ADVANCING EARTH AND SPACE SCIENCES

Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE

10.1029/2023GC011282

Key Points:

- A 195 m section, representing ~2 Myr, yields a magnetostratigraphy comprizing nine major magnetozone couplets and seven submagnetozones
- Primary magnetizations are predominantly carried by hematite with lesser important detrital magnetite. Data pass regional fold tests
- A reversal frequency of 15.7 ± 0.75 Myr^{-1} is calculated, suggesting that the geodynamo was in a hyperactive state at ~333 Ma

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Hounslow, M. W., Biggin, A. J., Cózar, P., Somerville, I. D., Kamenikova, T., & Sprain, C. J. (2024). A hyperactive geomagnetic field in the late Visean (Early Carboniferous) from the late Asbian stratotype section in northwest England, UK. *Geochemistry, Geophysics, Geosystems*, *25*, e2023GC011282. https://doi.org/10.1029/2023GC011282

Received 6 OCT 2023
Accepted 2 MAR 2024

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A Hyperactive Geomagnetic Field in the Late Visean (Early Carboniferous) From the Late Asbian Stratotype Section in Northwest England, UK

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Plain Language Summary Nearly synchronous global changes in geomagnetic polarity give both a detailed irregular pacing to geological time and provide a glimpse into heat transfer processes across the core—mantle boundary which drives the Earth's geodynamo. Although the Late Carboniferous is characterized by some well-studied reversals, details of the tempo of polarity changes in the Early Carboniferous are unknown. This work addresses this by providing a detailed record of polarity changes over a ~2 million year interval at around 334.5–332.5 million years ago-from the Trowbarrow Quarry section in NW England. We demonstrate that these limestones likely preserve magnetization from close to their time of formation and record at least 31 polarity reversals. These observations support the idea that the Earth's dynamo was in a hyperactive reversing state similar to those sustained for tens of Myr in the Late Jurassic, parts of the Cambrian and the Late Ediacaran. It further corroborates a ~200 Myr cyclicity in paleomagnetic field behavior since the Precambrian, potentially linked to variable core heat flow forced by mantle convection.

Abstract The pattern of geomagnetic polarity changes during the Early Carboniferous (Mississippian) is not known in detail. This information sparsity is addressed by determining a magnetostratigraphy from the late Asbian (late Visean at ~333 Ma) in Trowbarrow Quarry, UK. This is the stratotype section of the late Asbian and has a detailed foraminiferal zonation based on the same set of paleomagnetic samples, establishing a detailed biostratigraphy. The 195 m-thick section was sampled at an average spacing of 1.1 m, yielding a detailed magnetostratigraphy comprising nine major magnetozone couplets, and seven submagnetozones. The section dataset has a 78% bias to normal polarity determined from 177 sampling levels. The magnetization is carried by a mixture of hematite and detrital magnetite, with 68% of specimens dominated by hematite magnetizations. The primary magnetization passes a fold test showing its age was prior to the latest Carboniferous. The hematite is inferred to be largely of detrital, eolian origin, although some reddened levels are associated with emergent surfaces, suggesting that a small fraction of hematite is associated with platform emergence. The Mississippian age magnetization is partly overprinted with Kiaman Superchron-age and Brunhes-age magnetizations. Using the duration of the section based on astrochronology indicates a reversal frequency of 15.7 ± 0.75 Myr^{-1}, indicating that the geodynamo was in a hyperactive reversing state between 335 and 333 Ma.

1. Introduction

Stratigraphic changes in geomagnetic polarity (magnetostratigraphy) have become one of the standard tools for stratigraphic study in the Mesozoic and Cenozoic, allowing environmental changes to be calibrated to precise time intervals (Hounslow et al., 2022; Miller & Wright, 2017; Nie et al., 2020). For much of the Pennsylvanian (Late Carboniferous), progress has been made in defining a polarity timescale (Opdyke & DiVenere, 2004; Opdyke et al., 2014), but details require validation, with those currently available largely based on few age-overlapping studies (Hounslow, 2022). In the Carboniferous, regional differences in stratigraphic scales and biozonations contribute to additional uncertainty in how to correlate between the various studies when compiling a composite global polarity scale (Hounslow, 2022). For much of the Early Carboniferous (Mississippian) and Devonian, changes in geomagnetic polarity are not known in detail or those intervals that have been studied are open to additional uncertainty (Green et al., 2021; Van der Boon et al., 2022).

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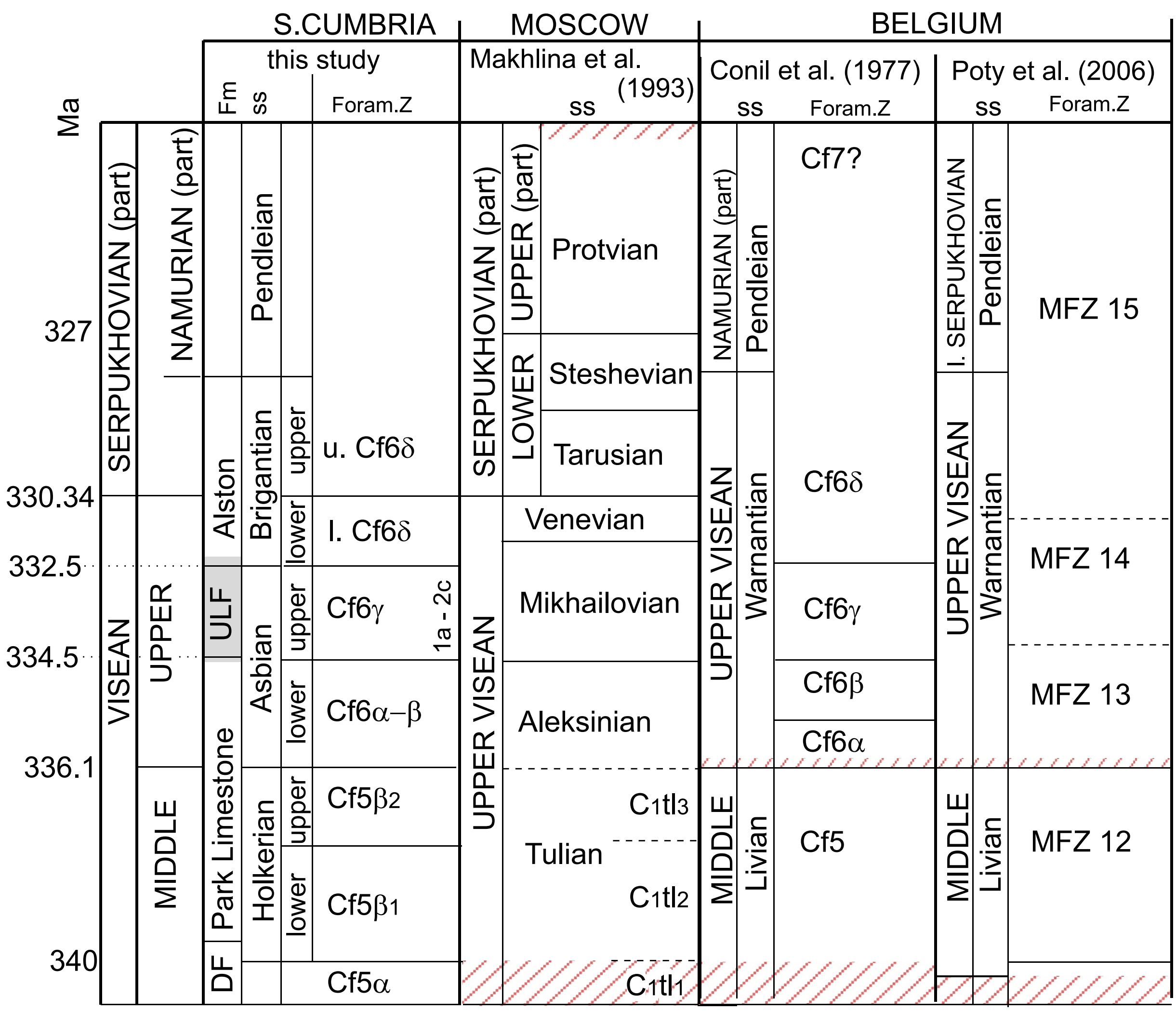

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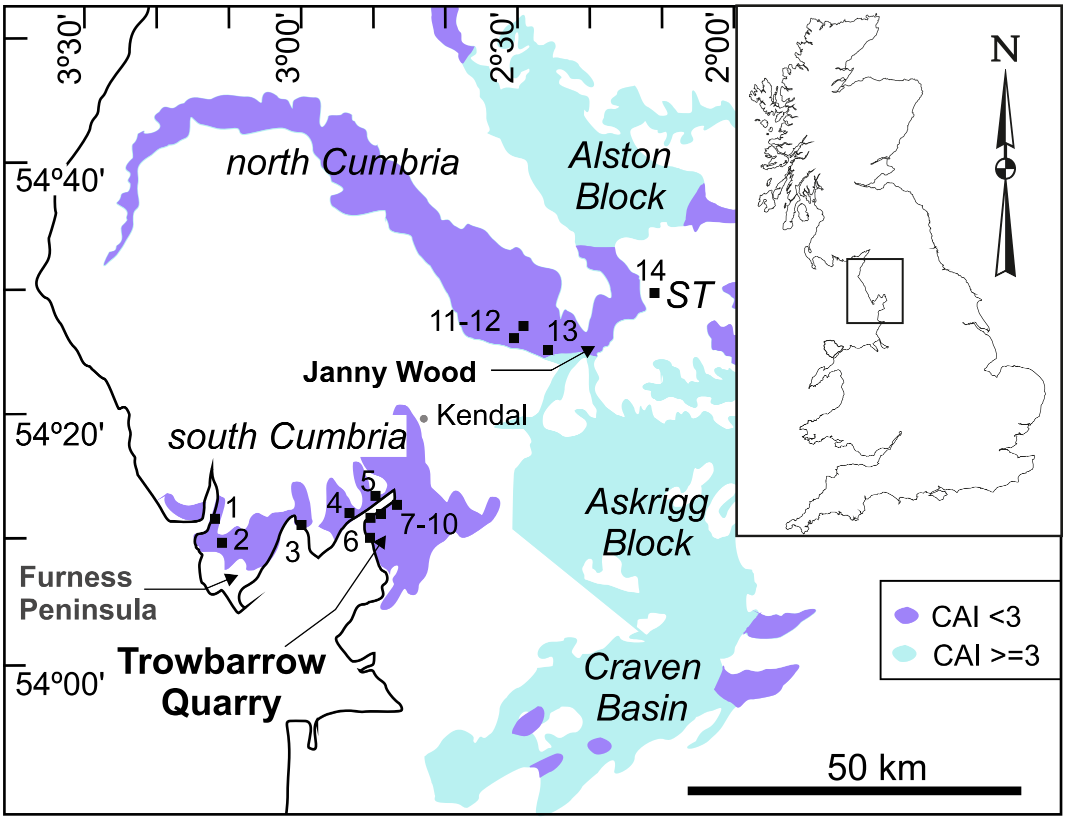
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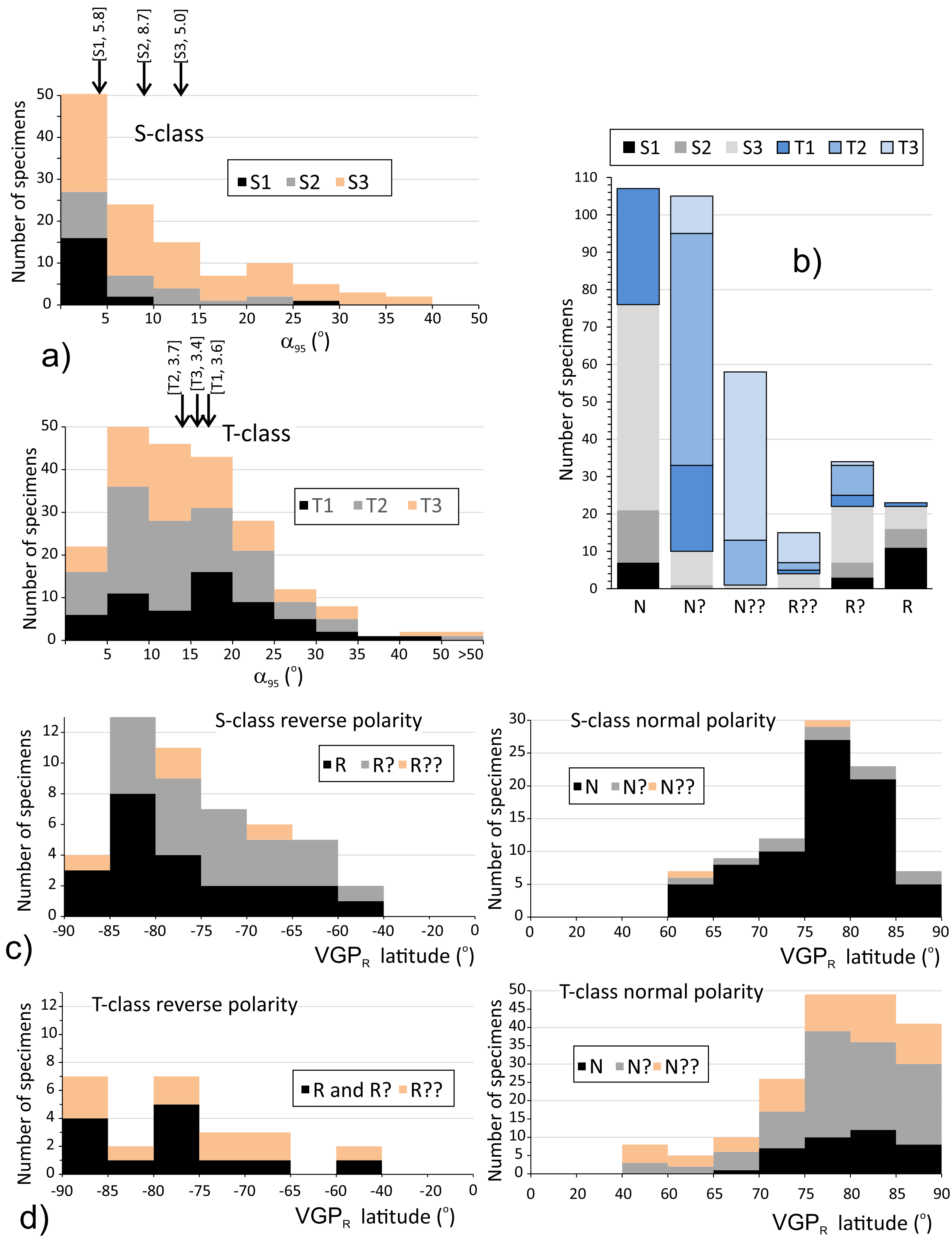

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Table 1
Trowbarrow Quarry Directional Means (With Tectonic Correction and Converted to Normal Polarity), Reversal Tests and South VGP Poles

Type/section/Unit	Dec(°)	Inc(°)	K/α_{95}(°)	Ns/Nl/Np	Reversal test	G_o/G_c(°)	Plat/Plong(°)	Dp/Dm (°)	A95 (min, max)
Humphrey Head Lmst Mb- Peghorn Lmst Mb									
Line fits[a]	30.7	−29.8	29.4/8.6	9/11/0	Ro-	11.6/30	−15.1/327.0	5.3/9.5	8.9 (5,21)
Locality mean[b]	34.1	−22.4	35.5/5.0	23/11/36	Ro	4.9/24	−18.1/322.2	2.8/5.3	4.3 (3.4,11.4)
Upper Urswick Limestone									
Line fits[a]	36.1	−29.3	23.1/3.1	64/93/0	R-	9.9/6.5*	−13.7/321.8	1.9/3.4	3.3 (2.3,6)
Locality means[b]	34.1	−27.5	38.3/2.3	101/93/111	Rc	5.5/10	−15.3/323.2	1.4/2.5	2.1 (1.9, 4.5)
Lower Urswick Limestone									
Line fits[a]	38.0	−27.4	26.1/5.2	22/31/0	R-	13.5/9.4*	−14.3/319.7	3.1/5.8	5.3 (3.5,11.7)
Locality means[b]	34.7	−25.3	35.8/3.3	52/31/71	Rb	5.1/7.7*	−16.4/322.3	1.9/3.6	2.7 (2.5,6.8)
Trowbarrow section									
Line fits[a]	36.1	−28.9	24.2/2.5	95/135/0	R-	10.1/5.1*	−14.1/319.6	3.1/5.7	2.6 (1.9, 4.7)
Locality means[b]	34.3	−26.1	36.9/1.8	176/135/218	R-	4.5/4.3	−16.1/322.8	1.1/2.0	1.5 (1.5,3.2)
Other Visean localities									
GC means[c]	36.6	−31.2	12/5.1	30/14/30	Rc	12.9/13.1	–	–	–
Locality means[a]	36.6	−31.2	29.7/4.9	30/14/30	Rc	4.9/10.4	−12.1/321.7	–	4.6 (3.1, 9.6)

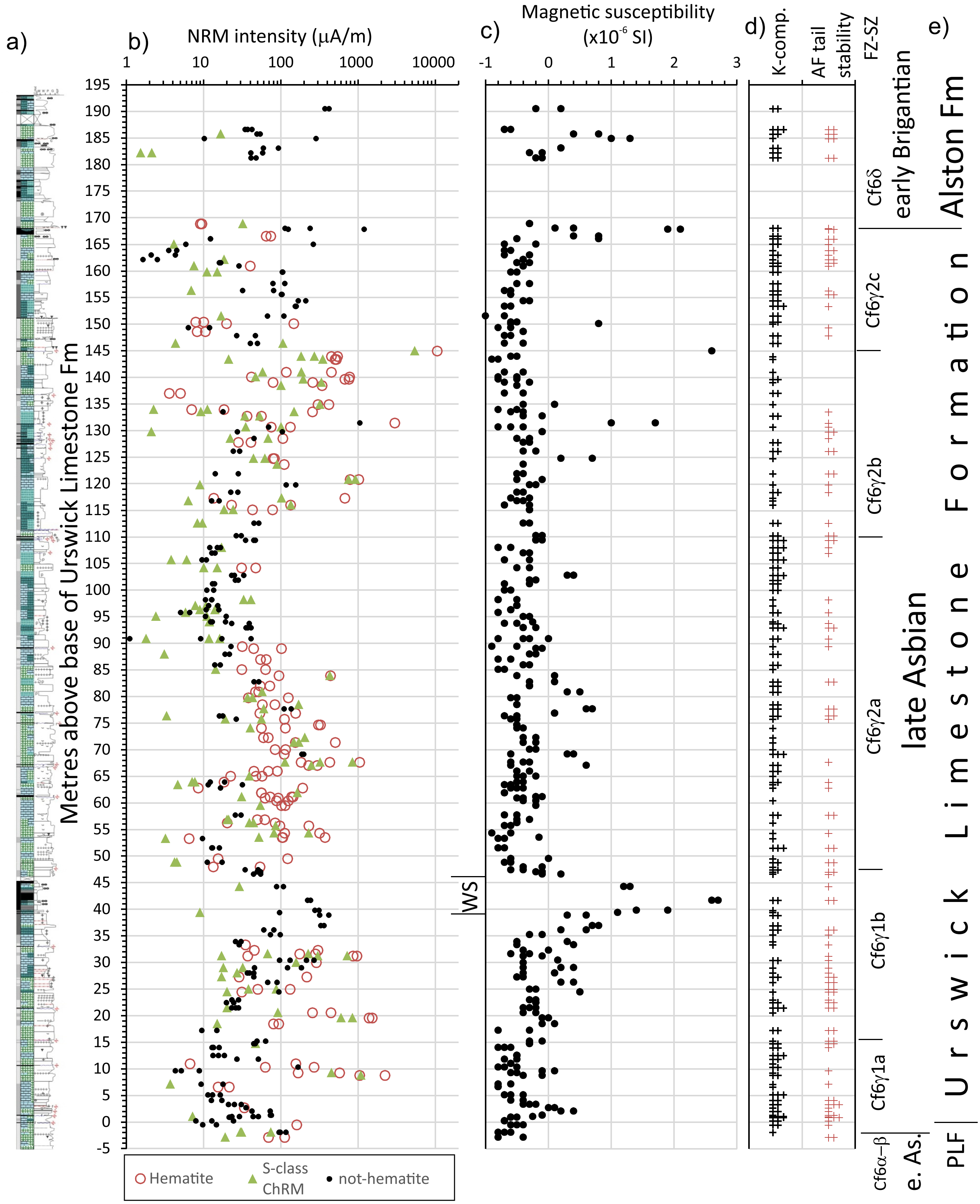
Note. Ns = number of levels (sites), Nl = number of specimens used with fitted lines, and Np = number of specimens with great circle planes used in the determining the mean direction. α95, Fisher 95% cone of confidence. *k*, Fisher precision parameter. G_o is the angular separation between the inverted reverse and normal directions, and G_c is the critical value for the reversal test. In the reversal test the G_o/G_c values flagged with * indicate common K values, others not flagged have statistically different K-values for reverse and normal populations, in which case a simulation reversal test was performed. Plat and Plong are the latitude and longitude of the mean south virtual geomagnetic pole1. A95 (min, max) = Fisher 95% confidence interval for VGP-based site mean (Ns sites), and $A95_{min}$ and $A95_{max}$ threshold values of Deenen et al. (2014). Statistics determined with Pmagtool v.5 (Hounslow, 2023b). [a] = conventional Fisher mean using specimens. [b] = using method of McFadden and McElhinny (1988) to find great circle intersection points (T-class data) and combined with S-class line fits for each sample mean. [c] = great circle combined mean using the method of McFadden and McElhinny (1988) on specimen level data.

3. Results

3.1. Magnetic Mineralogy

Some 82% of the limestones have magnetic susceptibility <0 (Figure 4c), so they are diamagnetic. Positive susceptibilities are not particularly confined to any particular carbonate lithology other than the two rudstone samples. Instead, positive magnetic susceptibility is mostly related to more shaley and argillaceous stratigraphic intervals, such as the Woodbine Shale and those in the Alston Fm (Figure 4c). NRM intensity is largely independent of magnetic susceptibility, suggesting that these largely express different magnetic phases (Figure 4b).

Specimens show a large range in S-ratio and B_{cr}, indicating that there is a strong mixture between hard IRM behavior with B_{cr} >100 mT and soft behavior with S-ratio 0.4–0.8 (Figure 5a). The largest proportion of samples have S-ratio < −0.6 (histogram in Figure 5a) There is no strong correspondence with lithology, but rudstone (only 2 samples), mudstones, and argillaceous packstones have the larger positive S-ratios, and grainstones the smaller (i.e., negative) S-ratios on average (Figure 5a). Since pure hematite has B_{cr} typically 100–800 mT (Peters & Dekkers, 2003), and there is limited evidence in thermal demagnetization of goethite (but see Figure S5 in Supporting Information S1), the relationship in Figure 5a is inferred to reflect a variable magnetic mixture of hematite and a softer phase. Some 68% of specimens have B_{cr} >100 mT, which shows that samples are largely hematite dominated. Since only some 7% of the sample set can be directly associated with observed reddening at the emergent surfaces (Figure 4b), the hematite has been contributed to these limestones in other ways, in addition to directly at emergent surfaces. The HIRM and IRM_{40mT} are proxies for the total contributions from the hematite and soft component (Walden & White, 1997) and are weakly co-related (Pearson $R^2 = 0.41$, power-relationship in Figure 5b), indicating some connection between their supply. Samples associated with the emergent surfaces have variable but generally larger HIRM (Figure 5b), confirming the field data and petrographic observations of Horbury (1987) that the reddening at these surfaces is associated with hematite. Wright et al. (1997) have inferred



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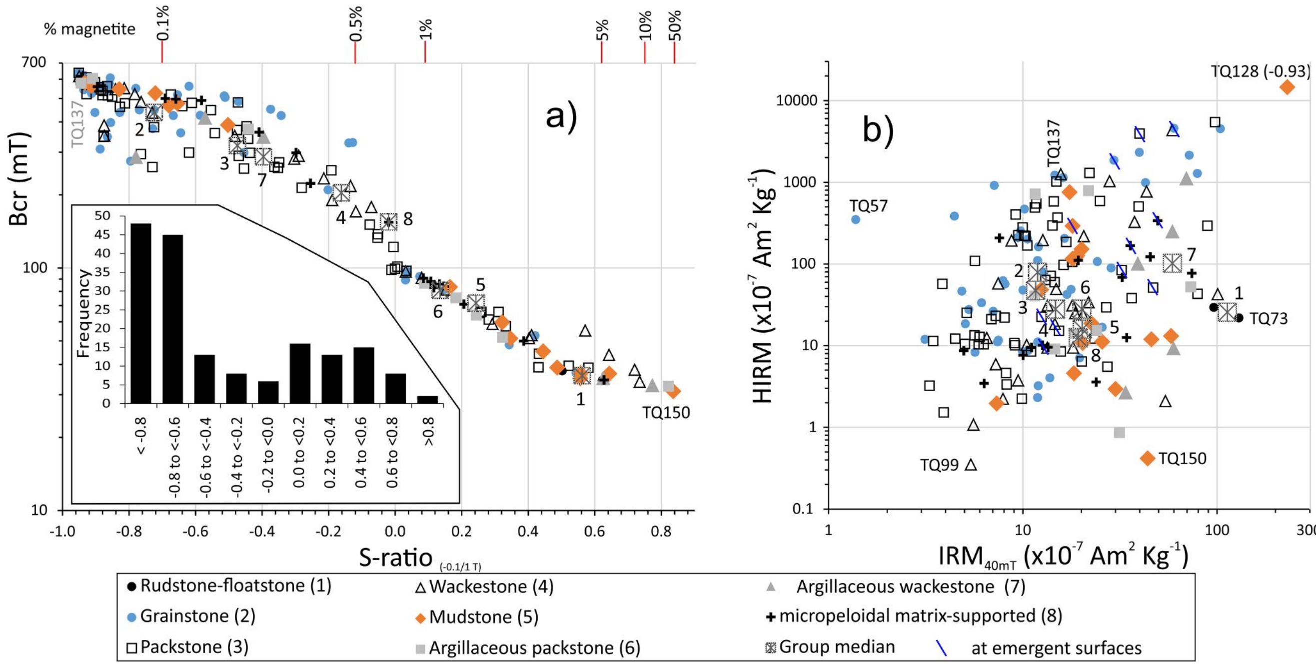

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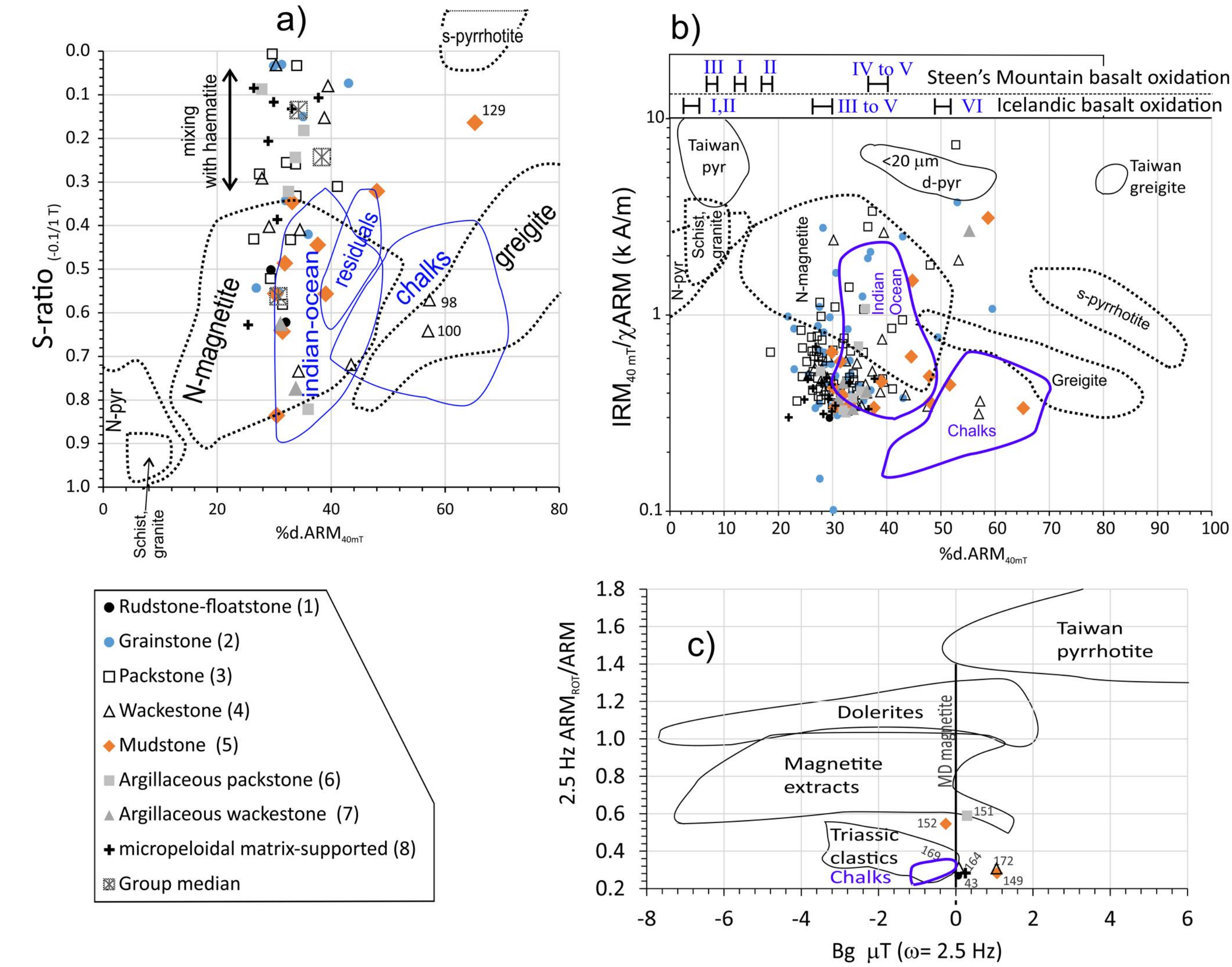

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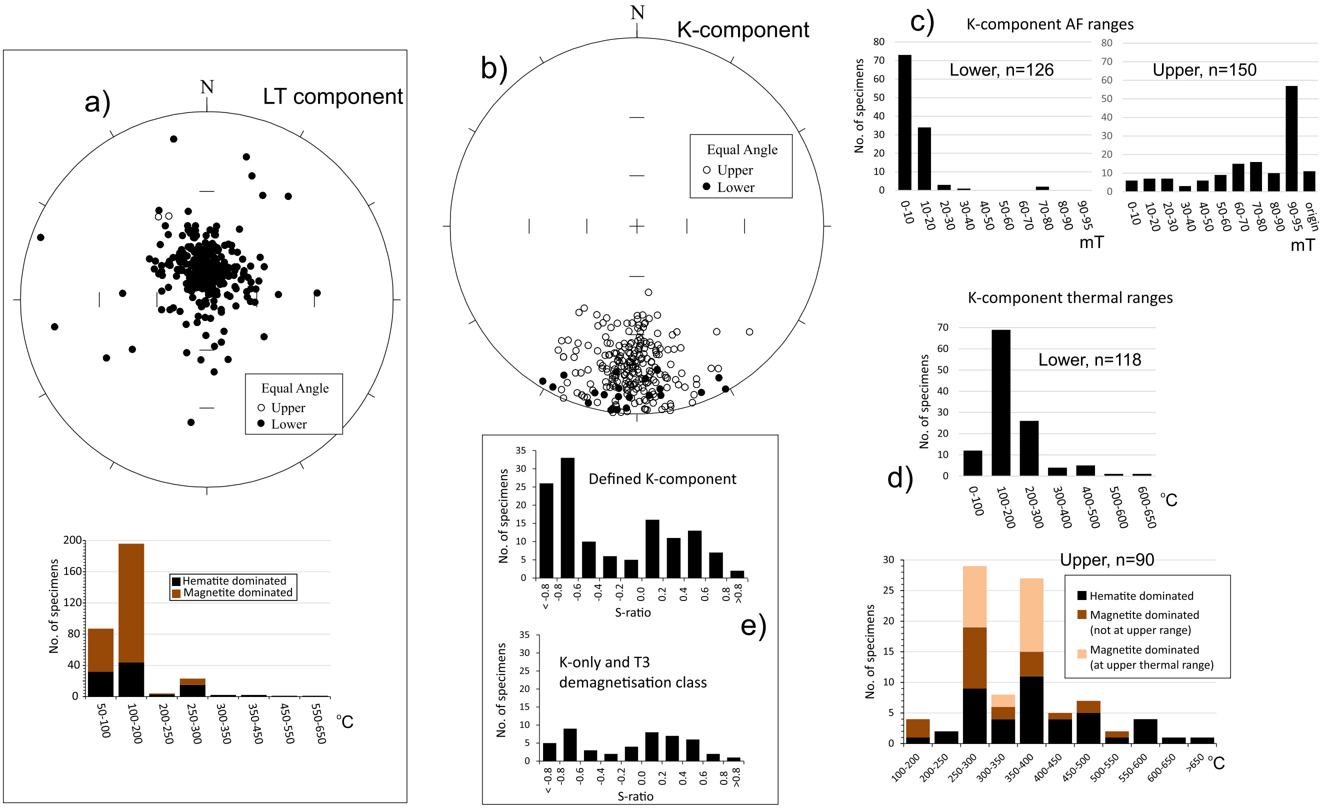

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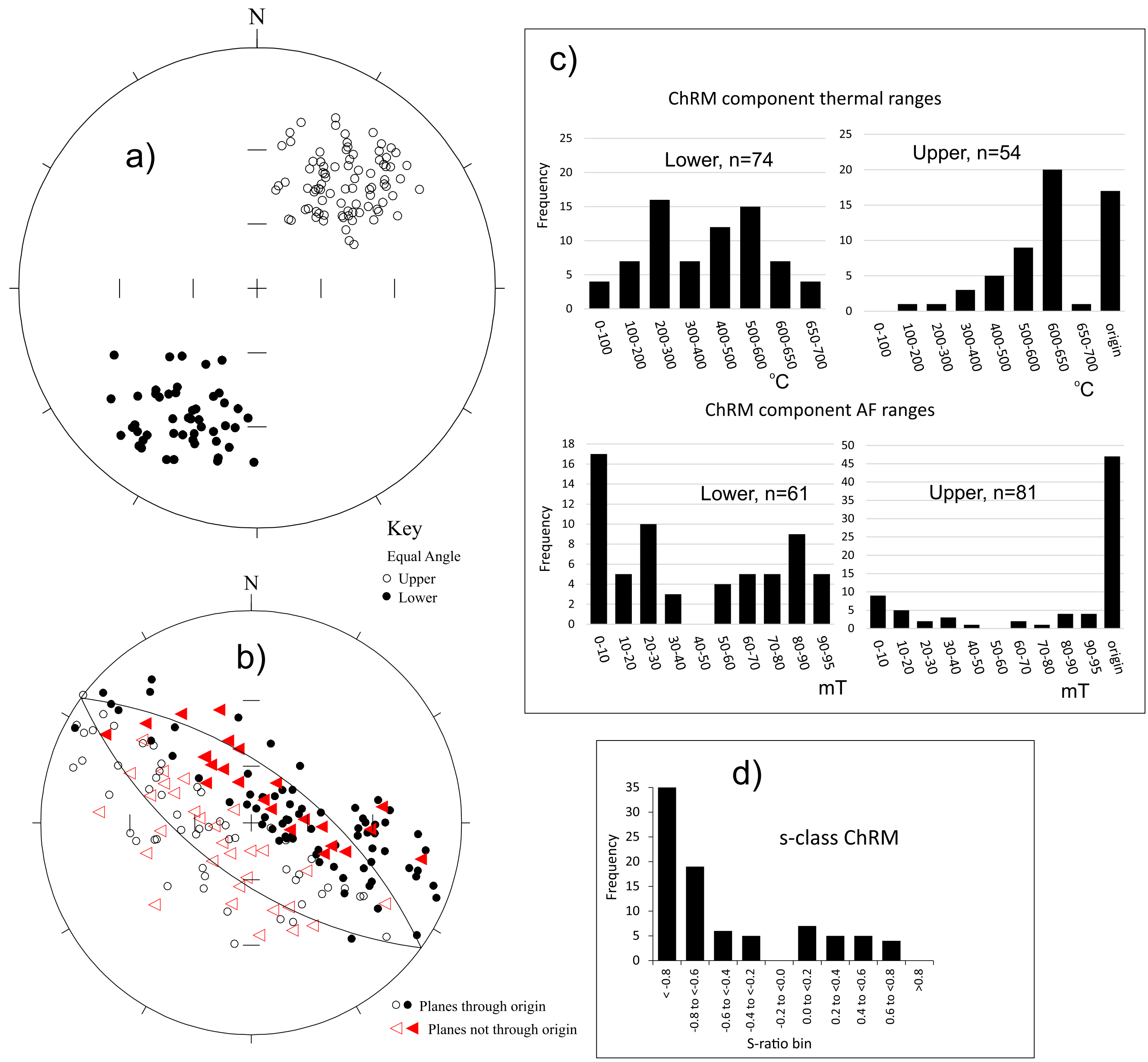

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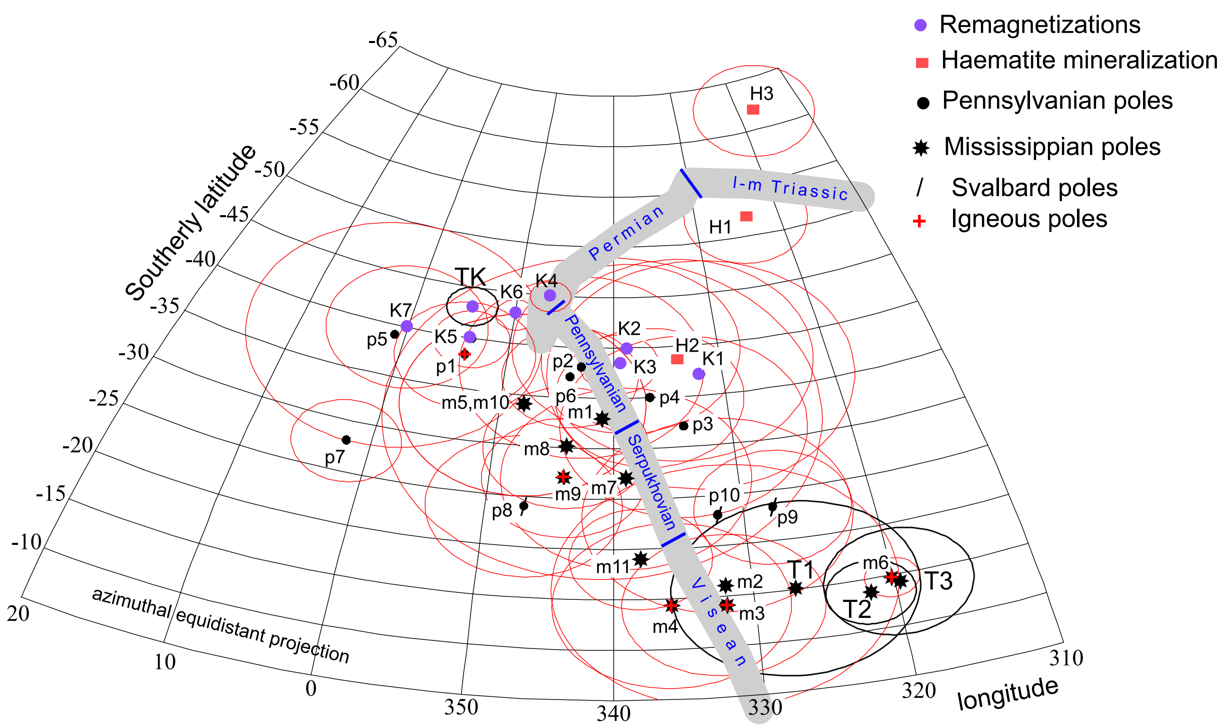

Remagnetizations
Haematite mineralization
Pennsylvanian poles
Mississippian poles
Svalbard poles
Igneous poles
Southerly latitude
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-60
-55
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-45
-40
-35
-30
-25
-20
-15
-10
20
10
0
350
340
330
320
310
longitude
azimuthal equidistant projection
l-m Triassic
Permian
Pennsylvanian
Serpukhovian
Visean
H1
H2
H3
TK
K1
K2
K3
K4
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K6
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m11
T1
T2
T3

Table 2
Mean ChRM and K-Component Directions From the Additional Localities

Locality and groups	Dec(°)	Inc(°)	K/α_{95}(°)	Ns/Nl/Np
ChRM means				
11–13 (RD) [a]	208	16	14/15	7/2/7
14 (MG) [a]	205	37	34/10	5/4/4
5,4,7 (GK1-GK7) [a]	211	35	11/15	8/2/9
6,2 (GK8-10, DF1-3) [a]	219	32	20/12	4/5/4
8 (GK11-13) [a]	233	48	7/32	3/1/5
9 (AS5-AS8) [a]	234	27	20/16	4/3/3
K-component means				
6, 8 (GK2)	183	−16	16/13	6/9/0
11–14 (RD-MG)	211	−27	38/15	3/4/0
3, 4,5,7,10 (GK1)	187	−16	21/7	11/23/0
9 (AS)	191	−15	62/6	4/5/0
2 (DFa)	180	7	65/10	2/5/0
1 (DFb)	198	−34	45/8	4/8/0
TQ1	182	−16	23/3.8	58/116/0
TQ2	183	−13	26/2.5	64/128/0

Note. ChRM in stratigraphic coordinates. K-component in geographic coordinates. TQ1 and TQ2 sets are the Trowbarrow Quarry dataset partitioned into a near vertical set (mean dip direction = 269.5°, 86.2°), and a less steeply overturned set (mean dip direction = 268.5°, 80.2°). Codes in () are the sampling codes indicated in Table S1 in Supporting Information S1. [a] = great circle combined mean using method of McFadden & McElhinny (1988) on specimen level data.

3.2.2. The Additional Sample Set

Demagnetization behavior of the additional set was similar to that from Trowbarrow Quarry (Figures S7, S10 in Supporting Information S1). In these also, both the LT and K-components were present alongside a dual polarity ChRM, which in most cases, was only a small fraction of the initial remanence (Figure S10 in Supporting Information S1 shows demagnetization diagrams). The remanence intensity was similarly often dominated by the K-component. Of the 103 specimens measured (42 samples), 51% displayed evidence of a Carboniferous magnetization (17% S-class; 34% T-class specimen data). When grouped by localities, the ChRM mean directions are similar to those at Trowbarrow (Table 2; Table S3 in Supporting Information S1). Of these specimens, 47% were reverse polarity and 53% were normal polarity.

Some 25% of specimens displayed only evidence of the LT component or the K-component (9% and 16% respectively) without any evident ChRM. These overprints were scattered throughout the localities but were dominant at localities 1 and 10. The remaining 22% of specimens were strongly impacted by strong thermal alteration during thermal demagnetization or erratic directional behavior. The mean direction (in geographic coordinates) of the LT component is 351°/+75° ($n = 71$, $k = 11.6$, $\alpha_{95} = 5.2°$), much like that seen at Trowbarrow.

These additional localities give a (sample) mean K-component direction (without locality 2) of 190°/−20° ($\alpha_{95} = 3.9°$, $k = 16$, $n_{\text{localities}} = 5$) some 9° different from that seen at Trowbarrow (Table 2; Figure S11b in Supporting Information S1), which is significant using the test of McFadden and McElhinny (1990). In addition, the sample-based means of the K-component show a fair degree of dispersion (Table 2; Figure S11c in Supporting Information S1), which together could suggest some post-Permian tilting or rotation. However, fold tests on the K-component indicate that this component was acquired close to zero percent untilting (Table 3), with 95% confidence limits on tilting, which include zero untilting (Figures S14 and S15 in Supporting Information S1). The Fisher block rotation fold test of Enkin and Watson (1996), which accounts for vertical axis rotations, gives better grouping at zero untilting.

Fold tests were performed using ChRM directions recovered from the additional and Trowbarrow sets combined. These used different data groupings to the K-fold test, since; (a) ChRM and K-components were not evenly distributed across the localities, (b) bedding dips varied at most localities, and (*c*) the requirements of the parametric bootstraps on the fold tests require minimum numbers of data. Consequently, some localities were regrouped. The fold tests support the conclusion that the ChRM was acquired pre-tilting (Table 3; Figures S12 and S13 in Supporting Information S1). The rocks from locality 14 are notably younger than the remaining, largely Visean localities, but excluding this locality does not significantly impact the fold test. A fold-test was not possible using only the Trowbarrow dataset, since bedding dip dispersion is too small.

3.3. Magnetostratigraphy at Trowbarrow

The section is dominated by normal polarity with the 182 sampling levels comprising 76.4% normal, 20.9% reverse and 2.8% of unknown polarity (Figure 10). The inferred polarity quality is generally unevenly distributed with demagnetization behavior with N, R and R? groups containing the bulk of the S-class behaviors, and the other groups the bulk of the T-class data (Figure 3b). Conversely, the VGP_R latitudes are only weakly related to the polarity quality groups (Figures 3c and 3d) due to their dependence on angular dispersion from the mean pole, something which is more weakly represented in the qualitative polarity quality groups. The VGP_R latitudes have a similar dispersion between normal and reverse polarity (Figures 3c and 3d; 10) suggesting that any possible directional contamination is equally represented in both polarities.

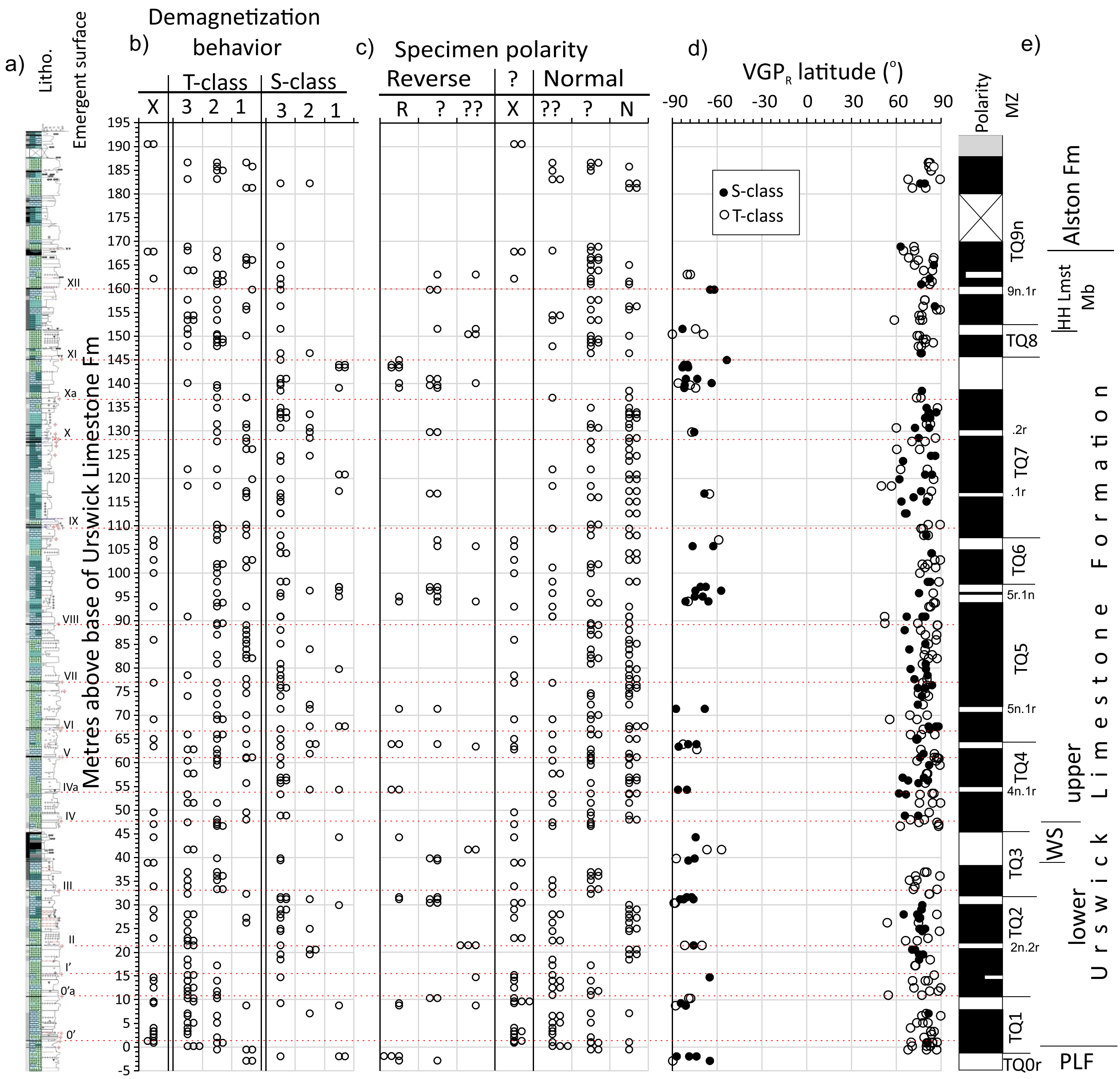
Table 3
Fold Tests on the ChRM and K-Components

Fold test type and locality	Sets	Bootstrap type	%U [−/+] or %U {p_0, p_{100},%s}	Ng/N	Figures in Supporting Information S1
ChRM means					
TQ + additional (no 2, 14)					
Progressive unfolding	grouped	parametric	106 [101,113]	8/-	S13a
TQ + additional (no 2)					
Progressive unfolding	grouped	parametric	108 [102,112]	7/-	S13b
McFadden	grouped	none	100 {0, 0.8, none}	7/-	
additional (no 2, 14)					
Progressive unfolding	grouped	parametric	112 [97,127]	5/-	S13c
additional (no 2)					
Progressive unfolding	grouped	parametric	111 [96,127]	6/-	S13d
McFadden	grouped	none	100 {0, 2.4, none}	5/-	
K-component tests (all rows in Table 2)					
Progressive unfolding	specimens	Re-sampling	4 [−7/+15]	-/303	S15a
Progressive unfolding	grouped	Parametric	5 [−2/+13]	8/-	S15b
Fisher block rotation	grouped	Parametric	0 [−10/+10]	8/-	S15c
McFadden	grouped	none	15 {0%, 0%; none}	8/-	
Excluding site 2					
Progressive unfolding	specimens	Re-sampling	1.7 [−5.7, 9.7]	-/298	S15d
Progressive unfolding	grouped	Parametric	−5 [−15,5]	7/-	S15e
Fisher block rotation	grouped	Parametric	0 [−10/+10]	7/-	S15f
McFadden	grouped	none	5 {0%, 0%; none}	7/-	

Note. Set is using either the specimen-data or grouped data (partitioned by bedding dips) as in Table 2. %U = most-likely unfolding percent and 95% confidence limits on unfolding displayed in [−/+.]. p_0, p_{100} are the probability of exceeding the f-statistic for the 0% and 100% unfolding cases respectively, that is, values <5% indicate the 0% or 100% unfolding scenarios are unlikely. %*s* = the acceptable unfolding percent for a synfolding solution. 95% confidence limits determined with 1,000 bootstrap simulations. Ng = number of site groups (with similar dips), *N* = number of specimens. The ChRM data from Trowbarrow (TQ site) was grouped into three sets, the Lower Urswick Limestone Fm, Upper Urswick Limestone Fm and the Humphrey Head Mb + Alston Fm. For the ChRM tests locality 2 was not used in the McFadden (1998) fold test since it has too few points. Using Pmagtool v.5 (Hounslow, 2023b). The DC foldtest of Enkin (2003) cannot be easily applied here since the bedding dips vary in the groups. Progressive unfolding is the test of Watson and Enkin (1993), and Fisher block rotation that of Enkin and Watson (1996).

Nine reverse magnetozones (TQ0r to TQ5r.1r, TQ5r.2r to TQ8r) are defined with two or more adjacent samples, each with multiple specimens (Figure 10e). Seven sub-magnetozones (TQ2n.2r, TQ4n.1r, TQ5n.1r, TQ5r.1n, TQ7n.1r, TQ7n.2r and TQ9n.1r) are defined with multiple specimens from a single sample. Two rather more tentative submagnetozones are defined with one or two lower quality specimens (TQ2n.1r, TQ9n.2r; Figure 10e).

Cózar et al. (2022c) have proposed a set of regionally correlated (between Ireland, northern England and south Wales) emergent surfaces, with Trowbarrow as the reference section (Figure 10a). Independent means of assessing the missing time in the rock record at these emergent surfaces could be based on a variety of generalized modeling and observational data (Barnett et al., 2002; Rygel et al., 2008), and cyclostratigraphy (Hounslow, Cózar, et al., 2024). If the magnetic polarity changes across the emergent surface, this suggests a possible missing interval, since there is no reason to suppose that changes in polarity and drops in sea-level should be coincident (unless by chance). Four of the emergent surfaces (O'a, II, Iva and XII) display a switch in polarity across these surfaces, suggesting that missing intervals may be present at the bases of magnetozone TQ2n, TQ2n.2n, TQ4n.1r, and TQ9n.2n. Also, the complex of paleosols around emergent surface X, show a change in polarity across the overlying paleosol at 129.5 m (base of TQ7n.2r). Other emergent surfaces do not coincide with polarity changes, so polarity offers no evidence of likely missing intervals. The base of TQ8n occurs some 1.5 m above surface XI, possibly coincident with a prominent burrowed surface some 70 cm below sample TQ142. Emergent surface VII is the most intensely mamillated surface and has the thickest silty paleosol in the quarry; therefore, it may



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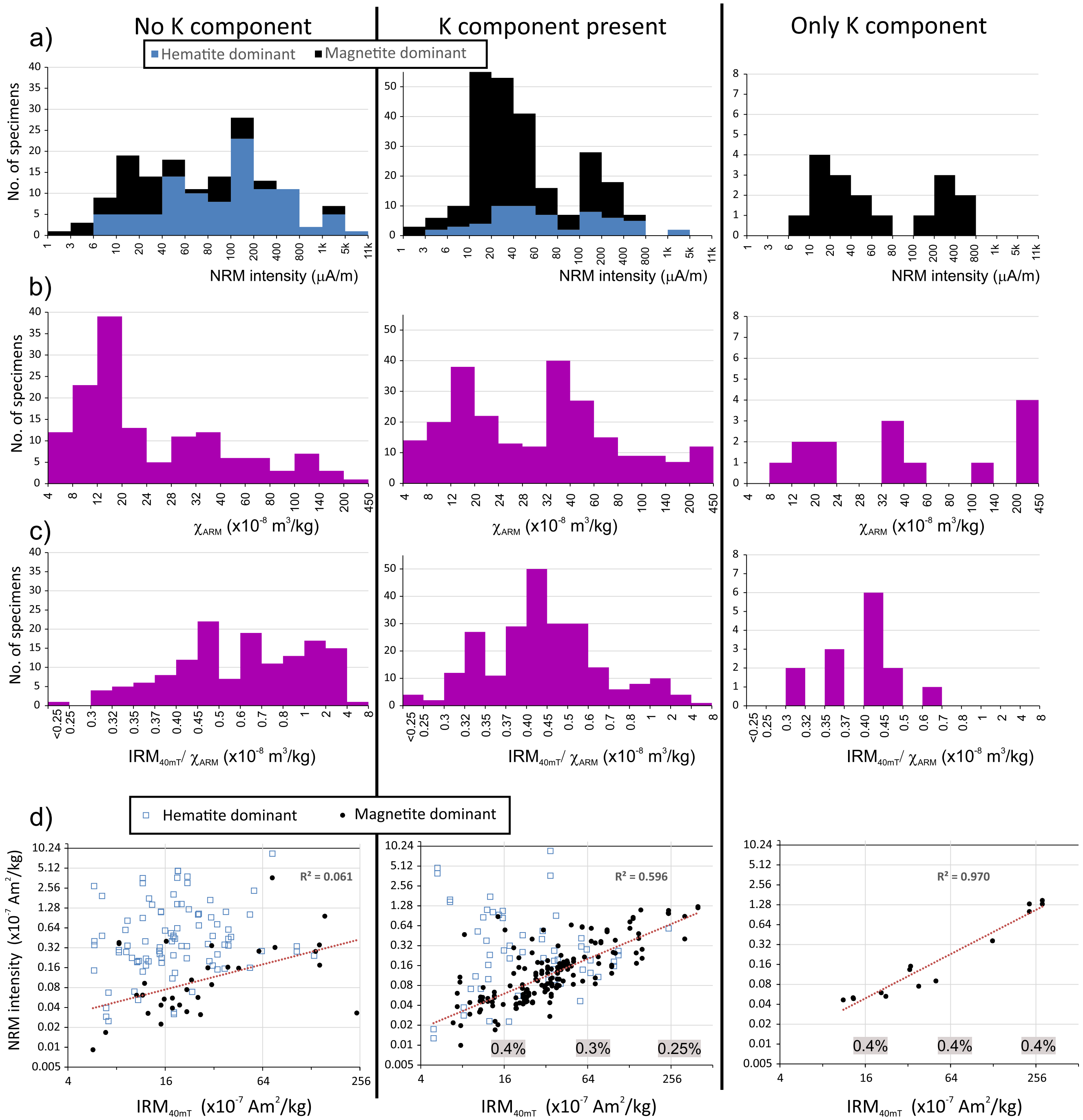

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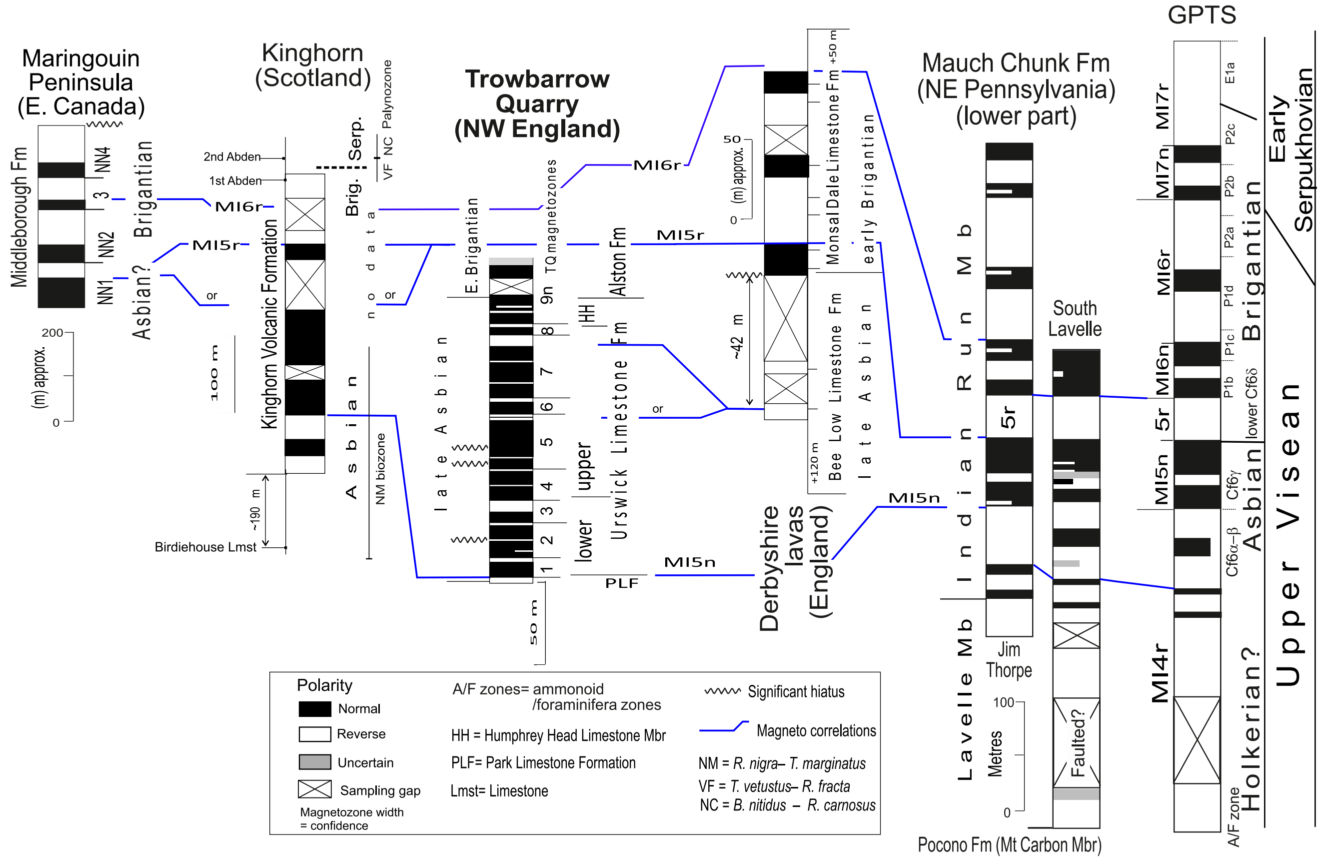

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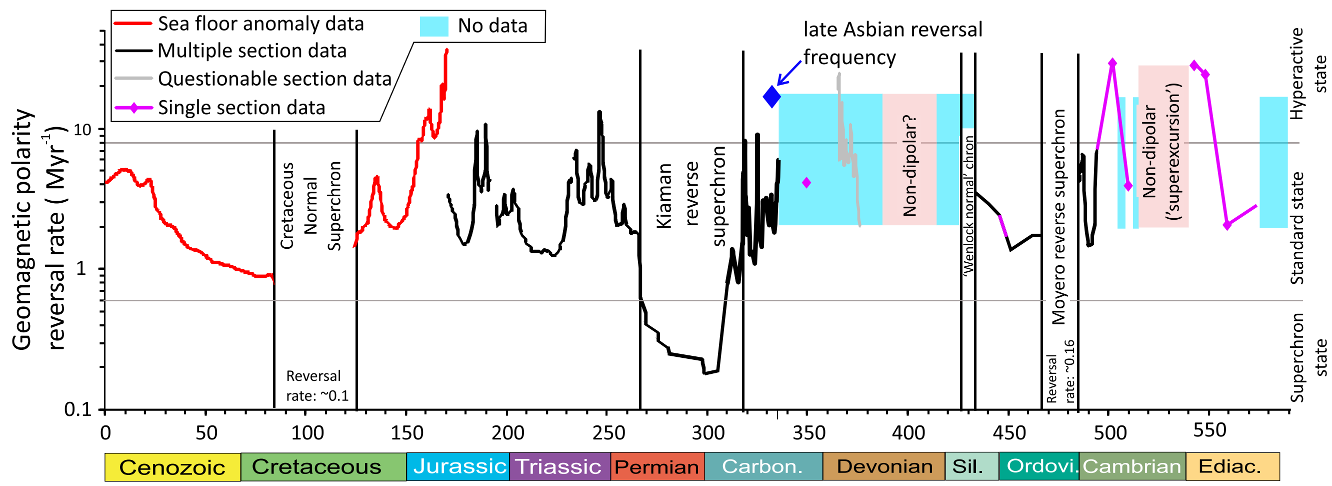

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ADVANCING EARTH AND SPACE SCIENCES

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