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Origin and age of the directions recorded during the Laschamp event in the Chaîne des Puys (France)

Guillaume Plenier [a], Jean-Pierre Valet [a,*], Gilles Guérin [b,1], Jean-Claude Lefèvre [c], Maxime LeGoff [a], Brian Carter-Stiglitz [d]

[a] Equipe de Paléomagnétisme, Institut de Physique du Globe de Paris, UMR 7154 CNRS, Université Paris VII, Paris, France
[b] Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS, Gif-sur-Yvette, France
[c] IDES- UMR 8148 CNRS-Université Paris-Sud, Laboratoire de Géochronologie Multi-Techniques, UPS-IPGP, Orsay, France
[d] Institute for Rock Magnetism, University of Minnesota, Minneapolis, MN 55455, USA

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Abstract

Excursions of the geomagnetic field are likely even more frequent than reversals and thus must be seen as a major characteristic of the geodynamo. The Laschamp event discovered in lava flows of Massif central (France) is the youngest and the most studied field excursion. Its geomagnetic origin has been controversial due to the existence of self-reversal processes. Taking advantage of new dated sites, the initial aim of this work was to find additional flows with intermediate or reverse directions but also to investigate the magnetic properties of normal polarity flows surrounding the event. This study combines thermal and alternating field demagnetization of 272 samples from 21 units including 12 new localities and 12 K–Ar datings of main units. No new site with intermediate or reverse polarity was found. Ten sites have a normal polarity and all sites studied at Olby, Louchadière and Royat display intermediate but scattered directions. Magnetic mineralogy is characterized by primary titanomagnetite, variable amounts of titanomaghemite and almost pure magnetite. We confirmed that reverse polarity flows are affected by self-reversals but we found that this is also the case for normal flows. A direct consequence is that self-reversals cannot be taken as responsible for the reverse directions but they likely contribute to generate dispersion. However the overall coherency of the directions indicates that this process was limited and despite complex magnetization, the geomagnetic origin of the Laschamp in the Chaîne des Puys is not questioned. All volcanic pole positions (VGPs) published so far show significant scatter but they remain consistent with each other. Interestingly, they do not coincide with the longitudinal loops seen in the sedimentary records and are compatible with a dominant non-dipolar field geometry. New K–Ar datings provide a coherent chronology of the successive polarities. The 37 ka old reverse directions of the Olby flow are chronologically consistent with the 41.9 kyr old normal polarity flows preceding the event. The Royat flow is only marginally intermediate and indicates that the end of the event was not younger than 33.3 ka in the Chaîne des Puys.

Keywords: geomagnetic field; reversals; excursions; short events; magnetostratigraphy; K-Ar dating

1. Introduction

In 1967 Bonhommet and Babkine (1967) reported on volcanic lava flows and a scoria cone from

* Corresponding author.
E-mail address: valet@ipgp.jussieu.fr (J.-P. Valet).
[1] Present address: Département des Sciences de la Terre, Université de Paris-Sud Orsay, Orsay, France.

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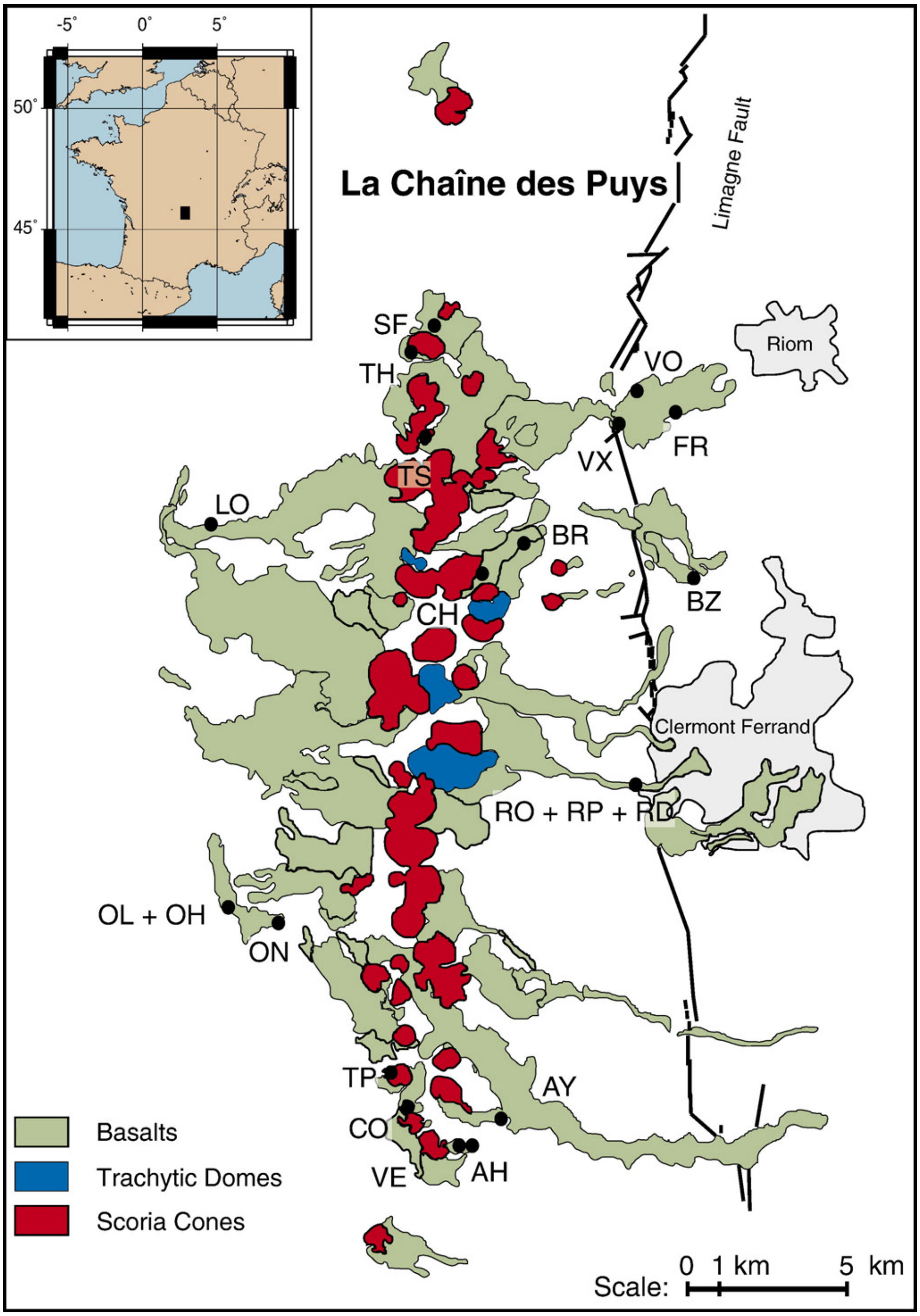

Fig. 1. Simplified geological map of la Chaîne des Puys (France) and location of the sampled sites. From North to South: SF, Suc des Filles; TH, Puy de Thiolet; VO, Volvic Riaumes; FR, Volvic le Fraisse; VX, Volvic LEP; TS, Puy des Trois Sols; LO, Louchadière-Fougères; BR, Bois Rigaude; BZ, Blanzat; CH, Puy de Chaumont; RD, Royat right bank, RO, Royat left bank; RP, Royat lower left bank; OL, historical Olby outcrop; OH, Olby top; ON, Olby-Pont des Eaux; TP, Puy de la Taupe; CO, Puy de Combegrasse; AY, Sauteyras; VE, Veyreras; AH, Veyreras High.

Laschamp and Olby in the Chaîne des Puys (France) which were almost completely reversely magnetized. Bonhommet and Zähringer (1969) rapidly discovered other flows from the same area with directions significantly away from the axial dipole. The possibility of self-reversal mechanisms being discarded in lava flows dominated by single domain magnetite (Whitney et al., 1971), they proposed that the field was almost reversed during this period which they named after the Laschamp village. However, the hypothesis that these directions could actually be linked to partial or complete remagnetization was not completely ruled out based on complex rock magnetic properties. This scenario was re-investigated by Heller (1980) and by Heller and Petersen (1982a,b) who noticed that many samples from Olby and Laschamp (to a lesser extent) underwent partial or complete self-reversals. Recent studies performed on samples from Olby (Krása et al., 2005), although confirming the occurrence of self-reversals, indicate that the characteristic high-temperature direction remains unaffected and most probably reflect the original magnetization. According to these last results and despite evidence for self-reversal mechanisms, the Olby and Laschamp lava flows would thus provide suitable spot readings of the field.

Two important parameters are critical to constrain further the geomagnetic origin of the Laschamp event. Paleointensity determinations are essential to estimate the strength of the dipole during this period (but they evidently depend on the origin of the magnetization), while accurate dating is needed to clarify the age and duration of the event. Roperch et al. (1988), Chauvin et al. (1989) and Leduc et al. (2006) performed paleointensity experiments and found field strength reduced to less than 1/6 of present field intensity. Composite records of relative paleointensity from sediments (Guyodo and Valet, 1996, 1999; Laj et al., 2004, 2006) and the global volcanic database (Perrin et al., 1998) for absolute paleointensity confirm that this period was indeed characterized by very low dipole field strength, thereby sustaining the geomagnetic hypothesis for the Laschamp record. Many attempts using different techniques converge to suggest a very short duration for the phenomenon, but absence of stratigraphy and dating uncertainties restrain any accurate estimate. The limits of the event are neither defined with good precision as there is no dated lava flows with normal polarity. The most recent and detailed study (Guillou et al., 2004) indicates a K–Ar age of 40.4±2.0 ka for the reverse directions recorded by the Laschamp flow, consistent with the period of low intensity in sediments.

Since the initial measurements conducted by Bonhommet and Babkine (1967), new outcrops have been dug out (roads, building constructions...) and several

Table 1
Paleomagnetic results

Site	Slat	Slong	*K–T* type	VTM	*n*/*N*	J_m (*n*)/J_m (*N*)	Inc	Dec	a95	k	Plat	Plong
AH	45.66	2.97	2-II	0/1	14/15	8.3/8.1	60.0	12.6	2.3	299.5	79.7	116
AY	45.67	2.99	8-I	1/1	5/8	6.9/6.7	60.0	357.4	10.0	59.7	84.9	205.5
CH	45.82	2.98	9-I, 1-II	0/2	7/11	4.3/4.4	43.4	6.5	6.1	98.3	68.8	166.5
CO	45.67	2.94	2-II	0/2	5/10	7.8/11.3	56.4	343.7	6.2	153.2	75	243.1
FR	45.87	3.06	4-I, 4-II	2/2	8/8	9.5	67.3	358.7	2.5	482.6	85.7	351.9
TP	45.68	2.94	3-II	1/2	8/8	12.1	47.6	4.0	4.7	139.4	72.7	171
TS	45.86	2.96	2-I	0/1	4/4	1.2	57.1	344.1	8.5	118.5	75.6	243.9
VE	45.66	2.96	2-I	1/1	4/4	8.6	49.6	350.6	8.6	116.3	73.1	211.9
VO	45.88	3.05	2-I	1/1	11/11	10.1	64.3	6.6	5.1	80.4	85.4	88
VX	45.88	3.04	2-I, 2-II	1/2	12/22	10.9/19.8	62.6	339.4	6.9	41.1	75.3	273.0
LO	45.84	2.87	2-I	0/2	8/11	3.5/5.1	65.8	123.4	8.9	40	16.1	38.4
OL	45.73	2.87	1-I, 1-II	0/2	8/21	1.3/1.6	−69.0	235.9	8.9	39.4	−53.7	241.4
OH	45.73	2.87	2-I	1/1	4/10	3.6/7.0	−62.4	258.2	11.8	61.6	−36.7	244.8
ON	45.72	2.88	1-I	1/1	5/13	1.7/2.9	−67.2	269.6	7.8	97.6	−33.4	233.3
Olby	45.73	2.87	4-I, 1-II	2/4	17/44	1.8/2.7	−67.6	252.0	5.5	43.7	−43.6	239.5
RD	45.77	3.05	2-I	2/2	10/10	4.0	61.2	298.5	3.1	250.2	46.7	291.5
RO	45.77	3.05	2-I	1/2	13/19	3.4/4.7	67.5	291.5	3.5	138.9	45.6	305.0
RP	45.77	3.05	2-I	1/2	8/9	3.6/3.7	59.5	279.7	4.7	141.0	33.6	298.6
BR	45.83	3.00	2-I, 3-II	1/2	13/27	2.9/6.7	16.3	125.5	52.7	1.6	–	–
BZ	45.83	3.07	3-I, 2-II	2/2	4/24	2.6/14.4	64.0	23.8	6.2	219.9	73.5	84.9
SF	45.90	2.96	1-I, 1-II	0/1	8/9	0.2/0.5	25.7	109.2	8.0	61.3	–	–
TH	45.89	2.95	3-I	0/1	6/18	3.3/18.0	53.4	47.1	8.1	69.3	52.6	94.5

Site, flow name (see Fig. 1); Slat and Slong, site latitude and longitude (WGS84; *K–T* type, magnetic susceptibility versus temperature behaviour (see text); VTM, ratio of thermomagnetic measurements with partial self-reversals; *n*/*N*, number of samples retained/total number of demagnetized samples; $J_m(n)/J_m(N)$, geometric mean of the natural remanent magnetization (A/m) for *n* and *N* samples; Inc and Dec, mean inclination and declination; α 95 and κ, 95% confidence cone and precision parameter of Fisher distribution; Plat and Plong, latitude and longitude of the virtual geomagnetic pole (VGP).

new sites with ages between 30 and 50 ka were detected using thermoluminescence dating (Guérin, 1982). Taking advantage of these determinations, the initial aim of this paper was to find additional intermediate lava flows and to revisit some of the original sites. The second purpose was to investigate further the magnetic characteristics of the flows and the mechanisms associated with self-reversals. Lastly, it is important to establish a more complete chronology in order to constrain further the age and timing of the Laschamp event.

2. Geology and sampling

The Chaîne des Puys is a volcanic field overlying a crystalline horst delimited by the Sioule and Limagne valleys on its western and eastern sides, respectively. About one hundred eruptive centres, mainly scoria cones, and a few maars and domes are spread over 30 km along a North–South alignment parallel to the Limagne major fault. Volcanic activity began around 100 ka and lasted until circa 8 ka (Boivin et al., 2004). Lava flows with composition ranging from basalt to mugearite spread on both sides of the central axis. The locations of the 21 units, including 12 new localities sampled for this study (Fig. 1) are given in Table 1. Eight samples on average were drilled at each site. In several cases, we collected more than 20 oriented cores in order to obtain a good estimate of within site dispersion. Cores were spread over the lower part of the outcrops at least 1 m away from each other. In most flows (9) a few cores could be sun oriented. Magnetic declination never exceeded 13°. No tilt correction was applied as no evidence for tilting was observed. In each location, at least one sample of massive rock (ca 30 cm in diameter) has been collected for K–Ar analysis. Only one of the previously studied outcrops at Louchadière (LO) was still accessible. Its quality appeared to be adequate for paleomagnetic studies but inappropriate for K–Ar dating.

3. Rock magnetic characteristics

Thermomagnetic experiments of low-field susceptibility (K) were performed between room temperature and 600 °C (in argon and air atmospheres) using a KLY3 susceptibility meter (AGICO) equipped with a furnace. We analyzed at least two samples per flow and all samples from three sites to determine the variability of the signal. We separate the 80 thermomagnetic curves into 2 distinct categories. The first group (Fig. 2a,b,c) represents about 70% of the diagrams and is characterized by a more complex behaviour upon heating than during cooling due to mineralogical transformations starting at temperatures on the order of 300 °C, as evidenced by some stepwise experiments. The heating curves display at least two distinct phases. A low temperature phase between room temperature and 200 °C depending on samples is indicated by a large drop of K (sometimes by more than 60%). A second loss of signal is observed in the medium-temperature range with a Curie temperature varying between 190 °C and 540 °C. In some cases there is also a third inflexion at 560±15 °C. The high temperature segments of the heating and cooling curves are not reversible but their low-temperature behaviour is very similar. In all cases, there is a rapid increase below 560±15 °C during cooling. The medium temperature phase disappeared after heating and is thus unstable. Almost fully reversible heating and cooling patterns (Fig. 2d) characterize the second category of thermomagnetic curves with a unique drop at 540±25 °C although some specimens still display a signal at 620 °C.

The reversible pattern and Curie temperatures of the low temperature phase suggest the presence of titanomagnetite with various titanium contents ($0.6<x<0.8$). Instability of the intermediate phase probably reflects inversion of titanomaghemite (Özdemir, 1987), resulting from low-temperature (<350 °C) oxidation (maghemitization) of primary low Curie temperature titanomagnetite. In accordance, the high temperature phase, very close to magnetite in composition and always observed during cooling, would represent the product of this inversion ($0.5<z<0.8$). Lastly, hematite (or cation-deficient magnetite) cannot be excluded based on some Curie temperatures higher than 580 °C. These interpretations are consistent with previous rock magnetic experiments and observations of thin section (Heller and Petersen, 1982a; Roperch et al., 1988; Krása et al., 2005). We also noticed a large variability in thermomagnetic behaviour of the samples from the same unit. The different types of thermomagnetic behaviour for each flow are given in Table 1.

Acquisition of isothermal remanent magnetization (IRM) was conducted on 16 samples from 9 units using the electromagnet of the St Maur laboratory (IPGP). Saturation was attained between 80 and 150 mT (Fig. 2e and f), consistent with magnetite and titanomagnetite. In a few cases higher coercivities (Fig. 2g) may be due to hematite. Six specimens were imparted a low-temperature SIRM at 10 K and its evolution was monitored between 10 and 300 K using the Quantum Design (MPMS2) SQUID magnetometer of the Institute for Rock Magnetism. The curves shown in Fig. 2h are typical of titanomagnetite with a

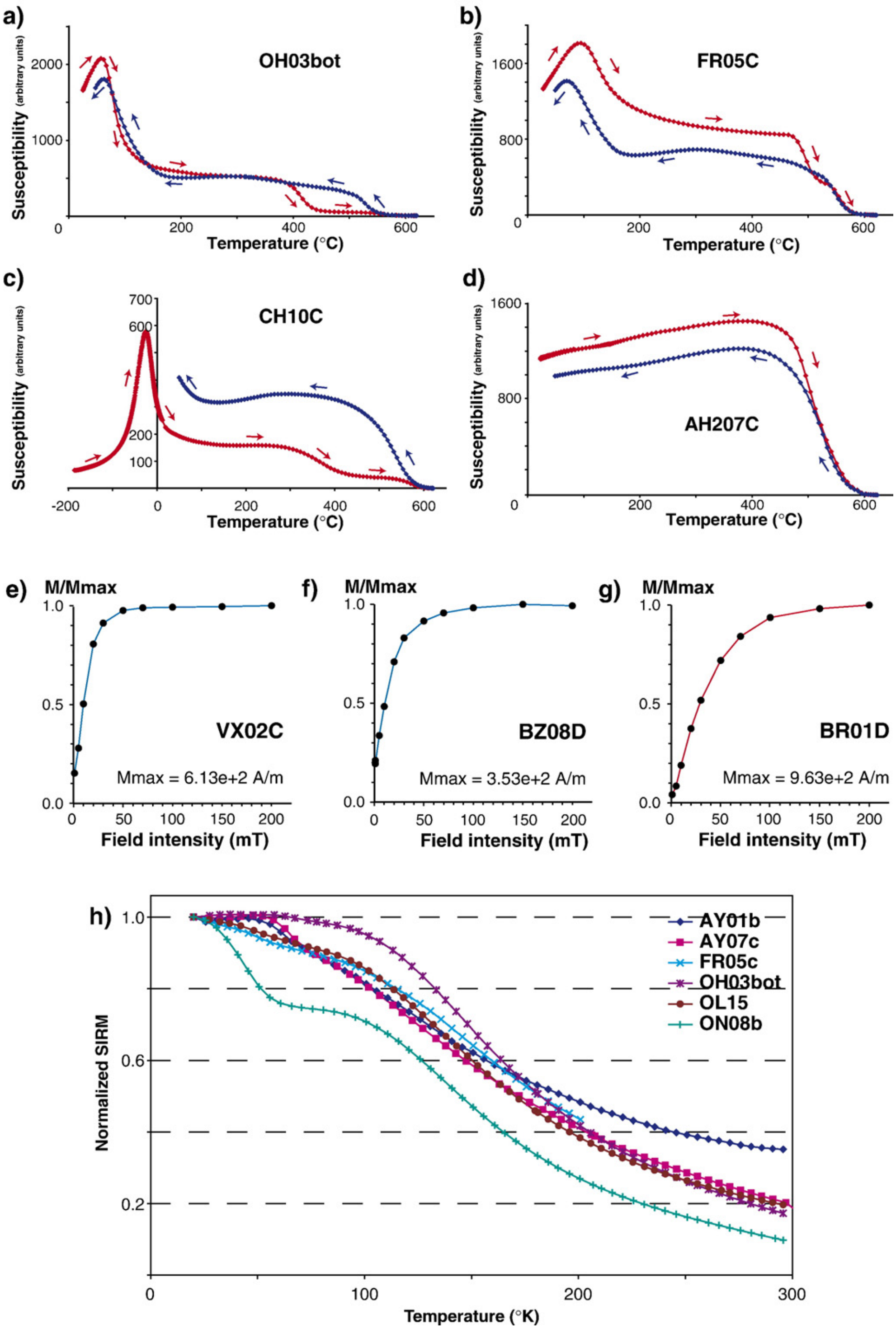

Fig. 2. Summary of rock magnetic experiments: (a) (b) (c) represent the first type and (d) the second type of behaviour for low-field susceptibility versus temperature (K–T) curves — (e) (f) (g): Acquisition of isothermal remanent magnetization — (h): Heating curves of saturated isothermal remanent magnetization acquired at 10 K up to room temperature.

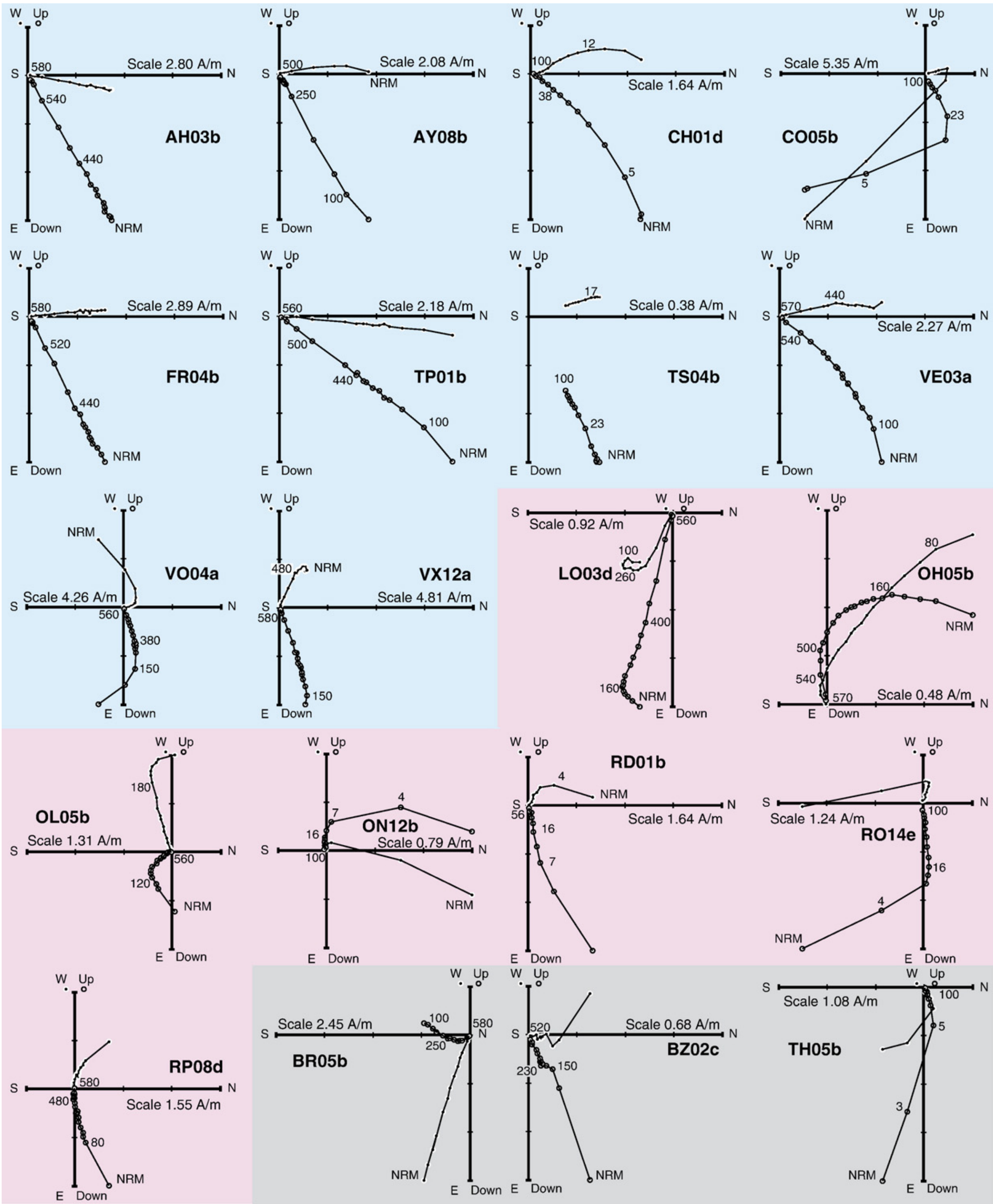

Fig. 3. Characteristic demagnetization curves.

high composition parameter (Moskowitz et al., 1998). These results are consistent with the interpretation of the low temperature phase derived from the thermomagnetic experiments.

Despite the presence of several mineralogical phases, we performed hysteresis measurements on 44 samples from ten units (Sauteyras, Bois Rigaude, Blanzat, Puy de Chaumont, Puy de Thiolet, Volvic LEP, Volvic le Fraisse, Olby top, historical Olby outcrop and Olby-Pont des Eaux) using the translation inductometer of St Maur. The rough estimate of magnetic granulometry derived from the Day plot (Day et al., 1977) (Mr/Ms versus Bcr/Bc) indicates that the specimens fall within the pseudo-single domain (PSD) range (cf. additional material). The distribution follows theoretical curves for single domain (SD) grains mixed with a proportion of multidomains varying between 40 and 80% (Dunlop, 2002).

4. Magnetic components and directional results

4.1. Demagnetization and vector analysis

All 272 samples were kept in zero field for at least one week. Remanent magnetization (NRM) was measured using JR-5 and JR-6 spinner magnetometers. Two pilot specimens from each unit were either stepwise thermally demagnetized at 20 successive steps separated by 10 to 50 °C or subjected to 13 alternating field demagnetization steps of 2 to 20 mT (Fig. 3). Bulk susceptibility was monitored to detect alteration during thermal treatment. The magnetization components were calculated by least-squares regression analysis (Kirschvink, 1980).

Six specimens were discarded for orientation errors. Forty two others were characterized by inconsistent directions frequently lying close to the horizontal plane and by strong magnetization intensities, sometimes up to 60 A/m. Such characteristics are typical of IRMs caused by lightning (Verrier and Rochette, 2002). In some cases lightning effects were restrained to the lower part of the unblocking temperature spectrum. Another set of 62 samples were discarded because their characteristic component represented less than 10% from the initial NRM. Thus more than 40% of the samples were rejected, which is unusually large for relatively young lava flows.

Only 8 specimens from the remaining 162 samples exhibited a single well-defined component, which did not deviate by more than 5° from the origin (Fig. 3). Not surprisingly these samples correspond to thermomagnetic diagrams characterized by a single phase of almost pure magnetite (Fig. 2d). The 154 other samples displayed more complex demagnetization characteristics with two distinct components. The first low-temperature and low-coercivity component, varied considerably in amplitude and represented 15 to 90% of the NRM depending on the samples. Its direction was mostly defined by no more than two demagnetization steps and frequently overlaid by another component. The most accurate determinations were obtained for at least 6 specimens from five flows with a 95% confidence cone lower than 25°. They were statistically indistinguishable from normal field polarity, which suggests either chemical or viscous origin. Since the unblocking temperature spectra of this component are similar to those of the titanomagnetite phase identified above, they are clearly associated. In many cases, this first component was not fully demagnetized before 300 °C and overlaps the high temperature component, which results in a fortuitous linear trend of medium temperatures directions in some demagnetization diagrams.

A second component was isolated beyond 250–300 °C or 40–50 mT. Given the range of temperature and coercivities, it is carried by the high temperature phase dominated by almost pure magnetite. The rock magnetic characteristics suggest that this phase could be derived from maghemitization of initial titanomagnetite. Low-temperature oxidation was likely favoured by fluid circulation during flow emplacement so that magnetization acquisition was contemporaneous of cooling (Krása et al., 2005). Weathering would have caused further alteration, whereas intermediate or almost fully reversed directions suggest that this happened over a short period of time. In any case, this is the only component with a characteristic direction.

4.2. Site directions

The stereoplots of all individual directions at each site (except Suc des Filles) are shown in Fig. 4, while Table 1 summarizes information concerning magnetic characteristics (technique of demagnetization, rejected samples...). The results can be classified within three categories.

Ten sites define the first category with their mean direction close to the axial dipole direction at the site latitude (Fig. 5a). The mean inclination of all these sites (Dec = 356.6°, Inc = 57.3°, $\alpha 95$ = 5.9°) is almost 8° lower than the expected axial dipole field inclination. Such a large deviation is not expected for paleosecular variation with a similar number of sites. As a direct consequence, the VGP positions (Fig. 5c) are located in the far-sided hemisphere with respect to site location (long 3.0° E, lat 45.8° N). The mean Virtual Geomagnetic Pole points close to the north at 204.4° E longitude and 82.4° N latitude. This observation is probably linked to the fact that low dipole field intensity prevailed between 33 and 45 ka which is the time interval encompassed by most lava flows studied here. If we assume that the time-averaged field has similar characteristics over a ten thousand as over a few million years long period, we can also expect an enhanced contribution of the long-term axial quadrupole component (g_2^0). Finally, we note that

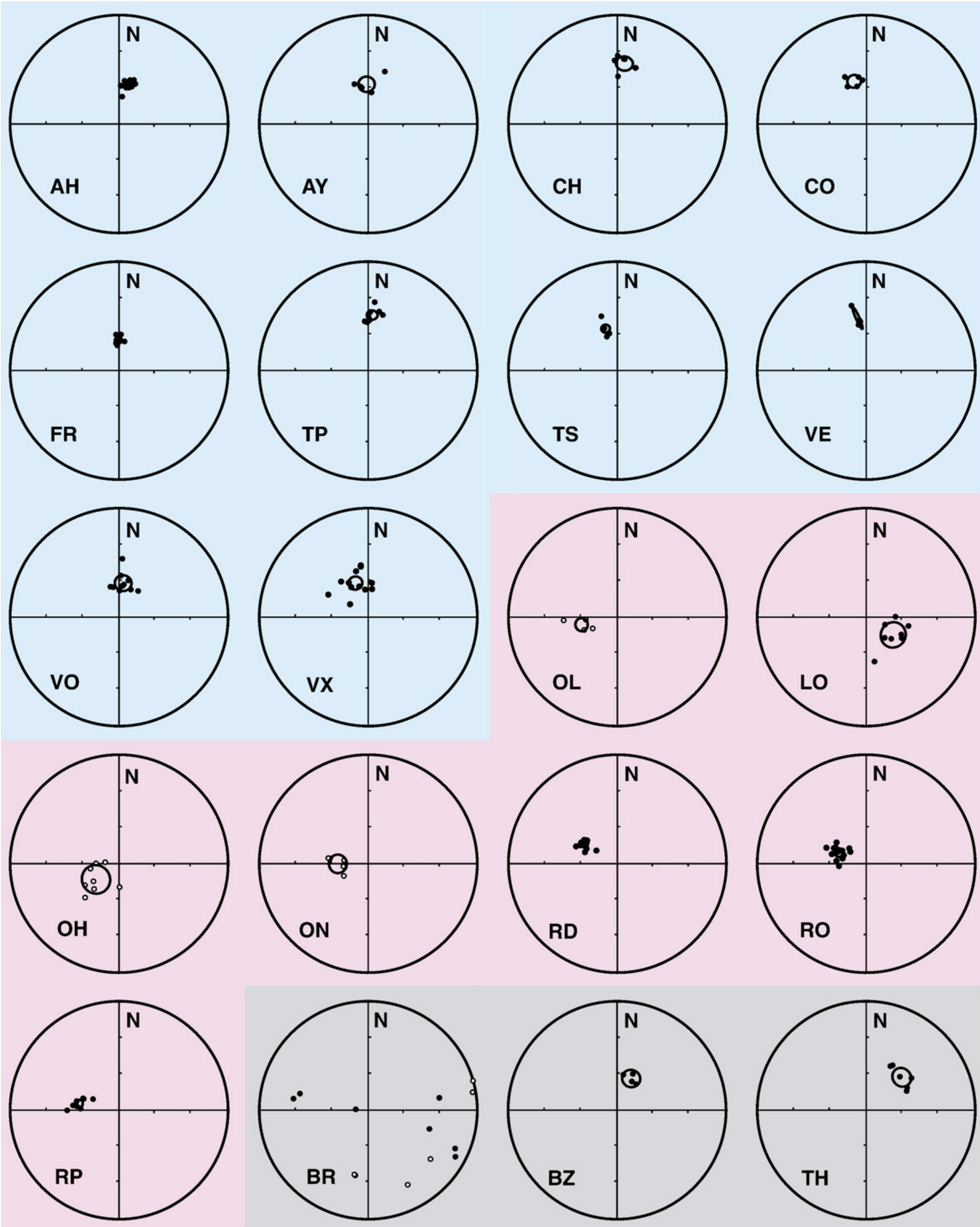

Fig. 4. Equal area projection (lower hemisphere) of the individual directions at each site with their 95% confidence ellipse (except Suc des Filles).

the angular standard deviation S_T is slightly lower ($S_T = 11.9°$ with $S_B = 11.3°$, $S_W = 10$) than the prediction (16.8°) of Model G (McFadden et al., 1991) at the site latitude, but the number of sites may not be large enough to consider this difference as being fully significant.

The second category gathers the seven sites (LO, OL, OH, ON, RD, RO and RP) from Louchadière, Olby and Royat. All exhibit directions “intermediate “ or “transitional” (Fig. 5b). The corresponding virtual geomagnetic poles (VGPs) (Fig. 5d) are distributed within three

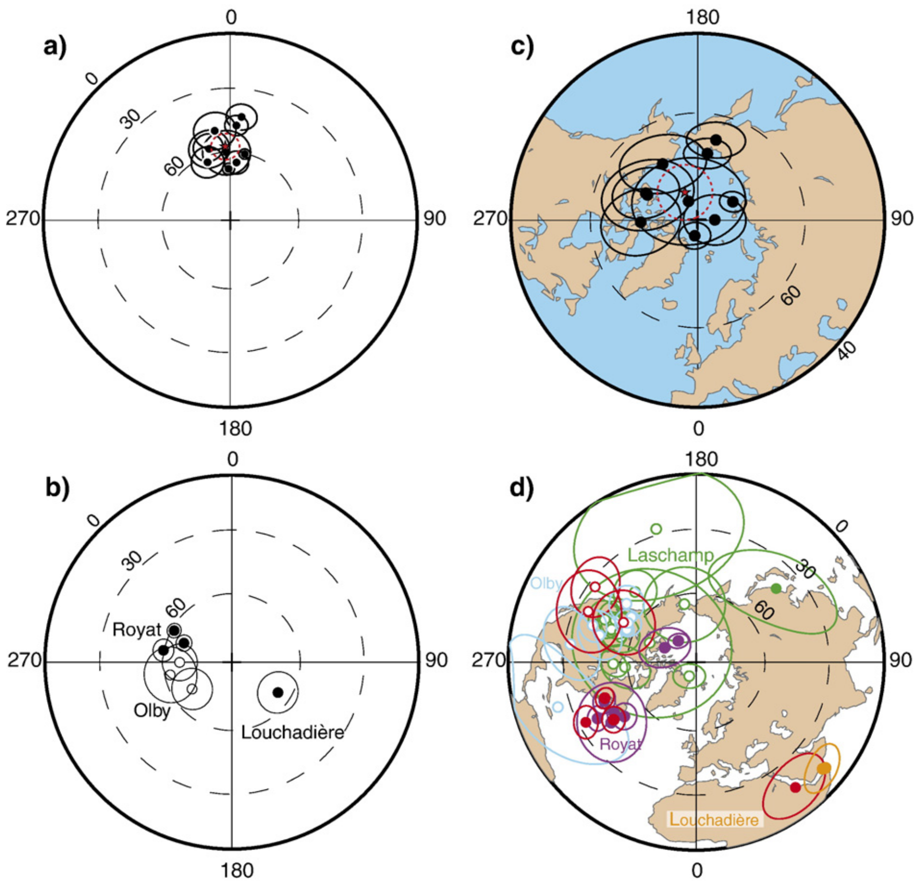

Fig. 5. a) Mean site directions of the 10 full normal polarity units plotted in equal area projection with their 95% confidence ellipse. The mean directions and their 95% confidence zone are shown in red; b) Mean directions for Louchadière, Olby and Royat intermediate flows; c) and d) Virtual Geomagnetic Poles (VGPs) of the directions plotted in a) and b). The VGPs from Laschamp, Louchadière, Olby and Royat intermediate flows obtained in previous studies (Bonhommet and Zähringer, 1969; Bonhommet, 1972; Gillot et al., 1979; Heller and Petersen, 1982a; Roperch et al., 1988; Chauvin et al., 1989; Guillou et al., 2004) are also shown for comparison.

distinct groups. The first one does not lie far from the South Pole and concerns the three Olby sites. A unique pole over northeastern Africa corresponds to Louchadière while the last three ones in mid-north-western Atlantic were obtained for Royat. Two out of the three VGP positions for Olby are similar but the third one differs by 20° of latitude. The overlapping circles of confidence indicate that the same lava flow was effectively sampled at three different locations. In contrast, the close but distinct directions found at Royat confirm that the three sites belong to three different flows, but were likely separated by a short time interval.

Lastly four sites with results that cannot be interpreted with confidence. Two sites Suc des Filles (SF) and Bois Rigaude (BR) did not provide any reliable direction. Only one characteristic direction is available for Suc des Filles, the other specimens being affected by very resistant overprint of chemical origin. The large scatter of the directions at Bois Rigaude cannot be explained by lightning strikes alone. We suspect that a hard chemical overprint overlies the characteristic component. The two other sites (BZ and TH) show a mean direction close to the axial dipole, but more than half of the samples did not yield any result. Because no characteristic component could be isolated with sufficient confidence at these sites, they will not be taken in consideration.

5. Transitional characteristics

5.1. Characteristics of magnetization

It is interesting to compare the present results with all other intermediate VGP positions that have been previously published. The stereoplot in Fig. 5d shows large dispersion of the Olby VGP latitudes extending over 30°

of latitude. The VGPs from Louchadière are at the same latitude and equally scattered over 40° of longitude. In each case the directions are evidently found in the same sector but large dispersion is not expected for distinct analyses conducted on the same flows. Several other unusual and intriguing characteristics are common to flows with intermediate polarity. A first remark is the very large number of rejected samples. Only sites RP and RD (Royat) provided acceptable results for almost all specimens, but these sites have marginal intermediate directions with VGP latitude of 46° N. A second observation is that the characteristic directions of the intermediate sites were determined from a little segment of magnetization, which does not represent more than 25% of the initial NRM. This is particularly true for the intermediate directions of the Olby flows which were derived from a few temperature steps (6) with relatively low quality (10 out of the 17 Olby directions have a maximum angular deviation larger than 5°).

Taking these observations in consideration one could even doubt that these flows faithfully recorded the geomagnetic field, and hence wonder how far intermediate directions measured at Olby, Louchadière and Royat can be trusted. We noticed that many lightning strikes affected several outcrops and were responsible for eliminating a large number of samples. However this hypothesis cannot be defended in all cases. Site BZ that was heavily sampled over 300 m along a very recent road cut provided incoherent directions for 20 out of the 24 measured samples. Lightning cannot be responsible for dispersion over such a large and very recent outcrop. No disturbance (fault, landslide, deformation...) is visible in the field and it is not realistic to envisage that the entire site would have been remagnetized by explosions or other shocks during road work. Interestingly, there is no significant difference between magnetic characteristics at this site and at the intermediate sites of Olby and Louchadière, which are all characterized by at least two components of magnetization and two mineralogies. We can thus suspect that many rejected samples from these two flows were affected by similar problems. We note that only 20% of the samples from flows with normal polarity were rejected whereas 40% were excluded from the sites with intermediate polarity. At this stage, it is important to remind that the Olby and the Laschamp lavas are prone to exhibit self-reversals.

5.2. Self-reversals

The possibility that self-reversal mechanisms would be responsible for the reverse directions at Laschamp and Olby (Bonhommet and Babkine, 1967) has been suggested very early. Heller (1980) and Heller and Petersen (1982a,b), using thermomagnetic experiments showed that several samples from Olby and to a lesser extent from Laschamp were effectively prone to self-reversals or partial self-reversals. In a recent and detailed study relying on thermomagnetic experiments and microscopic observations, Krása et al. (2005) confirmed the existence of non-oxidized magnetically soft titanomagnetite (mother phase) and a magnetically hard high-temperature daughter phase resulting from low temperature oxidation of the mother phase. During initial cooling the daughter phase is formed at higher temperatures than the Curie temperature of the mother phase and acquires a stable magnetization. The two phases being magnetically coupled, the residual low Curie temperature phase acquires a magnetization which is antiparallel to the external field. This would thus differ from self-reversals caused by ionic-reordering in titanomaghemite as reported recently by Doubrovine and Tarduno (2004) in oceanic basalts.

Taking advantage of our large sampling and considering the absence of relation between magnetic mineralogy and polarity, we repeated a similar study on samples with intermediate directions but we performed also the same experiments on normal polarity flows. Magnetization of thirty one samples (at least one per flow) was documented by a triaxial Vibrating Thermo-Magnetometer (Le Goff and Gallet, 2004) during heating–cooling cycles performed in zero field. Measurements of twin specimens from the same sample were performed to check for reproducibility and stability of the results. It is normally expected that magnetization decreases during heating until reaching the Curie temperature and then increases during cooling but with lower amplitude due to temperature dependence of the spontaneous magnetization (Fig 6a and c). Acquisition of self-reversals is indicated by an increase of magnetization when reaching the blocking temperature spectrum of the self-reversed magnetization component (Fig 6b,d,e). The self-reversal would be total if there were a change of sign of remanence during heating and cooling in zero field.

The results are reported in Table 1. The most striking observation was that half of the samples from normal polarity flows exhibited partial self-reversals (Fig. 6b and e). Two out of the 4 samples studied from the Olby flow (OH, OL, and ON) were prone to partial self-reversal. Half of the studied samples from the other flows with intermediate directions did not display any characteristic hump in their cooling curve. In fact, partial self-reversals are independent of polarity and were observed provided that there are two coupled magnetic

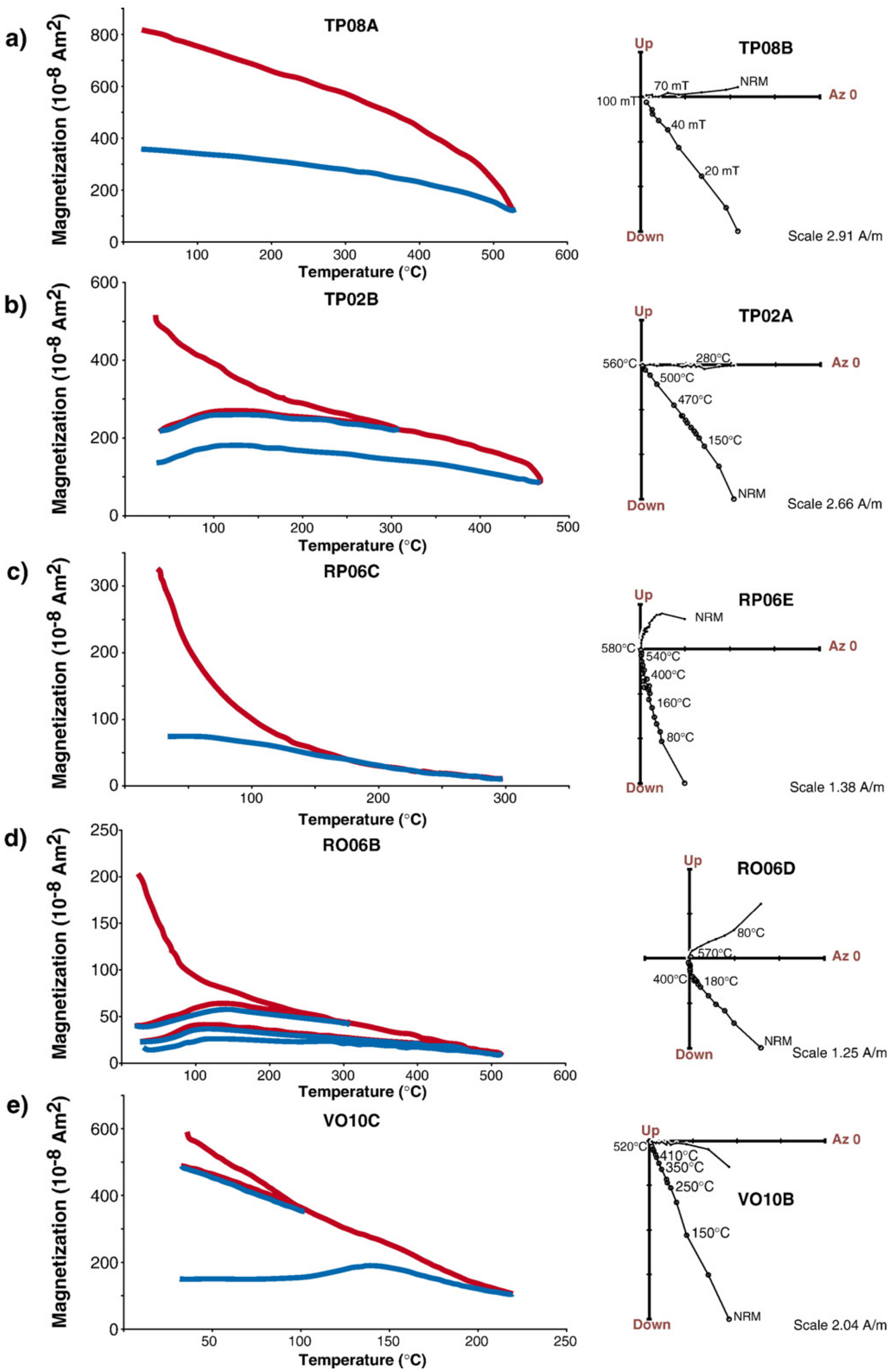

Fig. 6. Left: continuous thermal demagnetization for normal (a, b and e) and intermediate (c and d) polarity flows. Right: orthogonal projections of the magnetization vector of a twin specimen during stepwise demagnetization.

phases with distinct Curie temperatures. When acquired during initial cooling, their magnetization component is antipodal to the high temperature component but smaller and thus undetectable. Their presence during successive laboratory thermal treatments indicates that a portion of the mother phase was not oxidized and that the process is reactivated during heating in air. This differs from the ion-reordering mechanisms reported by Doubrovine and Tarduno (2004) in which no-self-reversal was observed in repeated runs. These results invalidate the hypothesis that self-reversals would be responsible for the reversed directions of the Laschamp and Olby flows but the self-reversed components probably contribute to the scatter of the directions.

In Fig. 6e we show that temperatures below 120–140 °C are not affected by self-reversals. A large viscous component is acquired over this range of temperature, while the spectrum concerned by partial self-reversed magnetization represents a smaller fraction of magnetization. Therefore, in contrast to Krása et al. (2005), we do not see any reason to consider that the viscous component replaced the partial self-reversed magnetic remanence of the mother phase at ambient temperatures. In this case viscosity would be associated with a reversed magnetization acquired in the field generated by the normal polarity of the daughter phase (for flows with normal polarity) but there is no indication for any reversed overprint in the samples. We thus consider that this low temperature phase is not involved in the processes yielding partial self-reversals probably because the range of grain sizes and their distribution is different.

5.3. Virtual geomagnetic poles

Given the brevity of the Laschamp, it is difficult to find lava flows and sediments that were able to record intermediate or reverse directions with sufficient resolution (Thouveny and Creer, 1992; Roberts and Winklhofer, 2004). Several volcanic records with intermediate or anomalous directions have been tentatively correlated to the Laschamp event. The best candidate proposed so far is the Skalamaelifell excursion (Kristjansson and Gudmundsson, 1980; Levi et al., 1990) from flows of the Reykjanes peninsula (Iceland). Another candidate could be the record from Amsterdam Island (Carvallo et al., 2003) but it is not clear whether the intermediate directions are associated with the Mono Lake or the Laschamp. Similarly, the 55±5 and 27±5 kyr old intermediate directions from the Hampton Park volcano and the Wiri volcano in Auckland, New-Zealand (Mochizuki et al., 2004) lie in the age range of Laschamp.

Despite complex magnetization processes, it is also important to consider the results obtained from sediments. The records from Lac St Front (Vlag et al., 1996) were obtained within the same geographical area and thus provide some additional indications regarding the existence of the event at least on a regional scale. Many other records indicate that the event is observed on a much more global scale. A first detailed study by Lund et al. (2005) involves three marine cores from the Bermuda Rise and the Blake Outer Ridge in Western North Atlantic. Two of them (JPC-14 and CH89-9) provided a detailed record of the Laschamp event with similar VGP paths describing a large clockwise looping from the East Pacific coast to Indonesia, reaching the southernmost position over Australia and then moving to west over Africa and western Europe. More recently, Laj et al. (2006) studied another core from the same area to which they added another record close to Iceland, two other nearby cores from the Gulf of Mexico and a last one from Southern Central Indian ocean. To those we can add a recent study from the Irminger Basin (Channell, 2006). Laj et al. (2006) reported that all VGPs follow the same clockwise loop. This simple structure was interpreted as reflecting dipolar geometry of the field during the Laschamp event, and is thus not consistent with the dominance of non-dipole components resulting from the large decrease of the axial dipole.

Based on similarity of their VGP paths, Lund et al. (2005) suggested that the Mono lake excursion (Denham and Cox, 1971; Liddicoat and Coe, 1979) recorded in Californian Pleistocene sediments could actually be related to the Laschamp. Alternatively it has been defended that the detailed pattern of field intensity changes suggests that the two events correspond to two different intensity lows (Laj et al., 2000) which would be separated in time by about 6 ka. The age of the Mono Lake excursion is still in debate and the last papers (Kent et al., 2002; Benson et al., 2003; Zimmerman et al., 2006) disagree with each other regarding its relation with the Laschamp.

In Fig. 7 we show all pole positions published so far from the same lava flows in the Chaîne des Puys that were studied by different groups including the present results. Also shown for comparison are the data from Skalamaelifell (Iceland), from Amsterdam Island (Watkins and Nougier, 1973; Carvallo et al., 2003), from the New-Zealand excursions (Mochizuki et al., 2004) and the loop observed in the sedimentary records (Laj et al., 2006). Despite their intrinsic scatter, the respective pole positions obtained from each individual flow are found within the same geographical sector for each site, a coherence which confirms their geomagnetic origin. We

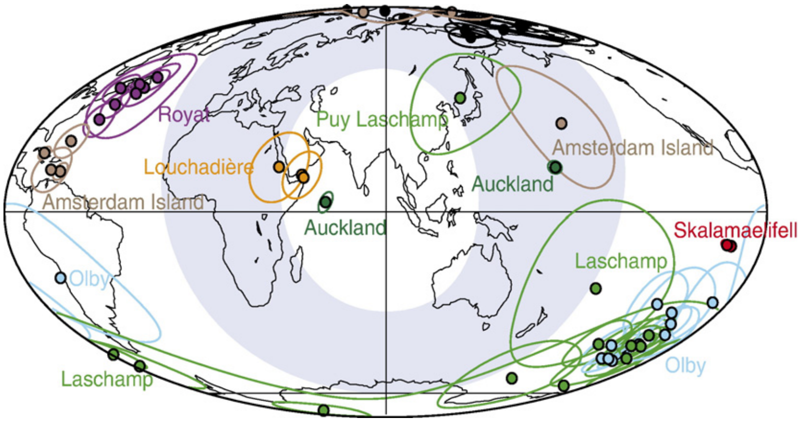

Fig. 7. Compilation of the Virtual Geomagnetic Poles (VGPs) published so far from volcanic lava flows linked to the Laschamp event (Bonhommet and Zähringer, 1969; Bonhommet, 1972; Watkins and Nougier, 1973; Gillot et al., 1979; Kristjansson and Gudmundsson, 1980; Heller and Petersen, 1982a; Roperch et al., 1988; Chauvin et al., 1989; Levi et al., 1990; Carvallo et al., 2003; Guillou et al., 2004; Mochizuki et al., 2004), including those obtained in the present study.

see also that the Skalamaelifell poles lie close to the Olby ones while the poles recorded at Amsterdam Island do not lie far away from those of Royat.

The volcanic results differ from the configuration of the VGP paths derived from the compilation of sedimentary records. The scattered distribution of the volcanic poles over the globe is incompatible with any type of dipolar configuration. As for reversal records, the timing of magnetization in sediments filters high frequency components, which induces smearing of the signal.

6. Dating of lava flows

6.1. Previous studies

The first potassium argon (K–Ar) dating on whole rocks of the Laschamp and Olby formations (Bonhommet and Zähringer, 1969) indicated an upper limit value of 20 ka for the Laschamp polarity event. Subsequently this result was improved by combining several methods. Hall and York (1978) proposed a weighted averaged K–Ar age of 45.4±2.5 ka and an argon/argon ($^{40}Ar/^{39}Ar$) age of 47.4±1.9 ka (all ages are quoted using a 1σ uncertainty). Baked clay and sediments with anomalous directions of magnetization found below the Royat flows were first dated at 25.8±2.2 ka (Huxtable et al., 1978) using thermoluminescence (TL) but later direct TL dating of plagioclase indicated ages of 41.1±2.9 ka and 43.5±3.9 ka (Guérin, 1982). Subsequent K–Ar analyses of whole rocks from the Laschamp flow provided values at 43±5 ka (Gillot et al., 1979) and 49±6.7 ka (Chauvin et al., 1989). In the meantime, new TL dating of quartz from a granite xenolith yielded an age of 35±3 ka (Gillot et al., 1979) and two determinations at 31.9±2.85 ka and 32.5±3.1 ka using plagioclase feldspars (Guérin and Valladas, 1980). The first ^{14}C measurements of the Olby flow gave a limit value of 36 ka but the first K–Ar date provided a much older result of 50±7.5 ka (Gillot et al., 1979). A subsequent K–Ar determination yielded an age of 38.2±6.3 ka (Chauvin et al., 1989) compatible with the determinations at 39±6 ka deduced from $^{30}Th/^{238}U$ age radioactive disequilibrium (Condomines, 1978) and with the TL age of 37.3±3.5 ka on plagioclase feldspars (Guérin and Valladas, 1980). Complementary plagioclase TL and K–Ar dating (Guérin, 1982) indicated that the reversely magnetized flow at Montmeyre belongs to the Matuyama period. The Laschamp event is only testified in the Chaîne des Puys by two reversed units at Olby and Laschamp, and by two other units with intermediate directions at Royat and Louchadière with ages estimates between 30 and 50 ka ago. The most probable value at about 40 ka is in agreement with the most recent radiometric dating at 40.4 by Guillou et al. (2004) with ±1.0 ka uncertainty at 1σ.

6.2. New K–Ar datings

We performed K–Ar measurements using the Cassignol–Gillot technique (Cassignol and Gillot, 1982) that relies on an atmospheric argon comparison and provides accurate dating of young lavas and/or lavas with low radiogenic content (Gillot and Cornette, 1986). Visual examination of petrographic thin sections was a first step to select samples. In the case of the Louchadière flow, the sample was rejected because of its scoriaceous texture, evidence for fumarolic alteration as well as strong iddingsitization of olivines. Because material from underlying thick continental crust could be a significant source of overestimated ages, special attention was also paid at using specimens without inherited xenoliths. Samples were crushed to a 125–250 μm in size fraction and cleaned using ultrasound for 15 min in a 5% nitric acid solution. Heavy liquid separations were performed in order to remove early crystallising phases from the microlithic groundmass used for both K and Ar measurements. Potassium was measured by flame emission and compared with reference materials MDO-G and ISH-G (Gillot et al., 1992). For each sample two independent determinations of potassium were combined to obtain a mean estimate with its uncertainty. Argon was measured with a mass spectrometer identical to the one described by Gillot and Cornette (1986). The interlaboratory standard GL-O and the recommended value of 6.679×10^{14} at/g of 40Ar* (Odin et al., 1982) were used for ^{40}Ar signal calibration. Typical uncertainties of 1% were obtained for ^{40}Ar signal calibration and for determination of potassium. Argon uncertainty is a function of radiogenic content of the sample. The detection limit of the system is presently of 0.1% of ^{40}Ar* (Quidelleur et al., 2001), which makes the Cassignol–Gillot technique extremely suitable for very young samples such as the ones from the Auvergne. We used the decay constants of Steiger and Jäger (1977).

6.3. Chronology

The final age of each sample has been obtained from two or three independent measurements of 40Ar* (radiogenic argon) which were combined to give a weighted mean determination with its uncertainty (given here at 1σ). In contrast to the former studies, the present study was not restrained to the intermediate or reverse polarity flows but concerns also older or younger surrounding flows with normal polarity. The K–Ar ages are reported in Table 2 with their uncertainties at the 1σ level and the resulting chronological succession of polarities is plotted in terms of VGP latitudes in Fig. 8. In the same figure are shown also older K–Ar determinations as well

Table 2
K–Ar results

Site	Weight	K%	40Ar*	40Ar* (at/g)	Age	Mean age (ka)	Unit age (ka)
RO	2.81944	1.513	0.76%	5.44E+10	34.4±4.5		
	2.77214	1.513	0.65%	4.72E+10	29.8±4.6		
	1.99229	1.513	0.78%	5.58E+10	35.3±4.5	32.9±1.0	
RD	3.22329	1.593	2.33%	5.66E+10	34.0±1.5		
	3.54086	1.593	2.13%	5.38E+10	32.3±1.6		
	3.35883	1.593	1.20%	5.16E+10	31.0±2.6	35.3±1.0	
RP	3.35564	1.520	2.14%	5.68E+10	35.8±1.7		
	3.43181	1.520	2.79%	5.57E+10	35.1±1.4	35.4±1.1	334.0±0.7
OH	4.40969	1.790	2.28%	6.84E+10	36.6 ±1.7		
	4.35604	1.790	2.15%	6.91E+10	36.9±1.8		
	4.61286	1.790	2.00%	7.04E+10	37.7±2.0	37.0±1.0	
OL	2.95694	1.766	1.33%	7.15E+10	38.7±3.0		
	2.95223	1.766	1.96%	6.67E+10	36.2±1.9	36.9±1.6	
ON	3.19756	1.788	3.10%	6.93E+10	37.1±1.3		
	3.27214	1.788	2.99%	6.91E+10	37.0±1.3	37.1±.9	37.0±0.7
VO	2.79129	1.492	1.47%	6.39E+10	41.0±2.8		
	2.81431	1.492	1.41%	6.37E+10	40.9±2.9	41.0±2.0	
FR	2.39756	1.404	1.22%	6.14E10	41.8±3.5		
	3.31065	1.404	1.13%	6.63E10	45.2±4.1	43.2±2.7	
VX	2.77428	1.632	1.11%	7.67E+10	45.0±4.1		
	2.79265	1.632	1.00%	6.73E+10	39.5±4.0	42.2±2.9	41.9±1.4
AY	2.89689	1.855	1.13%	3.77E+10	19.4±1.7		
	3.14667	1.855	1.18%	4.04E+10	20.8±1.8	20.1±1.2	
BZ	2.69593	1.273	1.31%	7.00E+10	52.7±4.1		
	2.95671	1.273	1.28%	6.93E+10	52.1±4.1	52.4±2.9	
AH	1.199	1.348	0.90%	7.87E+10	55.9±6.3		
	1.553	1.348	0.86%	6.97E+10	49.5±5.8	52.4±4.3	

Site, site name (see Fig. 1); Weight, independent aliquot that was measured; K%, concentration in potassium measured by flame spectroscopy; 40Ar*, proportion of radiogenic argon; 40Ar* (at/g), number of atom per gram of sample; Age of each aliquot; Mean age, weighted mean age for each site; Unit age, weighted mean age of coeval sites.

as the most recent ages (Guillou et al., 2004) of the Laschamp flow.

New unspiked K–Ar age determinations of the Olby flow were obtained from three different outcrops and have a weighted mean age of 37.0±0.7 ka which is compatible with the most recent $^{40}Ar/^{39}Ar$ determination of 39.2±2.5 ka for the same flow (Guillou et al., 2004, uncertainty was recalculated at 1σ). However, the unspiked K–Ar dating of the Olby material by Guillou et al indicates an age of 41.4±1 ka (1σ), thus 4.4 kyr older than in the present study. Because this last determination completely overlaps the age interval of 41.9±1.4 ka obtained for the youngest flows with normal polarity at Volvic, we give more confidence to the Ar/Ar age. As testified by initial geochronological studies of the Olby flows and other volcanic units, inherited components (likely in crustally derived xenocrysts) can affect age determinations in the Chaîne des Puys. Whole rock K–Ar measurements of the Olby flow yielded an age of ca 50 ka (Gillot et al., 1979). Since then, the procedure of sample preparation limits any contribution of inherited argon by using a fraction of groundmass without pheno- and xenocrystic components (olivine, pyroxene, feldspar) that are potential carriers of inherited $^{40}Ar^*$. Guillou et al. (2004) suggested that their $^{40}Ar/^{39}Ar$ isochron estimates which are younger by 2.2 kyr than their unspiked K–Ar ages of the same groundmass material could result from little inheritance of $^{40}Ar^*$ beyond detection limit of $^{40}Ar/^{39}Ar$ plateau tests. Thus the consistent chronology of the present results led us to consider that the $^{40}Ar^*$ carriers were efficiently removed by our measurement procedure especially as the amount of argon is likely to be different from one outcrop to another. The overall agreement between the ages found in this study for different outcrops of the same unit at Olby as well as for different overlying flows at Royat suggests that variations due to inherited argon are lower than the average statistical error of 2 kyr for these measurements.

The ages obtained for the three Royat outcrops have a weighted mean of 34±0.7 ka. These flows have a mean VGP position close to 45°, thus just at the limit of intermediate polarity. Given the absence of other directions lying as far away from the dipolar direction at the site, we consider that they are not linked to standard secular variation, but well related to the Laschamp event. Actually, their position and directions (Fig. 5b and d) suggest that they may be associated with the end of the event. The present age difference between the Royat and Olby flows is 3±1 ka. This means that the ages of these flows differ by no less than 1 kyr and no more than 4 kyr, values obviously too similar for being related to different events. The intermediate polarity of the Royat flows led us to consider that the return to normal polarity must obviously be younger but also very close to the age of these flows. Thus, the value of 33.3 ka (34–0.7 ka) is our best age estimate for the end of the Laschamp in the Chaîne des Puys. Unfortunately,

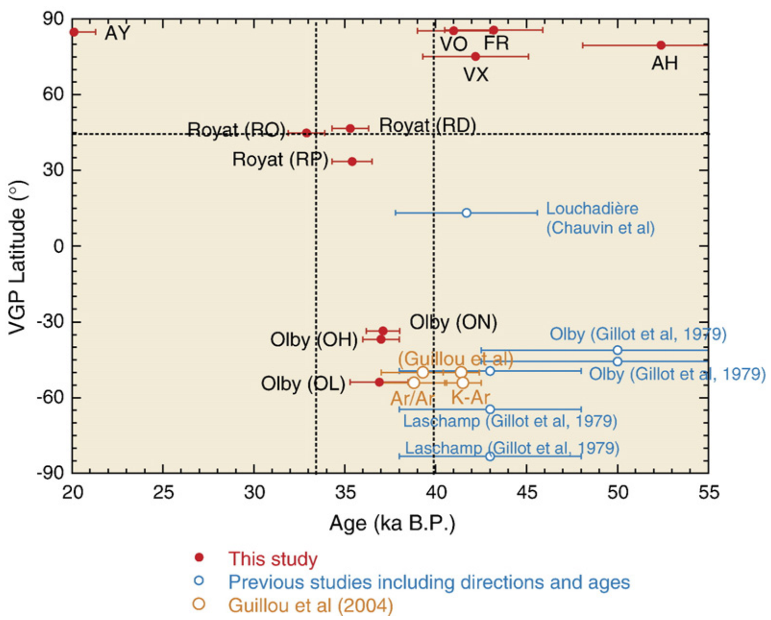

Fig. 8. VGP latitudes as a function of time derived from all studies (including the present one) with directions and K–Ar ages in the Chaîne des Puys (Gillot et al., 1979; Chauvin et al., 1989; Guillou et al., 2004). The dashed lines are our best estimate for the upper and lower limits of the event.

no younger flow of normal polarity could be dated so far to provide a more rigorous timing constraint. The mean age of 41.9±1.4 ka of the three normal polarity sites VO, VX and FR and the reverse polarity of Olby flows dated at 37±0.7 ka constrain the onset of the event. Taking the uncertainties into account, we infer that the Laschamp event did not begin prior to 43.3 ka (41.9+1.4 ka) and not later than 36.3 ka (37–0.7 ka), thus at 39.8 ka. Altogether these estimates lead us to propose that the Laschamp event most likely spanned between 33.3 and 39.8 ka.

The present age of the Olby flow at 37.0±0.7 ka is in better agreement with the GRIP than with the GISP2 record age model, which partially depends on radiocarbon calibration. At this point we would remind that the IntCal working group declined to make a recommendation for radiocarbon calibration concerning the period prior to 26 ka BP because of the large scatter and offsets between the available data sets (Van der Plicht et al., 2004). Another potential source of discrepancies lies in the uncertainty of the ^{40}K decay constant which can reach ±970 yr when comparing K–Ar ages with those of other geochronometers.

The time interval 33.3–39.8 ka proposed in this study includes the age of the first intensity low (34 ka) in the NAPIS-75 stack curve (Laj et al., 2000) which is linked to the Mono Lake excursion and relies on GRIP chronology (Meese et al., 1997; Johnsen et al., 2001; Beer et al., 2002). In the same stack the intensity low linked to the Laschamp event is 40 ka old and relies on the GISP2 age model. In other words, the two intensity anomalies would differ by about 6 kyr. We discussed above that the Royat and Olby flows cannot be associated with different events (their age difference is robust), even if we assume that there were systematic errors in the age calibration of NAPIS-75 or in our K–Ar determinations. In contrast, as already mentioned, the position and the origin of the Mono Lake remain controversial (Kent et al., 2002; Benson et al., 2003). The high resolution chronology of the Wilson Creek formation developed recently by Zimmerman et al. (2006) assigns both the Mono Lake and the Laschamp to the same 41 ka old intensity low of GLOBIS paleointensity curve and was determined on the basis of the GISP2 age model. The same intensity low has an age estimate of 38.5 ka in the NAPIS curve. The present chronology of Laschamp is thus consistent with the suggestion that these two records could represent independent data sets of the same event. This is also compatible with the similarity of the clockwise VGP paths of the sedimentary records of Mono Lake and Laschamp noticed by Lund et al. (2005). We note that a recent high resolution sedimentary record (Channell, 2006) displays two intervals of negative inclinations dated at 32–34 ka and 39–41 ka, respectively.

7. Conclusion

Despite sampling of twelve new lava flows with ages coeval to the Laschamp, we did not find any new intermediate or reverse direction in the Chaîne des Puys. We identified ten flows with well-defined full normal polarity and a far-sided mean pole position which could result from the very weak dipole field during this period.

This study confirms that the Olby lava flow is prone to exhibit self-reversals (Heller, 1980; Heller and Petersen, 1982a,b; Krása et al., 2005). However we observed that self-reversals occur also in lava flows with well-defined normal polarity. Thus they cannot be taken as responsible for the intermediate and reversed directions observed at several locations. We agree with the scheme described by Krása et al. (2005) which defends that the low Tb component carried by primary titanomagnetite is subjected to self-reversal. However, we do not think that this component was totally replaced by a viscous overprint but rather that the viscous normal component is carried by different (maybe coarser) grains of initial titanomagnetite. Above 120 °C self-reversal mechanisms alter a fraction of the primary phase with low blocking temperatures but they do not affect the final directions. This tiny component overlaps the characteristic direction (with similar high blocking temperatures). It cannot be detected on samples with normal polarity but is responsible for relatively large dispersion of the directions in transitional lava flows. Consequently, we do not question the geomagnetic origin of the transitional directions from Olby and Louchadière but they must be interpreted considering their scatter.

Seven of the studied sites from Olby and Royat are characterized by transitional directions. Their VGP positions do not exactly coincide with the previously published records, which results from dispersion described above. The compilation of all records obtained so far reveals the complex structure of the field during this period with four groups of VGPs lying roughly northeast and southwest of America, in the northern Pacific and over east Africa. The fact that they do not fit with the results of the longitudinal loop of the sedimentary records provides new constraints that should help to understand the origin of the discrepancies between the two kinds of records.

Finally, new K–Ar determinations obtained for transitional flows but also for flows with normal polarity allow us to establish a first coherent chronology of directions associated with the Laschamp event. The upper limit of 33.3 ka is defined by the Royat lava flow and the existence of three flows with normal polarity indicates that the event is likely not older than 39.8 ka. These ages are 1 to 4 kyr younger than those derived from ice cores and ^{14}C dating (Lund et al., 2005; Laj et al., 2006) and from recent dating of the Laschamp flow (Guillou et al., 2004). The discrepancies can certainly be resolved within the uncertainties inherent to all dating techniques.

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