New contributions to the Early Pliocene geomagnetic field strength: Case study of southern Caucasus volcanics

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RESUMEN

Realizamos un estudio de paleointensidad con el método de Thellier sobre la secuencia volcánica de 3.8 Ma en Georgia (Sur del Cáucaso). Estudios paleomagnéticos previos de esta sucesión revelaron que ocho flujos consecutivos de lava registraron una polaridad magnética reversa en la base de la sección, seguida por una zona de polaridad normal en 18 flujos consecutivos. 27 muestras de 9 flujos de ambas zonas fueron preseleccionados para experimentos de paleointensidad debido a su bajo índice de magnetización viscosa, magnetización remanente estable, curvas termomagnéticas reversibles y a una fracción menor de granos magnéticos con estructura de multidominio. 13 muestras de 6 distintas unidades de enfriamiento permitieron una estimación confiable de la paleointensidad con la variación del momento virtual dipolar (MVD) promedio desde 5.8 hasta 7.6*10^{22} Am^2. Nuestros resultados, aunque no numerosos, son de una alta calidad técnica y comparables con otros datos de paleointensidad recientemente obtenidos en flujos de lava más jóvenes. Las fracciones de la magnetización natural remanente usadas para la determinación de paleointensidad varían de 28 a 65% y los factores de calidad varían entre 4.7 y 19.4, siendo normalmente mayores de 5. El momento virtual dipolar promedio obtenido en este estudio es ligeramente menor con respecto al campo geomagnético actual, pero coincide con el promedio del Plioceno temprano. Los resultados obtenidos son también similares a los recientemente reportados para el Mioceno tardío (8-10 Ma), lo cual probablemente indique que la intensidad del campo geomagnético era estable y relativamente alta en el periodo aproximado de 10 a 4 Ma. Se requieren más datos para entender mejor el modo de transición entre el campo geomagnético bajo en el Mesozoico y el actual campo geomagnético de alta intensidad.

PALABRAS CLAVE: Paleomagnetismo, paleointensidad, método Thellier, Cáucaso, Plioceno.

ABSTRACT

We carried out a Thellier paleointensity study on a ~ 3.8 My Pliocene lava flow succession from Georgia (southern Caucasus). Previous paleomagnetic studies on this succession revealed that eight consecutive lava flows record a reverse polarity direction at the base of the section followed by a thick normal polarity zone of eighteen consecutive flows. 27 samples from 9 flows from both polarity zones were preselected for paleointensity experiments because of their low magnetic viscosity index, stable remanent magnetization, reversible thermomagnetic curves and minor fraction of grains with a multidomain magnetic structure. Altogether, 13 samples from 6 different cooling units yielded reliable paleointensity estimates with flow-mean virtual dipole moments ranging from 5.8 to 7.6*10^{22} Am^2. Our results, although not numerous, are of high technical quality and comparable to other paleointensity data recently obtained on younger lava flows. The NRM fractions used for paleointensity determination range from 28 to 65% and the quality factors varies between 4.7 and 19.4, being normally greater than 5. The mean virtual dipole moment (VDM) obtained in this study is slightly lower than the present day geomagnetic field strength but it is in accordance with the mean early Pliocene worldwide VDM. The results are also similar to those recently reported for the late Miocene (8-10 My), which may indicate that geomagnetic field strength was stable and relatively high from about 10 to 4 My. More data are needed to better understand the transition mode between Mesozoic low and the present high geomagnetic field.

KEY WORDS: Paleomagnetism, paleointensity, Thellier method, Caucasus, Pliocene.

INTRODUCTION

Geomagnetic field strength is of considerable interest in our understanding of the physical processes in the Earth's liquid core that generate the field (Merrill and McFadden, 1999). The spatial and temporal variations in the Earth's magnetic field can provide powerful constraints on the mechanism of the geodynamo. Moreover, Camps and Prévot (1996) recently showed that in any correct model of the geomagnetic field, the intensity should necessarily be incorporated. However, reliable paleointensity data are still scarce and not yet enough to be used to obtain general characteris-

tics of the Earth's magnetic field (Riisager, 1999). In addition, the geographic distribution of paleointensity results is uneven (e.g. Tanaka *et al.*, 1995; Perrin and Shcherbakov, 1997). Few reliable results are available from the Southern Hemisphere and large areas of the former Soviet republics. This irregularity impedes an accurate analysis of the fine-scale changes in the statistical characteristics of geomagnetic field variations (Jacobs, 1994).

Absolute paleointensity determination can be obtained only on volcanic rocks which satisfy some special magnetic criteria (Kosterov and Prévot, 1998). Sedimentary units yield

only relative paleointensities. Due to problems with the choice of normalization parameters, sedimentary units may provide erroneous results (Goguitchaichvili *et al.*, 1999a). Submarine basaltic glasses may provide high technical quality paleointensity results (Juárez *et al.*, 1998) but their geomagnetic significance may be questioned (Goguitchaichvili *et al.*, 1999a). In most cases, continental volcanic rocks carrying thermoremanent magnetization seem to be the most suitable material, both in terms of paleodirection and paleointensity determination. The south Caucasus volcanic provinces offer good opportunities for paleointensity and paleomagnetic studies. The present study was aimed to obtain the first reliable absolute geomagnetic intensity results from southern Caucasus. Camps *et al.* (1996) already carried out paleointensity study on some Georgian Pliocene basalts. However, these results should be considered as unreliable because (1) no preselection of the samples was made before undertaking paleointensity experiments and (2) no control heatings (so-called 'pTRM checks') were performed during the measurements. In present study, we chose the volcanic rocks from Georgia because (1) they are widely distributed in large volcanic provinces and are easy to access, (2) they record faithfully the direction of the geomagnetic field at the time of their eruption (Goguitchaichvili *et al.*, 1997) and (3) most of them are fresh for isotopic dating and have already yielded reliable Ar-Ar ages.

GEOLOGY AND PALEOMAGNETISM

Alpine, late Miocene to Holocene, compression is responsible for intense volcanic activity in the southern Caucasus (Maissuradze, 1989). According to geological and petrologic studies (Milanovski, 1978), three phases of volcanic activity can be distinguished: 1) late Miocene to early Pliocene, 2) middle to late Pliocene or Pleistocene, and 3) Quaternary. In the southern Caucasus, late-orogenic subaerial volcanism occurred in four main areas: the south Georgian volcanic province, the Khrami basin, the small Caucasus and the Kazbeki region. The Akhalkalaki volcanic area, which is the subject of the present study, is located in the western part of the south Georgian volcanic province (Figure 1). Goguitchaichvili *et al.* (1997) studied in detail a 250-m thick volcanic sequence of 26 consecutive lava flows. This site (Tchuntchka volcanic section) is situated at 41°28'**N,** 43°22'**E** near the road from Aspindza to Akhalkalaki (Figure 1). Its units are made up of doleritic-basaltic and, less frequently, of basaltic-andesitic lava flows, which lie discordantly on the Goderzi Miocene volcanic tuffs. Goguitchaichvili *et al.* (1997) proposed, based on Ar-Ar data by Camps *et al.* (1996), a mean age of 3.83 ± 0.09 Ma as the best estimate of the time of emplacement of the Tchuntchka volcanic sequence.

Two polarity zones were identified from bottom to top of the Tchuntchka site. The sequence starts with a reverse polarity zone (subsection X) constituted by eight consecu-

tive lava flows with mean paleodirection: D=180.3°, I=-59.4°, α_{95}=4.8°, k=135. The next 18 consecutive flows (subsection Y) are all normally magnetized with mean paleodirection: D=355.5°, I=54.2°, α_{95}=2.5°, k=226. No evidence of paleosoil development or sedimentation has been observed between the X and Y subsections and both seem to be petrologically similar, showing a porphyritic-fluidal texture with doleritic tendency. Thus, the R-N reversal found in Tchuntchka sequence may be assigned to the Gilbert-Cochiti geomagnetic reversal.

SAMPLE SELECTION

Pre-selection of the flows was based on the (1) viscosity index measurements, (2) demagnetization of remanence, (3) temperature dependence of initial magnetic susceptibility and (4) thermomagnetic estimation of domain structure. Magnetic characteristics of the representative samples selected for Thellier paleointensity measurements are summarized in Figure 2 and 3, and can be described as follows:

1. The selected samples do not yield a big capacity for viscous remanence acquisition. Viscosity experiments (Thellier and Thellier, 1944; Prévot *et al.*, 1983) provided viscosity indexes generally less than 5%, which is small enough to obtain precise measurements of the remanence during the process of thermal demagnetization (Prévot *et al.*, 1985).

2. The selected samples belong to the sites with very low angular dispersion (all α_{95} are within 5°) of cleaned natural remanent magnetization (NRM). They carry essentially a stable, single component magnetization, observed both upon thermal and alternating field (AF) treatments (Figure 2, left part). A generally minor secondary component, probably of viscous origin, is easily removed at low temperatures/AF fields. The median destructive fields (MDF) range mostly in the 40-50 mT interval, suggesting the existence of small pseudo-single domain grains as remanence carriers (Dunlop and Ozdemir, 1997). The major part of remanence is destroyed at 500-575°C, which points to low-Ti titanomagnetite as being responsible for magnetization.

3. Low-field continuous susceptibility measurements were performed in a vacuum using a Bartington susceptibility meter MS2 equipped with a furnace in Montpellier (France) paleomagnetic laboratory. The selected samples show the presence of a single ferrimagnetic phase with a Curie point compatible with Ti-poor titanomagnetite (Figure 2, right part). However, sometimes the cooling and heating curves are not perfectly reversible.

4. As blocking and unblocking temperatures of multidomain grains are not equal, the presence of such grains can be detected by means of partial thermoremanence (pTRM)

Fig. 1. Akhalkalaki volcanic region: geological setting. The star shows location of Tchuntchka sampling site.

acquisition and demagnetization experiments. A pTRM acquired, for example, between 300°C and room temperature would not be completely demagnetized below the Curie temperature (Bolshakov and Shcherbakova, 1979; Worm *et al*., 1988). For our experiments, first the NRM of samples was demagnetized using the VSTM (Orion Ltd) aparatus (Figure 3, curve 1) and then cooled to room temperature in a 50 µT field so that a TRM was acquired. Afterwards, this TRM was demagnetized (curve 2). Subsequently, pTRM was given to each of the samples between 300 and 25°C, which was subsequently thermally demagnetized (curve 3). The amount of remanent magnetization still present after heating above the highest pTRM acquisition temperature can provide information about the fraction of multidomain grains in a sample (Shcherbakova

et al., 1996). For the selected sample, pTRM unblocking temperatures were rather similar to their blocking temperatures (Figure 3). This probably indicates that remanence is carried mainly by single domain or 'small' pseudo-singledomain grains, which are suitable materials for Thellier paleointensity experiments.

In total only 27 samples belonging to 9 lava flows providing the above described magnetic characteristics were selected for the paleointensity experiments.

PALEOINTENSITY DETERMINATION

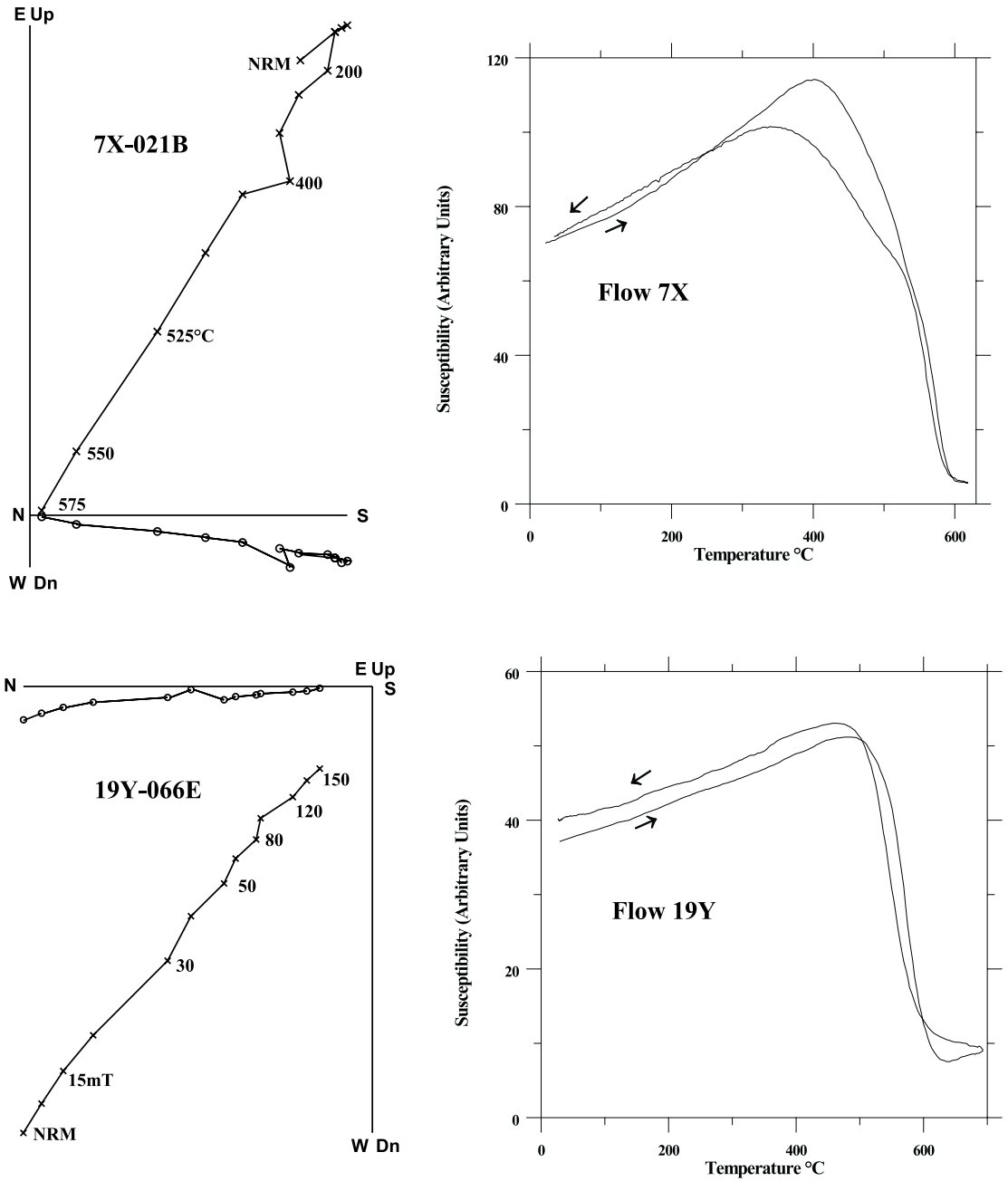Paleointensity experiments were performed using the Thellier method in its classic form (Thellier and Thellier,

Fig. 2. Summary of magnetic characteristics of selected samples for Thellier paleointensity experiments (see also text). In the orthogonal diagrams the stars/circles denote to vertical/horizontal planes.

1959). At each temperature step, the specimens were heated twice with an applied field: positive for the first heating, and negative for the second. The temperature settings were established from earlier studies of the unblocking temperature spectrum (Goguitchaichvili *et al*., 1997). The heatings and coolings were made in air and the laboratory field set to 50 microtesla. Eight temperature steps were distributed between 250°C and 580°C. The pTRM/NRM checks (so-called pTRM

checks) (Goguitchaichvili *et al*., 1999b) were performed only twice (Figure 4) to avoid additional heatings, which may alter significantly the remanence.

Paleointensity data are reported on the classical Arai-Nagata (Nagata *et al*., 1963) plot on Figure 4 and the results are given in Table 1. We accepted only determinations: (1) which were obtained from at least 5 NRM-TRM points cor-
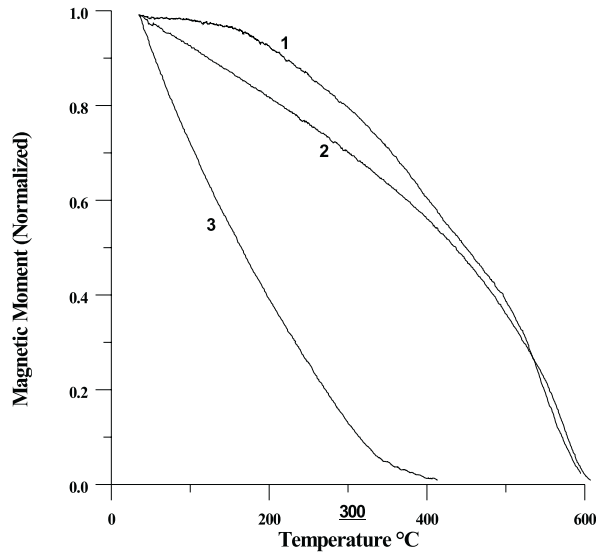
Fig. 3. Flow 6, sample 6X-019D. Continuous thermal demagneti-zation of natural remanent magnetization (curve 1), thermorema-nence (curve 2) acquired in a field of 50 μT, and partial thermore-manence (curve 3) acquired in a field of 50 μT, cooling down from 300°C to room temperature.

responding to a NRM fraction larger than 1/3 (Table 2), (2) yielding quality factor (Coe *et al*., 1978) of about 5 or more and (3) with positive 'pTRM' checks. In one case, we ac-cepted the individual determination with slightly lower NRM fraction (sample 6X_2, Table 1), and with a quality factor of 4.7. The paleointensity estimate from this sample is very close to the site mean paleointensity (Table 1). In most cases the linearity observed up to 540°C (Figure 4) and the control heatings were successful, i.e. the deviation of 'pTRM' checks were less than 15%. The direction of NRM left at each step, obtained from the paleointensity experiments, are reason-ably linear and point to the origin. No deviation of NRM-left-directions towards the direction of applied laboratory field were observed. Finally, only 13 samples, coming from 6 individual lava flows, yielded acceptable paleointensity es-timates. For these samples the NRM fraction, f, used for de-termination ranges between 0.28 to 0.65 and the quality fac-tor, q, varies from 4.7 to 19.4 (generally more than 5). The mean paleointensity values per flow range from 32.4 ± 5.6 to 46.3 ± 6.2 μT and the corresponding Virtual Dipole Mo-ments (VDMs) range from 5.8 ± 1.0 to 7.6 ± 0.7 (10^{22} Am^2).

DISCUSSION AND CONCLUSIONS

Reliable absolute intensity results have been obtained from southern Caucasus volcanic provinces. Although our results are not numerous, they are important because of the good technical quality of the determinations, attested to by the reasonably high quality factors. The Thellier method of paleointensity determination, which is considered the most
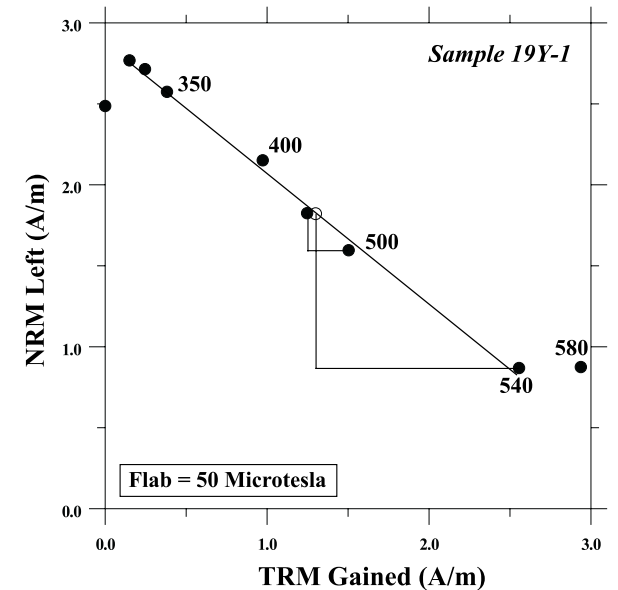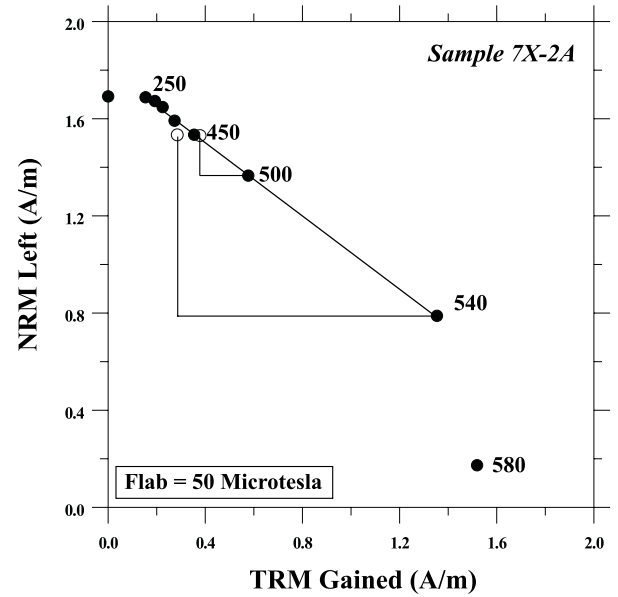

Fig. 4. Representative NRM-TRM (Arai-Nagata) plots for the early Pliocene Tchuntchka volcanic lava flows.

reliable one (Goguitchaichvili *et al*., 1999b), imposes many restrictions on the choice of samples that can be used for a successful determination (Coe, 1967; Levi, 1977; Prévot *et al*., 1985; Pick and Tauxe, 1993; Kosterov and Prévot, 1998). In this context, the fact that only 13 samples (from more than 150 sampled) yielded acceptable results is not excep-tional in a Thellier paleointensity study if correct preselection of the suitable samples and strict analysis of the obtained data are made.

Table 1

Paleointensity results from the Tchuntchka lava flows. INC is mean paleoinclination as obtained by demagnetization of a sister sample, n is number of NRM-TRM points used for determination, Tmin-Tmax is the temperature interval used for paleointensity determination, f, g and q are the fraction of extrapolated NRM used for intensity determination, the gap factor and quality factor (Coe *et al.*, 1978) respectively. Fa is the individual paleointensity estimate with associated error, Fe is site mean paleointensity, VDM and VDMe are individual and site mean virtual dipole moments.

Sample	INC	n	Tmin-Tmax	f	g	q	Fa (error)	VDM	*Fe (s.d.)*	*VDMe (s.d.)*
1X_1	-67.7	7	250-540	0.38	0.57	9.2	41.9 (1.1)	6.5	**46.3 (6.2)**	*7.2 (1.0)*
1X_2	-67.2	7	250-540	0.44	0.71	11.4	50.7 (0.9)	7.9		
2X_1	-61.2	6	250-500	0.32	0.74	7.8	**30.9 (0.9)**	*5.2*		
6X_1	-57.6	6	250-500	0.39	0.71	7.3	46.5 (1.7)	8.2	**42.3 (4.2)**	*7.6 (0.7)*
6X_2	-55.2	6	250-500	0.28	0.8	4.7	42.3 (1.9)	7.7		
6X_3	-57.2	6	250-500	0.35	0.76	8.2	38.1 (1.3)	6.8		
7X_1	-57.1	6	250-500	0.58	0.77	13.8	26.6 (0.8)	4.7	**32.4 (5.6)**	*5.8 (1.0)*
7X_2	-55.3	7	250-540	0.52	0.72	19.4	37.9 (0.6)	6.9		
7X_3	-57.8	6	250-500	0.33	0.79	6.3	32.6 (1.4)	5.7		
11Y_1	56.5	7	250-540	0.43	0.69	8.6	**47.5 (1.9)**	*8.5*		
19Y_1	51.6	7	250-540	0.65	0.68	10.5	41.6 (1.7)	7.9	**38.0 (3.9)**	*7.1 (0.8)*
19Y_2	53.3	5	250-450	0.33	0.74	5.8	38.5 (2.7)	7.2		
19Y_3	53.1	6	250-500	0.38	0.82	8.1	33.9 (1.4)	6.3		

Table 2

Region	*N*	*VDM*	*S.D.*	*Ref.*
Japan	3	8.1	1.2	*1*
Armenia	3	6.9	0.7	*2,3*
Tchekia	4	8.7	2.6	*4*
Fr. Polynesia	8	9.7	3.1	*5*
Hawaii	21	9	3.1	*6,7*
Iceland	27	6.5	4.4	*5,8,9*
Georgia	6	6.9	1.2	*This study*
ALL	*72*	*7.97*	*1.23*	

Average virtual dipole moment (10^{22} Am^2) for various regions during early Pliocene (from Thellier paleointensity data). N refers to the number of cooling units used to calculate the average VDM. References: (1) Sasajima *et al.*, 1969, (2) Bol'shakov and Solodovnikov, 1969, (3) Bagina *et al.*, 1976, (4) Krs, 1979, (5) Senanyake *et al.*, 1982, (6) Bogue and Coe, 1984, (7) Bogue and Paul, 1993, (8) Tanaka *et al.*, 1995, (9) Goguitchaichvili *et al.*, 1999b.

The mean virtual dipole moment obtained from Georgia early Pliocene volcanics is $6.9 \pm 1.2 *10^{22}$ Am^2, which is in good agreement with Icelandic average VDM (Table 2) for the same period (Goguichaichvili *et al.*, 1999b). Combining all published paleointensity results (Thellier determination only from continental volcanic units) we obtained a worldwide early Pliocene VDM equal to $7.97 \pm 1.23 *10^{22}$ Am^2. The obtained results are also similar to those recently reported for the late Miocene (8-10My) (Goguitchaichvili *et al.*, 2000), which may indicate that the geomagnetic field strength was constant and relatively high from about 10 to 4 My. More data are needed to better understand the transition mode between Mesozoic low (Prévot *et al.*, 1990) and the present high geomagnetic field.

ACKNOWLEDGMENT

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