Paleointensity determinations from the Etendeka province, Namibia, support a low-magnetic field strength leading up to the Cretaceous normal superchron

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Abstract Paleointensity estimates provide much needed information on field generation within Earth’s core and upon the convective processes at work within the mantle. We present new paleointensity estimates from the early Cretaceous Etendeka large igneous province in Namibia (~135 Ma), which add to the sparse Southern Hemisphere data set. The Early Cretaceous marks an important change in the Earth’s magnetic field from a state of rapid polarity reversals, to one of long-term stability associated with the onset of the Cretaceous Normal Superchron at ~121 Ma. Paleointensity determinations, using the IZZI protocol, were carried out on a total of 172 specimens from 14 sites encompassing the exposed stratigraphy of the Etendeka province. Numerous checks of data reliability were considered before results were accepted, including partial thermoremanent magnetization (pTRM) checks and pTRM tail checks, hysteresis properties, thermomagnetic analyses, observations under reflected light, and changes to room-temperature susceptibility during the experiments. Following these checks, a total of 64 individual samples from five sites were considered to provide reliable paleointensity determinations. These results were combined to provide site mean data with an overall average virtual dipole moment (VDM) for the study of 2.5 ± 1.0 × 10²² Am². This value equates to approximately 30% of present Earth’s field and, when considered alongside existing studies, suggests that Earth’s field strength was low in the time leading up to the Cretaceous normal superchron.

1. Introduction

The ancient geomagnetic field intensity (paleointensity) recorded through time, provides insights into its generation within the core and the convective processes within the Earth’s mantle, which help maintain and amplify that field. Despite a wealth of efforts to determine paleointensity through geological time, the quantity of reliable data collected remains low, hampering studies of long-term field variation. The low quantity of available data is a product of two limiting factors: (1) the high failure rate of paleointensity techniques; and (2) the time consuming nature of the experiments (e.g., 30 samples take approximately 3 weeks to process with failure rates of the order of ~0.5%). A strong hemisphere bias also exists within the published data set, with the majority of paleointensity determinations sourced from the Northern Hemisphere [Tanaka et al., 1995].

The early Cretaceous is a time of particular interest for the Earth’s magnetic field, because it is thought that the field was weaker for a period of time, termed the “Mesozoic dipole low” (MDL) [e.g., Prévat et al., 1990], possibly linked to Earth’s field changing from a state defined by relatively rapid reversals, to a state defined instead by the approximately 40 million year stability of the Cretaceous normal superchron (CNS) between 120.6 and 83 Ma (Chron C34N) [Gee and Kent, 2007]. Estimates of the time scale of the transition from rapid reversals to a superchron vary from only a few million years to much longer timeframes [e.g., Hulot and Gallot, 2003; McFadden and Merrill, 2000]. Changes in the reversal frequency have also been proposed to be mirrored by changes in field intensity, with periods of rapid reversals being associated with weaker dipole fields [e.g., Cox, 1968; Merrill et al., 1998]. This relationship was predicted in the model of Larson and Olson [1991], which linked processes at the core-mantle boundary to reversal frequency. These proposed variations have been argued to be associated with changes in mantle heat flow, where periods of high-mantle heat flow lead to an agitated, more active, mantle, and a hyperactive geodynamo with frequent reversals.
but low-field strengths [Biggin et al., 2012]. If this model is correct, the CNS should display high-field strengths, while the periods of rapid reversals should display lower-field strengths.

Studies of the early Cretaceous, before the onset of the CNS, do not provide a consensus as to the overall field strength at this time [e.g., Goguitchaichvili et al., 2002a, 2002b; Kosterov et al., 1998; Perrin and Shcherbakov, 1997]. Pick and Tauxe [1993] suggested the low-field strengths of the MDL persisted into the CNS, but the more recent studies of Tarduno et al. [2001, 2002] and Tauxe and Staudigel [2004] present high field values during the CNS. Investigations of the time immediately preceding the CNS [e.g., Zhu et al., 2003] found low-field strengths during the period of rapid reversals. The limited availability of data, however, hampers our ability to test hypotheses regarding variations in the strength of the Earth’s magnetic field through time. Further studies are therefore needed to better define and understand the time-varying properties of Earth’s magnetic field.

The Paraná-Etendeka large igneous province represents a huge outpouring of volcanics at \( \approx 135 \) Ma based upon the absolute ages of Renne et al. [1996], obtained from the middle of the Etendeka stratigraphy. The stable magnetic remanence of these lavas and the timing of their formation provide a possible window for a detailed study of Earth’s paleofield strength over a confined time period within a period of high-frequency reversals in the early Cretaceous [e.g., Ernesto et al., 1990; Goguitchaichvili et al., 2002b; Renne et al., 1996]. A number of paleointensity studies of this age concentrate on the South American (Paraná) portion of the province [e.g., Goguitchaichvili et al., 2002b; Goguitchaichvili et al., 2008; Kosterov et al., 1998; Mena et al., 2011] and their earlier associated intrusive volcanics [e.g., Ruiz et al., 2009], but no paleointensity studies have been published from the African (Etendeka) portion of the province. Given the high number of individual flows within the province, multiple estimations of paleointensity may be possible, allowing investigation of field strength variability, and the determination of reliable data points for the global latitude-independent virtual dipole moment (VDM) database from the Southern Hemisphere. In this study, we present new paleointensity values from the Etendeka portion of the Paraná-Etendeka large igneous province spanning the duration of volcanic activity within the province.

2. Ages and Sampling

The Paraná-Etendeka large igneous province was formed prior to the opening of the South Atlantic in the Early Cretaceous, and it is now exposed in South America and Africa [Peate, 1997]. The province consists of a series of predominantly mafic lavas punctuated by some large volume silicic units with these units recording a number of reversals of Earth’s magnetic field [Dodd et al., 2015; Marsh et al., 2001; Milner et al., 1992; Renne et al., 1996]. We have recently produced a magnetostatigraphy for the bulk of the Etendeka province [Dodd et al., 2015] based on samples from 70 sites that produced high-quality directional data. We used this information in our selection of 14 flows for paleointensity determinations. The flows were chosen based on their: (1) stratigraphic position within the province in order to span the complete stratigraphy; (2) varying polarities, with samples from sites recording both normal and reverse field states; (3) clean demagnetization data showing single component characteristic remanence directions (ChRM) following removal of any low-temperature/field viscous overprints (Figure 1). Standard 25.4 mm diameter cores were collected using a portable petrol-powered rock drill and were oriented using both magnetic and sun compasses. A total of 249 individually oriented drill core samples were collected from the 14 chosen flows, yielding 338 specimens when cut. Of these, 172 specimens were chosen for paleointensity analysis.

3. Rock Magnetic Properties

Rock magnetic properties are important for determining whether the results of any paleointensity study provide reliable paleointensity determinations, by identifying the composition and domain state of the magnetic minerals present, and the behavior of those minerals on heating. In this study, the rock magnetic properties of rock chips from each of the 14 flows were investigated while simultaneously conducting pilot paleointensity experiments containing samples from each flow. This was done because samples displaying ideal rock magnetic characteristics can still fail to provide reliable paleointensity data.

3.1. Methods

3.1.1. Hysteresis

Room-temperature hysteresis measurements, with an applied field of 0.5 T and step size of 3 mT, were obtained using a Princeton Measurements vibrating sample magnetometer (VSM) in the paleomagnetic
laboratory at Imperial College London. When combined with backfield curves, the following parameters were extracted: the coercive force ($H_c$), the coercivity of remanence ($H_{cr}$), the saturation magnetization ($M_s$), and the remanent saturation ($M_{rs}$).

### 3.1.2. Thermomagnetic Analyses

Thermomagnetic curves were measured to characterize sample behavior, with the reversibility of the thermomagnetic ($M_s$-$T$) curves being used to monitor for possible alteration of the samples on heating. Measurements were obtained using a furnace attachment for the Princeton Measurements vibrating sample magnetometer (VSM) at Imperial College London. Each sample was submitted to heating and cooling in a helium environment to minimize alteration, with an applied field of 300 mT, a maximum temperature of 650–700°C, and temperature step size of 1°C.

### 3.1.3. Reflected Light Spectroscopy

A specimen from each flow was diamond polished and examined under reflected light, both pre and post-heating to 650°C, in order to look for any indication of alteration and oxidation of the magnetic minerals.
3.2. Results

3.2.1. Hysteresis

The ratios of the extracted parameters ($M_r/M_s$ versus $H_c/H_e$) are plotted on a “Day plot” [Day et al., 1977] (Figure 2). Results reveal that the majority of recorded remanence was held by grains falling within the pseudosingle domain (PSD) region, as is common for natural volcanic samples (Figure 2). Samples from site Cm15, however, fall within the single domain (SD) region, considered “ideal” for paleointensity determination while those from site Cm11 fall within the multidomain (MD) region. The process by which remanent magnetization is recorded in MD sized grains is not well understood and Cm11 reveals a remanence unlikely to produce reliable paleointensity determinations.

3.2.2. Thermomagnetic Analyses

Curie temperatures were estimated from thermomagnetic curves using the second-derivative method [Tauxe, 1998] with a running average of 5 points and with errors on the Curie temperatures estimated to be ±10°C. Four types of behavior on heating/cooling were identified in the thermomagnetic curves, classified as either type a, b, c, or d (see example $M_s$-T curves shown in Figure 3). The majority of flows displayed approximately reversible thermomagnetic curves with the only suggestion of alteration being a slight decrease in the susceptibility in the cooling curve relative to that recorded in the heating curves, but specimens recorded little further change (Type a and b, Figures 3a and 3b). Those sites with samples unaffected by heating and thus producing reversible thermomagnetic curves are most likely to provide successful paleointensity results, while those indicating substantial mineral alteration and irreversible curves would be unlikely to provide robust paleointensity data due to the likely alteration of primary remanence through mineral alteration. Type c behavior, e.g., Cm1 and Cm7 (Figure 3c), hinted at minor alteration in the heating curve, however, the scale of this is, alone, not sufficient to exclude these sites from further investigation. Figure 3d presents an irreversible curve classified as type d behavior (sites Cm3, Cm17); these sites are those most likely to produce unreliable paleointensity results through alteration of the magnetic minerals on heating.

Curie temperature analysis revealed 10/14 sites with Curie temperatures above 569°C but ≤ 580°C (when the ±10°C error is considered), suggesting titanomagnetite is the main remanence carrier for these sites.
with varying but minimal proportions of Ti$^{4+}$ substitution ($x$)(Fe$_{3-x}$Ti$_x$O$_4$). Sites Cm2 and Cm17 showed considerably higher Curie temperatures, exceeding 620°C, indicating the presence of high proportions of haematite or partially oxidized magnetite. Samples from sites Cm7 and Cm16 both showed Curie temperatures of 600°C with samples from Cm7 indicating minor alteration on heating likely to be representative of the inversion of (titano)maghemitite to (titano)hematite, commonly found in surface-weathered rocks (references as in Dunlop and Ozdemir [1997]). The 10 sites with Curie temperatures suggestive of a magnetic mineralogy dominated by low-Ti titanomagnetites are the most likely to provide reliable data with those dominated by hematite unlikely to yield any results.

3.2.3. Reflected light Spectroscopy

Observations under reflected light revealed samples free from alteration, samples showing alteration on heating, and samples showing alteration both pre and postheating. The samples from sites Cm2 and Cm17 revealed heavily altered and oxidized magnetic minerals in both pre and postheating images, mirroring the results of the thermomagnetic analyses (Figure 4a). Samples from sites Cm3, Cm7, Cm10, and Cm11 showed possible exsolution structures or revealed slight mottling possibly indicative of higher titanium contents, which may promote alteration during heating (Figure 4bi). The remaining flows, prior to heating, revealed no clear evidence of exsolution or alteration, with cruciform textures a common feature indicating rapid cooling (Figure 4di) [Haggerty, 1981].

Samples from sites Cm3, Cm6, Cm7, Cm10, Cm11, and Cm16 showed signs of heating-induced alteration of the magnetic mineralogy subsequent to the paleointensity experiments. Those from sites Cm6, Cm7, Cm10, and Cm11 showed the heaviest alteration with an irregular trellis lamellae texture, the common feature.
indicative of high-temperature oxidation (Figure 4cii) [Haggerty, 1981]. Samples from Cm3 and Cm16 showed more minor alteration (Figure 4bi). Samples from sites Cm1, Cm4, Cm5, Cm12, Cm15, and Cm18 showed little or no evidence of alteration (Figure 4dii). While observable postheating alteration such as this might suggest that these flow units are not capable of retaining a primary magnetization and are therefore unreliable recorders it should be also be noted that: (1) surface oxidation (given the abundance of available oxygen) may be more prolific than alteration within a specimen; (2) any single sample may not be representative of the whole flow; and (3) imaged grains are amongst the largest magnetic minerals within a sample rather than being the smaller single domain grains thought to carry the magnetic remanence. Evidence of such surface oxidation was found for sites Cm6 and Cm7, which were among samples trimmed and repolished postheating and found to be unaltered beneath the surface (Figure 4ciii). Major alteration also leads to failure to produce successful/reliable paleointensity estimates and should therefore also be identified in Thellier experiments. We, therefore, used the reflected light observations in conjunction with other rock magnetic properties, rather than being used as a sole indicator of potential failure of a paleointensity experiment.

4. Paleointensity

4.1. Methods

Both the pilot and final paleointensity runs followed the IZZI (in-field, zero-field, zero-field, in-field) protocol [e.g., Tauxe and Staudigel, 2004; Yu and Tauxe, 2005; Yu et al., 2004], including partial thermoremanent magnetization (pTRM) checks for identifying alteration [e.g., Prévat et al., 1985], and pTRM tail checks for detecting multidomain grains [e.g., Riisager and Riisager, 2001]. A laboratory field of 30 µT was applied during in-field steps, chosen as a best estimate of the conditions at the time of acquisition based on the paleointensity values obtained in the study of Goguitchaichvilli et al. [2008] from the Paraná portion of province. A total of 21 temperature steps from 100°C up to 650°C were used for the pilot sample runs with initial steps of 50°C, reducing to 25°C,
20°C, and 10°C in the region of bulk demagnetization. Both pTRM and pTRM tail checks (totaling six and five, respectively), were concentrated at the higher temperature steps to detect mineral alteration in the regions likely to be used for paleointensity determination. In addition to the pTRM checks used to identify alteration, the room-temperature susceptibility of individual samples was measured between heating steps using a Bartington susceptibility meter. This provides an additional measure of any alteration resulting from the heating process.

### 4.2. Results

Data, from pilot and final runs, are reported on Arai-Nagata plots and analyzed in ThellierTool [Leonhardt et al., 2004] using the modified criteria of Paterson et al. [2014] (see supporting information Table S1 for the full modified A and B class criteria), and individual sample results are presented in supporting information Table S2. Examples of both accepted and rejected Arai plots, demagnetization curves, and Zijderveld plots are shown in Figure 5. Paleointensity determinations were only accepted (at “A” class) if they met the following requirements [Paterson et al., 2014]: (1) estimates were obtained from at least five NRM-TRM points, which correspond to a total NRM fraction exceeding 35%; (2) estimates had corresponding quality factors exceeding 5; (3) specimens showed positive pTRM checks with maximum absolute differences <7; (4) specimens showed positive pTRM tail checks with maximum absolute differences under <10; and (5) estimates were obtained from high-temperature portions of the NRM considered more likely to represent primary remanence rather than later viscous overprints (supporting information Table S1).

Following the results of the rock magnetic analyses, and after analysis of the pilot paleointensity experiments, the samples included within the final paleointensity experiments included only those from sites that had resulted in useable paleointensity estimates and rock magnetic data that were consistent with the samples carrying a primary magnetization (see Table 1). Ideal sites/flows would therefore fall within either the SD or PSD regions of the Day Plot, produce reversible thermomagnetic curves and show no clear indication of alteration, exsolution, or alteration under reflected light. Sites Cm2, Cm3, Cm11, and Cm17 showed multiple indications of mineral alteration during heating suggesting these flows to be poor recorders of magnetic remanence.

Including cores measured in the pilot runs, a total of 172 cores were subjected to paleointensity experiments, yielding 103 individual paleointensity estimates following the selection criteria of Paterson et al. [2014]. Twenty of these samples were from sites Cm2, 3, 11, and 17, which exhibited multiple indications of alteration and, indeed, only eight of these yielded paleointensity estimates, with low individual site success rates (down to 0%) and poor correspondence between samples from the same site. Paleointensity data from these sites were considered unreliable, and samples from these flows were omitted from later paleointensity experiments. Following the analyses of the pilot paleointensity runs, the steps used in the later paleointensity runs were also adjusted so that the majority of steps were concentrated in the region of bulk demagnetization, i.e., 21 temperature steps were instead spread between 150°C and 650°C, with an initial step size of 100°C fining to 50°C, 25°C and 10°C in the region of bulk demagnetization and including six pTRM and six pTRM tail checks.

Post removal of sites Cm2, Cm3, Cm11, and Cm17, considered unreliable, the remaining 10 sites and 152 specimens were found to yield 95 paleointensity estimates, 57 of A grade and 38 of B grade (supporting information Table S2). The NRM fraction used for paleointensity determination ranges from 0.4 to 1 and the quality factor varies from 1.5 to 43 with 95% of specimens having quality factors exceeding 5, and 57% exceeding 10. We regard these as being data of good technical quality. The arithmetic mean paleointensities per flow were calculated and are also reported as latitude-independent virtual dipole moments (VDMs) for comparison with global values (Table 2 and supporting information Table S2). The mean flow values obtained ranged from 3.9 ± 0.6 µT (Cm10) to 19.9 ± 5.0 µT (Cm12), with corresponding VDMs ranging from 0.9 ± 0.2 to 3.7 ± 0.9 (×10²² Am²).

### 5. Discussion

An increasing number of studies are also assessing the internal consistency of data for within-flow variation, alongside using existing rock magnetic property checks. Such studies have allowed varying degrees of distribution about the mean: Selkin and Tauxe [2000] use 25%, while Biggin and Thomas [2003] use 10%.
Figure 5. Example (i) Arai, (ii) demagnetization, and (iii) Zijderveld plots generated from the paleointensity data with pTRM checks represented as triangles on Arai plots and in the Zijderveld plots, filled symbols represent declination and hollow inclination. Successful specimens from sites (ai–aiii) Cm1, (bi–biii) Cm6, and (ci–ciii) Cm16 are represented, while di–diii represent data from site Cm4, which passed tests of statistical reliability but were later discarded due to questions regarding reliability. (ei–eiii) Numerous specimens from Cm10 failed to provide useable data and an example of a failed specimen are shown.
Table 1. Selection Criteria for Paleointensity Sites, Including the Rock Magnetic Properties From Hysteresis and Backfield Remanence Curves Alongside Subsequent Domain State Classifications (Figure 2)*

| Flow Unit (Sample Represented in Cols 2, 3, 4, 5, and 6) | Thermomagnetic Behaviour (See Figure 3) | Curie Temperature (±10°C) | Reflected Light Microscopy (* = Minor Alteration) | Pilot Paleointensity Yields Values | Yes/No Based on Rock Magnetic and Pilot Susceptibility During Paleointensity Determination | Average % Change in Room-Temperature Susceptibility |
|-----------------------------------------------------------|-----------------------------------------|--------------------------|--------------------------------------------------|---------------------------------|---------------------------------------------|-----------------------------------------------|
| CM1(n)                                                    | PSD                                      | c                        | 570                                              | Yes                             | Yes                                         | 5.3                                           |
| CM2(a)                                                    | PSD                                      | a                        | 649                                              | Alteration                      | No                                          |                                               |
| CM3(h)                                                    | PSD                                      | d                        | 589                                              | *                               | Yes                                         |                                               |
| CM4(e)                                                    | PSD                                      | a/b                      | 579                                              | *                               | Yes                                         |                                               |
| CM5(m)                                                    | PSD                                      | a                        | 590                                              | Yes                             | Yes                                         | 33.8                                          |
| CM6(i)                                                    | PSD                                      | a                        | 571                                              | Alteration                      | Yes                                         |                                               |
| CM7(i)                                                    | PSD                                      | c                        | 600                                              | Alteration                      | Yes                                         |                                               |
| CM10(h)                                                   | PSD                                      | b                        | 579                                              | Alteration                      | Yes                                         |                                               |
| CM11(e)                                                   | MD                                       | a                        | 580                                              | Alteration                      | Yes                                         |                                               |
| CM12(w)                                                   | PSD                                      | a                        | 590                                              | Yes                             | Yes                                         | 0.7                                           |
| CM15(q)                                                   | PSD                                      | b                        | 570                                              | Alteration                      | Yes                                         |                                               |
| CM16(f)                                                   | PSD                                      | a                        | 600                                              | *                               | Yes                                         | 13.5                                          |
| CM17(i)                                                   | PSD                                      | d                        | 629                                              | Alteration                      | No                                          |                                               |
| CM18(g)                                                   | PSD                                      | b                        | 569                                              | Yes                             | Yes                                         | 6.0                                           |

*Curie temperatures, determined using thermomagnetic curves and the second-derivative method of Tauxe [1998] with running average of 5 and errors estimated to be ±10°C, are presented and the reversibility classified (e.g., Figure 3). Results of reflected light microscopy revealed are presented, i.e., whether alteration is noticed alongside whether the pilot paleointensity runs provided paleointensity estimations accepted using the modified criteria of Paterson et al. [2014]. Column nine summarizes the results of these findings stating whether, based upon the rock magnetic and pilot paleointensity runs, each flow should be further considered. Column 10, calculated following paleointensity measurements, represents the change in room-temperature susceptibility.

removing flows that fail to show internal consistency. Doing this, however, results in a bias of results toward higher average fields because their larger magnitudes allow a greater range of acceptable values than flows with lower average fields; a mean field of 50 μT with an allowed internal variation of 10% would allow a range of 45–55 μT (10 μT) whereas a mean field of 20 μT would allow only 18–22 μT (4 μT). Given the consistently low paleointensity values obtained in this study, we use the within-site reliability check as a reason for rejection of a site only where there is further cause for reevaluation of the results from a particular flow.

5.1. Assessing Reliability

Following site-level analyses, the results presented in supporting information Table S2 are further assessed for reliability. The focus of this assessment is on those sites where there was indication of alteration during rock magnetic analyses, while also considering the results of the pre and post heating room-temperature susceptibility measurements. Site average gains/losses in room-temperature susceptibility, measured between the initial and last heating steps, were calculated (Table 1). Sites showing variations in susceptibility in excess of 20% suggesting major alteration and changes to the magnetic mineralogy occurred during the heating and measurement process. As a consequence, these sites were considered unlikely to record a reliable paleointensity. These sites are therefore not discussed further. Sites Cm16 and Cm7 show

Table 2. Site Mean Virtual Dipole Moments Obtained for All Sites Excluding Cm2, Cm3, Cm11, and Cm17†

| Flow Unit | Number Measured | Number of Results | Average Flow VDM (10²² Am²) |
|-----------|-----------------|-------------------|-------------------------------|
| Cm1       | 23              | 16                | 3.3 ± 0.2                     |
| Cm4       | 12              | 6                 | 2.0 ± 0.6                     |
| Cm5       | 6               | 5                 | 1.8 ± 0.3                     |
| Cm6       | 18              | 11                | 2.2 ± 0.4                     |
| Cm7       | 17              | 11                | 2.0 ± 0.6                     |
| Cm10      | 14              | 4                 | 0.9 ± 0.2                     |
| Cm12      | 18              | 14                | 3.7 ± 0.9                     |
| Cm15      | 9               | 6                 | 0.7 ± 0.1                     |
| Cm16      | 16              | 10                | 1.9 ± 0.4                     |
| Cm18      | 19              | 12                | 1.1 ± 0.1                     |

†Those sites in bold were used for calculation of the final mean virtual dipole moment (VDM) following all assessments of reliability (Table 1). The averages presented in this table are based upon the individual sample data presented in supporting information Table S2.
variations in susceptibility of between 10% and 20%. Cm16 not only showed alteration of the surface under reflected light but also of similar alteration at depth, accompanied by a high Curie temperature. Results from this site were subsequently omitted from the overall site mean; however, we note this may be an overly conservative approach as the internal consistency of the data suggested good quality. Cm7 also displayed surface alteration of its mineral constituents when examined under reflected light, however, this alteration was not observed below the surface and the site showed high success rates (>60%) with the data obtained also being of high quality. We also consider internal variation using a fixed range allowance of $6\%$ from the mean, based on a high field value of 50 $\mu$T and an allowed variation of 10%. Data from site Cm7 revealed one outlying specimen which provided a value falling $<1\mu$T under the allowed minimum; however, this sample indicated data of similar quality and falls easily within the more lenient allowance of Selkin and Tauxe [2000]. Given the quality, consistency and other rock magnetic properties of this site, data from Cm7 were considered to provide reliable data.

5.2. Paleointensity Through Time

Following the reliability criteria outlined above, we consider data from 5 sites as being accurate representations of the strength of the magnetic field in the early Cretaceous (Cm1, Cm6, Cm7, Cm12, and Cm18; Table 2). The relative values obtained for the flows show no clear temporal trend through the province to either

Figure 6. (a) Calculated site mean VDM values plotted against their stratigraphic positions illustrating the time-varying changes of field intensity with accepted values (i.e., those used in calculating the mean) in black and those considered unreliable in gray. The dashed line represents the unconformity. (b) The mean VDM from this study (represented by a hollow symbol) is presented alongside other estimates of similar age. The mean VDMs (black filled symbol) and VADMs (gray filled symbols) from the following studies: Goguitchaichvili et al. [2002a, 2008], Kosterov et al. [1998], Mena et al. [2011], Pick and Tauxe [1993], Ruiz et al. [2006, 2008], Selkin and Tauxe [1997], Shcherbakova et al. [2011], Zhu et al. [2001, 2003, 2004], and those references within Tauxe [2006] are plotted as circles (mean of $<5$ individual results) or squares (mean of $>5$ individual results) for comparison (associated standard deviations were used as error bars). Present Earth’s field (PEF) is indicated by a dashed line. (c) The approximate distribution of the individual flow VDMs based upon the relative position of these sites within the Etendeka stratigraphy using the associated magnetostratigraphy of Dodd et al. [2015] as a timeframe.
weaker or stronger paleofields, although no reliable values were obtained for the central portion of the stratigraphy (Figure 6). A significant jump in intensity can be noticed between Cm12 and Cm18 in the lowermost part of sampled stratigraphy with only a small stratigraphic separation. This suggests that field strength variability may have been high during this period, despite the absolute intensities gained in this study showing values consistently lower than present Earth’s field (PEF) (Figure 6). The five accepted units from the 14 sampled flows provide a mean VDM of $2.5 \pm 1.0 \times 10^{22}$ Am$^2$, which equates to only $\approx 30\%$ of PEF. Including the omitted flows (Cm4, Cm5, Cm10, Cm15, and Cm16) alters the mean very little, giving instead a value of $2.0 \pm 1.0 \times 10^{22}$ Am$^2$. This may suggest that stringent criteria and numerous checks may result in the exclusion of what is actually reliable data.

5.3. Comparison With Literature

The PINT and MaGIC databases [Biggin et al., 2009, 2010; Tauxe and Yamazaki, 2007] were used to collate data both from the Paraná volcanics in South America and from studies from further afield of similar age (i.e., within the interval 120 to 135 Ma), and which were obtained using the widely accepted Thellier-based technique including pTRM checks. These previous studies, when compared and combined with the mean value obtained in this study, support a low-field strength prior to the onset of the CNS (Figure 6b) [Goguitchaichvili et al., 2002b, 2008; Kosterov et al., 1998; Mena et al., 2011; Pick and Tauxe, 1993; Rüsager et al., 2003; Ruiz et al., 2005, 2009; Sakai et al., 1997; Scherbakova et al., 2011; Zhu et al., 2001, 2003, 2004] and those references within Tauxe [2006] from pre and post-CNS onset are presented. Mean VDMs (solid symbols) and VADMs (hollow symbols) based on <5 estimates are represented by squares, while mean values based on \(\geq 5\) are represented by circles. The gray bar indicates the area where the majority of the mean values fall, both before and after CNS onset. No jump or obvious variation in field strength can be noted across this transition in the state of Earth’s magnetic field.

Figure 7. Here data from the studies of Goguitchaichvili et al. [2002b, 2008], Kosterov et al. [1998], Mena et al. [2011], Pick and Tauxe [1993], Rüsager et al. [2003], Ruiz et al. [2005, 2009], Sakai et al. [1997], Scherbakova et al. [2011], Zhu et al. [2001, 2003, 2004], and those references within Tauxe [2006] from pre and post-CNS onset are presented. Mean VDMs (solid symbols) and VADMs (hollow symbols) based on <5 estimates are represented by squares, while mean values based on >5 are represented by circles. The gray bar indicates the area where the majority of the mean values fall, both before and after CNS onset. No jump or obvious variation in field strength can be noted across this transition in the state of Earth’s magnetic field.

weak and strong, although no reliable values were obtained for the central portion of the stratigraphy (Figure 6). A significant jump in intensity can be noticed between Cm12 and Cm18 in the lowermost part of sampled stratigraphy with only a small stratigraphic separation. This suggests that field strength variability may have been high during this period, despite the absolute intensities gained in this study showing values consistently lower than present Earth’s field (PEF) (Figure 6). The five accepted units from the 14 sampled flows provide a mean VDM of $2.5 \pm 1.0 \times 10^{22}$ Am$^2$, which equates to only $\approx 30\%$ of PEF. Including the omitted flows (Cm4, Cm5, Cm10, Cm15, and Cm16) alters the mean very little, giving instead a value of $2.0 \pm 1.0 \times 10^{22}$ Am$^2$. This may suggest that stringent criteria and numerous checks may result in the exclusion of what is actually reliable data.

5.3. Comparison With Literature

The PINT and MaGIC databases [Biggin et al., 2009, 2010; Tauxe and Yamazaki, 2007] were used to collate data both from the Paraná volcanics in South America and from studies from further afield of similar age (i.e., within the interval 120 to 135 Ma), and which were obtained using the widely accepted Thellier-based technique including pTRM checks. These previous studies, when compared and combined with the mean value obtained in this study, support a low-field strength prior to the onset of the CNS (Figure 6b) [Goguitchaichvili et al., 2002b, 2008; Kosterov et al., 1998; Mena et al., 2011; Pick and Tauxe, 1993; Ruiz et al., 2005, 2009; Sakai et al., 1997; Scherbakova et al., 2011; Zhu et al., 2001, 2003, 2004] and those references within Tauxe [2006]. Given that the time preceding the CNS is also a time of frequent magnetic reversals, the high concentration of studies producing paleointensities dominated by values of low magnitude would seem to support a link between high reversal rates and lower-field strengths. The onset of the CNS at 120.6 Ma [Gee and Kent, 2007] occurs shortly after Paraná–Etendeka volcanism, and low values seem consistent up until the onset of the superchron. If magnetic field strength does follow a change between a turbulent and hyperactive geodynamo state and a, subsequent, stable state, low values so close to the CNS would suggest this transition occurs rapidly. However, for a rapid transition, paleointensities obtained from the early CNS would also need to rapidly indicate a strengthened field. Evidence of such a rapid state change would thus be needed within studies of rocks in the period marking the initial onset period of the CNS (approximately 120–100 Ma). The PINT database [Biggin et al., 2009, 2010] was again used to collate values obtained across this time [Pick and Tauxe, 1993; Rüsager et al., 2003; Ruiz et al., 2005; Sakai et al., 1997; Scherbakova et al., 2011; Zhu et al., 2001, 2003, 2004] (those within Tauxe [2006]). When paleointensity values from pre and post-CNS onset are compared no indication of a jump in field strength is observed (Figure 7). This may suggest that field strength is not closely linked to reversal frequency, or that despite the change to a stable state, field strengths do not rapidly recover but increase more slowly. Thus, the field may not have reached the higher values obtained by, for example, Tauxe and Staudigel [2004] until later in the CNS rather than at or during the initial onset of stability. These observations clearly indicate the need for further studies of field strength, specifically within the early/central portion of the CNS in order to establish how, or indeed whether, field strength was built up or varied during this long normal polarity event.
Long-term studies of field variability would therefore benefit greatly from further studies of intervals where similar transitions, i.e., between high-frequency reversals and subsequent long periods of stability, can be seen, in order to establish if any correlations can be made between similar transitions but of varying age.

6. Conclusions

New, robust, paleointensity values with a mean VDM of 2.5 ± 1.0 × 10⁻²² Am² support low field intensities prior to the CNS, with evidence of low values persisting right up until the onset of this superchron. These values also add crucial data to the limited Southern Hemisphere database, although more globally distributed paleointensity determinations are clearly required to fully characterize the variation in the Earth’s magnetic field at this time. Our data, when combined with other published data, suggest a change from low to high-field strength across the transition into the CNS. However, we must await further paleointensity determinations from the oldest part of the CNS before we can assess whether the change from a low field intensity to a high field intensity is a rapid, or more slowly, process.

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