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Paleomagnetic secular variation study of Ar–Ar dated lavas flows from Tacambaro area (Central Mexico): Possible evidence of Intra-Jaramillo geomagnetic excursion in volcanic rocks

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ABSTRACT

More than 350 oriented paleomagnetic cores were obtained for rock-magnetic and paleomagnetic analysis from radiometrically dated (⁴⁰Ar–³⁹Ar) magmatic rocks occurring in the southern segment (Jorullo and Tacámbaro areas) of the Michoacán–Guanajuato Volcanic Field in the Trans-Mexican Volcanic Belt. Most of the lavas (37) stem from monogenetic volcanoes dated at less than 4 Ma. Two additional sites were sampled from the plutonic basement dated at 33–30 Ma. Primary remanences carried by low-Ti titanomagnetites allowed to determining 34 reliable site-mean directions of mostly normal (27) but also reversed (7) polarities. The mean directions of these two populations are antipodal, and suggest neither major vertical-axis rotations with respect to the North America craton nor tilting in the region for the last 4 Ma (rotation and flattening of the inclination parameters being less than -5.9 ± 3.8 and 0.1 ± 3.9 , respectively). The corresponding paleomagnetic pole obtained for Pliocene–Pleistocene times is PLAT = 83.4°, PLON = 2.4° ($N = 32$, $A95 = 2.7^\circ$). Virtual geomagnetic poles also contribute to the time averaged field global database and to the paleosecular variation (PSV) investigations at low latitudes from lavas for the last 5 Ma, showing a geomagnetic dispersion value that is in agreement with available PSV models. When comparing the magnetic polarities and corresponding radiometric ages of the studied sites with the Cenozoic geomagnetic polarity time scale (GPTS), a good correlation is observable. This finding underscores the suitability of data obtained on lavas in Central Mexico for contributing to the GPTS. Furthermore, the detection of short-lived geomagnetic features seems possible, since the possible evidence of Intra-Jaramillo geomagnetic excursion could be documented for the first time in these volcanic rocks.

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1. Introduction

The present characteristics of the Earth's magnetic field (EMF) are well known from data obtained at magnetic observatories and from remote measurements by the means of satellites. The EMF is not static, since its direction and strength vary with time. Studies of the spatial and temporal variations of the EMF and of the nature of its time-averaged field have remained central topics of paleomagnetic research. These studies permit investigation of

the internal geodynamo processes that generate the field, and allow tectonic and stratigraphic applications of paleomagnetic data. Besides secular variation, one of the main characteristics of the EMF is that it switches its polarity. The duration of geomagnetic polarity intervals is rather variable, ranging between some tens of thousands and several millions of years. Polarity transitions, however, are very short, their duration being estimated to be of the order of 10^3 – 10^4 years (e.g., Merrill and McFadden, 2003). A polarity reversal is a global event, experienced simultaneously all over the Earth. Thus, geomagnetic reversals provide a convenient means of stratigraphic correlation and dating. Recognition of brief polarity excursions as a part of the Earth's paleomagnetic field

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behavior has developed during the last two decades together with astrochronological calibration of the polarity timescale. During this time, numerous geomagnetic excursions (short-lived episodes when Earth's magnetic field deviates into an intermediate polarity state) have been discovered in the previously believed stable Brunhes and Matuyama chrons (e.g., Singer et al., 2002; Laj and Channell, 2007). Their number, however, is still a matter of debate. Laj and Channell (2007), for instance, consider that in the Brunhes chron only seven adequately defined excursions with acceptable age control can be found, whereas five additional excursions still need further ratification either in definition of magnetic data or refinement of the age models, and Singer et al. (2002) propose the development of a Geomagnetic Instability Time Scale (GITS) for the Brunhes and late Matuyama chrons.

Volcanic rocks allow a reliable and instantaneous record of the Earth's magnetic field by means of the acquisition of thermoremanent magnetisation (TRM), even though they provide a discontinuous record because they are tied to volcanic eruptions that are discrete in time. Nevertheless, because volcanic rocks are in principle able to offer a more faithful though instantaneous image of the Earth's magnetic field, the paleomagnetic study of lava flows can be of major interest for the knowledge of characteristics and variations of the ancient geomagnetic field. In order to be useful, this kind of paleomagnetic studies needs to be supplemented by precise radiometric dates.

This investigation aims to contribute to the time averaged field global database and investigations of the paleosecular variations at low latitudes as well as instabilities in the geomagnetic time scale for the last 5 Ma, based on a detailed rock-magnetic and paleomagnetic study of 37 volcanic units (more than 350 standard paleomagnetic cores) associated with the Michoacán-Guanajuato Volcanic Field (MGVF) in the Trans-Mexican Volcanic Belt. The available ages range from 4 Ma to <5000 years BP but also include 2 Oligocene ages (33, 30 Ma) from the MGVF basement (Guilbaud et al., 2012). The MGVF with >1000 volcanic constructs seem to be particularly adequate for paleomagnetic targets. There is probably no other Plio-Quaternary volcanic field in the world displaying such a large number of accessible monogenetic volcanoes spreading a wide range of ages and it can be said that in this respect it is a unique feature. Such an advantage is exploited in this study for paleomagnetic purposes.

2. Geological setting and ages

The Trans-Mexican Volcanic Belt (TMVB) is an active continental arc related to the subduction of the Cocos and Rivera plates below the North American plate (Fig. 1). A peculiar and still unexplained feature of the belt is the large number of small volcanoes (>3000) that occur everywhere along and across it, while large stratovolcanoes are few and sparsely distributed. The density of small volcanoes varies widely across the arc to reach maximum values in its central-western part, where they form the Michoacán-Guanajuato Volcanic Field (MGVF). This large (ca. 40,000 km²) field with poorly defined limits consists of a large number (>1000) of closely-spaced small volcanic constructs that vary from scoria cones to lava shields, small domes, viscous flows, and rare maars (Hasenaka and Carmichael, 1985, 1987; Guilbaud et al., 2011, 2012). These small volcanoes are believed to have formed by single short-lived eruptions, and hence are called monogenetic. Large (polygenetic) stratovolcanoes are absent in this area, except the probably extinct Tancitaro volcano. The two youngest volcanoes of the MGVF, Paricutin (1943–1952) and Jorullo (1759–1774), occur in close proximity to each other, and are located at the arc-front limit of the field, along the trace of an important seismically active fault zone (Chapala-Oaxaca) (Guilbaud et al., 2011).

The area surrounding Jorullo (Fig. 1, area A) volcano (thereafter called the Jorullo area) and an adjoining area to the NE (Fig. 1, area B) that encloses the small city of Tacámbaro (thereafter called the Tacámbaro area) have been the subject of recent geological and geochronological studies (Guilbaud et al., 2011, 2012). In these areas, MGVF products are mostly basaltic andesitic to andesitic lava flows that range from ca. 4 Ma to <1000 years old. These young volcanics were emplaced on top and around strongly eroded and faulted Tertiary volcanic and plutonic rocks that represent the remains of an ancient volcanic arc that ran parallel to the Pacific coast.

Our sampling strategy was largely conditioned by Guilbaud et al. (2011, 2012) who provide 14 and 33 new Ar–Ar incremental heating ages for the Jorullo and Tacámbaro areas, respectively, as well as 10 ¹⁴C ages on paleosols underlying young volcanic fallout deposits. From this dataset, we sampled only sites with available radiometric dating information, of easy access and yielding fresh, apparently unaltered outcrops (Figs. 2 and 3). Most samples were taken from young (3 Ma to <5000 years-old) lava flows. The subdivision of timescales used on Figs. 2 and 3 has been made accordingly to an internationally recognized time scale specified in the article (USGS geological time scale, 2007) that does not specify subdivisions within the Pleistocene period. Basically the subdivision chosen in the work has been made according to the collected Ar–Ar data and the range of morphologies that could be attributed to volcanoes of each time period. Specifically, degradation processes are faster at the beginning of the “life” of a volcano (within the first 100,000–200,000 years) than after, and thus we can easily separate between volcanoes that are < or >100,000 years old than those that have between 1,100,000 years and 1,500,000 years old.

The preparation of samples for Ar–Ar geochronology was the following. Samples were crushed, sieved, and hand-picked for biotite crystals (for the granodiorite and dike samples) and whole-rock (matrix) chips (for the other samples). This method allows avoiding the “contamination” of the measured age by crystals of older ages (xenocrysts). Note that the lava samples contained low amounts of phenocrysts (<10 vol.%) and sparse xenocrysts, limiting the possible affectation. Since the ages on the oldest, basement samples (granodiorite and cutting dikes) are based on biotite crystals, they represent cooling ages rather than older, emplacement ages.

The plutonic basement was sampled at two locations in the Jorullo area (JO-14 and JO-18). We also drilled one ca. 1 Ma basaltic dike (JO-03) exposed at a quarry of a scoria cone. It should be noticed that not all of the paleomagnetic sampling sites coincide exactly with geochronological sample coordinates. In some cases, in order to collect samples from in situ structures, sites were drilled as close as possible (Table 1) to the radiometrically dated samples.

In total, 302 oriented samples belonging to 37 individual lava flows were collected at the Jorullo (Fig. 2) and Tacámbaro (Fig. 3) areas. Each flow was sampled systematically, both horizontally and vertically (dip less than 4°). In general, samples were obtained near the base of flows in order to obtain samples from the densest and finest-grained parts. Cores were sampled with a gasoline-powered portable drill, and oriented in most cases with both magnetic and sun compasses. The magnetic declination over the study area is about 6.9° E while the correction applied to azimuth measurements varied between 4° and 11°. Thus, no major deviation is observed. The cores were later sliced into standard specimen cores (2.5 cm in diameter and 2.1 cm high) for laboratory measurements.

3. Rock-magnetic characteristics

In order to identify the magnetic carriers responsible for the remanent magnetization and to obtain information about their

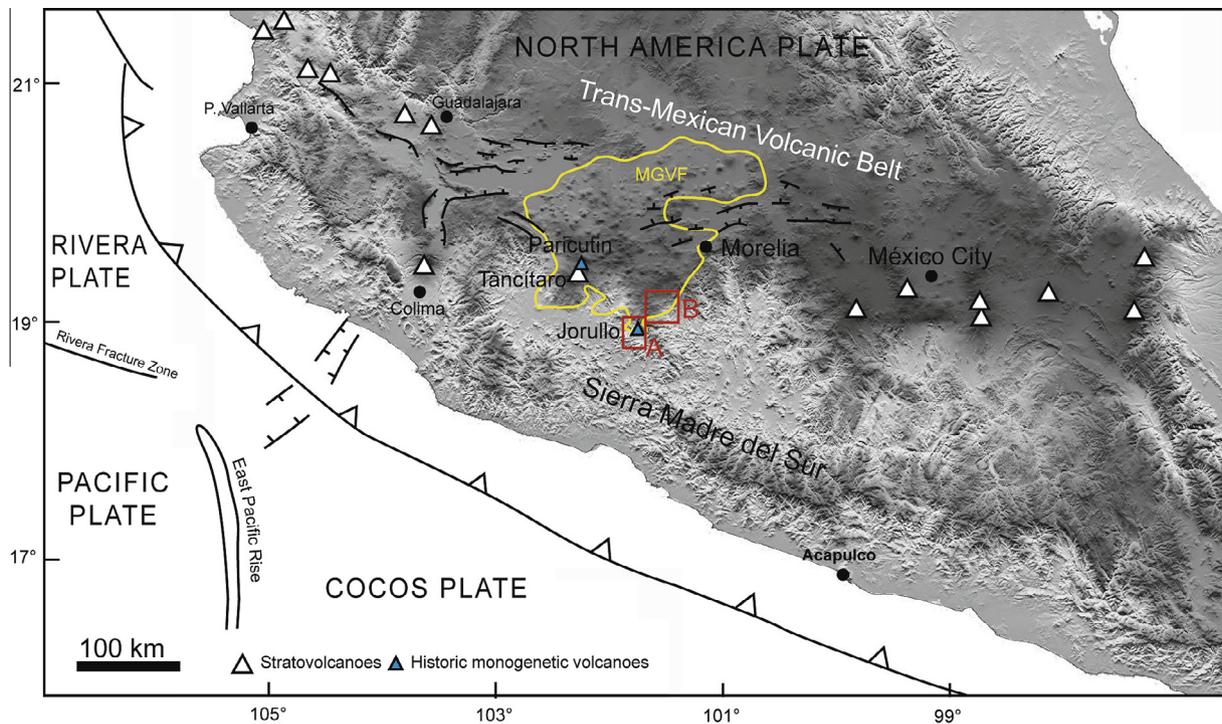


Fig. 1. Schematic map of Central Mexico showing the Michoacan Guanajuato Volcanic Field bordered by yellow line. A and B refer to Jorullo and Tacámbaro study areas, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

paleomagnetic stability, several rock-magnetic experiments were carried out. These experiments included: (a) measurements of saturation remanent magnetization vs. temperature curves – so called J_s - T curves, (b) measurements of susceptibility vs. temperature from about -180 °C to room temperature, (c) hysteresis experiments, and (d) isothermal remanent magnetization (IRM) acquisition curves.

Low-temperature (from about -185 °C to room temperature) susceptibility was recorded using a Kappabridge-KLY3 (AGICO) susceptibility meter equipped with furnace. Hysteresis, IRM and strong field remanence vs. temperature experiments were carried out using a Variable Field Translation Balance (VFTB) in the University of Burgos, Spain. For these measurements, one whole-rock powdered sample was taken from each flow and subjected to the following measurement sequence: (i) IRM acquisition, (ii) back-field, (iii) hysteresis curve and (iv) J_s - T curve.

For the measurement of J_s - T curves, samples were heated in air up to approximately 600 °C or sometimes up to 700 °C and cooled down to room temperature. Curie points were determined using the method described in Grommé et al. (1969). Two types of thermomagnetic behavior could be clearly distinguished: Most of the curves are characterized by a simple behavior, with low-Ti titanomagnetite as the only carrier of remanence and a moderate to high degree of reversibility (Fig. 4, samples 98JT049A and 98JT018A). In ca. 40% of the analyzed samples, two phases could be distinguished in the heating curve (Fig. 4, samples 98JT008 and 98JT028A): A high Curie-temperature phase corresponding to low Ti-titanomagnetite but also a low Curie-temperature phase, with Curie temperatures between 320 and 390 °C. In the cooling curves, only a single phase (low-Ti titanomagnetite) could be recognized. Relatively simple behavior was also observed during low-T susceptibility experiments (Fig. 5): the curves display a rather monotonic decrease from about -185 °C to room temperature without showing any evidence for transition. The small inflections observed at ca. -180 °C (Fig. 5, sample 98TJ120) are due to an experimental artifact rather than to mineralogical characteristics. As shown by Ozdemir

et al. (1993), the Verwey transition may be largely suppressed for the titanomagnetites with variable titanium content. Alternatively, similar behavior may also stem from non-stoichiometric (partially oxidized) magnetite.

Hysteresis parameters were obtained from hysteresis and back-field curves (Fig. 6) and the RockMag Analyzer 1.0 software (Leonhardt, 2006) was used to analyse the measured curves. The saturation remanent magnetization (J_{rs}), the saturation magnetization (J_s), and the coercitive force (H_c) were calculated after correction for the paramagnetic contribution. Judging from the H_{ci}/H_c vs. J_{rs}/J_s hysteresis ratios displayed in a Day plot (not shown), the domain structure of all studied samples plots in the PSD (pseudo-single-domain) area (Day et al., 1977). This behavior might be also explained by a mixture of single-domain (SD) and multi-domain (MD) particles (Dunlop, 2002). Isothermal remanent magnetisation acquisition curves were recorded in a maximum applied field of approximately 1T. Relatively low-coercivity phases are the main carriers of remanence since almost full saturation is reached at 250 mT applied fields. No evidence for strong coercivity phases was detected.

4. Remanence properties

Remanent magnetization was measured with a JR-6 spinner magnetometer at the LIMNA paleomagnetic laboratory in Morelia, Mexico. Measurements were recorded after stabilization of the remanence in this magnetometer. In all sites, two pilot samples were selected for thermal demagnetization and two for alternating field (AF) demagnetization, and analysis of demagnetization results allowed choosing the most suitable technique for each case. AF demagnetization up to 95 mT was performed with a Molspin AF-demagnetizer and thermal demagnetization up to 575 – 675 °C with an ASC TD-48 furnace. Directions of remanent magnetization components were determined in all cases by means of principal component analysis (Kirschvink, 1980).

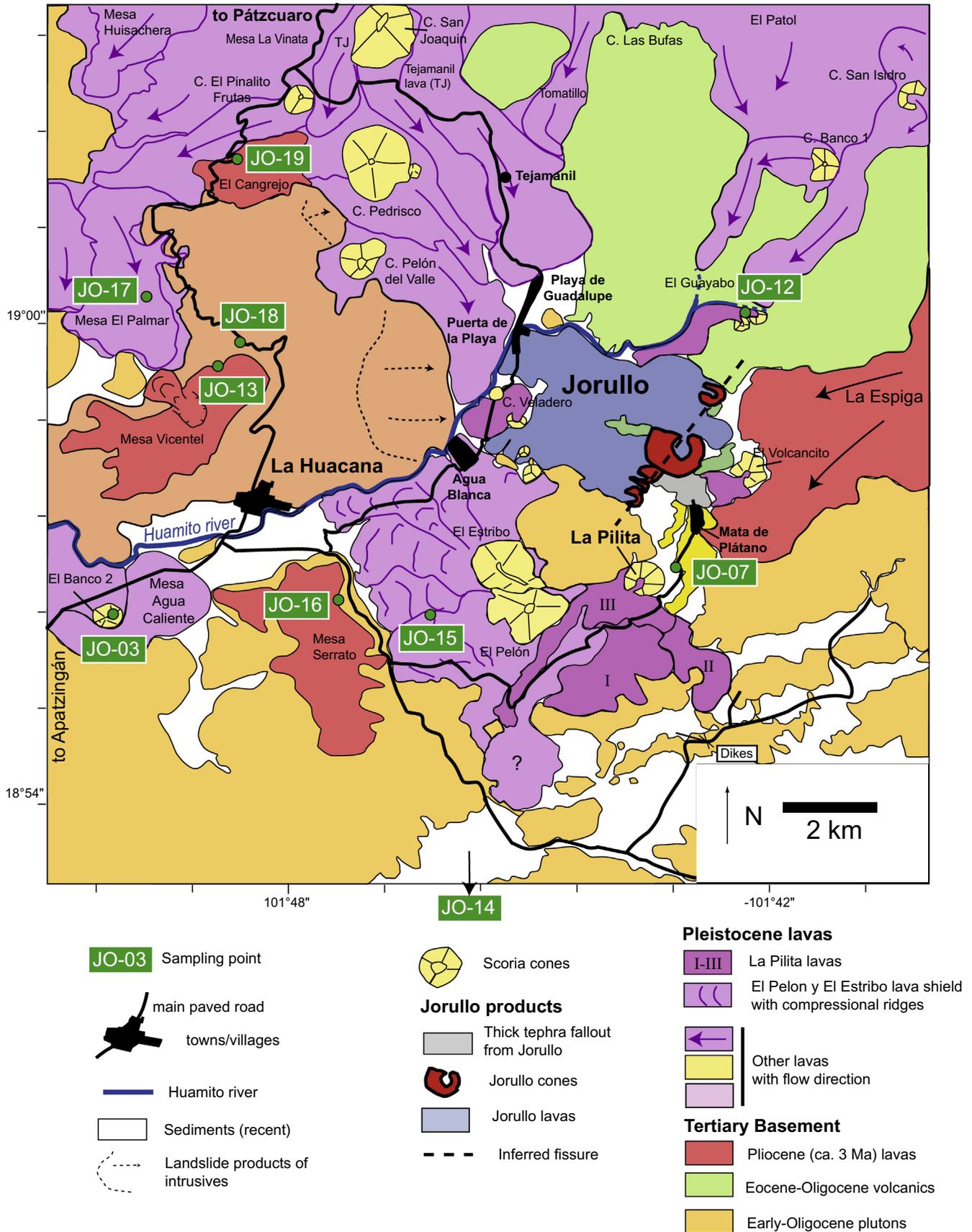


Fig. 2. Geological map of the Jorullo area showing the location of sites, adapted from Guilbaud et al. (2011).

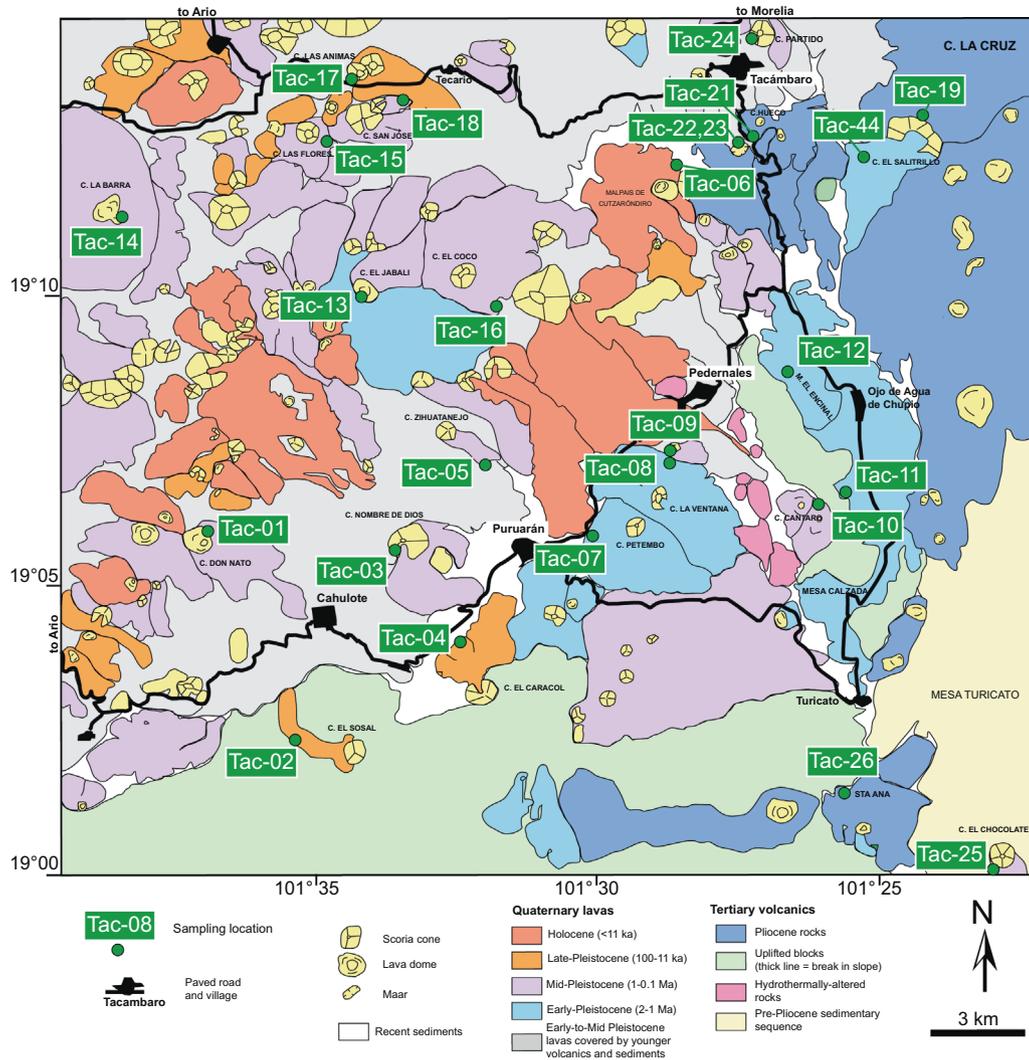


Fig. 3. Geological map of the Tacámbaro area showing the location of sites, adapted from Guilbaud et al. (2012).

85% of the collected samples gave successful fits (see N/n in Table 1) contributing to ChRM mean directions (see Dec, Inc in Table 1). In most cases, sometimes besides a small viscous overprint, only a single paleomagnetic component could be distinguished (Fig. 7, samples 98JT016B and 98JT018A), but in some cases two or more components (samples 98JT001A and 98JT012A) could be found. In some samples, due to the presence of lightning-induced overprints and overlapping unblocking temperature and coercivity spectra, no characteristic remanent magnetization (ChRM) could be isolated. Analysis of remagnetization circles also failed to provide satisfactory results in these cases. Although in most sites only few specimens provided unreliable or anomalous results that had to be rejected, no coherent paleomagnetic results could be obtained in sites Tac-01, Tac-16 and JO-03. All three sites were hence omitted from further analysis. In site Tac-22, nine cores were sampled. Reliable and consistent results were obtained only in four specimens, which were all sampled from a reddish block apparently cooled down in situ. The remaining five specimens, which were not sampled in that block, did not provide coherent directions, so that we consider that only the directions from the block represent the original magnetization of site Tac-22. In site JO-12 only 4 out of 9 analyzed specimens provided reliable results. Although this rather low success rate might question the reliability of the paleomagnetic direction obtained in JO-12, we have considered it to be acceptable because of the good

quality of the four successful individual determinations. Thus a mean ChRM direction could be determined in 34 of 37 studied sites (Table 1). Mean paleodirections of most sites showed a radius of 95% confidence cones $\alpha_{95} < 10^\circ$ and are characterized by a rather high precision parameter value, exceeding $k = 50$ in all but two cases, being useful for tectonic and geomagnetic purposes.

5. Main results and discussion

5.1. Paleomagnetic results

Three sites yielded reverse polarity magnetization at the Jorullo locality (Fig. 8a) while four reversely magnetized lava flows were detected in the Tacámbaro volcanic field (Fig. 8b). All remaining sites are normally magnetized (Table 1). The mean paleodirection of the reverse polarity sites yields the following values: declination $D = 174.7^\circ$, inclination $I = -30.8^\circ$ ($N = 7$, $\alpha_{95} = 7.9^\circ$, $k = 59$), while normal sites (omitting the two Oligocene sites) provided the following results: declination $D = 352.5^\circ$, inclination $I = 33.6^\circ$ ($N = 32$, $\alpha_{95} = 3.9^\circ$, $k = 56$). Comparison of both mean directions (Fig. 8c) shows that the hypothesis that normal and reversed distributions share a common mean direction could not be rejected at the 95% confidence level (McFadden and Lowes, 1981) because the angle between the two mean directions (3.4°) was lower than

Table 1

Flow-mean paleodirections of characteristic remanence, location and available isotopic age determinations for samples from the Jorullo (JO-) and Tacámbaro (Tac-) areas. n – number of specimens used for calculation, N – number of treated samples, Inc – inclination, Dec – declination, α_{95} and k – radius of 95% confidence cone and precision parameter of Fisher statistic, respectively, Lat., Long. – geographic latitude and longitude of studied sites; VGP_{lat}, VGP_{long} – virtual geomagnetic pole positions for each lava flow.

Site	N/n	Inc (°)	Dec (°)	α_{95} (°)	k	Lat. site (N)	Lon. site (W)	Ar–Ar age	VGP Lat.	VGP Lon.
Tac-04 (C. El Caracol)	8/8	24.8	348.9	8.6	81	19.070	101.541	-0.05 ± 0.15	77.737	343.567
Tac-06 (M. de Cutzaróndiro)	8/8	23.4	334.4	5.1	146	19.206	101.476	<5000 years BP	64.415	359.414
JO-12 (El Guayabo)	4/9	31.7	354.5	3.4	589	19.001	101.704	0.03 ± 0.03	84.458	353.183
Tac-17 (C. Las Animas)	8/9	34.9	346.3	8.2	52	19.228	101.574	0.05 ± 0.04	77.068	13.843
Tac-02 (C. El Sosal)	7/8	38.6	1.8	8.4	58	19.041	101.590	0.06 ± 0.02	86.801	133.104
Tac-22 (Alberca)	4/9	11.4	5.2	10.8	37	19.212	101.458	0.06 ± 0.05	75.624	260.161
Tac-23 (Alberca 2)	8/8	46.4	353.3	6.3	94	19.212	101.458	0.06 ± 0.05	79.524	66.84
Tac-16 (C. El Coyo)	No coherent results					19.165	101.530	0.11 ± 0.04		
Tac-18 (C. Chepelopez)	8/8	25.1	352.7	5.5	156	19.224	101.559	0.22 ± 0.04	80.749	331.874
Tac-09 (C. Flogopitaro)	8/8	34.6	354.8	3.1	375	19.125	101.478	0.32 ± 0.02	85.085	11.236
Tac-03A (C. Nombre de Dios)	8/8	42.3	352.5	5.9	129	19.094	101.561	0.38 ± 0.01	81.209	50.537
Tac-03B (C. Nombre de Dios)	8/8	52.5	353.8	3.9	298	19.094	101.561	0.38 ± 0.01	74.947	81.170
Tac-01 (C. Don Nato)	No coherent results					19.100	101.614	0.38 ± 0.18		
Tac-25 (C. Chocolate)	8/8	22.9	346.3	8.1	58	19.004	101.378	0.51 ± 0.04	75.030	345.153
Tac-14 (C. La Barra)	7/8	28.9	355.8	11	23	19.189	101.648	0.53 ± 0.01	84.505	329.144
Tac-05 (C. Zihuatajejo)	8/8	43.1	352.6	2.2	917	19.121	101.531	0.59 ± 0.44	80.924	53.841
Tac-10 (C. Cantaro)	7/8	29.2	354.3	6.8	76	19.110	101.429	0.60 ± 0.05	83.530	339.578
Tac-24 (C. Partido)	8/8	44.8	349.4	4.3	198	19.240	101.455	0.62 ± 0.03	77.895	49.669
Tac-15 (C. Las Flores)	6/8	21.2	351.6	5.4	254	19.211	101.582	0.73 ± 0.02	78.448	327.316
JO-07 (Mata de Plátano)	9/9	-31.2	171.7	4.5	178	18.949	101.719	0.81 ± 0.01	81.83	358.11
JO-15 (C. El Pelón)	7/9	-29.2	166.6	3.8	246	18.935	101.772	0.93 ± 0.12	76.79	359.28
Tac-13 (C. El Jabali)	8/8	37.6	357.6	6.6	81	19.168	101.572	0.96 ± 0.07	87.058	51.980
JO-17 (Mesa El Palmar)	7/8	-31.4	178.1	7.4	81	19.006	101.831	1.03 ± 0.02	87.28	323.75
JO-03 (C. El Banco 2)	No coherent results					18.941	101.837	1.06 ± 0.047		
Tac-08 (C. La Ventana)	8/8	38.2	355.1	2.5	591	19.122	101.478	1.64 ± 0.04	84.836	39.453
Tac-07 (C. Petembo)	8/8	37.8	348.2	6.7	82	19.097	101.501	1.70 ± 0.02	78.728	24.243
Tac-12 (Mesa El Encinal)	8/8	-42.3	170.8	4.2	118	19.147	101.443	1.74 ± 0.11	79.95	315.01
Tac-11 (M. Calzada)	6/8	-16.7	174.7	7.6	54	19.120	101.424	1.74 ± 0.11	78.24	308.03
Tac-20 (C. El Salitrillo)	6/8	-28.3	169.5	6.7	68	19.210	101.420	1.81 ± 0.03	79.15	350.6
Tac-26 (C. Sta Ana)	8/8	36.6	349.8	3.4	315	19.028	101.424	2.68 ± 0.03	80.305	21.090
Tac-21 (C. Hueco)	8/8	43.2	351.3	3.9	244	19.215	101.457	2.68 ± 0.03	79.99	49.42
JO-19 (El Cangrejo)	9/9	36.2	357.3	2.2	928	19.033	101.812	2.74 ± 0.02	87.241	35.003
JO-16 (Mesa Serrato)	5/9	24.8	347.3	10.4	141	18.943	101.787	2.90 ± 0.13	76.433	347.726
JO-13 (Mesa Vicente)	7/7	25.2	358	4.1	176	18.989	101.813	2.95 ± 0.04	83.938	300.579
Tac-19 (C. La Cruz 2)	8/8	-35	192.5	4.6	172	19.223	101.407	4.18 ± 0.08	78.21	188.98
JO-14 (Aplitic dike)	9/9	27.1	21.3	5.7	96	18.861	101.775	30.3 ± 0.1	69.112	201.012
JO-18 (Pluton La Huacana)	9/9	41.9	358.5	3.4	314	18.995	101.809	32.7 ± 0.2	84.648	86.972

the critical angle (8.3°) at which the hypothesis would be rejected, with a quality classification (McFadden and McElhinny, 1990) type “B” of the positive reversal test ($5^\circ < \text{critical angle} < 10^\circ$). The mean paleomagnetic direction obtained in this study merging both normal and reverse-polarity lavas is: $D = 353.0^\circ$, $I = 33.0^\circ$ ($N = 32$, $\alpha_{95} = 3.4^\circ$, $k = 57$). The corresponding paleomagnetic pole (Fig. 9) obtained for Pliocene–Pleistocene times in the studied area is $\text{PLAT} = 83.4^\circ$, $\text{PLON} = 2.4^\circ$ ($N = 32$, $A95 = 2.7^\circ$).

The obtained direction is in perfect agreement with the expected paleodirection for Pliocene–Pleistocene times, as derived from available reference poles for stable North America. Hence, the amounts of both the rotation R (observed minus expected declinations) and flattening of inclination F (expected minus observed inclinations) suggest that no major block rotation is observed (neither tilting) in the studied area. These R and F parameters have been evaluated with their confidence limits (Demarest, 1983) using the available Global Apparent Polar Wander paths (GAPWaP) in North American co-ordinates given by Besse and Courtillot (2002) ($N = 30$; mean age = 3.1 Ma; $R = -2.9 \pm 3.9$; $F = 2.3 \pm 4.1$) or Torsvik et al. (2012) ($N = 24$; youngest running mean path = 0 Ma; $R = -5.4 \pm 3.6$; $F = 1.9 \pm 3.6$); and also from the recommended APWP for Laurentia compiled by Torsvik et al. (2012) ($N = 15$; youngest running mean path = 0 Ma; $R = -5.9 \pm 3.8$; $F = 0.1 \pm 3.9$).

If we analyze the <4 Ma dataset split between younger (Brunhes chron) and older lavas (mostly from the Gauss and Matuyama chrons; with reverse directions flipped antipodally), identical mean directions are observed, with values $D = 352.2^\circ$, $I = 32.9^\circ$ ($N = 17$, $\alpha_{95} = 5.5^\circ$, $k = 44$) and $D = 353.9^\circ$, $I = 33.1^\circ$ ($N = 15$,

$\alpha_{95} = 4.3^\circ$, $k = 81$), respectively. Then, we cannot detect any potential increase of the rotation R parameter with age. This study results are consistent with previous studies on the same region (Maciel et al., 2009) which suggested no major vertical-axis rotations in the region are paleomagnetically observed.

5.2. Paleosecular variation

The paleosecular variation issue in Central Mexico is critical for the following reasons: Johnson et al. (2008) recently published a comprehensive synthesis of a new generation of paleomagnetic data compilations from lavas erupted during the last 5 Ma. The latitudinal dependence of virtual geomagnetic pole (VGP) scatter for 0–5 Ma data sets compiled by Johnson et al. (2008) appeared much less important than the classical statistical model of McElhinny and McFadden (1997). The vision of the latitude dependence of VGP scatter put forward by Johnson et al. (2008) depends critically on a latitudinal set of data from about 20°N which is the case of these sites. The formula $S_F^2 = S_T^2 - S_W^2/n$ was used for estimating the scatter of paleosecular variation in this study where S_F is the angular dispersion, S_T the total angular dispersion $S_T = [(1/N - 1) \sum_{i=1}^N \delta_i^2]^{1/2}$ (Cox, 1969), N the number of sites used in the calculation, δ_i the angular distance of the i th virtual geomagnetic pole (VGP) from the axial dipole, S_W the within-site dispersion (following McElhinny and McFadden, 1997) and, n the average number of samples per site. We obtained a scatter $S_F = 8.3^\circ$ with an upper limit $S_U = 10.0^\circ$ and a lower limit $S_L = 7.1^\circ$ for the 32 sites less than 4 Ma. This value is lower with respect

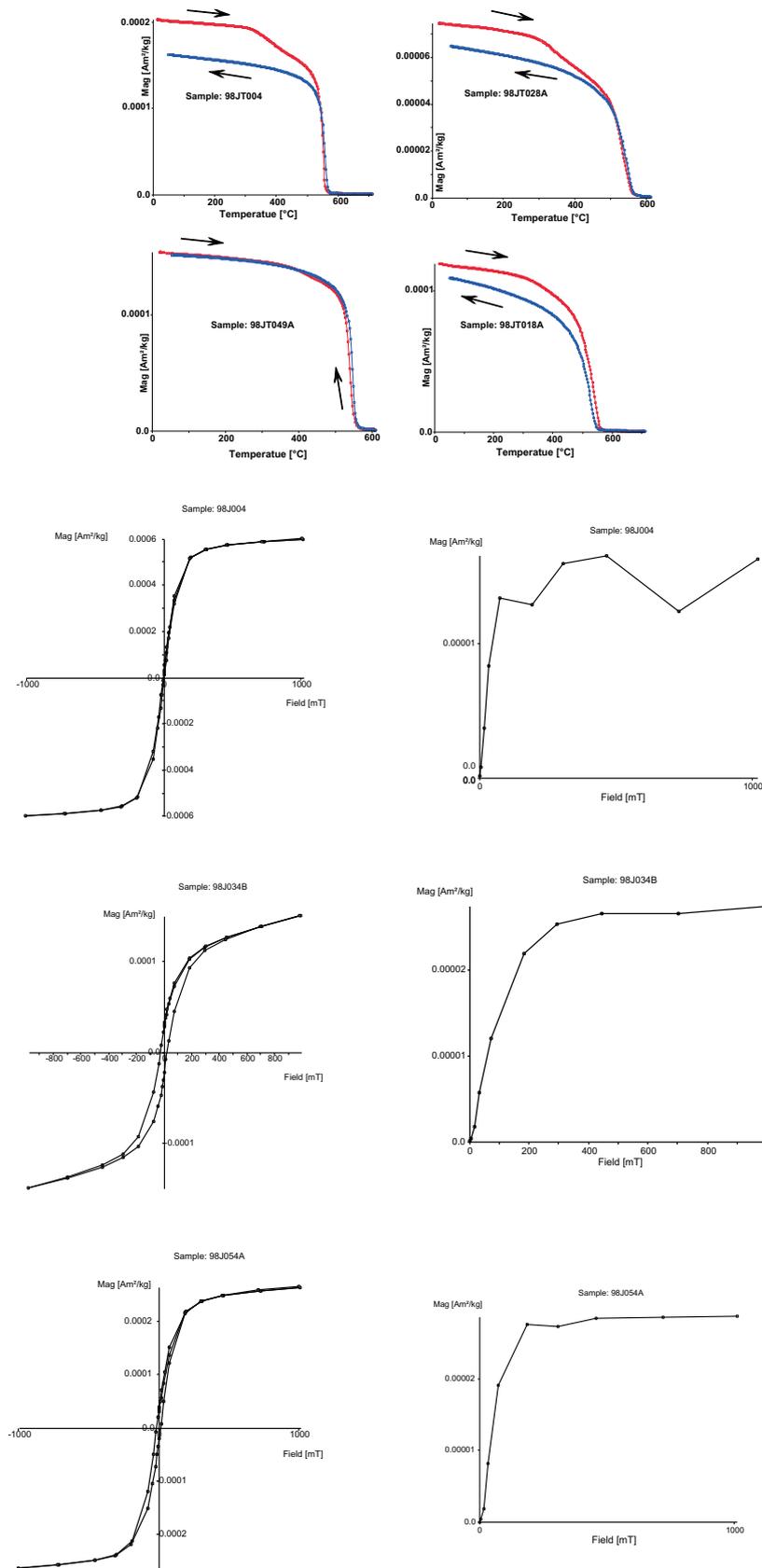


Fig. 4. Susceptibility versus temperature (in air) curves of representative samples.

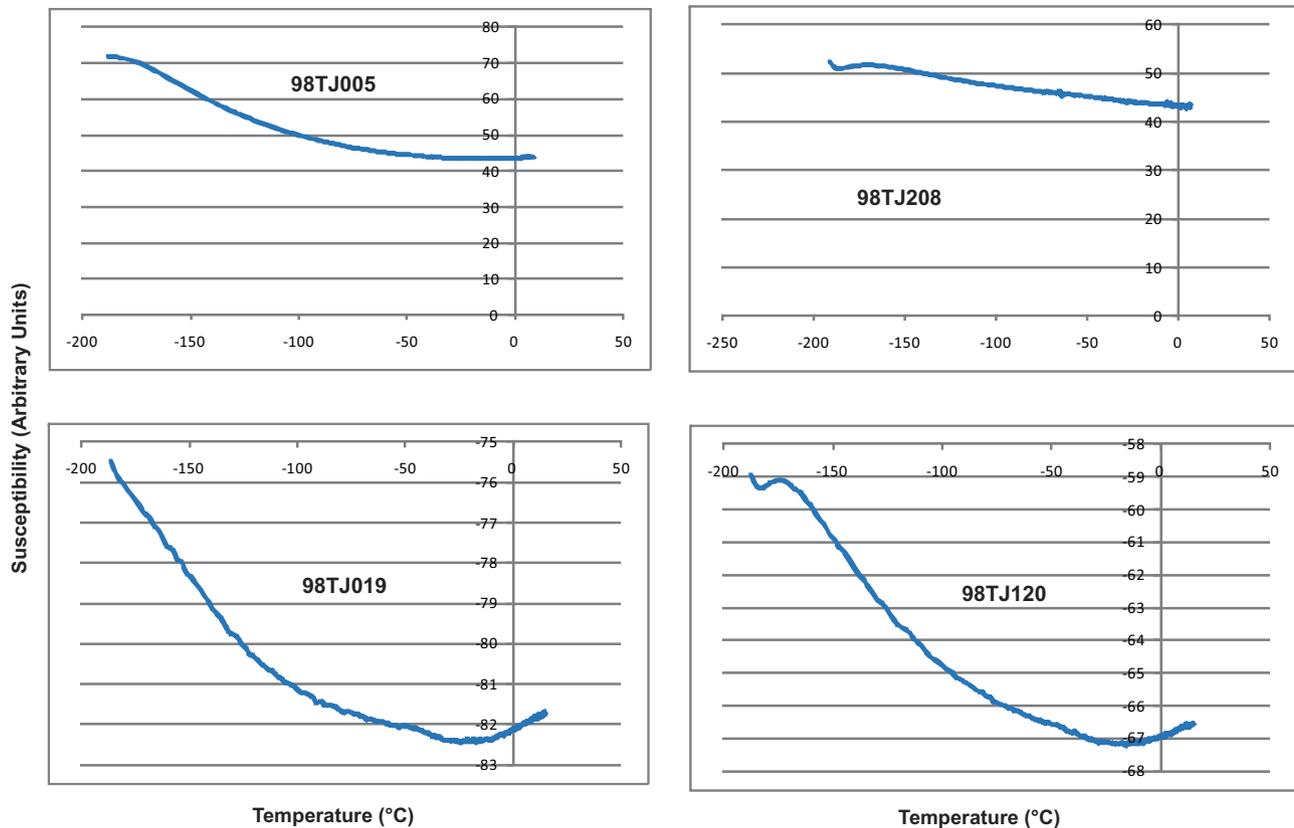


Fig. 5. Susceptibility vs. temperature representative curves recorder from -185°C to room temperature.

to the Model G fit to the Johnson et al. (2008) databases for the last 5 Ma but still in agreement considering the uncertainties. Similar values of the geomagnetic dispersions are observed when these parameters are calculated separately for the time intervals corresponding to the Brunhes chron ($N = 17$, $S_F = 9.2^{\circ 12.0^{\circ}}_{7.5^{\circ}}$) and the older chrons ($N = 15$, $S_F = 7.3^{\circ 9.8^{\circ}}_{5.9^{\circ}}$).

5.3. Polarities-ages correlations

As previously mentioned, $^{40}\text{Ar}/^{39}\text{Ar}$ or ^{14}C age data were available for all studied sites (Guilbaud et al., 2011, 2012) (Table 1). Correlations of observed polarities with these geochronological datings are shown in Fig. 10.

All except one of the 19 youngest sites belong to the Tacámbaro locality. They yield ages between present and 0.73 Ma, so that they can be correlated to the Brunhes chron. As expected, in all 17 cases in which a ChRM direction could be determined, it was observed to display a normal-polarity (from Tac-04 to Tac-15 in Table 1).

Sites JO-07, JO-15, and JO-17 (Jorullo) as well as sites Tac-11 and Tac-12 (Tacámbaro) yield reverse-polarity directions, which is in agreement with their radiometric ages which place these sites in the reverse-polarity Matuyama chron.

Normal-polarity site Tac-13 yields a 0.96 ± 0.07 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age, placing its ChRM unambiguously into the normal-polarity Jaramillo C1r.1n subchron (0.990–1.070 Ma, Cande and Kent, 1995), positioned inside the Matuyama chron. In site JO-17, however, a very similar, yet better-constrained 1.03 ± 0.02 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age and a reverse-polarity ChRM direction are obtained, ascribing this result to the reverse-polarity Intra-Jaramillo excursion (e.g., Laj and Channell, 2007). This excursion has been detected in the Jingbian loess sequence in Northern China (Guo et al., 2002), in marine cores from New Zealand and at ODP sites 983 and 984,

where it was correlated to marine isotope stage (MIS) 30 at 1.048 Ma (Channell and Kleiven, 2000; Channell et al., 2002). The results from site JO-17 supply for the first time evidence of the Intra-Jaramillo excursion in volcanic rocks. It should be noted that both Tac-13 and JO-17 paleomagnetic samples were taken very close (<100 m) to the Ar–Ar dated samples, excluding any possible error related to sampling.

Sites Tac-26, Tac-21, JO-19, JO-16 and JO-13 all have age ranges that belong to the normal-polarity subchron C2An.1n, which lasted from 2.581 to 3.040 Ma (Cande and Kent, 1995; Gradstein et al., 2004) and is positioned in the Gauss polarity chron, and they provide, as expected, normal-polarity directions.

Site Tac-19 yields a 4.18 ± 0.08 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age, which would allow to correlate (following Cande and Kent, 1995 and Gradstein et al., 2004) its ChRM direction either to the reverse-polarity chron C2Ar (3.580–4.180 Ma) or the normal-polarity subchron C3n.1n (4.180–4.290 Ma). Its reverse-polarity ChRM remanence direction unequivocally assigns this result to the former interval, hence reducing its age uncertainty.

Both sampled Oligocene dykes (sites JO-14 and JO-18) were found to carry a normal polarity magnetization. In JO-14 a 30.3 ± 0.1 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age was obtained, which could correspond to reverse-polarity chron C11r (30.217–30.627 Ma, e.g., Gradstein et al., 2004), but is not incompatible with the normal subchron C11n.2n (29.853–30.217 Ma). Due to its normal polarity magnetization site JO-14 has to be correlated with the latter one. Site JO-18, on the other hand, yielded a 32.7 ± 0.2 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age, which corresponds to reverse-polarity chron C12r. Paleomagnetic determinations on both dykes were characterized by good-quality data that do not allow any doubts about their polarity. Again this contradictory result has to be ascribed to the available $^{40}\text{Ar}/^{39}\text{Ar}$ age or to a too small uncertainty in the age determination. Another

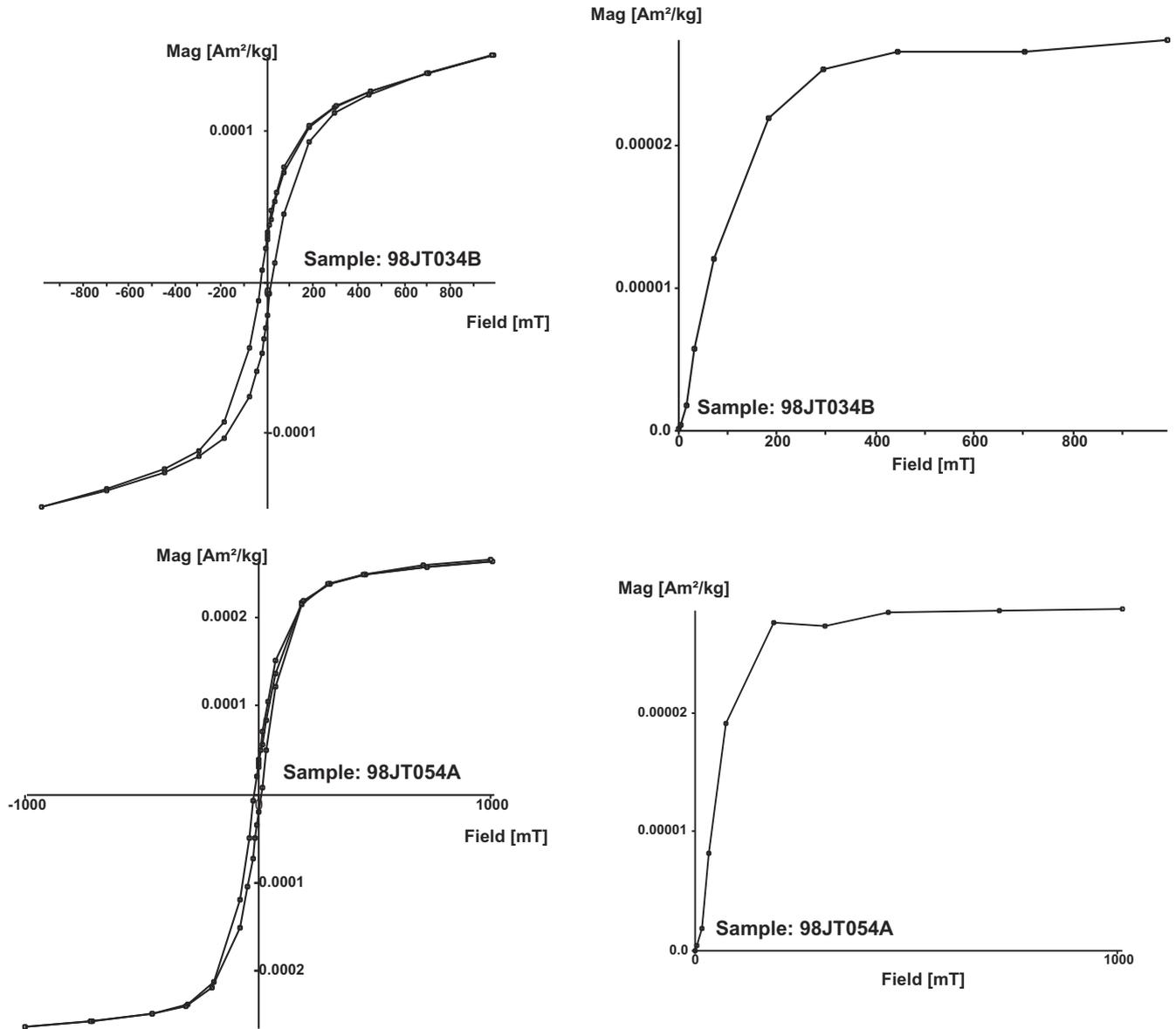


Fig. 6. Typical examples of hysteresis loops (uncorrected) and associated isothermal remanence acquisition curves.

possible explanation would be however, the occurrence of a yet non-detected normal-polarity event at 32.7 ± 0.2 Ma.

Although the general agreement found above between polarities/assigned ages of the studied sites and the geomagnetic polarity time scale, some mismatches have also been found, which are discussed below in terms of the potential overlapping of the corresponding uncertainty limits of confidence.

Samples corresponding to sites Tac-08 and Tac-07 both yielded rather similar $^{40}\text{Ar}/^{39}\text{Ar}$ ages (1.64 ± 0.04 Ma for Tac-08; 1.70 ± 0.02 Ma for Tac-07). Again, Tac-08 site is located very close to the radiometrically dated sample, while Tac-07 (lava flow) is situated some 2 km far from the dated sample (volcanic bomb), but both materials (the bomb and the lava) belong to the same monogenetic volcano (Cerro Petembo). Besides, the age spectra obtained by the isotopic measurements have well-defined plateaus, ensuring reliable results (Fig. 6 and Table DR1 in Guilbaud et al., 2011). Interestingly, the $^{40}\text{Ar}/^{39}\text{Ar}$ ages place both sites in the Matuyama reversed polarity chron, but in these sites normal polarity directions were obtained. If the uncertainty of the $^{40}\text{Ar}/^{39}\text{Ar}$ determination of site Tac-08 (± 0.04 Ma) is taken into account, as well as

the uncertainty in the order of 10 kyr of the limits of the subchrons, the $^{40}\text{Ar}/^{39}\text{Ar}$ age and positive polarity of site Tac-08 may be compatible with a correlation of this site with the Gilsa excursion, which lasted from 1.567 to 1.575 Ma (e.g., Laj and Channell, 2007). Normal polarity site Tac-07, however, cannot be correlated with any normal-polarity interval in its Ar–Ar age-range, as no excursions have been detected so far between the Gilsa excursion and the Olduvai chron C2n (1.778–1.945 Ma, Lourens et al., 1996). Because no particular problems related to paleomagnetic measurements and interpretation of the data at this site were observed, the incompatibility of paleomagnetic and radioisotopic results remains to be elucidated, even though the error in the Ar–Ar age may be slightly higher than estimated and the site may be correlated to the nearest normal polarity interval, the Olduvai chron (C2n).

Site Tac-20, on the other hand, yields a 1.81 ± 0.03 Ma $^{40}\text{Ar}/^{39}\text{Ar}$ age and a reverse-polarity magnetization, providing again contradictory results, as the obtained age would place site Tac-20 in the normal-polarity Olduvai chron. If, however, following similar arguments as for site Tac-08, the uncertainties of the $^{40}\text{Ar}/^{39}\text{Ar}$ determination and the limits of the subchron (ca. 10 kyr) are taken

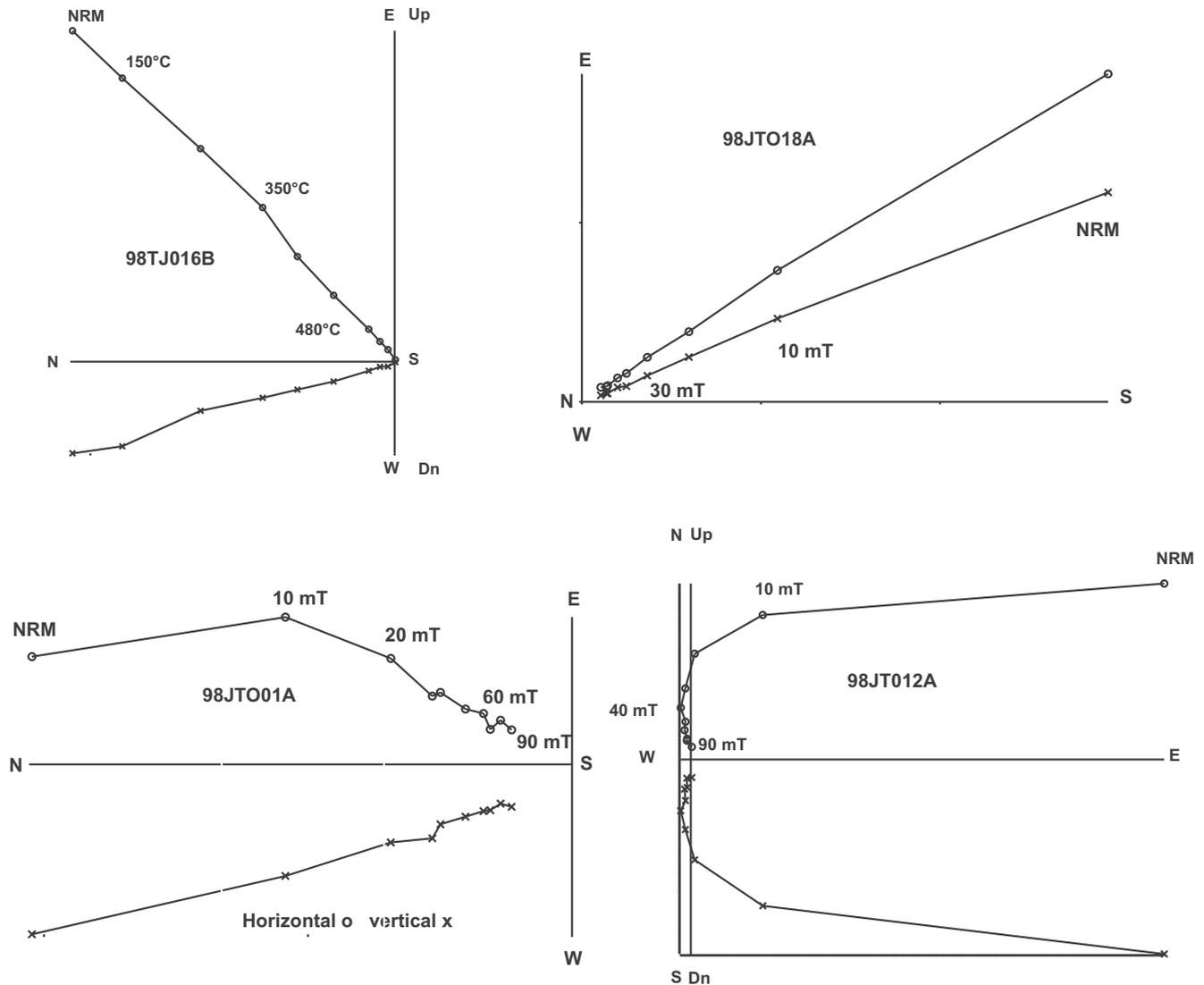


Fig. 7. Orthogonal vector plots of stepwise thermal or alternating field demagnetization of representative samples. The numbers refer either to the temperatures in °C or to peak alternating fields in mT. o-projections into the horizontal plane, x-projections into the vertical plane.

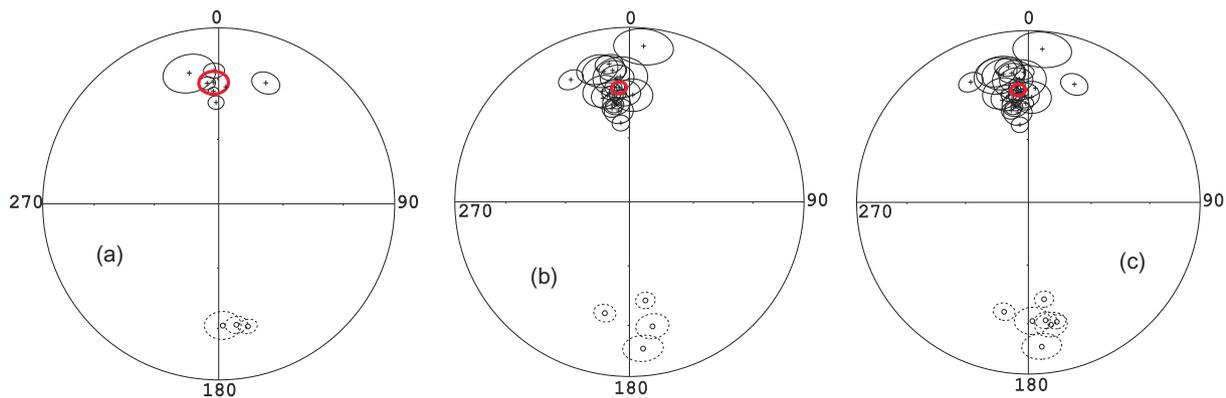


Fig. 8. Equal-area projections of the flow-mean characteristic paleodirections: (a) Jorullo (b) Tacámbaro and (c) all sites.

into account, the age of site Tac-20 might be correlated with the subchron C1r.3r (in the Matuyama chron), which lasted from 1.185 to 1.778 Ma (e.g., [Gradstein et al., 2004](#)).

Although the geomagnetic polarity time scale is now carefully calibrated with reliable Ar–Ar datings at least for the last 1 Ma, it

may still contain minor uncertainties for some of the polarity boundaries within the Bruhnes and Matuyama chrons. A strong argument to support our preferred interpretation comes from a recently published paper by [Michalk et al. \(2013\)](#) where two other lava flows from the Trans-Mexican Volcanic Belt dated at 0.95

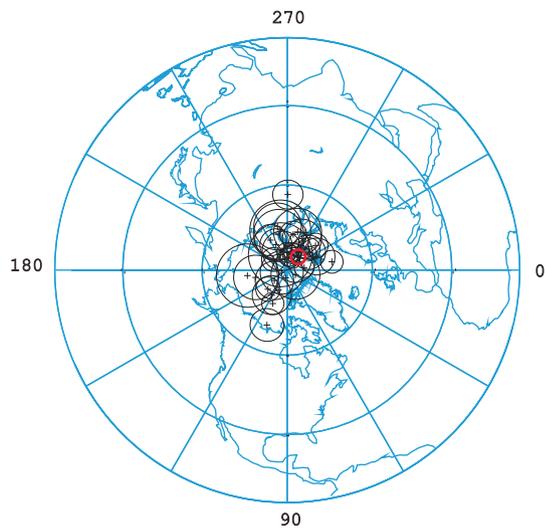


Fig. 9. Site-mean virtual geomagnetic pole positions for the Jorullo and Tacámbaro areas.

and 1.63 Ma respectively show normal polarity magnetizations interpreted as geomagnetic excursions within the Matuyama chron. This reinforces our interpretation of lava flows dated as 0.96 and 1.64 Ma to correspond the Santa Rosa and Gilsa excursions, respectively.

5.4. Summary and conclusions

This study provides new rock magnetic and paleomagnetic data obtained from recently dated products from single short-lived eruptions in the MGVF and their plutonic basement.

Identical mean directions have been obtained from younger ($N = 17$, Brunhes chron) and older ($N = 15$, mostly Gauss-Matuyama chrons) lavas datasets. Normal and reversed mean directions showed to be antipodal for all samples dated at <4 Ma ($N = 32$). The paleomagnetic pole obtained for Pliocene–Pleistocene times ($N = 32$, PLAT = 83.4° , PLON = 2.4° , A95 = 2.7°) suggest no major vertical-axis rotations (neither tilting) in the region. The geomagnetic dispersion calculated from these VGPs is in agreement with available paleosecular variation models, although showing slightly lower values, and contributes to the PSV from Lavas database for the key latitudinal band of 20° .

A straightforward correlation was obtained between the observed magnetic polarity of the studied sites, their corresponding radiometric age and the Cenozoic geomagnetic polarity time scale (GPTS). This highlights the potentiality of the studied lavas for their contribution to the GPTS, especially to detect short-lived geomagnetic features, providing here the first evidence of the Intra-Jaramillo geomagnetic excursion in volcanic rocks. This ‘short-lived’ excursion presumed here within the worldwide observed Jaramillo chron should be confirmed from the study based on stratigraphically superimposed (consecutive lava flows) sites.

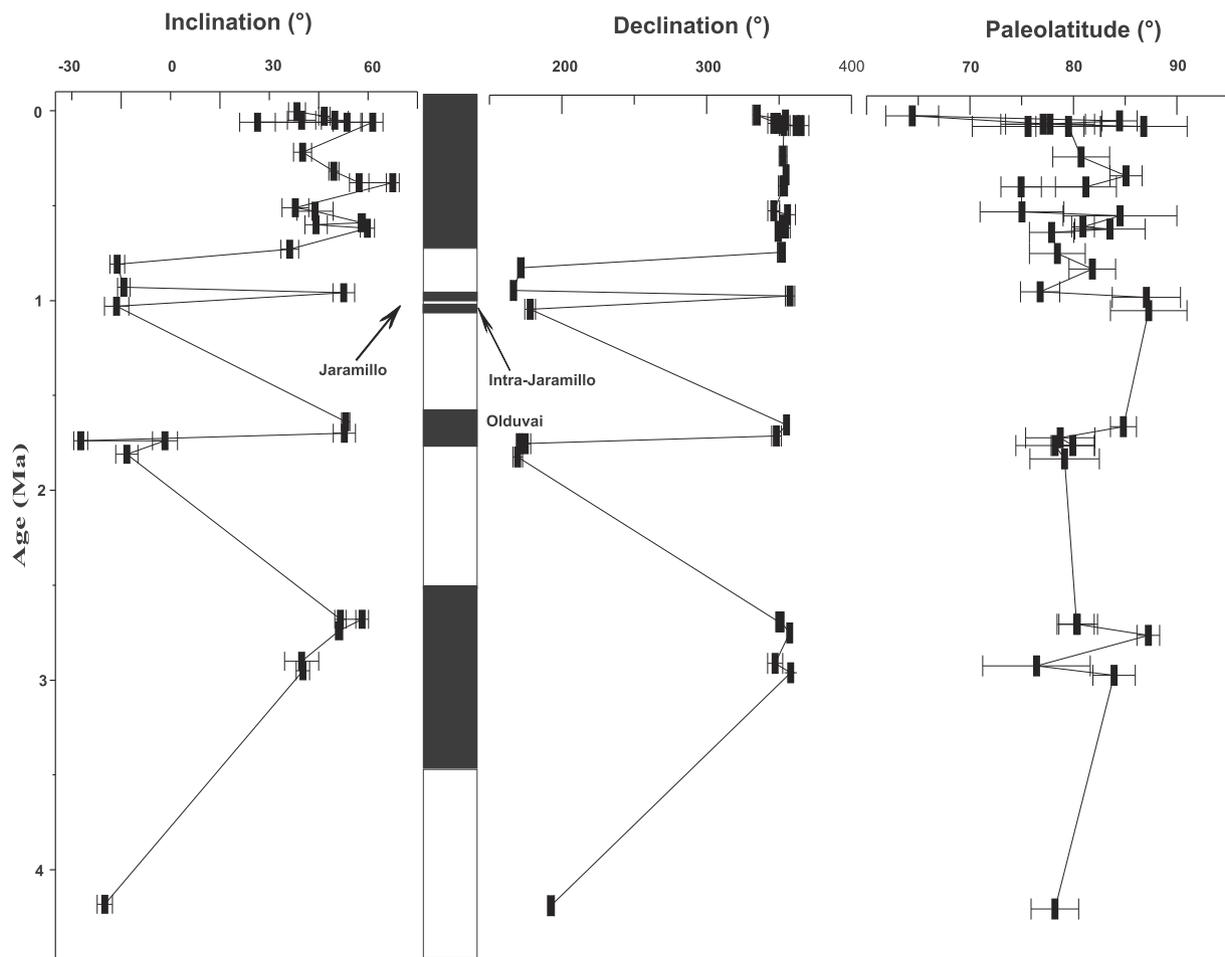


Fig. 10. Flow mean magnetic inclination, declination and paleolatitude of virtual geomagnetic poles vs. age in Ma.

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