Magnetic rock properties of the gabbros from the ODP Drill Hole 1105 A of the Atlantis Bank, Southwest Indian Ridge

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Laboratory studies of 30 samples from 158 m long drill core of the Hole 1105 A (ODP Leg 179) of the Atlantis Bank, Southwest Indian Ridge have revealed magnetic properties of the gabbros, olivine gabbros, oxide gabbros and olivine oxide gabbros down the core. Comparison of modal proportions of the oxides, grain sizes and magnetization parameters of the rocks has confirmed that most coarse-grained oxide mineral bearing rocks record low Koenigsberger ratio (2 to 5) and median destructive fields (5 to 7 mT). Average natural remanent magnetization (J_{nrm}) and stable remanent magnetization (J_{st}) of the core samples are 5.8 A/m and 1.9 A/m, respectively. Their mean stable magnetic inclination is $66° \pm 4°$, about 14° steeper than the expected dipole inclination of the area similar to the one reported at Hole 735 B. The excess inclination perhaps marks a tectonic block rotation of the reversely magnetized rocks of the bank. We interpret that gabbros and serpentinites devoid of basaltic carapace significantly contribute to seafloor spreading anomalies of the bank.

1. Introduction

Efforts to construct generic models of the oceanic crust produced by fast and slow spreading ridges are limited by the limited insights into the deeper crust. An intriguing question that remains unanswered is to what extent lower crustal rocks contribute to linear marine magnetic anomalies. The Atlantis Bank (32°43.13′S, 57°16.65′E), east of the Atlantis II Fracture Zone is a window in the Indian Ocean where lower crustal rocks, gabbros of the ultra slow, 8 mm/yr spreading Southwest Indian Ridge (SWIR) are exposed at the seafloor (figure 1) where the crust is relatively young about 11.5 Ma.

Seafloor spreading studies consider the upper crust basalts (500 to 2000 m thick) with uniform magnetization for generation of synthetic seafloor spreading anomalies. Anomaly picks for identification of magnetic isochrons of the observed field are largely based on shapes irrespective of their amplitude misfits between the observed and synthetic anomalies. Inversion studies of the observed seafloor spreading anomalies have also revealed that the magnetization strength required to produce them must be higher than the measured magnetization of basalts (Klitgord *et al* 1975; Harrison 1981). Thus, the study of the lower crust magnetic properties and extent of their possible contributions to the observed magnetic anomalies are most critical in the larger context of crustal studies.

The present study reports laboratory results of the magnetic properties of carefully selected 30 discrete mini-core gabbro rock samples from the 150 m long recovered vertical core of the ODP Leg 179 (Hole 1105 A) drilled from the Atlantis Bank during April–June 1998 and compares them with that of the gabbroic rocks from the Hole 735 B of the bank to shed light on their variability inflicted by magmatic and tectonic processes.

Keywords. Southwest Indian Ridge; Atlantis Bank; ODP Drill Hole 1105 A; gabbros; serpentinites.

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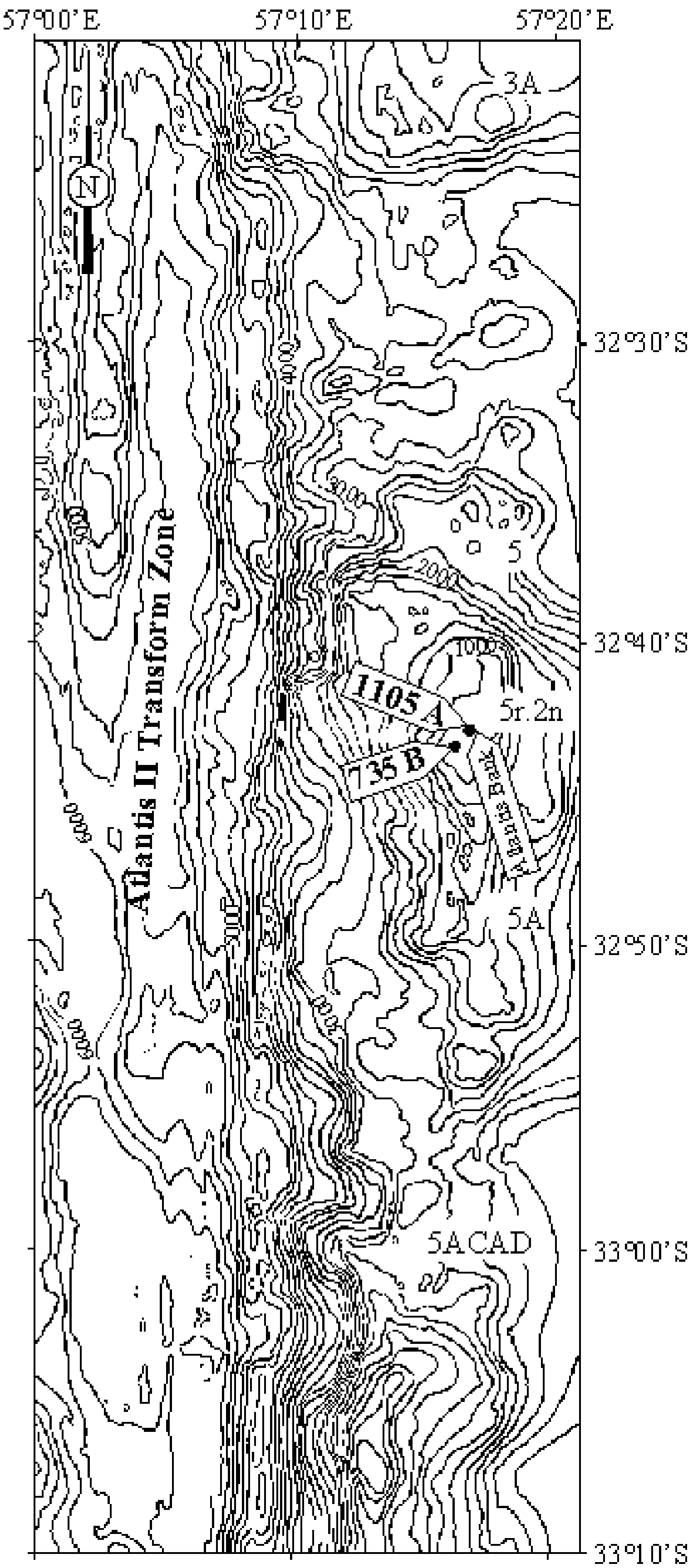

Figure 1. Locations of the Ocean Drilling program Holes 1105 A and 735 B on the Atlantis Bank of the SWIR show that Hole 1105 A is more distal to the Atlantis II fracture Zone and the sites are in a line parallel to the ridge axis. Bathymetry contours are shown with an interval of 200 m. Seafloor spreading anomaly numbers are following Dick et al. (1991) as per the magnetic polarity time scale of Cande and Kent (1995) and shown with bold letters.

2. Previous studies

The Atlantis Bank is a flat-topped terrace in water depth of about 695 m (figure 1) where basaltic flows have been tectonically unroofed and the lower crustal rocks (gabbros) are exposed at the seafloor (Shipboard Scientific Party Leg 118, 1989; Shipboard Scientific Party Leg 176, 1998). Magnetic isochron 5r.2n corresponding to 11.5 Ma (Shipboard Scientific Party Leg 118, 1989) is noted in the area of the Atlantis Bank (Dick *et al* 1991). Kikawa and Pariso (1991) have carried out forward model studies of the magnetic anomalies of oceanic layers 2 and 3 rocks of varied thickness and magnetization and inferred that the anomaly amplitudes and shapes are retained by considering the contributions of the lower crustal rocks (Shipboard Scientific Party Leg 176, 1998). Further, they concluded that

- the gabbros have the stable magnetic polarity component of strength more than 1.6 A/m and
- the gabbroic rocks contribute to 40% of the seafloor spreading magnetic anomalies.

Serpentinites within the upper crust of 0 – 37 Ma age show NRM up to 3.6 A/m (Nazarova 1994). Beneath the Atlantis Bank seismically defined crust, 4 to 5 km thick consists of 2–3 km thick lower crust of partially serpentinized upper mantle (Muller *et al* 1997, 1999 and 2000; Minshull *et al* 1998).

The drill core of Hole 1105 A of ODP Leg 179 consists of 141 rock intervals. They were broadly defined as four basic units:

- gabbros composed of medium- to coarse-grained gabbros and olivine gabbros
- gabbros composed of medium- to coarse-grained oxide and oxide olivine gabbros. The main difference compared to the upper unit rocks is higher proportions of oxide gabbros.
- Gabbros composed dominantly of olivine gabbros separated from the above and below units, both of which are characterised by the oxide rich gabbros and
- gabbros contain either an accessory amount of olivine or completely lack olivine (Shipboard Scientific Party Leg 179, 1999).

Thick zones of ductile shear and ductile deformation are present in top 90 m and below, respectively of the core with zones of ductile deformation being common in oxide rich gabbros. Initial results of the downhole geophysical measurements (Shipboard Scientific Party of Leg 179, 1999) have indicated that the core exhibits a single coherent magnetic direction with an average inclination of 67°, instead of inclination corresponding to the present latitude, −52° at the bank.

3. Experimental procedure

Palaeomagnetism measurements, Natural Remanent Magnetism (J_{nrm}) and inclination (I_{nrm}) were carried out on 30 mini-core samples (2.5 cm dia and 2.1 to 2.7 cm long) onboard JOIDES RESOLUTION (JR, ODP drill vessel) using Super Conducting Quantum Interference Device (SQUIDS) magnetometer. Subsequently initial susceptibility (K) was measured using low field Hystersis susceptibility apparatus at NGRI, Hyderabad. Stepwise alternating field demagnetization (AFD) of the samples up to 80 mT was done with three-axis demagnetizer until the magnetization decreased to below 15% of the NRM. Progressive thermal demagnetization of six mini-core samples one to three from each rock types: gabbros, olivine and oxide gabbros and olivine oxide gabbros using the Schonstedt thermal demagnetizer onboard JR were performed by heating and cooling the samples in air between 20°C and 800°C at short times (i.e., 20 to 30 minutes heating cycle and 10 to 20 minutes cooling cycle) to minimize the effect of oxidation on the samples at elevated temperatures. Zijderveld diagrams plotted from demagnetization data were used to determine the stable inclination by performing a least squares approximation (Zijderveld 1967). Figures 2(a–d) show the typical behaviour of magnetization during demagnetization.

4. Results

Results of the laboratory studies of magnetic properties of the gabbroic rocks drilled at the hole and salient features are summarised in the following.

4.1 *NRM intensity (J_{nrm}) and inclination (I_{nrm})*

The gabbros, at shallow depth, have the lowest, 0.89 to 4.7 A/m intensities. While the olivine gabbros intensities vary from 0.706 to 17.3 A/m, the intensities of the oxide olivine gabbros, which occur at about 38 m and further deep, vary from 0.11 to 33.7 A/m and are the strongest. The NRM intensity of the oxide gabbros and oxide olivine gabbros with averages varying from 5.57 A/m to 11.7 A/m are distinct and easily correlated to the modal proportions of oxide minerals; ilmenite, titanomagnetite etc. that are present in the rocks (table 1 and figures 2(a–d)). The stable NRM inclinations include positive (reversed) with a mean of 66°.

4.2 *Initial susceptibility*

The susceptibility values range from 1.26×10^{-3} to 19.52×10^{-2} SI. The gabbros at shallow depth show

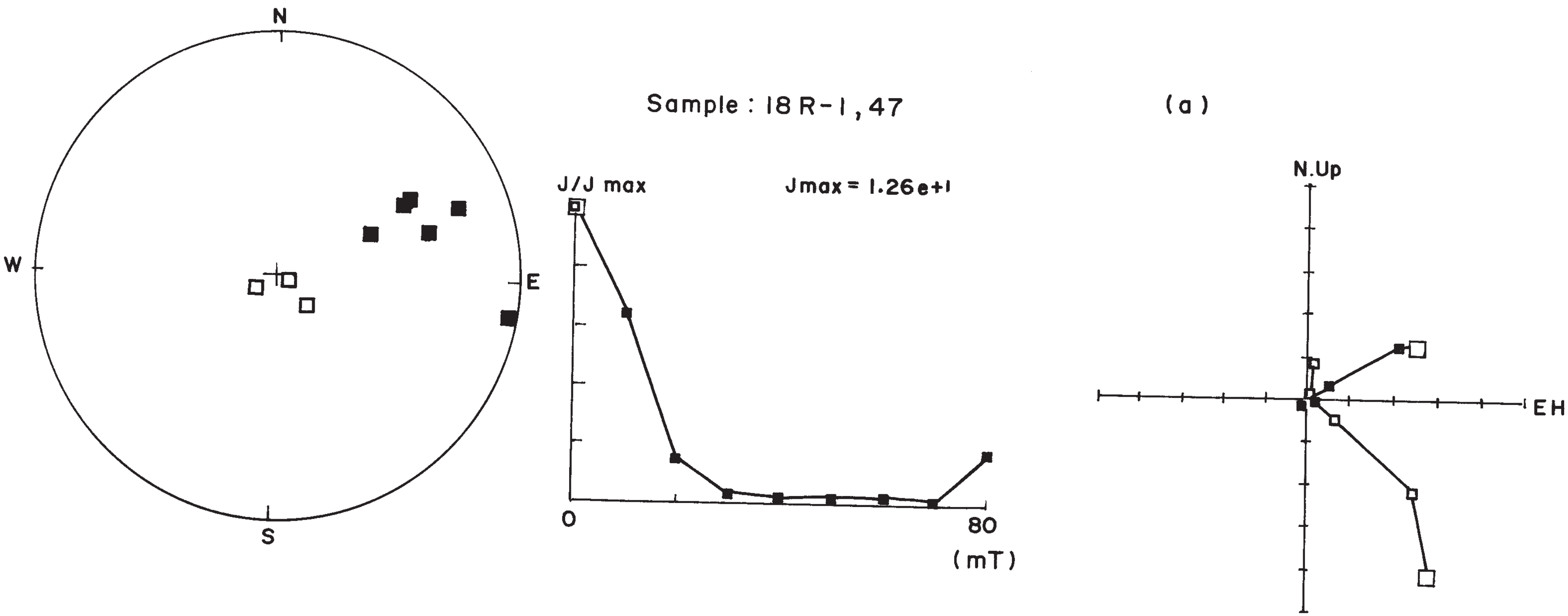

Figure 2. Typical plots of AF and thermal demagnetizations of **(a)** very unstable and strong secondary component of oxide olivine gabbro (sample 18R-1, 47) which could be removed during lower steps of demagnetization itself. The Zijderveld diagram on the right shows consistency in inclination and declination and the stability of remanence component and secondary magnetization parallel to it. The remanence direction becomes antipodal and stray at higher steps, 50 to 80 mT of demagnetization in this case. The stereographic projection of it in the left shows insignificant change in remanence directions.

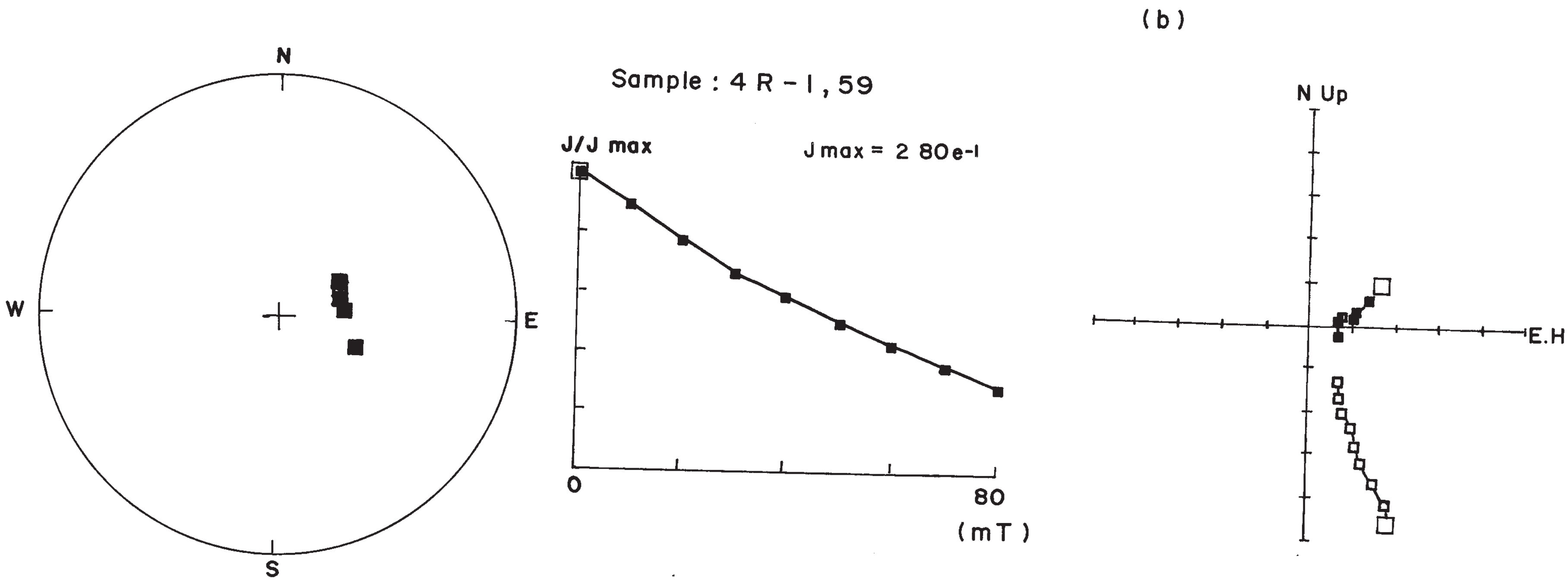

Figure 2. **(b)** Stable remanence data of gabbros (sample 4R-1, 59). The Zijderveld diagram in the right shows no significant change in magnetic direction during demagnetization. The stereographic projection of the same on the left shows also the same of the total intensity vector.

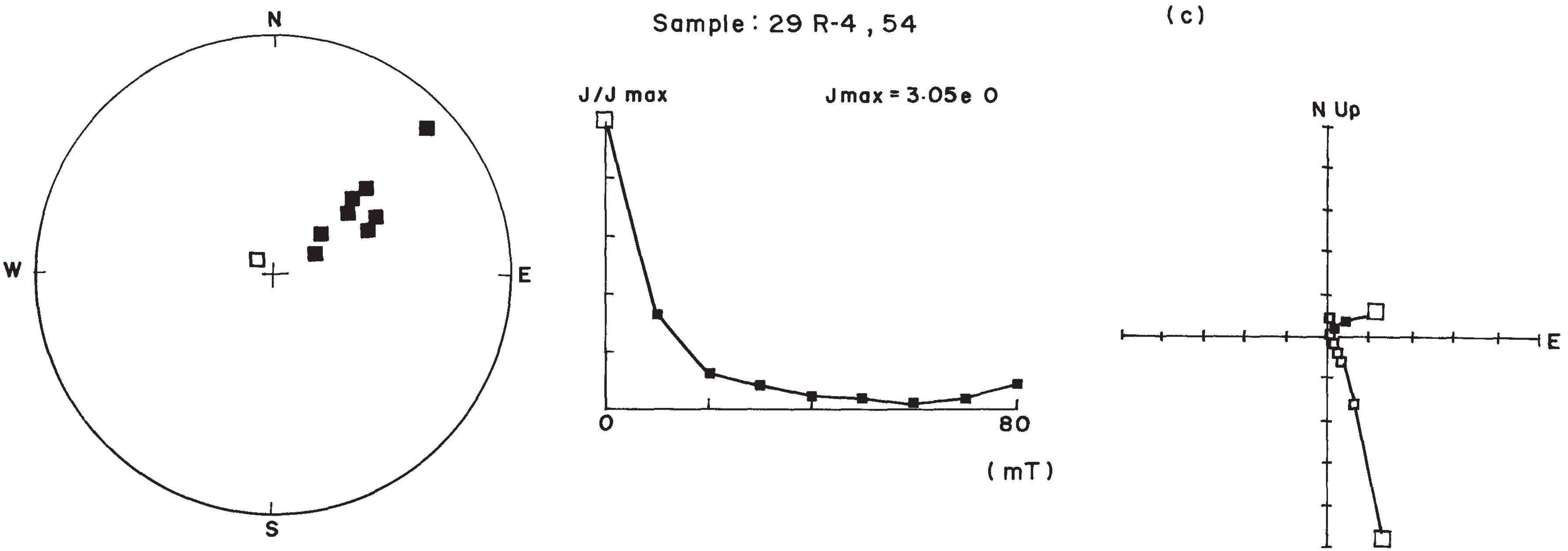

Figure 2. **(c)** Stable remanence data of oxide gabbro (sample 29R-4, 54) which is nearly same as in 2(a). The only difference is stray (almost antipodal) remanence direction at 80 mT step of demagnetization.

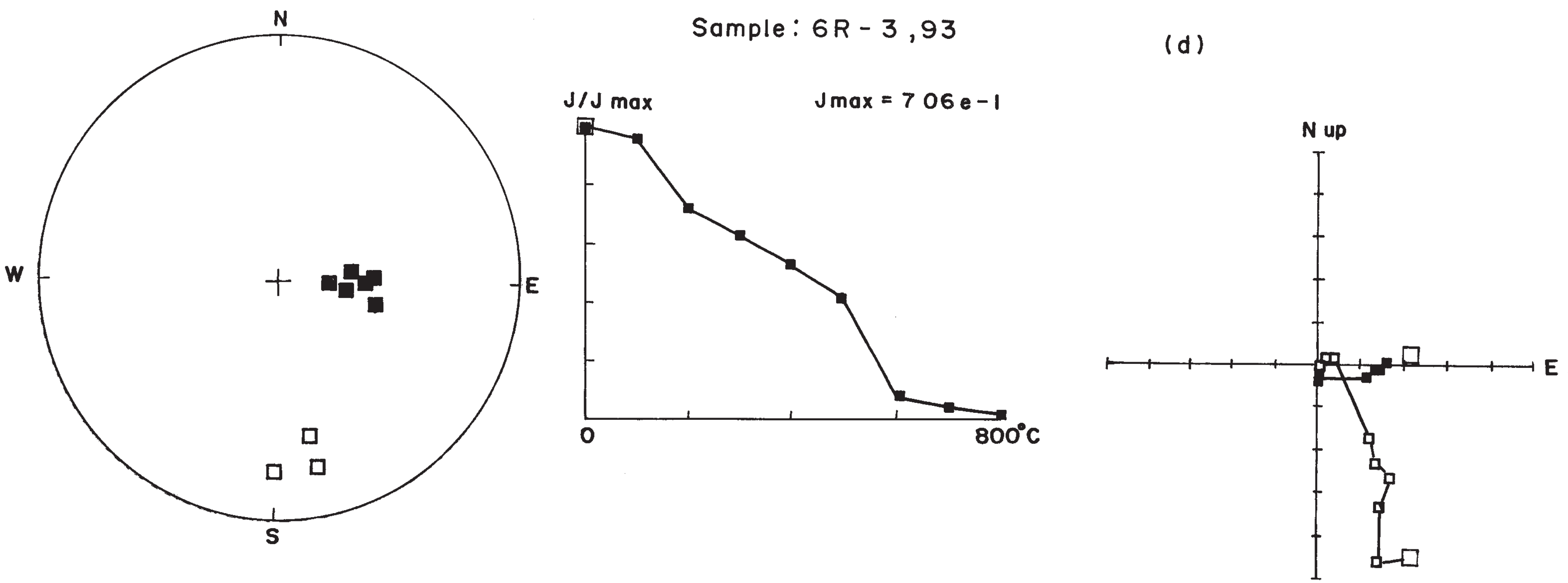

Figure 2. **(d)** Stable remanence data of thermal demagnetization of olivine gabbro (sample 6R-3, 93). Stable remanence directions become antipodal and stray at higher steps, 600° to 800°C of thermal demagnetization, typical blocking temperature of magnetization of magnetite.

Table 1. *Magnetic properties of gabbros from Hole 1105 A.*

Core/sect. (cm)	Depth (mbsf)	J_{nrm} A/m	J_{st} A/m	K (SI)	MDF (mT)	Q_n	I_{nrm}	I_{st}	D_s
Rock type: gabbros									
1R-02, 94	17.20	7.90E − 1	2.07E − 1	5.78	7.0	4.64	70°	54°	86°
3R-01, 73	29.40	1.67E − 0	1.38E − 0	–	–	–	69°	67°	64°
3R-02, 124	31.44	1.01E − 0	3.41E − 1	12.70	5.0	2.70	81°	75°	266°
4R-01, 59	33.99	2.80E − 1	1.72E − 1	1.26	49.0	7.57	67°	67°	72°
4R-02, 23	34.70	1.07E − 0	4.13E − 1	11.06	6.0	3.27	74°	60°	37°
4R-03, 54	36.40	5.54E − 1	1.66E − 1	3.52	9.0	5.35	78°	72°	232°
12R-02, 31	73.10	4.69E − 0	3.80E − 0	–	–	–	79°	73°	312°
14R-01, 113	82.10	8.91E − 1	2.77E − 1	10.68	7.0	2.83	84°	71°	14°
14R-03, 24	83.88	2.92E − 1	2.31E − 1	–	–	–	77°	73°	167°
21R-01, 56	111.40	4.85E − 1	1.84E − 1	3.9	-	4.23	78°	63°	58°
Rock type: olivine gabbros									
6R-01, 129	44.10	2.72E − 1	1.22E − 1	6.54	30.0	1.41	37°	64°	69°
6R-03, 93	46.70	7.06E − 1	5.00E − 1	–	–	–	64°	63°	93°
16R-01, 36	91.00	1.73E + 1	5.39E − 0	175.98	7.0	3.34	64°	63°	3°
20R-01, 43	110.20	6.20E − 1	3.64E − 1	7.04	21.0	2.99	80°	81°	154°
25R-04, 65	113.70	1.49E − 0	6.44E − 1	8.67	9.0	5.84	76°	77°	184°
Rock type: oxide gabbros									
7R-02, 6	49.20	1.30E + 1	4.26E − 0	83.09	5.0	5.32	86°	78°	189°
9R-02, 91	59.80	7.19E − 1	3.67E − 1	3.52	17.0	6.94	61°	72°	324°
9R-03, 122	61.50	1.30E + 1	3.12E − 0	–	7.0	–	69°	78°	157°
11R-01, 47	67.47	2.45E − 0	7.89E − 1	–	7.0	–	64°	66°	168°
19R-01, 62	105.80	6.15E − 0	1.91E − 0	40.22	6.0	5.19	69°	69°	175°
21R-02, 107	113.20	1.32E − 0	5.27E − 1	12.57	12.0	3.57	76°	77°	272°
21R-03, 40	113.90	2.90E − 0	0.94E − 0	55.81	6.0	1.78	64°	56°	16°
24R-03, 61	127.85	1.04E − 0	0.81E − 0	–	–	–	73°	66°	61°
29R-04, 54	153.0	3.05E − 0	7.38E − 1	26.15	7.0	3.96	75°	57°	54°
Rock type: oxide olivine gabbros									
4R-04, 43	37.70	2.19E + 1	7.33E − 0	160.39	6.0	4.64	77°	68°	358°
5R-01, 81	39.10	3.37E + 1	9.58E − 0	195.21	7.0	5.86	71°	72°	308°
5R-02, 9	39.90	1.10E + 1	3.77E − 0	86.73	6.0	4.25	59°	63°	82°
17R-04, 41	100.40	1.10E + 1	5.01E − 0	124.32	5.0	3.01	68°	63°	204°
18R-01, 47	100.70	1.26E + 1	4.70E − 0	194.71	13.0	2.20	56°	38°	64°
18R-01, 127	101.50	1.11E − 1	2.69E − 2	2.14	17.0	1.75	36°	66°	310°
25R-01, 13	130.30	2.85E − 1	0.96E − 0	2.57	10.0	20.50	20°	35°	220°
30R-03, 12	157.20	8.43E − 1	5.91E − 1	–	–	–	75°	77°	345°

less 1.26×10^{-3} to 11.06×10^{-3} SI values. The oxide-olivine gabbros show higher values, 2.14×10^{-3} to 19.52×10^{-2} SI. The split cores susceptibilities are also higher (figure 3b) and consistent with the larger content of the oxide minerals, ilmenite, titano-magnetite, etc. The increase in the susceptibility down the core marks increase in magnetic mineral content and/or the geological processes forming them.

4.3 *Koenigsberger ratio* (Q_n)

The Q_n values range from 1 to 8 excepting the sample 25R-1, 13, which has the high (20.5) ratio (table 1). Majority of the samples show Q_n values between 2 and 6. The magnetite and ilmenite-rich gabbros may acquire strong secondary component of magnetization and signify relative importance of the secondary component to induced magnetization. The overall distribution of the Q_n values is not different excluding the Q_n values of the oxide rich gabbros and comparable to those of the oceanic gabbros reported by Fox and Opdyke (1973), Pariso *et al* (1991).

4.4 *Alternating – field and thermal demagnetizations*

The progressive demagnetization of the mini-cores have revealed median destructive field (MDF) varying from 5 to 49 mT and more than two thirds of the samples have MDF values less, between 5 and 10 mT (table 1). Most of the gabbros exhibit a less change in the remanence direction and rapid decrease in intensity during lower steps of demagnetization followed by the appearance of a stable remanence at higher demagnetization steps (figures 2a and b, samples 18R-1, 47 and 4R-1, 59). This type of change indicates that the samples

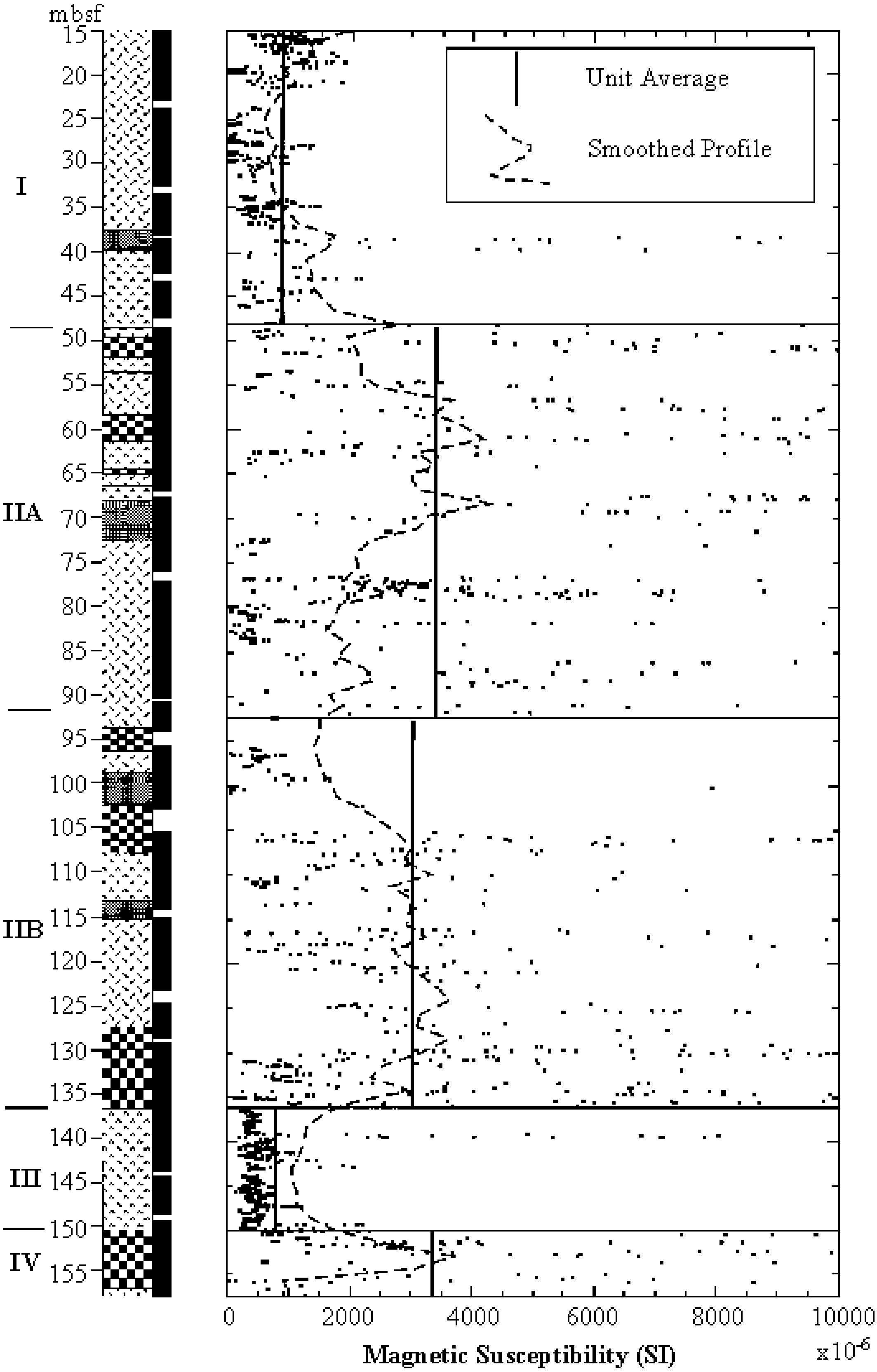

Figure 3(a). Plots of litho-stratigraphy versus susceptibility of the split cores, smoothed curve is the weighted moving average of data. Symbols of the litho log are as given in figure 3(b).

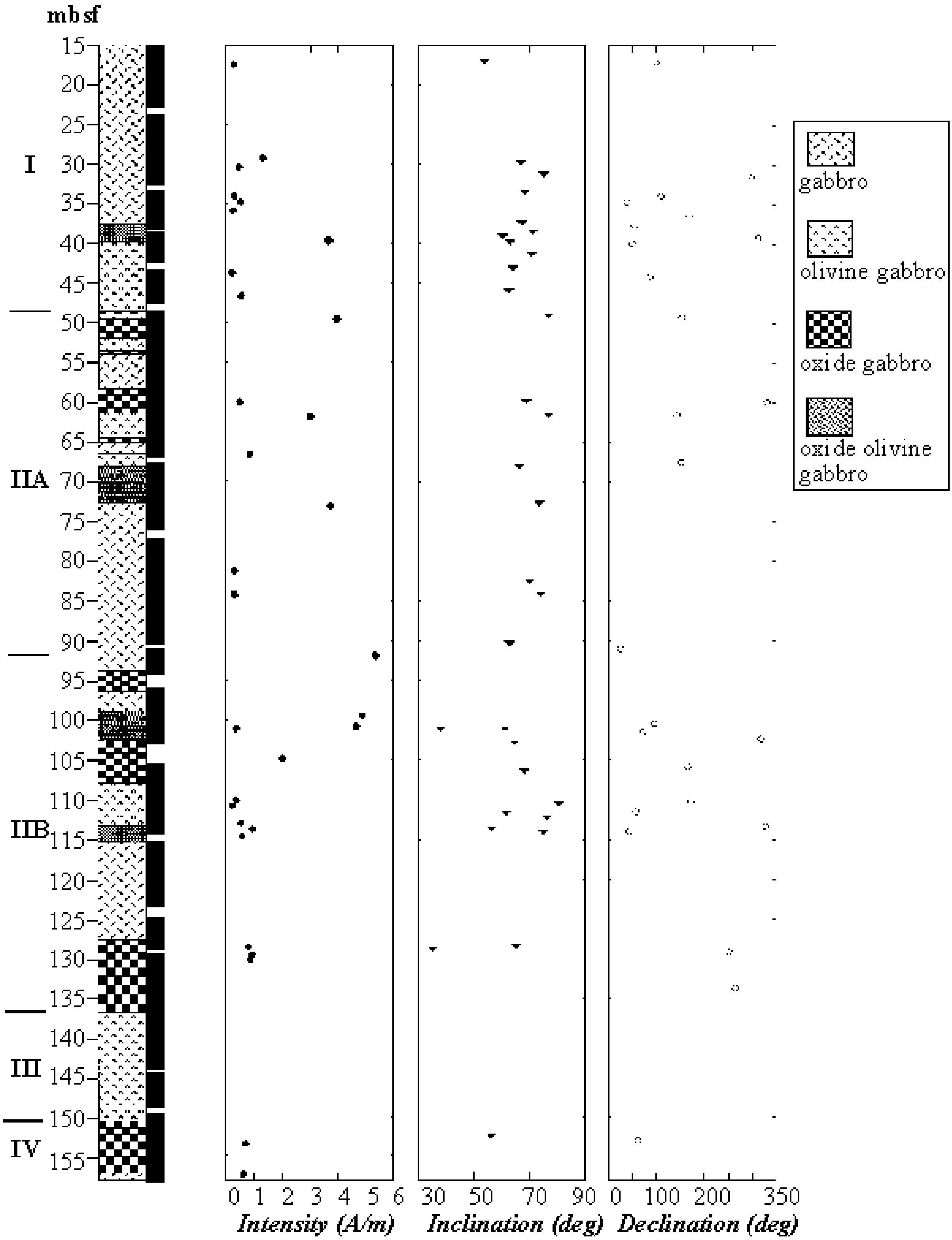

Figure 3(b). Remanent magnetic intensity, inclination and declination down the core are shown. The lithological boundaries of the geological units are identified by Shipboard Scientific Party Leg 179 (1999). The remanent magnetic intensity and susceptibility down the core show correspondence with the oxide minerals.

possess unstable NRMs and low MDFs. The unstable secondary magnetizations common in Fe-Ti oxide gabbros (figure 2b, sample 4R-1, 59) are in planes close to the stable magnetizations. Samples having higher MDF values show invariably smaller angular change in remanence (figure 2c, sample 29R-4, 54) and appear to possess large coercivity. Igneous petrological studies (Shipboard Scientific Party Leg 179, 1999) interpreted oxidation of the minerals constituents of the gabbros especially olivine during deformation process resulting in formation of secondary minerals and their magnetization.

All of the thermal demagnetizations performed on the samples including samples containing fairly large amounts of Fe-Ti oxide minerals show consistent intensity and inclination up to 600°C (figure 2d, sample 6R-3, 93). It exhibits stable component of remanence indicating magnetic minerals of high blocking temperature (560° to 580°C) such as magnetite etc.

4.5 *Stable NRM intensity* (J_{st}) *and inclination* (I_{st})

The plots of inclinations, declinations and intensities for progressive demagnetizations of the samples are shown in Zijderveld diagrams (figures 2a–d). The average stable Normal Remanent Magnetizations (J_{st}) and inclination (I_{st}) after discarding scattered values vary from 1.22×10^{-1} to 9.58 A/m with a mean of 1.98 A/m and $66° \pm 4°$ respectively (table 2). A least square fit of the stable inclination (I_{st}) using a polynomial of degree two (figure 4) shows the inclination $66° \pm 4°$. The geocentric axial paleo dipole magnetic field at the Hole 1105 A (33°S) of the 11.5 Ma age crust is 52°. It means that the observed stable inclination is reverse and steeper. As per the down hole logging results, General Purpose Inclinometery Tool, GPIT the hole vertical deviations remain under 3 to 5° and absolute value of the magnetic field inclination fluctuates between 57.7° and 63.3° with a mean around 60.6° (Shipboard Scientific Party Leg 179, 1999) implying certainly steepening of the inclination by $> 9°$.

4.6 *Lithology and magnetic properties*

The specific units and/or their structure of the 141 intervals of the gabbro rocks cores drilled have been explicitly reflected in most magnetic properties recorded from split and mini-core studies on board JR and in the laboratory (figures 3a and b).

4.6.1 *Unit I*

The unit, in 15 to 48.4 m depth interval, susceptibility mean on split cores is around 800×10^{-6} SI. The average stable remanent magnetic intensity (J_{st}) of the gabbroic rocks of this unit is 7.17×10^{-1} A/m (figure 3b and table 2), which is much lower than the mean intensity, 19.8×10^{-1} A/m of gabbros (table 2) and of J_{nrm} of the rocks, 58.75×10^{-1} A/m (table 1).

4.6.2 *Unit II*

The lithological unit II, in 48.14 to 136.38 m depth interval, shows higher magnetic susceptibilities of the oxide gabbro with a mean around 3500×10^{-6} SI (figure 3a) coinciding with the higher proportions of the oxide gabbros and Fe-Ti oxides and sulphides. The mean stable intensity of magnetization of olivine gabbro is 13.9×10^{-1} A/m, which is lower than the mean, 19.8×10^{-1} A/m and J_{nrm} of olivine gabbros, 40.77×10^{-1} A/m. The increased folds of the J_{nrm} indicate large secondary magnetization contribution from the oxide and sulfide minerals. The magnetic susceptibility plot (figure 3a) clearly depicts the change in susceptibility values at units IIA and IIB boundary and aid in demarcating the apparent grain size boundary with a mean slightly lower for the upper part of the unit IIB. Perhaps the large grain sizes of multi-domain structure are subjected to alterations following hydrothermal activity and formation of more oxides and sulfides minerals around them and acquire secondary magnetization, but show less magnetic susceptibilities compared to upper units. The fine-grained magnetites of high coercivity mark stable inclinations and intensities as well.

4.6.3 *Unit III*

The magnetic susceptibility records of the unit in 136.38 to 150.6 m depth interval (figure 3a) are the lowest, with a mean of 700×10^{-6} SI and are close to the gabbros at the shallow depth of unit I. Most of the rocks are massive and coarse to pegmatite in grain size with large, subhedral clinopyroxene poikcrysts (< 55 mm) (Shipboard Scientific Party Leg 179, 1999).

4.6.4 *Unit IV*

The mean magnetic susceptibility of the unit in 150.6 to 157.44 m depth interval is about 3400×10^{-6} SI and almost equals to unit IIB of oxides and olivine gabbros (figure 3a). Their average J_{st} is 14.95×10^{-1} A/m and J_{nrm} is 5.57 A/m. The J_{nrm} values again mark higher magnetic strength in oxide minerals.

5. Oceanic crust and magnetic anomalies

Magnetic anomalies have been computed following forward model studies of Talwani and Heirtzler (1964) for the oceanic crust consisting of gabbros and serpentinites of varied magnetizations. Model parameters are given in figure 5(a–f).

In the first model figure 5(a), the computed magnetic anomalies amplitudes are up to 300 nT.

Table 2. *Summary of magnetic properties of gabbros from Hole 1105 A.*

Rock type	J_{nrm} A/m	J_{nrm} A/m (Average)	J_{st} A/m	J_{st} A/m (Average)
Gabbros	$> 2.92 \times 10^{-1} < 4.69 \times 10^{0}$	11.73×10^{-1}	$> 1.66 \times 10^{-1} < 3.80 \times 10^{0}$	7.17×10^{-1}
Olivine gabbros	$> 2.72 \times 10^{-1} < 1.73 \times 10^{1}$	40.77×10^{-1}	$> 1.22 \times 10^{-1} < 5.39 \times 10^{0}$	13.9×10^{-1}
Oxide gabbros	$> 7.19 \times 10^{-1} < 1.30 \times 10^{1}$	5.57×10^{0}	$> 3.67 \times 10^{-1} < 4.26 \times 10^{0}$	14.95×10^{-1}
Oxide olivine gabbros	$> 1.11 \times 10^{-1} < 3.37 \times 10^{1}$	1.17×10^{1}	$> 2.69 \times 10^{-1} < 9.58 \times 10^{0}$	39.95×10^{-1}
	Mean =	58.75×10^{-1}		19.8×10^{-1}

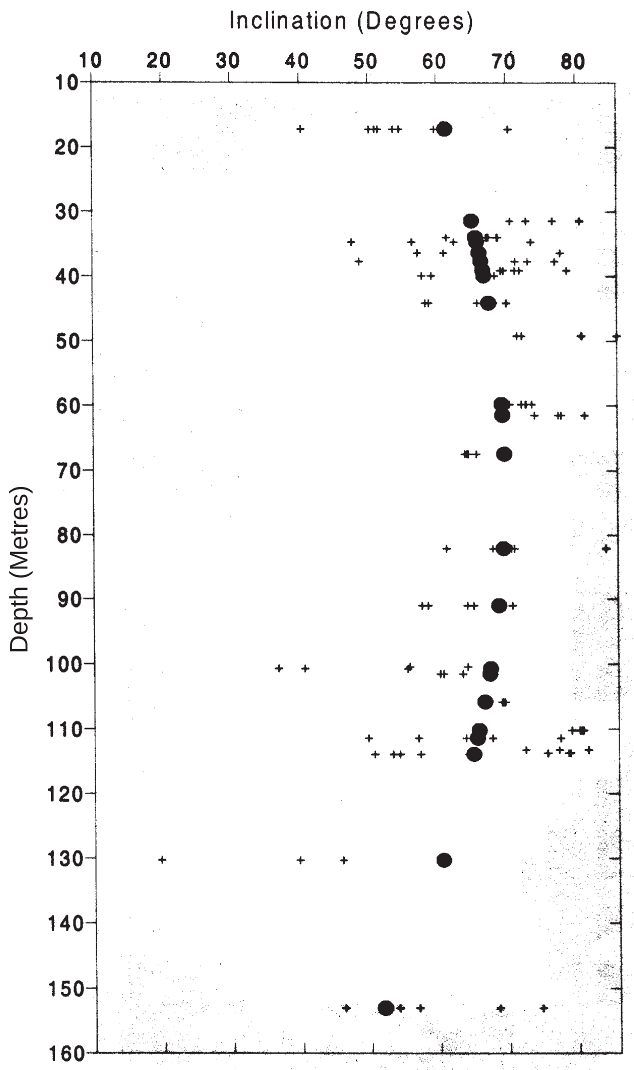

Figure 4. Stable inclinations are plotted down the core. Depths are in meters. Plus and solid circles are inclinations during step-wise demagnetisations and their means respectively.

In the second model figure 5(b), as normal and reversely magnetised blocks of serpentinites (3 km thick) of opposite sense of magnetization with respect to the overlying blocks of gabbroic rocks are placed, asymmetric anomaly amplitudes are very much reduced and vary between 50 and 120 nT only. As in the third model figure 5(c), both rock types of same dimensions, magnetic parameters and also the same sense of magnetization are considered, the computed magnetic anomalies are well resolved, sinusoidal and their amplitudes are up to 400 nT, which are similar to the newtations and amplitudes of seafloor spreading magnetic anomalies. The much reduced anomalies amplitudes of the second model may not adequately represent the seafloor spreading anomalies. The model figure 5(d), is similar to the first model with higher, 5.8 A/m magnetic strength of the gabbros. The computed sinusoidal magnetic anomalies amplitudes are few hundreds of nano-tesla. The models in figures 5(e) and 5(f) show magnetic anomalies of crust consisting of gabbros and serpentinite blocks as placed in models 5(b) and 5(c) but with higher 5.8 A/m magnetic strength of gabbros i.e., the average NRM intensity noticed in the present study. Anomaly amplitudes are again reduced by at least 50% in case of reverse sense of magnetizations between the upper and lower blocks.

Even though the basaltic carapace of the bank is tectonically unroofed, gabbros underlain by serpentinites contribute to the seafloor spreading magnetic anomalies consistent with adjoining areas, which imply the same magnetization of the eroded basalts and gabbros. The east coast magnetic anomaly of north America has been attributed to unipolar magnetization of a pile of out-poured volcanic material, 5 km to more than 10 km thick (Talwani *et al* 1994). The 501 m long oceanic gabbros (both fresh and altered rocks) of the Hole 735B show single stable magnetic polarity (Kikawa and Pariso 1991). Dick *et al* (2000) have suggested that the 1.5 km thick gabbros contribute to the overlying linear magnetic anomalies. Is unipolar magnetization of a minimum 4 km thick crust consisting of basalts and gabbros of the bank, in case basalts are not eroded, imminent to contribute to the observed seafloor spreading magnetic anomalies? And a more rapid or complex cooling history possible than that expected from simple conductive models.

Serpentinization is likely to occur around 400°C i.e., below Curie isotherm of magnetization of magnetite, etc. of the juvenile crust point to the pres-

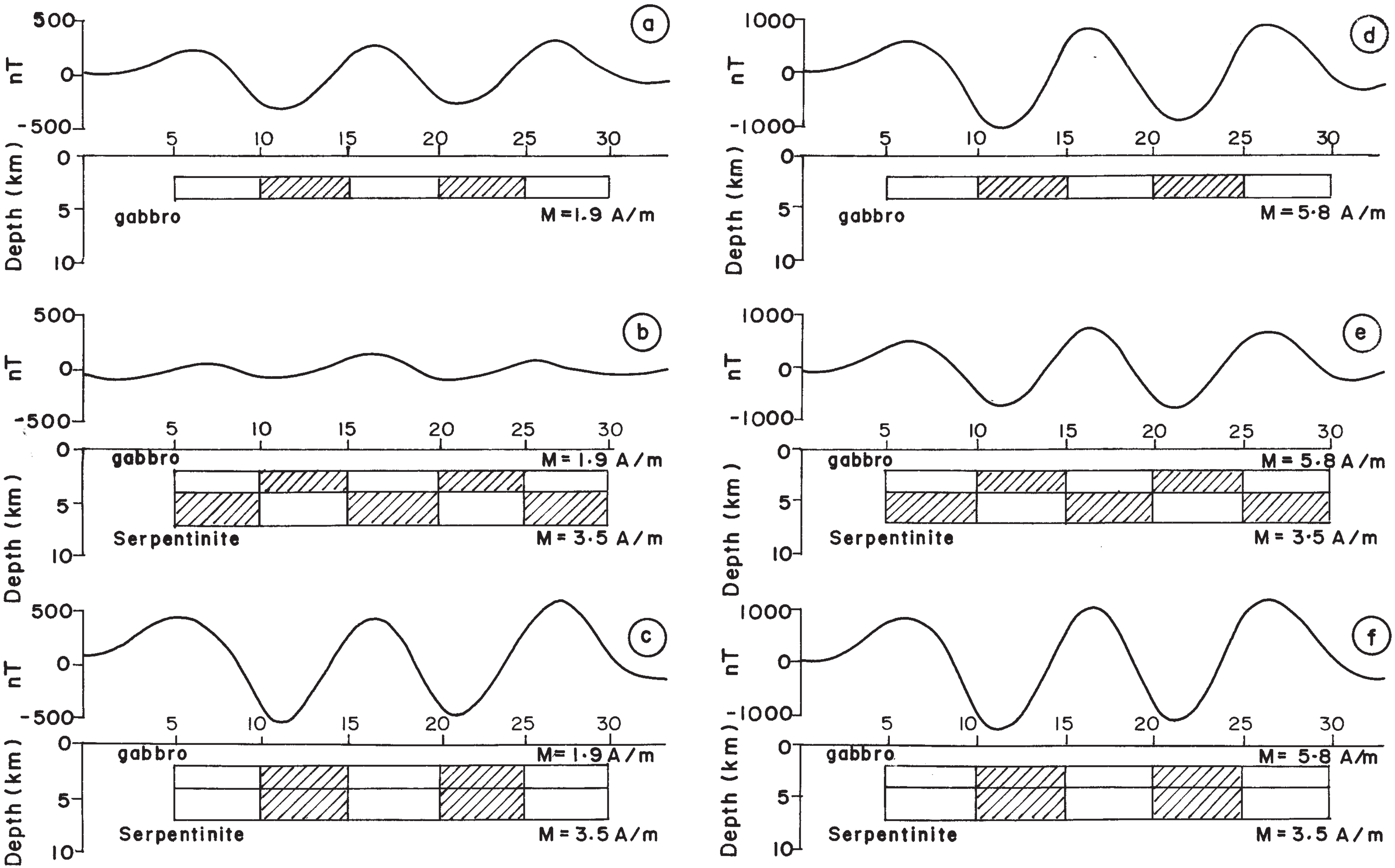

Figure 5. Marine magnetic anomalies are calculated considering **(a)** layer 2 (gabbros) consists of series of N–S trending blocks, 2 km thick and 5 km wide and parallel to the Atlantis Bank and at 2 km depth of normal and reverse magnetization of 1.9 A/m magnetization, 52° inclination and 66° declination, **(b)** layer 2 of the above dimensions is underlain by serpentinites blocks of 3 km thick and direction of magnetization antipodal to the corresponding overlying rocks. The intensity, inclination and declination of magnetization of the serpentinites are 3.5 A/m, 52° and 66° respectively, **(c)** layer 2 underlain by serpentinites of blocks of same dimension and magnetization parameters but same direction of magnetization, **(d)** layer 2 (gabbros) consists of blocks, 2 km thick and 5 km wide at 2 km depth of normal and reverse magnetization (1.9 A/m magnetization, 66° inclination and - 60° declination). And figures 5(e) and 5(f) show magnetic anomalies of the crust of gabbros and serpentinites of similar dimensions as above but differing and same sense of magnetization (5.8 A/m magnetization, 66° inclination and −60° declination) respectively for gabbros.

ence of the complex/rapid mechanism of cooling. The intense crustal tectonic process of the juvenile oceanic crust at the bank will allow hydrothermal circulation deep into the crust leading to rapid cooling of the crustal rocks and serpentinization. The same sense of magnetization of the gabbros and serpentinites contributes to the linear magnetic anomalies implying that some or part of the serpentinites magnetization is the same as that of the gabbros i.e., parallel to ambient magnetic field. So, active tectonics and hydrothermal circulation might have played significantly for lowered temperatures and unipolar magnetization of the crust. Seafloor spreading anomalies of significant amplitudes can as well be generated in case of only the 2 km thick upper oceanic crust of high magnetic strength. Such magnetic intensities are rarely found (Klitgod *et al* 1975; Harrison 1981). Therefore unipolar magnetization of entire crustal rocks and contribution to the observed seafloor spreading anomalies cannot be ruled out.

In many reversal events, minimum duration for magnetic reversal is $\sim$0.5 m.y. which is nearly five times the time interval for formation of the 5r.2n crust. But the seismic refraction results of the Atlantis Bank (Muller *et al* 1997; Minshull *et al* 1998) had revealed serpentinites at about 2 km subsurface depths. Magnetic strength of the serpentinites is quite high and contributes to the observed magnetic anomalies (Fox and Opdyke 1973; Kikawa and Pariso 1991; Nazarova 1994). In fact the serpentinites at deeper depth are less subjected to weathering and could be much more strong magnetically. Therefore, contributions to the seafloor spreading anomalies of the gabbros and serpentinites need to be considered at the Atlantis Bank areas of SWIR in order to explain true amplitudes and shapes of the anomalies.

6. Discussions

The laboratory measured magnetic properties of the gabbros have revealed the higher 1.9 A/m stable magnetic strength of the rocks and stable remanent directions 66°. High Q_n ratios and magnetic strength increase down the core indicating that the rocks possess strong remanence and could contribute significantly to the seafloor spreading magnetic anomalies. Linear magnetic anomalies, magnetic isochron 5r.2n ($\approx$ 11.5 Ma) of the bank has been reported (Shipboard Scientific Party Leg 118, 1989). It is quite revealing that even in the case of the eroded basaltic carapace the seafloor spreading anomalies are not obliterated. It means that even the top basalts, which are eroded in this case and gabbros and serpentinites must have acquired magnetization concurrently in the same direction implying that the 5 km thick oceanic crust reaches below Curie isotherm in the isochron short span time and register magnetizations of the same polarity of the ambient earth's magnetic fields in them.

Duration of the magnetic polarity event, 5r.2n is relatively short, < 0.1 m.y. according to Cande and Kent (1995) magnetic polarity time scale. The model studies supported by the magnetic properties of the gabbros and serpentinites have led to infer that the entire crust of the bank acquires magnetic strength in a single-polarity. If so, one needs to consider the time span for the entire tectonized crustal column to reach below the Curie isotherm T_c (i.e., 540° to 570°C of magnetic minerals) and blocking temperature T_B in less than 0.1 m.y.

Comparison of the litho-stratigraphy of the Holes 1105 A and 735 B of the Atlantis Bank and ductile deformation features reveals that the basic rock types at the two holes are the same even though they are about 1.3 km apart. Dick *et al* (2000) noted the hybrid origin of the olivine gabbros (primitive ferro-gabbros) locally intruded by late magmatic liquids especially within the top 500 m gabbros section meaning closed system differentiation and redistribution. The magnetic properties: NRM, MDF and Q_n ratios of the rocks match well in both cases of the holes. The excess mean stable inclination, above theoretical inclination 52° of the area has been explained due to tectonic block rotation. The nearly same litho-magneto-stratigraphy of the rocks implies no significant spatial variation in them but coeval tectonics. It implies that the entire crustal column, consisting of layers 2, 3A and 3B of about 5 km thick had acquired reversed polarity magnetization or effective unipolar magnetization that contribute to the anomalies. Therefore, it is necessary to consider single polarity of the entire crust to simulate true amplitudes of the synthetic seafloor spreading anomalies in order to compare them to the observed anomalies. It is possible to acquire the magnetization of the rocks in a very short time span, < 0.1 m.y. span of time in this case.

7. Summary and conclusion

The present paper reports results of laboratory and onboard JR measured magnetic properties of the 30 mini core samples of the 158 m long gabbros drilled from Hole 1105 A (ODP Leg 179) and 2-D forward magnetic model studies of the crust of the Atlantis Bank of the SWIR. The measured stable remanent magnetic intensity and inclinations are 1.9 A/m and 66°, which are in close conformity with the results at the Hole 735 B.

The observed steepness in inclination that is in excess by 14° compared to the theoretical value of the region around 33°S is due to tectonic block rotation by the same amount consequent to the magnetization.

Comparison of the results with that of Hole 735 B rocks of the bank has led us to conclude that the contributions of the lower crust rocks: gabbros and serpentinites are necessarily to be considered to explain the observed seafloor spreading anomaly's true amplitudes.

The lateral homogeneities of the crustal properties, tectonics and cooling process point to possible single volcanic/ magma source of the rocks and one-time geologic/tectonic process contributing to the magnetization features recorded in them.

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