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Archeomagnetism of Piton de la Fournaise: Bearing on volcanic activity at La Réunion Island and geomagnetic secular variation in Southern Indian Ocean

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ABSTRACT

Historical and other recent lavas from Piton de la Fournaise (La Réunion Island) are studied using the large sample archeomagnetic method which provides here paleodirections of the Earth Magnetic Field with confidence cones between 0.9 and 2.5°, thus offering a precise record of the geomagnetic field and potential dating constraints. Ages of the lavas are known thanks to historical chronicles (from 1708) or ^{14}C dating and their analysis give information about the directional secular variation (SV) in a region where observatory measurements are scarce and not available before the end of the 19th century. For the past 250 yr we find a high value of inclination (−50 to −55°) with respect to the geographic latitude (21°S), connected with a very restricted directional SV. Conversely, the older volcanic units present a larger SV with magnetic inclinations of between −31° and −46°, and declinations from 16°W to 10°E. These results, which are in reasonable agreement with instrumental measurements made on ships in the vicinity of La Réunion, allow us to infer that undated lavas of the northern part of the caldera emanated from eruptions during the second half of the 1700s. Other volcanic products (e.g. Mare Longue flow, Piton Chisny cone and flows and Pointe Langevin), despite their fresh morphology, are necessarily older than about 1500 AD. Further knowledge of the path of the SV in the more distant past, and therefore further archeomagnetic dating, is hampered by the lack of a precise chronology through radiometric or other similar methods. Available models of the geomagnetic field during the last millennium, which suffer from the scarcity of data in the Southern Hemisphere, are discussed in the light of our results.

1. Introduction

Archeomagnetism can be defined as a branch of Paleomagnetism devoted to recent variations of the Earth Magnetic Field (EMF) recorded in baked artifacts whose ages are known thanks to archeological dating (Evans and Hoye, 2005; Gallet et al., 2002; Hagstrum and Blinmann, 2010; Thellier, 1981). By extension, Archeomagnetism also includes volcanic materials resulting from eruptions dated by human history (Genevey et al., 2002; Hoye, 1981; Tanguy et al., 2003). Archeomagnetic variations of the EMF are obviously smaller in amplitude than those over geological timescales and thus require highly precise determinations. Following Thellier's work, we developed at the St. Maur laboratory, a particular methodology involving the collection of large samples (0.5 to 1 kg each) and their measurement using an inductometer specially designed for the size of the samples (LeGoff et al., 2006). This large sample method (LSM) was successfully applied to Italian volcanoes, showing that most of the "historically dated" lavas prior to the 1700s were in fact older by centuries and sometimes more than a millennium (Tanguy et al., 2009), simply because the historical accounts were not precise enough for identification of the lavas themselves.

On La Réunion Island where the shield volcano Piton de la Fournaise erupts frequently (Peltier et al., 2009), it was interesting to seek whether experience gained in Italy might lead to good results, for two purposes. Firstly, there are only a few instrumental measurements of the EMF prior to the end of the 19th century in this region of the Southern Hemisphere, and secondly, the lack of age determination for many of the morphologically recent lavas makes it impossible to reconstruct a comprehensive eruptive history before the 1900s. Here, we present preliminary data on the directional secular variation (SV) obtained from 18 volcanic units ascribed to the last 2000 yr on the basis of historical evidence or ^{14}C dating. In addition, magnetic directional data are provided on some undated lava flows whose well-preserved morphology implies ages within the same range.

Comparisons with available instrumental measurements and field models are also discussed. For instance, the reliability of field modeling over a millennial scale, such as those constructed by Korte

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et al. (2009) (using archeomagnetic, volcanic and sedimentary data), clearly suffers from the poor distribution of data available in the Southern Hemisphere. The new data presented here contribute to filling this gap to further understand the behavior of the Earth's magnetic field.

2. Piton de la Fournaise shield volcano and archeomagnetic sampling

La Réunion Island (21.07°S, 55.32°E) is roughly elliptical in shape (70 × 50 km) and represents the emerged part of a large hotspot volcano which culminates at Piton des Neiges (3070 m), a deeply eroded ancestor edifice (Lénat et al., 2009). The Piton de la Fournaise (PDLF) active volcano developed in the SE part of the island (21.23°S, 55.71°E) with a current elevation of 2632 m on the northern rim of a double summit caldera named the Bory and Dolomieu craters (Bachèlery, 1981; Michon et al., 2007; Staudacher et al., 2009). Because it was superimposed on the SE slope of its ancestor, PDLF underwent several flank collapses, the last of which formed the Enclos Fouqué, a horseshoe-shaped depression that opens eastward on the Indian Ocean (Fig. 1). The Enclos Fouqué is delimited by steep walls called the Rempart de Bois Blanc to the North and the Rempart du Tremblet to the South. In recent times, PDLF has produced numerous eruptions, usually every few months or years (Lacroix, 1936; Lénat, 1989; Peltier et al., 2009). The eruptions are largely effusive and consist of basaltic fire fountains and lava flows, most of which are channeled within the Grand Brûlé, i.e. the lower reaches of the Enclos Fouqué. Lava flows of different eruptive episodes are largely superimposed and become indistinguishable after a matter of decades. Some eruptions, however, may be qualified "eccentric" (Lacroix, 1936) as they occur outside the Enclos Fouqué, although their mechanism is not different from that of other lateral eruptions. They sometimes built cinder cones such as the Puys Ramond, Piton Chisny, Petit Cratère or Piton Taïpoul. Other eccentric lava flows have outpoured through fissures without forming cinder cones, on the NE flank in 1708, 1977 and 1998 and on the SE flank in 1776, 1800 and 1986. These eruptions are well recorded because of the destruction or unique features which resulted close to inhabited areas. The 1708 lava flow overwhelmed the village of Sainte Rose (Quai La Rose at the time). The 1977 flow partly devastated Piton Sainte Rose, another village of the NE coast. The 1776 lavas formed a prominent delta known as Pointe de la Table on the SE shore. This delta was enlarged further by the 1986 flows which originated in the same area.

Violent explosive eruptions at PDLF are rather scarce and consist of phreatomagmatic activity producing spatter lavas and ash layers that may include carbonized wood suitable for ^{14}C dating, as occurred about 1900 yr ago at the Commerson crater (#17, on Fig. 1) (Bachèlery, 1981). Carbonized wood was also found, though rarely, beneath eccentric lava flows or pyroclastic cones. Minor explosions are mentioned episodically over the past several centuries, sometimes

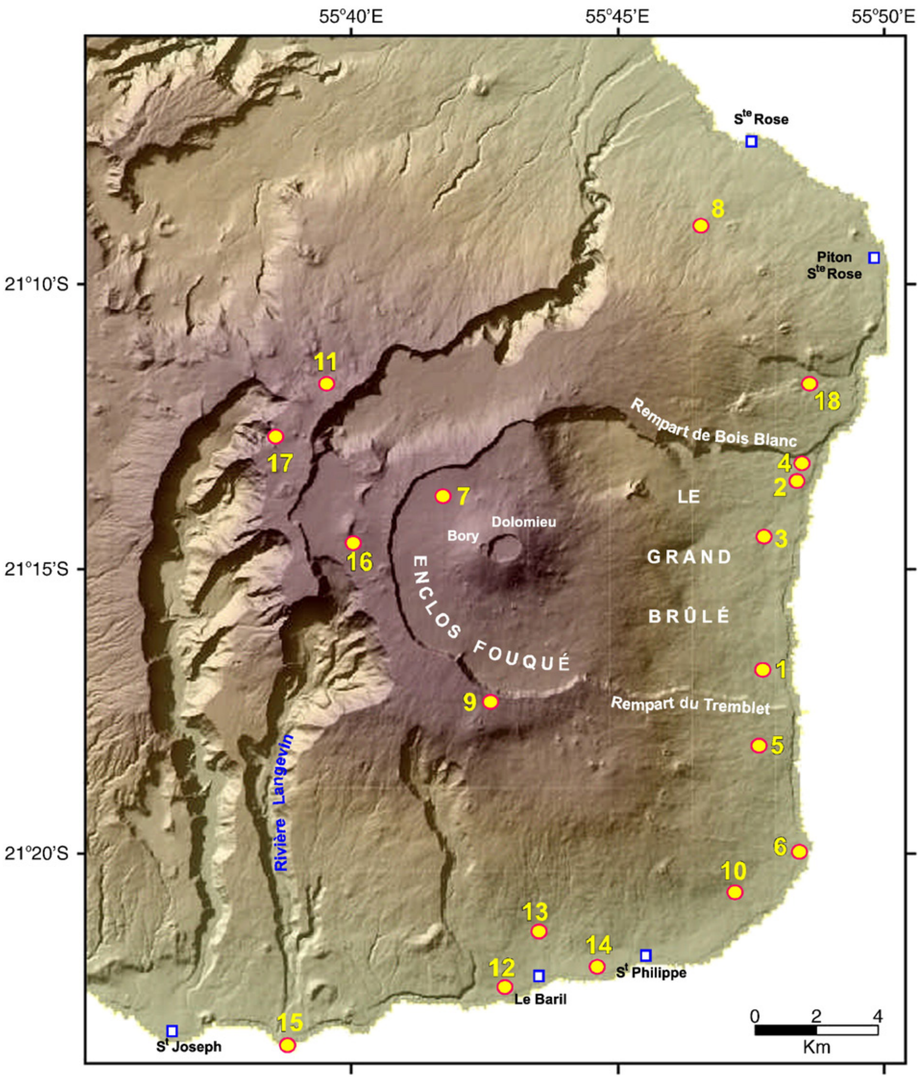

Fig. 1. Map of Piton de la Fournaise (PDLF) showing our archeomagnetic sampling sites. Numbers are those reported in Table 3.

Table 1
Historical eruptions of Piton de la Fournaise, 1640–1931. Summary from Lacroix (1936, 1938), eccentric eruptions in bold character.

1671, 1705	Unspecified activity in the Grand Brûlé
1708	Eccentric eruption above Sainte Rose, reaching the sea on the NE coast
1709–1721	Almost continuous activity (?)
1733–1734, 1751	Lava flows to the sea in Grand Brûlé
1753	Large eruption, earthquakes, ashfall on the whole island, multiple lava flows reaching the sea
1766–1768	Large eruption with production of Pele's hair, and then continuous mild activity
1774	Small eccentric eruption close to the Tremblet rampart (ESE of the summit)
1776	Large eccentric eruption to the SE reaching the sea (Pointe de la Table)
1786	Lava outflow together with a tectonic earthquake near Mauritius
1786–1801	"at least two lava flows every year"
1787	Explosions from the summit crater, lava flow to the sea
1791	Large eruption, flows to the sea, seismic shocks, explosions (opening of Dolomieu crater?)
1792, 1794	Lava flows to the sea
1800	Eccentric eruption on ESE flank, reaching the sea
1802	A long-lived eruption begins in January with an explosion and ashfall to Saint-Denis. In March, aa flow made of oceanite from the base of Piton de Crac to the sea. New outburst in April with ashfall to Sainte Rose, probable continuous activity within the Dolomieu crater
1807	Lava flow on 23 March, followed by continuous glow at the crater until 27 May
1809–1810	Continuous (?) activity within the central crater
1812	Large oceanite eruption in the Piton de Crac area, 18 flows merge in a single, 120 m width aa flow, eventually reaching the sea. Abundant production of Pele's hair and fallout on the whole island
1814–1816	Intermittent glow and Pele's hair within the crater; minor lava flows
1821	Violent explosions with incandescent scoriae are followed by three lava flows, one of which reaches the sea
1824, 1830, 1832, 1842	Lava flows, two of which reaching the sea
1844	Pahoehoe lava coming from Piton de Crac and reaching the sea
1845–1850	Lava flows, at least one every year
1858–1860	Lava flows, one of which reaches the sea, ash explosions
1863–1865	Lava flows, one of which (1863) reaching the sea near the Rempart de Bois Blanc
1868	Lava flow along the Rempart du Tremblet, reaching the sea
1871, 1874	Lava flows remaining in the upper region, ash explosions and Pele's hair to Sainte Rose
1889–1890	Several eruptions with Pele's hair and lava flows, some of which reach the sea
1897	A large lava flow along the base of Bois Blanc reaches the sea on a width of 400 m
1898–1902	At least 10 small to moderate eruptions during this period, possibly to the sea in 1899
1904–1929	At least 18 small to moderate eruptions, mostly in the Piton de Crac region. Unspecified activity several times at the summit crater.
1931	Large eruption of oceanite reaching the sea in the vicinity of Rempart de Bois Blanc. Fallout of Pele's hair at Plaine des Cafres (site of the present observatory).

producing noticeable quantities of Pele's hair. All the accounts pertaining to the ancient historical eruptions of PDLF are quoted by Alfred Lacroix in his book *Le volcan actif de l'île de la Réunion* and its supplement (Lacroix, 1936, 1938). The main volcanological data that may be extracted from these accounts are summarized in Table 1.

Because La Réunion was uninhabited before 1640, and because most of the subsequent lava flows are irretrievably lost to sampling within the Enclos Fouqué, the historical period at PDLF is limited to a small part of volcanic products of the last three centuries. We thus collected samples from the 1708, 1776 and 1800 eccentric lava flows, to which we added the 1931 and 1976 flows in the Grand Brulé. These two flows were still outcropping along the RN2 road at the beginning of this study in 1985. Two other flows in the Grand Brûlé are presumed to be dated from 1858 (or 1890?) and 1863 (?) with a large degree of uncertainty. In addition, some of the older eccentric flows or pyroclastic cones exhibiting very fresh morphology were dated through the ^{14}C method (Bachèlery, 1981; Sigmarsson et al., 2005). For each volcanic unit the sampled carbonized wood was made of several centimeter-sized fragments. In the present work (Table 2) the radiocarbon ages were calibrated using the CALIB 6.0 program online version (Stuiver and Reimer, 1993; Stuiver et al., 2005). CALIB makes the conversion from radiocarbon age to calibrated calendar year by calculating the probability distribution of the sample's true age. The SHCal04 calibration data set was used (McCormac et al., 2004), given the range of ages used in this study and the location of La Réunion in the Southern hemisphere. For each sample the most likely age is given with an indication of the dating probability.

All the magnetically studied flows and cinder cones are listed in Table 3, resulting in 243 large samples coming from 18 sampling units, of which 6 are historically dated (#1, 2, 3, 4, 6 and 8), 2 others are presumed to be also from this period (#4 and 7), 5 are ^{14}C dated (#9, 10, 11, 13 and 17) and 5 consist of undated flows exhibiting very fresh morphologies (#12, 14, 15, 16 and 18). The Piton Taïpoul scoria cone (#9) was believed to date from 1440 to 1670 AD, however the carbonized wood was found not within the cone, but under the nearest lava flow (magnetically not sampled), so the Piton Taïpoul itself remains undated.

Details of sampling through our particular archeomagnetic method are given at the beginning of Section 4. In volcanic terrains, however, it is well-known that the magnetic direction can be more or less distorted by the underlying volcanic pile. In order to check the extent of this distortion at PDLF, we will first deal with instrumental measurements of the present EMF over selected archeomagnetic sites.

Table 2
Radiocarbon ages of recent lavas from Piton de la Fournaise (from Bachèlery, 1981, see text for explanation of the calibration method).

Sample	^{14}C age yr BP	95.4% (2σ) cal age ranges	Dating probability
Taipoul	355 ± 75	cal AD 1440–1670	0.935
Rav Ango	455 ± 75	cal AD 1400–1640	1.000
Petit Cratère	470 ± 75	cal AD 1400–1630	1.000
Baril 1	575 ± 75	cal AD 1290–1490	1.000
Chisny/Langevin	1105 ± 60	cal AD 870–1050	0.863
		cal AD 1060–1150	0.132
Commerson	1890 ± 75	cal AD 20–380	1.000

3. Instrumental measurements of the present EMF on Piton de la Fournaise

We measured, in November 1990, the EMF acting on PDLF by using a three component fluxgate magnetometer in the same manner as described for the Mt. Etna stratovolcano (Tanguy and LeGoff, 2004). In both cases, the purpose of the study was to investigate the amplitude of the distortion caused by previously magnetized lava flows on the ambient magnetic field. With this aim in mind, measurements were carried out about 30 cm above the ground, on a sheet of paper fixed on

Table 3
Archeomagnetic directions of Piton de la Fournaise Lavas. N, number of samples used for calculations; n, total number of samples. I, magnetic inclination, D, declination, α95 and k, precision parameters. See Table 2 for ^{14}C calibrated ages.

Volcanic units	N/n	I (°)	D (°)	α95 (°)	k
1) 1976 flow along RN2 in Grand Brûlé	17/20	−53.1	−19.3	1	1162
2) 1931 flow near Vierge au Parasol	12/12	−52.1	−12.2	1.3	891
3) 1890 (or 1858?) flow, BRGM track	9/9	−53	−12.5	1.4	1072
4) 1863 (?) flow, base of Rempart de Bois Blanc (2 sites)	11/11	−51.2	−15.1	1.9	488
5) 1800 flow along Sentier du volcan (2 sites)	11/12	−50.8	−15.9	1.1	1391
6) 1776 flow at Pointe de la Table (2 sites)	19/20	−55.4	−12.8	1	1070
7) Pahoehoe flows within Enclos Fouqué, W of the older Formica Leo cone (1753? see text)	10/10	−50.6	−19.4	0.9	2411
8) 1708 flow below EDF reservoirs (2 sites)	16/19	−46.5	−16.2	1.4	595
9) Piton Taïpoul pyroclastic cone (see text for age)	8/10	−46.2	−1.5	1.6	880
10) Ravine Ango flow, ^{14}C dated 1520 circa	10/10	−34.8	−10.5	1.7	658
11) Petit Cratère cone and flow, ^{14}C dated 1515 circa	9/10	−37.1	−9.8	2.5	337
12) Baril 2 flow, W of Hotel du Baril (undated)	9/9	−37.6	−3.7	1.3	1298
13) Baril 1 flow, N of Hotel du Baril, ^{14}C dated 1390 circa	7/10	−35.7	−0.4	2	673
14) Mare Longue flow near the sea (undated) (2 sites)	14/14	−37.1	−6.1	1.2	982
15) Pointe Langevin flow (see text, Section 5, for age determination)	8/8	−31.7	−3.5	1.5	1017
16) Piton Chisny flows (3 sites, see text Section 5,for age determination)	24/26	−35.8	−7.1	1.1	620
17) Commerson crater pyroclasts, ^{14}C dated 200 AD circa (3 sites)	16/23	−49.6	−8.7	1.6	463
18) Piton Indivis flow (undated)	9/10	−35.8	+10.4	1.7	762

a horizontal tripod, and the magnetic North determined by making the Y component of the fluxgate equal to zero. Then, the shadow of the sun (for geographical North) was traced by using the same device as for the archeomagnetic samples. Declination was directly obtained from these two directions and inclination was calculated from the X and Z values given by the fluxgate (giving also the intensity F).

We thus performed measurements on the whole area for 10 of our studied archeomagnetic sites (Table 4): Mare Longue (MARL), 1976 flow, 1931 flow, Piton Indivis flow (INDV), 1776 flow, 1708 flow, Baril flow (BARIL), Commerson crater (COMM), Piton Chisny flow (CHISN), and caldera flow around the Formica Leo cone (FORM). In addition, we similarly determined the present field on 3 other sites outside the volcano, in regions where thick sedimentary deposits act as insulators: Saint Benoit (SBEN) on the eastern shore, Hermitage (HERM) and Grande Anse (GANS) to the West and SW. As expected, the results from these 3 sites are well clustered with a mean of I = −54.7°, D = −19.6°. These values fairly correspond to those deduced from the IGRF (I = −54.5°, D = −18.7°) for the region considered, and can be used as a reference direction to which the present EMF measured on the archeomagnetic sites is compared.

Fig. 2 shows that most of the archeomagnetic sites located low on the volcano exhibit a magnetic orientation close to that of our reference, D and I remaining within 2° of the geomagnetic direction given by the sites SBEN, HERM and GANS. Only the Commerson crater (COMM site 17, at an elevation of 2300 m) differs substantially from the reference, the 5° higher inclination being ascribed to the fact that this particular site was struck by lightning. We conclude that distortion of the EMF by the volcanic pile of PDLF usually remains within ±2° for its direction and ±1300 nT for its intensity, i.e. within the error expected from archeomagnetic sampling (see alpha 95, Table 3).

4. Archeomagnetic study of the lavas

Our large sample method (LSM) is extensively discussed elsewhere (e.g. Tanguy et al., 2003). On each kg-sized sample, detached with a hammer and then replaced in its original position, we make a plastered horizontal surface 5–7 cm in diameter on which the sun shadow is marked with a precision of a few tenths of a degree. This method allows us to sample with the same accuracy either lava flows or hot-emplaced pyroclasts such as welded scoriae found in the many cinder cones of PDLF. In the latter case, plaster is poured directly on a scoria of suitable size, which is further oriented without any displacement. As compared to the classical paleomagnetic minicores sampled by drilling, each of our large samples has the advantage of a better homogeneity of magnetization on a larger scale, better accuracy of orientation both in the field and laboratory, and no risk of parasitic drilling induced remanent magnetization (DIRM, Audunsson and Levi, 1989; Genevey et al., 2002), which may represent a large source of directional biases in core-drilling samples. We typically collected from each volcanic unit 10 samples or more distributed over a distance of several meters and often tens of meters. Whenever possible, we also prospected several sites, sometimes kilometers apart, of the same volcanic unit. As indicated in Section 3, we independently checked that no large distortion of the EMF was present over the whole area of sampling.

Following our previous studies on Italian volcanoes, the stability of the Thermo-Remanent Magnetization (TRM) of the lavas was checked by making two sets of measurements, the samples being first placed in their normal position (that occupied on the volcano) and the second after staying at least 2 weeks in reverse position within the present

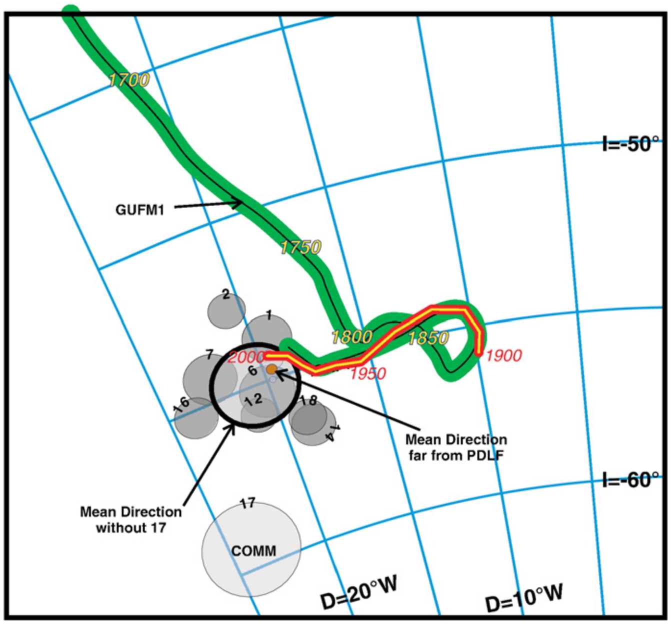

Fig. 2. Results from instrumental measurements of the current EMF performed on some archeomagnetic sampling sites (numbers are those reported in Table 3). Further archeomagnetic measures from the Commerson crater (COMM, n. 17) revealed that this particular site was struck by lightning.

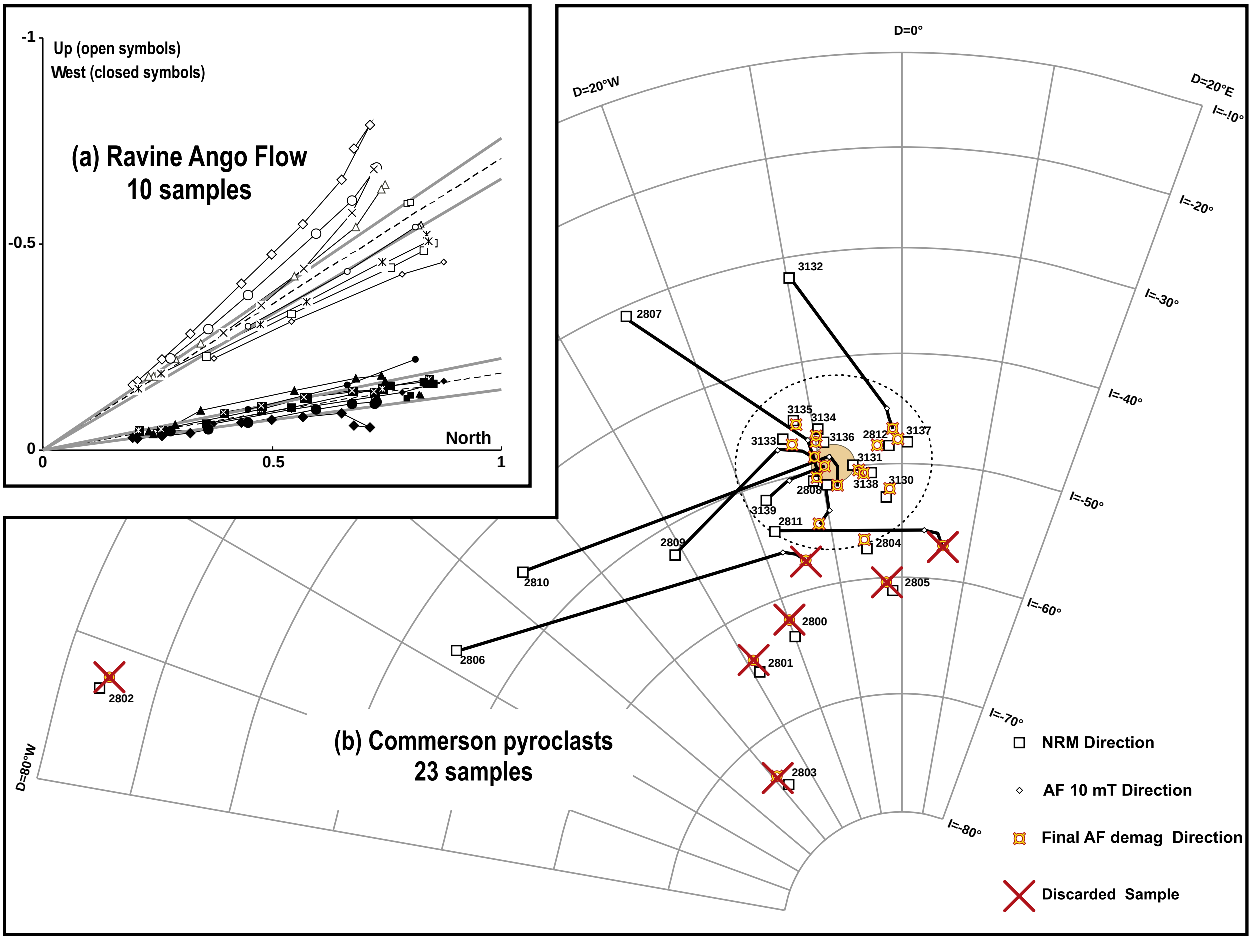

Fig. 3. AF demagnetization examples. (a) Orthogonal plot of unit vectors of the whole 10 sample directions of the Ravine Ango flow. Applied AF was between 5 and 40 mT, with different steps. Dotted and grey lines represent the Fisher mean direction. (b) Bauer plot of the particular case of the 23 samples of Commerson pyroclast. The pink circle is the Fisher mean direction, and the dotted circle represents the critical rejection circle of McFadden (1982). Final AF demag directions are for 20 to 40 mT.

EMF. The resulting unstable viscous remanent magnetization (VRM) was found very weak and never exceeded a few percent of the whole magnetization. For each site, pilot samples were submitted to alternating fields (AF) demagnetization in order to detect possible parasitic Isothermal Remanent Magnetization (IRM) due to lightning. When present, IRM was eliminated by AF cleaning up to 20–40 mT, and we checked on pilot samples that further demagnetization does not alter the paleodirections. Fig. 3a shows an example of common AF behavior for the Ravine Ango site where the 10 samples present a very small scattering around the mean direction. In a few cases when strong IRM cannot be entirely separated from the TRM, the sample was eliminated from the mean results of the site. Other cases of discarding consist of samples which are suspected to have been moved during cooling as revealed by their aberrant orientation. These discarded samples are very rare, except for the Commerson crater which consists of three sites all composed of pyroclasts (lava spatters or welded scoriae). On Fig. 3b we can observe that i) stable directions from the 1st site (samples 2800 to 2805) are scattered and well outside the McFadden (1982) critical circle of rejection (displaced after cooling), and ii) when present, the parasitic magnetization is almost removed after 10 mT AF. Unfortunately, the 1st site is that where sampling for the ^{14}C dating was performed.

Our final results (Table 3 and Fig. 4), are well-defined having the statistical parameters α95 in the range 0.9° to 2.5°, and k in the range 463 to 2411. It is widely recognized that the strong magnetization of volcanic rocks causes a shallow inclination recorded in the samples, mainly resulting from magnetic refraction owing to the underlying

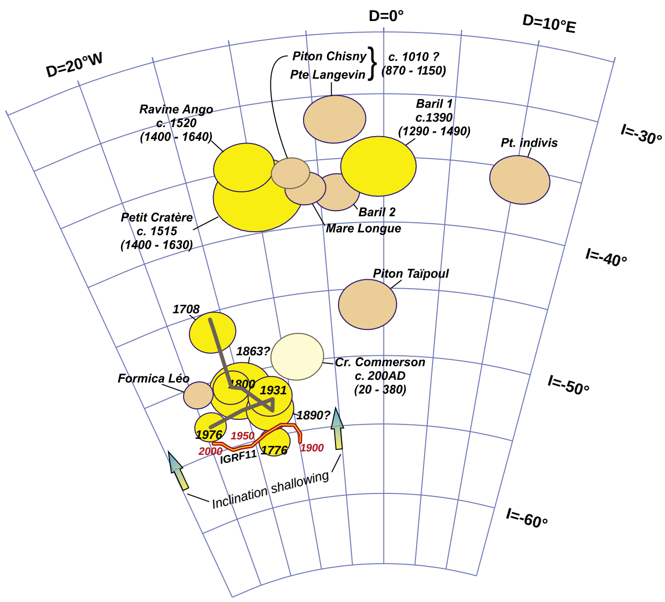

Fig. 4. Archeomagnetic directions obtained from the PDLF lavas (Table 3), represented by their 95% Fisher confidence circles. The brown line links our historically dated points except 1776 (see Section 6). Pink circles represent undated or doubtfully dated lavas. The light yellow circle is Commerson pyroclasts ^{14}C dated 20–380 AD. The arrows show the tendency implied by the shallowing inclination (see end of Section 3).

lavas or early magnetized parts of the cooling flow itself (Chevallier, 1925; Coe, 1979; Tanguy, 1990). This effect is evident for the 1976, 1931 and 1890 flows, which erupted at a time when the EMF can be considered to be well-determined thanks to data from observatories. Results from these flows show about 2° shallower inclination than that predicted from IGRF 11 (Fig. 4).

5. Discussion of the results

As illustrated in Fig. 5, the directional SV at La Réunion during the last 250 yr appears very different from that in Western Europe (Alexandrescu et al., 1997). While in Europe the path of the SV forms a single large oval encompassing about 15°, at PDLF all the points are clustered within half of this value, with the trend of the SV possibly making very tight loops. However, there is a decrease of inclination in 1708 continuing to circa 1500 (Petit Cratère and Ravine Ango, Fig. 4) and 1390 AD (Baril 1 flow), the paleodirection becoming close to that expected from an axial dipole (I ~−35°). The undated point of Piton Indivis is the only one to show an Eastward Declination of +10°.

We first compared these results to direct measurements made aboard trade ships (Fig. 6) compiled by Jackson et al. (2000) for their models, and made available by the British Geological Survey through the courtesy of Susan Macmillan (pers. comm. to M. LeGoff). In the Indian Ocean, close to La Réunion, thousands of measures of D have been performed since 1596, but only a few tens of I values after 1771. For both D and I, the directional dispersion reaches several degrees. Furthermore, the inclination measurements were made almost exclusively to the South of the island with an irregular temporal distribution. By selecting those measurements made within a 350 km-radius around PDLF and by reduction of I according to the present shape of the EMF (about 1° of inclination by 1° of latitude), we obtain the dispersion ovals of the mean directions represented in pink on Fig. 6 for the time intervals 1886–1876, 1847–1824, and 1780–1771, together with the dispersion range of D before 1771. This analysis shows that the global model GUFM1 from Jackson et al. (2000) fits fairly well the regional data, indicating that the modeling is not affected by any other on-board measurements from the rest of the world. However, the lack of any precise measure of I in any part of the world before 1700, nor of any intensity data, does not preclude a possible dilatation/contraction of the curve (D, I) from GUFM1 along a magnetic meridian. On Fig. 6 is also reported the path of the SV for the period after 1893, relocated from the Mauritius observatory (Eva Fareau, IPGP library responsable, pers. comm.), together with the IGRF 11 (since 1900).

Other compilations of data from archeological materials, volcanic or lake deposits have allowed the calculation of global models of the EMF extending over the past millennia. Five data sets and associated models are extensively discussed in Donadini et al (2009) and Korte et al. (2009). We have calculated the mean path of the directional SV predicted by these models during the last millennium (inset in Fig. 7). All the models fit the GUFM1 coefficients after 1650 AD, and they look similar during this period. Before 1650 AD, large discrepancies can be observed with respect to the data sets used, i.e. archeomagnetic data set (ARCH3k), sedimentary data alone (SED3k) or mixed with archeological ones (CALS3k), and to the different constraints and bootstrap methods applied. These data sets contain no archeomagnetic or lake data from the La Réunion region (as none are available; Figs. 2 and 3 in Donadini et al., 2009), the nearest being sediments in Kenya, more than 3000 km apart. It is not surprising that the ARCH3k model (great majority of data from Northern Hemisphere) differs greatly from the three others where sediments (found in Southern Hemisphere) are used. Nevertheless, the path of these three models for the last millennium is roughly in agreement with our data. Fig. 7 shows that two models (CALS3k.3MAST and SED3k.1MAST) best fit our results, keeping in mind that 2° of the shallow inclination should be corrected as shown by the dotted line elongated circles (particularly visible for the recent period).

For archeomagnetic dating of the PDLF lavas, we need firstly to have a reliable reference curve and secondly that the EMF changes sufficiently for discriminating the alpha 95 circles of the paleodirections in the lavas. The past 250 yr have, however, shown limited directional secular variation in the La Réunion region and we can only affirm that no large directional error affected the sampled flows

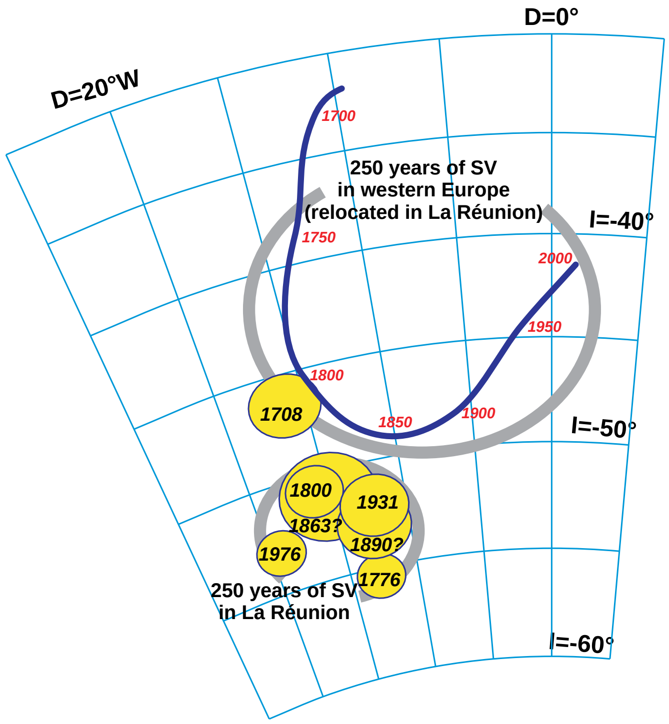

Fig. 5. Directional secular variation at PDLF for the last 3 centuries as compared to that of Europe relocated to Réunion (thick blue line).

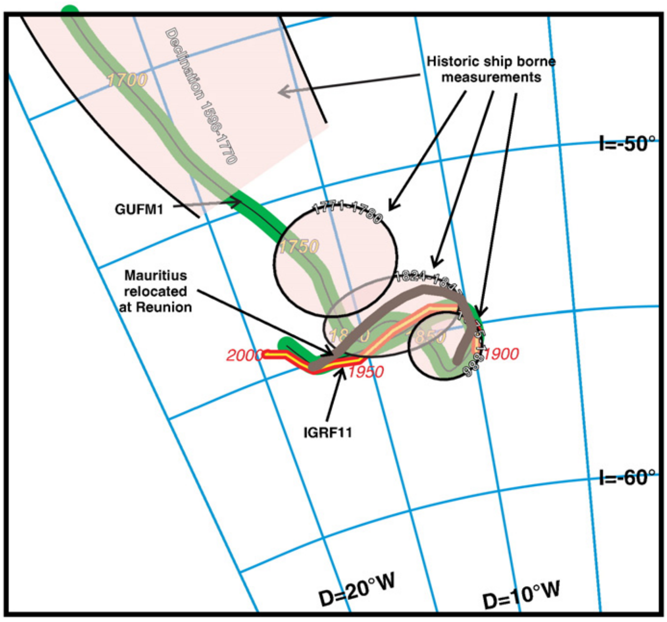

Fig. 6. Directional secular variation for the XXth century from Mauritius observatory relocated to Réunion as compared to IGRF 11. The transparent pink areas are confidence zones from inclination and/or declination measurements aboard ships (Section 5). The green line shows GUFM1 model.

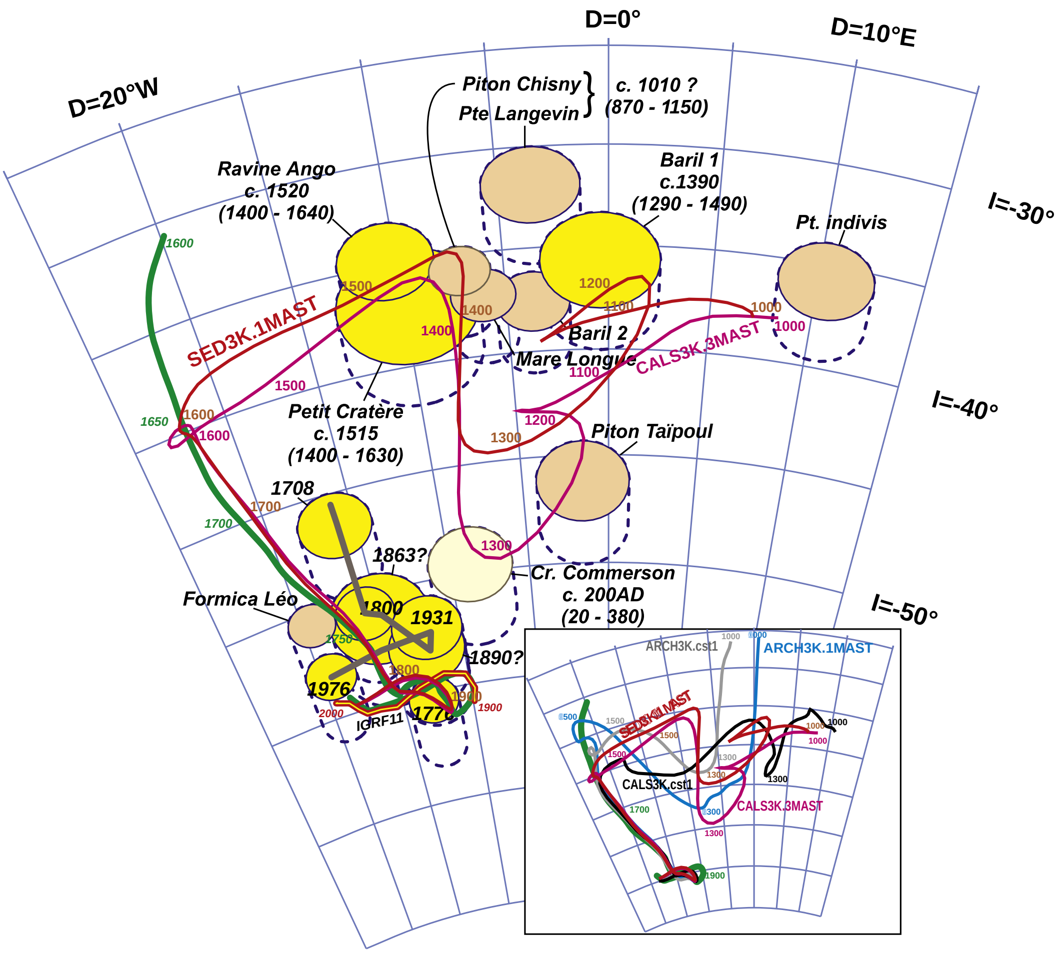

Fig. 7. Results from PDLF lavas compared to global models GUFM1 (green), CALS3K (magenta) and SED3K (red). Insert shows the extent of all the models discussed in Section 5. The thin blue dashed elongated circles and the thick blue dashed line indicate a probable 2° shallowing in inclination (see end of Section 4).

during this period (Fig. 7). The 1776 flow shows an anomalous direction of about 4° with respect to that of 1800, a fact that might result from post-eruptive collapse of the sampled region located just north of the feeding fissure. The degree of anisotropy of susceptibility of around 0.5% (measured with Agico KLY3) cannot explain the anomaly. Such a weak value is common for lavas.

When reasonably accepting' that the path of the SV (GUFM1) encompasses the paleodirection from the undated flows at the bottom of the caldera around the Formica Leo cone (Fig. 7), we may then conclude that these flows erupted between 1750 and 1800. This view agrees well with an independent study based on image analysis (Lénat et al., 2001) which leads to a probable emission by sustained activity from 1751 to 1794. Further into the past, the remarkable agreement between paleodirections and ^{14}C dating (circa 1500 AD) of the Petit Cratère and Ravine Ango flow leaves little doubt that these volcanic materials belong to the same eruptive period. From a structural standpoint, it is interesting to note that a unique 20 km-long fissure passing through the summit might have fed two diametrically opposed lava flows.

Fig. 7 also shows that the Mare Longue flow, despite a very fresh morphology, is necessarily older than circa 1500, and probably younger than Baril 1 (c. 1390). Similarly, the Piton Chisny products could have been produced at the same epoch. However a ^{14}C dating made on a lava flow several km down from Piton Chisny in the Rivière Langevin valley gave an age of 870–1150 AD (Table 2). This flow closely resembles our lavas sampled around Piton Chisny (olivine basalt containing dunite inclusions). On the other hand, the paleodirections of the Piton Chisny and Langevin lavas are different at the 95% confidence level (i.e. corresponding to two different eruptions), so that the proper age of Piton Chisny remains questioned.

Finally, the CALS3k.3 and SED3k.1 models seem to indicate that the Piton Indivis well-preserved lavas erupted towards 1000 AD, and the Piton Taïpoul cone was formed in about 1200. The Commerson crater pyroclasts dated 20–380 AD, that we sampled in two sites different from that of 14C dating (Section 4), could belong to an eruption at circa 1300, although a more ancient age cannot be excluded.

Clearly we lack independently dated lavas in order to trace the path of the directional SV for the period older than about 1500 AD and, therefore, any firm conclusion on archeomagnetic dating at PDLF remains pending until a reliable reference curve becomes available. Even if this aim is achieved, a multidisciplinary investigation would be useful for solving the ambiguities due to the same directions presented by the EMF at intervals of decades or centuries.

6. Conclusions

The large sample archeomagnetic method applied to the lavas of the past few centuries from Piton de la Fournaise gives new results on both the volcanic activity and the directional secular variation of the Earth's magnetic field in this region of the Southern hemisphere. Our main conclusions are as follows:

1) The secular variation at La Réunion appears significantly different from that observed in Europe. In particular, the small amplitude of the observed directional variations during the past 250 yr (I within

−50° and −55°, D from −13° to −19°) makes any archeomagnetic dating difficult for this period.
2) The global geomagnetic field models agree roughly with our results for indicating a larger directional SV for the span time 1750–1000 AD. It ensues that the Mare Longue, Piton Taïpoul, Piton Chisny and Piton Indivis lavas, are older than about 1500 AD, despite their fresh morphology.
3) Any further reconstruction of the SV at PDLF, and therefore any archeomagnetic dating, is dependent on the availability of new accurate geochronological data, such as ^{14}C or similar.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at doi:10.1016/j.epsl.2011.01.019.

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