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Absolute Thellier paleointensities from Ponta Grossa dikes (southern Brazil) and the early Cretaceous geomagnetic field strength

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Resumen

Se presentan los estudios de propiedades magnéticas y paleointensidades por el método de Thellier en los diques de ~130.5 Ma de Ponta Grossa, sur de Brasil. Para este estudio se seleccionaron 29 muestras, correspondientes a siete unidades de enfriamiento, en términos de su bajo índice de viscosidad magnética, magnetizaciones remanentes estables y curvas termomagnéticas reversibles para los análisis de paleointensidades. Diecinueve muestras mostraron curvas Arai cóncavas, pruebas pTRM negativas o pruebas pTRM positivas con adquisición de TRM no correlacionado a eliminación de NRM, por lo que fueron retiradas de los análisis subsecuentes. Determinaciones de paleointensidad de alta calidad técnica, que cumplen con estrictos criterios, se obtuvieron para 10 muestras provenientes de 3 diques. Las paleointensidades promedio para los 3 diques varían de 25.6 ± 4.3 a 11.3 ± 2.1 μT, que corresponden a momentos dipolares virtuales VDM de 5.7 ± 0.9 a 2.5 ± 0.5 (10^{22} Am^2). El valor medio del momento dipolar VDM es 4.1 ± 1.6 x 10^{22} Am^2. Los valores de paleointensidades sugieren una variación grande para los diques y el momento dipolar VDM es inferior al momento dipolar determinado para la Provincia Magmática del Paraná. Las paleointensidades determinadas en los diques Ponta Grossa concuerdan con las determinaciones en vidrios basálticos submarinos en el intervalo 130-120 Ma, lo que sugiere una intensidad del campo paleomagnético relativamente baja en el periodo anterior al Super-Crón Normal del Cretácico.

Palabras clave: Cretácico temprano, paleointensidades, magnetismo de rocas, diques Ponta Grossa, cuenca del Paraná, Brasil.

Abstract

We report a detailed rock magnetic and Thellier paleointensity study from ~ 130.5 Ma Ponta Grossa Dike Swarms in Southern Brazil. Twenty-nine samples from seven cooling units were pre-selected for paleointensity experiments based on their low viscosity index, stable remanent magnetization and close to reversible continuous thermomagnetic curves. 19 samples characterized by negative pTRM tests, Arai concave-up curves or positive pTRM tests with NRM loss uncorrelated with TRM acquisition were rejected. High quality reliable paleointensity determinations are determined from detailed evaluation criteria, with 10 samples belonging to three dikes passing the tests. The site-mean paleointensity values obtained in this study range from 25.6 ± 4.3 to 11.3 ± 2.1 μT and the corresponding VDM's range from 5.7 ± 0.9 to 2.5 ± 0.5 (10^{22} Am^2). These data yield a VDM mean value of 4.1 ± 1.6 x 10^{22} Am^2. Significant variability of Earth's magnetic field strength is observed for Ponta Grossa Dikes with the mean value being significantly lower as compared to the mean VDM obtained from the nearby Paraná Magmatic Province. The paleointensities for the Ponta Grossa Dikes are in agreement with absolute paleointensities retrieved from the submarine basaltic glasses from 130 to 120 Ma. It seems that a relatively low field prevailed just before the Cretaceous Normal Superchron.

Key words: Early Cretaceous, paleointensity, rock magnetism, Ponta Grossa dike swarms, Paraná basin, Brazil.

Introduction

The Earth's magnetic field strength may have been significantly different in the geological past because of different factors that may influence magnetohydrodynamic processes within the Earth's fluid outer core. The Cretaceous is a key interval in the history of the Earth's magnetic field. The currently debated relationship between the frequency of reversals, secular variation, and paleointensity should be clearly expressed during Cretaceous Normal Superchron (CNS; Tarduno *et al.*, 2002) when the reversal rate was almost zero.

Already Koenigsberger (1938) argued that low paleointensity prevailed during some periods of the Mesozoic. These pioneering data were interpreted to reflect the decay of magnetic remanence with time. Prévot *et al.*, (1990); Perrin and Scherbakov, (1997) and Pick and Tauxe (1993) suggested extension of the Mesozoic dipole low into the whole Cretaceous period. Recently available reliable paleointensity data (Tarduno *et al.*, 2001, 2002; Tauxe, 2006, Granot *et al.*, 2007) suggest, however, that the paleostrength during the early Cretaceous may have been comparable or even higher than present intensity and not 'anomalously' low as suggested in previous studies. The paucity of data makes difficult to derive any firm conclusions about the evolution of geomagnetic intensity through geological time.

Although the data becomes abundant during last years, the age distribution of paleointensity data is still quite patchy with 39% of the data being younger than 1 Ma (Tauxe and Yamazaki, 2007). Moreover, most data come from the Northern Hemisphere. A preliminary paleointensity study was already performed on Ponta Grossa dikes using the multisample technique (Brandt *et al.*, 2008). Main handicap of this technique is the difficulty to correct raw paleointensity values by anisotropy effects which are particularly important for dikes. The samples are aligned (using a special sample holder) to held the laboratory field direction parallel to the NRM (Natural Remanent Magnetization) direction of samples. In case of highly anisotropic materials, it cannot be ascertained that the ancient field direction was exactly parallel to the NRM directions. Another limitation is the impossibility to monitor the creation (if any) of chemical remanence (CRM) during the heatings in air.

In this study, we contribute to the investigation of the long-term variation of geomagnetic field strength by reporting new reliable paleointensities from ~ 130.5 Ma Ponta Grossa Dike Swarms from Southern Brazil. These rocks formed just before the Cretaceous Normal Superchron and thus are of particular interest for investigating the field variations in the Early Cretaceous and the relationship between field strength and reversals.

Sampling Details and Available Ages

Almost all Mesozoic tholeiitic dike swarms in Brazil are concentrated towards the continental margins (Sial *et al.*, 1987). The most important mafic dike swarms in Brazil occur in the Ponta Grossa (PG) region (Fig. 1) and are associated with the flood basalt suites of the Paraná basin (Piccirillo *et al.*, 1990). The Ponta Grossa Arch is a large (~134,000 km^2 after Raposo and Ernesto, 1995) tectonic feature on the eastern border of the Paleozoic-Mesozoic Paraná Basin, with north and south limits corresponding to the Guapiara and Rio Piquiri lineaments respectively. This region comprises hundreds of dikes, predominantly basaltic and andesitic but also (rarely) of rhyolitic composition. All previous studies suggest that Ponta Grossa dikes were probably feeders of the stratovolcanoes built in northern Paraná towards the continental margin and later eroded.

Renne *et al.* (1996) reported numerous ^{40}Ar/ ^{39}Ar high quality plateau ages. The age-probability distribution for the dominant pulse (131.4 ± 0.4 to 129.2 ± 0.4 Ma) shows a pronounced peak at 130.5 Ma; this distribution probably reflects the magma production history in the region. These geochronological data are consistent with conclusions (based on paleomagnetic and stratigraphic data) that the PG dikes are younger than the volumetrically dominant volcanism of the southern Paraná Magmatic Province, which occurred at 133-132 Ma.

In total, we obtained 235 standard paleomagnetic cores belonging to 29 sites (Fig. 1) distributed along road outcrops in Ponta Grossa region, Southern Brazil. The samples were distributed throughout each dike both horizontally and vertically. In general, samples were obtained at least 30 cm distance from the dike edge. Cores were obtained with a gasoline-powered portable drill, and then oriented in most cases with both magnetic and sun compasses.

Sample Selection for Thellier Paleointensity Experiments

Pre-selection of the samples for Thellier paleointensity experiments was mainly based on analyses of viscosity index measurements, coercivity and unblocking spectra and vectorial composition from demagnetization of natural remanent magnetization and temperature dependence of low-field magnetic susceptibility. Magnetic hysteresis measurements combined with IRM (isothermal remanent magnetization) acquisition experiments were used to estimate the domain state of main magnetic carriers.

Magnetic characteristics of typical samples selected for Thellier paleointensity experiments are as follows:

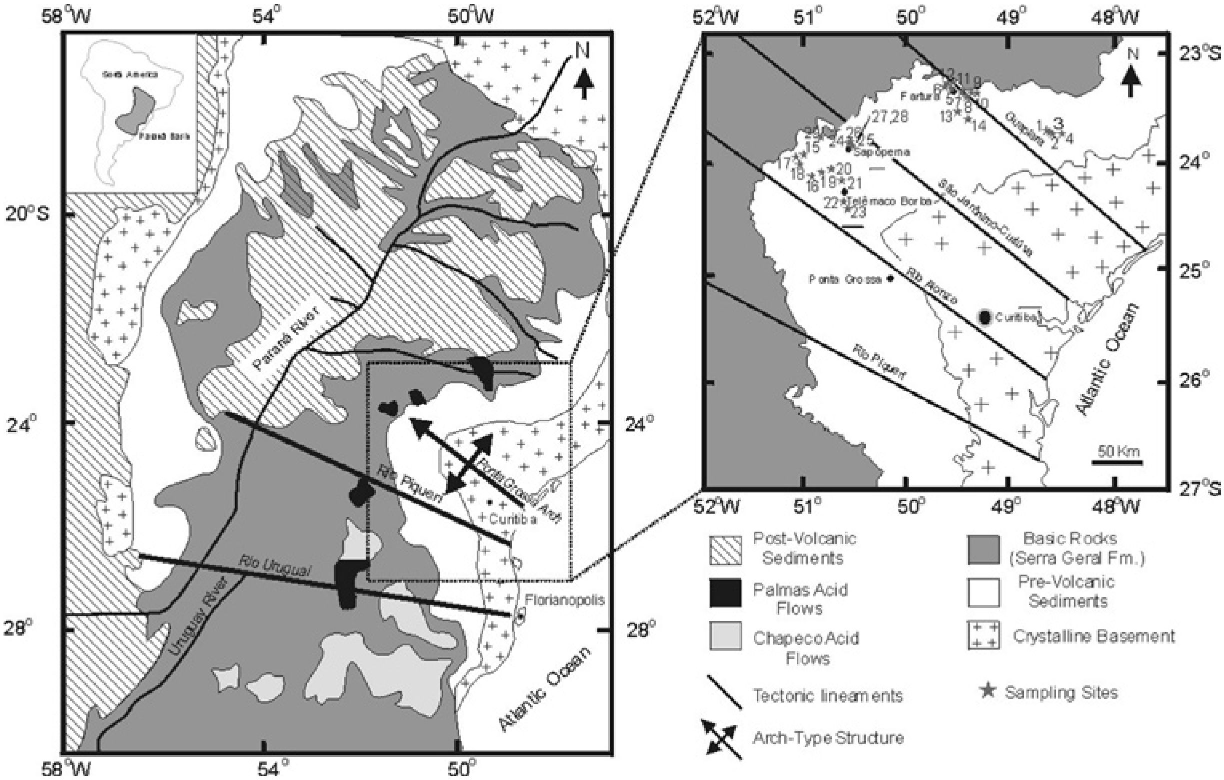

Fig. 1. Simplified geologic map of Southern Brazil showing the location of studied sites (adopted from Brandt *et al.*, 2009).

a) Ponta Grossa Dikes are likely to have a relatively high Brunhes-age VRM (viscous remanent magnetization). In storage tests (Prévot *et al.*, 1983), 132 samples exhibited viscosity indexes higher than 5 %. These samples were discarded for Thellier experiments.

b) Selected samples carry essentially a stable, univectorial remanent magnetization, observed upon both thermal (sample 03D011A, Fig. 2) and alternating field (sample 03D012A) treatment. Minor secondary components probably of viscous origin is sometime present but easily removed at first steps of demagnetization procedure. The median destructive fields range mostly in the 30-40 mT interval, suggesting the existence of 'small pseudo-single domain grains' as remanence carriers (Dunlop and Ozdemir, 1997). Some other samples (03D064A and 03D059A) exhibit clearly defined two component magnetizations probably of chemical origin.

c) Low-field continuous susceptibility measurements performed in air (using a Bartington susceptibilitymeter MS2 equipped with furnace) show the presence of a single ferrimagnetic phase with Curie temperature compatible with Ti-poor titanomagnetite (sample 03D014, Fig. 3). This is a case of 58 samples out of 235 analyzed. Remained samples displayed highly unstable thermal behavior during heating and cooling cycles (03D054 and 03D103) and thus were discarded for paleointensity experiments.

d) Hysteresis measurements at room temperature show (Fig. 4) that the studied samples fall in the 'small pseudo-single-domain' grain size region on a plot Mr/Mrs vs Hcr/Hc (Day *et al.*, 1977). This probably indicates a mixture of multidomain and a significant amount of single-domain (SD) grains (Fig. 5, Parry, 1982; Dunlop, 2002). IRM (isothermal remanent magnetization) acquisition curves show the saturation at moderate fields (150-200 mT), which point to the presence of titanomagnetite.

In total, we selected 29 samples from 7 dikes for the paleointensity experiments having the above-described magnetic characteristics.

Paleointensity measurements

Paleointensity experiments were performed using the Thellier method (Thellier and Thellier, 1959) in its modified form (Coe, 1967). All heatings were made in vacuum better than 10^{-2} mbar. Eleven temperature steps (Fig. 6) were distributed between room temperature and 570°C, and the laboratory field was set to 30 μT. Control heatings, commonly referred as pTRM checks (Prévot *et al.*, 1985), were performed after every second heating step throughout the whole experiment. All remanences

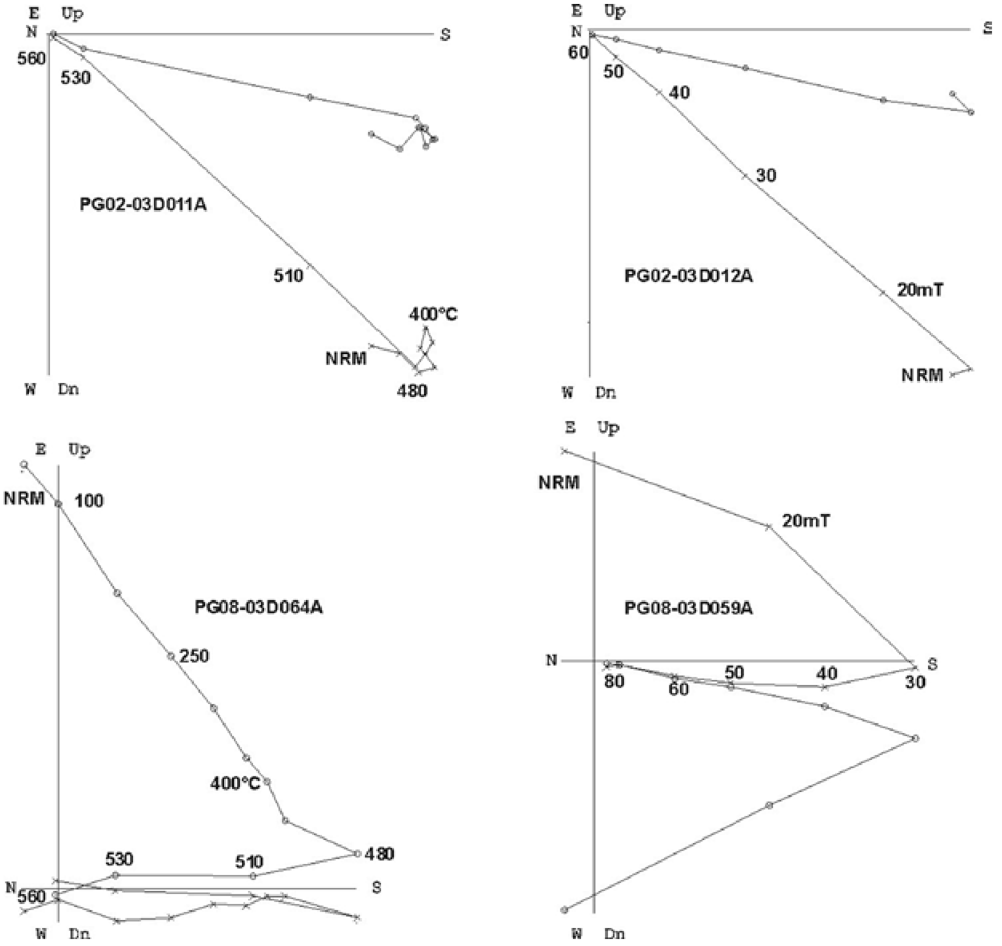

Fig. 2. Orthogonal vector plots of stepwise thermal or alternating field demagnetization of representative samples (stratigraphic coordinates). The numbers refer either to the temperatures in °C or to peak alternating fields in mT. o - projections into the horizontal plane, x – projections into the vertical plane.

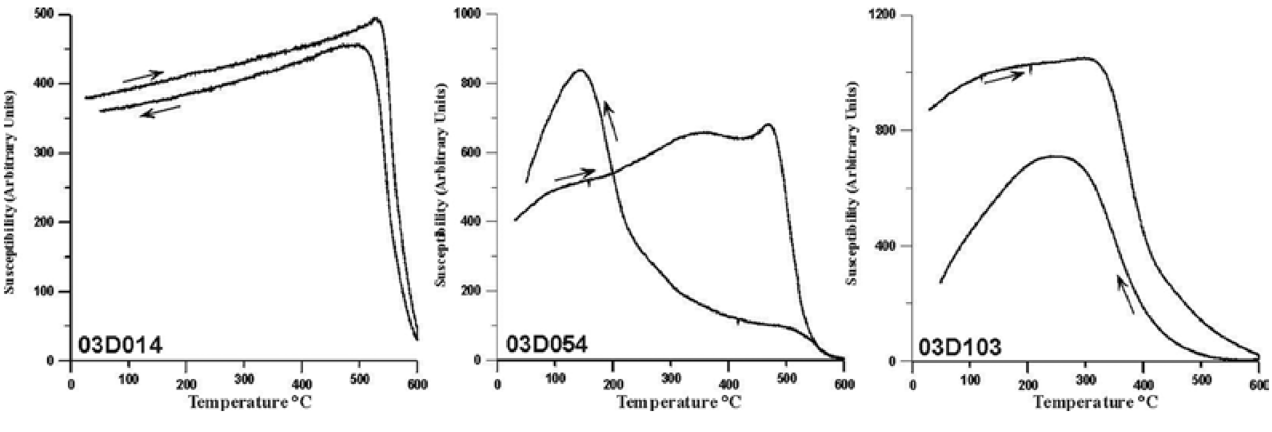

Fig. 3. Susceptibility versus temperature (in air) curves of representative samples. The arrows indicate the heating and cooling curves.

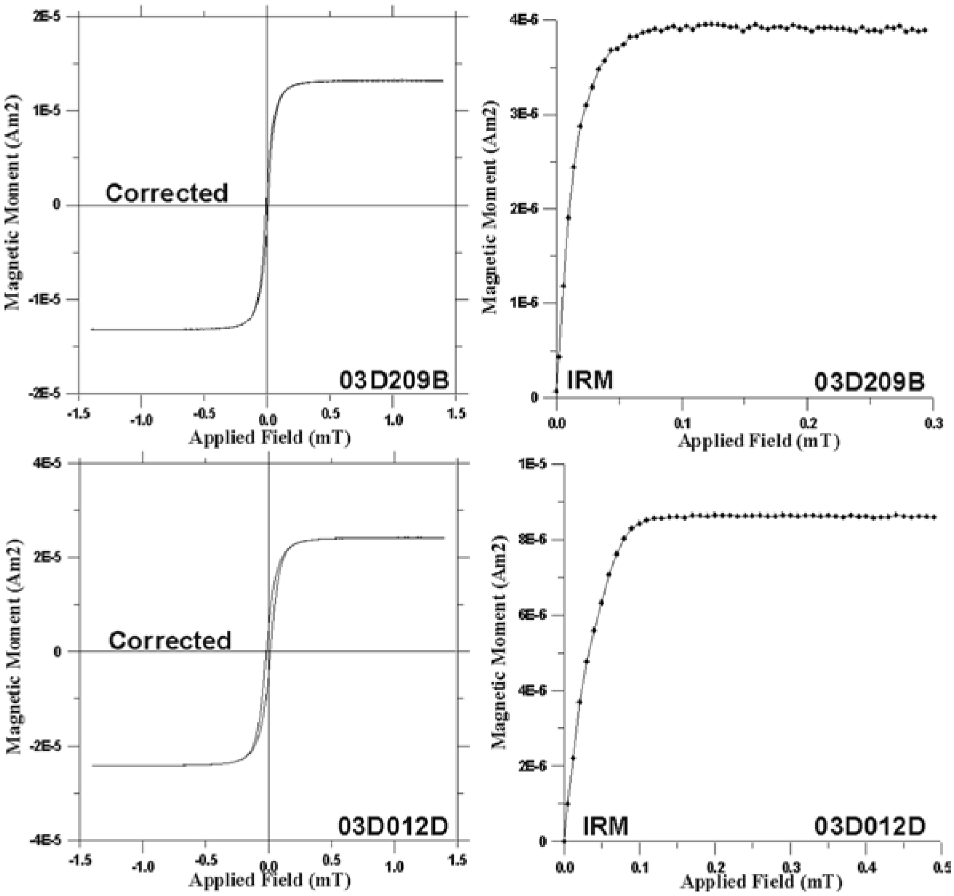

Fig. 4. Typical examples of hysteresis loops (corrected for dia/paramagnetism) of small chip samples from the studied volcanic units.

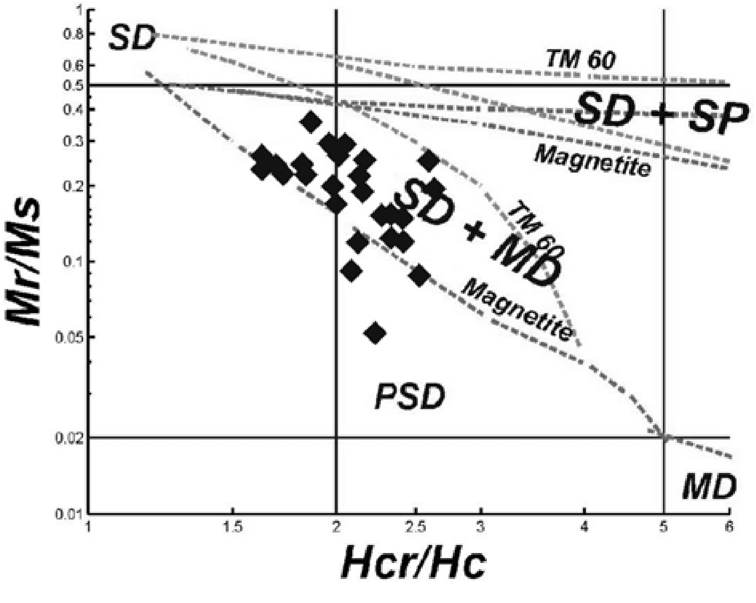

Fig. 5. Room temperature hysteresis parameters plotted on Dunlop's (2002) curve (see text for more details).

were measured using both JR5A and JR6 spinner magnetometers.

We accepted only determinations that satisfied all of the following requirements: a) obtained from at least 7 NRM-TRM points corresponding to a NRM fraction, f, (Coe *et al.*, 1978) larger than about 1/3 with quality factor, *q*, (Coe *et al.*, 1978) of about 5 or more (Table 1). b) At least three positive pTRM checks. We define pTRM checks as positive if the repeat pTRM value agrees with the first measurement within 15%. c) The directions of NRM end points at each step obtained from paleointensity experiments are stable and linear pointing to the origin. No significant deviation of NRM remaining directions towards the direction of applied laboratory field was observed. d) For accepted determinations γ values (the ratio of potential CRM(T) to the magnitude of NRM(T) for each double heating step in the direction of the laboratory field during heating, Goguitchaichvili *et al.*, 1999), are < 10° which attest that no significant CRM (chemical remanent magnetization) is acquired during the laboratory heatings.

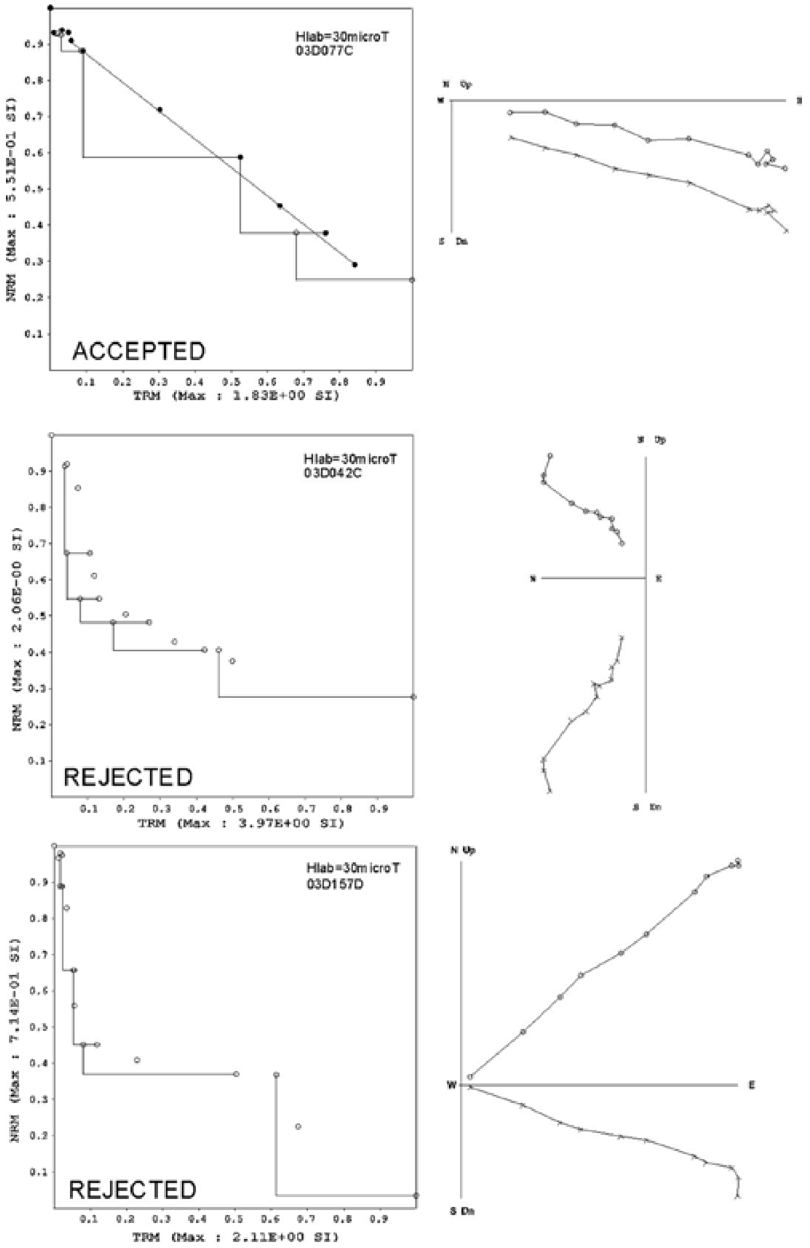

Fig. 6. The representative NRM-TRM plots and associated orthogonal diagrams from Ponta Grossa Dikes. In the orthogonal diagrams we used same notations as in the fig. 2.

Table 1

Paleointensity results from Ponta Grossa Dikes, n is number of NRM-TRM points used for palaeointensity determination, Tmin-Tmax is the temperature interval used, *f*, *g* and *q* are the fraction of extrapolated NRM used, the gap factor and quality factor (Coe *et al.*, 1978) respectively. F_E is paleointensity estimate for individual specimen, and $\sigma(F_E)$ is its standard error; F_E is average paleointensity of individual lava flow, the plus and minus sign corresponding to standard deviation; VDM and VDMe are individual and average virtual dipole moments.

Paleointensity results from Ponta Grossa dikes

Site	*Sample*	*n*	*Tmin-Tmax*	*f*	*g*	*q*	$F_E \pm \sigma(F_E)$	*VDM*	*FE* ± s.d.	*VDMe*
PG02	03D008C	7	200-480	0.71	0.81	15.9	18.2 ± 0.8	4.08	**18.2 ± 0.8**	**4.1 ± 1.3**
	03D011B	8	200-510	0.63	0.71	6.9	19.3 ± 0.9	4.33		
	03D012C	8	200-510	0.49	0.78	7.6	16.3 ± 0.8	3.66		
	03D014C	7	300-510	0.74	0.81	8.2	18.8 ± 0.9	4.22		
PG10	03D074C	9	300-540	0.75	0.82	21.6	11.3 ± 0.3	2.54	**11.3 ± 2.1**	**2.5 ± 0.5**
	03D076B	9	300-540	0.53	0.88	12.7	13.5 ± 0.8	3.03		
	03D077C	9	350-560	0.71	0.83	19.7	9.2 ± 0.4	2.06		
PG23	03D175B	7	300-510	0.66	0.88	12.6	23.9 ± 0.5	5.36	**25.6 ± 4.3**	**5.7 ± 0.9**
	03D176C	7	300-510	0.64	0.78	8.9	22.3 ± 1.2	5.0		
	03D178C	7	300-510	0.56	0.82	6.4	30.5 ± 2.0	6.85		

The reasons for failure of Thellier experiments were negative pTRM checks and/or typical 'concave-up' behavior (Dunlop and Özdemir, 1997) detected in some cases (samples 03D042C and 03D057D, Fig. 6). An important loss of NRM without any noticeable TRM acquisition but with positive pTRM checks is observed. This phenomenon can be due to irreversible variations of coercive force (Kosterov and Prévot, 1998) at low temperature and can be interpreted as transformation from a single-domain or pseudo-single-domain 'metastable' state to multidomain state which results in a large NRM lost without any correlated TRM acquisition during the subsequent cooling.

Main Results and Discussion

Ten samples, from three individual cooling units, yield acceptable paleointensity estimates (Fig. 6, Table 1) while 19 determinations were rejected based on negative pTRM tests (11 samples) Arai concave-up curves (8 samples yielding positive pTRM tests with NRM loss uncorrelated with TRM acquisition). For accepted samples, the NRM fraction *f* used for determination ranges between 0.49 to 0.77 and the quality factor *q* varies from 6.4 to 23.6. The Thellier and Thellier (1959) method of geomagnetic absolute intensity determination, which is considered the most reliable one (Goguitchaichvili *et al.*, 1999), imposes many restrictions on the choice of samples that can be used for a successful determination (Coe, 1967, Levi, 1977, Prevot *et al.*, 1985, Pick and Tauxe, 1993, Kosterov and Prévot, 1998). The almost 70 percent failure rate that we find in our study is not exceptional for a Thellier paleointensity study, if correct pre-selection of suitable samples and strict analysis of the obtained data are made. Although the final results from the pre-selection and paleointensity experiments are not numerous, the high technical quality determination, attested by the high quality factors defined by Coe *et al.* (1978) lend support for the paleointensity estimates for the dikes.

The site-mean paleointensity values obtained in this study for the dikes are 25.6 ± 4.3, 18.2 ± 0.8 and 11.3 ± 2.1 μT, with corresponding VDM's are 5.7 ± 0.9, 4.1 ± 1.3 and 2.5 ± 0.5 (10^{22} Am^2). These data yield a mean value of 4.1 ± 1.6 x 10^{22} Am^2. Brandt *et al.* (2008) obtained intensities between 5.7 ± 0.2 μT to 26.4 ± 0. 7 μT (average of 13.4 ± 1.9 μT). Virtual dipole moments for these sites range from 1.3 ± 0.04 to 6.0 ± 0.2 10^{22} Am^2 (average of 2.9 ± 0.5 10^{22} Am^2).

Paleointensity data (selected applying same strict selection criteria as in present study) from nearby Paraná Magmatic Province (PMP) are as strong and variable as those from Troodos Ophiolite (Fig. 7, Tauxe, 2006; Granot *et al.*, 2007; Goguitchaichvili *et al.*, 2008). Globally, early Cretaceous paleointensities appear similar to Brunhes data. The important variability of Earth's magnetic field strength is also observed for Ponta Grossa Dikes. The mean paleointensity for each dike is well defined, with low standard deviations. This suggests that the differences

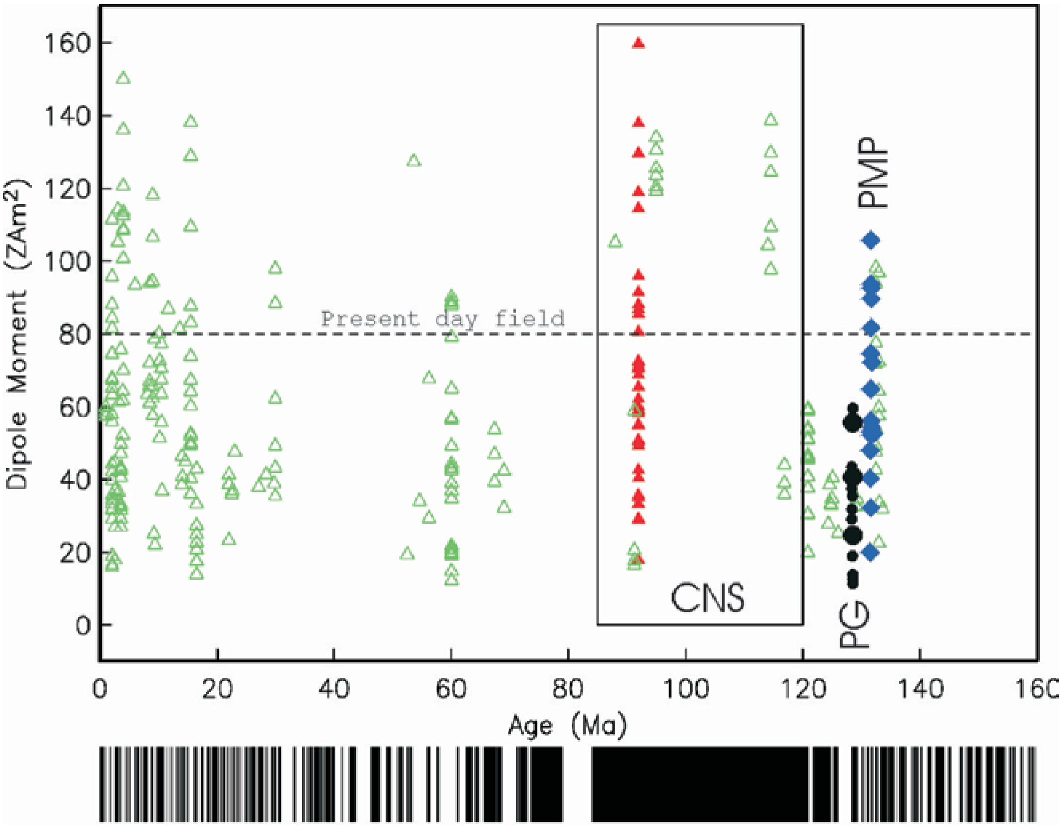

Fig. 7. Summary of virtual dipole moment data versus age. In red are the Troodos submarine basaltic glass data (Tauxe, 2006). The PMP data are shown in blue and date from Ponta Grossa are shown in black (small symbols refer to the data of Brandt *et al.*, 2009). The present field is the dotted line. Also shown is the Geomagnetic Polarity Time Scale.

between dikes may relate to variability of the field strength during the time span represented by the dikes. The mean overall value is significantly lower as compared to the mean VDM obtained from the Paraná Magmatic Province. In contrast, these new data are in excellent agreement with absolute paleointensities retrieved from the submarine basaltic glasses from 130 to 120 Ma (Tauxe, 2006). It seems that relatively variable low field prevailed just before the Cretaceous Normal Superchron.

Acknowledgment

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