  
1092 magnetic data at 2.5 km depth.

1093

1094 **Figure 9:** (a): Image of the tilt derivative of the RTE magnetic field. (b): Magnetic lineaments  
1095 associated to dolerite dykes interpreted from the tilt derivative map and rose diagram of dyke  
1096 orientations.

1097

1098



1099 **Figure 10:** Simplified geological map of the Malian part of the KKI and surrounding rocks of  
1100 the Taoudeni basin displaying key lithological units and structural framework interpreted  
1101 from gravity and magnetic data.

1102

1103 **Table captions**

1104

1105 **Table 1:** Zoom on deep shears and thrusts interpreted in the studied area and their regional-  
1106 scale gravity response. Abbreviation: 1VD = First vertical derivative; BA = Bouguer  
1107 anomaly; Upward Cnt = Upward continuation.

1108

1109 **Table 2:** Key parameters of geophysical data sets from Mali

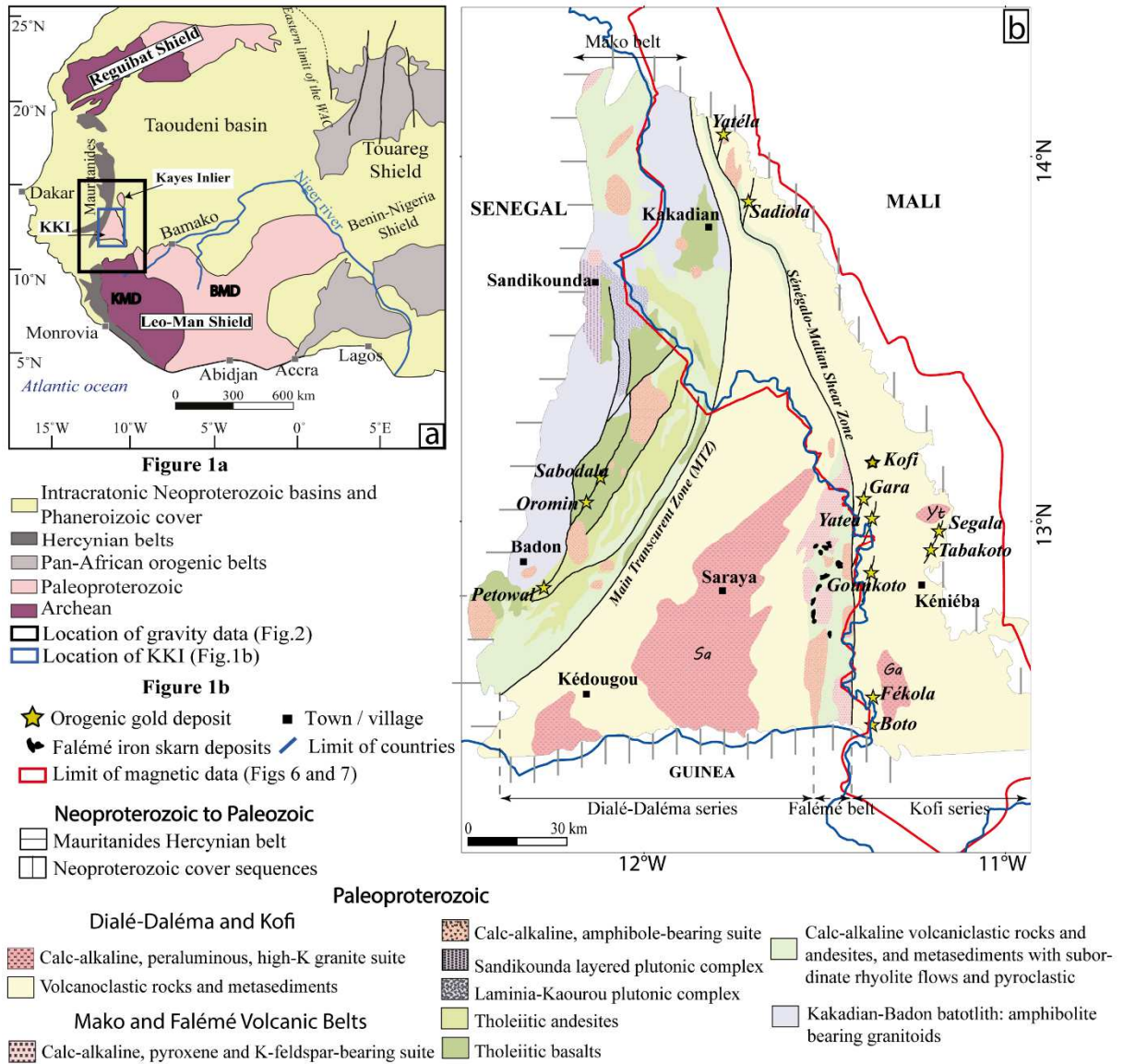
1110

1111 **Table 3:** Zoom on near-surface faults and shear zones interpreted in the Malian part of the  
1112 KKI and their local-scale magnetic response. Abbreviation: RTE = Reduced to Equator; 1VD  
1113 = First vertical derivative.

1114

1115 FIG1:

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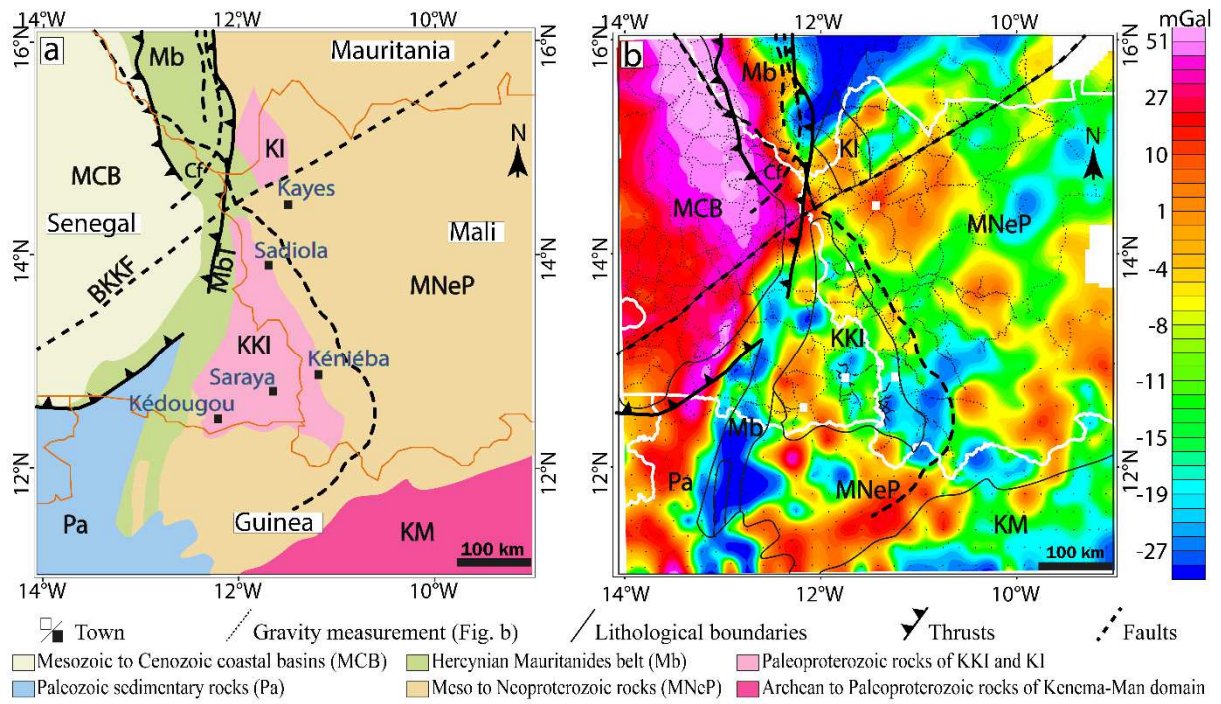
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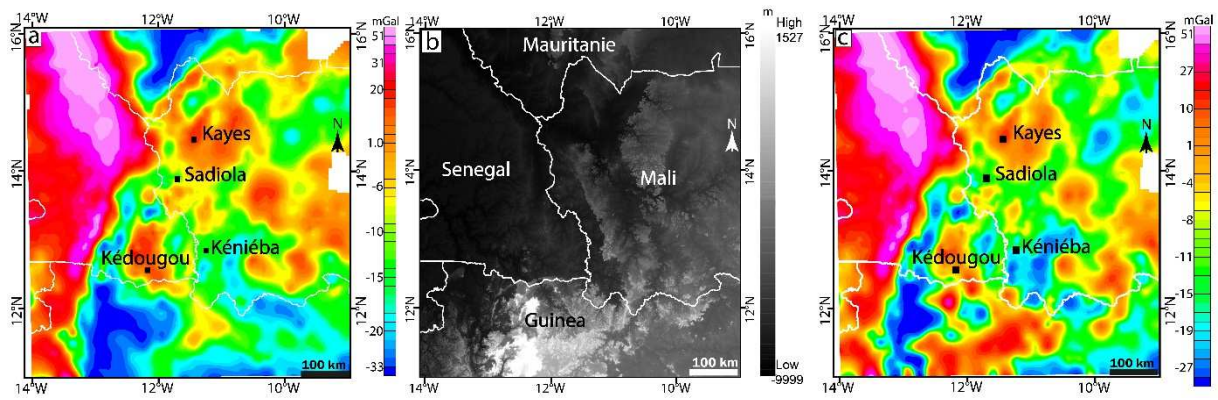
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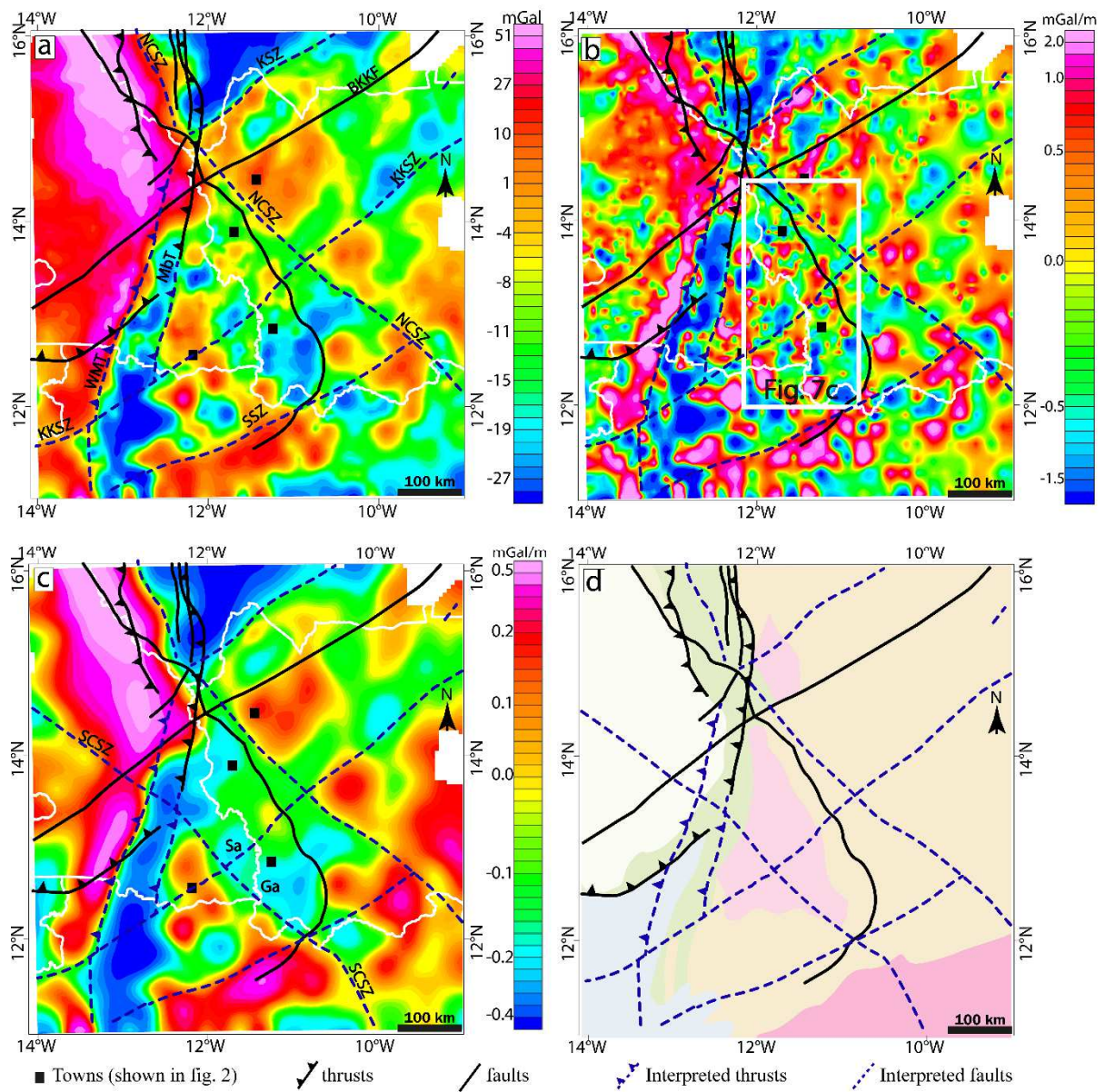
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1124 FIG3:



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1126 FIG4:



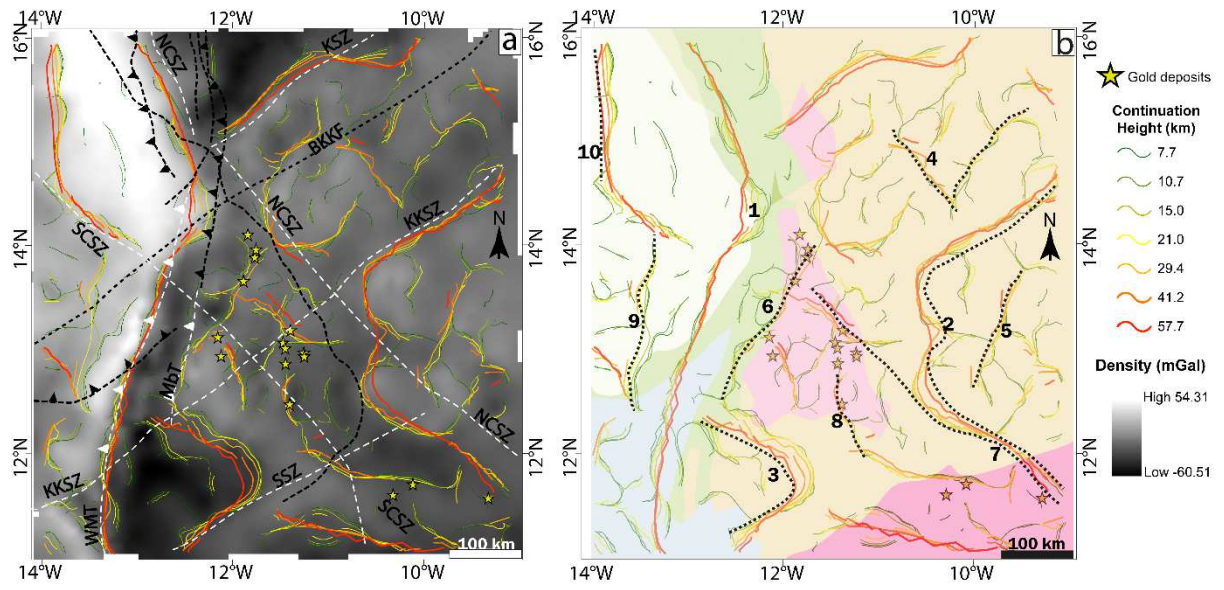
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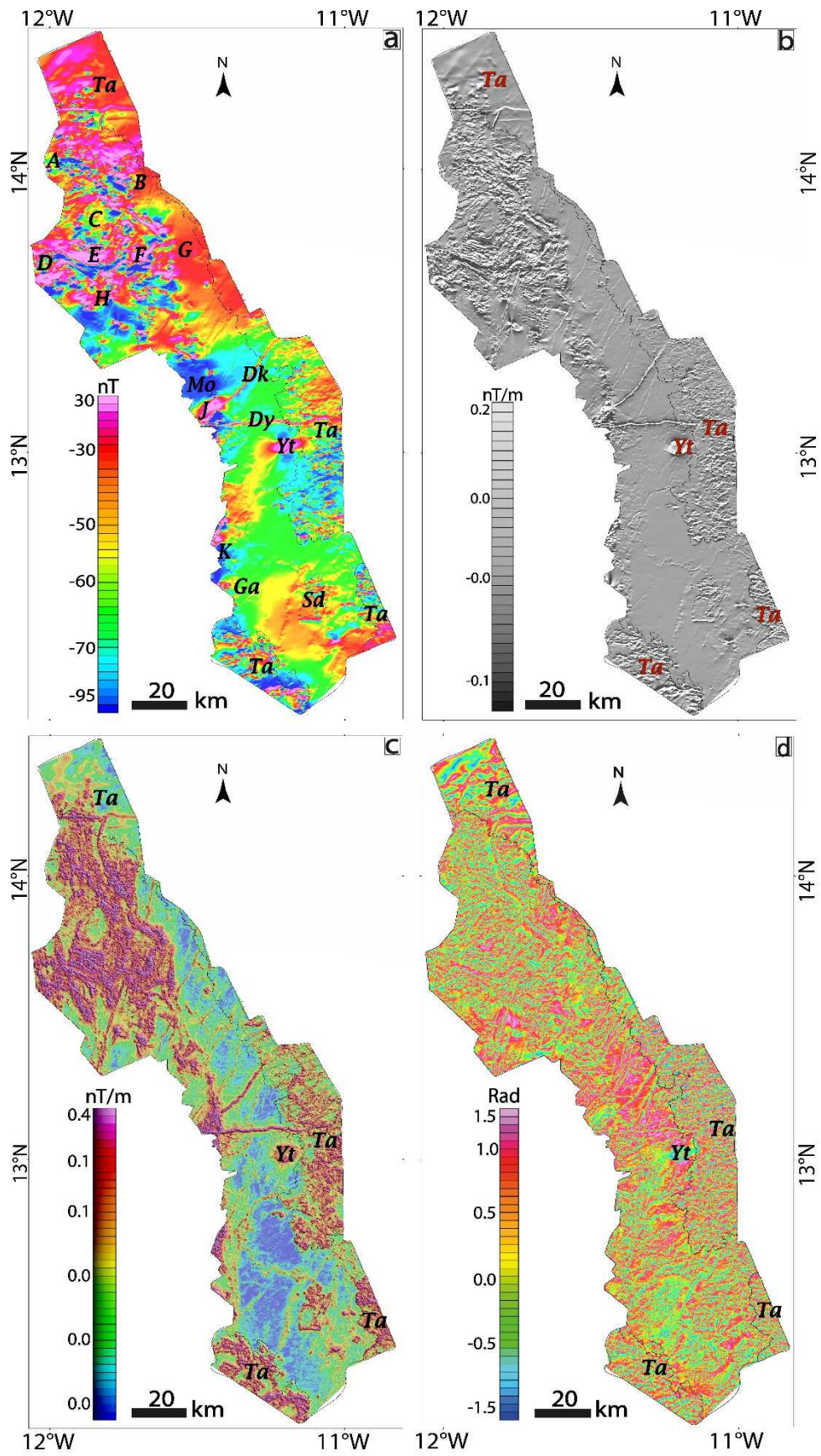
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1134 FIG6:



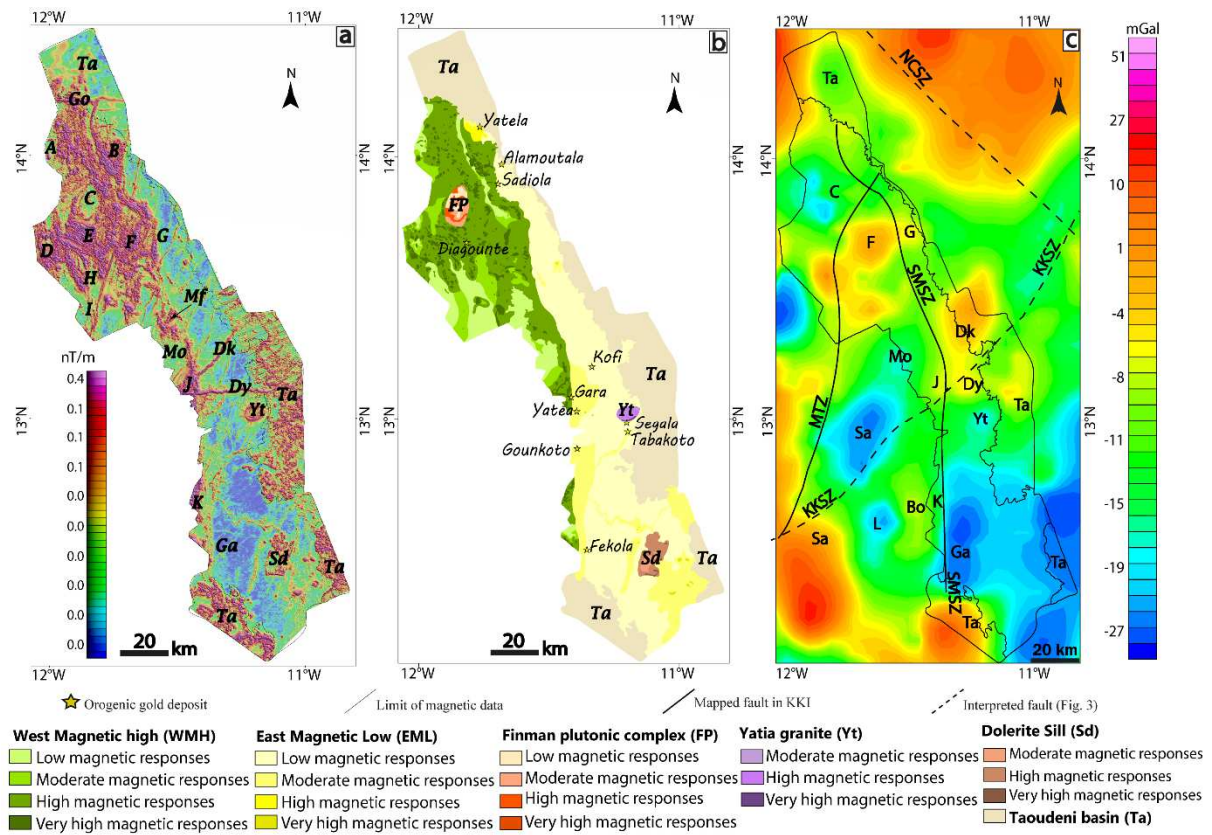
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1137 FIG7:

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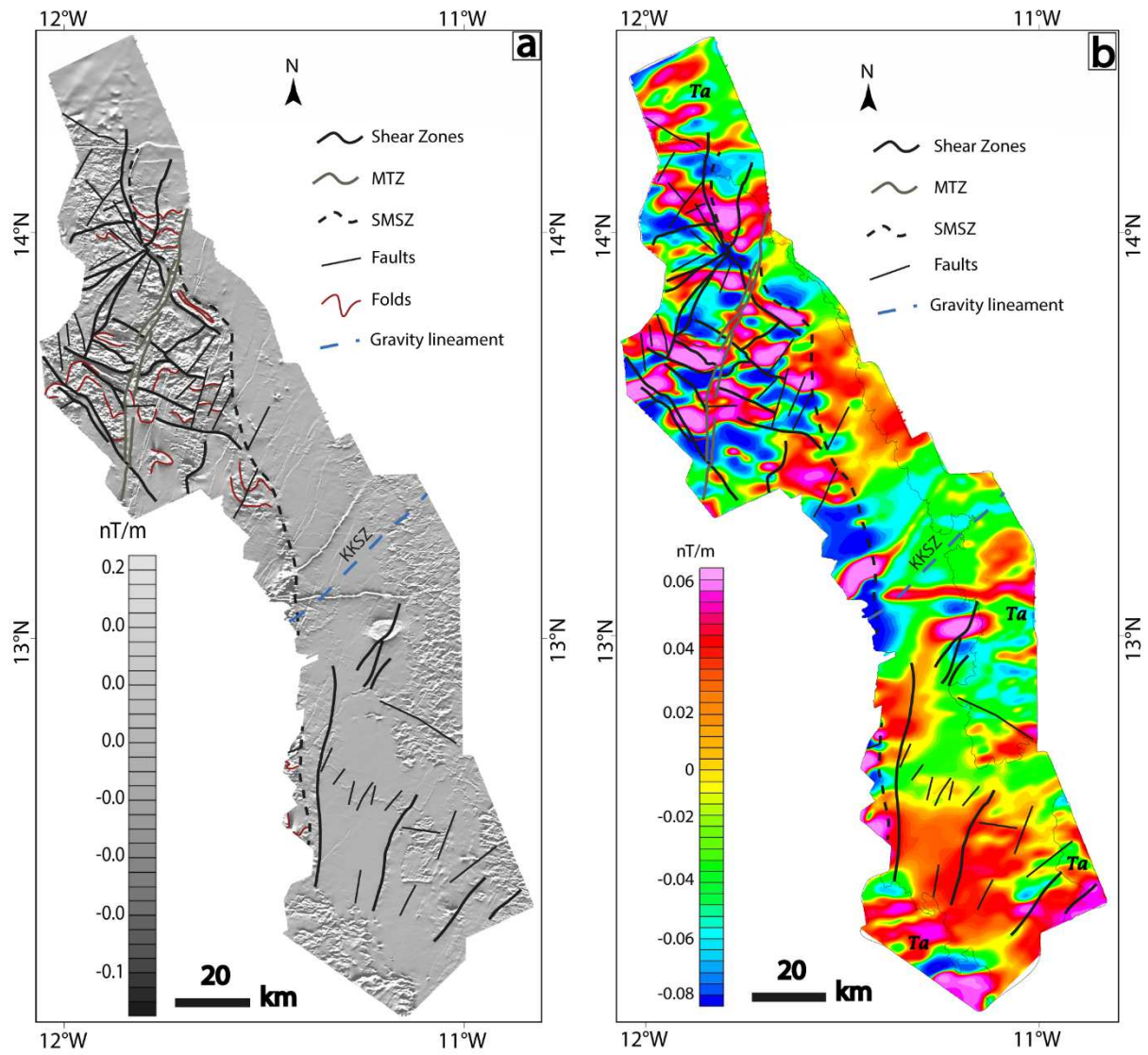


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1141 FIG8:

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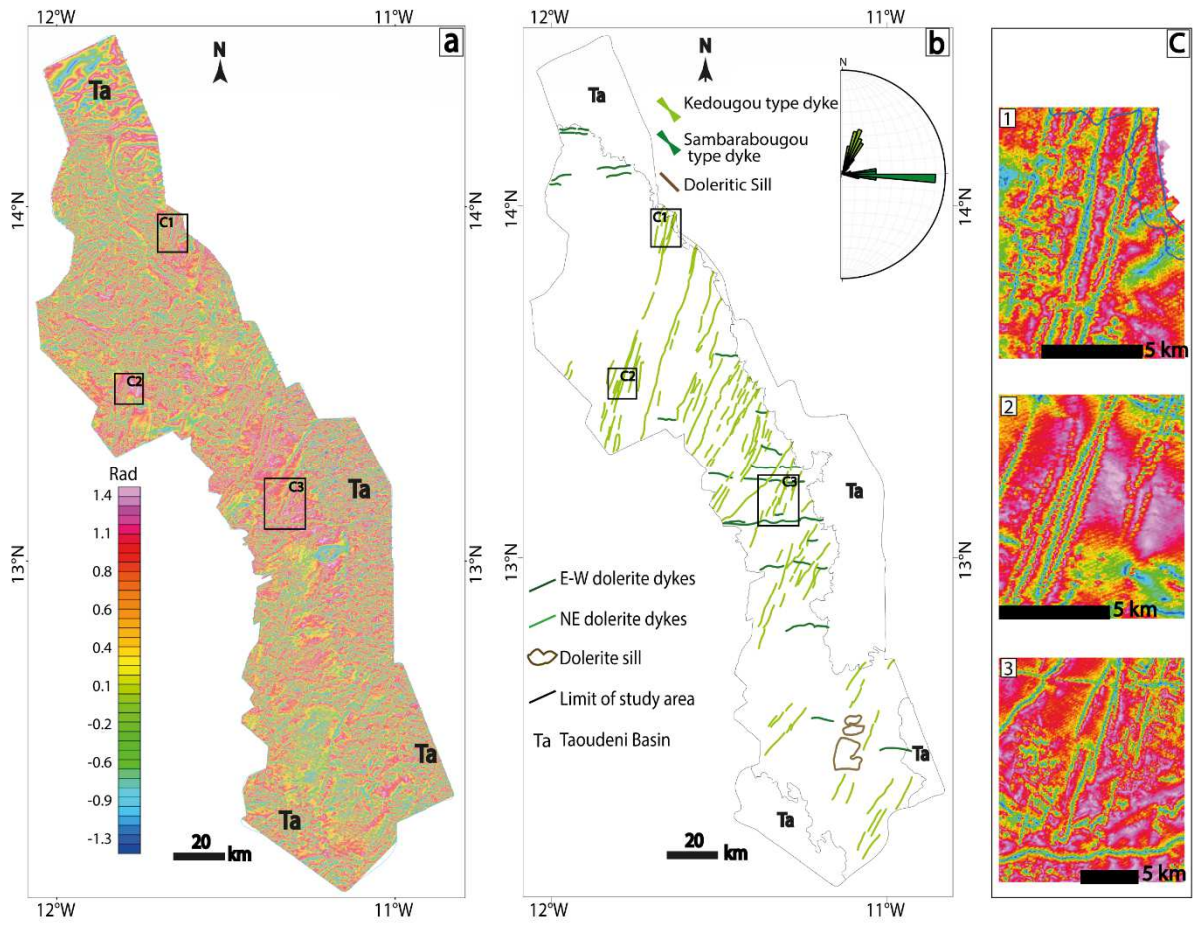
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1148 FIG9:

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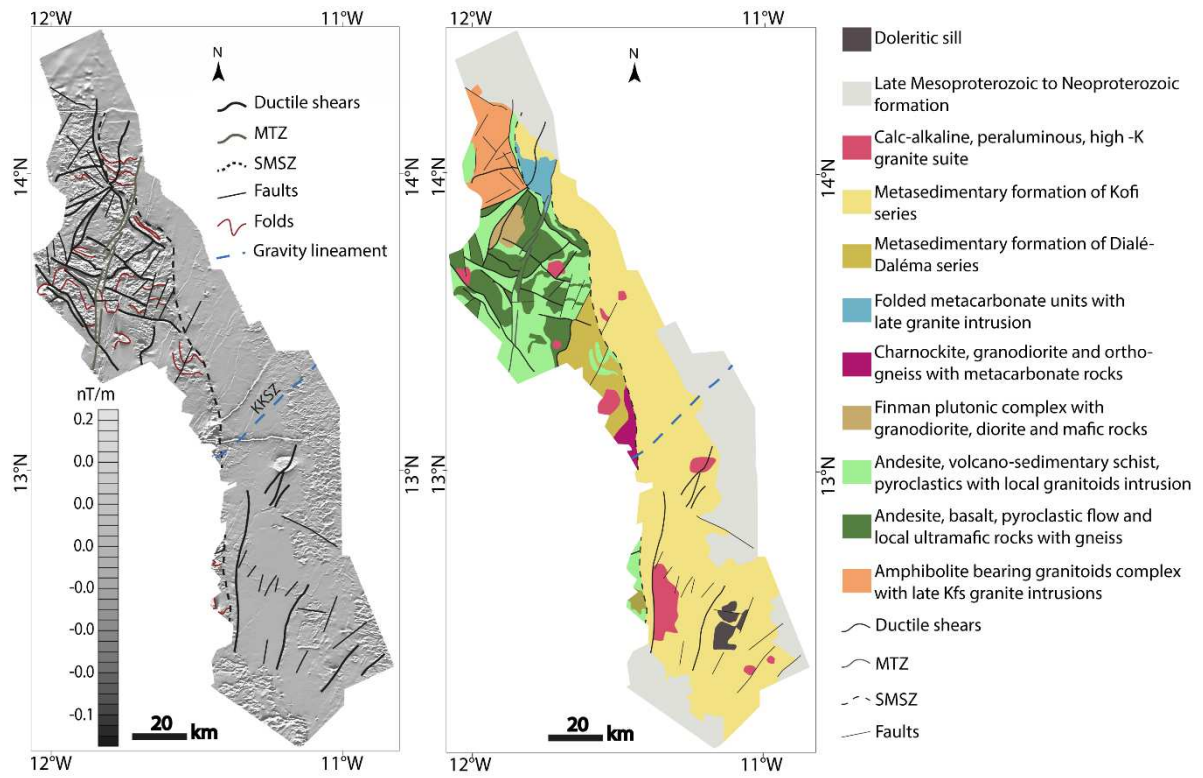
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1153 FIG10:

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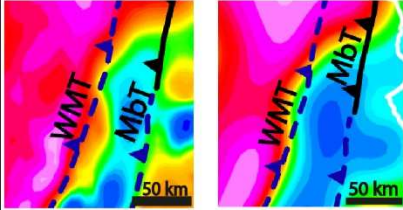
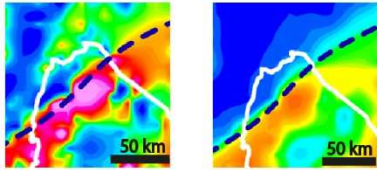
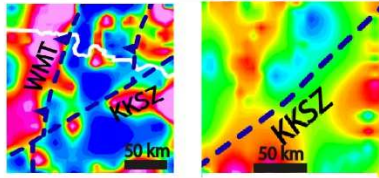
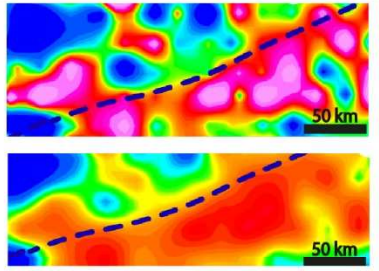
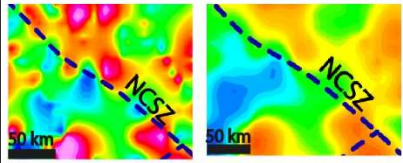
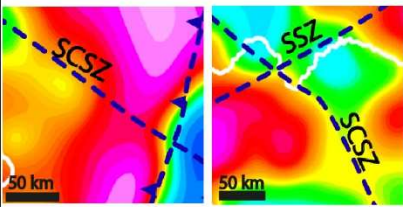
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1160 Table 1:

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Structure	Name	Sense	Gravity characteristics	Map gravity responses	Images on
Deep unexposed faults from complete Bouguer anomaly map and its first vertical derivative analyses	MTZ and WMT	Undefined	Apparent alignment of gravity anomalies/contacts defined as borders of gravity anomalies; gravity lineaments along offset of gravity anomalies; and gravity lineaments from offset of density or juxtaposition of contrasted gravity domains		BA and Upward Cnt
	KSZ	Undefined			1VD and BA
	KKSZ	Dextral			1VD
	SSZ	Sinistral			1VD and BA
	NCSZ	Undefined			1VD and BA
	SCSZ	Undefined			Upward Cnt

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1165 Table 2:

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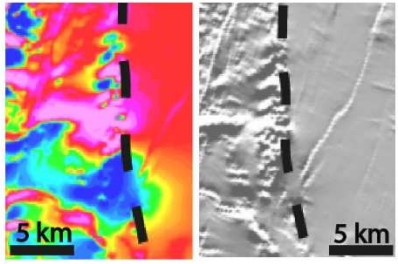
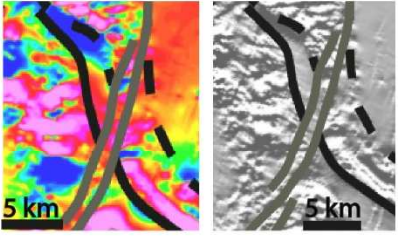
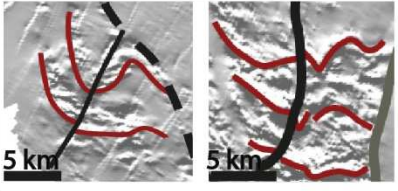
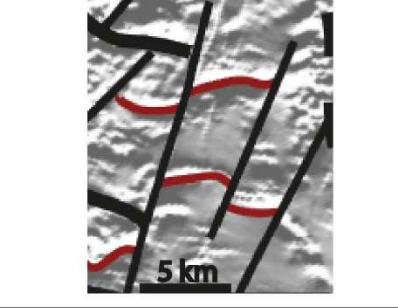


	<i>High - Sense</i>	<i>Kevron</i>
<i>Survey area</i>	Kéniéba	Kéniéba
<i>Survey period</i>	1996 and 1997	2001
<i>Acquisition company</i>	High – Sense Geophysics Ltd	Kevron Pty Ltd
<i>Survey type</i>	Combined airborne	Combined airborne
<i>Altitude</i>	100 m	100 m
<i>Flight orientation</i>	000 – 180° and 065 – 245°	000 – 180° and 065 – 245°
<i>Line spacing</i>	200 m	200 m
<i>Tie line orientation</i>	065 – 245° and 155 – 335°	065 – 245° and 155 – 335°
<i>Tie line spacing</i>	3000 m	3000 m
<i>Time interval in recording</i>	0.1 s	0.1 s

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1168

1169 Table 3:

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Structure	Name	Sense	Magnetic characteristics	Corresponded images	Images on
Near-surface structural framework from the RTE and its first vertical derivative maps	SMSZ	Undefined	Abrupt magnetic contact between contrasting magnetic domains		RTE and IVD
	MTZ	Sinistral and Dextral	Slightly curved discontinuity that cuts (locally offset) magnetic units		RTE and IVD
	Folds	Sinistral (fault)	Folded magnetic horizons with fault/shear in axial plane		IVD
	Faults in Mako belt	Sinistral and Dextral	Straight discontinuities that cut and offset high magnetic units		IVD
	Faults in Kofi series	Dextral			IVD
	Faults in mafic sill	Sinistral			IVD

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