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On the reliability of Mesozoic Dipole Low: New absolute paleointensity results from Paraná Flood Basalts (Brazil)

Avto Goguitchaichvili, Luis M. Alva-Valdivia, Jaime Urrutia, and Juan Morales
Instituto de Geofisica, U.N.A.M., México D.F., México

Omar Ferreira Lopes
Universidade Federal do Paraná, Departamento de Geologia, Curitiba, Brazil

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[1] Thellier paleointensity experiments were carried out on Early Cretaceous Paraná Flood Basalts. Forty-two samples from 11 lava flows yielded apparently reliable absolute intensity determinations. The mean paleointensity values per flow obtained in this study are ranging from 19.4 ± 4.0 to 46.7 ± 7.0 μT and the corresponding Virtual Dipole Moments are ranging from 4.0 ± 0.6 to 10.5 ± 1.1 (10^{22} Am^2). These yield a mean value of 7.2 ± 2.3 × 10^{22} Am^2, which is about 92% of the present geomagnetic axial dipole. Our results in conjunction with *Tarduno et al.*'s [2001] data suggest that the paleostrength during early Cretaceous period might be comparable or even much higher than recent field intensity and not 'anomalously low' as previously suggested. Thus, the Mesozoic Dipole Low (MDL) may probably be considered as unreliable. *INDEX TERMS:* 1521 Geomagnetism and Paleomagnetism: Paleointensity; 1522 Geomagnetism and Paleomagnetism: Paleomagnetic secular variation; 1532 Geomagnetism and Paleomagnetism: Reference fields (regional, global); 1540 Geomagnetism and Paleomagnetism: Rock and mineral magnetism; 1560 Geomagnetism and Paleomagnetism: Time variations—secular and long term

1. Introduction

[2] Variation of paleointensity over geologic time may indicate modulation of geodynamo action in the core by the convective state of the lower mantle. Thus, determinations of the absolute intensity of the Earth's magnetic field in the past are decisive for understanding the processes in the core that give rise to the geomagnetic field and how and why the Earth's magnetic field reverses polarity. Despite of about forty years of research, paleointensity data are scarce [*Selkin and Tauxe*, 2000] and they cannot be yet used to document a long-term variation in the intensity of the Earth's magnetic field through geological time.

[3] *Prévot et al.* [1990] based on paleointensity data compilation since the Triassic period [*Bol'shakov and Solodovnikov*, 1983] first underlined the existence of relatively low field during Mesozoic time (mainly from 180 to 120 Ma). The dipole strength was found only one third of the Cenozoic value, prevailing during most of Mesozoic time. *Kosterov et al.* [1998] and *Perrin and Shcherbakov* [1997] confirmed this Mesozoic Dipole Low (MDL) by detailed experimental and statistical analyses of the paleointensity records. More recently, based on new high technical quality data from submarine basaltic glasses, *Juarez et al.* [1998] argued that the average dipole moment of the Earth over the past 160 Ma was only half of present day field, suggesting that MDL was not 'low' but of average intensity. High geomagnetic intensities of (12.5 ± 1.4) × 10^{22} Am^2 have been reported [*Tarduno et al.*, 2001] for the interval 113–116 Ma, which are consistent with some inferences from computer simulations [*Glatzmaier et al.*, 1999]. *Zhu et al.* [2001] found relatively low dipole-field intensity just prior to the Cretaceous normal superchron. Thus, more reliable paleointensity data are strongly needed to confirm or reject the MDL.

[4] In this paper, we present new paleointensity results from Paraná Flood Basalts (southern Brazil) erupted between 133 and 132 Ma [*Renne et al.*, 1996; *Tamrat et al.*, 1999].

2. Ages and Sampling Details

[5] The Paraná Magmatic Province (PMP) represents one of the world's largest volumes of Mesozoic continental flood basalt, covering an area about 1.2 × 10^6 km^2, located in southern Brazil (mainly), Uruguay, Paraguay and Argentina. The Paraná lavas (Serra Geral Formation) overlie the Botucatu formation (Jurassic-Cretaceous), which is composed of typical aeolian sandstones representing the top of the Gond-

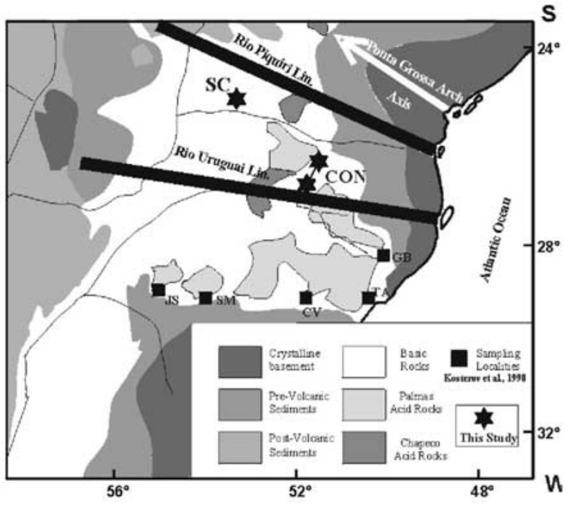

Figure 1. Simplified geological map of Paraná flood basalts with indication of paleomagnetic sections, modified from *Kosterov et al.* [1998].

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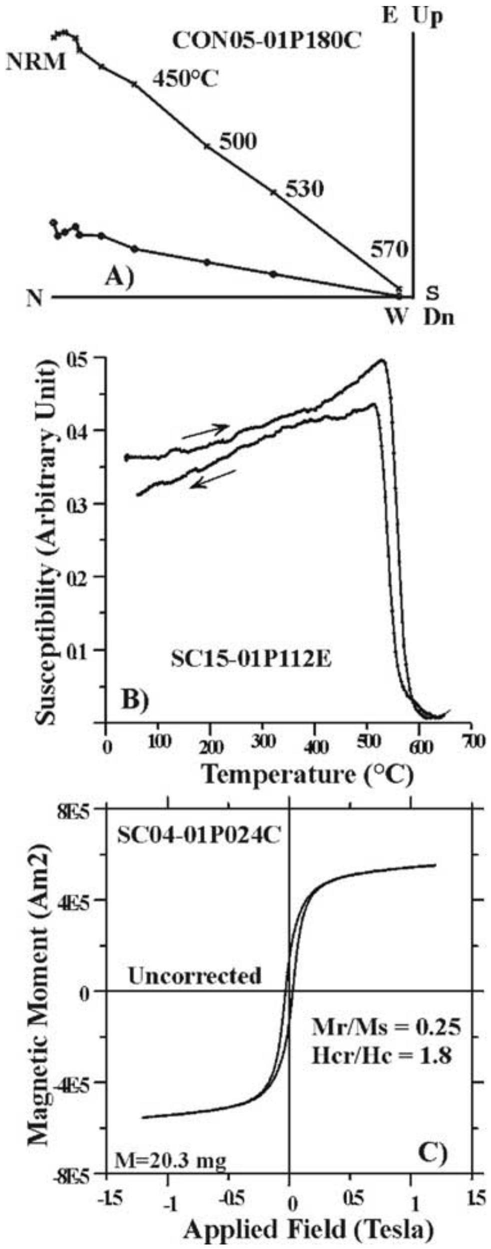

Figure 2. Summary of the magnetic characteristics of the typical samples, selected for Thellier paleointensity experiments. (a) Orthogonal vector plot of stepwise thermal demagnetization (stratigraphic coordinates). The numbers refer to temperatures in °C. o-projections into the horizontal plane, x-projections into the vertical plane. (b) Susceptibility versus temperature curve. The arrows indicate the heating and cooling curves. (c) Example of hysteresis loop (uncorrected).

wana sequence. *Renne et al.* [1996] showed that the entire PMP erupted in a very narrow age interval (mainly 133–132 Ma) although slightly older ages have been reported.

[6] The PMP is divided into three major parts by the Rio Uruguay and Rio Piquiri tectonic lineaments (Figure 1) which existed since Devonian. This division is not only tectonic but also can be traced by geochemical data [*Kosterov et al.*, 1998]. Tholeiitic basalts are the dominant rock type, however, volcanic suites may also include some acid and basic rocks [*Tamrat et al.*, 1999]. Paleomagnetic sampling was done in the central part of PMP (Figure 1) between both major lineaments. Cores were drilled in the field and oriented in most cases with both magnetic and sun compasses. Two sequences were sampled (35 lava flows, about 300 standard paleomagnetic cores): 156 cores belonging to 18 lava flows were collected at Salto Caixa hydroelectrical station and along the road Capitan Leonidas-Cascavel (SC: 25°24′S, 53°34′W); 17 cooling units were sampled along the highway BR153 from Rio Uruguay level to Concordia and Irani (CON: between 27°22′S, 51°59′W and 26°47′S, 51°42′W). It is quite possible that our section SC corresponds to section CI from *Tamrat et al.* [1999] although no paleomagnetic holes were found at our sampling area.

3. Rock-Magnetic Properties

[7] Magnetic characteristics of typical samples selected for Thellier paleointensity measurements are summarized in Figure 2 and could be described as follows:

1. Selected samples carry essentially a single and stable component of magnetization, observed upon thermal (Figure 2a) treatment. A generally minor secondary component, probably of viscous origin, was present but was easily removed. The greater part of remanent magnetization, in most cases was removed at temperatures between 530 and 570°C, which points to low-Ti titanomagnetites as responsible for magnetization.

2. Low-field continuous susceptibility measurements with temperature show the presence of a single ferrimagnetic phase with Curie point compatible with Ti-poor titanomagnetite (Figure 2b). Polished section observations

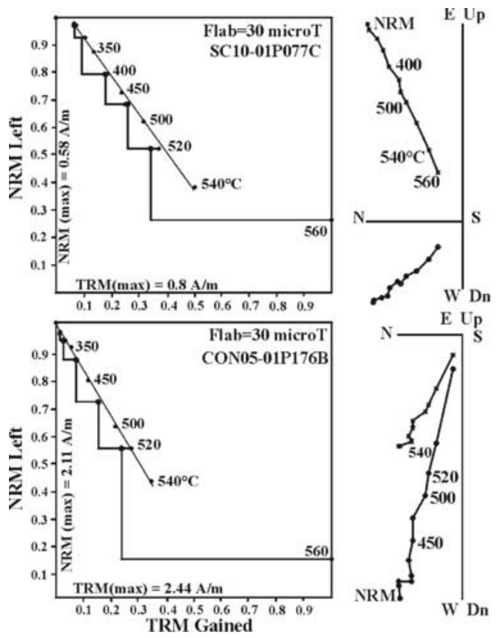

Figure 3. The representative NRM-TRM plots and associated orthogonal diagrams for Paraná samples. In the orthogonal diagrams we used same notations as in the Figure 2a.

Table 1. Paleointensity Results from Paraná Magmatic Province

Site	*Sample*	*Inc*	*Dec*	*n*	*Tmin–Tmax*	*f*	*g*	*q*	$F_E \pm \sigma(F_E)$	*VDM*	$\mathrm{F_E}$ ± s.d.	*VDMe*
SC01	01P002D	−46.7	3.6	7	300–520	0.66	0.79	8.8	21.5 ± 1.1	4.32	**24.6 ± 4.8**	**5.1 ± 0.9**
	01P003C	−40.6	8.7	6	350–520	0.64	0.74	5.6	20.8 ± 1.3	4.44		
	01P005B	−42.9	3.9	6	350–520	0.51	0.77	4.4	24.7 ± 2.6	5.16		
	01P007D	−47.2	358.9	8	250–520	0.59	0.81	10.4	31.4 ± 1.6	6.27		
SC04	01P024B	−45.8	6.1	8	300–540	0.58	0.82	6.3	19.7 ± 1.3	3.99	**19.4 ± 2.7**	**4.0 ± 0.6**
	01P029B	−40.5	15.3	8	300–540	0.56	0.85	9.8	21.9 ± 1.1	4.68		
	01P031D	−40.2	1.6	7	300–520	0.36	0.85	4.3	16.5 ± 1.0	3.39		
SC08	01P057A	−35.5	5.5	9	250–540	0.60	0.83	8.5	37.8 ± 2.6	8.45	**43.5 ± 5.9**	**9.5 ± 1.2**
	01P060B	−40.8	358.6	8	250–520	0.47	0.84	7.8	49.1 ± 2.5	10.5		
	01P061B	−38.5	355.8	8	250–520	0.50	0.82	6.7	48.1 ± 2.8	10.5		
	01P062D	−39.3	2.7	8	250–520	0.54	0.85	6.8	39.1 ± 2.5	8.45		
SC10	01P075D	−42.6	3.3	7	250–520	0.32	0.81	5.4	35.7 ± 2.3	7.48	**35.3 ± 5.7**	**7.4 ± 1.4**
	01P076B	−48.1	355.6	8	200–520	0.46	0.86	6.6	29.1 ± 1.7	5.75		
	01P077C	−45.1	1.9	9	200–540	0.65	0.85	12.2	31.2 ± 1.1	6.35		
	01P078C	−40.3	8.6	7	250–500	0.31	0.76	12.5	43.9 ± 0.9	9.4		
	01P079C	−41.1	2.5	7	250–500	0.39	0.82	4.4	36.4 ± 2.2	7.74		
SC15	01P110C	−25.3	13.8	10	20–540	0.46	0.88	6.8	22.9 ± 1.3	5.5	**22.1 ± 1.9**	**5.3 ± 0.5**
	01P111D	−28.1	11.3	8	250–520	0.42	0.84	6.5	24.3 ± 1.8	5.74		
	01P112C	−26.1	8.8	8	250–520	0.44	0.80	5.8	21.6 ± 1.4	5.16		
	01P113E	−23.3	5.9	7	300–520	0.51	0.81	4.9	21.3 ± 2.1	5.17		
	01P115B	−27.3	11.7	8	250–520	0.54	0.86	4.8	23.5 ± 2.3	5.58		
	01P116A	−29.7	11.6	7	250–500	0.30	0.79	6.1	19.1 ± 1.0	4.46		
CON03	01P159B	−54.3	10.1	10	20–540	0.65	0.87	12.5	38.4 ± 1.8	7.06	**33.4 ± 3.5**	**6.4 ± 0.5**
	01P161B	−54.4	7.7	9	250–560	0.74	0.86	17.3	32.8 ± 1.2	6.02		
	01P165C	−48.6	8.1	8	250–520	0.51	0.86	12.7	32.3 ± 1.5	6.35		
	01P167C	−47.5	5.4	9	250–540	0.55	0.84	7.3	30.2 ± 1.9	6.01		
CON05	01P176B	−35.1	8.1	10	20–540	0.58	0.86	12.4	45.5 ± 1.8	10.2	**45.6 ± 4.5**	**10.5 ± 1.1**
	01P178B	−31.1	10.2	9	200–520	0.39	0.85	4.6	40.1 ± 3.7	9.27		
	01P181B	−29.2	11.1	9	250–540	0.45	0.79	7.6	48.5 ± 3.8	11.4		
	01P182C	−30.5	9.2	9	250–540	0.64	0.83	5.9	42.1 ± 3.8	9.78		
	01P183C	−31.3	11.3	9	200–520	0.47	0.81	5.4	51.1 ± 3.2	11.8		
CON06	01P189C	−45.7	3.7	8	250–520	0.38	0.83	6.4	46.6 ± 2.6	9.46	**43.6 ± 2.7**	**8.8 ± 0.6**
	01P190B	−43.8	2.8	8	250–520	0.31	0.83	6.2	42.6 ± 1.7	8.82		
	01P191B	−48.5	5.3	9	20–520	0.47	0.89	13.3	41.5 ± 1.4	8.17		
CON07	01P192B	−48.1	6.2	8	250–520	0.33	0.84	3.8	43.2 ± 2.9	8.54	**46.7 ± 7.0**	**9.6 ± 1.4**
	01P194B	−45.6	6.8	8	250–520	0.34	0.83	5.3	54.9 ± 3.1	11.2		
	01P195C	−44.6	9.6	8	250–520	0.35	0.81	7.8	49.9 ± 1.8	10.2		
	01P199B	−40.7	7.6	9	250–540	0.39	0.82	9.8	39.1 ± 1.8	8.34		
CON09	01P210B	−36.8	8.2	8	250–520	0.51	0.81	7.9	26.2 ± 1.4	5.79		
CON14	01P247B	−43.2	350.5	8	250–520	0.42	0.84	7.6	31.1 ± 1.4	6.48	**27.3 ± 6.4**	**5.6 ± 1.3**
	01P251B	−45.6	347.3	8	250–540	0.64	0.84	4.5	30.8 ± 3.7	6.26		
	01P253B	−45.1	352.8	9	200–540	0.68	0.88	11.8	19.9 ± 1.1	4.06		

under microscope also confirmed the presence of ‘near magnetite’ phase associated with exsoluted ilmenite of trellis or sometimes sandwich texture. These intergrowths typically develop higher than 600°C and consequently, the NRM (natural remanent magnetization) carried by these samples should be a thermoremanent magnetization.

3. Hysteresis measurements at room temperature (using AGFM-Micromag apparatus) show (Figure 2c) that the studied samples fall in the ‘small’ pseudo-single-domain grain size region. This probably indicates a mixture of multidomain and a significant amount of single-domain (SD) grains.

[8] In all we selected 117 samples for the paleointensity experiments, which belong to 19 lava flows having the above-described magnetic characteristics.

4. Paleointensity Experiments

[9] Paleointensity experiments were performed using the Thellier method in its classic form [*Thellier and Thellier*, 1959]. All heatings were made in a vacuum better than 10^{-2} mbar. Eleven temperature steps were distributed between room temperature and 560°C, and the laboratory field was set to 30 μT. Control heatings, commonly referred as pTRM checks, were performed after every heating step throughout the whole experiment (Figure 3).

[10] Paleointensity data are reported on the classical Arai-Nagata plot on Figure 3 and results are given in Table 1. We accepted only determinations: (1) obtained from at least 5 NRM-TRM points corresponding to a NRM fraction larger than about 1/3 (Table 1), (2) yielding quality factor [*Coe et al.*, 1978] generally above 5, (3) with positive ‘pTRM’ checks i.e. the deviation of ‘pTRM’ checks were less than 15% and (4) with reasonably linear Zijderveld diagrams obtained from the paleointensity experiments.

5. Discussion and Main Results

[11] Forty-two samples from 11 lava flows yielded apparently reliable absolute intensity determinations. The NRM fraction f used for paleointensity determination ranges between 0.30 to 0.74 and the quality factor q varies from 4.3 to 17.3, being normally greater than 5 (Table 1). These results correspond to data of good technical quality. One lava flow (CON09) is represented by a single but high technical quality determination. This sample was omitted in

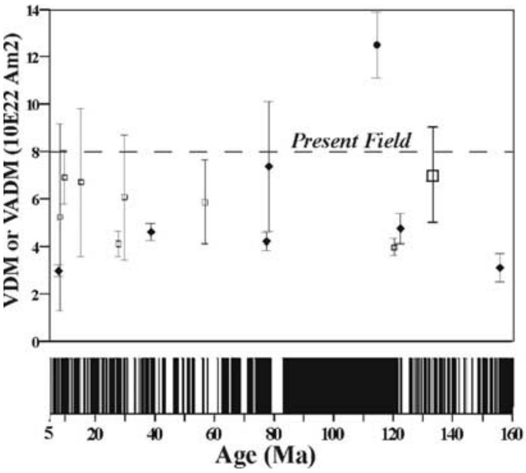

Figure 4. Evolution of mean virtual dipole moments (VDMs) and virtual axial dipole moments (VADMs) for 5 to 160 Ma. Open squares are mean VDM obtained from continental lava flows (This study—big symbols). Diamonds are mean VADMs obtained from submarine basaltic glass. Closed circle is mean VDM obtained single plagioclase crystals. The paleointensity data set are the same that reported in *Riisager et al.* [2002].

calculating mean paleointensity or virtual dipole moment (VDM).

[12] The mean paleointensity values per flow obtained in this study are ranging from 19.4 ± 4.0 to 46.7 ± 7.0 μT and the corresponding Virtual Dipole Moments are ranging from 4.0 ± 0.6 to 10.5 ± 1.1 (10^{22} Am^2). These data yield a mean value of 7.2 ± 2.3 × 10^{22} Am^2, which is about 92% of the present geomagnetic axial dipole.

[13] Paraná mean VDM is shown on Figure 4 together with 14 other selected mean VDMs and VADMs (virtual axial dipole moment) for the period 5–160 Ma. Paleointensity data reported by *Prévot et al.* [1990] and *Bol'shakov and Solodovnikov*, [1983] are not shown on figure because they do not meet the basic acceptance criteria we imposed in this paper. We selected data using quite modest criteria [*Riisager et al.*, 2002] demanding a) the mean based on more than 9 successful determinations from at least three cooling units, b) no transitional data and c) paleointensity estimates obtained with Thellier method with pTRM checks. The perhaps most striking observation from inspecting Figure 4 is that, in spite of the many published paleointensity studies, there exists only 15 paleomagnetic dipole moment estimates in the 5–160 Ma period that fulfil the above mentioned criteria. Based on these data it is not possible to make firm conclusions about the evolution of geomagnetic intensity through geological time. Our results altogether with *Tarduno et al*'s [2001] data suggest that the paleostrength during early Cretaceous period may be comparable or even much higher than recent field intensity and not 'anomalousely low' as suggested by several authors. Thus, the proposal for the Mesozoic Dipole Low may probably need to be considered as unreliable. Reliable paleointensity results for whole Mesozoic time are still scarce and of dissimilar qualities. More reliable determinations are needed to definitively reject or confirm the MDL.

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A. Goguitchaichvili, L. Alva-Valdivia, J. Urrutia, and J. Morales, Instituto de Geofisica, UNAM, Ciudad Universitaria S/N, 04510 Mexico D.F., Mexico. (avto@tonatiuh.igeofcu.unam.mx)

O. Ferreira-Lopes, Universidade Federal do Paraná, Departamento de Geologia, Jardim de las Americas, Curitiba, Brazil.