Magnetic properties and remanent magnetization of four stony meteorites

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Magnetic properties of four stony meteorites, namely, Allende, Dhajala and St. Severin (chondrites) and Norton County (achondrite) were studied. The intensity of NRM, susceptibility and the Koenigsberger ratio of these meteorites are moderate and in the range of igneous rocks. Saturation remanent hysteresis experiments of these meteorites reveal high remanent coercive forces, giving them very high retentive capability. A study of susceptibility variation with temperature (in low temperature region) and the Lowrie-Fuller Test reveals that the magnetic material in these rocks is in a very fine grained form giving high stability to these meteorites. The laboratory demagnetization experiments (AF and thermal) indicate high mdf and blocking temperatures suggest their suitability to palaeofield intensity determinations. These magnetic properties which are similar to those of other stony meteorites suggest that the magnetic mineral in these meteorites is probably tetrataenite along with other minerals such as troilite, kamacite, magnetite, etc., with high coercive force and carry a magnetic remanence acquired in an extraterrestrial field.

MAGNETIC properties of meteorites provide information about the magnetic environment wherein they were magnetized. Studies were carried out on meteorites for estimating the palaeofield intensities and stability of remanent magnetism[1–6]. Since studies on magnetic properties are limited, in this investigation we have subjected four stony meteorite samples, namely Allende, Dhajala and St. Severin (chondrites) and Norton County (achondrite) available to us to several laboratory tests to derive as much information as possible. Being very rare, very small sized (millimeter) samples only were available for these studies. The experiments included study of natural remanent magnetic intensity, susceptibility, Koenigsberger ratio, variation of susceptibility with temperature up to liquid nitrogen temperature, saturation remanent hysteresis, stability of natural remanent magnetism to AF and thermal demagnetization. These were attempted with the objective of arriving at an understanding about the remanence carrier in these meteorites and also the nature of remanence carried by these meteorites. In fact, some of the studies that are usually carried out on terrestrial rocks have been extended to meteorites with a view to compare and correlate.

Astatic and spinner (Schonstedt) magnetometers were used for measuring remanent magnetic directions and intensities. A Schonstedt thermal demagnetizer and a two-axis tumbling arrangement similar to that described by Creer[7] were made use of in thermal and AF demagnetization studies, respectively. The hysteresis parameters were measured by magnetizing the sample to saturation using DC magnetic fields and then reducing the resulting saturation magnetization to zero, using successively increasing fields in opposite directions[8]. The susceptibility was measured on a susceptibility and low-field hysteresis apparatus[9] and its variation with temperature (in the low temperature region) was studied by immersing the sample in liquid nitrogen.

Samples of different sizes and shapes from four meteorites, viz. Allende, Dhajala, St. Severin and Norton County were available to us for laboratory investigations. Stability of remanent magnetism was studied with reference to arbitrary reference marks drawn on the samples. The small size of the Norton County sample restricted the measurements that could be made on it.

Observed values of natural remanent intensity (Jn), susceptibility (K), and Koenigsberger ratio (Qn) computed (ratio of natural remanent intensity to induced intensity in a field of 0.05 milli Tesla) for the meteorite samples are listed in Table 1. The Jn and K values vary between 0.41 to 1.04 A/m and 1.06 to 30.78×10^{-3} SI units respectively. The Qn-ratios computed are between 0.07 and 1.37. The NRM intensities observed are similar to those reported earlier[1–3] for Allende and Orgueil, whereas for Dhajala, an iron-rich meteorite[10] from Gujarat India, it is one order higher. The observed susceptibility values of these four meteorites are more or less identical, with Dhajala registering a value of an order more than the rest. Therefore, the Jn and K values of these meteorites appear to be moderate and comparable with those of igneous rocks of terrestrial origin containing magnetite and other minerals. The Qn values suggest no dominance of spurious viscous components of magnetization in these meteorites.

Coercivity of remanence is considered an important rock magnetic property of a magnetic material. It is related to the retentive capacity of remanence in rocks. It

Table 1. Magnetic properties of some stony meteorites

Meteorite	Allende	Dhajala	St. Severin	Norton County
Classification	C Chondr.	H Chondr.	LL Chondr.	Achondrite
Sample no.	2TF	T-11	7-T	N-23-5
Jn (A/m)	0.73	1.04	0.87	0.41
$K \times 10^{-3}$ SI units	1.06	30.78	3.92	4.72
Qn-ratio	1.37	0.07	0.44	0.17
Hs (mT)	200	750	750	–
Hcr (mT)	55	65	125	–
$Jrs \times 10^{-3}$ (A/m)	0.06	0.67	1.07	–
T_B (°C)	675	650	675	–
Domain nature	CD	Maghaemitic	CD	CD

Jn = Natural remanent magnetic intensity; K = Magnetic susceptibility; Qn = Koenigsberger ratio; Hs = Saturating field; Hcr = Remanent coercive force; Jrs = Saturation remanent magnetization; T_B = Blocking temperature.

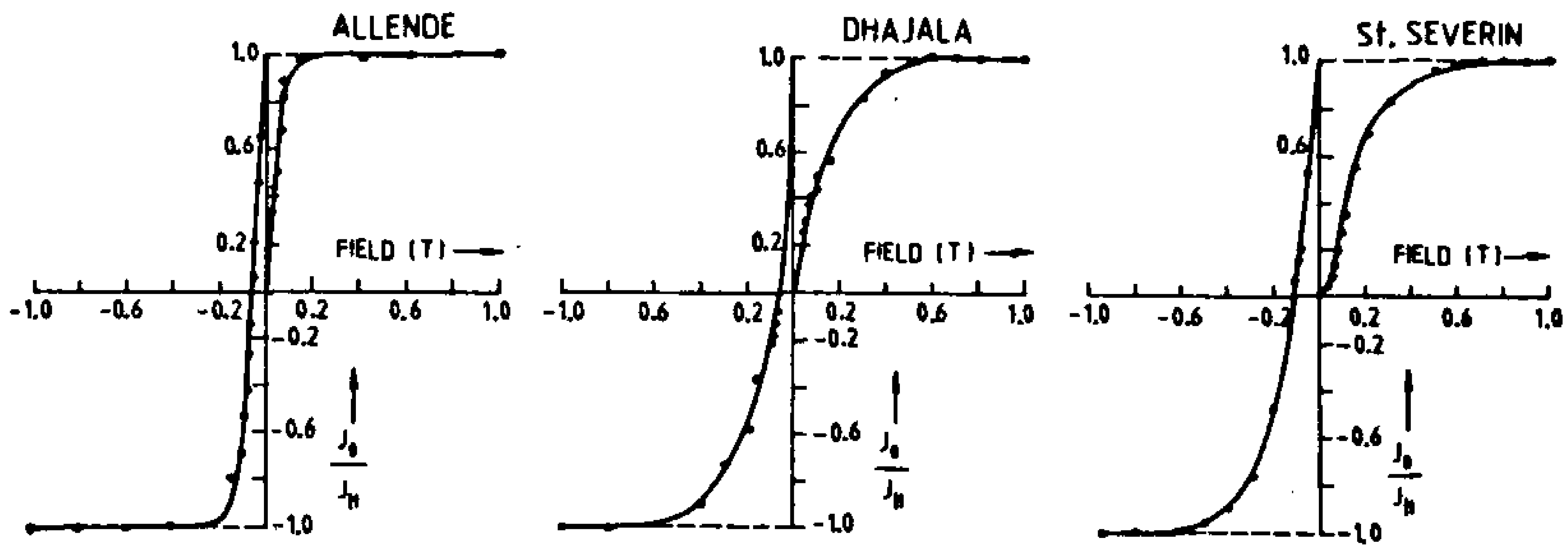

Figure 1. Saturation remanent hysteresis curves for the meteorites Allende, Dhajala and St. Severin. Magnetizing field is in Tesla and intensity of acquired magnetization is normalized.

depends on the composition as well as the size of the magnetic grains in rocks. We have studied the remanent hysteresis properties of Allende, Dhajala and St. Severin meteorites by magnetizing them in increasing DC magnetic fields up to 1 Tesla, till the samples are saturated and thereafter by reducing the resulting saturation magnetization to zero and saturating the sample in the opposite direction. The entire procedure is once again repeated by reversing the sample and saturating it to obtain a complete hysteresis curve. Remanent hysteresis curves obtained for the meteorite samples are shown in Figure 1. The hysteresis parameters are listed in Table 1. These curves indicate remanent coercive forces of 125–55 mT requiring saturating fields 750–200 mT, with saturation remanent magnetizations of 1066.5–58.6 A/m. It can be noted that Allende sample saturated in a very low saturating field of 200 mT with a remanent coercive force of 55 mT and with a low saturation remanent magnetization of 58.6 A/m. St. Severin showed the highest coercivity with high saturation remanent magnetization. Dhajala, the Indian mateorite sample, is comparable with Allende in remanent coercivity and with St. Severin in saturation remanent magnetization intensity and saturating field. It can further be stated that the hysteresis parameters of meteorites are comparable with those of terrestrial rocks but are slightly higher. Petrographic study of Allende and St. Severin meteorites reveal tetrataenite, an iron–nickel alloy as the magnetic mineral in these meteorites[2,3,5,6]. In Dhajala, the petrological studies[10] also reveal the presence of troilite, kamacite, taenite, chromite, etc. and are responsible for the observed magnetic properties in it.

Granulometric techniques were used to quickly ascertain the nature of magnetic grains as well as their domain states in rocks[11,12]. One of them is the study of variation of susceptibility with temperature. On the basis of extensive studies on basalts, they have proposed typical K-T curves for inferring different domain states (SP, SD, MD, CD, etc.) in them. When a magnetic material (magnetite) is cooled to liquid nitrogen temperature, it undergoes a phase transition at its isotropic point of

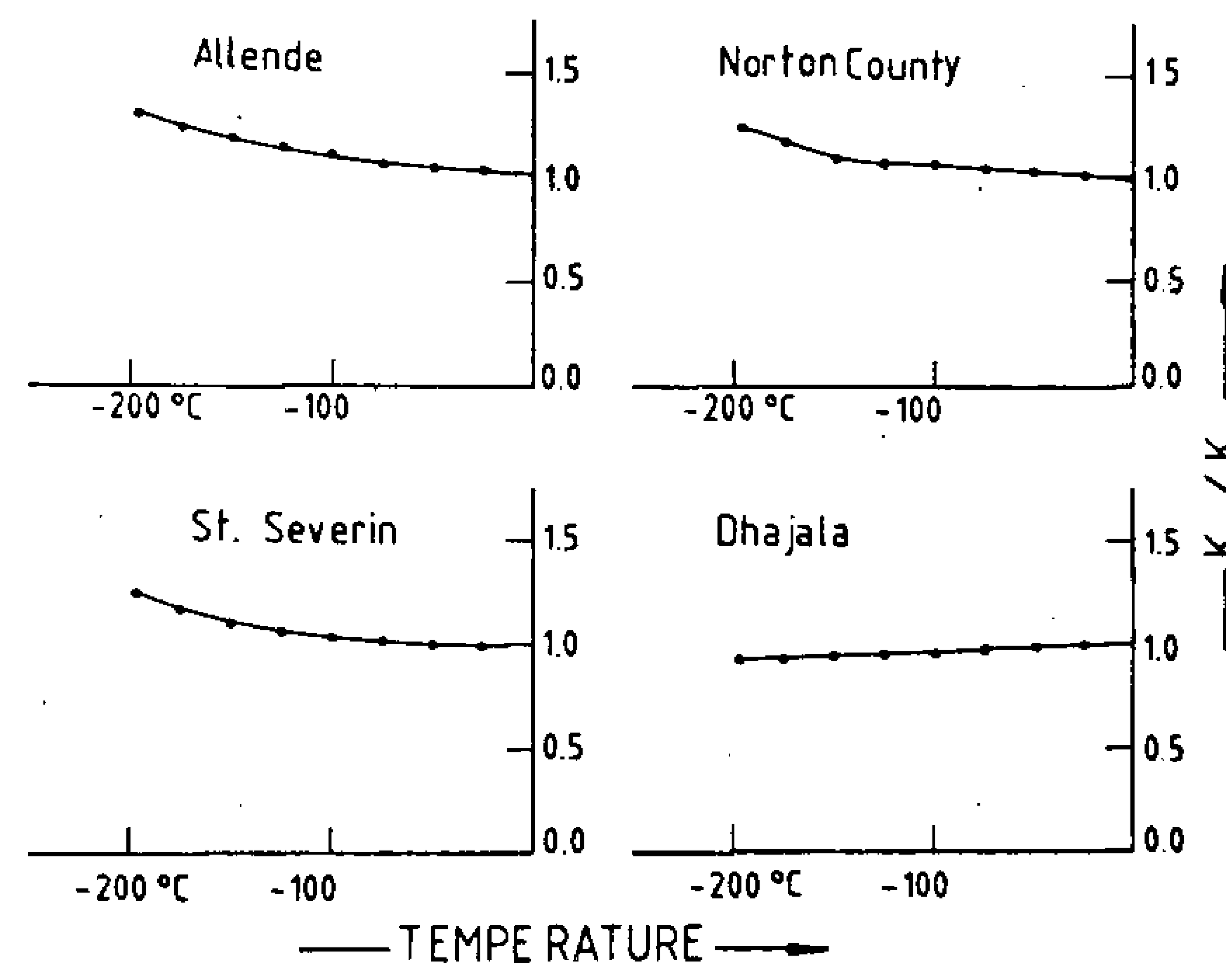

Figure 2. Susceptibility variation with temperature, as the samples are cooled in liquid nitrogen. Note the increase in its value at −196° for Allende, Norton County and St. Severin and a slight decrease for Dhajala.

−150°C and shows a susceptibility peak at this temperature.

In our present study, we observed K-T curves on the meteorite samples on the low temperature region by cooling them in liquid nitrogen. The observed K-T curves are shown in Figure 2. The curves for Allende, Norton County and St. Severin show an increase in relative susceptibility (1.25) at −196°C, whereas the Dhajala sample showed a slight decrease in relative susceptibility (0.94) at −196°C compared with their values at room temperature without any peak at −150°C. Therefore, it can be inferred from these studies that the magnetic grains in Dhajala are similar in form to those of maghaemite, while in the rest of them they are in the CD state[13] which are therefore inferred to be in fine-grained state in these meteorites.

Stability of remanent magnetism of the meteorite samples has been tested by both alternating field and

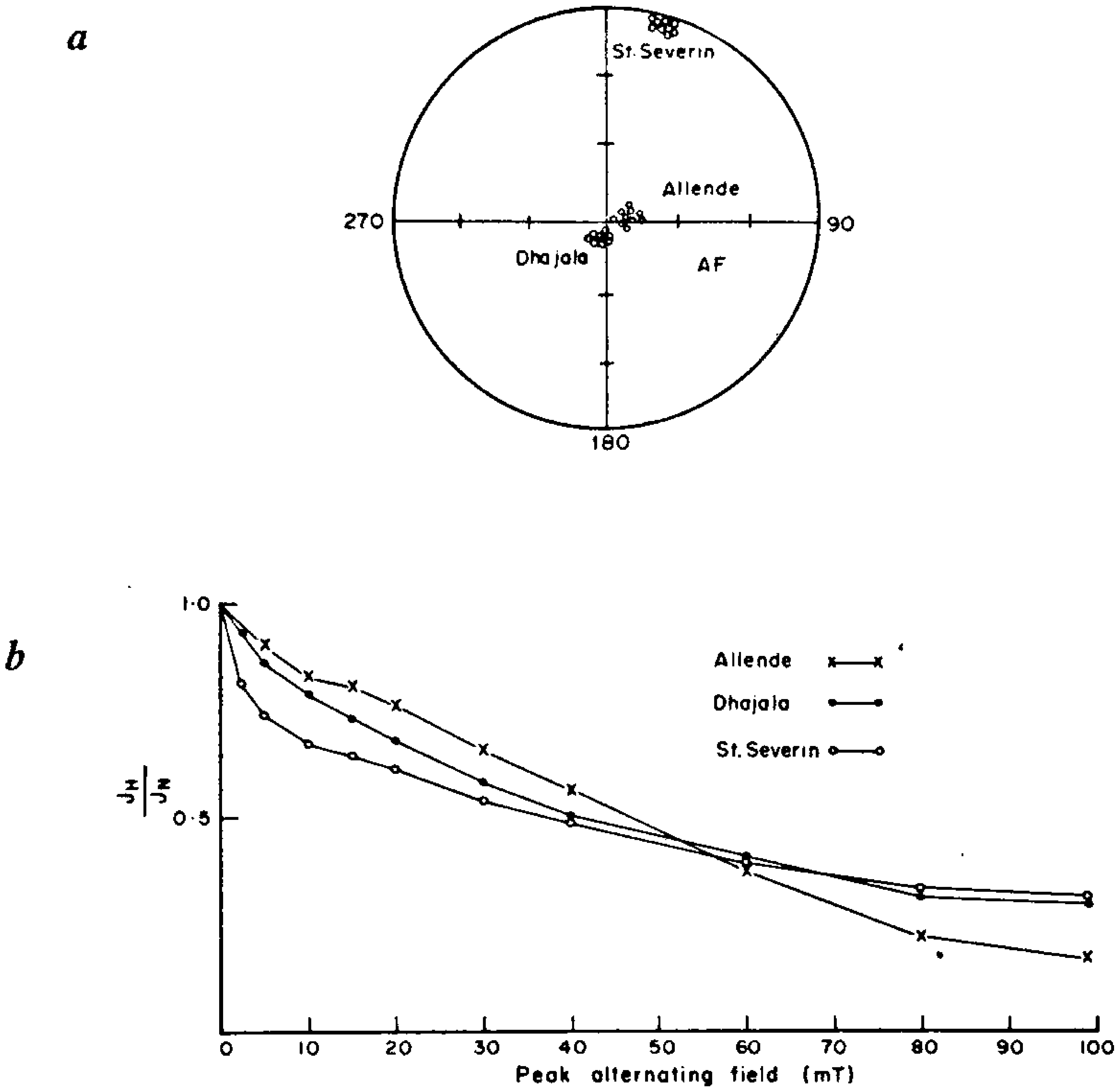

Figure 3. AF demagnetization characteristics of Allende, Dhajala and St. Severin meteorites. *a*, Vector migration and *b*, Intensity decay diagrams in progressively increasing peak fields. Open (closed) circles represent upward (downward) inclinations.

thermal demagnetization methods by drawing arbitrary reference marks. Samples from Allende, Dhajala and St. Severin only could be studied and that from Norton County, being too small, could not be studied. In both the studies the samples were subjected to increasing peak fields and temperatures in steps up to 100 mT and 700°C in about 11 and 14 steps respectively. Remanent magnetism was measured after each demagnetization treatment. The samples showed extreme stability of remanent magnetism during both AF and thermal demagnetization studies. Typical laboratory demagnetization characteristics are given in Figure 3 (AF) and Figure 4 (thermal).

During AF demagnetization, the vector shows extreme stability (Figure 3 *a*) until the highest peak field that is applied with high mdf (median destructive field) values in excess of 40 mT (Figure 3 *b*). During thermal demagnetization, the vectors changed sign of inclination (very shallow to shallow) at higher temperatures (Figure 4 *a*) for different samples at different stages (viz. Allende: 625°C; Dhajala: 500°C and St. Severin: 550°C) and they have high blocking temperatures of 650 to 675°C (Figure 4 *b*). After crossing the blocking temperature, the vectors fluctuate wildly as the intensity dropped to very low levels (Figure 4 *b*).

We have induced laboratory magnetizations also to these samples and subjected them to AF demagnetization in similar steps as the NRM up to 100 mT (Lowrie-Fuller Test). Then the NRM, TRM and S_{IRM} demagnetization curves are compared in Figure 5 to infer the domain state of the magnetic carrier in these meteorites. These studies indicate mixed behaviour of SD (single domain) and MD (multi domain) grain states of magnetic carrier in these meteorite samples[14]. Existence of such high and low coercivity remanence carriers is quite common in meteorites containing alloys of iron and nickel[15].

The stability of remanent magnetism of Allende meteorite was tested[1–3] and it was found to be most suitable for palaeofield intensity determination. We feel that similar studies can also be carried out on our meteorite samples i.e. St. Severin, Dhajala and Norton County also, in view of the stable nature of remanence in them but a suitable quantity of these samples is not available to us to carry out the palaeofield intensity determination studies.

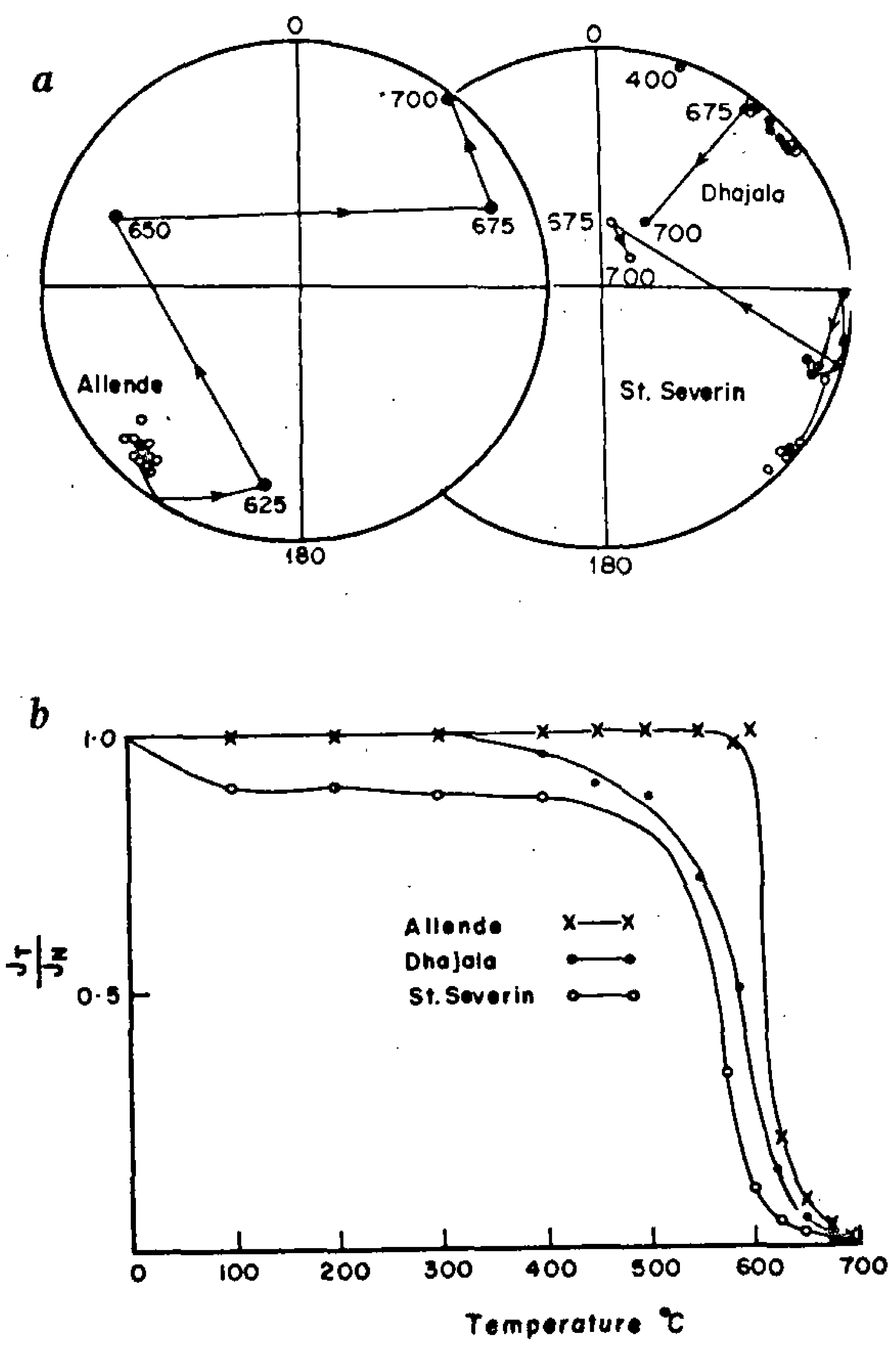

Figure 4. Thermal demagnetization characteristics of Allende, Dhajala and St. Severin meteorites. *a*, Vector migration and *b*, Intensity decay diagrams in progressively increasing temperatures. Open (closed) circles represent upward (downward) inclinations.

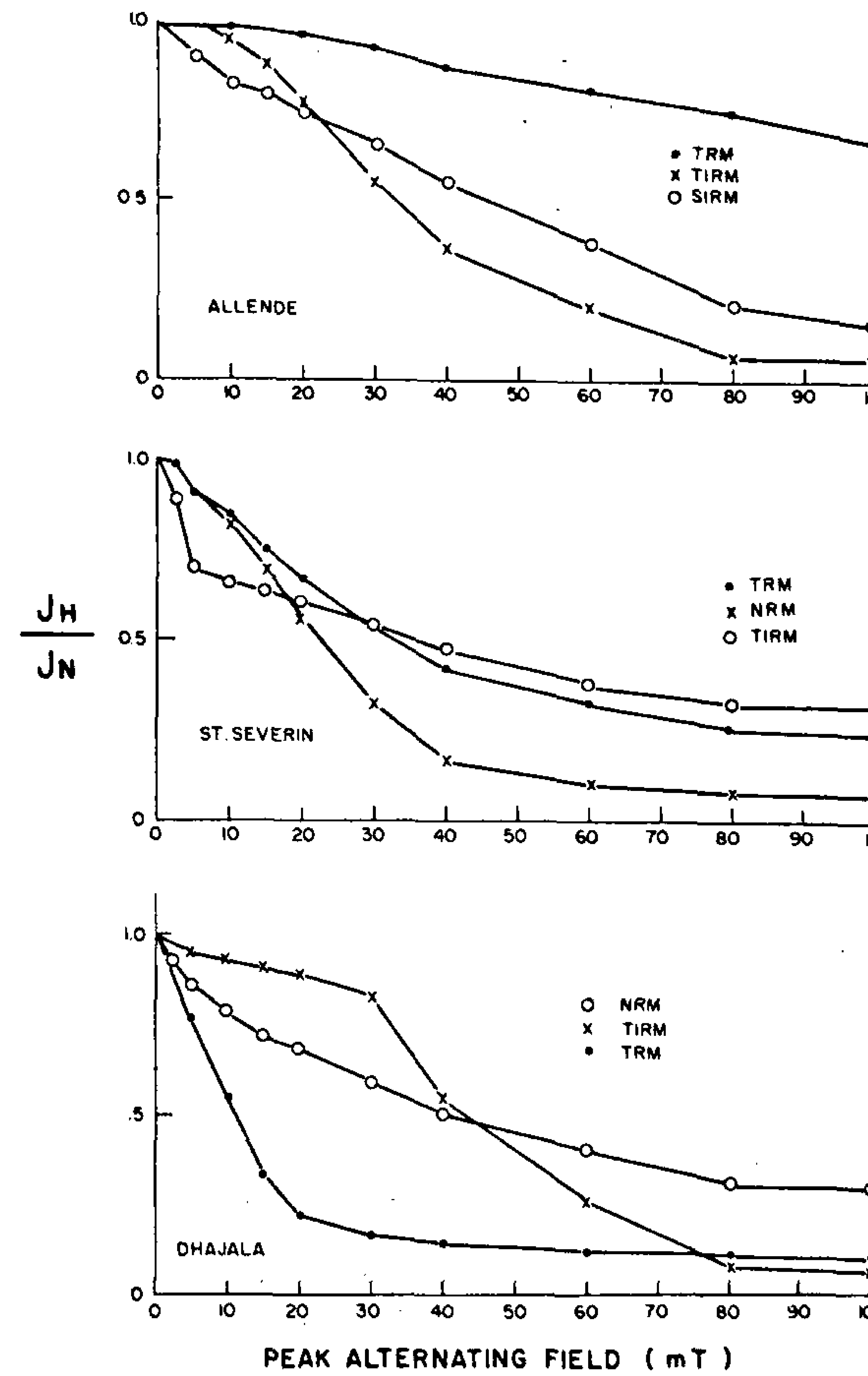

Figure 5. AF demagnetization of NRM, TRM and S_{IRM} magnetizations of Allende, St. Severin and Dhajala meteorites in progressively increasing peak fields.

The magnetic properties of these stony meteorites are quite comparable with those of the other stony meteorites and reflect proportion of ferromagnetic mineral content in them. Remanent coercive force values of these meteorites are higher than those of the terrestrial rocks containing magnetite and therefore, the magnetic mineral in these meteorites must be an alloy of NiFe, which is most common in meteorites. Studies on meteorites[2,3,5,6,16] indicate tetrataenite, an alloy of iron–nickel responsible for the stable remanence with high coercivity in them. Tetrataenite is a recently identified ordered iron–nickel alloy possessing high remanent coercive force[17]. The properties of this alloy are not fully understood and it cannot be easily synthesized in a form suitable for magnetic studies. In meteorites it is most probably formed during very slow cooling of iron and nickel of appropriate composition after metamorphic heating in the meteorite parent body. The magnetic grains in these meteorites are in critical SD and MD states. Therefore, these magnetic properties under study are similar to those of the other stony meteorites and point out that the magnetic carrier in these meteorites could also be tetrataenite, that attributes high stability of natural remanent magnetism of these meteorites to laboratory demagnetization. This stability of the remanent vector to laboratory demagnetization indicates their suitability to palaeofield intensity studies similar to the Allende meteorite reported earlier. The high stability of remanent magnetic vector to the laboratory AF and thermal demagnetization also point out that the remanence in these meteorites was acquired in extraterrestrial fields[15,17,18].

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Low-moderate seismicity in the vicinity of Palghat Gap, south India and its implications

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Low-moderate seismicity has been detected within the Palghat Gap, a large physiographic feature in south India. An M_L 4.3 earthquake that occurred on 2 December 1994 near Wadakkancheri in Trichur district, Kerala was also located within the confines of this feature. A few small tremors have previously been reported from the source region of the 1994 earthquake as well. Historic records show the occurrence of two earthquakes near Coimbatore, on the northern extremity of the gap. Continued low level seismic activity, originating from this area is recorded by the stations of the Gauribidanur Seismic Array (GBA). Thus, regional seismicity points to the presence of active structures and enhanced stress concentration within the Palghat Gap. On the basis of these observations, we suggest a reevaluation of this regional feature in terms of its potential to generate larger earthquakes in the future.

MONITORING earthquakes in regions characterized as 'stable', is gaining more importance with the growing realization that undetected seismogenic faults may be responding to current crustal deformation processes. Earthquake reports from various intraplate regions indicate their association with faults of varying reactivation periods, sustaining the overall rate of both small and large earthquakes. Because these faults may have never been reactivated during the recorded history, an earthquake may occur as a total surprise. Peninsular India has been the site of several moderate earthquakes, some of them highly damaging (1967 Koyna and 1993 Killari events, for example). However, very little is known about their mechanisms and causative structures. Because of the sparse distribution of seismic stations in peninsular India, quite often the information on background seismic activity is inadequate, and the nature of precursory activity, seldom understood. Understanding patterns of earthquakes and their characteristics may help to constrain the nature of regional seismicity and identify potential seismic source zones. In this paper, we argue for the need to update the seismic hazard associated with the Palghat Gap on the basis of the historic seismicity and the characteristics of the recent seismicity (Figure 1).

The Palghat Gap is the most conspicuous physiographic feature in southern India (Figure 2). The east–west orientation of the geomorphic features, including that of the Bharathapuzha river, is in general agreement with the trend of this feature. Considered as a possible shear zone, this feature passes through Palghat in Kerala, and is marked by high rising hills to its north and south[1-3]. Rao and Srinivasan[1] detected several shear and fracture zones and minor faults around Palghat, between Coimbatore and Anaimalai hill ranges. More specifically, they suggested that the shear zones occur on the southern and northern margins which show variations in width, about 4 km in the northern and 2–6 km in the southern sides. Based on the structural map prepared for the area, a deep-rooted rupture in the E–W direction was proposed. In another study, Kesavamani and Bose[4] inferred three major directions of fracture zones, NW–SE, NE–SW and E–W, based on regional magnetic and resistivity surveys. The E–W-trending fracture zones along the margins, according to them, correspond to tensile fractures, while the NW–SE and NE–SW-trending fractures may be shear fractures. The magnetic lows identified in the area generally conform to the river and stream courses. These studies, in short, project a picture marked by high level of tectonic disturbance.

The rocks and the mineral assemblage in the gap area indicate upper amphibolite–granulite facies metamorphism (300–450°C), which may have undergone cycles