Rock magnetic and Magnetic Anisotropy of Igneous Rocks from Taimyr Peninsula, Arctic Russia

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1. Abstract

Studies of rock magnetism and anisotropy of magnetic susceptibility (AMS) on folded igneous rocks from South Taimyr Peninsula, Arctic Russia are presented. The magnetic remanence is principally carried by fine grained, low-temperature oxidized titanomagnetite, and hematite is the secondary carrier in the basalts. The sills display remarkably homogeneous magnetic properties and contain larger grains with ilmenite lamellae, attesting to slow cooling. Basaltic flows possess slightly more variable magnetic properties, and homogeneous skeletal titanomagnetite suggests rapid cooling. Differences in magnetic properties in sills and basalts are caused by titanomagnetite concentration as well as grain size. Stepwise thermal demagnetization shows a stable primary remanence in the sills and basaltic flows; statistic analysis reveals that the characteristic remanence components are isolated with small within-site dispersion of the mean direction. AMS study was performed on untreated samples and samples that had been previously heated to 600°C during a paleomagnetic study to investigate the AMS properties. Laboratory heating did not lead to obviously consistent axis orientations.

2. Introduction

The Taimyr Peninsula lies between the Laptev and Kara seas, and occupies a central position in the geologic setting of Arctic Siberia. Rock magnetic studies of the South Taimyr igneous complex (75°N, 100°E) can not only better define magnetic carriers and their relative contribution to both the mean magnetic susceptibility and its anisotropy, but also provide a proof of remanent magnetism discussion. Based on the rock magnetic analysis, we reveal magnetic properties are related to initial grain-size variations, differential secondary chemical alterations of titanomagnetite (TM) phases, and original cooling rate differences (Petersen, 1976; Ellwood, 1986; Walderhaug, 1993). In this paper, laboratory heating experiments are performed on South Taimyr igneous rocks to get better defined AMS fabrics (Ellwood, 1986; Tarling and Hrouda, 1993; Walderhaug, 1993), and magnetic fabrics before and after heating treatment are compared to make a discussion.

3. Geological Setting and Sampling

Taimyr Peninsula is traditionally divided into three domains: North, Central and South Taimyr. Taimyr igneous rocks intrude and fold together with the Carboniferous-Lower Triassic continental clastic succession around a ENE-WSW-trending axis. The eruptive units are exposed primarily within a large band that extends across the length of the Taimyr Peninsula. The sills are 3–5 m thick and intrude the Carboniferous-Lower Triassic continental classic succession; the basaltic flows are three to five meters thick with well-preserved columnar jointing. The eruptive and intrusive rocks are generally given Permo-Triassic age designations (Bezzubtsev et al., 1983). Paleomagnetic data give ages between 230-220 Ma and 250-220 Ma for sills and basalts, respectively. Precise $^{40}Ar/^{39}Ar$ ages indicate an intrusion age of sills in the range 229-227 Ma, consistent with the paleomagnetic age (Walderhaug et al., 2005).

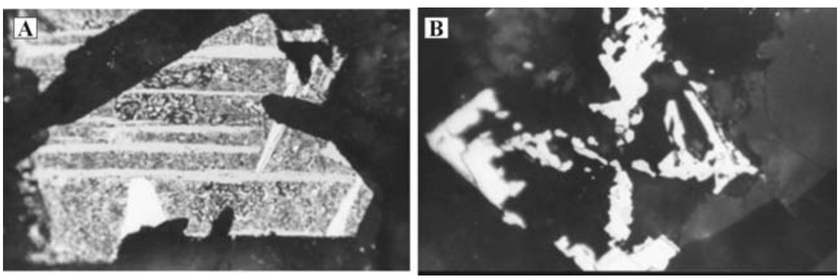

Fig. 1. Representative microphotographs of oxide magnetic minerals showing typical mineral textures; sills (A); basaltic flows (B).

4. Rock Magnetic Properties and Remanence

Identification of opaque minerals may assist in determining the origin of magnetization and the degree of deuteric and low-temperature oxidation affecting the opaque phases. As shown in Fig. 1, TM is the main magnetic phase; the sills exhibit plenty of relatively large grains ranging from TM to crystals showing ilmenite lamellae (Fig. 1A), attesting to relatively slow initial cooling; some shrinkage cracks and granular surfaces indicate low-temperature alteration (Fig. 1A). In contrast, basaltic flows illustrate homogeneous skeletal crystalline lattice (Fig. 1B), consistent with rapid cooling with little or no secondary alteration. Non-magnetic pyrite is present.

Site mean values of intensities (J) and magnetic susceptibilities (K_m) (Fig. 3A, B) for the sills and basaltic flows are typical of K_m governed by the ferromagnetic fraction (Tarling and Hrouda, 1993), and thus paramagnetic minerals can clearly be discounted because their mean susceptibilities are on the order of 5×10^{-4} SI (Wagner et al., 1981; Hrouda, 1982) which are less than most susceptibilities of this study. Consistently high Curie temperatures (510°C-580°C for sills and 450°C-580°C for basaltic flows) from thermomagnetic analysis indicate relatively uniform chemical composition of magnetic phases in both sills and basalts, leaving variations in TM concentration as the main controlling influence on J. According to the modified ratio $Q'=(10^7/4\pi)*(J_r/kH)$ SI, where H is the magnitude of the present geomagnetic field, most specimens were characterized by high values (Q'>1), indicating finer grains in single-domain (SD) or pseudo-single-domain (PSD) states contribute to stable remanence; while some specimens from sites S3-6, 13 & 14 illustrate Q'<1, consistent with partial contribution from larger PSD or multidomain (MD) magnetic grains. Remenent coercive force (H_{cr}) values obtained from isothermal remanence acquisition curves suggest that remanence is mainly carried by PSD or SD grains in most cases.

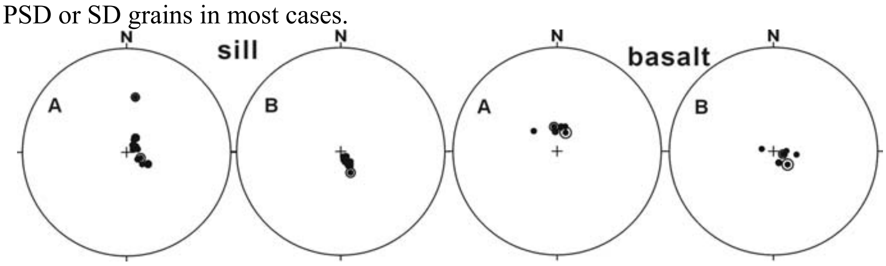

Fig. 2. Stereographic projections of average characteristic remanent magnetization directions with α_{95} confidence limit circles for each site in Taimyr igneous rocks. A: In situ. B: Bed-corrected. Low hemisphere.

Table 1 Directional statistics for the principal remanence component in sills and basalts. N = number of demagnetised samples; n = number of samples used to calculate means; D(°)/I(°) = mean Declination/Inclination; κ = Fisher precision parameter; α_{95} = 95 per cent confidence circle of mean.

	Unbed-corrected						Bed-corrected			
Rock types	N	n	D(°)	I(°)	k	α95	D(°)	I(°)	k	α95
Sills	92	76	65.6°	76.3°	17.62	11.2	358.9°	65.5°	47.71	8.8
Basalt flows	50	44	147.5°	75.4°	196.62	3.3	115.4°	78°	34.68	10.4

A selection of samples were thermally demagnetised, with a MMTD1 furnace, at temperatures as high as 600-660°C and typically in 10-13 steps. Directions of remanent magnetization were determined by principal component analysis (Kirschvink, 1980). In sills, initial components are relatively minor and are removed by low temperatures (<350ºC); steeply down-pointing components are determined with much higher temperatures mainly from 500ºC to 590ºC. Basaltic flows show a single-component, down-pointing magnetisation, with blocking temperatures between 435ºC and 550ºC or even above 660ºC in some case. Unblocking temperatures suggest that Ti-poor TM and TM are the most likely carriers of the remanence at most sites, although hematite seems to be significant in some basaltic samples. Characteristic remanence (ChRM) directions are summarized in Table 1 and Fig. 3. The within-site dispersion of ChRM directions is very small: α_{95} is less than 5° and Fisher precision parameter Κ varies from 122 to 970 at all sill sites; Κ exceeds 2000 at one basalt site S19. Application of tilt corrections makes data cluster better than in-situ directions and gives tight between-site grouping for both sill and basalt samples. The improvement in between-site grouping after the possible bed corrections implies that the rocks have been tilted since solidification.

5. AMS of the Sills and Basalts

AMS is generally a complex phenomenon due to the mixed contribution of different magnetic minerals and domain states to the overall anisotropy of a sample. As revealed in Fig. 3A, K_m increased after heat treatment above 600°C in the sill mainly due to chemical conversion, growth of new oxides, or grain size variation; magnetite develops within original crystals, giving a strong increase in susceptibility. In contrast, K_m decreased in the basalt (Fig. 3B), likely indicating alteration of magnetic minerals, transformation of magnetic phases (i.e. oxidation of magnetite to hematite) or the producing of SD-PSD state upon heating up (Hirt and Gehring, 1991; Walderhaug, 1993; Henry, 2003). P (K_1/K_3) values are the usual for igneous rocks with a primary magnetic fabric (Hrouda, 1982; Staudigel et al., 1992; Callot et al., 2001). Heating leads to a general decrease of $P(K_1/K_3)$ (Fig. 3A, B), may be due to the removal of secondary anisotropies related to tectonics (Park et al., 1988) and low temperature oxidation, implying a primary emplacement effect overlain by spurious secondary AMS components (Hirt and Gehring, 1991; Walderhaug, 1993). In addition, alteration of magnetic minerals and formation of new magnetic phases further contribute to a lowering of anisotropy. Both values L (K_1/K_2) and F (K_2/K_3) show a decrease after heating (Fig. 3A, B). The shape of the AMS ellipsoid has no significant tendency towards either an oblate or a prolate fabric prior to thermally treatment (Fig. 3A, B), similar to what Knight and Walker (1988) found in the Hawaiian basic dyke, but shows a consistent oblate pattern for heated basalts (Fig. 3B). A relative decrease of P in Taimyr igneous rocks on heating is in contrast with the results of Henry (2003) but consistent with Walderhaug (1993). Strongly defined fabrics have been reported (Potter and Stephenson, 1988; Hirt and Gehring, 1991; Rochette, 1992; Walderhaug, 1993), but the heating treatment has caused changes other than a simple modification (Henry 2003).

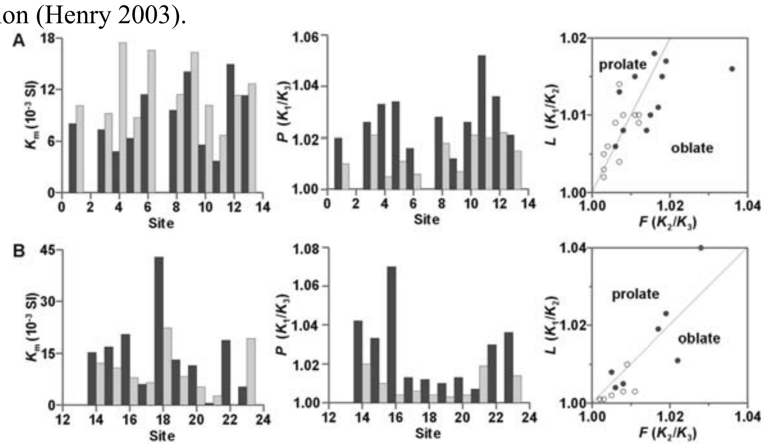

Fig. 3. Profiles of bulk susceptibility, anisotropy degree (P), and Flinnplot for sills (A) and basalts (B) before (black) and after (grey columns and open circles) heating selected samples. Foliation (F) vs. lineation (L) diagrams indicate the shape of the anisotropy of magnetic susceptibility ellipsoid.

The distribution of AMS principal axes is presented in Fig. 4. It appears that sites S5 and S11 from sills undergone shallow-inclined K_1 axes move out of the plane of bedding and towards the bedding normal, K_2 and K_3 move towards the bedding plane, resulting in an improved definition of K_1 axes after heating to 600°C; accordingly, ellipsoid shapes also change as shown in Fig. 3A, B. A transition from PSD or larger grains to SD ones could cause the swap of K_1 and K_3 axes when grains are controlled by uniaxial shape anisotropy (Potter and Stephenson, 1988; Walderhaug, 1993). This mechanism could explain both the change in ellipsoid shape and minimum axis orientation, and is consistent with the observation that sills contain PSD or SD+MD grains. Sites S17 and S19 from the basalt undergone significant axis shift, with K_1 and K_2 axes exchanging position; interestingly, K_3 axes relatively keep stable (Fig. 4). Laboratory heating of Taimyr igneous rocks yield more information on changes in effective magnetic properties, although the heating did not achieve significantly consistent axis direction.

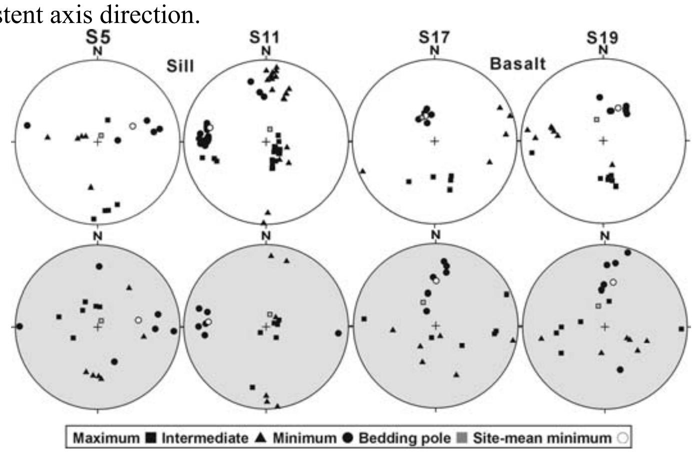

Fig. 4. Stereoplots of the AMS axes before (open) and after (grey) heating at 600 °C for sites S5, S11, S17 and S19. The site-mean minimum axis is calculated by Fisher statistics. Low hemisphere.

Inverse magnetic fabrics have been observed previously and have been ascribed to either SD magnetite (Potter and Stephenson, 1988; Rochette, 1992; Walderhaug, 1993). It is well known that SD magnetite has an inverse magnetic fabric (Potter and Stephenson, 1988), with its K_1 axis perpendicular to the sill plane (site S11 and the heated site S5 in Fig. 4), as opposite to the normal fabric in which K_3 axis should be normal to the basalt plane (unheated sites S17, 19 in Fig. 4). Partial contributions of SD and PSD or MD magnetite may yield intermediate fabrics, with K_2 axes normal to the bedding plane and K_1 and K_3 on the plane, or with no consistent orientation (unheated site S5 in Fig. 4). In this case, higher bulk susceptibility values and magnetic mineralogy have confirmed the possibility of SD behaviour which always lead to the axis inversion during AMS measurement (Potter and Stephenson, 1988; Walderhaug, 1993; Dragoni, 1997).

The interpretation of magnetic fabric is not always clear (Tarling and Hrouda, 1993). Individual AMS components may relate to magma-flow directions, cooling stress, and tectonic stress associated with magma emplacement (Walderhaug, 1993; Dragoni, 1997), rendering any predictions of "expected" initial AMS directions uncertain.According to Dawson and Hargraves (1985) K_1 axes of a flowing magma point to the flow direction and K_3 are aligned perpendicular to the dyke wall, and that K_1 approximate the pole of a dyke wall when the magma is stationary. As a tabular intrusive structure parallel to any planes or layering in the country rock, the studied sill agrees with the second case where K_1 axes are the bedding normal. Interpretation of the sill anisotropy in terms of the above model is therefore problematic, but a primary flow-controlled magnetic fabric remains a possibility.

6. Discussion and Conclusion

The ferromagnetic contribution to AMS is dominant in the Permo-Triassic sills and basalts. The mean magnetic susceptibility (K_m) for all the studied rocks is usually high. Variations in magnetic properties across these rocks are caused by varying TM concentration as well as grain size. Coarse and fine (larger PSD or MD and SD) TM grains are the main magnetic minerals in sills, whereas for the basalt, the magnetic minerals are PSD Ti-poor TM grains. The inverse fabric was recognized (Fig. 4) in the studied sill, possibly contributed by SD magnetic minerals. Newly formed ferromagnetic grains during heating either simply replace pre-existing ones or correspond to exsolution from pre-existing minerals (Hirt and Gehring, 1991; Tarling and Hrouda, 1993; Henry, 2003). Heating leads to changes or formation of new magnetic minerals and new garin sizes. Heating produces AMS changes, which does not always correspond to simple enhancement of the magnetic fabric for all samples.

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