The Strength of the Geomagnetic Field at the Cretaceous-Tertiary Boundary: Palaeointensity Results from the Deccan Traps (India) and the Disko Lavas (Greenland)

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The lavas of the Deccan Traps (India) and Disko Island (West Greenland) were both erupted close to the Cretaceous-Tertiary (K-T) boundary. Ar–Ar dating has provided plateau dates of 67.1 ± 1.1 Ma and 67.4 ± 0.4 Ma for samples respectively near the base and near the top of the Deccan succession, and the uppermost flow of the Disko succession has a preliminary age of 64.7 ± 1.4 Ma. Palaeointensities have been obtained from orientated samples from 47 Indian and 38 Greenlandic sites, using the SHAW (1974) technique with the ROLPH and SHAW (1985) correction for laboratory alteration. The intensity values show considerable scatter, but the mean virtual dipole moment calculated for the Deccan is $4.2 \pm 0.3 \times 10^{22}$ Am² and for Disko is $5.8 \pm 0.6 \times 10^{22}$ Am² compared to the present value of about 8×10^{22} Am². Studies of the variation of low-field susceptibility between -196°C and 700°C shows that the proportion of samples containing multi-domain magnetite is somewhat higher than in some younger lavas, suggesting hydrothermal alteration, which could account for some of the scatter in the palaeointensity values.

1. Introduction

Whilst the reversal record of the Earth's magnetic field is reasonably well defined for the last 200 million years, information about the field strength prior to 20 Ma is rather scarce. The time-averaged virtual dipole moment (VDM) seems to have remained at its present value of about 8×10^{22} Am² throughout the Upper Tertiary (MCFADDEN and MCELHINNY, 1982), and based on a small number of data points, PRÉVOT *et al.* (1990) proposed that the field strength has remained virtually constant since the Late Jurassic. The frequency with which the geomagnetic field reverses, on the other hand, has steadily increased since the long Cretaceous normal polarity chron (118–83 Ma) (MCFADDEN and MERRILL, 1984).

We have investigated the palaeomagnetic field close to the K-T boundary using samples from two well separated sites: the Disko Island lavas on the west coast of Greenland and the Deccan Traps in western India. Ar–Ar dating has been attempted in order to determine the age and duration of the volcanism in the two areas. The

palaeointensity experiments were performed on samples from pre-existing palaeomagnetic collections from Disko (ATHAVALLE and SHARMA, 1975) and from the Deccan (SUBBARAO *et al.*, 1989), although a new set of samples from India were included. It is critical that the natural remanent magnetisation (NRM) of rocks used in palaeointensity experiments is a pure thermo-remanence (TRM), otherwise the value obtained will not accurately reflect the strength of the ancient field. In order to determine the magnetic mineralogy of the basalts the temperature-dependence of susceptibility from liquid nitrogen temperature (-196°C) to 700°C has been measured for selected samples from each area.

2. Sample Details

The plateau basalts of the Disko-Nûgssuaq region of western Greenland overlie marine and limnic strata of Cretaceous-Early Tertiary age. The youngest sediments are considered to be of Late Danian (ROSENKRANTZ, 1970). TARLING and OTULANA (1972) quote K-Ar ages of 57 and 70 Ma from repeat measurements of a lava from Ubekendt Island, and DEUTSCH and KRISTJANSSON (1974) quote a K-Ar age of 70 ± 4 Ma from Disko. ATHAVALLE and SHARMA (1975) measured a 1200 m composite section of about fifty lava flows on Disko Island. They found that the top three-quarters of the section were reversely magnetised, and the remainder, apart from the lowest flow, were of normal polarity.

The age of the huge outpouring of basalts which resulted in the Deccan Traps has been determined by radiometric and biostratigraphic means to be anywhere from mid-Cretaceous to mid-Tertiary, but in a review of the published data COURTILOTT *et al.* (1986) conclude that the most likely time of activity was close to the K-T boundary. Subsequent ^{40}Ar - ^{39}Ar dates have supported this conclusion: DUNCAN and PYLE (1988) obtained eight acceptable plateau dates from nine samples that covered most of the succession, with values ranging from 64.8 ± 0.9 (1 σ) to 68.5 ± 1.2 Ma (an additional plateau date of 60.8 ± 2.1 Ma was considered too low); COURTILOTT *et al.* (1988) obtained five plateaus from fifteen samples, ranging from 63.6 ± 0.2 (1 σ) to 67.6 ± 1.8 Ma.

There have been many palaeomagnetic studies of the Deccan lavas (e.g. KONO *et al.*, 1972; PAL *et al.*, 1971) and the N-R-N magnetostratigraphy which has been determined supports a short duration for the igneous activity. For this study we have collected cores from 26 sites in the Deccan traps, the locations of which are listed in Table 1, and have also used specimens from sections to the north and south of the Narmada River (SUBBARAO *et al.*, 1989).

3. $^{40}\text{Ar}/^{39}\text{Ar}$ Dating

One of us (AEM) has attempted to obtain additional radiometric dates for the Deccan, and, for the first time, a date for the Disko lavas. A further two plateau dates from eight samples were obtained for the Deccan Traps (Fig. 1), using the procedure described by MUSSETT (1986), and the plateau criteria of LANPHERE and DALRYMPLE (1978). These were 67.1 ± 1.1 (1 σ) from a lava in the Narmada River, near the base of the known succession, and 67.4 ± 0.4 for a Mahabaleshwar lava, near the top of the succession. The Disko lavas were particularly difficult to date, as the lavas often have high calcium and water levels probably caused by hydrothermal activity. However, a

preliminary age of 64.7 ± 1.4 Ma has been obtained for site 21 (alt. 1450 m) at the very top of the section.

4. Rock Magnetism

A good knowledge of the magnetic mineralogy of the rocks is a prerequisite for assessing the reliability of a palaeointensity study. The variation of low-field susceptibility between liquid nitrogen temperature (-196°C) and 700°C provides information about the composition and grain size distribution of the magnetic minerals in the rocks. The interpretation of the low-temperature curves is a complex matter, over which there has been strong debate (RADHAKRISHNAMURTY, 1985; SENANAYAKE and MCELHINNY, 1981), but a consensus has now been reached on many points (RADHAKRISHNAMURTY *et al.*, 1991). Little has been published about high temperature susceptibility (RADHAKRISHNAMURTY and LIKHTE, 1970; DUNLOP, 1975)—whilst the general principles are understood, the changes observed in individual samples are not.

Nineteen Disko samples, selected at random from the collection of ATHAVALLE and SHARMA (1975), were measured (Table 1), as were specimens from each site of the new Indian collection. Results for the Narmada River sections have already been reported by SUBBARAO *et al.* (1989).

The classifications of low-temperature behaviour (Fig. 2, Table 1) are those of SENANAYAKE and MCELHINNY (1981), though the interpretations have been developed by experiment (SHERWOOD, 1988, 1990) and discussions (Radhakrishnamurty, personal communication). When the relative susceptibility ratio K_{78}/K_{293} is small (<0.4) the presence of Ti-rich titanomagnetite (Ti 0.5–0.7) is indicated, whereas ratios between 0.7 and 1 can indicate single domain (SD) magnetite. Various interpretations for group 2 behaviour have been suggested, but when the relative susceptibility ratio is very high (>1.5) it would appear to be caused by a predominance of paramagnetic material whose susceptibility, following the Curie-Weiss law is inversely proportional to absolute temperature. The peak in susceptibility, seen in Group 3 samples at about -145°C , seems to correspond to a change in sign of the magnetocrystalline anisotropy constant K_1 of magnetite: this behaviour appears to be restricted to samples containing multi-domain (MD) magnetite (RADHAKRISHNAMURTY, 1985). Many rocks contain a mixture of compositions or grainsizes so the observed behaviour may be complex.

Classification of high temperature susceptibility curves is more difficult: heating and cooling curves are often completely different, indicating that thermal alteration has occurred. A classification is proposed in Fig. 3. The increase of susceptibility with temperature is due to the HOPKINSON (1889) effect, and the peak corresponds to the unblocking temperature of the grain. In samples with SD and PSD grains the blocking temperature spectrum is grain size dependent and its maximum is not necessarily close to the Curie temperature; the height and width of the Hopkinson susceptibility peak will depend on the width of the blocking temperature spectrum. Large MD grains normally have a narrow blocking temperature spectrum close to the Curie temperature, and therefore a narrow Hopkinson peak is predicted (DUNLOP, 1975).

Several features may be observed (Table 1). Firstly, whilst group 3 behaviour is the most common for the two sets of samples, the majority of Disko samples containing MD magnetite have reversible curves with a single broad high temperature peak (type 1a), whereas over half of the MD magnetite-bearing Deccan samples have two peaks (type

Table 1. Rock magnetic parameters and sample details.

1) Disko

Locality/Site	Alt	LT K	RS	HT K
2 10	1190	3	1.08	1a
2 17	970	3	1.30	1a
2 20	920	3	1.18	1a
3 21	1450	3	1.10	1a
3 26	1320	1	0.35	2a
3 27	1295	1	0.48	2a
3 32	1180	3	1.15	1a
3 35	1105	3	1.18	1a
4 37	20	2	2.40	5
5 39	680	1	0.80	3b
5 43	625	3	1.25	1a
5 47	570	2	1.68	1b
5 49	530	3	0.50	2a
5 51	495	3	1.32	1a
5 54	370	3	1.10	1a
6 56	450	3	1.13	3a
6 59	380	2	1.55	6
7 62	300	3	1.23	6
7 64	230	1	0.46	4a

Note: locality and site numbers as in ATHAVALLE and SHARMA (1975).

2) Deccan

Site	Lat	Long	LT K	RS	HT K
IG1	19.7	73.4	3	1.16	1a
IG5	19.7	73.5	3	1.09	1a
IG9	19.7	73.5	3	0.89	2a
IG11	19.7	73.5	3	0.84	2a
IG24	19.75	73.6	3	1.25	1c
GS21	19.65	73.7	3	0.97	1a
TRM11	19.9	73.5	3	0.86	2a
BO3	19.3	74.0	1	0.70	2b
MD45	19.3	73.9	3	0.87	2a
KH1	18.8	73.4	1	0.45	2b
PUNE1	18.5	73.9	3	0.82	2a
PUNE2	18.5	73.9	3	0.91	2a
RN1	22.5	75.75	1	0.35	2c
RN3	22.4	75.6	1	0.70	2b
RN4	22.3	75.5	2/1	0.80	4b
RN5	22.3	75.5	1	0.42	2b
RN6	22.6	74.1	1	0.53	2b
RN8	22.6	74.1	3	0.96	3b
RN9	22.6	74.1	1	0.70	3b
RN10	22.6	74.1	1	0.90	3b
RN11	21.5	75.6	3	0.80	3b
RN14	21.8	75.5	1	0.54	3b
RN15	22.2	75.6	3	1.16	2a
RN16	22.2	75.6	3	0.93	3b
RN17	22.2	75.6	3	0.72	2a
RN18	22.1	74.9	2/1	0.94	2a

Table 1. (continued).

3) Summary—Low vs. high type (Ds=Disko, Dc=Deccan)

	Ds1	Dc1	1	Ds2	Dc2	2	Ds3	Dc3	3	Tot
1a	—	—	—	—	—	—	9	3	12	12
1b	—	—	—	1	—	1	—	—	—	1
1c	—	—	—	—	—	—	—	1	1	1
2a	2	—	2	—	1	1	1	8	9	12
2b	—	5	5	—	—	—	—	—	—	5
2c	—	1	1	—	—	—	—	—	—	1
3a	—	—	—	—	—	—	1	—	1	1
3b	1	3	4	—	—	—	—	3	3	7
4a	1	—	1	—	—	—	—	—	—	1
4b	—	—	—	—	1	1	—	—	—	1
5	—	—	—	1	—	1	—	—	—	1
6	—	—	—	1	—	1	1	—	1	2
Tot	4	9	13	3	0	3	12	15	27	45

2a). Secondly, only very few group 1 samples have relative susceptibility ratios less than 0.5, indicative of Ti-rich titanomagnetite, and these alter to a high blocking temperature phase on heating. This suggests that there has been low temperature oxidation in the sample as experiments on young lavas have shown that alteration of low Curie temperature phases during heating is not severe when the rock is fresh.

SUBBARAO *et al.* (1989) suggest that the MD magnetite-bearing Deccan lavas have all undergone hydrothermal alteration, and to support this they show a correlation between water content and those samples with MD magnetite. With collections of younger rocks, the majority of samples have shown group one low temperature behaviour, indicating the presence of Ti-rich titanomagnetite or SD magnetite (e.g. SHERWOOD, 1988, 1990). However, the degree of deuteric oxidation can affect the low-temperature susceptibility behaviour. Primary deuteric oxidation to form coarse ilmenite and magnetite intergrowths is another possible cause of group 3 behaviour. However, it would seem likely that many of the Disko and Deccan lavas have been hydrothermally altered. Although SUBBARAO *et al.* (1989) report increased scatter in NRM directions on some of the hydrothermally altered Narmada lavas, hydrothermal alteration can change the NRM intensity without affecting its direction (PRÉVOT and GROMMÉ, 1975). Unfortunately it is not known which of the lavas remain sufficiently unaltered to give reliable palaeointensity values.

5. Palaeointensity Experiments

Despite doubts about the suitability of some of the samples for palaeointensity work, over 200 palaeointensity experiments have been undertaken using the ARM-correction method of ROLPH and SHAW (1985), which is a variation of the SHAW (1974) technique and corrects for the effect of thermal alteration during installation of the laboratory TRM. The experiments were carried out using 9 mm diameter samples on a specially designed fully-automated cryogenic magnetometer (SHAW *et al.*, 1984).

Figure 4 shows two typical palaeointensity plots. The site mean palaeointensity

Fig. 1. $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages were obtained from samples near the base (RN3) and near the top (ABC19) of the Deccan Trap succession.

Fig. 2. Examples of the main types of low temperature susceptibility behaviour observed in the Disko and Deccan lavas.

Fig. 3. The classification of high temperature susceptibility behaviour used in Table 2.

Fig. 4. Two examples of palaeointensity determinations: the large plots are obtained using the Rolph and Shaw correction technique and the smaller ones are those which would be used in a standard SHAW (1974) calculation.

Table 2. Palaeointensity results.

1) Disko

Loc	Site	Alt	Dec	Inc	Int	N	VDM
2	9	910	145	-76	21.4±3.0	3	3.0±0.4
2	10	1190	172	-72	63.4±3.8	8	9.3±0.6
2	11	1165	144.5	-59	15.6±1.3	2	2.7±0.2
2	12	1130	144.5	-59	29.8	1	5.2
2	13	1188	205	-75.5	36.3±6.4	5	5.1±0.9
2	14	1080	131	-62	20.2±1.8	5	3.4±0.3
2	15	1050	143	-49	10.2±1.1	6	2.0±0.2
2	16	1010	113.5	-72.5	17.8±2.1	7	2.6±0.3
2	17	970	173	-69	70.6±6.2	8	10.7±0.9
2	18	965	146	-71.5	40.6±6.2	7	6.0±0.9
2	19	940	143.5	-68	24.3±4.5	7	3.7±0.7
2	20	920	172	-72.5	21.7±4.3	5	3.2±0.6
3	21	1450	158	-72.5	36.8±5.0	8	5.4±0.7
3	22	1420	251	-80.5	59.8±5.1	4	8.0±0.7
3	23	1380	175	-76.5	24.0±6.6	2	3.3±0.9
3	24	1360	170.5	-62.5	26.0±6.0	2	4.3±1.0
3	25	1340	128.5	-63.5	36.0	1	5.9
3	26	1320	143.5	-67	25.1±2.9	2	3.9±0.5
3	27	1295	196	-78.5	51.8±3.0	2	7.1±0.4
3	28	1280	81	-47	74.6±4.4	4	14.9±0.9
3	29	1235	159	-74	35.5	1	5.1
3	32	1180	233	-79	22.6±3.6	3	3.1±0.5
3	33	1160	231	-82.5	25.4±0.9	3	3.4±0.1
3	34	1145	247	-69.5	78.2±9.0	2	11.8±1.4
3	35	1105	187.5	-68.5	36.8	1	5.6
5	39	680	150	-76	51.1±3.0	11	7.2±0.5
5	40	705	143	-81.5	76.6±34.2	5	10.2±4.6
5	41	650	109.5	-62	76.1±5.2	7	12.7±0.9
5	42	640	153	-65	57.6±17.9	4	9.2±2.9
5	43	625	141	-63.5	19.8±2.0	8	3.2±0.3
5	44	615	92	-74	29.8±6.2	9	4.3±0.9
5	45	600	107	-85	19.8±1.6	6	2.6±0.2
5	46	590	126.5	-61	24.7±1.8	6	4.2±0.3
5	49	530	91.5	-75.5	12.8	1	1.8
5	52	460	96	-76	53.5	1	7.5
5	53	400	154	-69	93.7	1	14.3
5	54	370	174	-80.5	22.0±4.7	3	3.0±0.6
6	60	350	355	62	14.6	1	2.4

Note: Locality and sites as described in ATHAVALLE and SHARMA (1975).

values are listed in Table 2. The error shown is the standard error on the mean, and no error is given when there is only a single successful determination. Single values are particularly common from the Narmada sections because repeat samples were not available. Palaeointensity values have been obtained from 47 Deccan sites (27 from the collection of SUBBARAO *et al.* (1989) and 20 from the new collection), and 38 Disko lavas. The mean intensity values vary from 4.3 to 55.6 μT for the Deccan and from 10.2 to 93.7 μT for Disko. The virtual dipole moments (VDM—SMITH, 1967) are also listed in Table

Table 2. (continued).

2) South and North Narmada Sections

Section	Site	Dec	Inc	Int	<i>n</i>	VDM
SN	1	129	70	31.9±13.4	2	4.8±2.0
SN	2	354	-63	28.3±23.1	2	4.7±3.8
SN	4	143	60	39.5	1	6.7
SN	6	107	70	21.0	1	3.2
SN	9	154	30	18.4	2	4.3±1.9
SN	15	115	46	28.4	2	5.7±1.1
SN	16	157	52	12.8	1	2.4
SN	17	137	55	13.9	1	2.5
SN	18	160	64	12.7	1	2.1
SN	19	116	33	29.3	1	6.7
SN	20	133	34	42.8	1	9.7
SN	21	136	3	30.4±0.8	2	7.8±0.2
SN	25	176	35	22.7±4.9	2	5.1±1.1
SN	26	40	-47	30.0	1	6.0
SN	27	342	-54	11.3±3.0	2	2.1±0.6
NN	1	146	47	4.3±0.4	2	0.9±0.1
NN	3	333	-65	8.4±0.4	2	1.4±0.1
NN	4	331	-56	13.3±5.0	2	2.4±1.0
NN	6	334	-53	14.8	1	2.8
NN	8	147	30	11.1±5.0	2	2.6±1.2
NN	9	193	33	19.4±0.4	2	4.4±0.1
NN	10	154	56	8.5	1	1.5
NN	12	137	37	14.2	1	3.1
NN	13	168	35	8.1±2.1	2	1.8±0.5
NN	16	146	37	10.0±2.5	2	2.6±0.7
NN	17	148	-9	11.8	1	3.0
NN	20	335	52	27.9	1	5.3

2, and plotted in Fig. 5. The mean VDM for the Deccan is $4.2 \pm 0.3 \times 10^{22}$ Am² (3.9 ± 0.4 for the Narmada sections (SUBBARAO *et al.*, 1989), and $4.6 \pm 0.5 \times 10^{22}$ Am² for the new collection). For the Disko lavas the mean VDM is $5.8 \pm 0.6 \times 10^{22}$ Am². The results have been treated with equal weight when calculating these mean VDMs. This may not be strictly correct as when there are two or more palaeointensity values from a single lava they are sometimes very different. This is particularly true of some of the Narmada lavas (Table 2).

6. Discussion and Conclusions

Whilst it is probably unwise to draw conclusions from individual results the following may be observed. There are a number of lavas, particularly from the Deccan collections, which have apparently intermediate NRM directions; these should give lower palaeointensities than the lavas with normal or reverse NRM directions. The fact that they do not suggests that either the directional results are suspect or the palaeointensity values do not reflect the ancient field intensity. Another interesting observation is that the intensities tend to be higher in the southern Narmada section than the northern one,

Table 2. (continued).

3) Deccan—new collection

Site	Dec	Inc	Int	<i>n</i>	VDM
IG1	297	−81	16.0±0.7	2	2.2±0.1
IG5	43	−33	16.6	1	3.8
IG9	155	27	17.8	1	4.2
IG11	160	38	15.1	1	3.4
IG24	149	71	55.6±12.8	2	8.2±1.9
TRM11	152	14	25.7	1	6.5
BO3	157	69	25.5±4.0	2	3.9±0.6
MD45	148	62	12.1±1.0	2	2.0±0.2
KH1	164	39	24.1±4.2	2	5.2±0.9
PUNE1	119	62	21.3±1.5	2	3.6±0.3
PUNE2	142	9	9.2±1.7	2	2.4±0.4
RN1	135	56	18.7±3.0	2	3.4±0.5
RN3	149	36	31.9	1	7.1
RN4	16	−55	15.1±4	2	2.8±0.7
RN8	172	32	21.2±2.1	2	4.9±0.5
RN9	208	77	25.4±0.1	2	3.5±0.1
RN10	231	75	21.6±3.3	2	3.1±0.5
RN16	166	7	45.5	1	11.7
RN17	154	6	13.7±0.2	2	3.5±0.1
RN18	164	72	45.5±4.4	2	6.7±0.7

although, according to SUBBARAO *et al.* (1989) the southern side is more altered.

The palaeointensities obtained from the Deccan are considerably lower than those obtained by KONO (1974) using the Thellier technique. He estimated a mean VDM of 7.2 ± 1.0 (standard error) $\times 10^{22}$ Am² using results from 9 lavas (including 2 intermediate flows). KONO (1974) preselected samples with directionally stable NRMs which also had a single high Curie point which meant that they should alter less on heating than samples with a low temperature phase. As SHERWOOD *et al.* (1988) and HOFFMAN *et al.* (1989) have noted, a few rocks which, using the preselection criteria, should give good palaeointensity values, will give anomalously high values. On the other hand, when all but the most basic preselection criterion, that of a stable NRM, have been ignored, palaeointensity results have been very low (SHERWOOD and SHAW, 1986). It is becoming increasingly clear that at present we do not understand the changes in magnetic mineralogy and the rock magnetic processes which occur in lavas.

RADHAKRISHNAMURTY *et al.* (1977) presented palaeointensity estimates from ten Deccan lavas. Using a continuous heating process where the magnetisation was monitored during heating in zero-field and cooling in a known laboratory field, they obtain a mean geomagnetic field which is 55% of its present strength. Expressed as a VDM, this would be about 4.2×10^{22} Am² which is identical to the value obtained here. Commenting on their earlier work, RADHAKRISHNAMURTY *et al.* (1991) note that thermal alteration commonly occurred during such experiments so uncorrected results should be regarded as unreliable.

The Disko palaeointensity values are often calculated from several, up to 11, samples, and probably should be regarded as more reliable than the Deccan results. The

Fig. 5. Histograms of site mean VDMs for the two areas.

Disko lavas were erupted between 2 and 3 million years after the Deccan Traps, so a major change in the mean dipole field strength is unlikely to have occurred in that time. The mean VDM from Disko falls neatly between the Deccan values obtained in this study and that of KONO (1974).

From our palaeointensity results it would appear that the field at the K-T field was between 50 and 75% of its present values. Dynamo theory predicts stronger fields during periods of infrequent reversals (PAL and ROBERTS, 1988). The time-averaged reversal frequency in the Late Cretaceous/Early Tertiary was lower than its present value (MCFADDEN and MERRILL, 1984), so a stronger geodynamo could be expected. Our results do not support this prediction, but other factors may be masking the effect of a change in reversal frequency. To conclusively prove or disprove the proposed relationship, we need to obtain palaeointensity results from periods of extremely low reversal frequency such as the Cretaceous Quiet zone or the Permian.

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