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FAST TRACK PAPER

Evolution of the geomagnetic field prior to the Matuyama–Brunhes transition: radiometric dating of a 820 ka excursion at La Palma

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SUMMARY

We present Cassignol technique K–Ar dating of lava flows from La Palma (Canary Islands, Spain) that bracket the Matuyama–Brunhes transition. An age of 821 ± 13 ka obtained for a transitionally magnetized flow (LS118) provides the first volcanic evidence for a geomagnetic excursion occurring about 40 kyr prior to the transition. This interval has been successfully correlated with intensity minima present in high-resolution deep-sea records before the Matuyama–Brunhes transition. This study, along with the growing number of well-dated excursions reported for the Brunhes and Matuyama Chrons, shows that the occurrence of excursions is a common feature of the evolution of the geomagnetic field during stable polarity intervals. However, the presence of two successive excursional states within 40 kyr prior to the actual reversal, conjugated with moderate averaged palaeointensity in this interval as deduced from deep-sea records, could suggest that favorable conditions for the reversal to occur existed since about 820 ka. The present study highlights the importance of detailed chronological constraints for our understanding of the transition of the geomagnetic field from a stable polarity to a reversal state.

Key words: geochronology, geomagnetic reversals, palaeomagnetism, quaternary.

INTRODUCTION

The polarity timescale is now well constrained for the last few million years and efforts are now being pursued toward a better characterization of the excursion timescale. Excursions of the geomagnetic field are relatively common features of its evolution (e.g. Champion *et al.* 1988; Langereis *et al.* 1997) and are clearly associated with field intensity minima (e.g. Valet & Meynadier 1993). In fast magnetic acquisition media, such as volcanic flows, they can display a local signature, which is highly site dependent (e.g. Carlut *et al.* 1999; Quidelleur *et al.* 1999). An excursion can be characterized as an interval of time during which the dipole field was low, but not necessarily associated with transitional directions at all times during this interval, depending on the geometry of the fast varying non-dipole components (e.g. Courtillot *et al.* 1992; Merrill & McFadden 1994).

The purpose of the present study is to precisely date an excursion identified in a volcanic sequence from La Palma (Quidelleur & Valet 1996). The oldest subaerial products of La Palma are found in the northern part of the Island (Abdel-Monem *et al.* 1972). Recent dating has constrained the earlier volcanism between 1.72 to 0.44 Ma (Guillou *et al.* 2001), with a strong activity around 800 ka, thereby providing several independent records of the MBT (Quidelleur & Valet 1996; Valet *et al.* 1999). The present study focuses on the Los Sauces (LS) section where detailed geomagnetic features have been recorded prior to the Matuyama–Brunhes transition (MBT) (Quidelleur & Valet 1996).

PALAEOMAGNETIC RECORD

A total of twenty flows from the LS section has been studied to provide a palaeomagnetic record of the MBT (see Quidelleur & Valet 1996) for a full data presentation). Table 1 and Fig. 1 focus on the twelve flows in direct stratigraphic contact bracketing the transition. The uppermost four flows display fully normal polarity directions with palaeointensity values around 30 μT, of the order of the present day field strength for this latitude. In the absence of absolute dating, the low palaeointensity value (7.7 μT) and the transitional direction recorded for flow LS118, as well as the steep inclinations and low field values for the four flows preceding the transition, were associated with the reversal process (Quidelleur & Valet 1996).

Table 1. Palaeomagnetic data (from: Quidelleur & Valet 1996). N: number of samples used in the analysis/total number of samples treated; Dec.: declination; Inc. inclination; α_{95}, 95 per cent confidence cone; VGP (N): Virtual Geomagnetic Pole latitude; VGP (E): Virtual Geomagnetic Pole longitude; NRM: average Natural Remanent Magnetization (in A m^{-1}) for non-overprinted samples; n: number of palaeointensity determinations; $F_a \pm \sigma F_a$: mean palaeointensity value and uncertainty (in μT).

Flow	N	Dec.	Inc.	α_{95}	VGP (N)	VGP (E)	NRM (A m^{-1})	n	$F_a \pm \sigma F_a$
LS108	4/4	4.4	58.6	5.0	79	0	–	–	–
LS109	5/5	5.9	61.3	6.9	76	0	–	1	28.4 ± 5.1
LS110	8/9	4.7	51.1	7.2	85	35	7.0	2	28.3 ± 1.0
LS111	5/6	2.8	40.9	4.8	84	137	8.0	1	29.5 ± 3.0
LS112	2/10	143.6	−56.4	–	–59	97	1.0	1	5.5 ± 0.4
LS113/114	11/11	152.0	−70.8	6.2	−57	133	0.7	4	5.4 ± 0.9
LS115	7/8	136.1	−74.5	8.4	−47	133	1.0	–	–
LS116	5/5	182.1	−74.6	6.3	−58	164	1.3	–	–
LS117	6/8	172.6	−43.5	10.5	−83	47	4.0	–	–
LS118	6/7	206.3	2.2	3.6	−51	−62	0.9	2	7.7 ± 1.0
LS119	5/5	192.0	−32.0	5.2	−74	−64	5.0	1	33.5 ± 4.0
LS120	5/5	189.9	−33.1	8.1	−76	−60	4.0	2	25.4 ± 4.7

CHRONOLOGICAL CONSTRAINTS

The K–Ar Cassignol technique (Cassignol & Gillot 1982) has been used to offer a chronological framework of the magnetic changes recorded in the LS section. This technique is specially suitable for low radiogenic and/or recent flows (Gillot & Cornette 1986; Quidelleur *et al.* 2001). In order to make the contribution of magmatic argon and weathered phases negligible, we have removed mafic phenocrysts and analyzed only the remaining groundmass obtained within a narrow density range. The mass spectrometer signal has been calibrated using the GL-O inter-laboratory standard with the recommended value (Odin 1982). Within less than a percent, it is compatible with recent determination of 523.1 and 28.02 Ma for MMhb-1 and FCT-san, respectively (Renne *et al.* 1998), and HD-B1 at 24.2 Ma (pers. comm.). Decay constants of Steiger & Jäger (1977) have been used. All uncertainties are quoted at the 1 sigma level.

Table 2 shows the ages obtained for the four dated flows from the LS section. For a typical sample from this study, the total uncertainty amounts to 12 kyr, i.e. 1.5 per cent of the measured age. It is comparable with the total uncertainty of good analytical $^{40}Ar/^{39}Ar$ ages, when error of 1–2 per cent on the age of the standard used as flux monitor is considered (e.g. Renne *et al.* 1998).

Flow LS119, which displays a full Reverse polarity (Fig. 1) is dated at 825 ± 14 ka. Only separated by scoria, the overlying flow LS118 has an age of 821 ± 13 ka. Two units above, LS116 is 797 ± 12 ka old. Finally, the first Normal polarity flow of this section is dated at 698 ± 10 ka, making the recorded palaeofield in LS111 clearly decoupled from the reversal process (Fig. 1).

DISCUSSION

Ages obtained here (Table 2), together with palaeomagnetic data of Quidelleur & Valet (1996), seem to support the hypothesis that a geomagnetic excursion has been recorded here prior to the MBT.

Duplicated Thellier & Thellier (1959) experiments, performed with back-checks, yielded reproducible low intensity values (see details in Quidelleur & Valet 1996) which strongly argue for an abnormal state of the geomagnetic field during eruptions of flow LS118. With a shallow inclination of 2° and a declination of 206°, associated with a palaeointensity lower than 8 μT (Table 1), there is no doubt that a geomagnetic excursion of the field has been recorded by this flow. An age of 821 ± 13 ka (Table 2) has been obtained for this geomagnetic excursion recorded by flow LS118 (herein referred as LP2; LP1 being the 600 ka old excursion recorded in a nearby section Quidelleur *et al.* 1999). Several lines of evidence show that it is distinct from the low palaeointensity features recorded in the overlying flows (Table 1 and Fig. 1). The natural remanent magnetization (NRM) intensity of flow LS117 is much stronger than those of flows LS118 and LS116. The VGP latitude of flow LS117 lies around 85°S, while those of bracketing flows remain below 60°S (Fig. 1).

The four units preceding the MBT (from LS116 to LS112; Fig. 1) display similar palaeomagnetic characteristics (steep inclination associated with low NRM value, and, when available, palaeointensity lower than 5 μT Quidelleur & Valet 1996), that can either be associated with the reversal itself, or either be interpreted as clues for another excursion preceding the transition. However, the K–Ar age of 797 ± 12 ka obtained for flow LS116 (Table 1) does not unambiguously argues for the presence of a second excursion recorded in the LS section. Moreover, this age is fully compatible with the recent MBT age of 789 ± 8 ka (pers. comm.).

Prior to this study, no clear evidence has been reported for a geomagnetic excursion around 820 ka. Fig. 2 shows, within the 0.75–0.95 Ma time interval, the evolution of the relative palaeointensity, (presumably reflecting variations in the dipole field strength), at several sites for which a good temporal control is available (ODP 851: Valet & Meynadier 1993; MD940: Meynadier *et al.* 1994; ODP 1021: Guyodo *et al.* 1999; ODP 983: Channell & Kleiven 2000; LC07: Dinarès-Turell *et al.* 2002). In records MD 940, ODP 851 and ODP 1021, a clear intensity minima is present in the time interval define by the age of 821 ± 13 ka obtained for the LP2 excursion (Table 2). On the other hand, both highs and lows are observed in cores LC07 and ODP 983, which prevents us to associate a clear intensity deep with LP2 in these cores. It should be noted that the same features are present for the Kamikatsura and Santa Rosa excursions, also identified in volcanic lava flows (Singer *et al.* 1999). We can interpret these observations in terms of a short duration of excursions, which exceeds the uncertainty in the absolute age provided by radiogenic dating.

Evidences for the unstable character of the field is provided by the numerous intensity minima, and to a lesser extent inclination excursions, recorded in deep-sea sediments (e.g. Guyodo *et al.* 1999; Lund *et al.* 2001). Unfortunately, directional records in sediments can suffer severe bias (e.g. Quidelleur *et al.* 1995) and one must to

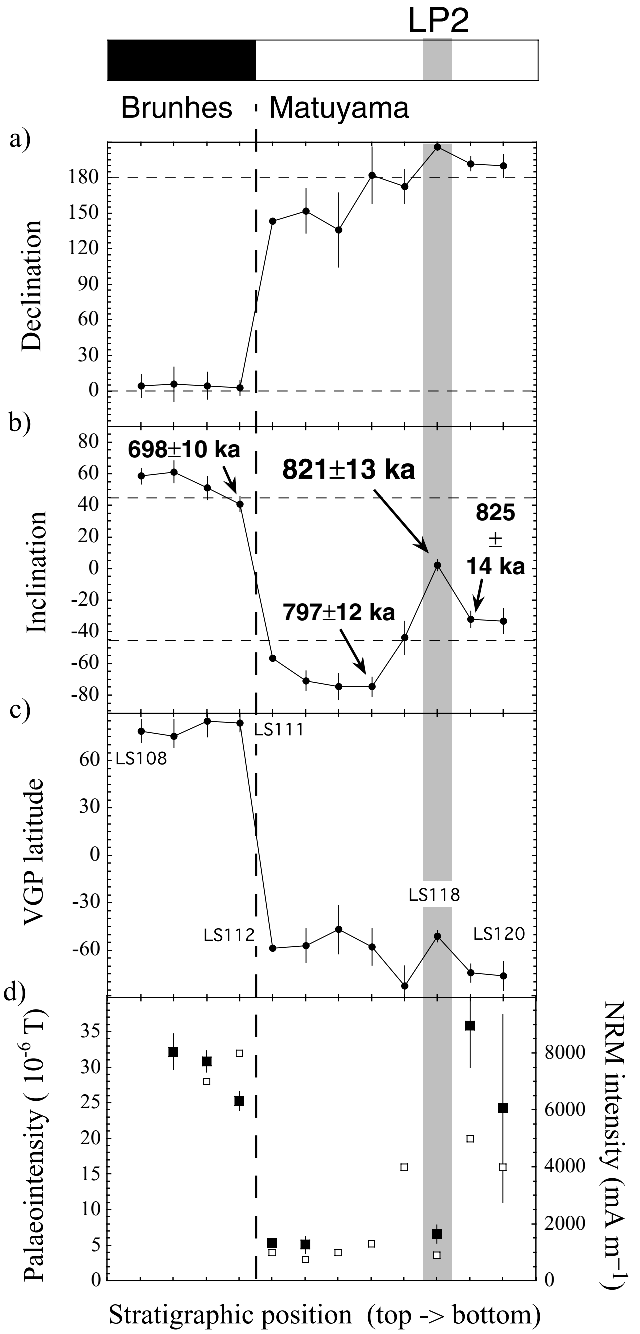

Figure 1. Evolution of the (a) declination, (b) inclination, (c) Virtual Geomagnetic Pole (VGP) latitude, and (d) palaeointensity (solid symbols; in μT) and mean NRM (open symbols; in mA m^{-1}), as a function of stratigraphic position in the LS section (see Quidelleur & Valet 1996 for details). The direction of the axial dipole field at La Palma is shown by dashed lines. Shading highlights the location of the LP2 excursion inferred from these data.

rely on volcanic series for absolute dating and full description of the field vector evolution during these intervals.

Our precisely dated record clearly shows the occurrence of an excursion at 821 ± 13 ka. Together with the precursor event previously identified 15 kyr before the reversal (Hartl & Tauxe 1996), two excursions are now described only a few 10^4 kyr apart, prior to the MB reversal. This could be interpreted as the initiation of a transitional state ending about 40 kyr later, with the actual MBT. The relatively low mean palaeointensity recorded in most deep-sea sediments in this interval (Fig. 2) also suggests that a favorable configuration for the reversal to occur might have persisted since 820 ka. Gubbins (1999) proposed that excursional state corresponds to field reversal in the outer core and not in the inner core whose characteristic time is significantly longer. This could imply a significant difference between duration of excursions and reversals as noted by Dormy *et al.* (2000). Our data show that, if the occurrence of the MBT is linked to the apparition of a mostly reversal state in the inner core, it may be triggered by the two short excursions discovered a few 10^4 kyr before the reversal.

Table 2. K–Ar result. K per cent: K content (in per cent); per cent $^{40}Ar^*$: percent of radiogenic 40 argon; $^{40}Ar^*$: number of atoms of radiogenic 40 argon released (in 10^{11} at g^{-1}); Age (in Ma); Un.: total uncertainty at the 1 σ level (in Ma); Pol.: polarity of the flow, I, intermediate; N, normal; R, reverse. The age uncertainty given here reflects the uncertainties in the K determination by flame spectrometry (1 per cent), in the radiogenic yield (Ar*) detection as derived from historic lavas analyses (0.1 per cent/Ar*), and in the mass spectrometer calibration (1 per cent). See Quidelleur *et al.* (1999) for details.

Flow	K per cent	per cent $^{40}Ar^*$	$^{40}Ar^*$	Age (Ma)	Un. (Ma)	Pol.
LS111	1.38	25.8	10.053	0.698	0.010	N
LS116	1.85	20.7	15.420	0.798	0.012	
		22.7	15.397	0.797	0.012	
			Mean:	0.797	0.012	R
LS118	0.972	12.1	8.3952	0.827	0.014	
		18.9	8.2082	0.808	0.012	
		19.6	8.4374	0.831	0.012	
			Mean:	0.821	0.013	I
LS119	0.753	10.8	6.5728	0.836	0.014	
		9.9	6.3972	0.813	0.014	
			Mean:	0.825	0.014	R

CONCLUSIONS

We have presented the first volcanic evidence for the existence of a geomagnetic excursion about 40 kyr prior to the MBT. It has been dated at 821 ± 13 ka, by K–Ar with the Cassignol technique, from a transitional flow of the LS section at La Palma. This interval has been correlated with intensity minima present in several high-resolution deep-sea records. The numerous occurrences of excursions previously observed throughout the Brunhes and Matuyama Chrons (e.g. Langereis *et al.* 1997; Guyodo *et al.* 1999), in addition with the one identified here, demonstrate that they are common features of the geomagnetic field during stable polarity intervals. It can be proposed that excursions are triggered by decrease of the axial dipole component, and that LP2 recorded here about 40 kyr before the MBT, together with a minimum observed in sediments 15 kyr before the transition (Hartl & Tauxe 1996), could have contributed to the occurrence of the reversal.

Finally, this study emphasizes the importance of accurate dating coupled with palaeomagnetic data of the full vector in order to describe the evolution of the magnetic field from volcanic sequences.

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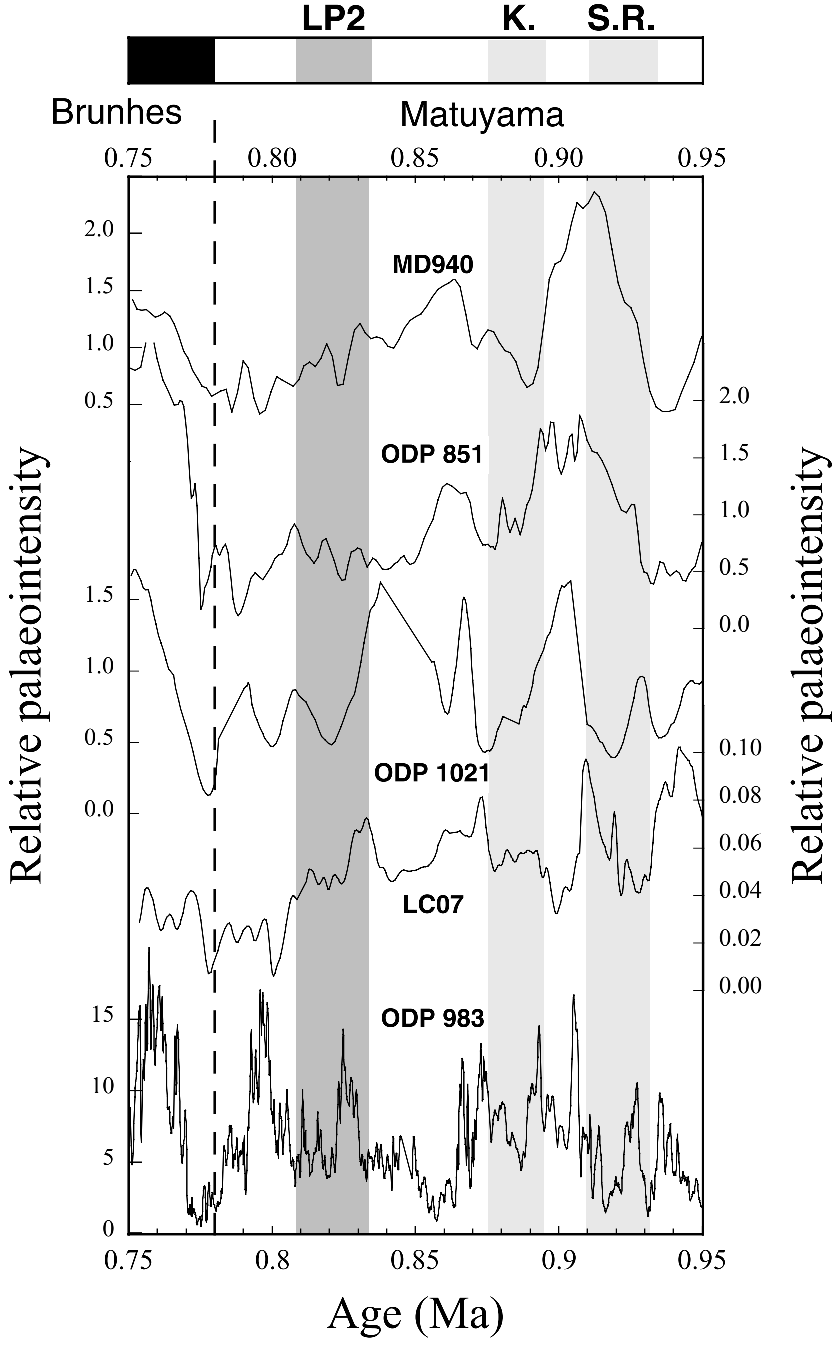

Figure 2. Relative palaeointensity records (here shown for the 0.95–0.75 Ma interval) from sites MD940 (Meynadier *et al.* 1994), ODP 851 (Valet & Meynadier 1993), ODP 1021: (Guyodo *et al.* 1999), LC07 (Dinarès-Turell *et al.* 2002) and ODP 983 (Channell & Kleiven 2000). The position of the LP2 excursion from this study is shown by dark shading. Previously dated excursions from volcanic flows are also shown. The Santa Rosa (S.R.) and Kamikatsura (K.) excursions, dated at 922 ± 12 and 886 ± 3 ka, respectively (Singer *et al.* 1999), are shown by light shading. Note that, in order to take into account a 1 per cent uncertainty in the age standard used by Singer *et al.* (1999), the uncertainty on the latter age has been arbitrarily increase to 9 ka.

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