Supplementary Material for "Magnetic Domain States and Critical Sizes in the Titanomagnetite Series"

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S1 - Curie Temperatures of Natural Samples

To demonstrate the importance of our study, we compiled 1391 Curie temperature measurements for igneous rocks from a compilation of 38 papers (Ozima et al., 1968; Larson et al., 1969; Kono, 1974; Coe et al., 1978, 1984; Chauvin et al., 1991; Sherwood et al., 1993; Mankinen, 1994; Tsunakawa & Shaw, 1994; Gonzalez et al., 1997; Rolph, 1997; Hill & Shaw, 1999, 2000; Calvo et al., 2002; Carvallo et al., 2003, 2004; Wang & Van der Voo, 2004; Feinberg et al., 2006; Matzka & Krása, 2007; Böhnel et al., 2009; Calvo-Rathert et al., 2009, 2011, 2013; Tanaka & Komuro, 2009; Ferk et al., 2010, 2012; Michalk et al., 2010; Paterson et al., 2010; Donadini et al., 2011; Fontana et al., 2011; de Groot et al., 2012, 2013; Vérard et al., 2012; Piper et al., 2013; Villasante-Marcos & Pavón-Carrasco, 2014; Ahn et al., 2016; Bowles et al., 2018, 2020). These results were filtered to exclude results which could not be titanomagnetites by using a maximum Curie temperature of 590∘C. A histogram of the results (with a maximis shown in Figure S1, ignoring results with a maximum temperature higher than that consistent with magne. Around 25% of these measured T_C values fall into the 580°C bin, indicating that the predominant carrier is magnetite in ∼25% of all igneous rocks. This indicates that the remaining 75% have a magnetization predominantly carried by titanomagnetites or other low T_{C} magnetic minerals.

S2 - Intrinsic Properties of the Titanomagnetite Series

To be able to simulate the titanomagnetite (TMx, where "x" denotes the titanium percentage) series using the Micromagnetic Earth Related Robust Interpreted Language Laboratory (MERRILL; Ó Conbhuí et al., 2018), continuous descriptions of intrinsic magnetic properties are needed. This includes compositional variations of the Curie temperature (T_{C}), as well as compositional and temperature dependence of saturation magnetization (M_s), the first and second anisotropy constants (k_1 and k_2, respectively), and the exchange interaction constant (A_{ex}). We fit these parameters to existing datasets, cited in their respective sections below. The results of our fits at room temperature for the compositions used in this study are shown in Table S1. Further details are given in the respective sections for each parameter.

S2.1 - Curie Temperature

A total of 95 T_{C} data spanning the full compositional range (magnetite to ülvospinel) were compiled from 19 sources (Akimoto et al., 1957; Uyeda, 1958; Syono, 1965; Ozima & Larson, 1970; Readman & O'Reilly, 1972; Robins, 1972; Hauptman, 1974; O'Donovan & O'Reilly, 1977; Rahman & Parry, 1978; Özdemir & O'Reilly, 1978; Keefer & Shive, 1981; Nishitani & Kono, 1983; Heider & Williams, 1988; Moskowitz, 1993; Wanamaker & Moskowitz, 1994; Hunt et al., 1995; Sahu & Moskowitz, 1995; Dunlop & Özdemir, 1997; Moskowitz et al., 1998). The data are presented in Figure S1 alongside the best-fit polynomial of the form:

$$T_{\mathrm{C}} = 372.37x^3 - 691.52x^2 - 413.85x + 580^{\circ}\mathrm{C}, \quad (1)$$

where x here denotes a fraction rather than a percentage (e.g. x=0.6 for TM60). The polynomial is constrained such that T_{C} is 580°C for magnetite and -153°C for ulvospinel.

S2.2 - Saturation Magnetization

A data set of 486 M_{s} measurements from 19 sources were compiled (Pauthenet & Bochirol, 1951; Akimoto et al., 1957; Uyeda, 1958; Syono, 1965; Ozima & Larson, 1970; Ozima & Sakamoto, 1971; Rahman & Parry, 1978; Özdemir & O'Reilly, 1978; Nishitani & Kono, 1983; Wechsler et al., 1984; Moskowitz & Halgedahl, 1987; Newell et al., 1990; Banerjee, 1991; Kąkol et al., 1991a, 1991b; Moskowitz, 1993; Kąkol et al., 1994; Moskowitz et al., 1998). This represents compositions from TM00 to TM70. MERRILL requires input Ms values as volume normalized magnetizations in A/m, but some studies report Ms as mass normalize in Am2/kg. To convert these units, we use a density-composition relationship derived from density data for TM00, TM60, and TM100 (Hunt et al., 1995; Dunlop and Özdemir, 1997): $\rho(x) = -418.03x + 5194.9$. The room temperature M_s values obtained from our fit to the data at the compositions used in this paper are given in Table S1.

S2.3 - Anisotropy Constants

For k_1, we compiled a set of 99 data from 13 sources, spanning TM00 to TM68 (Bickford Jr, 1950; Williams & Bozorth, 1953; Calhoun, 1954; Bickford et al., 1957; Syono, 1965; Fletcher & O'Reilly, 1974; Moskowitz & Halgedahl, 1987; Kąkol et al., 1991b; Aragón, 1992; Kąkol et al., 1994; Sahu & Moskowitz, 1995; Hunt et al., 1995; Martín-Hernández et al., 2006).

For k_2 only 27 data points are available from four sources, spanning TM00 to TM55 (Bickford et al., 1957; Syono & Ishikawa, 1963; Kąkol et al., 1991b; Martín-Hernández et al., 2006) We note that the limited compositional range of k_2 data restricts room temperature micromagnetic models to TM00–TM60. The room temperature k_1 and k_2 values obtained from our fits to the data at the compositions used in this paper are given in Table S1.

S2.4 - Exchange Constant

Limited data are available for the variation of the exchange interaction (A_{ex}) for the titanomagnetite series – data are only available for magnetite at a range of temperatures (Heider & Williams, 1988). A fit to these temperatures yielded the following relation:

$$A_{ex}(T) = 1.3838 \times 10^{-11} \left(1 - \frac{T}{T_C}\right)^{0.67448}, \tag{2}$$

where T and T_C are measured in °C and $T_C = 580$°C for magnetite. The fit to the data is plotted in Figure . This fit results in a room temperature (20°C) A_{ex} of 1.351×10^{-11} for magnetite. To scale this for compositional variation in the titanomagnetite series we use a Curie temperature scaling law proposed by Chikazumi (1964) and used in early TM studies (Butler & Banerjee, 1975; Moskowitz, 1980; Moskowitz & Halgedahl, 1987). A_{ex} at room temperature is therefore given by the formula:

$$A_{\mathrm{ex}}(x) = 1.3838 \times 10^{-11} \left(\frac{T_{\mathrm{C}}(x) + 273.15}{853.15} \right) \left(1 - \frac{20}{T_{\mathrm{C}}(x)} \right)^{0.67448}, \quad (3)$$

where $T_{\mathrm{C}}(x)$ is given by Equation 1.

Text S3 - Visualization of Magnetization States

The relative helicity h_{rel} - used to calculate the presence of vortex cores and magnetization states is given by the formula:

$$h_{rel} = \frac{\hat{m} \cdot \nabla \times \hat{m}}{||\nabla \times \hat{m}||}, \quad (4)$$

where $\hat{m}$ is the magnetization unit vector at a given location in the mesh. An isosurface of $|h_{rel}| = 0.95$ was plotted for everywhere that $||\nabla \times \hat{m}|| \geq 1$ (as h_{rel} becomes noisy when $||\nabla \times \hat{m}||$ is close to zero).

$|s_c|$, used to color the LEM states, is given by:

$$|s_c| = \frac{|\hat{m} \cdot M|}{||M||} \quad , \quad M = \iiint_V \hat{m} \; dV. \quad (5)$$

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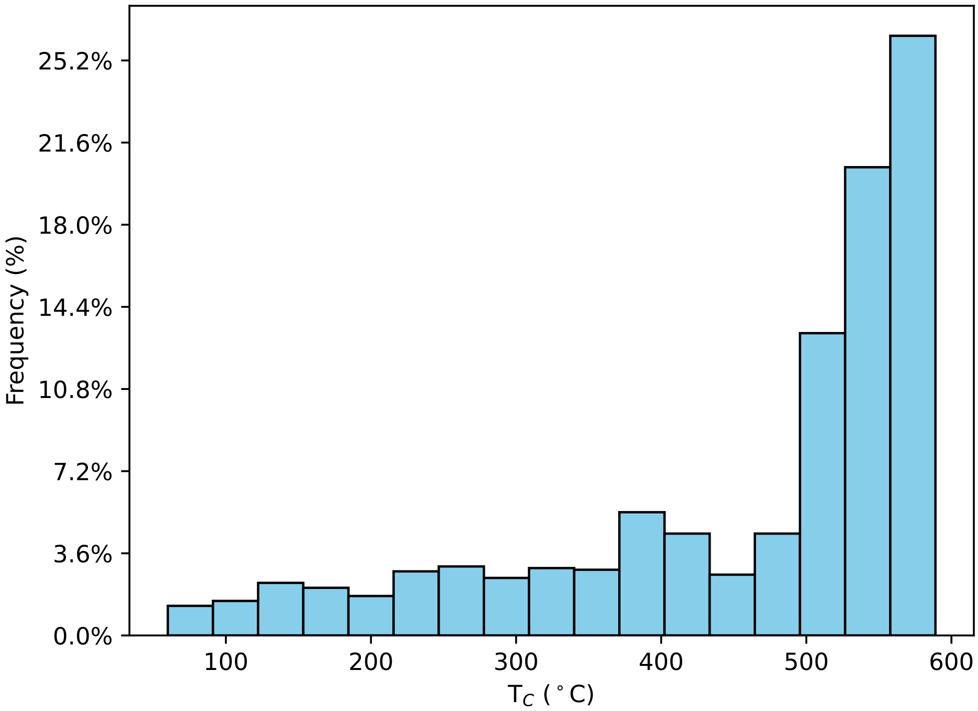

Figure S1. Histogram of measured Curie temperatures of igneous rocks from a compilation of 38 papers.

Table S1. Rock magnetic properties for the TM series at 20°C, generated by fitting to the datasets referenced in the text.

x (%)	T_C (°C)	M_s (kA/m)	k_1 (10^4 J/m^3)	k_2 (10^4 J/m^3)	A_{ex} (10^{-11} J/m)
0	580.00	488.46	-1.2209	-0.4303	1.3514
5	557.63	450.33	-1.7818	0.0841	1.3147
10	532.07	414.59	-2.1315	0.3954	1.2727
15	503.62	381.01	-2.2983	0.5217	1.2259
20	472.55	349.40	-2.3095	0.4995	1.1747
25	439.14	319.54	-2.1919	0.3826	1.1196
30	403.66	291.22	-1.9718	0.2385	1.0608
35	366.41	264.22	-1.6752	0.1452	0.9988
40	327.65	238.33	-1.3274	0.1826	0.9340
45	287.67	213.32	-0.9534	0.4214	0.8665
50	246.74	188.96	-0.5781	0.9008	0.7965
55	205.15	164.97	-0.2261	1.5900	0.7239
60	163.17	141.06	0.0772	2.3172	0.6480

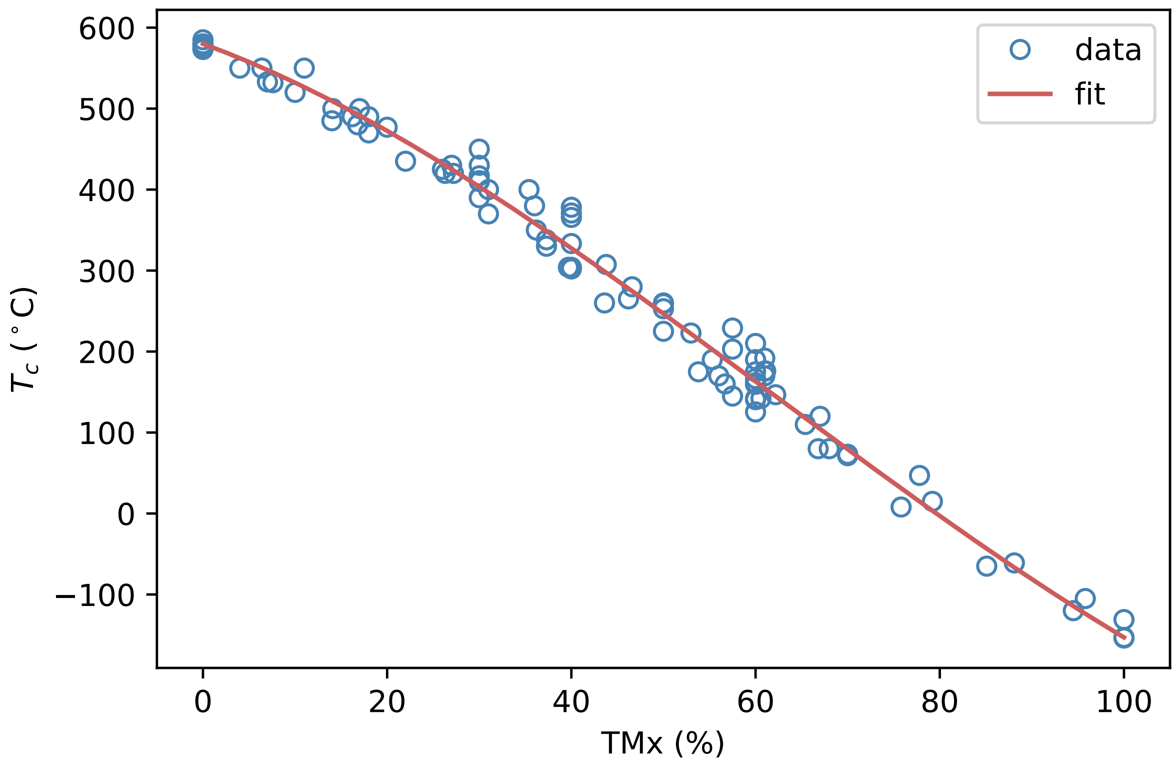

Figure S1. Curie temperature as a function of titanomagnetite composition. Blue circles: Individual data points, Red line: polynomial fit to data.

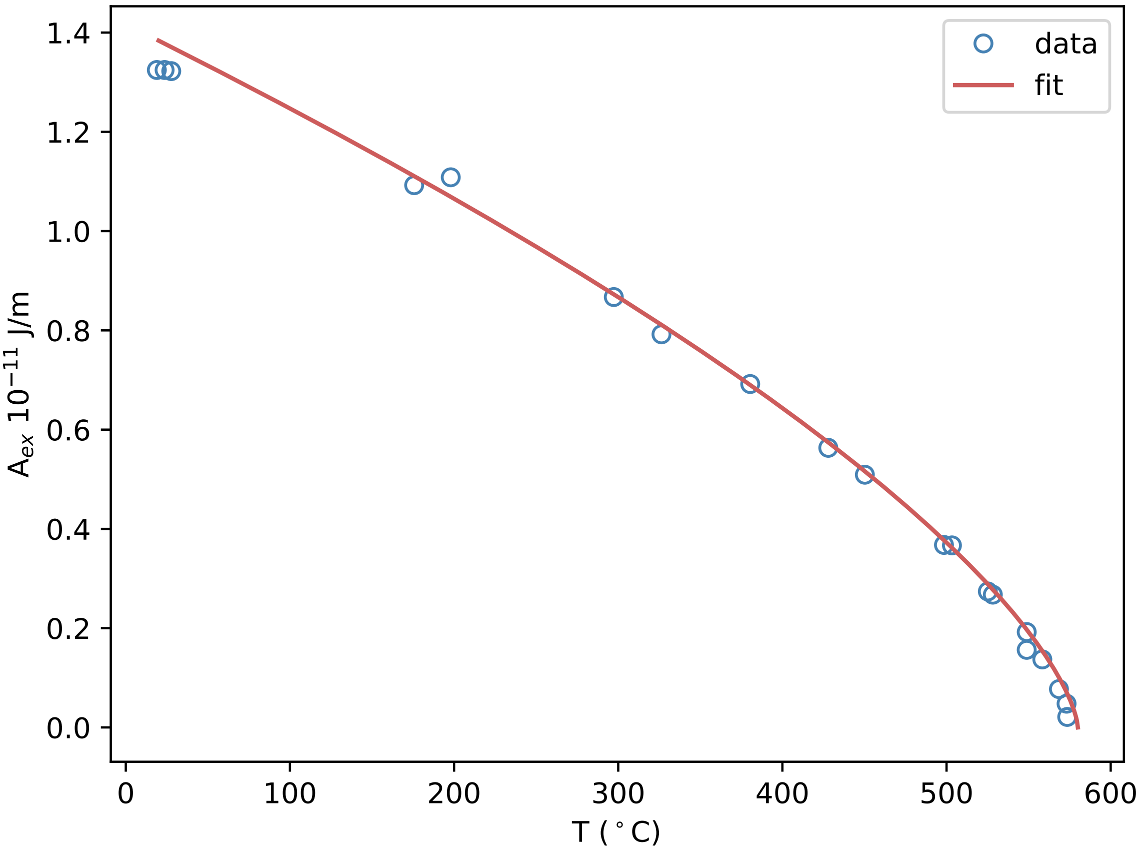

Figure S2. Exchange constant for magnetite as a function of temperature (blue circles) and fit to these data (red line) given by Equation 2.