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Rock magnetic investigation of possible sources of the Bangui magnetic anomaly

Mariane Ouabego, Yoann Quesnel, Pierre Rochette, François Demory, E. M. Fozing, T. Njanko, Jean-Claude Hippolyte, Pascal Affaton

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Corresponding Author: Dr. Yoann Quesnel,

Corresponding Author's Institution: Aix-Marseille University, CNRS

First Author: Mariane Ouabego

Order of Authors: Mariane Ouabego; Yoann Quesnel; Pierre Rochette, Pr.; François Demory, Dr.; Eric M Fozing; Théophile Njanko; Jean-Claude Hippolyte; Pascal Affaton

Abstract: The Bangui Magnetic Anomaly (BMA) is the largest lithospheric magnetic field anomaly on Earth at low latitudes. Previous studies investigated its geological source using constraints from satellite and ground magnetic field measurements, as well as from surface magnetic susceptibility measurements on rocks from the Panafrican Mobile Belt Zone (PMBZ). Here we combine magnetic field data modelling and rock magnetic property measurements (susceptibility and natural remanent magnetization, NRM) on many samples from this PMBZ and the surrounding formations. It reveals that NRM is a significant component of the total magnetization (Mt) of the BMA source, which reaches 4.3 A/m with maximum thicknesses of 38 and 54 km beneath the western and eastern parts of the BMA. Only the isolated and relatively thin banded iron formations and some migmatites show such Mt values. Thus we suggest that the thick BMA source may be composed either by overlapped slices of such metamorphic rocks, or by an iron-rich mafic source, or by a combination of these two geological structures.

Dr. QUESNEL Yoann
CEREGE, Aix-Marseille University
Europole de l'Arbois, BP80
13545 Aix-en-Provence cedex 04, FRANCE
Ph. : +33-442971590
Email : quesnel@cerege.fr

Physics of the Earth and Planetary Interiors

Aix-en-Provence (France),
March, 15th 2013

Object: cover letter for revised manuscript submission in PEPI

Dear Editors,

the following manuscript entitled « Rock magnetic investigation of possible sources of the Bangui magnetic anomaly » submitted to Physics of the Earth and Planetary Interiors (PEPI) was revised. Most of the reviewers' comments were taken into account, and the standard of English was improved. As suggested by Reviewer 1, we revised the introduction of the Bangui magnetic anomaly (BMA), particularly by adding the suggested references. This reviewer also suggested to submit this work to another journal but we still feel that PEPI fits the main issue of this paper: investigating the magnetization of the rock formations at the origin of the Bangui magnetic anomaly (BMA). The most important part of our study concerns the magnetic property measurements of rock samples from the BMA area. The numerical modeling of the source of the BMA was just used here to compare with those rock magnetism observations (also using previously-published numerical models). Using the helpful specific comments from Reviewer 1, we revised the final model and investigated the non-unicity. Some of these additional results are now shown in a new Supplementary Material file that is cited in the revised manuscript. We confirm that the initial mean value (4.3 A/m) of total magnetization (M_t) associated to the BMA source indeed corresponds to the best model to explain the magnetic field observations (even if larger M_t values produce reasonable models), and fits the magnetic property measurements of few rock samples of this area. One figure (Figure 8) was added to better highlight the fact that such strongly-magnetized rocks are not common (but exist) in the Panafrican belt area whatever the location.

The first author (M. Ouabego) and all co-authors (Y. Quesnel, P. Rochette, F. Demory, E.M. Fozing, T. Njanko, J.C. Hippolyte and P. Affaton) confirm that the data, results and ideas were not previously published or under consideration for publication elsewhere. The second author, Y.

Quesnel, is still the corresponding author for this manuscript. All authors were involved in the work, approve the revised manuscript, and still agree to submit it to PEPI. The revised manuscript now contains 51 references, 2 tables and 8 figures (Figures 2, 3 in colors), as well as a Supplementary Material.

Sincerely,

Dr. Yoann Quesnel

A handwritten signature in black ink, appearing to read 'Yoann Quesnel', written in a cursive style.

**Letter of reply to reviews of
'Rock magnetic investigation of possible sources of the Bangui magnetic anomaly'
by M. Ouabego, Y. Quesnel, P. Rochette, F. Demory, E.M. Fozing, T. Njanko, J.-C.
Hippolyte, and P. Affaton**

Introduction

Our manuscript entitled 'Rock magnetic investigation of possible sources of the Bangui magnetic anomaly' submitted to Physics of the Earth and Planetary Interiors (PEPI) has been revised considering the comments from the reviewers. In the following letter, our responses to their comments (in italic) are described. Their constructive criticisms greatly helped us to improve this manuscript. One figure (Figure 8) has been added in the article to show modelled total magnetization range for Cameroon and Centrafrican Republic rock samples.

1 – Reply to comments of Reviewer 1

Referee 1 made both broad and specific comments, which are dealt with below in order in which he made them. The specific comments correspond to the annotations of our manuscript in the PDF file associated to the review.

1.1 – Broader comments

This paper uses a few rock magnetic property measurements in the region of the Central African Republic and models a couple of gravity and magnetic profiles across the Bangui magnetic anomaly. Unfortunately, the manuscript has a lot of problems (discussed below and in the extensively annotated manuscript) and should be rejected. I have tried to be helpful and made several comments and suggestions that could be used to revise the research as well as the manuscript. The revision will make it possible to submit it to a journal like J. of African Earth Sciences.

Some context of the previous research and its discussion is appropriate here since the authors mention only a few of the key references and so I must conclude that they are not familiar with the other papers. Regan and Marsh (1982) modelled this anomaly as crustal scale physical property contrasts between cratonic regions and collisional belts. Ravat (1989, see Girdler et al., 1992 paper) modelled this feature as a concentrated near-surface ore-like body ("Fe-Ni-rich meteorite or Fe-rich iron formation") in addition to the crustal scale physical property contrasts similar to Regan and Marsh. See also Ravat et al. (1992, Tectonophysics paper related to South American and African regions affected by the breakup of Pangaea) and the vertical cross-section of the model in Langel and Hinze (1998, a book). Girdler et al. (1992) modelled it as an 800 km diameter disc-like region of thermal, shock, and/or chemical remanent magnetisation adding up to 10 A/m, and remanent inclination and declination of +25° and N18°W, respectively. (Caveat: Only remanent magnetisation cannot be the source of this anomaly since the tectonic and geologic contrasts can be reasonably justified as least as part of the source region.) Ravat et al. (2002, J. Geodynamics - be careful if using the methods in this paper since there are errors in some of the equations in this paper) used gradient-based interpretation methods like the Euler method and the Analytical Signal (which should really be called total gradient for 3-dimensional sources) whose results agree with the disc-like source of Girdler et al. and so a source similar to theirs must have a significant contribution toward the long-wavelength part of the Bangui magnetic anomaly. Hemant and Maus (2005, JGR) used GIS-based geologic provinces from the CGMW geology and tectonic maps of the world to suggest that the Bangui anomaly, for the most part, can be modelled also as originating from geologic and tectonic contrasts like Regan and Marsh, but the Hemant and Maus model for the geologic boundaries is more objective than Regan and Marsh's. Each of these papers have

added some new method, idea or an additional supporting evidence for an older idea with a new methodology or a refined geologic boundary information.

Answer: the numerical modeling of the source of the Bangui Magnetic Anomaly (BMA) is not the key purpose of our publication, and we acknowledge that by its own it would not have warranted publication. Our most original contribution is the rock magnetic part. However, the modeling is necessary (also using previously-published models) to place some magnetization constraints about the potential rocks that we investigated. Still, we have to mention that the modeling of ground magnetic data (western profile) was never performed in previous publications. Nevertheless, we agree with the reviewer that the description of the previously-published models of the source of the BMA was too short. Therefore we completed the introduction section using reviewer's indications, in particular adding the references mentioned above.

The associated modifications concern:

Previous version → Page 2, Section 1 (Introduction), Paragraph 1, Lines 37 to 45

Revised version → Page 2, Section 1 (Introduction), Paragraph 1, Lines 38 to 51

The most valuable outcome of this study could have been to assess the NRM directions and the direction of primary remanence (unless nothing useful could deduced from these directions, in which case the reasons should be discussed and would be of some interest). This could have been done in the context of the model of Girdler et al. (1992) and the supporting results of Ravat et al. (2002). It is really surprising that the authours do not discuss this at all since they themselves collected the rocks and made the rock magnetic measurements, presumably for this very purpose.

Answer: unfortunately we did not have the possibility to take the orientation of our samples, because the main purpose of this sampling mission was to improve the geological understanding of the Bangui area. The idea of studying the magnetization of these sampled rocks came afterwards. Therefore we only deal with magnetization intensities in our study. Besides many difficulties (mainly because of rare outcrops) arose during the sampling campaign in Centrafrica. Now we hope to get new - and perhaps oriented – rock samples in future campaigns, but the actual political situation (Feb 2013) and the lack of fundings prevents us to organize such missions. One has to realize that Centrafrica's politico-economic situation makes it very hazardous to organize field work.

The authours also discuss some interesting alternative interpretations in the discussion section. However, instead of modelling those alternatives and examining their feasibility, the authours present a contrived model that appears geologically unfeasible and indefensible. This choice is baffling to me. The authours also make many assumptions (see the heavily annotated manuscript) that are either incorrect or indefensible. For example, what is the connection between magnetisation of surface rocks and postulating a deep high magnetization and low density layer? There is none and it appears that the model is generated to simply fit the anomaly profiles by thinning and thickening layers. As a result, this manuscript requires a lot of additional work and therefore I am recommending the rejection.

Answer: the question raised by the reviewer is really the key point to understand the BMA's geological source. We acknowledge in the text (the word 'assumption' is used Line 291 in Discussion section of the revised manuscript) that the surface lithologies are not necessarily represented at depth. However, the fact that successive orogenies have « stirred » the crustal section by complex vertical differential movements indicates a non zero probability that the deep lithologies could be found outcropping. Our manuscript just wants to highlight that surface rocks like Banded Iron Formations or others can carry remanent magnetization intensities compatible with those predicted by BMA source models (including ours, even if it concerns only two profiles; see also below our answer to the specific comment (« Lines 168 to 182 ») about the used modeling method). This rock magnetization investigation was not made until now. It does not mean that these strongly-magnetized rocks are the source of the BMA, but they are good candidates to contribute to the anomaly (see Discussion section 6 of the revised manuscript).

1.2 – Specific comments

I have several other comments which can be found in the attached annotated manuscript. I have also suggested several improvements in the logic, the research and the language. See the blue inserts which need to be clicked on and opened. See also the blue and red text deletions.

Answer: almost all annotations (in the PDF file attached to the review email) from this reviewer concerning the suggestions to improve the logic, the research and the language, as well as the suggestions of text deletions were applied. In the following we only answered to his comments/questions inserted as text annotations (in red) in the PDF file.

Lines 37-45: There are actually several interpretations of the anomaly. See summary comments in the review document.

Answer: it corresponds to one of the broad comments abovementioned.

The associated modifications concern:

Previous version → Page 2, Section 1 (Introduction), Paragraph 1, Lines 37 to 45

Revised version → Page 2, Section 1 (Introduction), Paragraph 1, Lines 38 to 51

Lines 44: what about partly shock remanence suggested by Girdler et al. ?

Answer: these authors suggested that the high magnetization of the BMA source body may be related to iron input from the putative impactor. We put forward that this is unrealistic (see the revised version of the Introduction section 1). An impact indeed remagnetizes the preexisting crust, but it does not necessarily enhance the magnetization with respect to a TRM of metamorphic origin for example.

The associated modifications concern:

Previous version → Page 2, Section 1 (Introduction), Paragraph 1, Line 44

Revised version → Page 2, Section 1 (Introduction), Paragraph 1, Lines 45-50

Line 64-65: use Ga and Ma everywhere instead of Gy and My.

Answer: this has been done.

The associated modifications concern:

Previous version → Page 3, Section 2 (Geological context), Paragraph 1, Lines 60, 66-67

Revised version → Page 3, Section 2 (Geological context), Paragraph 1, Lines 66 and 72-73

Line 77: it would be good to show these nappe trends with boulder lines on the figure.

Answer: this has been done on the revised Figure 1c, and the associated formation is mentioned in the revised manuscript.

The associated modifications concern:

Previous version → Page 4, Section 2 (Geological context), Paragraph 1, Lines 75-76

Revised version → Page 4, Section 2 (Geological context), Paragraph 1, Lines 81-82

Line 81: Generally, Bangui anomaly is seen as having three lobes, a negative in the center and positive and negative lobes in the north and south. Why does this paper and modelling in it consider primarily only the central and northern lobes? Not clear..

Answer: we agree with the reviewer. Our description was incorrect. Therefore we modified this sentence. We also added later in this section that no ground data were available over the southern positive lobe. Therefore only the central and northern parts of the anomaly were considered in this study.

The associated modifications concern:

Previous version → Page 4, Section 3 (Geophysical context), Paragraph 1, Line 81

Revised version → Page 4, Section 3 (Geophysical context), Paragraph 1, Lines 87-88 and Paragraph 2, Line 99

Line 89: This is an assumption. Remove at this point and say that you use this assumption at an appropriate juncture.

Answer: we removed the corresponding sentence.

The associated deletion concerns:

Previous version → Page 4, Section 3 (Geophysical context), Paragraph 1, Line 88-89

Line 95: This processing is incorrect. For the field measured at a particular epoch should be processed with the IGRF of that epoch. That is what an anomaly is. This needs to be redone. The main field has changed sufficiently from 1960 to 2010 that the subsequent analysis and the induced assumption in the modelling are in principle problematic. (Note that it will make an iota of difference to the conclusions of this paper, but there are also other problems...)

Answer: our sentence was not clear. We considered the model published by Finlay et al. (2010), but using DGRF coefficients of year 1960. Thus this is really the 1960 main field that we applied. We modified this sentence to clarify this point.

The associated modifications concern:

Previous version → Page 4, Section 3 (Geophysical context), Paragraph 1, Lines 95-96

Revised version → Page 5, Section 3 (Geophysical context), Paragraph 2, Lines 103-104

Lines 100-101: Reword. This sentence makes no sense at all. I can't guess what is meant here to be able to fix it.

Answer: we agree with the reviewer. This sentence was linked to the previous one but this analysis of the anomaly is vague. We modified and completed this sentence to better describe the differences in the shape of the anomaly between satellite and ground data maps.

The associated modifications concern:

Previous version → Page 5, Section 3 (Geophysical context), Paragraph 1, Lines 100-101

Revised version → Page 5, Section 3 (Geophysical context), Paragraph 2, Lines 106-115

Line 103: This is a huge lobe. Confine is a wrong choice of verbs. One cannot « confine nearby » anything...If you want to use confine then use confine to an area between latitudes xxx and xxx and longitudes xxx and xxx.

Answer: we removed this sentence since it is linked with the shape of the ground data signal better described in the revised manuscript (see our answer to the previous comment).

The associated modifications concern:

Previous version → Page 5, Section 3 (Geophysical context), Paragraph 1, Lines 103-104

Revised version → Page 5, Section 3 (Geophysical context), Paragraph 2, Lines 106-115

Line 107: Not clear how this follows from aforementioned thoughts. Need to explain better the reason.

Answer: we removed this sentence.

The associated deletion concerns:

Previous version → Page 5, Section 3 (Geophysical context), Paragraph 1, Line 107

Lines 119-121: For the ground magnetic the original data should be used and if there are problems with the 1960 IGRF in this region, then the CM4 for the closest epoch to observations should be used. This is fine for the satellite magnetic anomaly, but not for the airborne magnetic anomaly.

Answer: we effectively set the 2011 Bangui geomagnetic field vector directions to the magnetization vector of the source body at the beginning of the modelling process, whatever the origin of the used data (satellite or ground). The reviewer is right: for ground data we should apply the 1960 Bangui geomagnetic field vector ($I = -14.5^\circ$; $D = -5^\circ$; $F = 33400$ nT), even if it is very similar to the 2011 vector ($I = -16.7^\circ$; $D = 0.2^\circ$; $F = 33580$ nT). It has no significant consequences on the new resulting parameters, but this has been applied to obtain the results described in Section

5.1 of the revised manuscript. We then modified the corresponding sentence in the revised version of the manuscript.

The associated modifications concern:

Previous version → Page 5, Section 4.1 (Magnetic anomaly modeling), Paragraph 1, Lines 119-121

Revised version → Page 6, Section 4.1 (Magnetic anomaly modeling), Paragraph 1, Lines 133-136

Line 133: Why randomly selected? Do you mean « randomly selected » from a suite of high susceptibility samples? If so, reword.

Answer: this first set of samples contains at least 1 sample for each lithology, and was randomly selected in the whole collection. Later, we selected among the remaining collection all samples with high susceptibility to complete this first set (to obtain 22 samples). We then modified the corresponding sentence in the revised version of the manuscript.

The associated modifications concern:

Previous version → Page 6, Section 4.2 (Sampling and rock magnetic measurements), Paragraph 1, Line 133

Revised version → Pages 6-7, Section 4.2 (Sampling and rock magnetic measurements), Paragraph 1, Lines 149-153

Line 152: why is this not done vectorially?

Answer: as we mentioned in a previous answer, we do not study the directions of magnetization since no orientation was acquired during sampling, but we are investigating the total magnetization intensity assuming that remanence is colinear to induced magnetization, as stated 2 sentences after this equation. Therefore no vector representation is needed for this equation. No modifications are needed.

Line 154: why 2.7? Is this representative?

Answer: this value corresponds to the mean density for a crust composed of metamorphic or magmatic rocks; as we are discussing large contrasts for magnetization, it is not necessary to have an accuracy better than a few % on density. No density measurements were done in our study. The chosen density for itabirite correspond to 25% hematite, 75% quartz, as determined by magnetic measurements. We slightly modified the corresponding sentence.

The associated modifications concern:

Previous version → Page 7, Section 4.2 (Sampling and rock magnetic measurements), Paragraph 3, Line 154

Revised version → Page 7, Section 4.2 (Sampling and rock magnetic measurements), Paragraph 3, Lines 172-173

Line 156: not valid? If you measured NRM, why assume this?

Answer: the NRM directions have no meaning without the original orientation of rock samples on the field (see our answer to a previous broad comment). This assumption (of NRM and induced magnetization to be colinear) will thus give the most important Mt values. If the colinearity is false, then the resulting Mt will be weaker. We added a sentence to be clearer.

The associated modifications concern:

Previous version → Page 7, Section 4.2 (Sampling and rock magnetic measurements), Paragraph 3, Line 156

Revised version → Page 8, Section 4.2 (Sampling and rock magnetic measurements), Paragraph 3, Lines 176-177

Lines 168 to 182: how can one infer this from unconstrained non-unique forward modelling? All this is based on unconstrained and non-unique forward modelling. These models don't look anything like geologically feasible geophysical models. The models look like they are contrived polygons made to fit the profiles...Nothing seems confirmed based on this modelling. In this type of

modelling, if you increase magnetisation, the thickness will decrease.

Answer: no other information than surface geology, magnetic and gravimetric data are available in Centrafrica. Therefore we can't constrain much the models. In previous studies dealing with BMA source modeling, reasonable assumptions (not 'data') about the parameters of the different magnetic blocks in the crust of this area were used to constrain the models. All these previously published models are also non-unique, sometimes as « geologically unrealistic » as ours, and consist of 'contrived polygons made to fit the profiles' too. Each is guided by an idea of geometry associated to a particular geological origin (like the disk to model the magnetic remains of an impactor (Girdler et al., 1992)). We do not want to question the quality of these previous models: they correspond to the best that one can do with the available data, and being guided by an idea of geological origin is a good way to work.

Like mentioned in the manuscript in Section 4.1, we here considered the surface geology (on the western profile mainly), gravimetric and specifically magnetic data to produce a model in order to assess the total magnetization of the BMA source at two locations (western and eastern profiles). Of course this is still non-unique but, at least, it fits the three kind of observations (no previously-published model was produced to fit all these data) on both the western and eastern part of the BMA. This continuity (of magnetic properties and average crustal depths) between the western and eastern BMA source models was a criterion to constrain the resulting models.

Besides, the non-unicity was investigated during the revision of this manuscript. Indeed no good fits of the two profiles have been obtained using simple geometries like large crustal prisms (approximately similar to those used in some previous publications like Regan and Marsh, 1982), particularly for the western magnetic and gravimetric profiles. So, more complex geometries (and not only the one shown in the publication) for the most magnetic source were tested. The used software (Oasis montaj – GM-SYS modelling module) allows to perform a constrained inversion on the geometry, densities and susceptibilities once the user has set preliminary nodes, density and susceptibility values to each layer. Thus the resulting model is constrained both by the user (manual forward modelling) and by the data (inverse modelling with spatial modifications that depend on the initial variability/uncertainty). Here, to find the possible total magnetization value associated to the geological source of the BMA (and to compare this value with those measured on the sampled geological formations), one of these 'geometric' models - that were able to fit both the western and eastern, magnetic and gravimetric profiles - was selected to apply different magnetization (and so, thickness) values. The general lateral N-S shape was kept (at least for closed Mt values), but the maximum thickness was particularly modified for each tested magnetization value. Table A1 included in a new Supplementary Material PDF file shows the resulting RMS on magnetic and gravity data along the two profiles for each case of total magnetization (associated to a maximum thickness) of the most magnetic source. These models result from a similar modeling methodology than the one above-mentioned: 1 → forward manual modeling (for instance, modification of the maximum thickness in response to the tested Mt value), 2 → by inversion, limited (i.e. constrained by the uncertainty) adjustments of this thickness and of the other nodes of the most magnetic body to converge towards the best configuration of these nodes.

However, for the western satellite magnetic data and eastern ground magnetic data profiles, no good fits could be obtained. This is due to the reasons mentioned in Section 4.1 of the main manuscript: the western profile is too short to solve for the long-wavelength signal observed by the satellite data (the downward continuation to 2.5 km cannot reproduce the small wavelengths), and, on the other hand, only few ground magnetic data – probably representing very small 'local' wavelengths – exist along the long eastern profile. For the ground magnetic data along the eastern profile, the 4.3 A/m model is still the 'best' one among all models (RMS=232.2 nT). The most important result is that, looking on all kind of data (particularly ground magnetic data of the western profile and satellite-derived magnetic data of the eastern profile), the 4.3 A/m model is the best one while its shape and associated density explain the gravimetric signal too. This is why we chose to show it in the manuscript with Table 1 (revised) and Figure 3 (revised). Figures A1 and A2 of the Supplementary Material show the 2.3 A/m and 10.3 A/m best models (i.e. 2 and 10 A/m remanent

magnetization associated to the most magnetic layer), to compare with Figure 3. As mentioned earlier, the general shape is slightly equivalent whatever the Mt values, but the maximum thickness is different. The shape of the other non-magnetic layers (that mainly fit the gravimetric anomaly) may be more 'non-unique'. We are aware that these tests do not solve for the non-unicity, but at least they investigate the Mt value of the most magnetic layer. This value is then discussed by the rock magnetic measurements in the next Section of the manuscript.

We modified the structure of Section 5.1, also mentioning the revised results on the Mt value investigations (Supplementary Material) and the corresponding 4.3 A/m best model (revised Figure 3 and Table 1). We stress that this is a minimum value, other more complex models with larger Mt values could be designed. This is confirmed by Table A1 in the Supplementary Material, which shows that larger Mt models (like 8.3 A/m, even 10.3 A/m) are still able to explain the data along the two profiles.

The associated modifications concern:

Previous version → Pages 7-8, Section 5.1 (Magnetic anomaly modeling), Paragraph 1, Lines 161-182

Revised version → Pages 8-9, Section 5.1 (Magnetic anomaly modeling), Paragraph 1, Lines 182-208 but see particularly Lines 184-187.

In addition, and as a separate point, how do you associate huge amount of iron with density as low as 2.68? These magnetizations and densities could work only with serpentinised peridotites. And the geometry and depth of the layers are inconsistent with serpentinised peridotite. This model is nothing like Regan and Marsh (1982) model and appears less plausible because of mafic lower crustal rock composition.

Answer: this comment highlights the main issue concerning the BMA source: a negative gravimetric anomaly is correlated with this magnetic anomaly. First we realized that, in our previously-submitted model, the host more dense rocks (formations 2, 3 and 4), assumed to be metabasalts, granulites and amphibolites, have unrealistic low densities. Granulites can have average densities as high as 3.0, with a mean value close to 2.9, while typical densities for metabasalts and amphibolites are about 3.0 and 2.85 (Christensen and Mooney, 1995; Rudnick and Fountain, 1995; Tripathi et al., 2012). So we reset our assumed densities with these larger values, allowing a density of 2.87 for the BMA source. We slightly modified the 'Results' section with these new density contrasts (see Lines 200-203). The geological implications of our results/investigations are fully discussed in the Discussion Section 6 (see particularly Paragraph 2, Lines 299-315). One non-unique hypothesis would be that the source is composed by about 10% of itabirites (banded iron formations with $M=50$ A/m) and 90% of a lower density and non-magnetic metasedimentary rock (schist, quartzite), and more magnetic amphibolite with density lower than 2.87. Note that in the itabirite hypothesis there is no need for a “huge amount of iron”: a 5 A/m magnetization can be reached with an average amount within the BMA body of only 2.5% of hematite (see Discussion in the revised text). Serpentinized peridotites are not consistent with the expected geology and the depth and geometry of the source layer, as pointed out by the reviewer. A mafic lower crustal rock composition is not warranted in fact. The density contrast may be linked to metamorphism only: more metamorphic granulites as the host rock, less metamorphic and thus less dense rocks for the BMA.

References:

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- Rudnick R.L., Fountain D.M., 1995. Nature and composition of the continental crust: A lower crustal perspective. *Reviews of Geophysics* 33, 267–309.
- Tripathi P., Pandey, O.P., Rao M.V.M.S., Koti Reddy G., 2012. Elastic properties of amphibolite and granulite facies mid-crustal basement rocks of the Deccan volcanic covered 1993 Latur-Killari earthquake region, Maharashtra (India) and mantle metasomatism. *Tectonophysics*

554, 159-168.

The associated modifications concern:

Previous version → Pages 7-8, Section 5.1 (Magnetic anomaly modeling), Paragraph 1, Lines 173-182

Revised version → Pages 8-9, Section 5.1 (Magnetic anomaly modeling), Paragraph 1, Lines 196-203.

Lines 207-208: Based on Fig 6, 8603 doesn't have >50 % initial susceptibility left..

Answer: we agree that this is not easy to see on the lower-left panel of Figure 6. However 8603 has an initial normalized magnetic susceptibility value of 0.14, and after 650°C, the value is 0.11. Thus it remains about 78% of the initial susceptibility, in accordance with our sentence. No modifications are needed.

Line 223: say which ones specifically...unclear

Answer: we specified those samples in the revised corresponding sentence.

The associated modifications concern:

Previous version → Page 10, Section 5.2 (Magnetic property measurements), Paragraph 3, Line 223

Revised version → Page 10, Section 5.2 (Magnetic property measurements), Paragraph 3, Lines 246-247

Line 244: the authors need to model the contribution of iron formations. They are not the sole source, but they must contribute at least a little... In this collisional environment, the banded iron formations are likely to be tectonically thickened...like Kursk, where roughly 25 % of the Kursk magnetic anomaly source is the BIFs. See Ravat et al. (1993, Tectonophysics). This has been confirmed later by an unpublished study. See Langel and Hinze book.

Answer: this point is largely developed in the Discussion Section (6), especially the link between the results from the magnetic profile modelling and from magnetization measurements. Indeed the banded-iron formations (BIFs) may compose the main magnetic source expected by modelling (here they can partially compose this model...and their magnetization is measured). However, a large pure BIF source is not possible since it will result in a too large magnetic field anomaly. We agree with the reviewer that the source is most probably composed by BIFs but mixed with another rock formation too. The main magnetic body of our modelling represents this heterogeneous magnetic source with Mt as a mean magnetization intensity. The thoughts derived from the results (modelling + magnetization measurement) are located in the Discussion Section . No modifications about the model are needed (see our previous answer to comments on Lines 168-182).

Line 260: No idea what this means. Rephrase...how are the banded iron-formations brought up? They are mostly formed in the near-surface environment and thickened in a compressive regime.

Answer: we agree with the reviewer that this sentence is unclear...therefore we modified it in the revised version of the manuscript, using the suggestion of the reviewer.

The associated modifications concern:

Previous version → Page 11, Section 6 (Discussion), Paragraph 1, Line 260

Revised version → Page 12, Section 6 (Discussion), Paragraph 1, Lines 296-298

Line 267: See comment on the previous page...

Answer: we modified the sentence and the references, according to the suggestions of the reviewer.

The associated modifications concern:

Previous version → Page 11, Section 6 (Discussion), Paragraph 2, Line 267

Revised version → Page 12, Section 6 (Discussion), Paragraph 2, Line 305

Line 271: 5 km BIF is a bit too much without other evidence but the itabirite percentage may be

more. 50-55 km crustal thickness may be a bit too much. Mention of thick BIFs is done in discussion section like an afterthought. If anything, this should be part of the model.

Answer: we agree with the reviewer and modified the corresponding values to 3-4 km of BIFs, so a BMA source with about 20% of itabirites. However, as mentioned above, no model that can fit most of the data along the two studied profiles is able to differentiate between itabirites and other BMA source formations. Only the mean value (Mt) of the total magnetization for this source can be investigated, as we did.

The associated modifications concern:

Previous version → Page 12, Section 6 (Discussion), Paragraph 2, Line 271

Revised version → Page 13, Section 6 (Discussion), Paragraph 2, Line 309

Lines 290-292: Geology and crustal rocks are not understood by 10 % of this and 10 % of that. One needs constraints to develop meaningful models.

Answer: we agree with the reviewer, but these thoughts are located in the Discussion section after the results of modelling and magnetization measurements. For the modelling part, as mentioned earlier and in Section 4.1, we did the best we could do with the constraints we had access to: magnetic properties of rocks from surface geology, magnetic and gravimetric anomaly data. We tried other possibility of number, geometry and magnetization of the layers of the model (Table A1 of Supplementary Material). We found that no reasonable models are able to detail the composition of the most magnetic layer beneath the BMA: we can only investigate its mean total magnetization (Mt) assuming a geometry suitable to fit most of the data along the two studied profiles. No modifications are needed.

Line 307-309: Amen! In this paper, it should be done.

Answer: the corresponding sentence was not correct. We modified it.

The associated modifications concern:

Previous version → Page 13, Section 7 (Conclusion), Paragraph 2, Lines 307-309

Revised version → Page 14, Section 7 (Conclusion), Paragraph 2, Lines 347-350

Lines 447-453: grammar: sentence fragment?

Answer: we splitted up this too long sentence, as the reviewer suggests.

The associated modifications concern:

Previous version → Page 19, Figure 1 caption, Lines 447-452

Revised version → Page 22, Figure 1 caption, Lines 521-525

Line 462: use filled circles as they are too small to consider them as « disks ».

Answer: this has been modified.

The associated modifications concern:

Previous version → Page 19, Figure 1 caption, Line 462

Revised version → Page 22, Figure 1 caption, Lines 536-537

Lines 474-475: the shades used are difficult to distinguish even in the high resolution version. Need to use distinctive colours or patterns.

Answer: this figure is now in color version, which allows to better distinguish the different layers of the model.

Line 475-476: why not?

Answer: these ground magnetic (interpolated) observations and predictions are now shown in the revised version of Figure 3. There are too few ground magnetic measurements along or near this profile, so the interpolated profile cannot really represent the real ground magnetic field anomaly signal. We replaced the two last sentences of the caption by one sentence about the magnetization intensity of the most magnetic layer of the models.

The associated modifications concern:

Previous version → Page 20, Figure 3 caption, Lines 475-477

Revised version → Page 23, Figure 3 caption, Lines 549-551

Figure 1: If you want to use the extracted part (b), then you need to show South America in part (a). I think it is a good idea to show South America in both (a) and (b).

Answer: South America palaeogeographic position is now inserted in both panels (also with Africa position in (b)) on the revised version of Figure 1, and the corresponding caption is modified.

The associated modifications concern:

Revised version → Page 21, Figure 1 caption, Lines 519-520 and Lines 526-527.

Figure 1: difficult to distinguish even on the high-resolution figure.

Answer: we agree with the reviewer and modified the patterns of formations 2 and 4 on the revised version of Figure 1.

Figure 1: would be good to show where the « nappes » mentioned in the text in the geology section are.

Answer: these are shown by formation 6, as it is indicated in the Figure 1 caption. We added this detail in the text where the nappes are cited, to help the reader.

The associated modifications concern:

Revised version → Page 4, Section 2 (Geological context), Paragraph 1, Lines 81-82

Figure 2: add country names.

Answer: the country names are now included in the revised version of Figure 2, and consequently the last sentence of the caption was removed.

The associated deletions concern:

Revised version → Page 20, Figure 2 caption, Lines 468-469

Figure 2: why the seismic colour scale? Generally only used to hide variations.

Answer: the colour scale has been modified in the revised version of Figure 2.

Figure 3: Shades are not distinguishable even on the high resolution figure. Certainly won't be in the journal. Use distinguishable colours or patterns.

Answer: Figure 3 is now in color in its revised version.

Figure 3: geologically simply unrealistic.

Answer: see above our answer to the comment on « Lines 168-182 » .

Figure 3: why is ground magnetics not modelled?

Answer: see above our answer to the comment on « Lines 475-476 », but now these data are included in the revised version of Figure 3.

Table 1: Problem using this direction for a ground magnetic survey done in 1960s.

Answer: see above our answer to the comment on « Line 95 ».

Table 1: Unrealistic unless they are serpentinites, and the source geometries and their depths are not consistent with serpentinite composition.

Answer: see above our answer to the second part of the comment on « Lines 168-182 » (comment starting with 'In addition...').

Table 1: Seems like metabasalt should have density much higher. Are you suggesting that these layers were originally oceanic crust and mantle?

Answer: as stated above (see Answer to the second comment on Lines '168 to 182'), we have revised densities toward higher values after a more thorough bibliography. Metabasalts (and/or amphibolites) should be around 2.9. In the Precambrian huge sequence of basalts have been emplaced on continental crust, so a oceanic hypothesis is not necessary.

Table 1: These rock types are really inferred (?) from modelled gravity and magnetics

Answer: we agree that this is tentative to attribute a rock type to each layer. However, as indicated earlier, this model just gives some reasonable constraints on the properties of the potential source(s) of the BMA, based on geology, gravity and magnetics. Again, our study aims at investigating the range of magnetization intensities plausible for this source. No modifications are needed.

2 – Reply to comments of Reviewer 2

Referee 2 made a broad comment and several substantive comments, which are dealt with below in order in which he made them.

This paper by Ouabego et al. on the Bangui magnetic anomaly is well presented and should be published after minor amendments.

Substantive comments :

Line 171: 'huge amount of iron' is a strange comment. 4 A/m magnetisation corresponds to about 3% magnetite, and if it is lamellar magnetism then maybe much less!

Answer: we agree with the reviewer and modified the corresponding sentence.

The associated modifications concern:

Previous version → Page 7, Section 5.1 (Magnetic anomaly modeling), Paragraph 1, Line 171

Revised version → Page 8, Section 5.1 (Magnetic anomaly modeling), Paragraph 1, Line 196

Line 182: Not sure why this is unrealistic. Some gabbro/norites and pyroxenites are in this range. But I'm sure remanence is 'realistic' too.

Answer: the reviewer is right, but the suggested rocks are not observed on surface in this area. They would also not fit with the low density constrain. Therefore we modified the corresponding sentence to precise that such high susceptibility values are unrealistic for the expected rocks in this area.

The associated modifications concern:

Previous version → Page 8, Section 5.1 (Magnetic anomaly modeling), Paragraph 1, Line 182

Revised version → Page 9, Section 5.1 (Magnetic anomaly modeling), Paragraph 1, Lines 206-207.

Line 208 Why wasn't BG240 taken to 690°C above the Néel point to confirm it is hematite and not instrument drift. It is a weak signal and unless the sample is removed and replaced to confirm the zero level at the peak temperature it is not possible to differentiate drift from signal.

Answer: we agree with the reviewer and added a sentence to highlight this possibility, even if hematite was identified by hysteresis measurements. We had problems with our furnace preventing heating above 650°C.

The associated modifications concern:

Previous version → Page 9, Section 5.2 (Magnetic property measurements), Paragraph 2, Line 208

Revised version → Page 10, Section 5.2 (Magnetic property measurements), Paragraph 2, Line 235-236.

Line 218 What about sample BG243 where you have '0.8 measured' compared with '7.5 modelled' the opposite way around so can't be lightning?

Answer: it may be the case of a multicomponent NRM, with opposite directions, or our assumed NRM/SIRM ratio is not relevant for that sample. We then modified the corresponding sentences.

The associated modifications concern:

Previous version → Page 9, Section 5.2 (Magnetic property measurements), Paragraph 3, Lines 216-218

Revised version → Page 10, Section 5.2 (Magnetic property measurements), Paragraph 3, Lines 247-248.

Line 301 Sentence beginning "This highlights the interest of..." needs rewording - confusing.

Answer: the corresponding sentence has been modified.

The associated modifications concern:

Previous version → Page 13, Section 7 (Conclusion), Paragraph 1, Line 301

Revised version → Page 14, Section 7 (Conclusion), Paragraph 1, Line 339-342.

Fig. 1 Suggest you check the scale. 1° of longitude near the equator (and 1° latitude anywhere for that matter) is approximately 110 km. According to the scale 1° = 270 km.

Answer: the scale has been modified in the revised version of Figure 1.

Fig. 2 Maybe add "The box corresponds to c) in Fig. 1"?

Also suggest you include IGRF ($D = 0.2^\circ$, $I = -15^\circ$, $F = 33680$ nT or whatever it is) which means the area is south of the geomagnetic equator and a magnetic high to the north is normal.

Answer: this reference to Fig 1c is clearly written in the caption of Figure 2, so we did not modify Figure 2 itself. The comment about the location of the area south to the geomagnetic equator is now included in the text, in the first paragraph of Section 3.

The associated modifications concern:

Revised version → Page 4, Section 3 (Geophysical context), Paragraph 1, Line 88.

Fig. 3 'Crustal magnetic models (bottom panels)'? Must be a legacy of an earlier version of the figure since the western profile is now the top panel. The satellite survey is downward continued to 2.5 km, so why should the predicted satellite profile in a) be the same as the ground profile? I didn't see anything about upward continuing the ground data to 2.5 km. I must have missed something.

Answer: indeed Figure 3 is difficult to introduce. They are 3 sub-figures in this Figure: on top right is the legend, on top left is the western profile plus the resulting associated model, and on bottom is the eastern profile plus the resulting associated model. In the latter top left and bottom subfigures, the bottom panels represent the crustal models. The caption describes this and so no modifications about this remark have been made. Concerning the second part of the reviewer's comment, the predicted satellite profile (dotted-dashed black line in the revised version of Figure 3) is slightly different than the ground data observed and predicted profiles (solid and dashed red lines), but very different than the observed satellite profile (solid black line). Indeed the downward continuation of the satellite data cannot resolve short wavelengths of the geomagnetic anomaly signal that we should really detect by an aeromagnetic survey at 2.5 km of altitude, for instance. The modelling predicts these wavelengths. Therefore the predicted 2.5 km altitude signal looks like to (but not completely) the ground data signal. The revised version (with colors) of Figure 3 should be clearer.

Fig 4. Hysteresis involves not only induced magnetisation. The magnetisation might be mostly induced for the top pair but it is mostly remanence for the bottom pair ($M_r/M_s > 0.5$). The ordinate should be relabelled 'magnetisation'. It is actually more strictly 'specific magnetisation' since it refers to both induced and remanent magnetic moment normalised to mass = specific magnetisation.

Answer: the reviewer is right; this figure and its associated caption have been modified using the reviewer's suggestions.

The associated modifications concern:

Previous version → Page 20, Figure 4 caption, Line 479.

Revised version → Page 23, Figure 4 caption, Line 553.

Fig 5. The ordinate label is 'Normalized Remanent Magnetisation' but then an induced magnetisation curve has been added, floating in space - maybe you could put the induced ordinate axis on the right hand side.

Answer: we just modified the ordinate label of the bottom figure where induced magnetization curve is shown too.

Minor editing:

Lines 63 - 69 west-african, Congolese, neoproterozoic and panafrican should all be capitalised.

*There are many other words throughout that should be capitalised. In addition in some places English English is used and in others American English e.g modelled vs modeled.
Line 315 even French! Sacre bleu..*

Answer: all these minor corrections have been made.

*Highlights (for review)

- We investigate the source of the Bangui magnetic anomaly
- We use satellite and ground magnetic field measurements
- We measure magnetic susceptibility and natural remanent magnetization on samples
- Few surface rocks have the required total magnetization to account for the BMA
- The whole crust beneath the BMA is strongly magnetic

1 **Rock magnetic investigation of possible sources of the Bangui magnetic anomaly**

2

3 Ouabego^{1,2}, M., Quesnel^{2*}, Y., Rochette², P., Demory², F., Fozing³, E.M., Njanko³, T.,
4 Hippolyte², J.-C., Affaton², P.

5

6 1 – Geosciences Laboratory, Bangui University, Bangui, Centrafrican Republic

7 2 – Aix Marseille University, CNRS, IRD, CEREGE UM34, 13545 Aix-en-Provence, France

8 3 – Environmental Geology Laboratory, Dschang University, BP67, Dschang, Cameroon

9

10 *Corresponding author :

11 Quesnel Yoann

12 Aix Marseille University, CNRS, IRD, CEREGE UM34, 13545 Aix-en-Provence, France

13 Ph.: +33 442971590

14 Fax: +33 442971595

15 Email: quesnel@cerege.fr

16

17 **Abstract**

18 The Bangui Magnetic Anomaly (BMA) is the largest lithospheric magnetic field anomaly on
19 Earth at low latitudes. Previous studies investigated its geological source using constraints
20 from satellite and ground magnetic field measurements, as well as from surface magnetic
21 susceptibility measurements on rocks from the Panafrican Mobile Belt Zone (PMBZ). Here
22 we combine magnetic field data modelling and rock magnetic property measurements
23 (susceptibility and natural remanent magnetization, NRM) on many samples from this PMBZ
24 and the surrounding formations. It reveals that NRM is a significant component of the total
25 magnetization (Mt) of the BMA source, which reaches 4.3 A/m with maximum thicknesses of

26 38 and 54 km beneath the western and eastern parts of the BMA. Only the isolated and
27 relatively thin banded iron formations and some migmatites show such Mt values. Thus we
28 suggest that the thick BMA source may be composed either by overlapped slices of such
29 metamorphic rocks, or by an iron-rich mafic source, or by a combination of these two
30 geological structures.

31

32 **Keywords:** Bangui magnetic anomaly, magnetization, geological source, modelling, banded
33 iron formation

34

35 **1 – Introduction**

36 Located in Centrafrican Republic, the Bangui Magnetic Anomaly (BMA) is one of the
37 largest lithospheric magnetic field anomaly on Earth, prominent even at satellite altitude.
38 Different models have been proposed concerning its geological source. First, Regan and
39 Marsh (1982) suggested that a geological metamorphic process affected the entire crust of this
40 area during the Panafrican orogenesis, creating physical property contrasts between cratonic
41 regions and collisional belts. Ravat (1989) reinforced this model but suggested an additional
42 concentrated near-surface ore-like body (see also Ravat et al., 2002 and Langel and Hinze,
43 1998). This shallow body could correspond to the remains of an iron meteorite that fell in this
44 area during the Proterozoic era (Girdler et al., 1992; see also De et al., 1998 and Gorshkov et
45 al., 1996). Shock, thermal and/or chemical remanent magnetizations acquired during and after
46 the impact should have led to this highly-magnetized body. However, the impact hypothesis is
47 less suitable since the impactor material does not survive in significant amount in large craters
48 and thus cannot contribute to such a large magnetic anomaly (Koeberl, 1998). Furthermore no
49 shock remanent magnetization was observed on the rock samples from this area (Marsh,
50 1977). All these studies lack of constraints from magnetic property measurements on the

51 corresponding rocks of this area. Here we combined rock magnetic measurements with
52 magnetic field anomaly modelling in order to investigate the possible source of the BMA.

53 In the first section, we summarize the geological context of the Centrafrican Republic,
54 especially in our studied area. Then, the BMA is introduced before the description of the
55 methods used. The next section details the results of magnetic property measurements and
56 BMA modelling over the studied area. The last section corresponds to a discussion on the
57 origin of the BMA, in the context of the general challenge involved in understanding large
58 and deep crustal anomalies using limited access to rock samples (e.g. Frost and Shive, 1986;
59 McEnroe et al., 2004, Rochette et al., 2005).

60

61 **2 – Geological context**

62 Central Africa is a key area of the African Plate since it constitutes the transition
63 between several old cratons (Figure 1a,b). This transition corresponds to several orogenic
64 belts such as the Panafrican belt (Nickles, 1952; Gérard, 1958; Black, 1966; Mestraud, 1971;
65 Alvarez, 1992, 1995; Rolin, 1995a,b). These belts are mobile zones of the Panafrican
66 Orogenesis at 600 ± 100 Ma (Kennedy, 1964; Rocci, 1965; Black, 1966). During this orogeny
67 plate movements closed oceanic areas leading to a belt of suture zones around the cratons in
68 the African regions of Gondwana. Our study area corresponds to Central Africa (Cameroon,
69 Centrafrican Republic, Chad and Congo) where the West-African and Congolese cratons are
70 separated by the Precambrian and Palaeozoic Oubanguides mobile zones (Figure 1b; Nickles,
71 1952; Gérard, 1958; Mestraud, 1971; Rolin, 1995b). Four geological domains are observed in
72 this area from the rare outcrops of the Archean terranes (about 3.5 Ga), the Eburnean
73 basement (2.4-2.2 Ga), the Neoproterozoic Panafrican cover (600 Ma) and the post-
74 Panafrican domain (Figure 1b,c). We focus our study on the southwestern part of the
75 Centrafrican Republic (Figure 1c) where the Oubanguides Panafrican Belt borders to the

76 north the Congo craton. Syn- and post-glacial Marinoen sediments cover the Neoproterozoic
77 layers (Alvarez, 1999; Rolin, 1995a). A collision of an oceanic plate led to the presence of
78 metamorphic rocks that were sampled in this area (granulites, quartzites including Banded
79 Iron Formations (BIF), migmatites, orthogneisses, metabasalts, metasediments and
80 metaperidotites). All metamorphic grades are found from granulite to green schist. The whole
81 sequence was remobilized during the Panafrican orogenesis in nappes (formation 6 on Figure
82 1c) cut by N140 and N70-trending reverse faults (Figure 1c).

83

84 **3 – Geophysical context**

85 The western part of Central Africa shows one of the most prominent large-scale
86 magnetic anomaly on Earth: the Bangui magnetic anomaly (BMA; Figure 2). It corresponds
87 to a multipolar magnetic anomaly with a negative central lobe and two positive north and
88 south lobes (all are located south to the geomagnetic equator). It reaches about 800 km of N-S
89 wavelength and about 1000 nT of amplitude at ground level. Its E-W axial extension also
90 reaches about 700 km. Near the magnetic equator and in the sub-tropical zone, this is the
91 largest magnetic field anomaly. Here we use the anomaly field from the Magnetic Field model
92 7 (MF7; modified from the MF6 of Maus et al. (2008)) and downward continued to near the
93 Earth's surface (2.5 km altitude – but this is considered as the 'satellite' signal in the
94 following). This model was derived using 2007-2010 magnetic data from the low-Earth orbit
95 CHAMP satellite. It resolves the crustal magnetic field anomalies with wavelengths larger
96 than 300 km, for example the long-wavelength part of the BMA.

97 Ground magnetic data with a heterogeneous spatial resolution are also used in this
98 study. They were acquired by LeDonche and Godivier (1962) in Centrafrican Republic and
99 Chad (therefore no ground data were acquired at the southern lobe of the BMA). The
100 published maps are of the horizontal and vertical components of the total magnetic field, as

101 well as the declination. To recover the total magnetic field (TF) anomaly, they subtracted the
102 corresponding International Geomagnetic Reference Field (IGRF) model values from TF
103 values. We preferred to apply the Definitive Geomagnetic Reference Field (DGRF) model for
104 year 1960 (coefficients published in Finlay et al. (2010)) to derive the anomaly. It should be
105 noted that the TF anomaly values are close to the horizontal component anomaly values, as
106 expected for such low latitudes near the magnetic equator. The shape of the BMA differs
107 between the satellite data map and the ground data map. Indeed the latter reveals that the
108 western limit of the negative lobe of the satellite-derived anomaly is more heterogeneous at
109 ground level, with a local positive E-W elongated central anomaly nearby (5°N , 17°E)
110 surrounding by local negative lobes south and north. Also, the E-W transition between the
111 central negative lobe and the northern positive one on the satellite-derived anomaly map is
112 about 0.3° north than the same transition on the ground data map. This could indicate that the
113 main source body lies in the lower and middle crusts but that only several branches of this
114 source may really reach the upper crust. The negative lobe of the anomaly is more intense (-
115 1000 nT) on the ground data map than on the satellite anomaly map (-400 nT). It is also very
116 well correlated to a negative Bouguer gravimetric anomaly (data from Boukéké et al., 1995)
117 of -125 mGal, indicating that the magnetization contrasts in the crust of this area may be
118 correlated to rock density contrasts from the same source region.

119

120 **4 – Methods**

121 *4.1 – Magnetic anomaly modelling*

122 To investigate the magnetic properties of the BMA source, we first used a modelling
123 method with the observed (ground as well as satellite-derived) magnetic and ground
124 gravimetric anomaly fields. The GM-SYS module of the GEOSOFT Oasis montaj software
125 was used. Gravity (Boukéké et al., 1995) and magnetic anomaly data along the NW-SE

126 profiles shown on Figure 2 were considered. The geometry of the different geological layers
127 was constrained by 1) our own field observations (only near the western profile), 2) data from
128 previous geological maps (Rolin, 1995a), and 3) gravimetric and magnetic anomaly data.
129 Along the western profile, only the surface geology, ground magnetic and gravimetric data
130 really constrained the model, because the satellite-derived magnetic signal cannot reproduce
131 the short wavelengths observed at 2.5 km altitude. On the other hand, along the long eastern
132 profile, too few surface observations, probably representing very 'local' anomalies, exist to
133 consider the interpolated profile as a reasonable constraint. The directions of the remanent
134 magnetization vector of the source body were initially set to the 2011 and 1960 Bangui
135 magnetic field directions (Finlay et al., 2010) for modelling of satellite-derived and ground
136 data, respectively, but could vary if necessary during the inversion. The main aim of the
137 magnetic modelling was to infer the approximate range of total magnetization (Mt) of the
138 most magnetic formation beneath the BMA under the assumptions of induced magnetization
139 constraint and of a source model geometry able to fit the data whatever the location (western
140 or eastern profiles).

141

142 *4.2 – Sampling and rock magnetic measurements*

143 Over 50 large hand samples were obtained in the area of Figure 1c, during several
144 field missions. Sampling was designed to cover all lithologies and degrees of metamorphism
145 observed in this area. Petrography was determined using thin sections and, in some cases, X-
146 ray diffraction and chemical analysis. Low field magnetic susceptibility measurements were
147 carried out using SM30 susceptibility meter (ZH Instruments) for large samples and KLY2
148 susceptibility meter (AGICO) for small samples. Mass susceptibility χ was calculated using
149 the weight of the samples. For remanence and further rock magnetic measurements a first set
150 of samples (chosen to be representative of all lithologies) was completed by all samples with

151 high susceptibility remaining in the collection: therefore the proportion of high susceptibility
152 samples is higher in the studied set. A total of 22 samples were thus fully investigated
153 magnetically. The Natural Remanent Magnetization (NRM) as well as saturation isothermal
154 remanent magnetization (SIRM) acquired at 1 T were measured using a spinner magnetometer
155 Minispin (Molspin) for large samples. In one case NRM was analysed by alternating field
156 demagnetization of a small sample using a superconducting rock magnetometer 760R (2G
157 enterprises). To characterize the magnetic minerals, thermomagnetic curves were acquired
158 using a MFK1 susceptibility meter (AGICO) with CS3 furnace (up to 650°C under argon
159 atmosphere), ambient temperature hysteresis measurements were performed with a vibrating
160 sample magnetometer Micromag 3900 (PMC) and its cryostat allowed measuring low
161 temperature remanent magnetizations.

162 To compare with the magnetic properties of somewhat similar formations within the
163 Panafrican belt, we analysed susceptibility data from East Cameroon (Betaré Oya area, see
164 Figure 1a,b and Kankeu et al., 2009) as well as West Cameroon (after Njanko et al., 2012 and
165 ongoing magnetic anisotropy investigations of amphibolites and granitoids). Some samples
166 from W Cameroon were also measured for rock magnetic properties.

167 Mass normalized rock magnetic measurements were used to evaluate in-situ M_t (in
168 A/m) of the sampled formations using the following formula:

169

$$170 \quad M_t = \rho (NRM + \chi H)$$

171

172 with ρ the rock density (2.7 g/cm³ for all rocks – a typical value for deep continental crust,
173 see Table 1 - except itabirites which were assumed to be 3.2 g/cm³) and H the present
174 magnetic field intensity in Bangui (33.6 μ T, i.e. 26.8 A/m). Using field intensities at the dates
175 of the discussed magnetic field surveys makes negligible changes. This formula assumes that

176 the induced and remanent magnetization components are colinear. Thus the resulting Mt
177 values computed with this equation will be maximum values. The Koenigsberger ratio
178 ($Q=NRM/\chi H$) was also calculated.

179

180 **5 – Results**

181 *5.1 – Magnetic anomaly modelling*

182 The best models to represent the crustal magnetization and density variations beneath
183 the western and eastern BMA profiles are shown in Figure 3, and the parameters associated to
184 each layer are indicated in Table 1. For the most magnetic layer, using a shape similar than the
185 one shown in Figure 3 but with different Mt value and associated thickness, a Mt of 4.3 A/m
186 indeed results in the best predictions of the data along both eastern and western profiles (see
187 Table A1, Figures A1 and A2 in Supplementary Material). Only the 2.5 km-altitude satellite-
188 derived magnetic data of the western profile and the ground magnetic data of the eastern
189 profile are not well predicted, as expected (see explanations in Section 4.1). The resulting
190 magnetization directions are similar to the input values. Similarly to the results of previous
191 BMA modelling studies, the superficial geological layers seem to be weakly magnetized.
192 With the selected shape, the top of the main magnetic source (layer 1) is 9 km deep beneath
193 the short western profile, 5 km deep beneath the long eastern profile. The total magnetic
194 thickness of this layer reaches 38 and 54 km beneath the western and eastern profiles,
195 respectively, even if significant lateral N-S thickness variations are observed beneath the
196 western profile (Figure 3). This confirms that a huge amount of strongly magnetized rocks is
197 preserved in the crust of Centrafrican Republic, even beneath the sampled area near Bangui.
198 The gravity and magnetization contrasts in the models are similar to those of the model
199 proposed by Marsh (1977) and Regan and Marsh (1982) using satellite data only and
200 modelling the whole BMA. In particular, the magnetic source seems to be less dense (density

201 contrast of about -0.03 g/cm^3) than the deep non-magnetic surrounding rocks (mainly layer
202 3), but denser ($> 0.2 \text{ g/cm}^3$) than the superficial non-magnetic formations (not considered in
203 model (b) of Figure 3). Note that a small relief of the Moho is necessary to completely
204 explain the shape of the gravity signal along the two profiles. Concerning the 4.3 A/m
205 magnetization intensity for the most magnetic layer of the best model, using only induced
206 magnetization would require a rather unrealistically high k of $16 \cdot 10^{-2} \text{ SI}$ for the rocks of the
207 studied area. Therefore we arbitrarily separated this M_t value into a NRM of 4 A/m and a
208 volumic susceptibility k of 10^{-2} SI (Table 1).

209

210 *5.2 – Magnetic property measurements*

211 Table 2 shows the magnetic properties of the 22 studied samples. Most of our strongly
212 magnetic samples have Koenigsberger ratios (Q) larger than 1 (minimum values 0.3),
213 stressing the importance of not relying only on susceptibility measurements. Only two
214 samples corresponding to migmatite (8576) and itabirite (8603), have M_t over 4.3 A/m , while
215 five other samples have $0.8 < M_t < 2.3 \text{ A/m}$, from the above lithologies plus granodiorite (8632)
216 and orthogneiss (240). Other lithologies (metaperidotites, metabasalts, granulite and non
217 itabiritic metasedimentary rocks) have negligible M_t . The strong M_t values are coherent with
218 the susceptibility measurements made by Marsh (1977) on outcrops from the area beneath the
219 large Bangui magnetic anomaly, eastward from our own sampling. Those samples with the
220 largest observed magnetic susceptibilities are itabirites from Bakala (k around 0.1 SI) and
221 charnockites from Kaga Bandaro (k around 0.02 SI). We do not elaborate further on Marsh
222 (1977) data obtained using a Bison large coil applied on the outcrops, as their precision and
223 cross-calibration with our more precise data is unknown.

224 Hysteresis loops obtained on chips from the 6 most magnetic samples reveal 4 samples
225 (Figure 4; including 8576) typical of multidomain magnetite $-M_r/M_s < 0.02$, $B_{cr}/B_c > 5$,

226 Bcr<20 mT- and two samples (8603 and 240) typical of hematite -Mrs/Ms>0.5, Bcr/Bc≈1.3,
227 Bcr>20 mT. Hematite appears multidomain for the itabirite sample (8603) and single domain
228 for the orthogneiss (240). To confirm these identifications, we measured low temperature
229 remanent magnetizations on the two most magnetic samples (Figure 5) and high-temperature
230 susceptibility on the 4 samples showing multidomain magnetite (Figure 6). At low
231 temperature, Morin and Verwey transitions are visible on 8603 and 8576 respectively (Figure
232 5), indicating that pure hematite and pure magnetite are indeed present in these rocks.
233 Magnetite Curie point (at 580°C; Figure 6) is observed on all samples but in 8603 and 240
234 over 50% of initial susceptibility remains over 650°C, indicative of hematite that should carry
235 most of the remanence. For sample 240, this weak residual signal may also correspond to
236 instrument drift, but the previous hysteresis measurements have shown hematite.

237 For surface rock samples, the measured NRM intensities can be biased by the viscous
238 remanent magnetization (VRM) component and other possible spurious unwanted
239 magnetizations, especially lightning induced IRM that can generate anomalously high NRM
240 (Verrier and Rochette, 2002). Therefore we scaled measured NRM with saturation IRM, and
241 computed theoretical in situ NRM intensities from measured SIRM. For samples containing
242 magnetite, we applied a theoretical NRM/SIRM ratio of 2% (Gattacceca and Rochette, 2004)
243 using a thermo-remanent magnetization (TRM) in the present magnetic field in Bangui. These
244 modelled Mt values are shown in the last column of Table 2. Only two samples exhibit
245 modelled values significantly different from the value computed using our NRM and
246 susceptibility measurements: magnetite-bearing migmatite (8576) and hematite-bearing gneiss
247 (243). For the latter, modelled value is much higher, possibly due to a multicomponent IRM
248 with opposite directions. Measured value for 8576 is 3 times larger than the modelled Mt,
249 suggesting that lightning has biased our NRM measurement, although much larger
250 NRM/SIRM ratios are commonly observed for samples affected by lightning (Verrier and

251 Rochette, 2002). An alternative-field demagnetization experiment with REM' ratio computed
252 following Gattacceca and Rochette (2004) does confirm that 8576 NRM is affected by
253 lightning, with REM' peaking at 30%. For samples containing hematite (8603 and 240), the
254 modelled Mt values (using NRM/SIRM = 50% after Kletetschka et al., 2000, and Dunlop and
255 Kletetschka, 2001) are similar to the observed ones (30 to 50%).

256 Finally, we compare the magnetic properties of our samples with those measured on
257 other rock samples from the Panafrican belt in Cameroon (Figure 7). For West Cameroon
258 Fomopea amphibolites (Njanko et al., 2012; geographic position near 5.5N and 10E), among
259 16 sites (with 2 to 4 samples per sites), the maximum k is $9 \cdot 10^{-2}$ SI, with 25% of the sites
260 above 10^{-2} SI. In the Nkambé area (6N and 10E), mostly with granitoids but also with
261 accessory amphibolites, the maximum k is $5 \cdot 10^{-2}$ SI in both lithologies, with 16% of the over
262 1200 samples above 10^{-2} SI (Fozing et al., in preparation). Rock magnetic measurements,
263 including hysteresis loops and thermomagnetic curves, have been performed on a selection of
264 48 samples (Table A2 of the Supplementary Material). They all show a multidomain to large
265 pseudo-single domain magnetite signal. Modelled Mt has been computed after SIRM and
266 susceptibility measurements (Figure 8). Only 15 samples yield values over 1 A/m, a single
267 one being over 4 A/m (at 6.8 A/m). For those strong samples, Q ratio is always over 1
268 (average around 2), stressing again the need to take remanence into account, even for
269 multidomain magnetite. For the East Cameroon study of Kankeu et al. (2009, at 5.5N and
270 14E), the susceptibility of 65 metasediments (schist, quartzite and gneiss) and 18 deformed
271 granites was measured. For these two classes, the maximum k is 2 and $5 \cdot 10^{-2}$ SI, with 5 and
272 61% of the samples above 10^{-2} SI, respectively.

273 It appears from Figure 7 that the mean magnetic susceptibility distribution is roughly
274 similar regardless of the location in the Panafrican belt, with metamorphic rocks derived from
275 basalts and granites having the strongest magnetic susceptibilities. These histograms confirm

276 on a larger scale the conclusion from our samples: no surface lithologies are able to account
277 for the BMA by induced magnetization alone (e.g. Shive, 1989). A review of the extensive
278 magnetic anisotropy work in Panafrican intrusives from NE Brasil (e.g. Archanjo et al., 1995,
279 1998, 2002) confirms this conclusion. When taking into account remanence it appears that
280 magnetite-bearing crustal rocks (granitoids and amphibolite) exceptionally reaches the BMA
281 total magnetization (Figure 8).

282

283 **6 – Discussion**

284 These results indicate that a single lithology -hematite-bearing itabirites, i.e. BIF,
285 interstratified with amphibolites and other metasediments- shows strong enough total
286 magnetization M_t to be the magnetic source of the BMA ($M_t > 4.3$ A/m). Lithologies rich in
287 multidomain magnetite (some amphibolites and granites) fail by about a factor 2 to account
288 for the BMA, assuming no significant enhancement of NRM at depth. No magnetic field
289 observations were made at the itabirite sampling locations (LeDonche and Godivier, 1962),
290 but such outcrops should result in a local small-wavelength high-amplitude magnetic field
291 anomalies. Our assumption that the deep crustal lithologies responsible for the BMA could be
292 outcropping over the BMA relies on the possibility that some slices from these deep
293 lithologies have been brought to the surface through orogenic processes (e.g. Rolin, 1991).
294 Our modelling shows that the deep magnetic source seems to be less dense than the deep non-
295 magnetic surrounding rocks (granulites?), but denser than most of the superficial non-
296 magnetic formations (quartzites and schists). We also note the numerous reverse faults in this
297 Panafrican belt around Bangui that witness a compressive regime which may have favored the
298 thickening of the iron-rich formations (Figure 1c).

299 The total magnetization intensity and the expected volume of the geological source of
300 the BMA are coherent with a mafic (basaltic) lower crust, as Pin and Poidevin (1987) and

301 Hemant and Maus (2005) suggested. This metabasalt or amphibolitic part of the Central
302 Africa's lower crust may be the root of the migmatite basement. However, our results also
303 suggest that BIF may compose the source of the BMA because of their magnetization. These
304 rocks are assumed to compose about 25% of the source of the Kursk magnetic anomaly in
305 Russia (Taylor, 1987; Ravat et al., 1993; Langel and Hinze, 1998). In such case, a positive
306 gravimetric anomaly should be associated to the BMA, as Schmidt et al. (2007) observed on a
307 similar geological formation in Australia (magnetization up to 100 A/m). However as itabirite
308 can be an order of magnitude more magnetized than the BMA source, a volume occupied by a
309 mixture of 10% itabirite (i.e. a maximum thickness of 2 km) and 90% of low density and less
310 magnetic rock can account for the BMA without inducing a significant excess of mass. As
311 mentioned earlier, a negative gravimetric contrast is associated to the BMA in its central part,
312 but a positive one is found west of Bangui nearby Cameroon border (Boukéké et al., 1995),
313 where a positive magnetic anomaly and itabirites are also observed. Finally, the combination
314 of these two possible magnetic formations (itabirites and amphibolite) may explain the long
315 wavelength and large intensity of the BMA.

316 It is interesting to note that probably all Panafrican metamorphic crustal formations,
317 including these magnetic rocks from the lower crust, may be found on surface today in the
318 Centrafrican Republic, while for other large magnetic anomalies like the Beattie magnetic
319 anomaly in South Africa, the source is from the upper and middle crust but covered by the
320 Karoo basin sediments (Quesnel et al., 2009). Two key points of our interpretation are the
321 possible Curie isotherm -deepened in case of hematite-bearing rocks- in the Central Africa
322 lithosphere, as well as the magnetic mineralogy that carries these strong magnetization
323 intensities at such depth (Frost and Shive, 1986; McEnroe et al., 2004). If it is hematite, our
324 study puts forward a candidate lithology: itabirite or BIF. If it is multidomain magnetite, then
325 the candidate lithology has not been sampled at the surface. It should be two times richer in

326 magnetite than the most magnetite-rich granitic and amphibolitic samples studied so far. Such
327 a high Fe amount should correspond to a positive gravity anomaly that is not observed.
328 However, a “homogeneous” tectonic mixing of BIF slices, a few km thick in total, with other
329 metasediments and a few tens of km thick series of magnetite-rich metamagmatic rocks may
330 be the best solution to account for all geophysical data.

331

332 **7 – Conclusion**

333 Using modelling and rock magnetism constraints, we investigated the source of the
334 BMA using samples obtained over the anomaly in Centrafrican Republic, as well as
335 geologically related areas in Cameroon. Modelling implies a total magnetization of the order
336 of 4 A/m on a thickness up to 54 km, possibly associated with relatively moderate density of
337 2.87. No surface sample can account for this magnetization based only on induced
338 magnetization. Large enough remanent magnetization intensities are observed for only two
339 surface samples, but lightning has affected one. This highlights the fact that modelled in-situ
340 NRMs based on IRM and magnetic mineralogy may be a more reliable indicator in magnetic
341 anomaly interpretation, compared to NRM actually measured on surface samples, which can
342 yield strongly-biased values with respect to NRM at depth.

343 The only remaining lithology, with NRM up to 50 A/m, is hematite-bearing itabirites
344 (BIF) that are Neoproterozoic iron-rich metasediments. Other magmatically-derived
345 lithologies rich in multidomain magnetite (migmatite, amphibolite, granite) can account for
346 only a few A/m at most. We suggest that the two types of geological formation may compose
347 the deep crust of this area and particularly the extended deep magnetic source. Further
348 constraints given by drilling or by other geophysical methods like seismics or
349 magnetotellurics are needed to validate (or not) this interpretation and the previously-
350 published models. Concerning magnetics, new high-resolution ground and airborne magnetic

351 field measurement surveys will surely improve the characterization of this source, including
352 its possible extensions toward the surface. In the same time, one should benefit from the
353 upcoming SWARM satellite mission (Friis-Christensen et al., 2006) that will allow the use of
354 lateral and vertical magnetic gradients to study such large magnetic anomalies.

355

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360

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515 **Figure captions**

516

517 **Figure 1:** Location (a), regional (b) and local (c) geological contexts of the studied area. In
518 (a), the black rectangle and disks correspond to the sampled areas in Centrafrican Republic
519 and Cameroon, respectively. The dotted-dashed line delineates the coastline of South
520 America, translated and rotated next to Africa. A zoom is shown in (b) where the relationships
521 between the different Archean blocks are reconstituted. Zone A corresponds to the
522 Paleoproterozoic rocks with Archean inheritances underlining the border of the mega-Congo
523 craton. Zone B are the Pan-African rocks with Paleoproterozoic inheritances. Zone C
524 represents the nappes of the 600 Ma Central African Belt. Zone D corresponds to the
525 Mesozoic sediments of the Benue trough and Zone E are the oceanic rocks. PF, Pernambuco
526 fault; ADF, Adamawa fault; TBF, Tchollire–Banyo fault; dotted-dashed lines: reconstituted
527 South America (SW one) and Africa (NE one) coastlines. This (b) regional map is modified
528 from Penaye et al. (2004), Poidevin (1991), Ferré et al. (1996), Feybesse et al. (1998),
529 Almeida et al. (2000) and Toteu et al. (2001). The dashed rectangle corresponds to the
530 Centrafrican sampled area (c), while the black disks show the approximate locations of the
531 sampled areas in Cameroon. In (c), modified from Rolin (1995a), details about the surface
532 lithology and the structural features of the studied area nearby Bangui are shown. 1, Archean
533 gneissic basement; 2, Paleoproterozoic migmatitic domain; 3, Lower-Neoproterozoic domain
534 with (a) quartzites and (b) itabirites; 4, Upper-Neoproterozoic schists; 5, Upper-
535 Neoproterozoic limestones/marbles; 6, Panafrican Gbayas Nappe with orthogneisses,
536 granulites and granites; 7, Post-Panafrican cover with sandstones and clays. Black filled
537 circles with names indicate the sampling sites.

538

539 **Figure 2:** Interpolated magnetic anomaly maps near the surface over Centrafrican Republic
540 and Chad. On left, gridded data from the satellite MF7 model (derived from Maus et al.
541 (2008) downward continued to 2.5 km of altitude). On right, ground magnetic data
542 interpolated from LeDonche and Godivier (1962). The solid lines correspond to the selected
543 profiles for modelling, while the rectangle indicates the location of Figure 1c.

544

545 **Figure 3:** Crustal magnetic models (bottom panels) along the NW-SE western (a) and eastern
546 (b) profiles (top panels) shown on Figure 2. Sat, satellite-derived magnetic data; Ground,
547 ground magnetic data; Gravi, ground gravity data (Boukéké et al., 1995); Obs, observations,
548 Pred, predictions. For models, layer density and magnetization properties are represented by
549 the filling color and/or pattern (see Table 1 for details). Formation 1 has a total magnetization
550 intensity (Mt) of 4.3 A/m, which corresponds to the best model with this source geometry (see
551 Supplementary Material).

552

553 **Figure 4:** Hysteresis curves (specific magnetization) of four samples. Bc, coercitive field; Ms,
554 saturation magnetization; Mrs, remanent magnetization at saturation; Bcr, coercitive field of
555 the remanent magnetization, derived from the back-field curve.

556

557 **Figure 5:** Low-temperature remanent magnetization (RM) curves for two samples (cooling
558 and subsequent heating of a room temperature IRM), showing the Verwey (in a) and Morin
559 (in b) transitions. For (b) is also shown the induced magnetization (IM) heating and cooling
560 curves, measured in a 0.3 T field.

561

562 **Figure 6:** Effect of heating (black) and cooling (gray) on the normalized magnetic
563 susceptibility of the same four samples as in Figure 4.

564

565 **Figure 7:** Histogram (in logarithmic representation) of k_m , the mean magnetic susceptibility,
566 for Cameroon and Centrafrican Republic (CR) rock samples.

567

568 **Figure 8:** Histogram of modelled total magnetization (Mt) derived from IRM and
569 susceptibility measurements on Panafrican magnetite-bearing rocks from Cameroon (black)
570 and Centrafrican Republic (white).

Figure 1 revised
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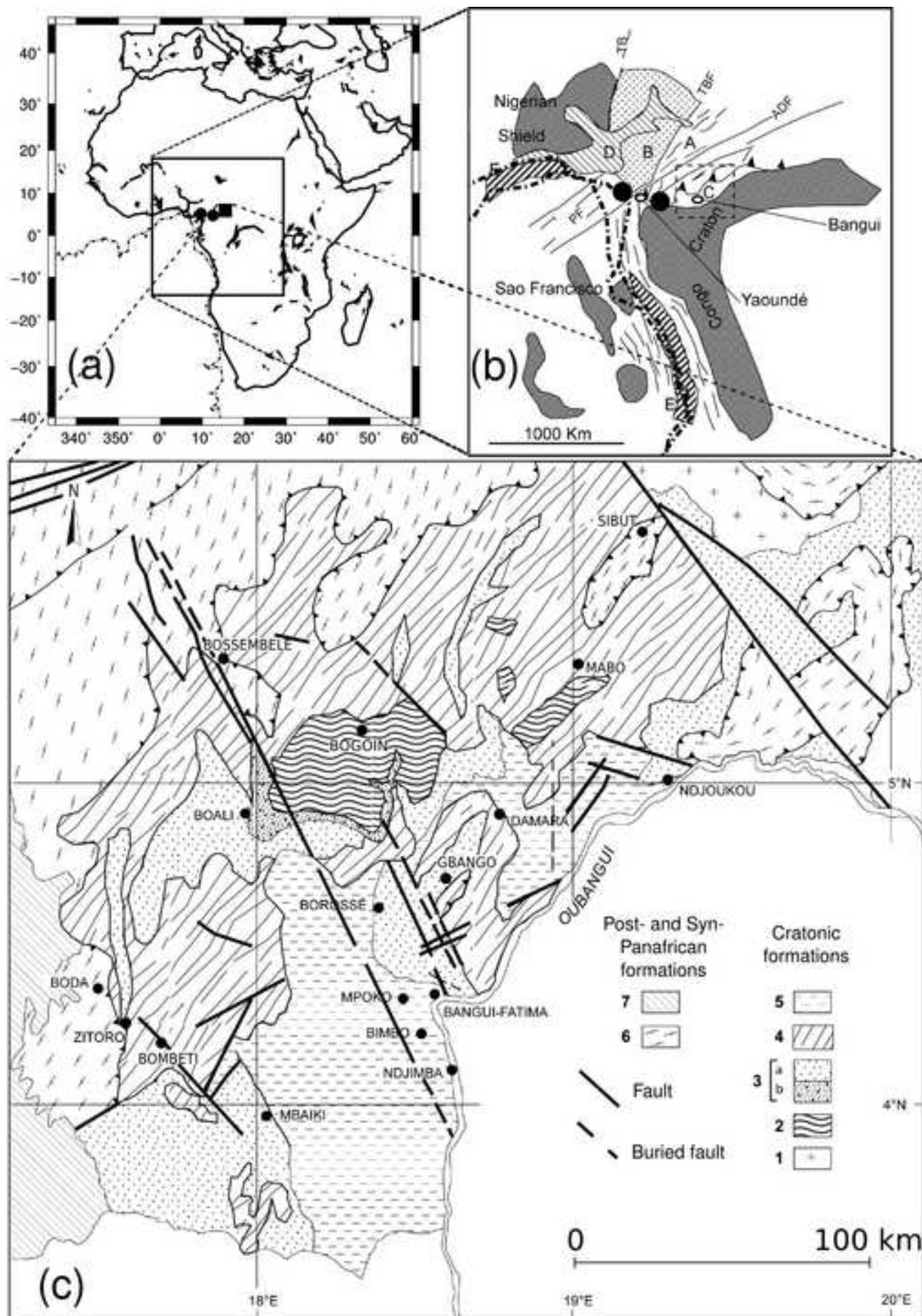


Figure 2 revised
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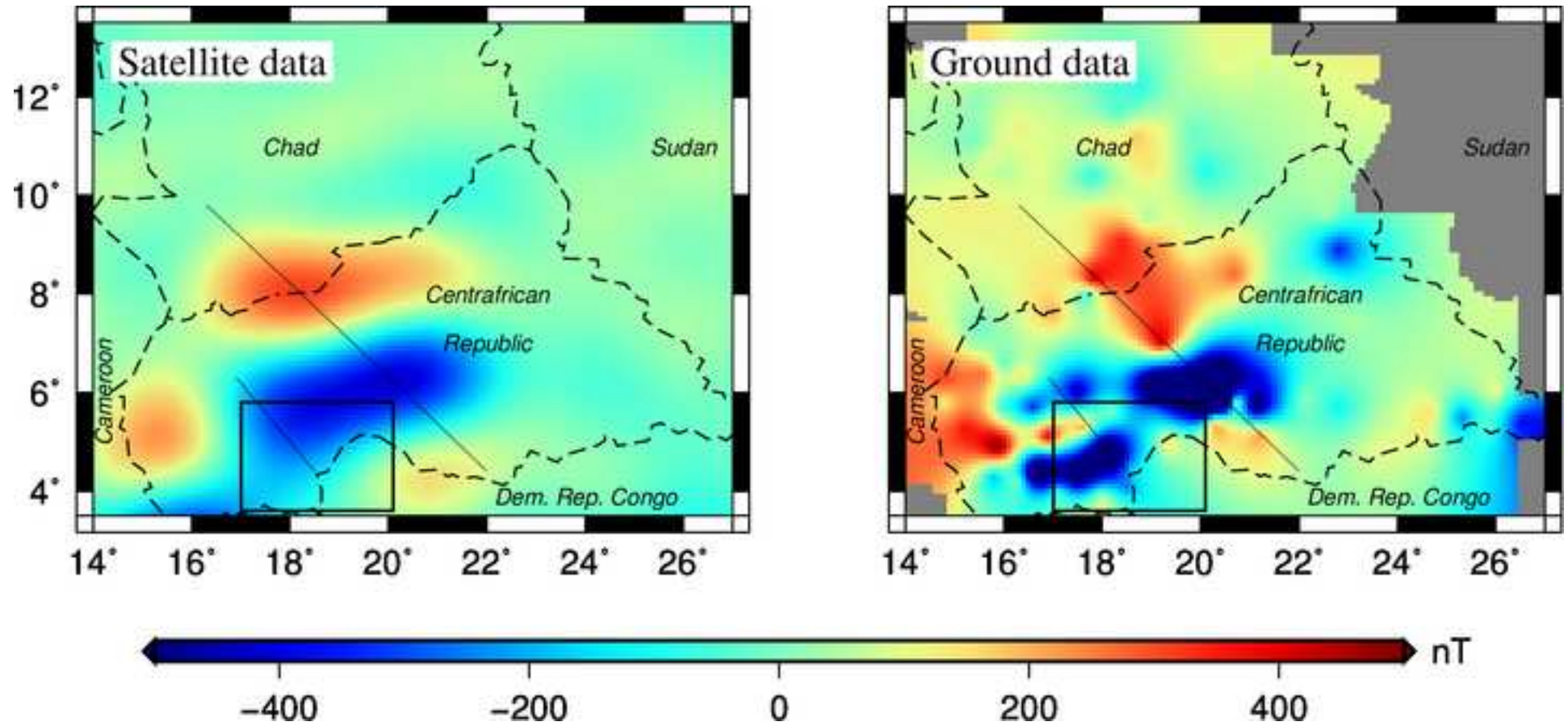


Figure 3 revised

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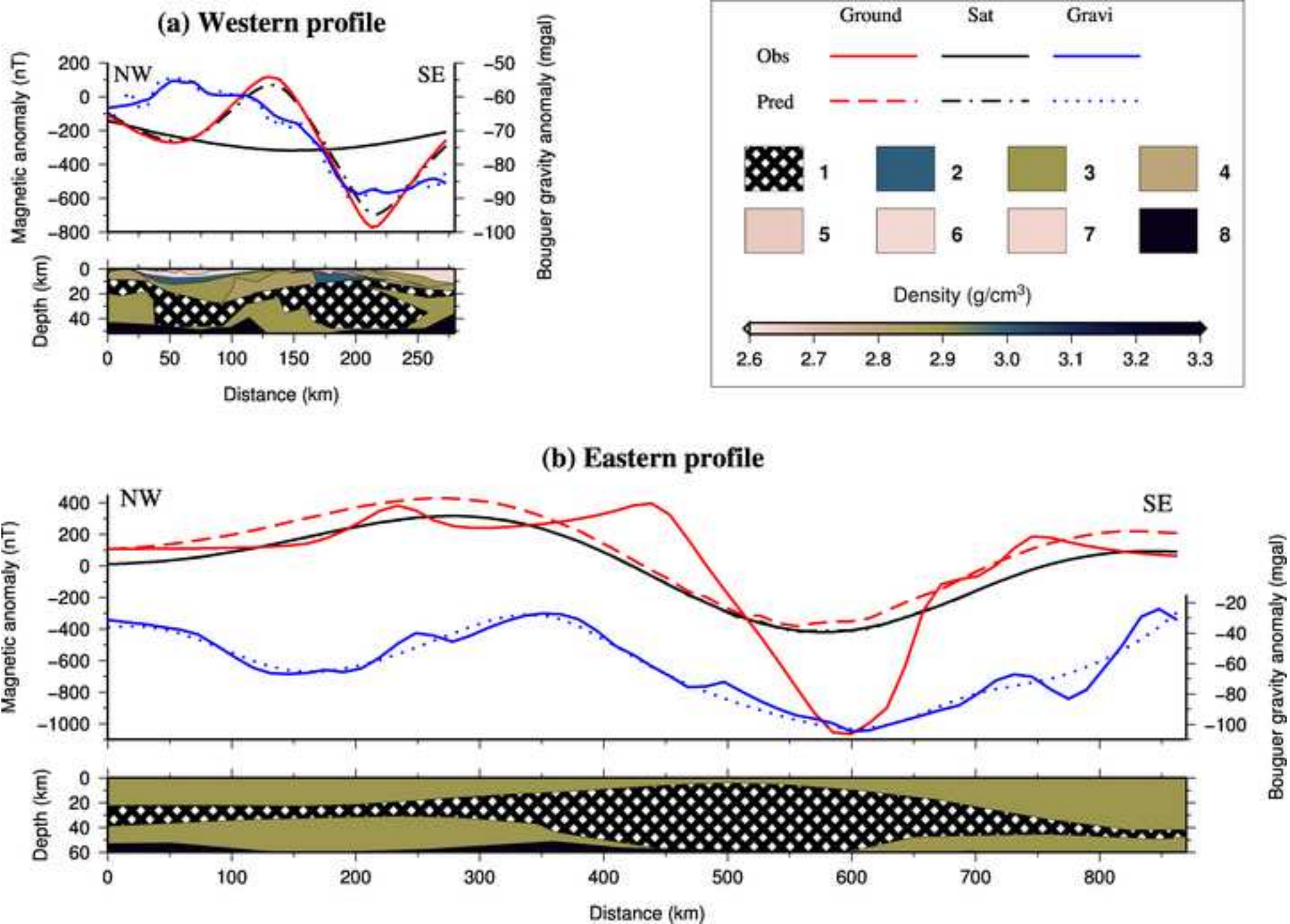


Figure 4 revised

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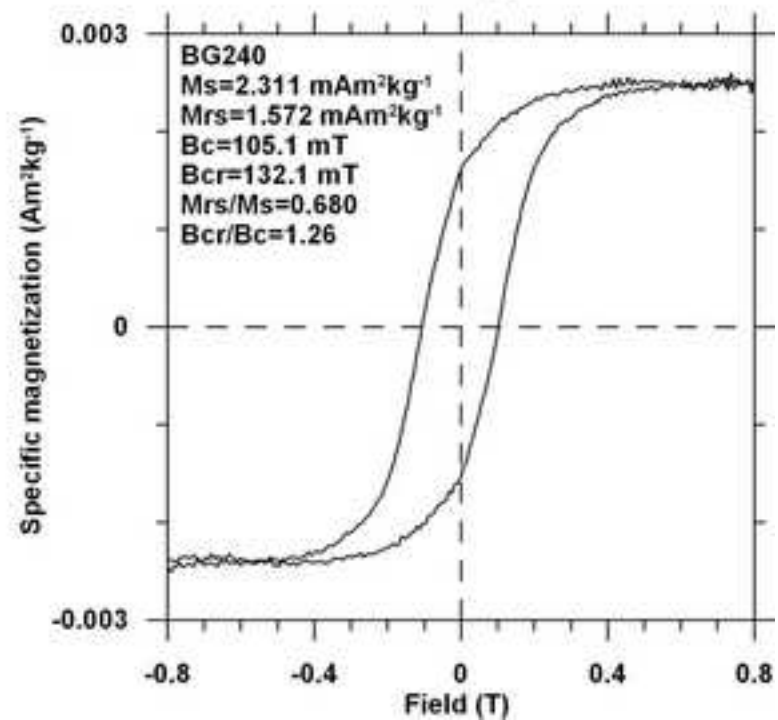
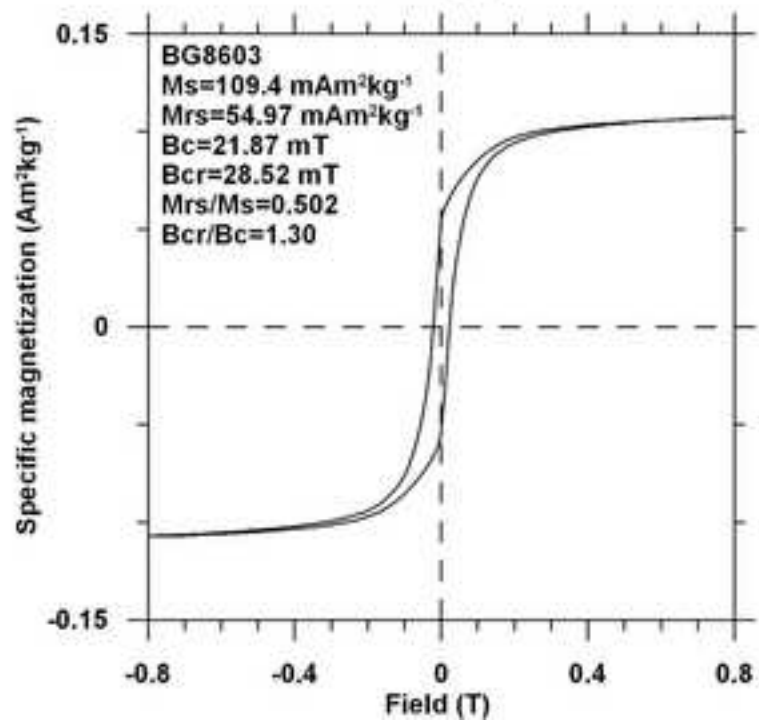
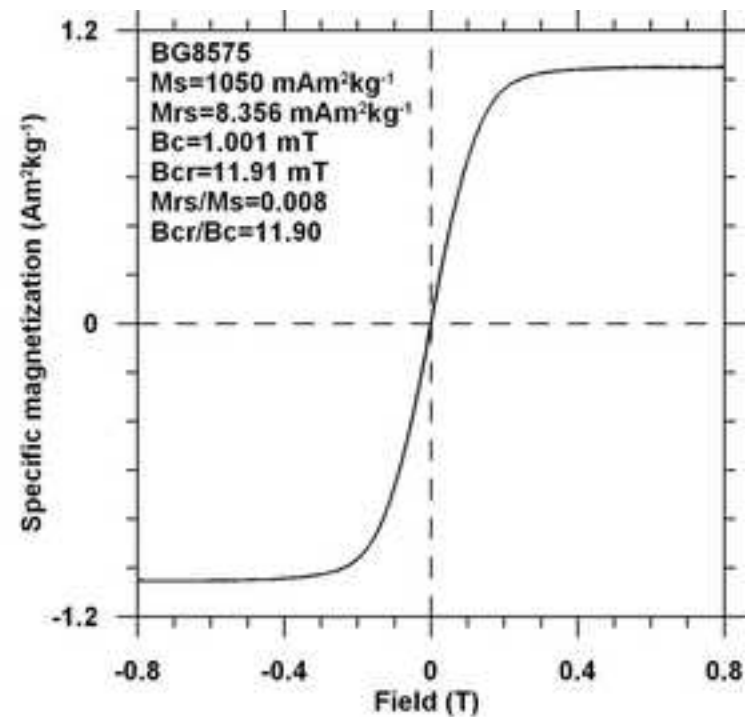
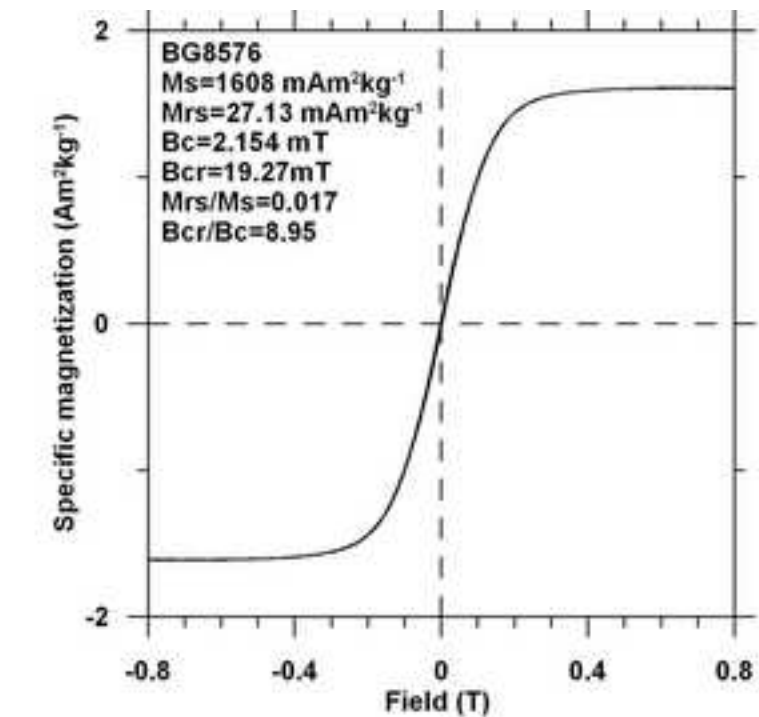


Figure 5 revised

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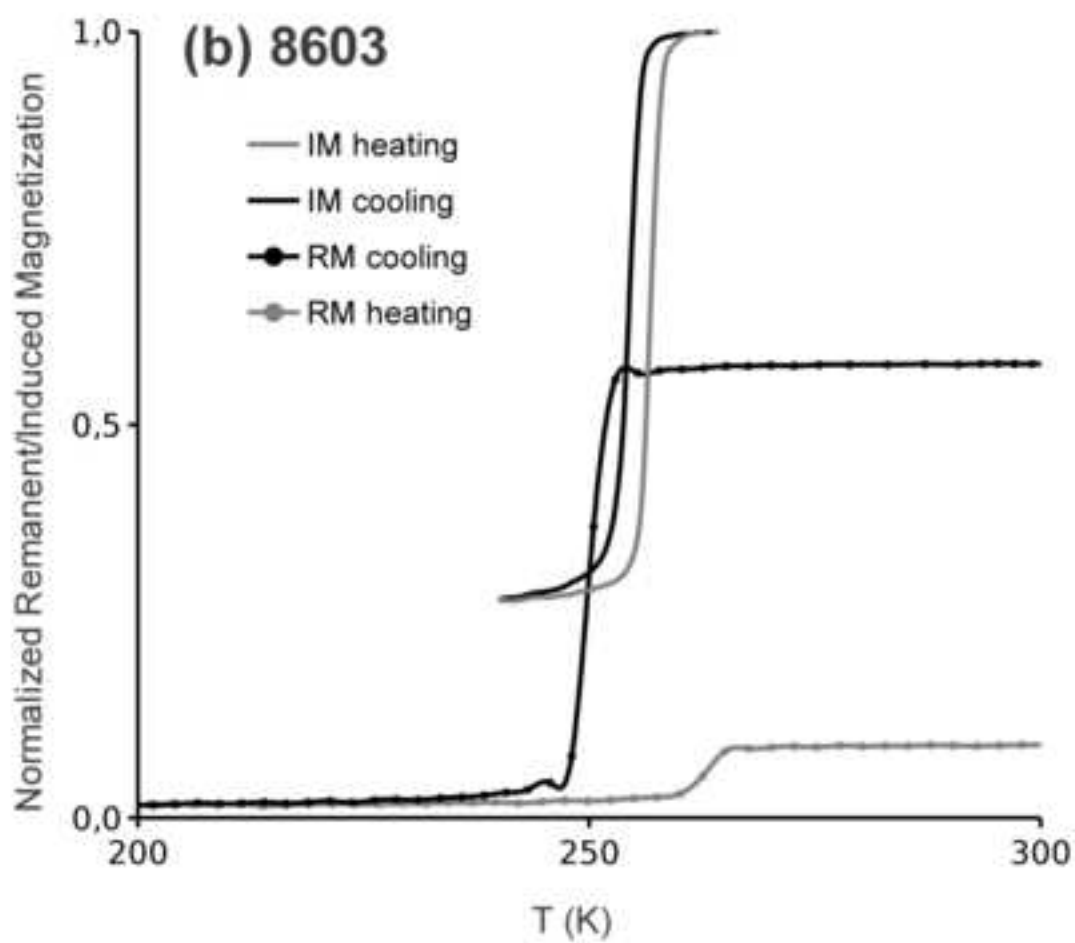
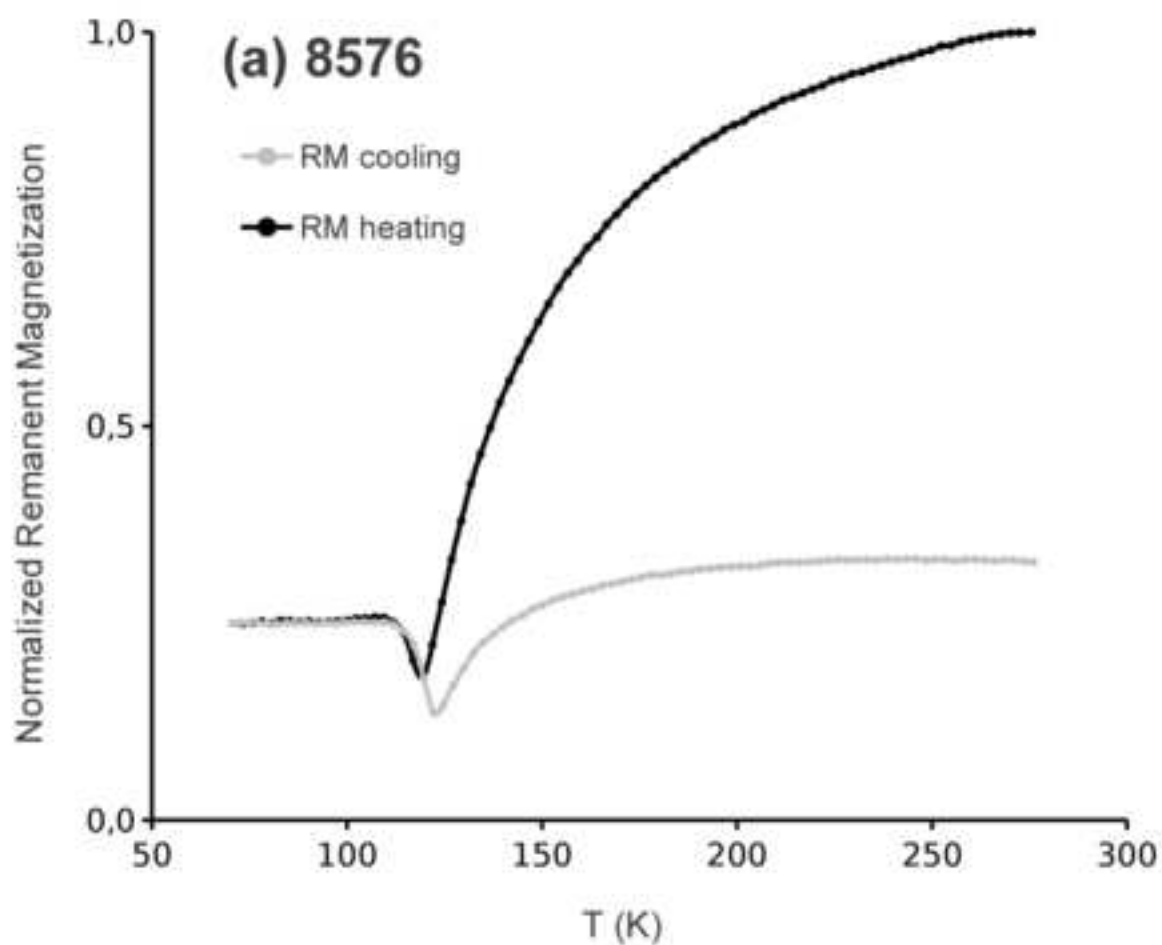


Figure 6
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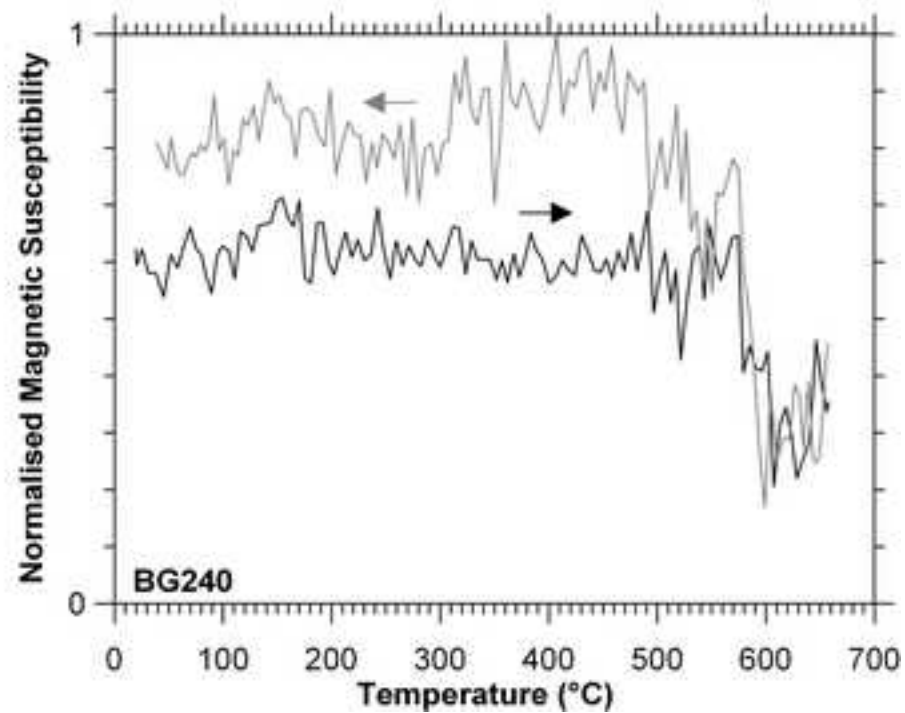
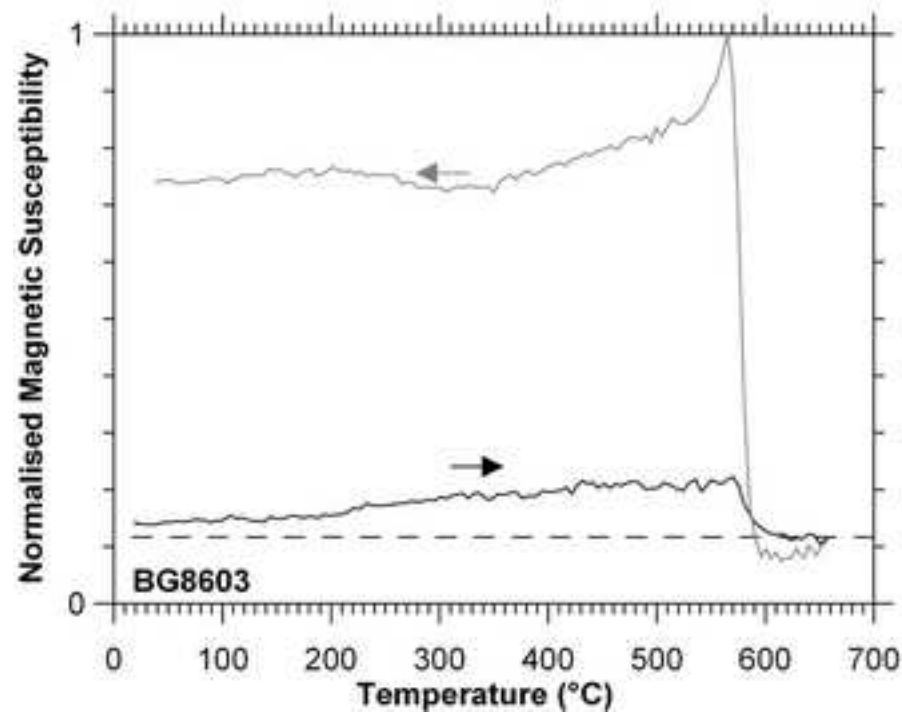
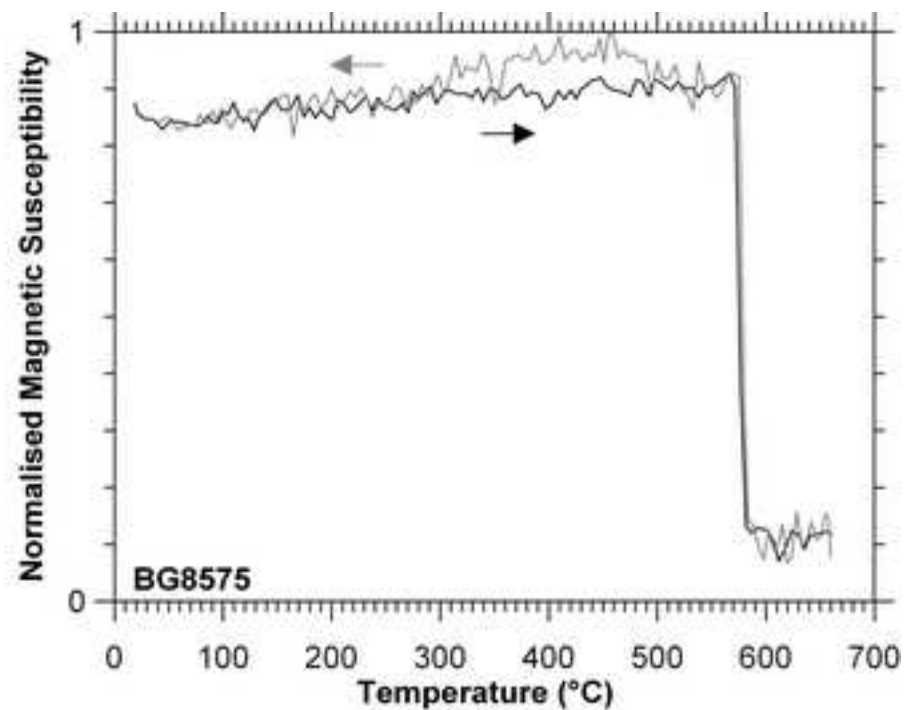
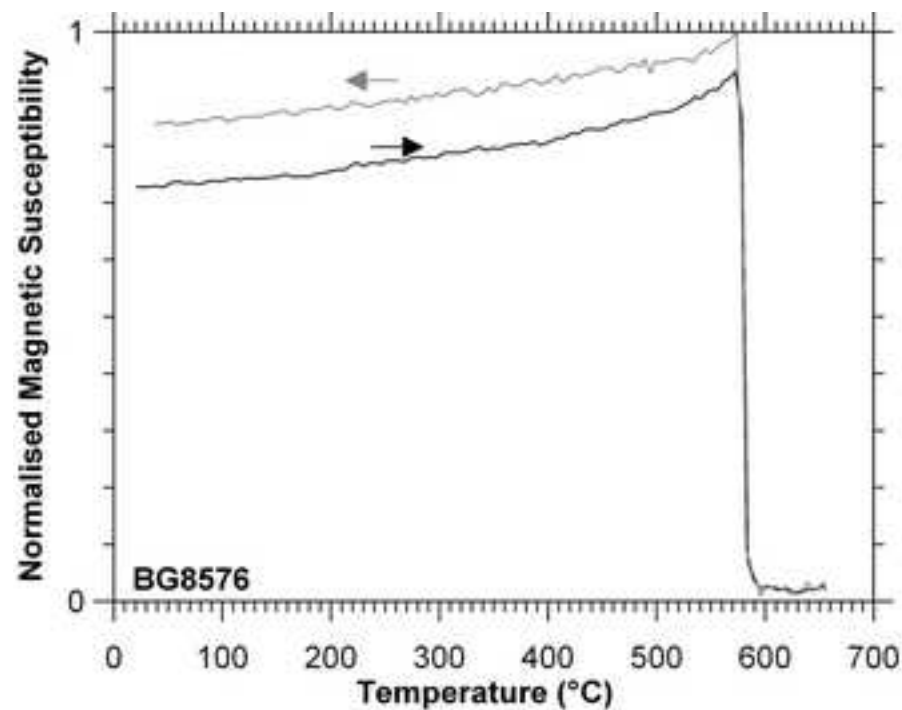


Figure 7 revised
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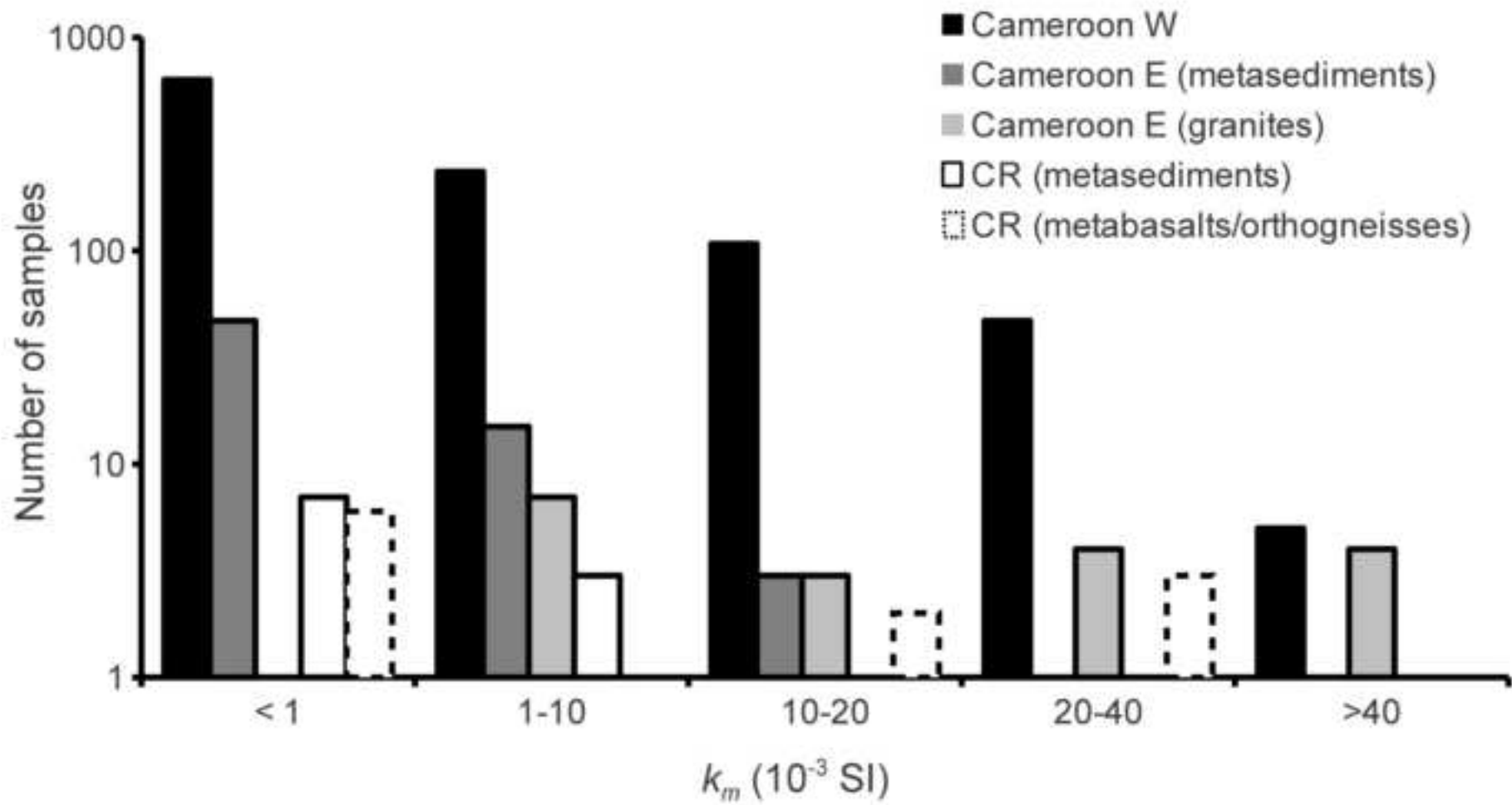
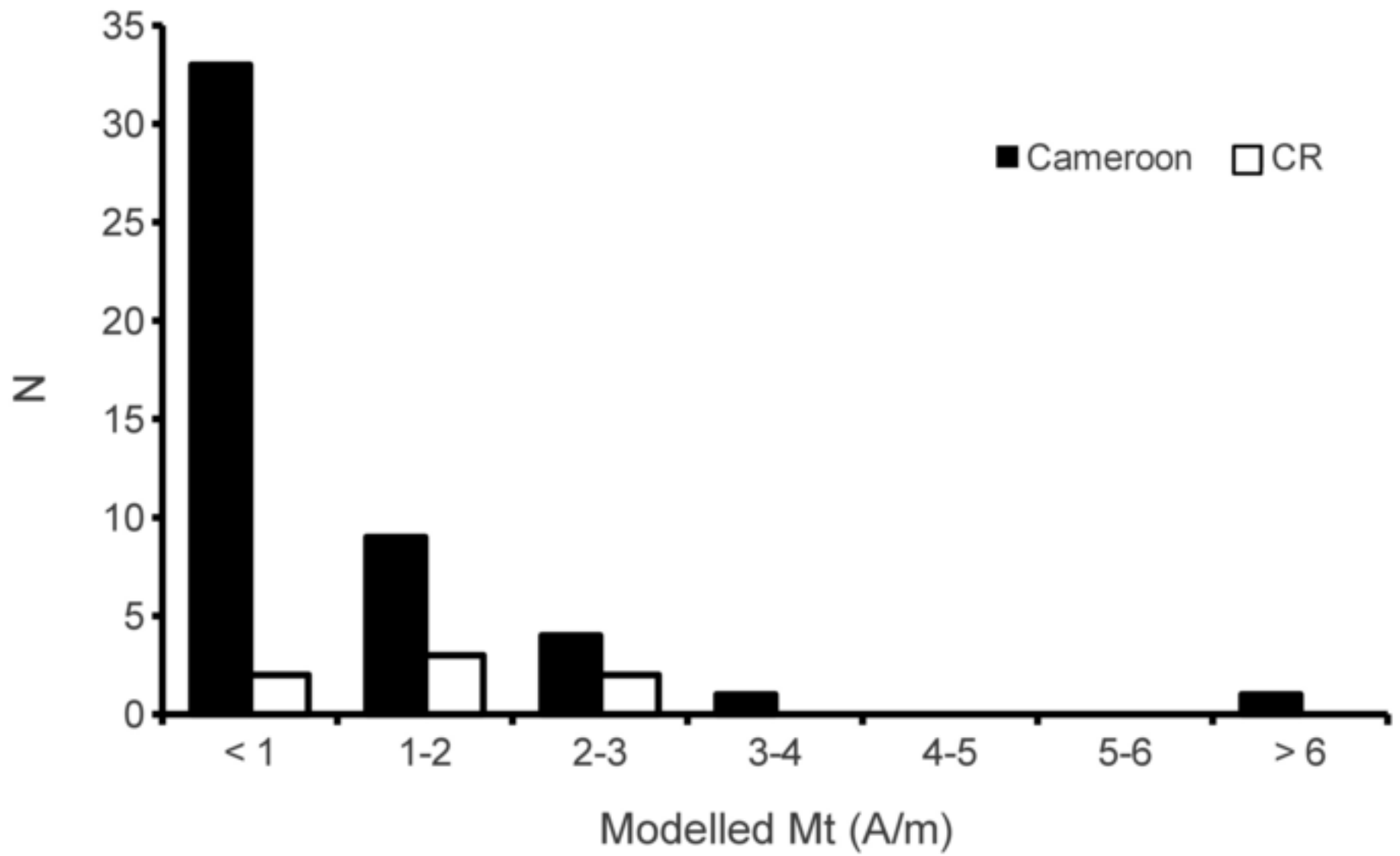


Figure 8 new
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1 **Table 1.** Magnetization* and density contrasts of the best models for the source of the BMA.

<i>Layer**</i>	<i>k</i> (10 ⁻³ SI)	NRM (A/m)	d (g.cm ⁻³)	<i>Rock type***</i>
1	10	4.0	2.870	<i>Magnetic source layer</i>
2	1	-	3.000	<i>Metabasalt</i>
3	1	-	2.900	<i>Granulite/Orthogneiss</i>
4	1	-	2.850	<i>Amphibolite</i>
5	1	-	2.665	<i>Quartzite</i>
6	1	-	2.630	<i>Schist</i>
7	1	-	2.640	<i>Panafrican nappe</i>
8	-	-	3.300	<i>Mantle rocks</i>

2 *all layers have their magnetization oriented in the 1960 (I= -14.5°, D=-5°) and 2011 (I= -16.76°, D=0.3°)

3 magnetic field directions in Bangui for the modelling of the ground and satellite magnetic data, respectively.

4 **see correspondance in Figure 3.

5 ***these rock types are expected with regards as their densities, their magnetization properties and the surface

6 geology.

1 **Table 2.** Magnetic properties of rock samples from the Bangui area.

<i>Lithology</i>	ID	χ ($10^{-9} \text{ m}^3 \cdot \text{kg}^{-1}$)	NRM ($\text{A} \cdot \text{m}^2 \cdot \text{kg}^{-1}$)	Mt (A/m)	Q	NRM/SIRM (%)	Laboratory	<i>Sampling site</i>
							modelled Mt (A/m)	
<i>Itabirite</i>	8603	798	23856.2	76.4	1117.8	43.6	88.1	<i>Bogoin</i>
	243	629	237.5	0.8	14.1	5.1	7.5	<i>Bogoin</i>
<i>Migmatite</i>	8576	12201	2041.1	6.4	6.3	7.6	2.3	<i>Mabo</i>
	8575	8496	66.0	0.8	0.3	0.7	1.1	<i>Mabo</i>
<i>Orthogneiss</i>	240	85	833.8	2.3	365.5	53.1	2.1	<i>Mabo</i>
	234	229	342.8	0.9	55.9	36.1	1.5	<i>Sibut</i>
	235	5165	102.7	0.7	0.7	3.4	0.5	<i>Sibut</i>
	216	23	0.9	0.0	1.4	-	-	<i>Galabadjia</i>
<i>Granodiorite</i>	8632	7587	382.9	1.6	1.9	1.6	1.8	<i>La Mbi</i>
<i>Metaperidotite</i>	8840	5223	76.7	0.6	0.5	0.8	0.9	<i>La Mbi</i>
	8838	1235	105.6	0.4	3.2	-	-	<i>La Mbi</i>
	8836	164	3.0	0.0	0.7	-	-	<i>Sibut</i>
<i>Quartzite</i>	203	1902	82.7	0.4	1.6	-	-	<i>Boali</i>
	8564	5	1.4	0.0	11.0	-	-	<i>Bossembélé</i>
	213	7	0.8	0.0	3.8	-	-	<i>Mbalki</i>
	452	20	0.4	0.0	0.7	-	-	<i>Ouango</i>
<i>Granulite</i>	230	304	38.8	0.1	4.8	-	-	<i>Sibut</i>
<i>Metabasalt</i>	8602	292	0.2	0.0	0.0	-	-	<i>Bogoin</i>
<i>Micaschist</i>	249	171	2.2	0.0	0.5	-	-	<i>Boali</i>
<i>Metasilexite</i>	217	52	1.3	0.0	0.9	-	-	<i>Kamaro</i>

<i>Cipolin</i>	8631	-1	0.4	0.0	-11.9	-	-	<i>Fatima</i>
	8610	-1	0.4	0.0	-13.0	-	-	<i>Ndjimba</i>

Supplementary Material (new)

[Click here to download Supplementary Material: SupplementaryMaterial.pdf](#)