PRELIMINARY IN PHASE AND OUT OF PHASE AMS STUDY AND PALEOMAGNETISM OF ~870 MA MAFIC DIKES IN WEST AFRICA (GHANA)

Paul Y. J. Antonio[1]*, Lenka Baratoux[2], Ricardo I. F. Da Trindade[1], Sonia Rousse[2], Mélina Macouin[2], Anne-Sophie Firmin[2], Carmen I. Martinez-Dopico[3], Arnaud Proietti [4] Ayite Anani[5], Adu Emmanuel W. K.[6], Prince Ofori Amponsah[6]

[1] Universidade de São Paulo (USP), Instituto de Astronomia, Geofísica e Ciências Atmosféricas (IAG), Rua do Matão, 1226, Cidade Universitária, 05508-090 São Paulo – Brasil.
[2] Université Paul Sabatier (UPS) - Toulouse III, Observatoire Midi-Pyrénées (OMP), Géosciences Environnement Toulouse (GET), 14 Avenue Edouard Belin 31400 Toulouse – France.
[3] INGEIS- Instituto de Geocronología y Geología Isotópica. Av. Int. Güiraldes, Ciudad Universitaria, Ciudad Autónoma de Buenos Aires – Argentina.
[4] Centre de Microcaractérisation Raimond Castaing, 3 Rue Caroline Aigle, 31400 Toulouse – France
[5] Ghana Geological Survey Authority, 6, 7th Avenue West Ridge, Box M80, Accra – Ghana
[6] University of Ghana, Department of Earth Science, P.O. Box LG 58, Legon, Accra – Ghana

*e-mail: mailto:paulantonio0931@gmail.com

ABSTRACT

Mid-Neoproterozoic is a period of transition between the supercontinent Rodinia and the amalgamation of Gondwana. An incomplete paleomagnetic database does not allow to constrain the precise paleogeography of this transition. This study concerns the West African craton, which remains the least studied craton in paleomagnetism. We propose a preliminary AMS study before showing the first paleomagnetic results obtained on the Manso dike swarms (~867 Ma). For the first time, in-phase and out-of-phase susceptibility was used to study the anisotropy fabric of dikes. Few differences were observed between classical AMS and out-of-phase AMS and require further magnetic mineralogy study to understand the implications. It was possible to isolate a characteristic direction during this pilot study on these dykes in order to obtain a new paleomagnetic pole of reference for the West African craton.

Keywords: Neoproterozoic, West Africa, Rodinia, AMS, Mafic dikes.

RESUMEN

El Neoproterozoico medio es un período de transición entre el supercontinente Rodinia y el amalgmamiento de Gondwana. Una base de datos paleomagnéticos incompleta no permite constreñir la paleogeografía precisa de esta transición. Este estudio aborda el Cratón de África Occidental que sigue siendo el cratón menos estudiado en paleomagnetismo. Proponemos un estudio preliminar de ASM antes de mostrar los primeros resultados paleomagnéticos obtenidos en los enjambres del dique de Manso (~867 Ma). Por primera vez, se utilizó la susceptibilidad en fase y desfasada para estudiar la fábrica de anisotropía de los diques. Se observaron pocas diferencias entre la ASM clásica y la ASM desfasada lo que requiere un estudio de mineralogía magnética adicional para comprender las implicancias. Fue posible aislar una dirección característica durante este estudio piloto sobre estos diques que permitió obtener un nuevo polo paleomagnético de referencia para el Cratón de África Occidental.

Palabras Claves: Neoproterozoico, África Occidental, Rodinia, ASM, Diques máficos.

1. Introduction

Mafic dike swarms represent an exceptional expression of crustal extension as feeding channels for basaltic magma allowing the transport from the mantle to the upper crust. These voluminous mantle-derived magmas were emplaced in all the cratons through Earth history (Ernst, 2014). Mafic dike swarms can represent the plumbing system of important magmatic events defined as Large Igneous Provinces (LIPs) (Coffin ; Eldholm, 1994). The plumbing system of LIPs can be composed by layered intrusions, sill provinces and giant dike swarms (Söderlund *et al.*, 2016). Mafic LIPs are characterized by typical volumes > 0.1 Mkm^3, area of extension > 0.1 Mkm^2 and emplacement by short pulses (1–5 Ma) during an time interval < 20 Ma (Bleeker, Ernst, 2006; Bryan; Ernst, 2008; Bryan, Ferrari, 2013; Coffin, Eldholm, 1994). For Precambrian mafic dikes, the thick piles of flood basalts at the surface were mainly eroded leaving the plumbing system as unique evidence of LIPs. With precise geochronology (U-Pb ages), it is possible to use the LIP barcodes between older cratons to determine the probability if these cratons were together across a span of time (Bleeker, 2003; Bleeker *et al.*, 2008; Ernst *et al.*, 2013) and the orientation of dike swarms can also be used to constrain the relative geometry of these cratons (Bleeker, Ernst, 2006). Furthermore, mafic dike swarms can be used as piercing point linked to a mantle plume with for example the giant circumferential dike swarms (Buchan, Ernst, 2019; Ernst, Buchan, 2001, 2003). Final and relevant paleogeography is obtained when the geological record (including the LIP records) is tested and in agreement with high-quality paleomagnetic data or "key poles" (Buchan, 2013; Ernst *et al.*, 2010).

New mapping of mafic dike swarms provide information about the different generation in the West African craton with 26 distinct dike swarms identified by aeromagnetic mapping according to their orientation (Jessell *et al.*, 2015). Two new Neoproterozoic dike swarms were recognized in the Leo-Man Shield (Ghana) and well-dated by U-Pb baddeleyite at 915± 7 Ma for the N070° Oda swarm, and 867± 16 Ma for the N355° Manso swarm (Figure 1) (Baratoux *et al.*, 2019). These Neoproterozoic dikes crosscut the Paleoproterozoic basement and regional tectonic structures, and are not deformed. In this work, we will present new results of AMS study for these dikes and will discuss the using and implications of in-phase versus out-of-phase susceptibility for mafic dikes.

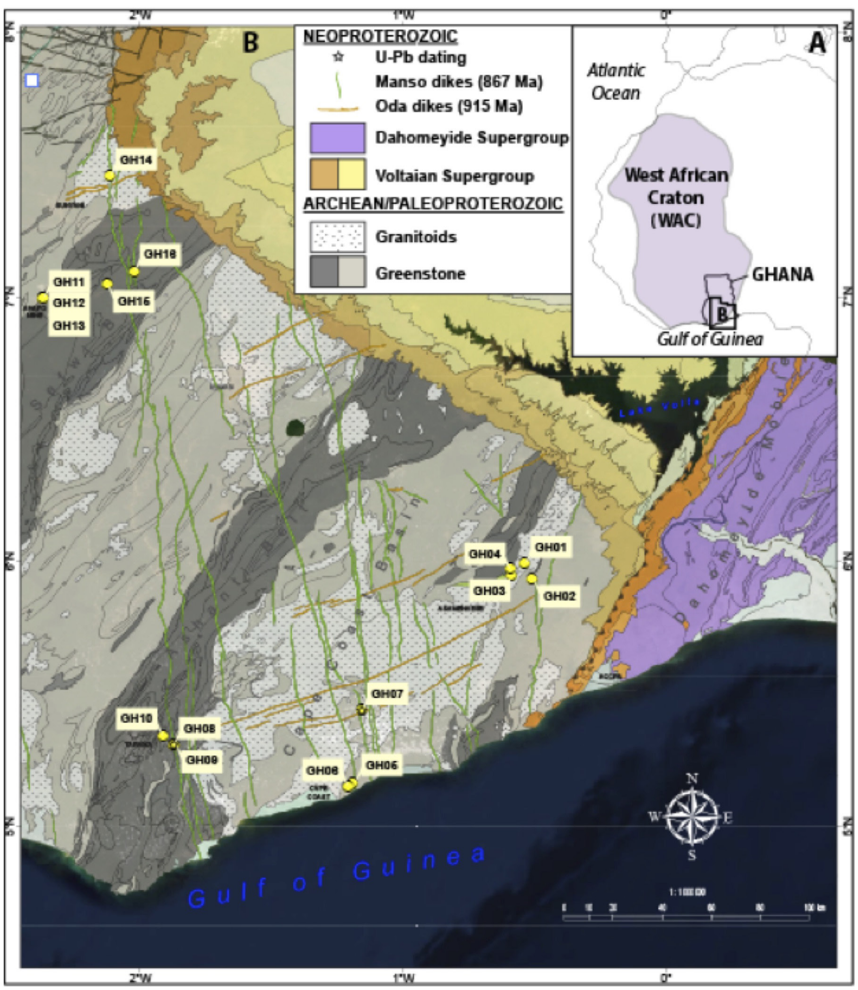

Figure 1. **A**. Localization of the study in West Africa. **B**. Geological map of the Neoproterozoic units of Ghana with the localization of sampled sites.

2. Geological setting and paleogeography

The West African Craton (WAC) is composed by two Proterozoic Shields (the Reguibat Rise and the Leo-Man Rise) stabilized at about ~2 Ga (Black *et al.*, 1979). These two Proterozoic Shields underlie Meso-Neoproterozoic Basins (Affaton *et al.*, 1991). The older sediments of Volta basin in southern (Ghana) emplaced at ~1000 Ma and detrital zircon ages between 2000–1000 Ma suggest a provenance from an adjacent continent, the Amazonian craton is suggested but without paleomagnetic constrain to support this link (Carney *et al.*, 2010; Kalsbeek *et al.*, 2008; Kalsbeek, Frei, 2010). In the mid-Neoproterozoic (~900-750 Ma), the Rodinia mobility and its breakup remains another contentious issue due to discordant paleomagnetic poles available (Li *et al.*, 2013). Rapid rotations and True Polar Wander events are suggested to explain theses discordances (Li *et al.*, 2004; Maloof *et al.*, 2006; Niu *et al.*, 2016). Thus, we need to acquire new high-quality paleomagnetic data to resolve the uncertain paleogeography of Neoproterozoic times which will be the objective of a next work.

3. Sampling and methodology

Due to the heavy vegetation cover and the presence of a thick (~30m) laterite, the outcrops of dikes in Ghana are a restraint to the rivers, presence of some blocks in forest and in the mine pits. 121 extracted oriented cylindrical cores were sampled in March 2019 using a portable gasoline powered rock drill (ASC Scientific) and eight hand-samples in the Ahafo mine pit (Newmont Company) (Figure 2-A). The number of samples by site (5-8) depended essentially on the agreement with the communities. Both solar and magnetic compasses were used for the orientation and no differences were observed after correction. The majority of dykes belong to the ~870 Ma Manso with only one Oda dike well-dated at ~915 Ma according to the geochronology and aeromagnetic data. We sampled 16 sites in a vast geographical area that goes from Accra to Sunyani in northern Ghana and via Cape Coast in southern Ghana (Figure 1). Oriented blocks have been cut in Geosciences Montpellier (France). Preparation in standard specimens (2.2 cm height) and a pilot study were carried out in the PMAG Toulouse (Geosciences Environnement Toulouse – GET, France). Both *in-phase* and *out-of-phase* magnetic susceptibility with anisotropy of magnetic susceptibility (AMS) were measured with a Kappabridge KLY5-A equipped with the 3D-Rotator (AGICO, Brno, Czech. Republic; sensitivity: 2×10^{-8} SI for field 400 A/m) (Hrouda *et al.*, 2018). Conventional stepwise Alternating Field (AF) was performed in this pilot study using a JR5-A spinner magnetometer and a LDA-3 AF demagnetizer (AGICO) in a MMLFC shielded room to eliminate the effect of magnetic field (< 200 nT). Magnetic mineralogy was investigated under optical microscopy and using a Scanning Electron Microscopy (SEM JEOL JSM 7100F TTLS LV – EDS/EBSD) of the Centre de MicroCaractérisation Raimond Castaing UMS 3623 of Toulouse.

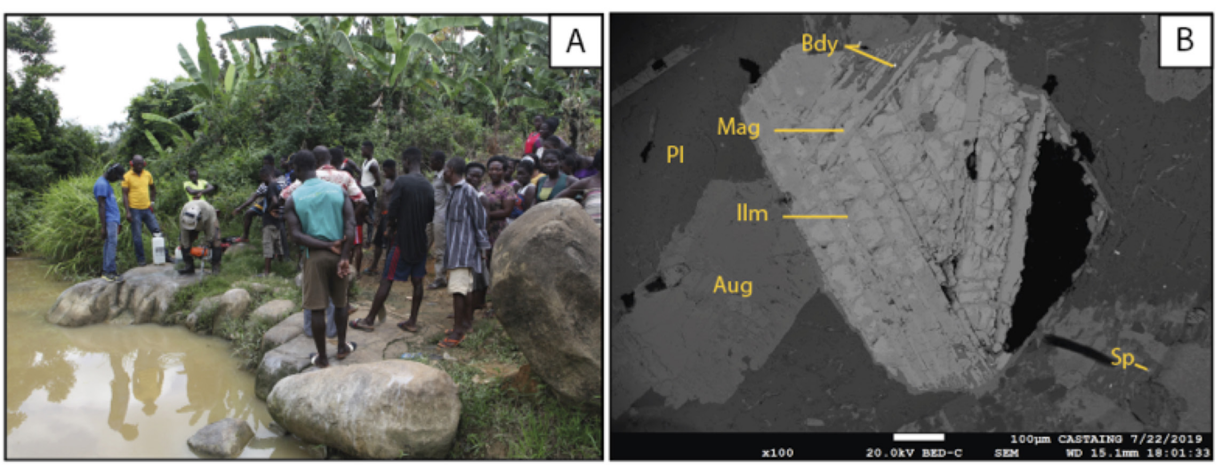

Figure 2. **A**. Sampling of a well *in situ* Manso dike (GH08). **B**. BSE micrograph of titanomagnetite (Mag) with exsolutions of ilmenite (Ilm), augite (Aug), plagioclase (Pl), spharelite (Sp), and baddeleyite (Bdy) (GH09).

4. Preliminary results

Petrology and description of samples

Manso dikes are coarse to medium-grained dolerites composed mainly of plagioclase and clinopyroxene (augite) with Fe-Ti oxides. Rare orthopyroxene and altered olivine were also observed. Most of the opaque phases show composite texture of ilmenite-magnetite grains and most probably titanomagnetite (Figure 2-B) (Haggerty, 1991). Intergrowth textures are generally related to a stable thermoremanent magnetization (TRM) (Evans ; Wayman, 1974). Baddeleyite and sulfide were also observed.

In phase and out of phase AMS results

The anisotropy of magnetic susceptibility (AMS) was measured to define the magnetic fabric of dikes. Mean magnetic susceptibility values are 46080± 11933 µSI for sites with stronger values (GH01, GH02, GH04 GH07; GH08, GH09, GH14, GH15, GH16), and 3168± 4995 µSI for sites with lower values (GH03, GH06, GH10, GH11, GH12, GH13). Magnetic susceptibility is generally correlated to the relative content of magnetic minerals in the bulk composition of the rock studied and coarse-medium grained dolerites (ex: GH16) seems to have stronger values than fine-grained dolerites (ex: GH10). The shape of the AMS ellipsoid is characterized by the degree of anisotropy P (K_1/K_3), and the shape parameter T ((2ln (K_2/K_3))/(ln (K_1/K_3))-1) where K_1, K_2 and K_3 are the principal directions (Jelinek, 1981). The anisotropy degree in the Manso dike swarms is low with values between 1.01 and 1.07 but for three sites P varies from 1.09 to 1.21 (GH03, GH06, an GH10) with a direction for K_1 around ~N75° that could be related to the direction of Oda dike swarms in the area. P values <10% is usual for igneous rocks with primary magnetic fabric (Hrouda, 1982). Preliminary AMS data could help us to differentiate the dike generations in Ghana where outcrops are limited and sparse. According to the T parameter, most of the sites have an oblate fabric (as GH08, see Figure 3-B) to triaxial. Only few sites have a prolate fabric (GH02, GH05, GH06, and GH10). The orientations of the principal AMS directions with respect to dike direction can be classified as normal, inverse, or intermediate (Raposo ; Ernesto, 1995; Rochette *et al.*, 1999). Comparing the sampled sites, it seems that inverse fabric is dominant, where the magnetic foliation (K_1-K_2) is perpendicular to the dike margins (Figure 3). Inverse magnetic fabric can be explained by the presence of single-domain titanomagnetite grains, anisotropic distribution of ferromagnetic minerals, and post-emplacement alteration (Chadima *et al.*, 2009). Measure of anisotropy of anhysteretic remanent magnetization (AMR) could help us to resolve this issue. Contrary to the in-phase susceptibility, the out-of-phase component is controlled only by ferromagnetic particles which are on the transition between SP (fully unblocked) and SD (fully blocked), the viscous phenomena (Hrouda *et al.*, 2013). The out-of-phase susceptibility is strongly grain volume dependent and we can use it in magnetic granulometry (Hrouda *et al.*, 2013) associated to standard methods. Out-of-phase magnetic susceptibility values are between -150 and 300 µSI with values of around 0 for most of specimens. A possible effect of the presence of paramagnetic and MD ferromagnetic fractions is also decreasing the phase angle of the out-of-phase component (Hrouda *et al.*, 2013). Unfortunately, no studies on volcanic rocks and dikes have been carried out until now. In many sites we don't observe differences between the ipAMS fabric and the opAMS fabric (Figure 3-A, C). Contrastingly, for some sites, we observe a clear difference between ipAMS and opAMS fabrics (Figure 3-B, D). For the GH08 site, the opAMS fabric is triaxial and was clearly oblate in ipAMS. The out-of-phase parameters permit to separate three behaviours for the specimens in the same site. A first group is with high susceptibility (10-25 µSI), a second intermediate (-10-5 µSI) and a third with lower values (< -20 µSI). Difference in degree of anisotropy can be really significant, for example, the GH08D2 specimen has a value of 4.5 whereas the mean site is 1.5 and lower for the third group. All these features will be studied in more detail using other methods used in magnetic mineralogy (hysteresis, IRM, thermomagnetic curves, comparison with paleomagnetic results and implications). Figure 3-E shows an example of AF demagnetization for the GH08 site. For this sample (GH08A1), it was possible to isolate a characteristic remanent magnetization stable between 12mT and 30 mT. Between 0 and 9 mT a component was calculated and represent the present field in Ghana. Others sites reveal a similar component with high inclination with a normal polarity (GH11, GH12, GH13), and reversed polarity (GH05, GH08, GH16). Results for the performed baked contact test will be presented at the LATINMAG with the paleomagnetic pole and its implications for the paleogeography of the Mid-Neoproterozoic.

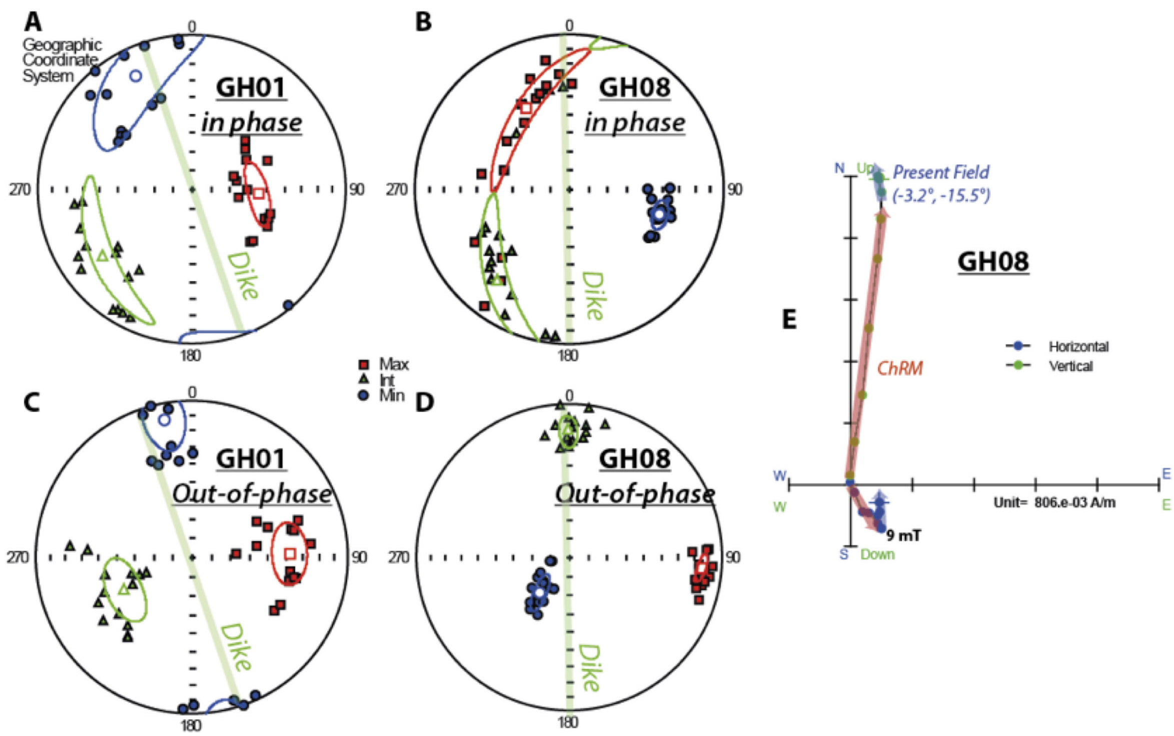

Figure 3. **A-B**. In-phase AMS for samples GH01 and GH08. **C, D**. Out-of-phase AMS for samples GH01 and GH08. **E**. Zijderveld diagram of an AF demagnetization (GH08).

5. Conclusions

We present preliminary results on the anisotropy magnetic susceptibility for the Manso dike swarms and we used for the first time the out-of-phase susceptibility to study the emplacement of dikes. Study of magnetic mineralogy will allow us to know more about the presence of MD/SD grain, as well as the possible contributions of the out-of-phase technique in AMS. AF pilot study reveal a magnetic component of high inclination for most dikes. A baked contact test supports its primary origin to obtain a new key pole for West Africa during the Neoproterozoic.

Acknowledgments

We thank FAPESP grants 2016/06114-6 for financial support (R. I. F. Trindade) and FAPESP research fellowships to Paul Y. J. Antonio (2018/23755-0 BEPE and 2017/18840-6). We thank the Geological Survey of Authority of Ghana for field-trip logistics and especially Mahu Eric Nene for his help. We thank the Newmont Company, Ltd. of Ahafo mine pit for accommodation, accessibility to the site and facilities. We thank Philippe de Parseval and Loic Drigo for help during analytical work in Toulouse and P. Camps for access to his duty standing drill press (Geosciences Montpellier). Thanks to Helen McFarlane and Quentin Masurel for the sampling preparation. This work would not have been possible without the assistance and hospitality of Ghanaian communities.

References

Affaton, P., Rahaman, M.A., Trompette, R., Sougy, J., 1991. The Dahomeyide Orogen: Tectonothermal Evolution and Relationships with the Volta Basin, In: Dallmeyer, R.D., Lécorché, J.P. (Eds.), The West African Orogens and Circum-Atlantic Correlatives. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 107-122.

Baratoux, L., Söderlund, U., Ernst, R., de Roever, E., Jessell, M., Kamo, S., Naba, S., Perrouty, S., Metelka, V., Yatte, D., 2019. New U–Pb Baddeleyite Ages of Mafic Dyke Swarms of the West African and Amazonian Cratons: Implication for Their Configuration in Supercontinents Through Time, Dyke Swarms of the World: A Modern Perspective. Springer, pp. 263-314.

Black, R., Caby, R., Moussine-Pouchkine, A., Bayer, R., Bertrand, J., Boullier, A., Fabre, J., Lesquer, A., 1979. Evidence for late Precambrian plate tectonics in West Africa. *Nature 278*, 223.

Bleeker, W., 2003. The late Archean record: a puzzle in ca. 35 pieces. *Lithos 71*, 99-134.

Bleeker, W., Ernst, R., 2006. Short-lived mantle generated magmatic events and their dyke swarms: the key unlocking Earth's paleogeographic record back to 2.6 Ga. Dyke swarms–time markers of crustal evolution, 3-26.

Bleeker, W., Hamilton, M., Söderlund, U., Ernst, R., 2008. Towards a complete magmatic event ''barcode'' for the Slave craton, I: A precise U–Pb baddeleyite age for the Hearne swarm with implications for a newly recognized Paleoproterozoic LIP across the western Canadian Shield, Annual Meeting, Abstracts, p. 23.

Bryan, S.E., Ernst, R.E., 2008. Revised definition of Large Igneous Provinces (LIPs). Earth-Science *Reviews 86*, 175-202.

Bryan, S.E., Ferrari, L., 2013. Large igneous provinces and silicic large igneous provinces: Progress in our understanding over the last 25 years. *Geological Society of America Bulletin 125*, 1053-1078.

Buchan, K.L., 2013. Key paleomagnetic poles and their use in Proterozoic continent and supercontinent reconstructions: A review. *Precambrian Research 238*, 93-110.

Buchan, K.L., Ernst, R.E., 2019. Giant circumferential dyke swarms: catalogue and characteristics, Dyke Swarms of the World: A Modern Perspective. Springer, pp. 1-44.

Carney, J.N., Jordan, C.J., Thomas, C.W., Condon, D.J., Kemp, S.J., Duodo, J.A., 2010. Lithostratigraphy, sedimentation and evolution of the Volta Basin in Ghana. *Precambrian Research 183*, 701-724.

Chadima, M., Cajz, V., Týcová, P., 2009. On the interpretation of normal and inverse magnetic fabric in dikes: Examples from the Eger Graben, NW Bohemian Massif. *Tectonophysics 466*, 47-63.

Coffin, M.F., Eldholm, O., 1994. Large igneous provinces: Crustal structure, dimensions, and external consequences. *Reviews of Geophysics 32*, 1-36.

Ernst, R., Srivastava, R., Bleeker, W., Hamilton, M., 2010. Precambrian Large Igneous Provinces (LIPs) and their dyke swarms: New insights from high-precision geochronology integrated with paleomagnetism and geochemistry. *Precambrian Research 183*, vii-xi.

Ernst, R.E., Buchan, K.L., 2001. The use of mafic dike swarms in identifying and locating mantle plumes. SPECIAL PAPERS-GEOLOGICAL SOCIETY OF AMERICA, 247-266.

Ernst, R.E., Buchan, K.L., 2003. Recognizing mantle plumes in the geological record. Annual Review of *Earth and Planetary Sciences 31*, 469-523.

Ernst, R.E., Bleeker, W., Söderlund, U., Kerr, A.C., 2013. Large Igneous Provinces and supercontinents: Toward completing the plate tectonic revolution. *Lithos 174*, 1-14.

Ernst, R.E., 2014. Large igneous provinces. Cambridge University Press, p. 304.

Evans, M.E., Wayman, M.L., 1974. An Investigation of the Role of Ultra-fine Titanomagnetite Intergrowths in Palaeomagnetism. *Geophysical Journal International 36*, 1-10.

Haggerty, S.E., 1991. Oxide textures; a mini-atlas. *Reviews in Mineralogy and Geochemistry 25*, 129-219.

Hrouda, F., 1982. Magnetic anisotropy of rocks and its application in geology and geophysics. *Geophysical Surveys 5*, 37-82.

Hrouda, F., Pokorný, J., Ježek, J., Chadima, M., 2013. Out-of-phase magnetic susceptibility of rocks and soils: a rapid tool for magnetic granulometry. *Geophysical Journal International 194*, 170-181.

Hrouda, F., Chadima, M., Ježek, J., Kadlec, J., 2018. Anisotropies of in-phase, out-of-phase, and frequency-dependent susceptibilities in three loess/palaeosol profiles in the Czech Republic; methodological implications. *Stud Geophys Geod 62*, 272-290.

Jelinek, V., 1981. Characterization of the magnetic fabric of rocks. *Tectonophysics 79*, T63-T67.

Jessell, M., Santoul, J., Baratoux, L., Youbi, N., Ernst, R.E., Metelka, V., Miller, J., Perrouty, S., 2015. An Updated Map of West African Mafic Dykes. J*ournal of African Earth Sciences 112*, 440-450.

Kalsbeek, F., Frei, D., Affaton, P., 2008. Constraints on provenance, stratigraphic correlation and structural context of the Volta basin, Ghana, from detrital zircon geochronology: An Amazonian connection? *Sedimentary Geology 212*, 86-95.

Kalsbeek, F., Frei, R., 2010. Geochemistry of Precambrian sedimentary rocks used to solve stratigraphical problems: An example from the Neoproterozoic Volta basin, Ghana. *Precambrian Research 176*, 65-76.

Li, Z.-X., Evans, D.A.D., Halverson, G.P., 2013. Neoproterozoic glaciations in a revised global palaeogeography from the breakup of Rodinia to the assembly of Gondwanaland. *Sedimentary Geology 294*, 219-232.

Li, Z.X., Evans, D.A.D., Zhang, S., 2004. A 90° spin on Rodinia: possible causal links between the Neoproterozoic supercontinent, superplume, true polar wander and low-latitude glaciation. *Earth and Planetary Science Letters 220*, 409-421.

Maloof, A.C., Halverson, G.P., Kirschvink, J.L., Schrag, D.P., Weiss, B.P., Hoffman, P.F., 2006. Combined paleomagnetic, isotopic, and stratigraphic evidence for true polar wander from the Neoproterozoic Akademikerbreen Group, Svalbard, Norway. *Geological Society of America Bulletin 118*, 1099-1124.

Niu, J., Li, Z.-X., Zhu, W., 2016. Palaeomagnetism and geochronology of mid-Neoproterozoic Yanbian dykes, South China: implications for a c. 820–800 Ma true polar wander event and the reconstruction of Rodinia. *Geological Society, London, Special Publications 424*, 191-211.

Raposo, M.I.B., Ernesto, M., 1995. Anisotropy of magnetic susceptibility in the Ponta Grossa dyke swarm (Brazil) and its relationship with magma flow direction. *Physics of the Earth and Planetary Interiors 87*, 183-196.

Rochette, P., Aubourg, C., Perrin, M., 1999. Is this magnetic fabric normal? A review and case studies in volcanic formations. *Tectonophysics 307*, 219-234.

Söderlund, U., Klausen, M.B., Ernst, R.E., Bleeker, W., 2016. New advances in using large igneous provinces (LIPs) to reconstruct ancient supercontinents. *GFF 138*, 1-5.