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Estimating emplacement rates for seaward-dipping reflectors associated with the U.S. East Coast Magnetic Anomaly

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SUMMARY

Along the eastern margin of North America, packages of volcanic seaward dipping reflectors (SDRs) are found proximal to a wide, positive, high amplitude magnetic anomaly, the East Coast Magnetic Anomaly (ECMA) that parallels much of the passive margin. The age and emplacement rates of the SDRs are largely unknown, but the packages have previously been included in volumetric estimates of the rapidly emplaced Central Atlantic Magmatic Province (CAMP). Here we compile the magnetic properties of SDR basalts and forward model the total-field magnetic anomaly that would be produced by SDR packages emplaced at various extension rates. We find that in order to match the wide, positive, and high amplitude character of the ECMA, the SDRs must either: preserve only a single magnetic chron and have been emplaced at unreasonably high full rates of extension (≥200 mm yr^{-1}), or have been emplaced at extension rates low enough (≤20 mm yr^{-1}) to allow for an induced magnetic anomaly to dominate the overall magnetic anomaly signal. An onshore drill site reveals basalt flows with both normal and reversed remanent magnetic polarity. This suggests that the ECMA SDRs were emplaced at rates of extension of around 20 mm yr^{-1} or less. Thus, we support suggestions that the ECMA is best interpreted as an induced anomaly arising from a susceptibility contrast between continental crust and magmatic SDR material. Based on the width of the SDR domain and extension rate estimates for the early Central Atlantic, we estimate the emplacement of the SDR packages took at least 6 Myr and may have taken as long as 31 Myr. This result suggests that either the current 600 kyr estimated duration of CAMP should be increased, or the offshore SDR material should be excluded from estimates of the igneous province volume. Finally, if packages of SDRs at other volcanic margins were emplaced at similar extension rates to those observed near the ECMA, then we expect that the magnetic anomaly from the packages may be similarly dominated by an induced magnetic anomaly signal. Because induced magnetic anomalies are almost exclusively positive for earth materials, this may explain the lack of wide, high amplitude, negative magnetic anomalies at volcanic passive margins where SDRs are observed.

Key words: Atlantic Ocean; North America; Magnetic anomalies: modelling and interpretation; Marine magnetic anomalies and palaeomagnetics; Continental margins: divergent; Large igneous provinces.

INTRODUCTION

The rifting of North America and West Africa began at ∼230 Ma with the formation of extensive sedimentary basin systems (Olsen 1997; Withjack *et al.* 2012). Following the onset of extension, a large igneous province, the Central Atlantic Magmatic Province (CAMP), was emplaced within the rift (May 1971; White & McKenzie 1989; Holbrook & Kelemen 1993; Wilson 1997; Marzoli *et al.* 1999; McHone 2003). Geochronologic dating of onshore CAMP basalts reveal rapid emplacement over ∼600 kyr at around 201 Ma (Blackburn *et al.* 2013). The onshore emplacement of CAMP is temporally proximal to the End-Triassic Extinction, and has been suggested as a cause of that mass-extinction event (Marzoli *et al.* 1999; Olsen *et al.* 2003; Schoene *et al.* 2010; Blackburn *et al.* 2013). Often associated with CAMP are extensive packages of Seaward Dipping Reflectors (SDRs; Hinz 1981) observed offshore and along the passive margin of Eastern North America (Klitgord *et al.* 1988; Austin *et al.* 1990; Sheridan *et al.* 1993). However, it is unclear whether these SDRs were formed synchronous with CAMP or represent a later stage of shelf magmatism (e.g. Withjack *et al.* 2012).

In an attempt to provide emplacement rate estimates for these SDRs, we model the magnetic anomaly patterns produced by SDRs with varying internal magnetization geometries and compare the results against observations from the margin. Deciphering the emplacement rates of these voluminous basalts can help clarify the temporal relationship between onshore CAMP magmatism, offshore SDR formation and the End-Triassic Extinction. Additionally, these SDR emplacement rate estimates can improve our understanding of Pangea breakup and the early seafloor spreading history of the Central Atlantic by providing much needed age control between the datable onshore basalts and the distal marine magnetic anomalies. Finally, these results may provide generalized insights into the magnetic anomaly patterns produced by SDRs at other volcanic margins.

BACKGROUND

The passive margin of Eastern North America (Fig. 1) is characterized by large volumes of offshore magmatic material (Hutchinson *et al.* 1983; LASE Study Group 1986; Klitgord *et al.* 1988; Austin *et al.* 1990; Sheridan *et al.* 1993; Kelemen & Holbrook 1995). Geophysical observations from the margin reveal a morphology that appears typical of a volcanic passive margin (Geoffroy 2005; Franke 2013) where magmatism appears to have been abundant and arrived relatively early during the rifting process. Elevated (>7.2 km s^{-1}) lower crustal seismic velocities suggest mafic intrusion of the continental crust or magmatic underplating prior to breakup (Fig. 2; Holbrook & Kelemen 1993; Lizarralde & Holbrook 1997). Long-offset multichannel seismic experiments have imaged packages of SDRs along much of the margin (Fig. 2; Klitgord *et al.* 1988; Austin *et al.* 1990; Sheridan *et al.* 1993; Oh *et al.* 1995). DSDP drilling observations from the Rockall Plateau (offshore Ireland and Scotland) suggest that SDRs are composed of subhorizontal basalt flows and interbedded sediments (Roberts *et al.* 1984). SDR packages are thought to be formed through the subaerial, syn-rift process of repeated diking, subsidence and extrusive infilling (Mutter *et al.* 1982; Buck 2017).

The SDRs offshore Eastern North America are spatially associated with the East Coast Magnetic Anomaly (ECMA; Klitgord *et al.* 1988; Austin *et al.* 1990; Sheridan *et al.* 1993). The ECMA is a 100–150 km wide, positive, high amplitude magnetic anomaly that parallels much of the North American margin (Fig. 1; Keller *et al.* 1954; Taylor *et al.* 1968; Behn & Lin 2000). The along-margin extent of the ECMA suggests that the total volume of the offshore magmatic material may reach up to 2.7×10^6 km^3 (Kelemen & Holbrook 1995). This volume is comparable to the 3.0×10^6 km^3 of the Deccan Traps (Sen 2001). While the onshore portions of CAMP are well-constrained chronologically (Blackburn *et al.* 2013), the age and emplacement rate of this large volume of offshore magmatic material is unknown. Therefore, deciphering the emplacement rate of this igneous material is critical for understanding its potential relationship with both CAMP and the End-Triassic Extinction.

Prior to the imaging of SDRs along the margin of Eastern North America, a number of hypotheses were suggested as the source of the ECMA (Rabinowitz 1974). In general these hypotheses advocated that the ECMA was either (1) an induced anomaly that arose from a susceptibility contrast between continental crust and intrusions near the shelf break (Keller *et al.* 1954; King *et al.* 1961; Taylor *et al.* 1968; Hutchinson *et al.* 1983; McBride & Nelson 1988) or (2) a remanent anomaly arising from normal polarity igneous crust (Emery *et al.* 1970; Luyendyk & Bunce 1973; Alsop & Talwani 1984). Once SDRs were clearly revealed around the ECMA, Talwani *et al.* (1995) advocated that the ECMA was best interpreted as a remanent anomaly produced by SDRs of exclusively normal magnetic polarity.

The interpretation of Talwani *et al.* (1995), that remanent magnetization produces the ECMA, was based on palaeomagnetic observations from DSDP/ODP expeditions where SDR basalts were drilled (Kent & Opdyke 1978; Krumsiek 1984; Schönharting & Abrahamsen 1989). Compiling these drilling results reveals that SDR basalts are similar to oceanic basalts, with high natural remanent magnetization and Königsberger Ratios that are generally between 1 and 10 (Fig. 3). The Königsberger Ratio is the ratio of a sample's remanent component of magnetization relative to the sample's induced component of magnetization. If a sample has a Königsberger Ratio greater than 1, it indicates that under isolated conditions, the measured total field magnetic anomaly produced by the sample will generally reflect the remanent component of magnetization. Recognizing the subhorizontal nature of SDR flows, Talwani *et al.* (1995) proposed that to account for the wide, high amplitude, positive character of the ECMA, the SDR package must have exclusively normal-polarity remanent magnetization. To account for this wide zone of normal polarity, Talwani *et al.* (1995) suggested that the SDRs must have been emplaced rapidly during a single, normal-polarity chron of the Jurassic.

Talwani *et al.* (1995)'s suggestion that the ECMA SDRs were emplaced over a single magnetic chron becomes problematic when the extent of the SDR domain (∼125 km) is compared to the duration of magnetic chrons from the Geomagnetic Timescale (Gee & Kent 2007). The magnetic chrons from the Rhaetian to Aalenian (205.81–170.3 Ma) are rarely ever longer than 1 Myr in duration (Fig. 4) and have mean and median reversal frequencies of 0.34 and 0.17 Myr, respectively (Ogg *et al.* 2016). Younger and better constrained C-Series and M-Series marine magnetic anomalies (Gee & Kent 2007) demonstrate similar reversal frequencies with a mean of 0.55 Myr and a median of 0.25 Myr (Fig. 4). Consequently, for the ∼125-km-wide domain of ECMA SDRs to have exclusively positive magnetization, it requires that the SDRs were emplaced either during an unusually long Late Triassic/Early Jurassic normal polarity chron, of which there is no clear evidence (Olsen *et al.* 2003), or emplaced at improbably high extension rates during a normal polarity chron of average duration (∼0.5 Myr).

An additional problem with the suggestion that remanent magnetization produces the ECMA is that globally there do not appear to be any SDR packages which produce wide, large amplitude, negative magnetic anomalies comparable to the ECMA. If SDR packages are formed rapidly enough to only record a single magnetic chron, then one would expect approximately half of the global SDR packages to have formed during magnetic chrons of reversed polarity and produce negative total field magnetic anomalies. However, no negative magnetic anomalies comparable to the ECMA are observed at volcanic margins. Instead, many volcanic margins, including Norway (e.g, Nunns 1980; Nunns & Peacock 1983), South America (e.g. Rabinowitz & LaBrecque 1979) and West Africa (e.g. Simpson & Plessis 1968; Collier *et al.* 2017) are largely characterized by positive magnetic anomalies.

SDR REMANENT ANOMALIES

Forward modelling setup

To better understand the patterns of magnetic anomalies produced by SDRs, we compute the remanent magnetization of an idealized two-dimensional package of SDR basalt flows using Oasis Montaj's

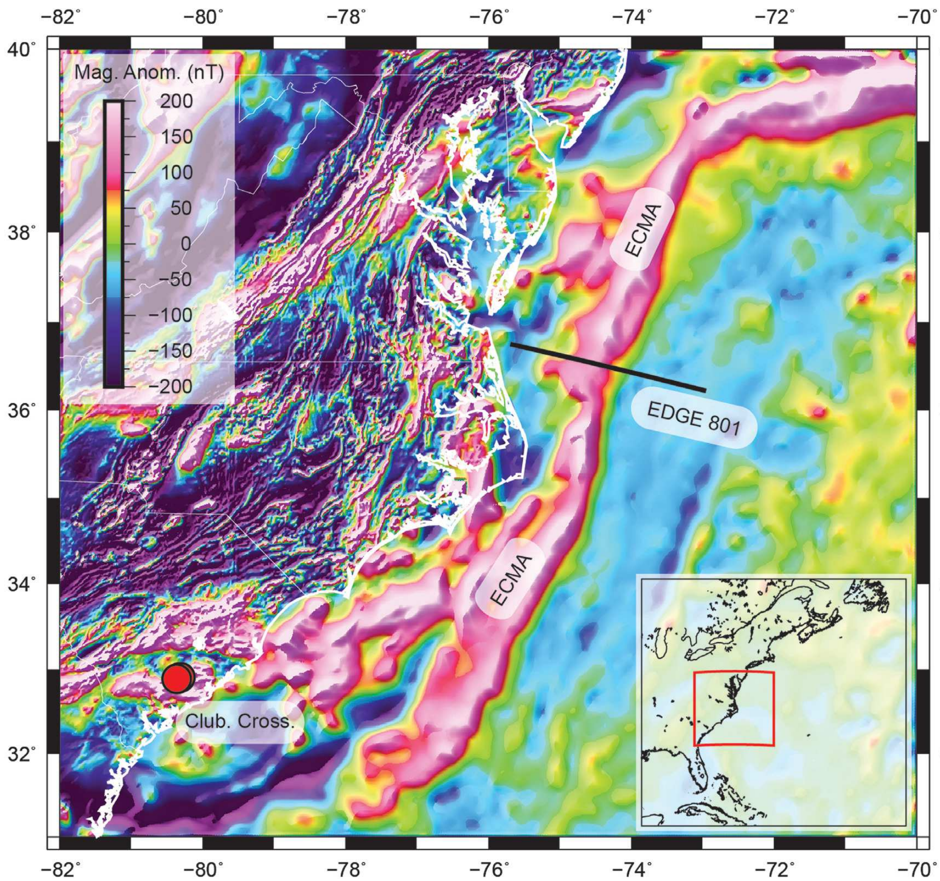

Figure 1. Magnetic anomaly map of the Eastern North American Margin region (Bankey *et al.* 2002; Meyer *et al.* 2017). The East Coast Magnetic Anomaly (ECMA) parallels much of the coastline. The location of the EDGE801 profile is shown in black. The Clubhouse Crossroad drill sites are shown as red circles.

GM-SYS software. The geometry of this package is based on recent global observations of SDRs compiled by Morgan & Watts (2018). The top of the package is assumed to be flat and at 5 km below the measurement depth. The overall dimensions of the package are 100 km in width by 5 km in thickness. Due to the dipping nature of SDRs the width of the package at any given depth is always 50 km. The dip of the package is assumed to gradually increases from ∼2° near the top to ∼14° at the base. Similar to the SDRs beneath the ECMA the flows dip towards the East. We assume the magnetic field above the SDRs is similar to that of the margin in the ECMA area, with a magnetic field strength of 50 000 nT and an inclination of +60°. The magnetic declination along the eastern margin of North America varies between 7° and 15°, to reduce the skew of the SDR magnetic anomalies we will assume the ambient field has a declination of 0° in our idealized forward model.

Based on compiled observations of SDR remanence from DSDP/ODP drill sites (Fig. 3), the modelled SDR basalts are assumed to preserve a remanent magnetization of 5 A m^{-1}. We estimate the palaeoinclination of the basalts using the PLATES relative plate motion framework (Lawver *et al.* 2018) in combination with an absolute framework from Torsvik *et al.* (2012). These reconstructions suggest that the SDR basalts beneath the ECMA were formed at ∼20° latitude, and will preserve either a normal inclination of +36° or reversed inclination of −36°. Because North America has only undergone minor rotation since SDR formation and to reduce the skew of magnetic anomalies, for our idealized forward models we assume the remanent magnetization has a declination of 0° (i.e. the same as the present-day field).

In order to produce consistent magnetic anomaly patterns that are easy to interpret, we assume that magnetic polarity reversals are regular in frequency, the first magnetic chron is of normal polarity, and that all chrons preserved within a SDR package are of equal width. Based on observed magnetic reversal frequencies (Fig. 4) we assume a magnetic reversal occurs every 0.5 Myr. Because of the assumption of regular reversals, the number of chrons preserved in the SDR package reflects the rate at which the package was emplaced. With 50 km of horizontal accommodation space to be filled on each conjugate plate, the relationship between full extension rate (ER in mm yr^{-1}) and the number of magnetic chrons within the SDR package is simplified and can be expressed in the following manner:

$$\#_{\mathrm{Chrons}} = (2 \times 50\,\mathrm{km}) / (0.5\,\mathrm{Myr} \times \mathrm{ER}). \qquad (1)$$

We test a range of full extension rates, between 200 and 10 mm yr^{-1}, and evenly divide the SDR package into the appropriate number of chrons (between 1 and 20 chrons, respectively). For a given rate of extension, all of the chrons within the package are of equal area and width. The magnetic anomalies produced by the packages are shown in Fig. 5. To help quantify the manner in which extension rate affects magnetization we compile the maximum amplitude anomaly and integrated anomaly produced by each modelled SDR package in Table 1.

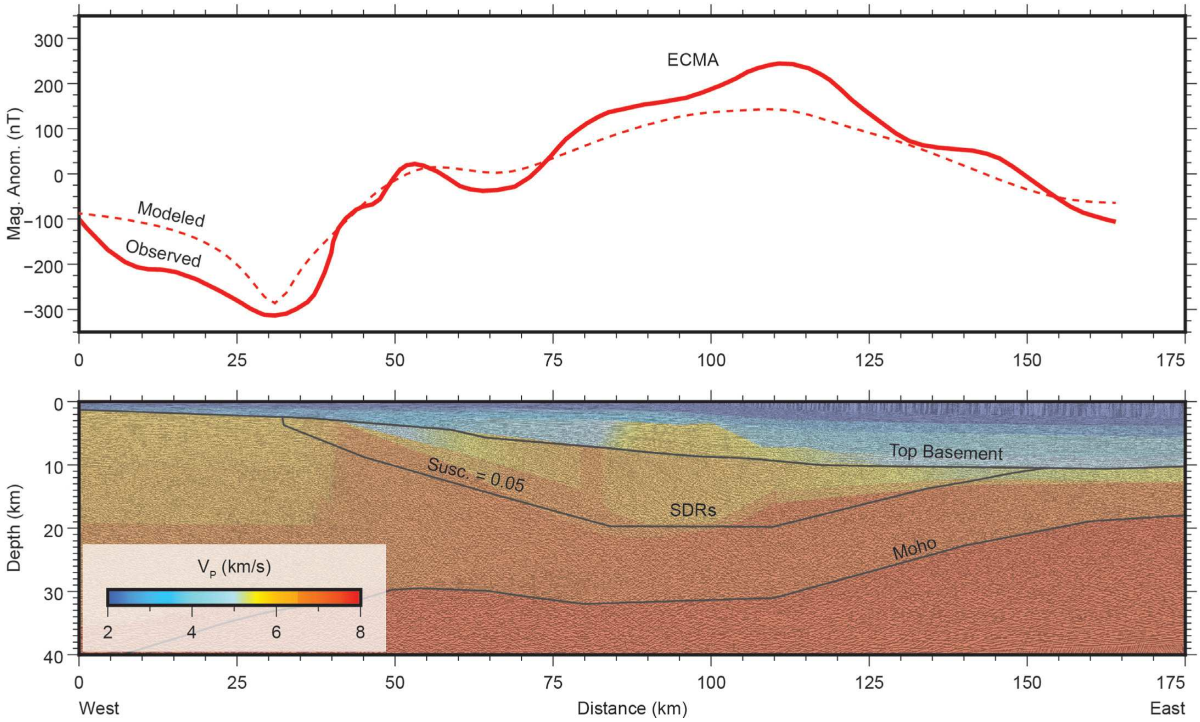

Figure 2. Geophysical data from the EDGE801 profile. Bottom panel: seismic velocity data from Holbrook & Kelemen (1993), multichannel reflection data, and outline of high susceptibility (0.05 SI) SDR basalts from this study. The sediments, mantle and non-SDR crust are modelled without any magnetic contribution. No remanent magnetization is modelled. The ambient field is assumed to be 50 000 nT with an inclination of 60° and a declination of 10°. Top panel: observed magnetic anomaly data (solid line; Talwani *et al.* 1995) and modelled magnetic anomaly (dashed line; this study).

Forward modelling results

When extension rates are sufficiently high, the modelled SDR basalts are emplaced so rapidly that only a single positive magnetic chron is recorded through remanent magnetization (Fig. 5a). A normal polarity chron recorded by the SDR produces a high amplitude total field magnetic anomaly that is similar in amplitude and sign to the ECMA. The almost exclusively positive nature of the total field anomaly produced by a single normal-polarity chron leads to an exceptionally high integrated magnetic anomaly (Table 1). The scenario modelled in Fig. 5(a) reflects the rapid formation conditions suggested by Talwani *et al.* (1995) for the SDRs beneath the ECMA. However, for the 100 km wide model domain, this interpretation requires a full extension rate of at least 200 mm yr^{-1}. This rate is faster than the fast-spreading East Pacific Rise (Rea & Scheidegger 1979; Müller *et al.* 2008) and about an order of magnitude faster than expected for continental extension (Bown & White 1995; Tetreault & Buiter 2017). We consider it unlikely that the SDRs beneath the ECMA were emplaced at these rates. Therefore, unless a long duration (>5 Myr), normal polarity chron is identified within the Late Triassic/Early Jurassic, it seems unreasonable that the SDRs beneath the ECMA record only a single magnetic chron. Instead, the SDRs were probably emplaced at lower rates of extension and record multiple magnetic chrons of different polarity.

As extension rates are decreased, the maximum amplitude and integrated magnetic anomaly produced by each SDR package is reduced (Figs 5b–e). Between extension rates of 100 and 50 mm yr^{-1} (Figs 5b and c) the maximum amplitude magnetic anomaly is reduced relative to the 200 mm yr^{-1} case (Table 1). Due to the presence of different polarity magnetic chrons, the SDR package produces both positive and negative total field magnetic anomalies. Due to the different polarity chrons being of equal width the integrated total field magnetic anomaly is greatly reduced relative to the 200 mm yr^{-1} model (Table 1).

At rates of crustal extension that are ≤20 mm yr^{-1}, chron layers are thin and often overlain by layers of an opposite magnetic polarity (Figs 5d and e). The stacking of the thin, varying-polarity, basalt layers causes the remanent anomalies of the layers to collectively cancel out, significantly limiting the maximum amplitude and integrated magnetic anomaly produced by the packages (Table 1). It is important to clarify that the SDR basalts in each model are modelled as adept recorders of magnetic remanence, but the layered distribution of thin, opposite polarity flows restricts the production of large total field magnetic anomalies. It therefore appears that at reasonable rates of continental extension (<20 mm yr^{-1}) and magnetic chron duration (0.5 Myr), our model results indicate that the subhorizontal geometry of SDR flows precludes the development of large, exclusively positive, high amplitude magnetic anomalies through remanent magnetization. Given these observations, it appears unlikely that the ECMA is produced by the remanent magnetization of the SDR packages.

THE SOURCE OF ECMA

If remanent magnetization is not responsible for producing the ECMA then an induced magnetic anomaly arising from a susceptibility contrast between continental crust and SDR-associated magmatic material represents the most likely source of the anomaly (Keller *et al.* 1954; King *et al.* 1961; Taylor *et al.* 1968; Hutchinson *et al.* 1983; McBride & Nelson 1988). Positive induced magnetic anomalies are produced when the magnetic moments of a ferrimagnetic material, such as magnetite, interact with the Earth's external

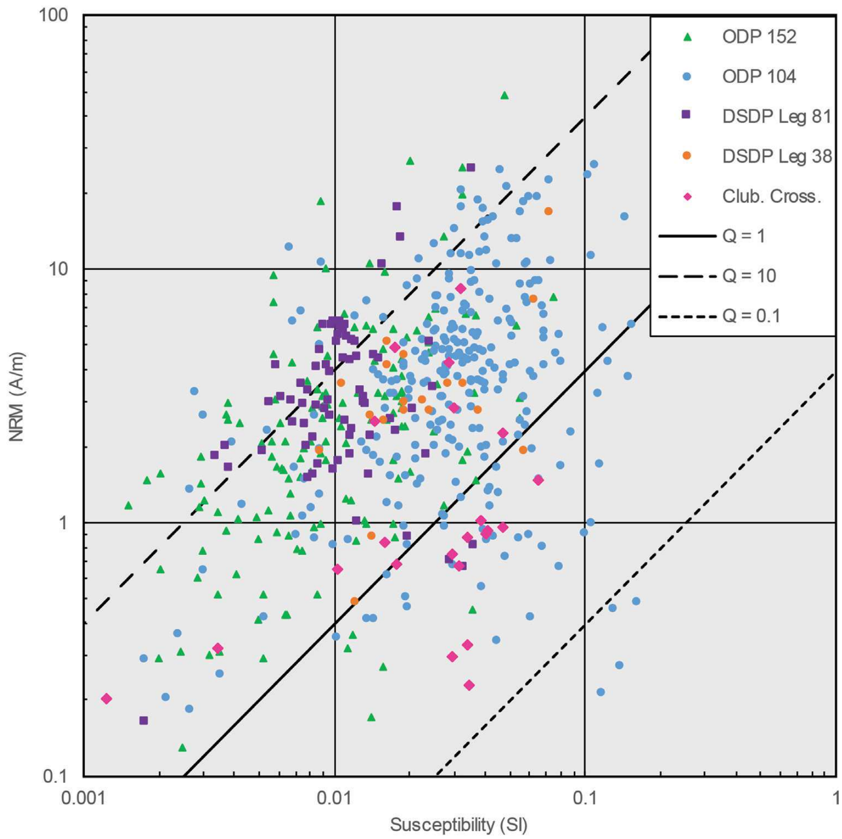

Figure 3. Natural remanent magnetization (NRM; A m^{-1}), and Magnetic Susceptibility (SIUnits) of SDR basalts from DSDP/ODP drilling (Kent & Opdyke 1978; Krumsiek 1984; Schönharting & Abrahamsen 1989; Vandamme & Ali 1998) and the Clubhouse Crossroads site (Phillips 1983). Königsberger Ratio (Q) lines are shown assuming a field intensity of 50 000 nT.

field. The magnitude of the induced magnetization is dependent on the strength of the field and the magnetic susceptibility of the material. SDR basalts have high susceptibilities (Fig. 3) that are conducive to producing large induced magnetic anomalies when they interact with the Earth's field. In basaltic materials, induced magnetic anomalies are often considered secondary to remanent magnetic anomalies, since samples of these rocks generally have a Königsberger Ratios >1 (remanent magnetization to induced magnetization ratio). However, because SDR remanent magnetization is hampered in its ability to contribute to the magnetic anomaly signal due to the subhorizontal layering of different-polarity package flows (Figs 5b–e), then induced magnetization will likely dominate an SDR package's collective total field magnetic anomaly even when individual SDR basalt samples have Königsberger Ratios >1.

We find that the SDR basalts along the eastern margin of North America will produce a magnetic anomaly that closely mimics the observed characteristics of the ECMA (Talwani *et al.* 1995), if the SDRs and associated igneous material have a magnetic susceptibility of 0.05 SI (Fig. 2). As such, we propose that the ECMA is most-simply interpreted as an induced anomaly that arises from susceptibility contrasts between the SDR basalts and the surrounding continental crust and shelf sediments. Given that an induced anomaly is able to so closely match the magnetic anomaly pattern of the ECMA, it suggests that remanent magnetization may be subordinate to induced magnetization along the margin. If this is the case, it would suggest that the SDRs beneath the ECMA were emplaced at normal rates of continental extension ($\leq$20 mm yr^{-1}) and not at the excessive extension rates required for the single polarity interpretation ($\geq$200 mm yr^{-1}) as per the Talwani *et al.* (1995) interpretation. If the SDRs were emplaced at higher rates ($\geq$50 mm yr^{-1}) we might expect more complexity in the observed magnetic anomaly, rather than the wide, high amplitude, and exclusively positive character of the ECMA. Minor differences between the modelled induced anomaly and the observed pattern of the ECMA are likely due to important, but poorly constrained variables that are discussed below.

Drilling results from the Clubhouse Crossroads sites in South Carolina (Fig. 1), support a model of multiple, thin, subhorizontal, opposite-polarity, SDR basalt layers along the eastern margin of North America (Phillips 1983). These drill sites sampled a 256 m section of basalts that are proposed to be a landward portion of the ECMA SDR flows (McBride *et al.* 1989; Oh *et al.* 1995). At the drill sites there is a large, positive, magnetic anomaly that appears to merge with the ECMA (Fig. 1). In drill hole CC#2 at Clubhouse Crossroads, the basalts were conducive to thermal demagnetization and palaeomagnetic analysis. These samples demonstrated a clear sequence of 5 reversed polarity and 4 normal polarity intervals (Phillips 1983). The average remanent inclination of these basalts was 35.4° ± 3.2°. These results indicate that the basalts along the Eastern North American passive margin were emplaced gradually over many magnetic chrons. The magnetic properties of Clubhouse Crossroads basalt samples are variable, with measured magnetic susceptibilities ranging from 0.0012 to 0.064 (SI), and Königsberger Ratios between 0.16 and 7.10 (Fig. 3). The magnetic susceptibility (0.05 SI) utilized in the model shown in Fig. 2, is within the range of

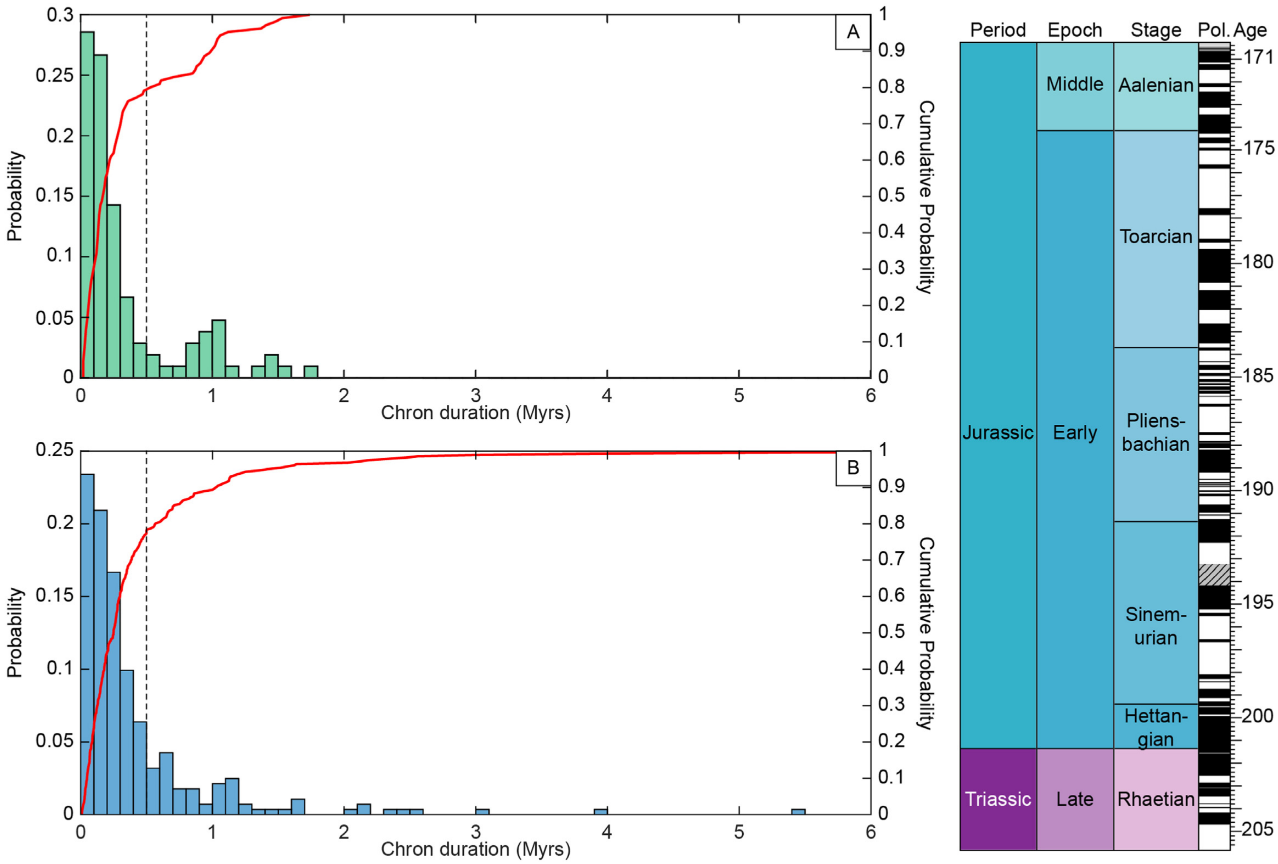

Figure 4. Right-hand panel: Rhaettian to Aalenian (205.81–170.3 Ma) Geological Timescale and Magnetic Polarity (Ogg *et al.* 2016), during which SDR emplacement and the breakup of North America and West Africa likely occurred. Left-hand panel: histograms and cumulative probability (red line) of magnetic chron durations from (A) The Rhaettian-Aalenian period and (B) for comparison, the C-Series and M-Series magnetic anomalies from Gee & Kent (2007). The assumed 0.5 Myr chron duration for the forward models is shown as a dashed line.

susceptibilities observed at Clubhouse Crossroads. Given our forward modelling results above (Figs 5b–e), we suspect that the positive, high amplitude magnetic anomaly observed at the Clubhouse Crossroad sites primarily reflects an induced magnetic anomaly, and that the encountered opposite-polarity subhorizontal flows do not significantly contribute to the total field anomaly signal. Collectively, the palaeomagnetic results from the Clubhouse Crossroads drill site appear to support our interpretation that the SDRs beneath the ECMA were emplaced gradually over many magnetic chrons.

TIMING OF SDR EMPLACEMENT

Given our model results and palaeomagnetic observations from the Clubhouse Crossroads drill sites, it appears that the SDR basalts associated with the ECMA were emplaced gradually over multiple magnetic chrons. Based on our forward modelling results (Fig. 5), we suggest that extension was slow enough ($\leq$20 mm yr^{-1}) during SDR emplacement, to inhibit a significant contribution from remanent magnetization to the overall magnetic anomaly signature. If extension was faster (50 mm yr^{-1}; Fig. 5c), we may expect more complexity in the magnetic anomaly pattern produced by the package, rather than the wide, high amplitude, and exclusively positive character of the ECMA. At low extension rates ($\leq$20 mm yr^{-1}), the subhorizontal layering of alternating-polarity flows facilitates the development of a large and exclusively positive magnetic anomaly through induced magnetization. Because of dampening of the remanent anomaly signal (Fig. 5), it is difficult to constrain the exact number of magnetic chrons preserved throughout the SDR domain. Therefore, the timing and duration of SDR emplacement can only be crudely approximated by estimating the total amount of extension and full extension rate that occurred during SDR formation. The exact relationship between SDR domain width and amount of horizontally accommodated extension within the domain is poorly constrained. We estimate that the ~125-km-wide SDR domain accommodated between 125 and 50 km in extension during formation. Labails *et al.* (2010) estimate full spreading rates for the early (pre-M25n) Central Atlantic that range between 8 and 17 mm yr^{-1}. If we accept these extension rate estimates for the earlier continental rifting, and if we accept our estimates for the total extension accommodated by the conjugate SDR domains, then we estimate that the SDRs were emplaced over a period between 6 and 31 Myr in duration. If SDR formation began simultaneously with CAMP at ~201 Ma, it suggests that their emplacement completed, and seafloor spreading began, sometime between ~195 and 170 Ma. While this timing is certainly a crude estimate, it suggests that SDR volcanism continued long after the 600 kyr period (Blackburn *et al.* 2013) of onshore CAMP volcanism.

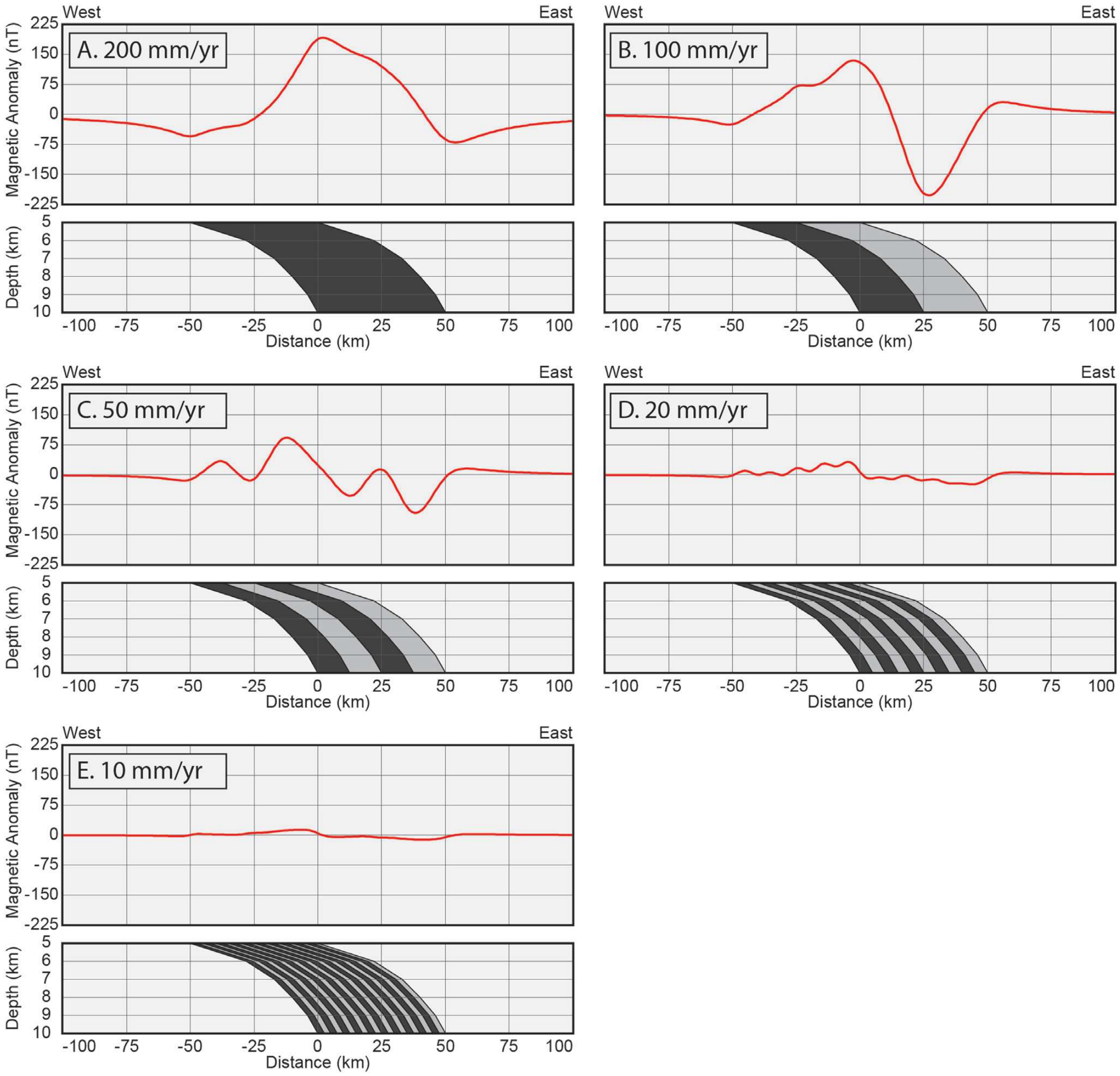

Figure 5. Magnetic anomalies (top panel; red line) produced by SDRs with varying chron layer geometries (bottom panel) depending on full extension rates. Normal polarity SDR chron layers are shown in black, reversed polarity SDR chron layers are shown in light grey. All chron layers are assumed to have a remanent magnetization of 5 A m^{-1}. The ambient field is assumed to be 50 000 nT with an inclination of 60° and a declination of 0°. Please note the vertical exaggeration of the SDR packages in these figures.

Table 1. Maximum amplitude magnetic anomaly (nT) and integrated magnetic anomaly (nT km) produced by each experiment shown in Fig. 5.

Full rate (mm yr^{-1})	Duration (Myr)	# of Chrons	Max. amplitude (nT)	Integrated anomaly (nT km)
200	0.5	1	191.8	2655
100	1	2	–203.0	−55.5
50	2	4	–95.6	−29.6
20	5	10	32.2	−12.0
10	10	20	13.6	–6.0

FURTHER APPLICATION AND POTENTIAL SHORTCOMINGS

Results from the forward modelling of SDR magnetic anomaly patterns may be applicable to more-generalized volcanic margin concepts. It is plausible that at other volcanic margins, SDRs are emplaced at extension rates <20 mm yr^{-1} (Tetreault & Buiter 2017), and with subhorizontal flow geometries that preclude the production of large, observable and remanent anomalies. If this is the case, then similar to the eastern margin of North America, many volcanic margins may be dominated by a positive, induced magnetic anomaly signal. The dominance of induced magnetization within SDRs may therefore explain the global lack of wide, high amplitude, negative anomalies across volcanic passive margins.

There are important simplifications in our idealized model that do not reflect real world conditions. Notable assumptions and simplifications include: (1) a regular rate of magnetic reversals, (2) a constant rate of extension, (3) a simplified SDR package geometry, (4) identical magnetic remanence across the package, (5) equal magnetic susceptibility across the package and (6) unaccounted viscous remanent magnetization. All of these properties can vary in real world conditions and have the ability to influence the patterns of marginal magnetic anomalies. However, unless SDRs are formed when magnetic chrons are highly variable in length, unusually long in duration (>1 Myr), and/or extension rates are ≥50 mm yr^{-1}, then individual chron layers should remain regular, thin and layered. Under these conditions, the remanent anomaly from opposite-polarity chron layers should limit the ability of the package to make a large positive anomaly resembling the ECMA. Differences in SDR package depth, package thickness, remanent magnetization and/or magnetic susceptibility can contribute complexity to the overall pattern and amplitude of the SDR package's magnetic anomaly. These type of complexities likely account for the minor misfit between the observed and modelled magnetic signal shown in Fig. 2. It is difficult to constrain whether this non-unique misfit is best reconciled through variation is susceptibility, remanence, thickness or depth, and therefore the misfit is left in place.

Finally, it is important to mention the potential influence of a secondary, viscous component of remanent magnetization. Some of the basalt samples from the Clubhouse Crossroads site demonstrate natural remanent magnetization inclinations that are normal polarity (positive), but upon demagnetization display primary remanent magnetization (thermoremanent) inclinations that are of reversed polarity (negative; Phillips 1983). This palaeomagnetic observation likely indicates a viscous overprint by the present-day field and may suggest a normal polarity bias in SDR basalt remanence that is difficult to constrain without direct palaeomagnetic analysis. If a present-day viscous overprint such as this one affects a large portion of the remanent magnetization of reversed polarity basalts in SDRs, then it represents an alternative explanation for the high amplitude positive nature of the ECMA, and the general lack of large negative anomalies at other volcanic passive margins.

CONCLUSIONS

Forward modelling results suggest that, at reasonable rates of continental extension (≤20 mm yr^{-1}) and magnetic reversal frequencies, the subhorizontal layering of basalts will inhibit the ability of an SDR package to produce a large magnetic anomalies like the ECMA through remanent magnetization. Palaeomagnetic results from the Clubhouse Crossroads drill site support a model of thin, subhorizontal layers, of alternating-polarity basalt flows along the eastern margin of North America. Given these observations, it appears that a positive induced magnetic anomaly, produced by a susceptibility contrast between continental crust and SDR basalt, is the most likely source of the ECMA (Keller *et al.* 1954; King *et al.* 1961; Taylor *et al.* 1968; Hutchinson *et al.* 1983; McBride & Nelson 1988). Consequently, we suggest that the offshore igneous material beneath the ECMA was emplaced gradually over a duration of 6 to 31 Myr. This result suggests that either the current estimated duration of CAMP (600 kyr; Blackburn *et al.* 2013) should be increased, or the large offshore igneous material should be excluded from volumetric estimates of the CAMP igneous province.

If most SDR flows are emplaced subhorizontally and at moderate rates of extension, then we would expect similar pattern of magnetic anomalies at other volcanic margins. In contrast to oceanic crust, the layered geometry of SDR flows causes cancellation of the total field anomaly produced by remanant magnetization. Thus, induced magnetization may dominate the magnetic signal even where individual SDR basalt samples have Königsberger Ratios that are >1. Since induced magnetic anomalies produce positive magnetic anomalies, their influence may explain the paucity of large negative magnetic anomalies globally across volcanic margins.

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