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Paleomagnetism of Ar-Ar dated lava flows from the Ceboruco-San Pedro volcanic field (western Mexico): Evidence for the Matuyama-Brunhes transition precursor and a fully reversed geomagnetic event in the Brunhes chron

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[1] We report a detailed paleomagnetic and rock magnetic study of 17 independent lava flows belonging to the Trans-Mexican Volcanic Belt; 175 oriented samples were collected in the Ceboruco-San Pedro volcanic field. These sites were previously dated by means of a state-of-the-art ^{40}Ar-^{39}Ar geochronological method and span from 819 to 2 ka. Rock magnetic experiments, which included continuous susceptibility and hysteresis measurements, point to simple magnetic mineralogy. In most cases, the remanence is carried by Ti-poor titanomagnetite of pseudosingle-domain magnetic structure. Fourteen flows give normal magnetic polarities, while two are reversely magnetized; only one cooling unit yields intermediate paleodirections. The paleodirections of the flow dated at 819 ± 25 ka correspond to a VGP latitude of 18°N. This anomalous field behavior apparently recorded prior to the Matuyama-Brunhes (M-B) reversal may coincide with the transitionally magnetized lavas on La Palma, Canary Islands (^{40}Ar-^{39}Ar age of 822.2 ± 8.7 ka), and with an event featured in several marine sediment records. Thus this geomagnetic event, defined as M-B precursor, is probably global in extent. Two independent lava flows, dated at 623 ± 91 and 614 ± 16 ka, yield reverse paleodirections. Age uncertainties make it difficult to claim the discovery of a new geomagnetic event. It is possible that these lavas erupted during the worldwide observable Big Lost event (^{40}Ar-^{39}Ar age of 580.2 ± 7.8 ka), which has probably been longer and more complex than it is generally believed for geomagnetic excursions.

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1. Introduction

[2] The Earth's magnetic field switches its polarity without periodicity. The fact that volcanic rocks recorded reversals of the geomagnetic field was already known in early studies [*Brunhes*, 1907; *Mercanton*, 1926]. Later, *Opdyke et al.* [1966] found a reversal record in deep-sea sediments as well. During a polarity change, the direction of the geomagnetic field switches through about 180°, the virtual geomagnetic poles (VGP) following widely different paths for different transitions [*Prévot and Camps*, 1993]. In addition to polarity changes, the Earth's magnetic field has often departed for brief periods from its usual axial configuration without establishing a reversed direction. This behavior, which has been reported in lava flows and sediments of various ages worldwide, has been called a geomagnetic excursion. The short periods (10^3 to 8×10^3 years after *Merrill and McFadden* [1999] and $\geq 3 \times 10^3$ years after *Gubbins* [1999]) during which the geomagnetic field changes polarity are of considerable interest in our understanding of the physical processes in the Earth's liquid core that generate the geomagnetic field. Detailed studies of geomagnetic transitions and excursions have also revealed new features concerning possible core-mantle interactions [*Hoffman*, 1992]. However, it is not always easy to distinguish between an excursion and a short reversal. *Gubbins* [1999] proposed that during excursions the field may

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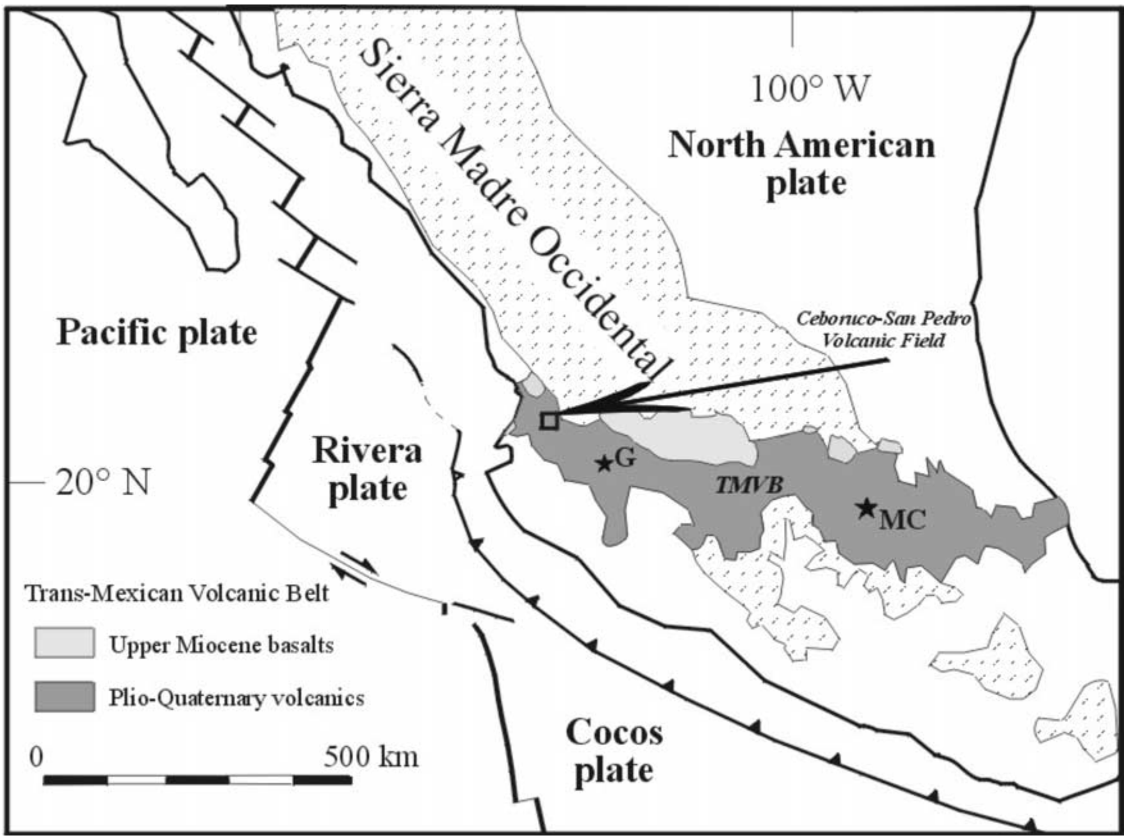

Figure 1. Plate tectonic setting of central Mexico, showing the Cenozoic volcanic provinces and outcrops of Mio-Pliocene mafic lavas. G, Guadalajara; MC, Mexico City; TMVB, Trans-Mexican Volcanic Belt.

reverse in the liquid outer core, which has timescale about 500 years, but not in the solid inner core.

[3] The geomagnetic polarity timescale is divided into two different sorts of features. Polarity chrons are divisions of geologic time during which the geomagnetic field was predominantly of one polarity. Polarity subchrons are shorter periods of opposite polarity within chrons. The last geomagnetic polarity reversal took place about 790 ka [*Singer et al.*, 2002; *Coe et al.*, 2004], marking the beginning of the present period of normal polarity, the Brunhes chron. *Cox* [1968] predicted that there should be numerous undiscovered geomagnetic events (excursions or shorter reversed intervals) within Brunhes chron. The most recent Geomagnetic Instability Time Scale (GITS, proposed by *Singer et al.* [2002] to describe geochronology of excursions; see also *Knudsen et al.* [2003]) shows evidence for 14 geomagnetic excursions in the Brunhes. However, only five events (Laschamps, Blake, Jamaica, Calabrian Ridge, and Big Lost) are documented by paleomagnetic and high-resolution geochronology studies using volcanic rocks. The remaining events were obtained from sedimentary records. Sediments can provide continuous records of magnetic field variation, while data from lavas, due to the sporadic nature of volcanic activity, yield rather discontinuous records of geomagnetic field variation. On the other hand, the results obtained from lavas are not subject to the controversies over reliability that makes interpretation of sedimentary data so difficult [*Tauxe*, 1993; *Dunlop and Özdemir*, 1997; *Goguitchaichvili et al.*, 1999a; *Love*, 2000]. Ideally, the presence of geomagnetic events should be confirmed or completed by information from lava flows [*Merrill and McFadden*, 1994; *Knudsen et al.*, 2003].

[4] In this study, we report a detailed rock magnetic and paleomagnetic investigation of lava flows associated with Ceboruco and San Pedro volcanoes in the Trans-Mexican Volcanic Belt (TMVB). All studied lava flows were recently directly dated by means of Ar-Ar experiments with incremental heating and span from about 819 to 2 ka.

2. Geological Setting and Sampling

[5] As the East Pacific Rise approached the North American plate, the Farallon plate was broken into smaller plates (e.g., Rivera plate). Consequently, the Middle Tertiary Sierra Madre Occidental (SMO) and the late Miocene-Holocene TMVB volcanic arcs were formed by Tertiary to present-day subduction along the Pacific margin of Mexico (Figure 1) coexisting now in space [*Rosas-Elguera et al.*, 1996]. The TMVB, one of the largest continental volcanic arcs on the North America plate, spans about 1,000 km and crosses central Mexico from the Pacific Ocean to the Gulf of Mexico.

[6] The Ceboruco-San Pedro volcanic field which is part of western TMVB is located northwest of Guadalajara (Figures 1 and 2). The area is dominated by Volcán

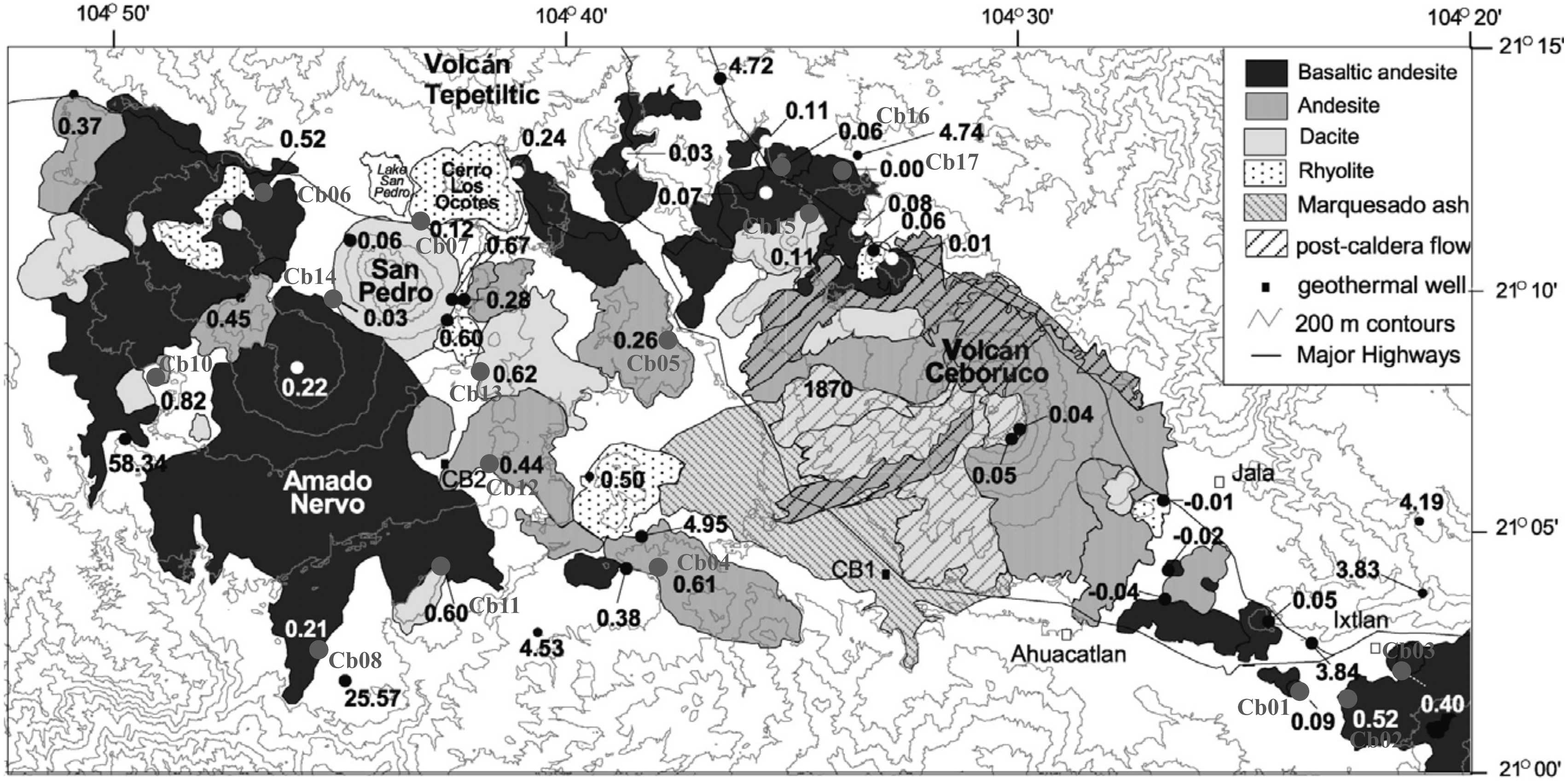

Figure 2. Simplified geologic map of the Ceboruco-San Pedro-Amado Nervo area with locations of sampling sites [modified from *Frey et al.*, 2004].

Table 1. Flow-Mean Paleodirections of Cleaned Remanence and Available Isotopic Age Determinations for Ceboruco-San Pedro Volcanics[a]

		Geographic										
Site	Lithology	Latitude, °N	Longitude, °W	Age, ka	n/N	I, deg	D, deg	α_{95}, deg	*k*	Plat	Plong	Pol
CB17	basaltic andesites	21.208	104.561	2 ± 31	6/8	44.8	358.2	7.4	68	84.5	238.7	N
CB14	dacites	21.163	104.750	27 ± 7	12/12	40	355.3	2.7	253	85.3	187.3	N
CB16	basaltic andesites	21.208	104.588	57 ± 50	8/8	30.2	358.2	5.1	149	84.8	95.2	N
CB01	basaltic andesites	21.026	104.394	85 ± 19	9/10	55.8	350.1	4.9	130	72.4	228.5	N
CB15	bacites	21.194	104.575	111 ± 22	7/9	41.9	11.6	8.6	96	78.9	327.6	N
CB07	rhyolites	21.194	104.723	117 ± 10	6/8	22.9	319.6	14.3	26	50.3	158.8	N
CB08	basaltic andesites	21.042	104.759	215 ± 26	7/8	59.2	30.6	4.8	197	57.8	302.6	N
CB09	andesites	21.129	104.946	250 ± 20	3/8	63.8	41.6	18.6	15	48.2	299.8	N?
CB05	andesites	21.149	104.628	264 ± 52	6/6	31.8	325.4	7.4	75	57.2	164.9	N
CB03	basaltic andesites	21.034	104.358	403 ± 15	7/9	41.4	11.5	6.7	84	79.0	329	N
CB12	andesites	21.105	104.695	441 ± 74	4/8	46.7	359.3	12.6	33	83.1	250.4	N
CB11	dacites	21.071	104.712	512 ± 34	1/8	52.9	4.6			76.9	272.8	N?
CB06	basaltic andesites	21.198	104.779	520 ± 25	8/9	11.3	8.4	2.5	696	72.6	46.5	N
CB02	basaltic andesites	21.027	104.380	521 ± 15	6/10	58.1	25.3	10.5	56	62.0	300.9	N
CB04	andesites	21.071	140.646	614 ± 16	6/10	−42.3	179.4	8.8	64	−86.5	66.6	R
CB13	dacites	21.138	104.697	623 ± 91	8/8	−33.8	161.4	8.5	48	−72.3	340.5	R
CB10	andesites	21.135	104.817	819 ± 25	8/8	−64.1	332.4	4.6	216	18.5	95.4	I

[a] Isotopic age determinations are from *Frey et al.* [2004]. N, number of treated samples; n, number of specimens used for calculation; I, inclination; D, declination; k and α_{95}, precision parameter and radius of 95% confidence cone of Fisher statistics, Plat/Plong, latitude/longitude of VGP position, Pol, magnetic polarity (N, normal; R, reversed; I, intermediate).

Ceboruco, a quaternary stratocone of andesite and dacite. The summit of present-day Ceboruco is at 2200 m and features two nested concentric calderas, resulting from a Plinian eruption about 1000 years ago and the subsequent collapse of an interior dome [*Nelson*, 1980; *Frey et al.*, 2004]. Peripheral to the central stratocone of Ceboruco, more than 70 volcanic vents have been identified within this volcanic field, which covers about 1600 km^2. The area has 16 monogenetic cinder cones [*Frey et al.*, 2004]. In addition, over 20 andesitic and dacite lava domes have erupted to the west of Ceboruco. The largest of these domes, San Pedro (Figure 2), is dacitic. In addition to cinder cones and domes, there are several low-lying basaltic andesite flows. A series of these flows are southwest of an adjacent to San Pedro and form the shield volcano Amado Nervo.

[7] Our sampling strategy was largely conditioned by *Frey et al.*'s [2004] recent study which gave 40 new Ar-Ar incremental heating ages for the Ceboruco-San Pedro volcanic field. We sampled only sites with available radiometric dating information (Table 1 and Figure 2), easy to access and yielding fresh, apparently not altered outcrops. In total, 175 oriented samples belonging to 17 individual lava flows (Table 1 and Figure 2) were collected. The samples were distributed throughout each flow both horizontally and vertically in order to minimize effects of block tilting. All lava flows sampled were horizontal (dip less than 3°). In general, samples were obtained at the very bottom of flows with the hope of collecting samples with the finest grains of material. Cores were sampled with a gasoline-powered portable drill, and then oriented in most cases with both magnetic and sun compasses.

[8] At our study area there are no sections with consecutive lava flows and horizon markers and thus no possibility to establish an unambiguous stratigraphic sequence. There are scattered lava flows without clear evidence of relative position. The studied sites generally present single lava flows without any evidence of under and overlying cooling units.

3. Magnetic Mineralogy

[9] In order to identify the magnetic carriers of the remanent magnetization and to obtain information about their paleomagnetic stability, rock magnetic experiments were carried out. These experiments included (1) measurements of continuous thermomagnetic curves (low field susceptibility versus temperature) and (2) hysteresis experiments.

3.1. Continuous Thermomagnetic Curves

[10] Low-field susceptibility measurements (K-T curves) in air were carried out using a Bartington susceptibility bridge equipped with a furnace. One sample from each site was heated up to about 600°C at a heating rate of 10°C/min and then cooled down at the same rate. The Curie temperature was determined by *Prévot et al.*'s [1983] method.

[11] Most of the sites (CB01, CB02, CB04, CB05, CB06, CB07, CB09, CB11, CB12, CB13, CB15 and CB16) show evidence for a single ferrimagnetic phase (Figure 3, samples 04C048 and 04C055) with a Curie point similar with that of Ti-poor titanomagnetite. The heating and cooling curves are fairly reversible, which attests the thermal stability of samples. Three sites (CB03, CB08 and CB17; Figure 3, sample 04C028) show the presence of two ferrimagnetic phases during heating and cooling. The lower Curie points range between 250 and 350°C, and the highest one is about 580°C. Both Ti-rich and Ti-poor titanomagnetites seem to coexist in these lava flows. In one case (sample 04C095), the curve yields apparently two different thermomagnetic phases during heating. The lower Curie point ranges between 360 and 420°C, while the highest one is about 580°C. The cooling curve shows only a single phase, with a Curie temperature close to that of magnetite. Such

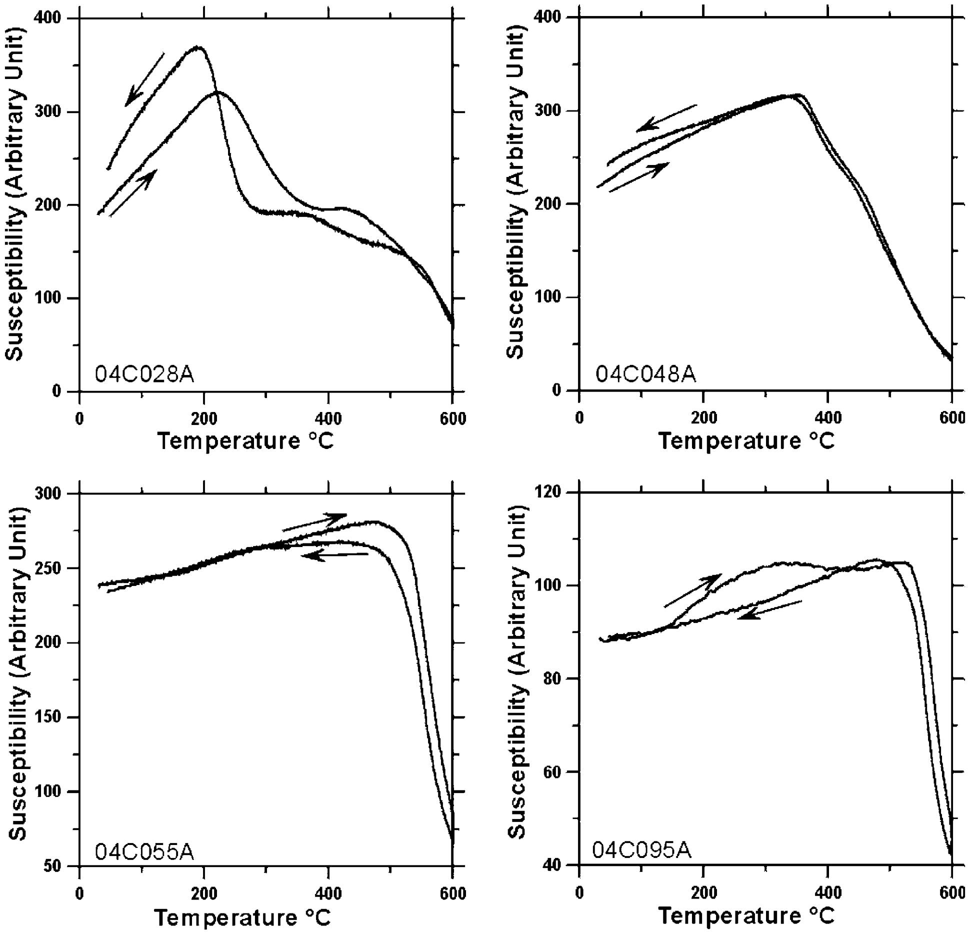

Figure 3. Susceptibility versus temperature (in air) curves of representative samples. Arrows indicate the heating and cooling curves.

irreversible K-T curves can be explained by titanomaghemite, which probably transformed into magnetite.

3.2. Hysteresis Experiments

[12] Hysteresis measurements were performed at room temperature on a specimen from all sampled sites using the alternating gradient force magnetometer (AGFM) apparatus in fields up to 1.4 T. The saturation remanent magnetization (J_{rs}), the saturation magnetization (J_s) and coercive force (H_c) were calculated after correction for the paramagnetic contribution. The coercivity of remanence (H_{cr}) was determined by applying progressively increasing backfield after saturation. Typical hysteresis plots are reported in Figure 4 (samples 04C048 and 04C083). The curves are quite symmetrical in all cases. Near the origin, no potbellied and wasp-waisted behaviors [*Tauxe et al.*, 1996] were detected, which probably reflects very restricted ranges of the coercivities. Judging from the ratios of hysteresis parameters (Figure 4), it seems that all samples fall in the pseudosingle domain (PSD) grain size region [*Day et al.*, 1977]. This may also indicate a mixture of multidomain (MD) and a significant amount of single domain (SD) grains [*Dunlop and Özdemir*, 1997; *Dunlop*, 2002]. Corresponding isothermal remanence (IRM) acquisition curves were found very similar for all samples. Saturation is reached in moderate fields of the order of 100–150 mT, which points to some spinels (most probably titanomagnetites) as remanence carriers.

[13] In single case (Figure 4, sample 04C140, site CB14), near the origin, a well-defined wasp-waisted loop can be detected which probably points to magnetic minerals of distinct coercivities [*Tauxe et al.*, 1996]. IRM acquisition curve shows no saturation at maximum applied field at 0.8 T. Both (titano)magnetites and (titano)hematites are probably present in this lava flow as also evidenced by remanence measurements (see below). No K-T curves were obtained for this site because of low initial magnetic susceptibility.

4. Remanence Properties and Paleodirections

[14] The remanent magnetizations of 6 to 12 samples from each lava flow (Table 1) were measured with a JR-6 (AGICO LtD) spinner magnetometer (nominal sensitivity $\sim 10^{-9}$ A m^2) at the paleomagnetic laboratory of National University of Mexico. Both alternating field (AF) demagnetization using a laboratory made AF demagnetizer and stepwise thermal demagnetization up to 575–620°C using a Magnetic Measurements LtD furnace were carried out. During thermal demagnetization, the low-field susceptibility at room temperature was measured after each step with a Bartington susceptibility meter.

[15] A primary remanent magnetization was successfully isolated for most of samples (Figure 5). In some cases (sites CB07, CB09, CB11 and CB12), significant secondary

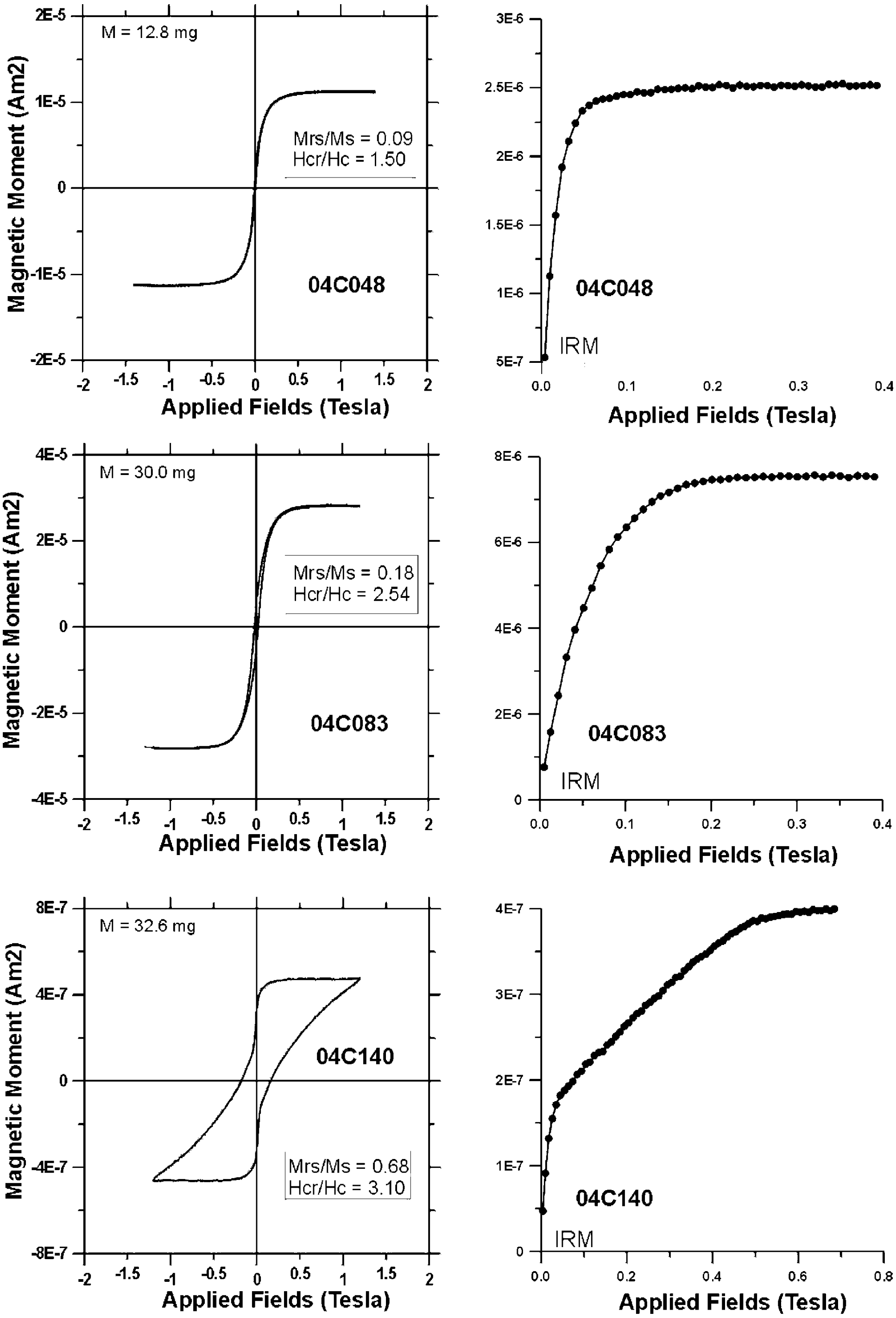

Figure 4. Typical examples of hysteresis loops (uncorrected) and associated isothermal remanence acquisition curves of small chip samples from the studied volcanic flows.

components, probably due to lightning were present (Figure 5, samples 04C048A and 04C054A) and easily removed by applying 15–20 mT alternating peak fields. The median destructive fields (MDF) range from 30 to 40 mT, suggesting small pseudosingle domain grains as remanent magnetization carriers [*Dunlop and Özdemir*, 1997]. Most of remanent magnetization, was usually removed at temperatures between 500 and 540°C, which indicate once again low-Ti titanomagnetites as carriers of magnetization. In a single case (Figure 5, sample 04C132A, Site CB14), almost half of remanent magnetization still persists after heatings at 620°C suggesting that the remanence is dominated by (titano)hematites, which is in agreement with hysteresis experiments.

[16] A characteristic magnetization direction was determined by the least squares method [*Kirschvink*, 1980], 5 to 10 points being taken in the principal component analysis for this determination. Directions were averaged by unit and the statistical parameters calculated assuming a Fisherian distribution. The average unit directions are in general quite

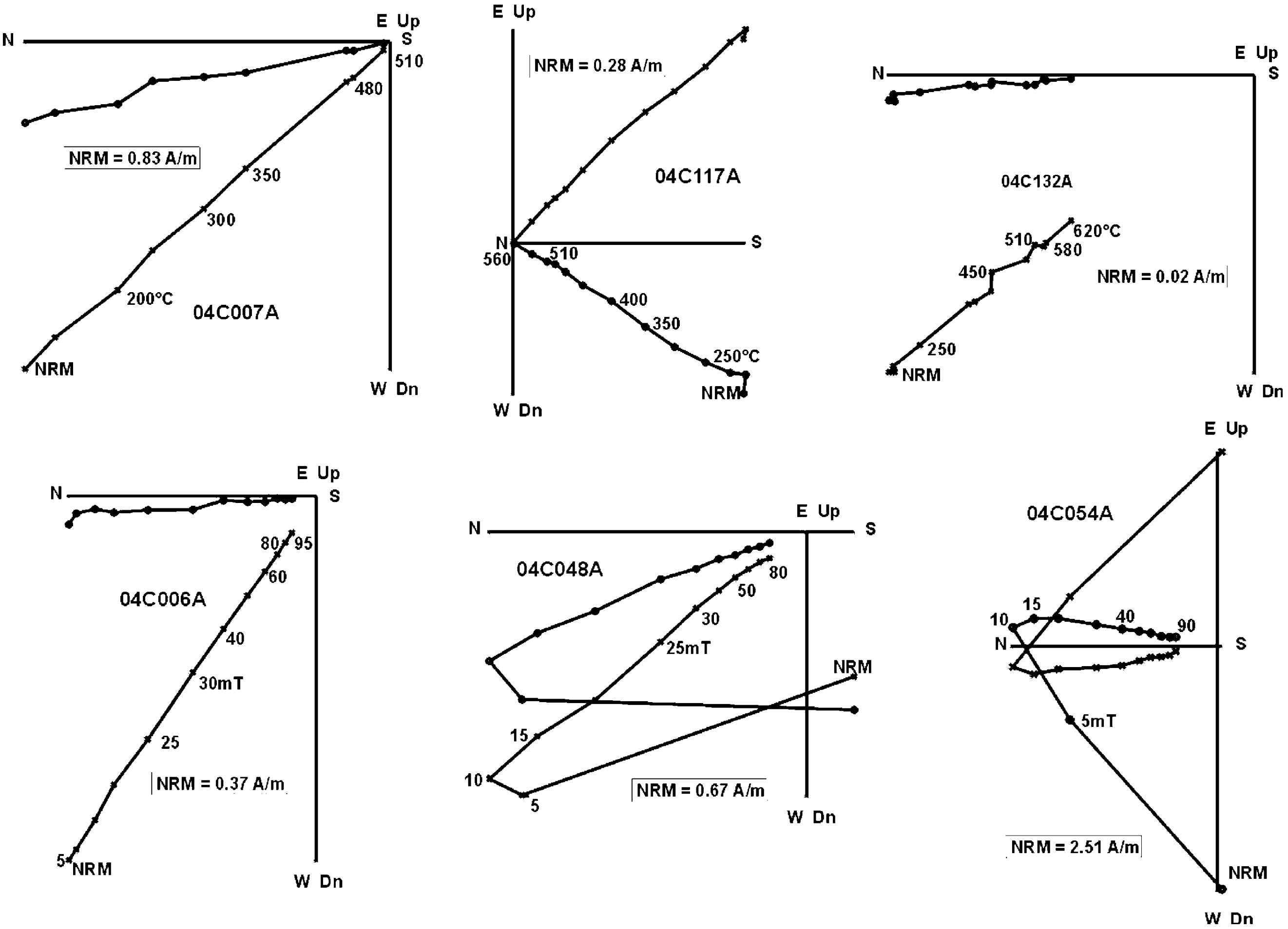

Figure 5. Orthogonal vector plots of stepwise thermal or alternating field demagnetization of representative samples (stratigraphic coordinates). The numbers refer either to the temperatures in °C or to peak alternating fields in mT. Circles, projections into the horizontal plane; crosses, projections into the vertical plane.

precisely determined (Table 1 and Figure 6a). All α_{95} are less than 12.6° except sites CB09 and CB07, which yielded higher directional dispersions.

5. Results and Discussion

[17] The paleodirections are rather precisely determined for all lava flows except sites CB07 and CB09 which yielded unusually high within site directional dispersion (α_{95} equal to 14.3° and 18.6°, respectively). Two lava flows yielded reverse polarity magnetization (Table 1 and Figure 6a) while one flow (CB10) seems to correspond to intermediate geomagnetic polarity. The remaining flows are normally magnetized as one would expect from Brunhes age cooling units. We consider the paleodirections determined in this study to be of primary origin. This is confirmed by the fact that normal and reversed polarities were determined. In addition, thermomagnetic curves show that the remanence is carried in most cases by Ti-poor titanomagnetite, resulting of oxy-exsolution of original titanomagnetite during the initial flow cooling, which indicates that the primary magnetization is a TRM (thermoremanent magnetization). Although some sites are characterized by the strong secondary components due to the lightning, primary remanent magnetization is retrieved from most of specimens using alternating field treatment.

[18] Characteristic remanent magnetization is successfully isolated for most of the samples. The mean paleodirection obtained from 13 flows (discarding flows CB07, CB09 because of relatively high dispersion, flow CB10 which yielded intermediate polarity and flow CB11 which is based on single determination) is I = 42.5°, D = 359.7°, k = 21, α_{95} = 9.3°. These directions are practically undistinguishable from the expected Plio-Quaternary paleodirections, as derived from reference poles for the North American craton [*Besse and Courtillot*, 2002].

[19] Paleointensity determination was also carried out. *Thellier and Thellier* [1959] paleointensity experiments were performed on 41 selected samples according to the rather classic selection criteria (stable, univectorial remanence, low-viscosity index and close to reversible susceptibility against temperature curves), but reliable absolute intensity determinations were obtained for only three samples which we believe is not enough to discuss the paleointensity variation trough time. The principal reason for failure was so-called concave-up behavior during the paleointensity experiments [*Kosterov and Prévot*, 1998].

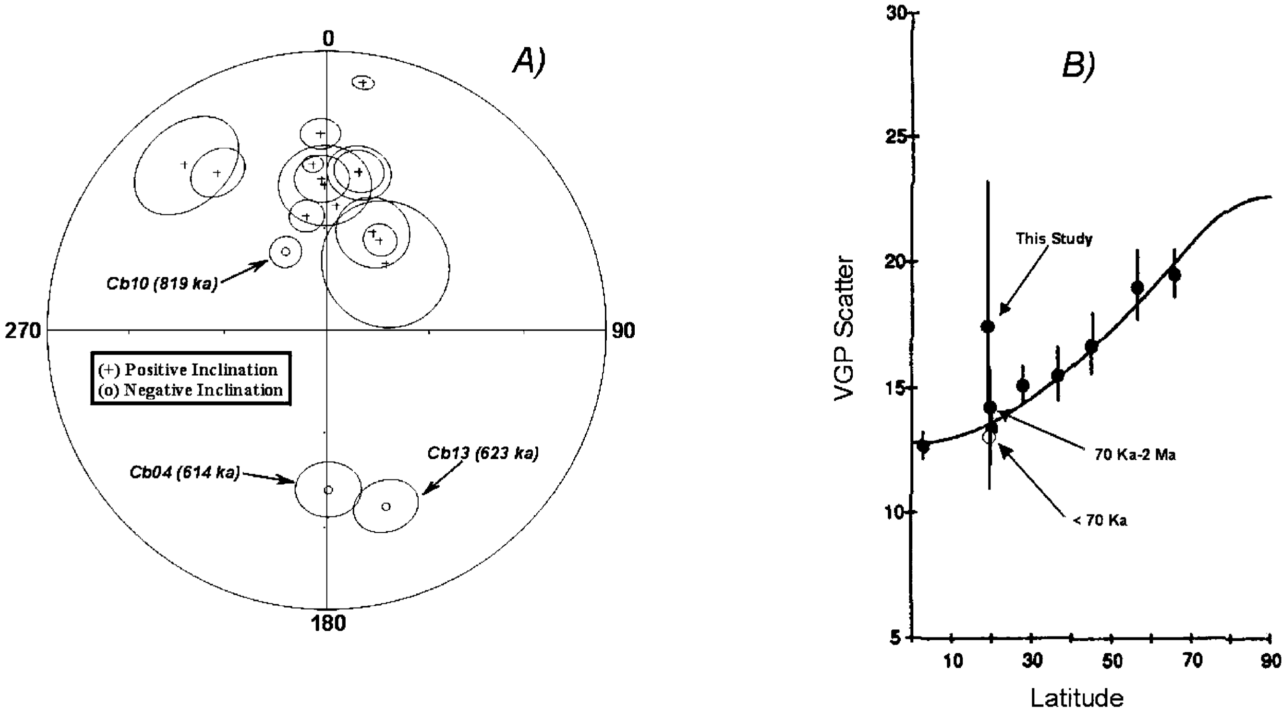

Figure 6. (a) Equal-area projections of the flow-mean characteristic paleodirections for the Ceboruco-San Pedro volcanics. (b) Paleosecular variation of lavas (PSVL) for the last 5 Myr. (Adopted from *McFadden et al.* [1988, 1991]).

[20] The classic formula $S_F^2 = S_T^2 - S_W^2/n$ was used for estimating paleosecular variation in this study, where S_T is the total angular dispersion $S_T = [(1/N - 1)\sum_{i=1}^{N} \delta i^2]^{1/2}$ [*Cox*, 1969], N is the number of sites used in the calculation, δ_i is the angular distance of the *i*th virtual geomagnetic pole (VGP) from the axial dipole, S_W is the within site dispersion, and *n* is the average number of sample per site. Using the new data obtained in this study, we obtained $S_F = 17.6$ with $S_U = 23.8$ and $S_L = 13.9$ (upper and lower limits, respectively) which is slightly higher comparing to the model of *McFadden et al.* [1988, 1991] for the last 5 Myr (Figure 6b). *Tauxe et al.* [2003] showed that a minimum of

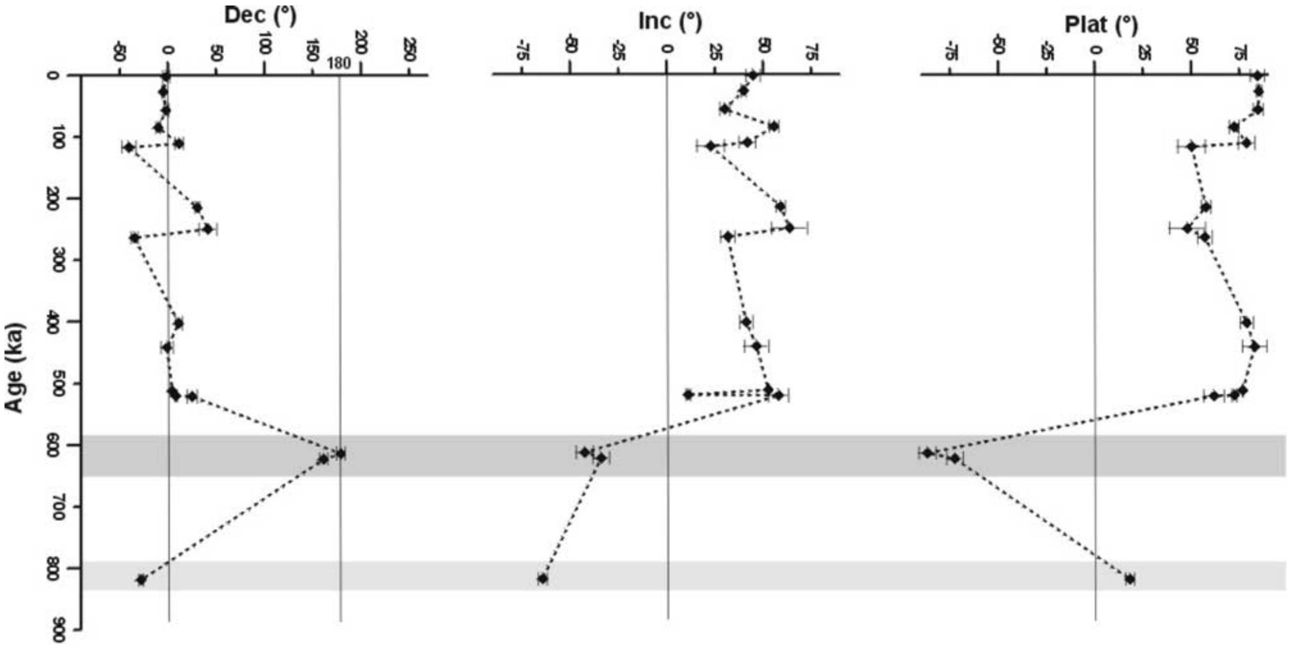

Figure 7. Flow-mean magnetic declination, inclination and paleolatitude of virtual geomagnetic poles against age.

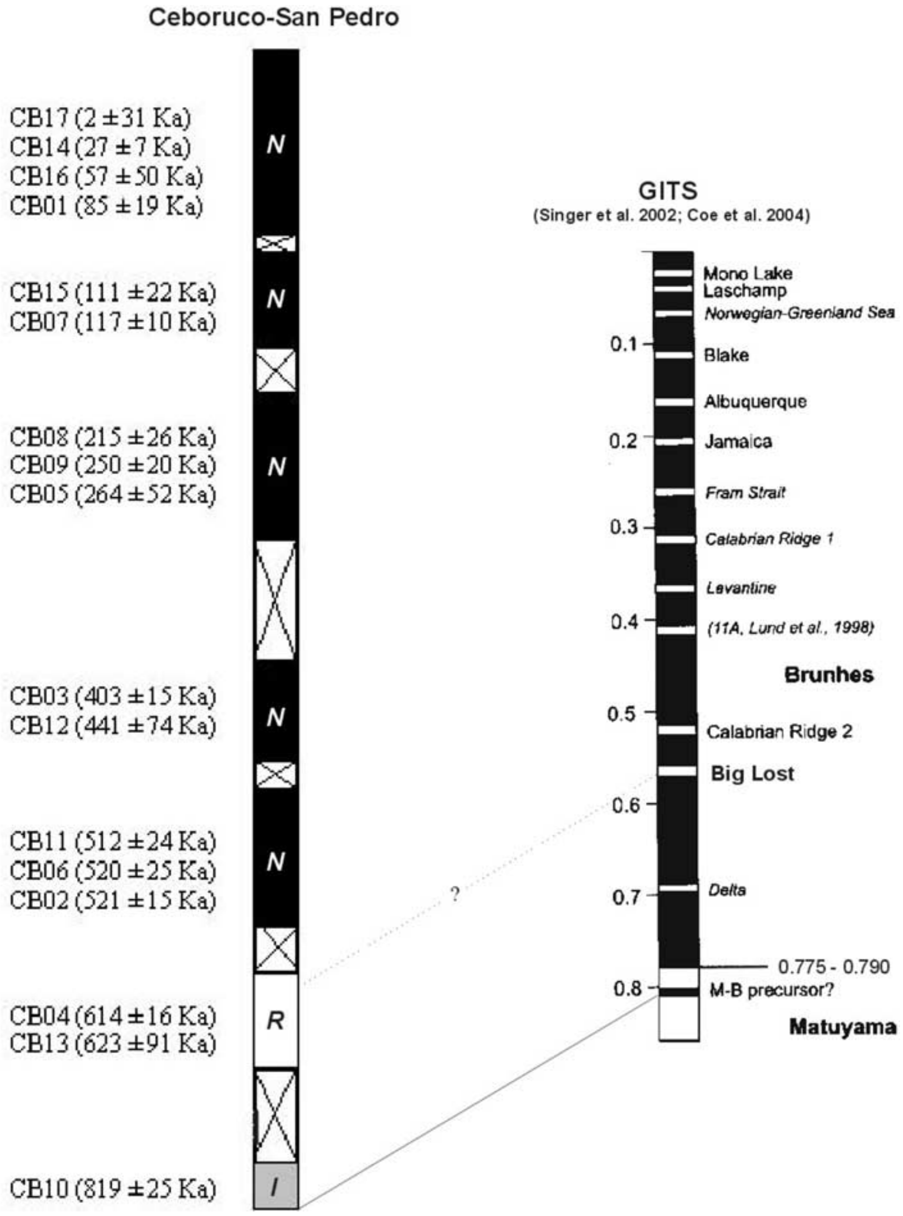

Figure 8. A tentative magnetostratigraphic correlation between Ceboruco-San Pedro volcanic units and reference Geomagnetic Instability Time Scale [*Singer et al.*, 2002].

five samples per site are needed to estimate the precision parameter sufficiently accurately to allow its use as a determinant of data quality. Moreover, several hundred paleomagnetic sites are needed to get an accurate determination of the average field direction. It is clear that our study alone does not give significant statistics on the dispersion of the geomagnetic field. Thus it is necessary to combine our data with currently available paleomagnetic results from the region. The conjunction of our data with previously published data from central and western Mexico [*Conte*, 2004] shows that the amplitude of the secular variation is consistent with values from other worldwide scattered sites.

[21] The mean paleodirection obtained for the lava flow CB10 ($I = -64.1°$, $D = 332.4°$, $\alpha_{95} = 4.6°$, $k = 216$, $n = 8$) corresponds to a virtual geomagnetic pole (VGP) latitude of 18°N. Whatever criteria are considered for the "cutoff angle" to separate intermediate and paleosecular variation regime of geomagnetic field, this direction is clearly transitional. The CB10 is rather precisely dated at 819 ± 25 ka. *Quidelleur et al.* [2002] [see also *Quidelleur and Valet*, 1996] reported first volcanic evidence of a geomagnetic excursion occurring some 40 kyr prior to the Matuyama-Brunhes (M-B) transition. An age of 821 ± 13 ka was obtained using the Cassignol K-Ar technique for a transitionally magnetized flow LS118 from Canary Islands. *Singer et al.* [2002] obtained the mean age of 822.2 ± 8.7 ka on three intermediate polarity lava flows (again from Canaries) using incremental heating ^{40}Ar-^{39}Ar method. These sties are associated with VGP latitudes between 65° and 56°, while their absolute paleointensity gave relatively low values [*Quidelleur and Valet*, 1996] as generally accepted for transitions and excursions [*Goguitchaichvili et al.*, 1999b]. More evidence for a

geomagnetic event just prior to M-B reversal comes from the sedimentary records [*Kent and Schneider*, 1995; *Hartl and Tauxe*, 1996; *Carcaillet et al.*, 2004]. They observed shallow inclinations together with a drop in relative paleointensity about 15 kyr prior to M-B transition. Thus the geomagnetic event, defined as M-B precursor (Figures 7 and 8), could be global in extent.

[22] The most important feature of the geomagnetic record obtained from Ceboruco-San Pedro volcanic field is that two independent lava flows (CB13 and CB04), dated as 623 ± 91 and 614 ± 16 ka, respectively, both yield fully reversed paleodirections. *Quidelleur and Valet* [1996], on the basis of transitionally magnetized lavas (Canary Islands) that gave an unspiked K-Ar age of 602 ± 24 ka, interpreted the event as a new excursion and proposed the name "La Palma." In addition, a relative paleointensity minimum of global extent was found in marine sediments at about 590 ka [*Guyodo and Valet*, 1999] supporting the findings of *Quidelleur and Valet* [1996]. However, on the basis of new high-quality Ar-Ar data, *Singer et al.* [2002] proposed that the lavas at Barranco de los Tilos recorded the Big Lost event (incremental heating ^{40}Ar-^{39}Ar age of 580.2 ± 7.8 ka) (Figures 7 and 8), rather than La Palma excursion. The Big Lost event was first described by *Champion et al.* [1981, 1988] in lava flows in Idaho. There are some marine evidence of the Big Lost event as well: *Lund et al.* [1998] identified in Ocean Drilling Program Leg 172 three cases of anomalous directions at 610 ka; *Langereis et al.* [1997] found additional evidence for Big Lost between 560 and 570 ka recorded in piston core from the Ionian sea. More recently, *Carcaillet et al.* [2004] found three virtual dipole moment (VDM) minima between 750 and 500 ka, the oldest (about 700 ka) being identified as Delta excursion. The only evidence of a fully reversed short event at 630–640 ka comes from the study of *Liu et al.* [1985, 1988], who investigated in detail the Lishi Loess Series in Xifeng area in China. The age uncertainties of the two independent completely reversed lava flows at Ceboruco-San Pedro volcanic field make it difficult to claim on the discovery of new geomagnetic event. It is possible that these lavas erupted during the worldwide observable Big Lost excursion, which probably has been longer and more complex than is generally believed for the geomagnetic events.

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