ANNALI DI GEOFISICA, VOL. 44, N. 2, April 2001

Self-potential changes associated with volcanic activity. Short-term signals associated with March 9, 1998 eruption on La Fournaise volcano (Réunion Island)

Jacques Zlotnicki (1) (2), **Jean Louis Le Mouël** (2), **Yoichi Sasai** (3), **Paul Yvetot** (4) **and Marie Hélène Ardisson** (4)
(1) *UMR6530, Clermont-Ferrand, France*
(2) *Laboratoire de Géomagnétisme, IPGP, Paris, France*
(3) *Earthquake Research Institute, University of Tokyo, Japan*
(4) *UMR6524, Laboratoire de Géophysique d'Orléans, France*

Abstract

After six years of quietness La Fournaise volcano entered into activity on March 9, 1998. Fissures opened gradually downwards on the northern flank of the cone. Two cones, Kapor and Krafft built, from which lava poured until September 1998. Several other vents opened during this eruption. Mappings, surveys, and continuous recordings of the Self-Potential have been performed on the volcano for twenty years. SP mappings disclose the variability of large scale SP anomalies due to the modification of the hydrothermal system over some ten years. Most of the eruptions take place along a Main Fracture Zone (MFZ) in which ground water flows prevail. SP measurements have also regularly been made on the northern flank of the cone, on a west-east profile crossing the MFZ. Between 1981 and 1992 an enlargement and a shift of the MFZ to the east are evidenced. In particular, the eastern fissural axis trending N35°E could be related to the possible collapse of the east flank of the volcano. After a decrease between 1992 and 1997, the SP anomaly was enhanced again by the 1998 eruption. Short scale, about 250 m wide, 750 mV amplitude anomalies were superimposed on a large scale one, 2500 m wide, and about 250 mV in amplitude. For several years, continuous stations have been measuring the electric field along two directions, with a 20 s sampling, in order to record the genesis of SP signals associated with the volcanic activity. Oscillations belonging to the ULF band were evidenced several days before the 1988 eruption, some of them at 9 km from the summit. Their amplitude reached several tens mV/km. These oscillations sometimes present a phase lag from one station to another; they progressively shift towards the location of the future effusive vents. The polarisation of the oscillations is similar to the polarisation of longer SP variations (1 h period or more) and are correlated with the structural anisotropy. Finally, during the last hours preceding the effusive activity, huge SP signals, up to a few Volts/km, appeared at the stations located on the MFZ, and especially on the branch where the magma migrated. We interpret these SP signals as due to electrokinetic effects generated by fluid flow in cracks opened by the stress field changes.

Key words *self-potential – electric precursor – ULF band – self-potential mapping – eruption.*

1. Introduction

La Fournaise volcano is a basaltic volcano, 2640 m high, located in the south-east part of Réunion Island (fig. 1a,b; lat.: 21°10S; long.: 55°30′E). The volcanic activity is expressed by fissure eruptions taking place along a mechanical weakness axis: the Main Fracture Zone

---

Mailing address: Dr. Jacques Zlotnicki, UMR6530, 5 rue Kessler, 63038 Clermont-Ferrand, France; e-mail: jacques.zlotnicki@opgc.univ-bpclermont.fr

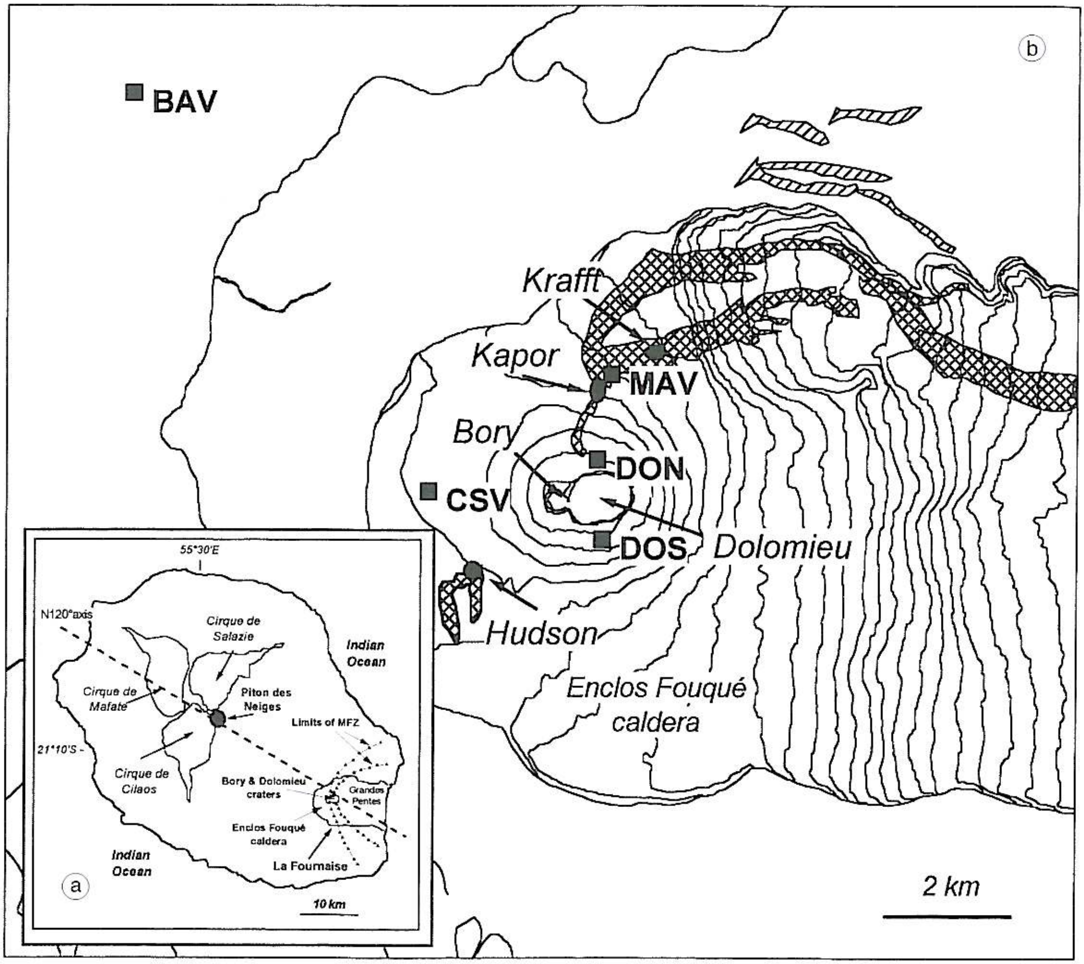

Fig. 1a,b. a) Location of Réunion Island. The dashed line corresponds to the N120°E volcanic axis, between Piton des Neiges and La Fournaise. The two lines with up triangles delineate the extension of the Major Fracture Zone (MFZ). b) Sketch of La Fournaise volcano with lava flow contours of the March-September 1998 eruption. Electric stations are shown by black squares.

(MFZ; Michel and Zlotnicki, 1995). Since the large eruption which occurred on the northern slope of the volcano in 1976, required evacuating several hundred inhabitants, the volcano has been the site of more than 30 eruptions or intrusive crises.

The monitoring of the volcano began in 1981, when an observatory was built at about 20 km from the summit. Magnetic measurements started in 1986 and volcanomagnetic signals, up to 15 nT in amplitude, were recorded in relation to most of the events (Zlotnicki and Le Mouël, 1988; Zlotnicki *et al.*, 1993). These signals were interpreted as due to electrokinetic effects (Zlotnicki and Le Mouël, 1990) according to the following reasoning.

First, the MFZ, as well as radial and concentric – with respect to the cone summit – fractures prevent large stress fields of several tens of MPa developing within the edifice; a dike can easily be injected in this unwelded system, migrating from an existing complex of dikes and sills located at a depth of a few kilometres below the summit (Briole, 1990; Zlotnicki *et al.*, 1990; Cayol and Cornet, 1998), or from deeper sources (Sean, 1998). A computation of the piezomagnetic effect at the ground surface resulting from a 10 MPa overpressure in a sphere of 1400 m in diameter buried at 5-6 km deep, gives a value of the order of 1 nT (Sasai, 1979, 1991; Pozzi *et al.*, 1983).

Second, annual rainfalls reach 5 m per year on the volcano summit. Inside the Enclos Fouqué caldera, all the water infiltrates the massif (fig. 1a,b). Water re-appears outside the caldera in the valley walls at low altitudes (about 1000 m), but most of the outcrops spring into the Indian Ocean below sea level along the direction of the MFZ (Sykioti, 1991; Violette, 1993). Inside the caldera the meteoric water is trapped and channelled by the main fractures such as the MFZ. The deeper the water percolates, the more its temperature increases. Hydrothermal cells result which carry electric charges, through electrokinetic and thermoelectric effects. Therefore, electric and magnetic signals are expected at the ground surface (*i.e.* Fitterman, 1978; Ishido, 1989). Computations of electrokinetic signals on La Fournaise give values adequate to explain the magnetic observations (Adler *et al.*, 1998).

This paper will focus on the electric signals associated with La Fournaise activity. We present the general features of the self-potential anomalies present on the volcano and their evolution over a large time span including the 1981-1992 active period (more than 25 eruptions), the 1992-1998 quiet period (no eruption), and the last period of renewed activity (1998 and later). We will use continuous recordings of the self-potential made at stations several kilometres apart during the outburst of the March 9, 1998 eruption.

2. The March 9, 1998 eruption

After the August 1992 eruption, La Fournaise entered a long quiet period. Only in November 1996 was a seismic crisis again recorded. This crisis was associated with an intrusion which stopped a few hundreds metres below the ground surface (Delorme, 1997). This 1996 event was followed by a slow increase in seismicity during 1997, and then by a rapid raise in January 1998. On March 6, 7, 8 and 9, 10, 35, 837 and 2300 earthquakes were recorded respectively. The focuses were at a depth of 2 km below the sea level during the night of March 8.

On March 9 at 1405 LT, a rapid slope change was recorded by the tiltmeters located in the vicinity of the summit. At 1505 LT a tremor started and became continuous five minutes later. Lava fountains progressively appeared along en-echelon fissures, from 2450 to 2100 m altitudes, on the northern flank of the Dolomieu crater (fig. 1a,b). Several hours later, lava fountains were limited to the lower tip of the fissures, and a cone started to build (Piton Kapor). A second cone, called Maurice and Katia Krafft, was built on March 10 (Sean, 1998).

Very few earthquakes were recorded on March 11 after 0200 LT. At about 0245 LT a small fissure was observed on the south-west flank of Bory crater (fig. 1a,b). A small cone (Hudson) was built which remained active until the last week of March.

During the following months, the effusive activity remained limited to the neighbourhood of Kapor and Krafft cones. In mid-July 1998, lava issued from the two cones reaching altitudes as low as 400 m. The tremor activity became sporadic. On August 7, the tremor activity sharply increased again, and on August 8, 9 and 14, fissures opened outside Enclos Fouqué caldera (fig. 1a,b). The eruption ended in September 1998.

3. Large scale SP anomalies and their time evolution

Several parameters can contribute to change the geometry and the amplitude of electrokinetic origin SP anomalies observed at the ground surface, even if the volcano structure does not change: the pressure gradient of fluids, the fluids temperature and chemical composition, and the refilling of the hydrothermal system.

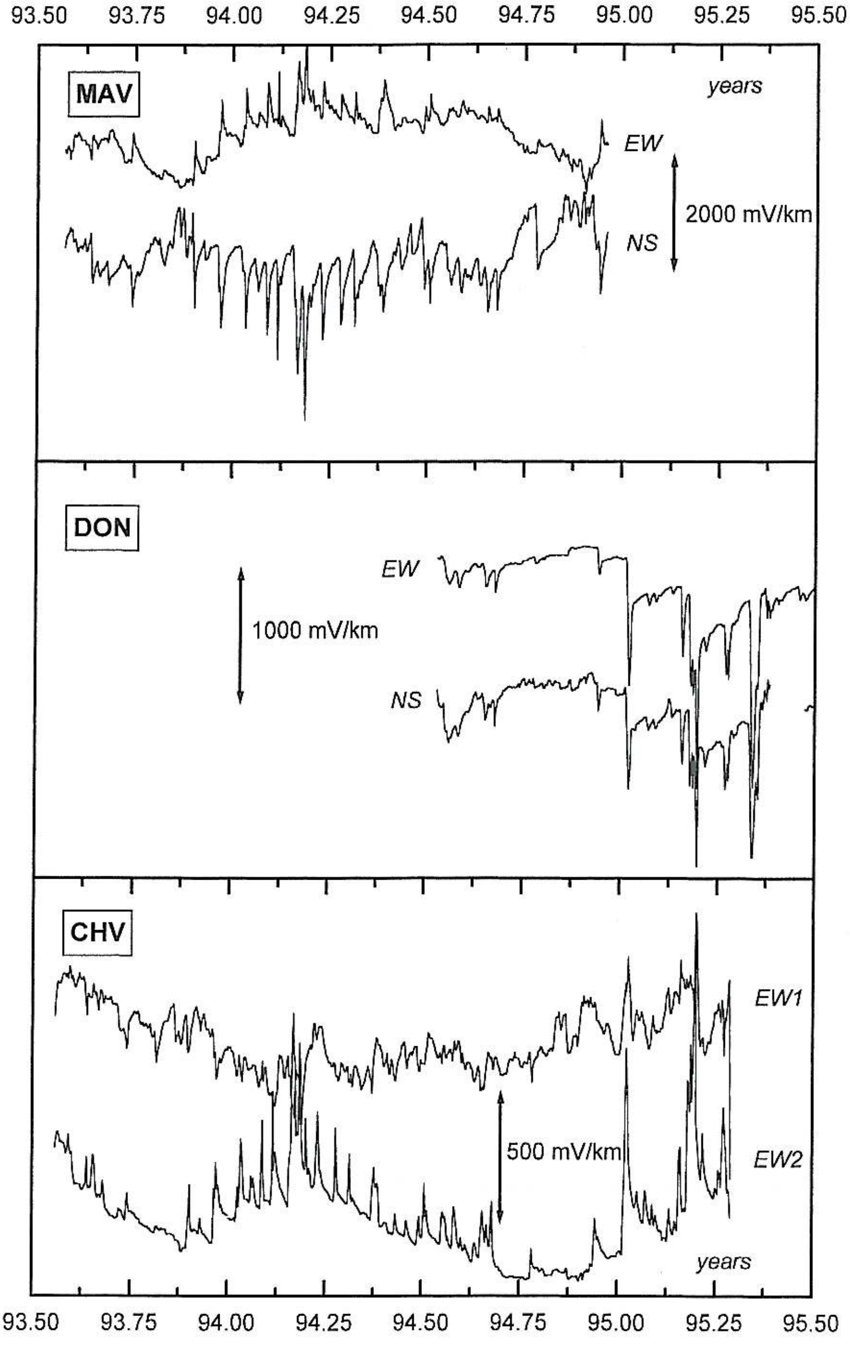

Fig. 2. Seasonal variations of the Self Potential recorded in different directions at several stations between 1993.5 and 1995.5

Much work has been devoted to estimating the relative order of magnitude of each mechanism. Pressure gradient generate amplitudes between 1 and 1000 mV/10 MPa (Zablocki, 1976; Ishido and Mitzutani, 1981; Fitterman, 1978). Temperature gradients generate amplitudes between – 0.25 and 1.5 mV/°C, with an average of 0.2 mV/°C (Corwin and Hoover, 1979; Morgan *et al.*, 1989). Chemical phenomena are difficult to evaluate and depend mainly on local conditions; nevertheless they generally imply negative potentials (Sato and Mooney, 1960).

Over several years time interval we can expect the average amount of annual rainfall to be almost constant (4.9 ± 0.3 m/yr on La Fournaise). But within one year, seasonal variations of rainfall and air temperature disturb the quasi-static pattern of the self-potential anomalies; about 56% of the rainfall on La Fournaise summit between January and March and the air temperature varied between 1°C and 18.1°C, with an average of 10.8°C over 13 years. On La Fournaise volcano potential gradients recorded at several stations show this annual change (fig. 2). The amplitude of the annual variation is not uniform: from about 50 to 500 mV/km; it appears to depend on the location of the station relatively to the MFZ and the main structural axes. Spikes due to large rainfalls are conspicuous on the northern cone flank where the 1992 SP mapping exhibits higher and sharper anomalies (see fig. 1 in Michel and Zlotnicki, 1998); fluid transfers and corresponding SP anomalies are enhanced along tectonic accidents. These results have to be taken into account when paths are regularly re-surveyed along structural accidents at different periods in a year (Malengrau *et al.*, 1994).

A Self-Potential mapping of the northern flank of Enclos Fouqué caldera was performed in 1981 (Lénat, 1987), and a second one was extended to the whole caldera in 1991-1992 (Zlotnicki *et al.*, 1994). In 1981 there had been no activity for several years, and the volcano could be considered in a quiet state; therefore the 1981 SP mapping can be considered as giving the 'zero level' of the anomalies.

Relatively to a reference point chosen far away enough from the active part of the volcano and taken as being at zero potential, negative anomalies are associated with downward infiltration of water while positive anomalies are due to fluids moving upwards (*i.e.* Massenet and Pham, 1985; Ballestracci and Nishida, 1987; Fitterman, 1992). In 1981, Lénat (1987) observed no large SP anomaly on the northern cone flank, but a positive anomaly, up to 1800 mV, centred on the cone. These observations mean that the cone was the site of a hydrothermal system which did not extend toward the north along the northern branch of the MFZ.

The 1981-1992 period includes 28 eruptions mainly located along the MFZ. The corresponding fissures, dikes, intrusions, and lava flow strongly disturbed the morphology of the hydrothermal system, especially along the MFZ and in the neighbourhood of the summit craters. Each volcanic event contributed to create a general SP pattern which outlines the main tectonic features of the volcano in which hydrothermal transfers are emphasised (fig. 3). If we assume that the reference point taken as zero potential is not subjected to large time changes, the amplitude of the SP signal generated by the 1981-1992 eruptions remains less than 1 V (Michel and Zlotnicki, 1998). Of course, local transient (few days to few months duration) signals can be larger: 1.25 V for instance for the August 1992 eruption (Zlotnicki *et al.*, 1994).

In order to evaluate the SP time changes across the MFZ in relation with the evolution of the hydrothermal system and the volcanic activity, we repeated measurements of the potential in 1992, 1997, and 1998, along the same profile, starting from the west flank of the cone, crossing the MFZ on the northern flank and ending on the east side of the cone (fig. 3). We can expect the potential of the reference point, located at the west of the surveys, to be almost constant: it is indeed located far away from the active part of the volcano, above a homogeneous substratum, and comparison between 1981 and 1992 SP mappings shows no noticeable change in the western part of the maps. Seasonal SP changes are also small in this area of Enclos Fouqué caldera.

The 1992 and 1998 profiles were realised with a 50 m sampling; the 1981 profile is computed from the 1981 SP mapping, and the 1997 profile was measured every 100-150 m in aver-

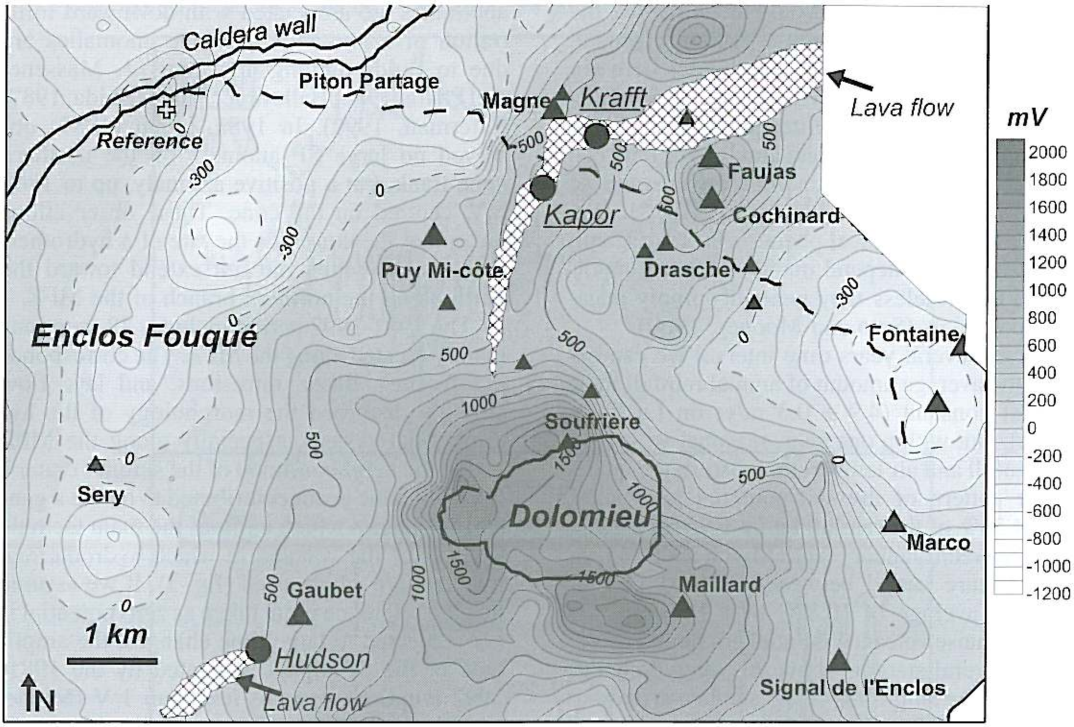

Fig. 3. Self-Potential mapping on the northern flank of the volcano (after Michel and Zlotnicki, 1998). Triangles correspond to major cones or craters. Heavy dashed line is the path used to re-survey the SP anomalies on the northern flank (see fig. 4).

age. Pb-$PbCl_2$ electrodes were used for the 1992, 1997 and 1998 surveys, and Cu-$CuSO_4$ electrodes for the 1981 one. GPS measurements were made every 300 m on average to constrain the 1992 and later surveys. Local reference points were also established to ensure a few identical locations for all the 1992-1998 surveys.

As said above, the 1981 SP survey can be considered the reference one. From west to east, the potential first decreases down to a minimum value of 500 mV, resumes smoothly a positive amplitude of about 350 mV at 2500 m distance from the reference point, and decreases again eastwards.

In 1992, we observed: i) the general pattern already in place in 1981; ii) a large double peaked positive anomaly with maxima centred along the two axes of N5°E and N35°E directions along which the eruptions of the 1981-1992 period took place (see fig. 7 in Michel and Zlotnicki, 1998). On the western part, the PS values jump from – 375 mV (at 2100 m from the reference) to about 625 mV in less than 500 m (N5°E axis). On the eastern part of the survey the decay is smoother: 1250 mV on a 1500 m length (N35°E axis). No sharp, large, short wavelength SP anomaly is observed on the MFZ itself.

The 1997 survey was made after five years of quiescence of La Fournaise volcano. Only the general pattern and the amplitude of the SP field can be studied (due to the large sampling interval). The general pattern is similar to the 1992 one. Two negative anomalies still enclose the positive one associated with the trace of the MFZ. These negative values are smaller than those measured in 1992, with an average of 200 mV. This difference between the two curves seems significant, especially if we take into account the months of the 1992 and 1997 surveys, July and April respectively. If indeed we take into account the seasonal variations of SP gradients measured along the MFZ (fig. 2), the decay from 1992 to 1997 of the SP anomalies observed along the N5°E and N35°E directions are more than 400 mV and 625 mV, respectively. These observations indicate that the SP decay between 1992 and 1997 concern a region about 2500 m wide, even if it culminates in the MFZ axis.

The 1998 survey was run on March 11, two days after the beginning of the March 9 eruption. The SP anomaly presents again a large positive amplitude in the central part of the MFZ (N5E°). The mean value of this main anomaly can be estimated to 400 mV more than the values of the 1997 survey. High and short wavelengths anomalies, 750 mV from peak to peak, 350 m in length, are located on the fissures axis. As in the case of the previous surveys, the SP anomaly increase starts at a distance of 2100 m from the reference point (fig. 4). One can suspect that the secondary axis of the MFZ (N35°E) is also affected by the 1998 eruption, up to distances of 4700 m from the reference. These changes show that the 1998 eruption disturbed the hydrothermal system all over the northern branch of the MFZ, over a width of 2600 m, generating an average increase in the potential of about 250 mV (if we suppose no change of the SP anomaly between 1997 and 1998).

4. Short-term electric signals associated with the March 9, 1998 eruption

Electric and magnetic stations have been installed for several years on La Fournaise (fig. 1a,b). The electric stations record the potential differences between $Pb-PbCl_2$ electrodes

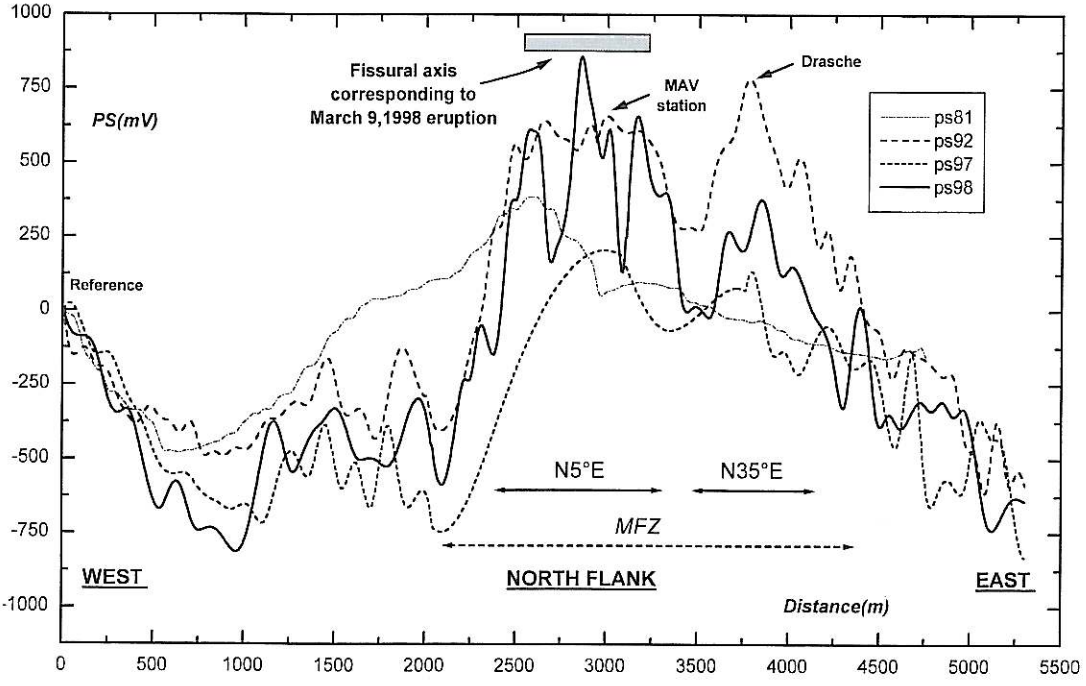

Fig. 4. Self-Potential anomaly along the profile described in fig. 3, made in 1981 (estimated), 1992, 1997 and on March 11, 1998. The zero potential is taken at the western end of the profile.

buried up to 200 m apart along two directions. Resolution is better than 10 μV. In 1998, data were collected with a sampling rate of 20 s. In this paper we will focus on SP data.

Only a small (a ten mV/km) daily variations and some small storms are recorded on the electrical stations until sharp variations appear on days 58, 63, and 67-68 before the March 9, 1998 eruption (fig. 5). Recordings of former years show that the weak rainfall occurring during this period cannot generate these SP variations. Part of the variations observed at mid-day 58 could possibly be due to a thunderstorm. The amplitude and behaviour of the SP variations appear to depend on the distance of the recording station from the summit and the Main Fracture Zone (MFZ): BAV and CSV stations, settled outside the cone, exhibit smooth and weak amplitude variations; even when the eruption occurred on day 68 (1505 LT). DOS station, located on the cone summit, and on the southern branch of the MFZ, also displays relatively

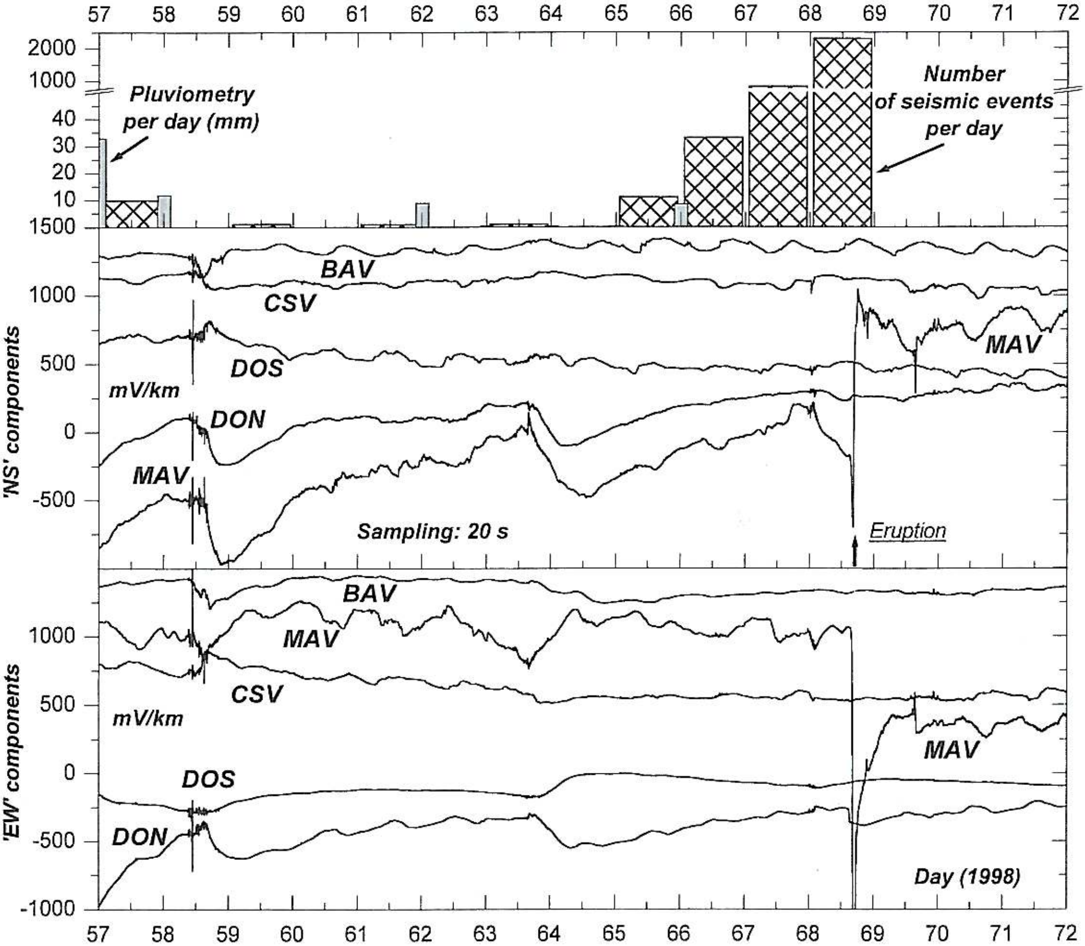

Fig. 5. Self-Potential variations of the two recorded components at BAV, CSV, DOS, DON, and MAV stations between days 57 and 72, 1998. In the upper part: number of earthquakes per day (after La Fournaise Observatory) and rainfall.

smooth trends on which rapid variations are superimposed (days 58, 63, 67-68). DON and MAV stations, located on the northern cone flank along the MFZ show large and correlated variations before the eruption, up to 500 mV/km, on which rapid variations are superimposed (see next paragraphs). Sharp variation starts at MAV on the night of day 67; it culminates with an amplitude of about 2000 mV/km when fissures open at 1505 LT on day 68. Let us consider now three sequences where rapid variations of periods less than a few hours are observed.

Sequence: 1400 LT - 2000 LT (day 63) – Well correlated variations, up to 130 mV/km, and of about 1 h time constant are simultaneously recorded at MAV, DON, and DOS (fig. 6). They mark the beginning of large variations which last until day 67, when new disturbances are again recorded (fig. 5). Superimposed onto these variations are more rapid and regular ones, called hereafter oscillations, which appear at MAV, DON, DOS, and with a lower amplitude at CSV. The largest amplitude is observed on the northern cone flank, where it reaches almost 40 mV/km at MAV. These oscillations have periods ranging from a few minutes (or less) to some ten minutes. The 20 s sampling is not fast enough to define accurately the characteristic periods of these oscillations, nevertheless 40-50 s, 70-80 s, and 120-140 s periods appear and wane. The morphology of the oscillations changes with time, and the time occurrence of trains of oscillations is not the same in all the stations (therefore they are not induced by the ionospheric field). Dashed lines have been tentatively reported in fig. 6 to point out the times when the signals (trains of waves) reach the different stations. They first appear on the summit, three minutes later at MAV, and about 10 to 20 min later at CSV. These trains of oscillations last from a few minutes to almost an hour, then are lacking during time intervals of ten minutes to half an hour, and then appear again. All of them disappear everywhere after about twelve hours.

The chronology of the events is the following. Oscillations with periods less than a few minutes appear at the stations located inside Enclos Fouqué caldera, with a larger amplitude on the northern flank. After these signals have reached a peak in amplitude, longer period variations (1-2 h) start. The amplitude of those latter variations remains larger on the northern cone flank. Afterwards, large and smooth variations appear associated with a recovery period of several days (fig. 5).

An estimation of the energy of the oscillations (periods less than 180 s) can be obtained by filtering the data with a one hour frequency high-pass filter and computing the variance with 200 s windows (fig. 7). The largest signals on both components at MAV are normalised to 100. Results on the north components are the following. A high level of energy is already present at MAV before the day 63 when spikes (large amplitude oscillations) also occur at DOS, and DON at 1000 LT. After about three hours of calm the energy sharply increases again at the three stations MAV, DON, and DOS (1500 LT on day 63) with maximum amplitudes of 100, 38, 32, and 8, respectively. Afterward the energy slowly decreases and returns to values comparable to those recorded before the spikes appeared. At CSV a diffuse energy is recorded during this time interval and there is no more energy after 2300 LT on day 63. The relative energy at each station can be estimated by the ratio E{MAV}/E{DON}, E{MAV}/E{DOS}, and E{MAV}/E{CSV} (fig. 7). The energy is clearly concentrated at MAV at the beginning of the considered period (till day 63.67 (1600 LT)); at that time E{MAV}/E{DON} and E{MAV}/E{DOS} are of the same order of magnitude. On day 64 the energy at DOS strongly decreases compared to those at DON and MAV; oscillations are mainly located on the northern flank of La Fournaise cone.

Sequence: 2200 LT (day 67) - 0400 LT (day 68) – Between 2200 LT (day 67) and 0400 LT (day 68) about 400 earthquakes are recorded; their foci are about 2 km below sea level (Sean, 1998). Large 1-2 h period electric variations, similar to those observed on day 63, are recorded after 000 LT (day 68) (figs. 8 and 9). At 0000 LT on day 68, the amplitudes reach 170, 120, 100, 40, 10 mV/km at MAV, CSV, DON, DOS, and BAV, respectively. It is noticeable that these large amplitude variations start after the appearance of the oscillations (2300 LT on day 67 for

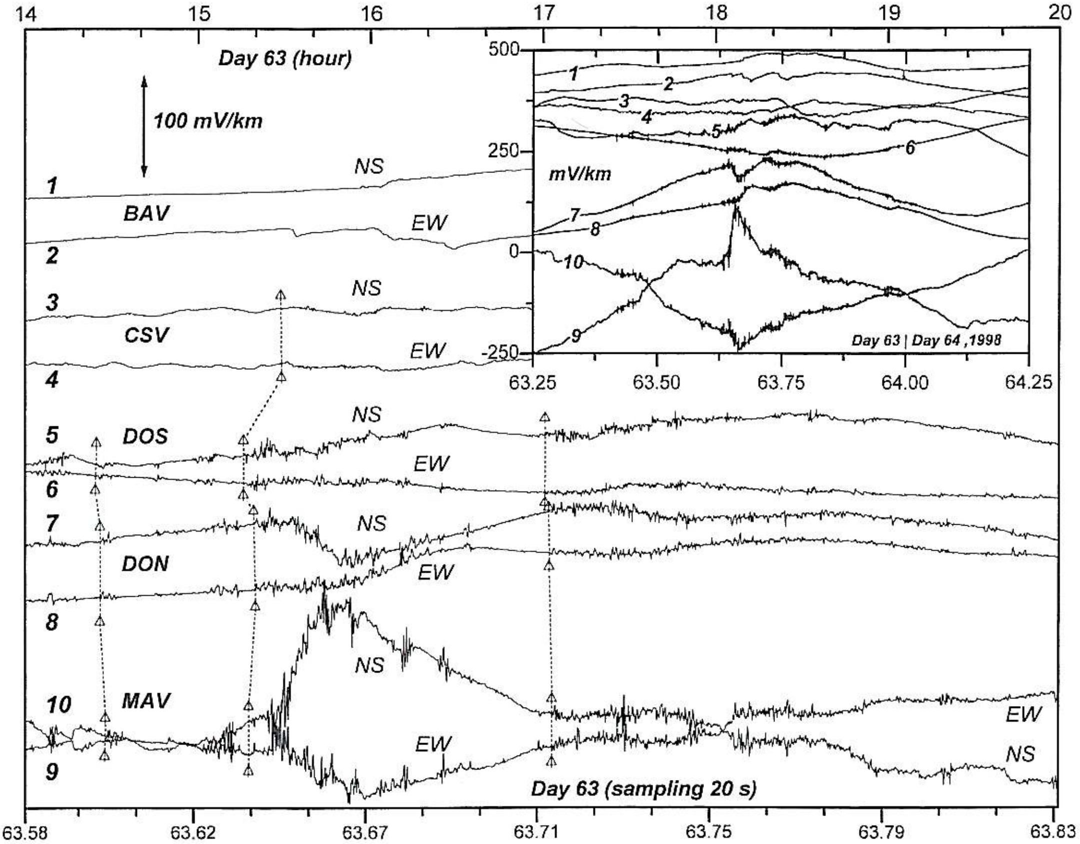

Fig. 6. 20 s recordings of the SP variations at the five stations between days 63.25 and 64.25 (small cartoon), and between 1400 LT and 2000 LT on day 63, 1998.

most of the stations). These oscillations occur only inside Enclos Fouqué caldera with a larger amplitude at MAV (100 mV/km) and a very weak amplitude at CSV (4 mV/km). At the beginning, they simultaneously appear in the three stations DOS, DON and MAV, several km apart from each other. After a 30 min calm period, oscillations appear on the summit at DON, 3 min later at DOS, 10 min later at MAV, and probably 20 min later at CSV. Around 0030 LT (day 68), oscillations appear first at DOS, 3 min later at DON and MAV and 8 min later at CSV. After 0100 LT (day 68), the time delay between oscillations at DON and CSV remains on the order of 10 min. These observations suggest a signal propagating towards the north of the cone. The estimation of the horizontal propagation velocity could be about 3 to 5 m/s. The oscillations have characteristic periods of about 40-50 s, 70-80 s, and 120-140 s. The oscillations are not observed at BAV, located 9 km away from the volcano.

Figure 9 presents the energy, computed in the same way as described before, of the SP variations of less than one hour period, and the corresponding energy ratios between days 67.5 and 69.5. The increase in the energy starts abruptly in comparison with the first sequence described above. Once more the energy is larger at MAV and DON, but some energy is now

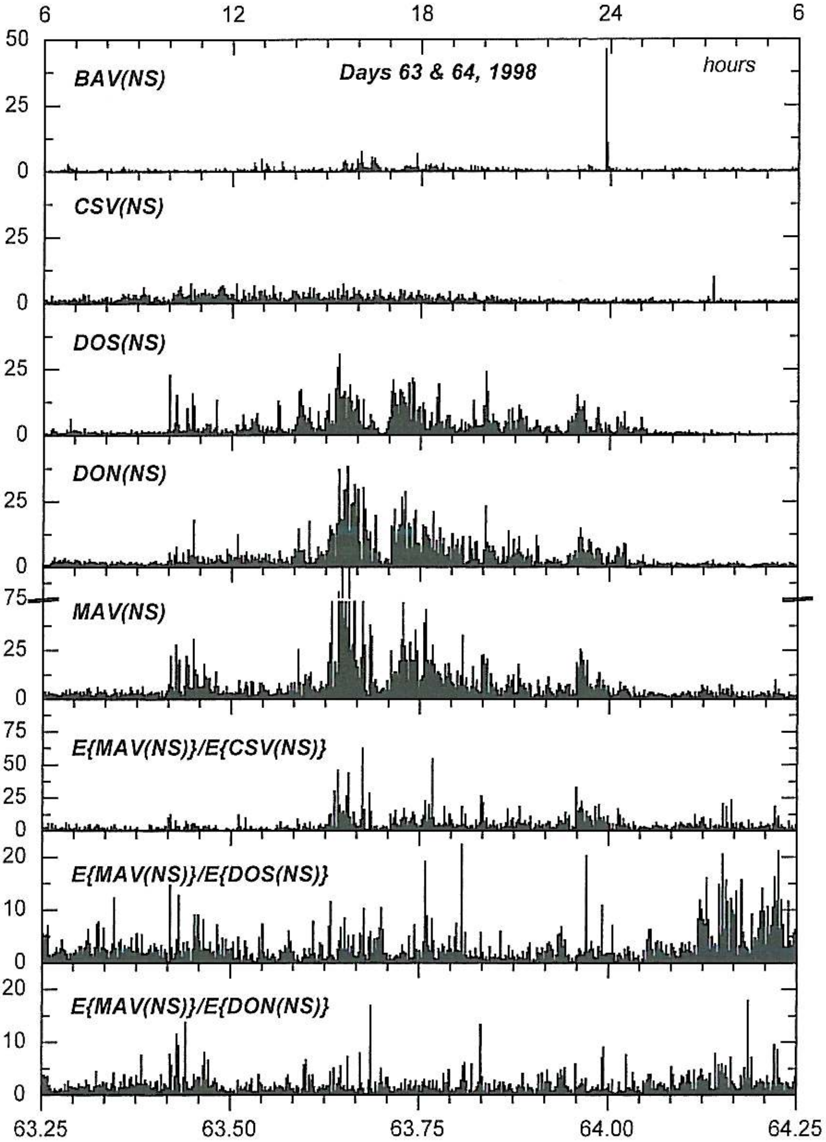

Fig. 7. Variance computed on 200 s windows at the five stations for the NS component between days 63.35 and 64.25. The three lower graphs present the ratio between variances at MAV, and CSV, DOS, and DON.

observed at CSV (see at 68.00 on fig. 9). At about 1600 LT, the energy at MAV sharply increases, indicating a displacement of the energy toward the north. The ratio E{MAV}/E{CSV}, E{MAV}/E{DON} and E{MAV}/E{DOS} also indicate an energy well located beneath the northern flank of the cone at the time when the eruption starts (1505 LT on day 68). It is noticeable that a weak energy is also present at BAV at about 1200 LT on day 68.

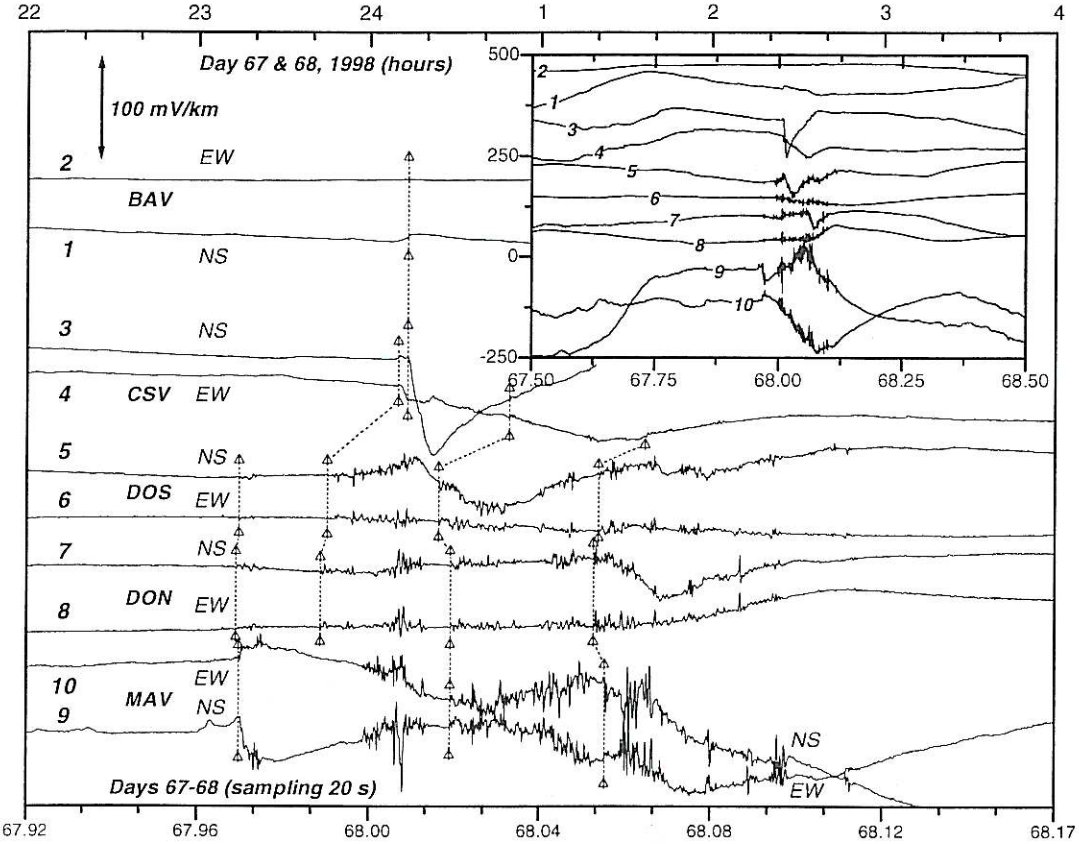

Fig. 8. 20 s recordings of the SP variations at the five stations between days 67.50 and 68.50 (small cartoon), and between 2200 LT (day 67) and 0400 LT (day 68).

Sequence: 1200 LT (day 68) – 2400 LT (day 68) – At 1200 LT earthquakes are registered with foci located above sea level. The volcano summit starts deforming rapidly, at about 1400 LT (Sean, 1998). At that time, the tiltmeter settled on the northern rim of Dolomieu crater indicates a migration of magma towards the north, with a peak in the rate of deformation between 1424 and 1429 LT. At 1505 LT a tremor starts and vents open.

SP recordings do not show any oscillations like those observed during the two sequences discussed previously; only large variations are recorded at MAV, DON, DOS and CSV (fig. 10). At DON, DOS and CSV they start at 1400 LT. At DOS, the traces present a weak minimum at about 1430 LT when the east SP component at DON starts to decrease rapidly; it stops about 10 min after the opening of fissures. The variations at DON are relayed by those at MAV starting at 1505 LT when the first vents become active. The signals at MAV, 2500 mV/km in amplitude, are associated with the progressive opening of fissures from 2450 m to 2100 m in altitude.

The SP variations show that the electric field is strongly disturbed by the March 9, 1998 eruption. The components of the electric field along the north and east geographic axes have been computed, and a polarisation diagram drawn

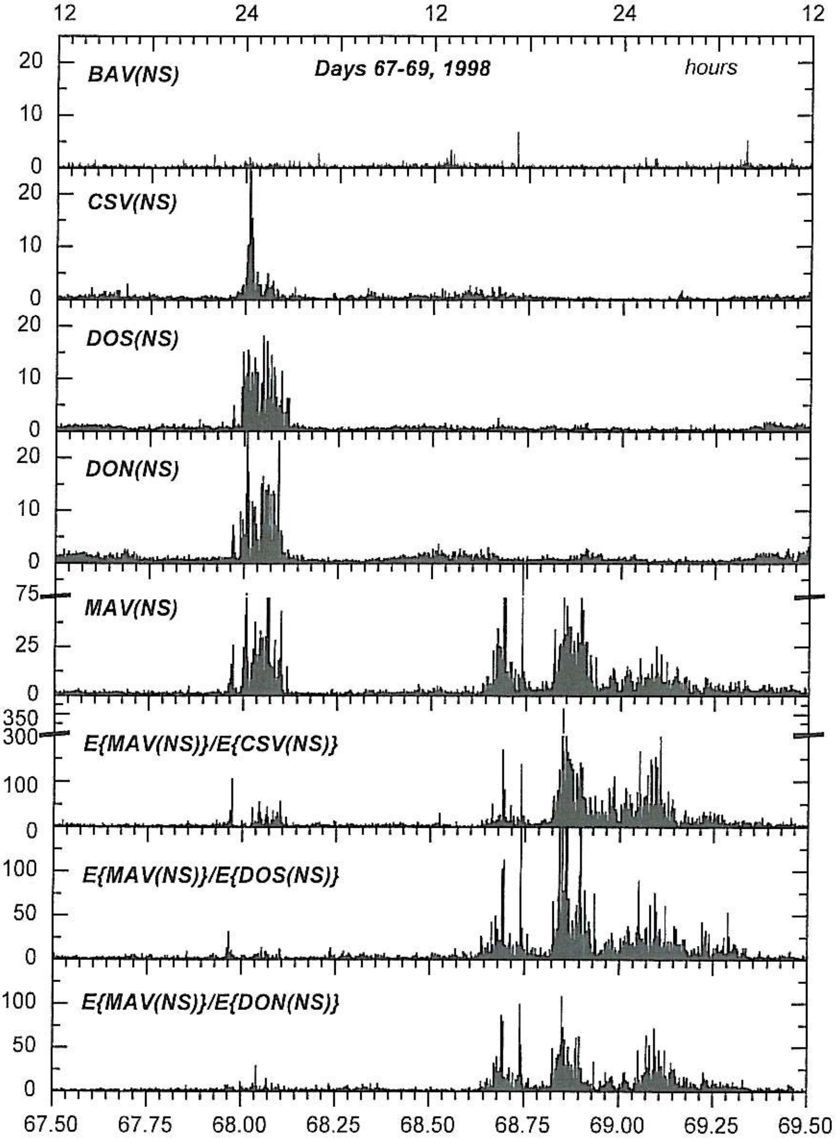

Fig. 9. Variance computed on 200 s windows at the five stations for the NS component between days 67.50 and 69.50. The three lower graphs present the ratio between variances at MAV, and CSV, DOS, and DON.

(fig. 11). On day 68 one can assume that the electric field at BAV, and maybe at DOS and MAV, is not largely affected by the volcanic activity before 0600 LT and after 1900 LT (it can be checked on previous recordings). Therefore a 'normal' polarity can be estimated in these stations. The normal polarities are N155°E, N150°E, and N140°E, in BAV, DOS, and MAV respectively. At DON, DOS, and CSV the oscillations and the 1-2 h period variations occurring

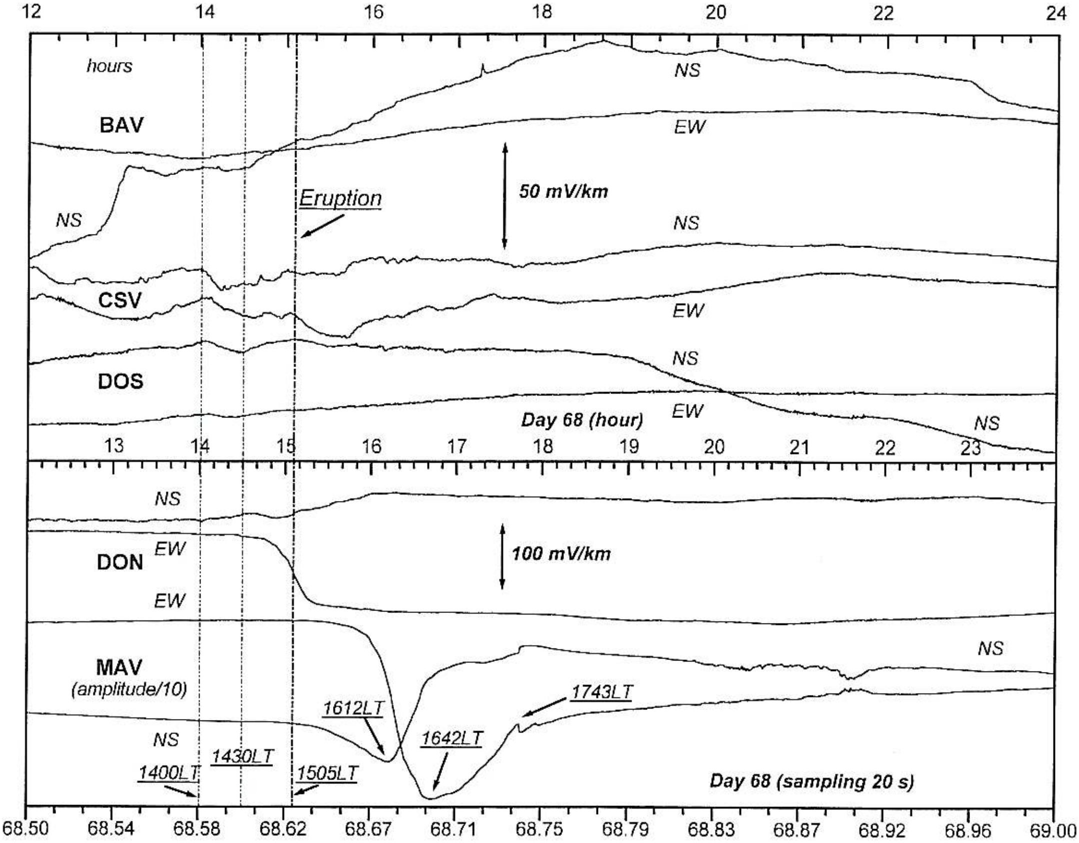

Fig. 10. 20 s recordings of the SP variations at the five stations between 1200 LT and 2400 LT on day 68, 1998.

about 16 h before the eruption prevent evaluation of such a normal polarity. From about 0700 LT to 1200 LT the electric field recovers a linear variation almost everywhere; at DON the polarity is practically orthogonal to the polarity observed previously. After 1200 LT almost all the stations present disturbances in the polarity of the electric field which become conspicuous at DOS, CSV, and DON after 1400 LT. Maybe some change could also exist at BAV. At DON the variations become larger and larger until 1520 LT when fissures have also opened in a south-north direction. At MAV the polarity and amplitude of the electric field evolve after 1500 LT; from a rough north-south direction the polarity rapidly switches to an east-west one before 1600 LT, moves to a south-east-north.West direction from 1600 until 1700 LT, takes again an west-east direction during three quarters of an hour, before recovering its normal N140°E direction. On the summit, the average amplitude of the variations are 20, 100 and 3000 mV/km, at DOS, DON and MAV respectively. The variations in the polarity and in the amplitude of the electric field are well related to the opening of fissures at 2450 m in altitude to the north of DON and their progressions toward MAV station.

The oscillations may have a higher frequency content than can be recorded with our 20 s sampling. Nevertheless, the polarity of the oscillations is relatively well defined (fig. 12). At

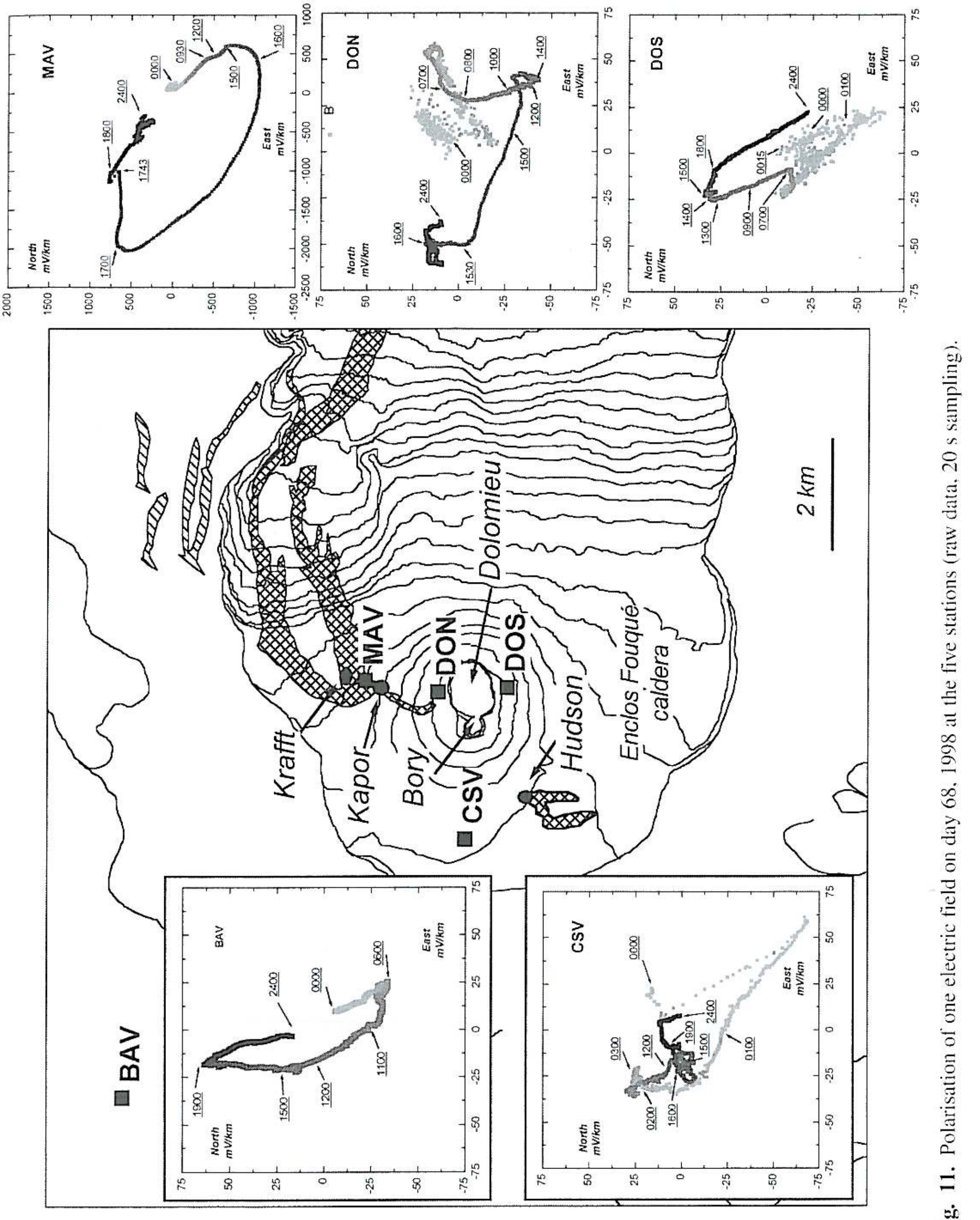

Fig. 11. Polarisation of one electric field on day 68, 1998 at the five stations (raw data, 20 s sampling).

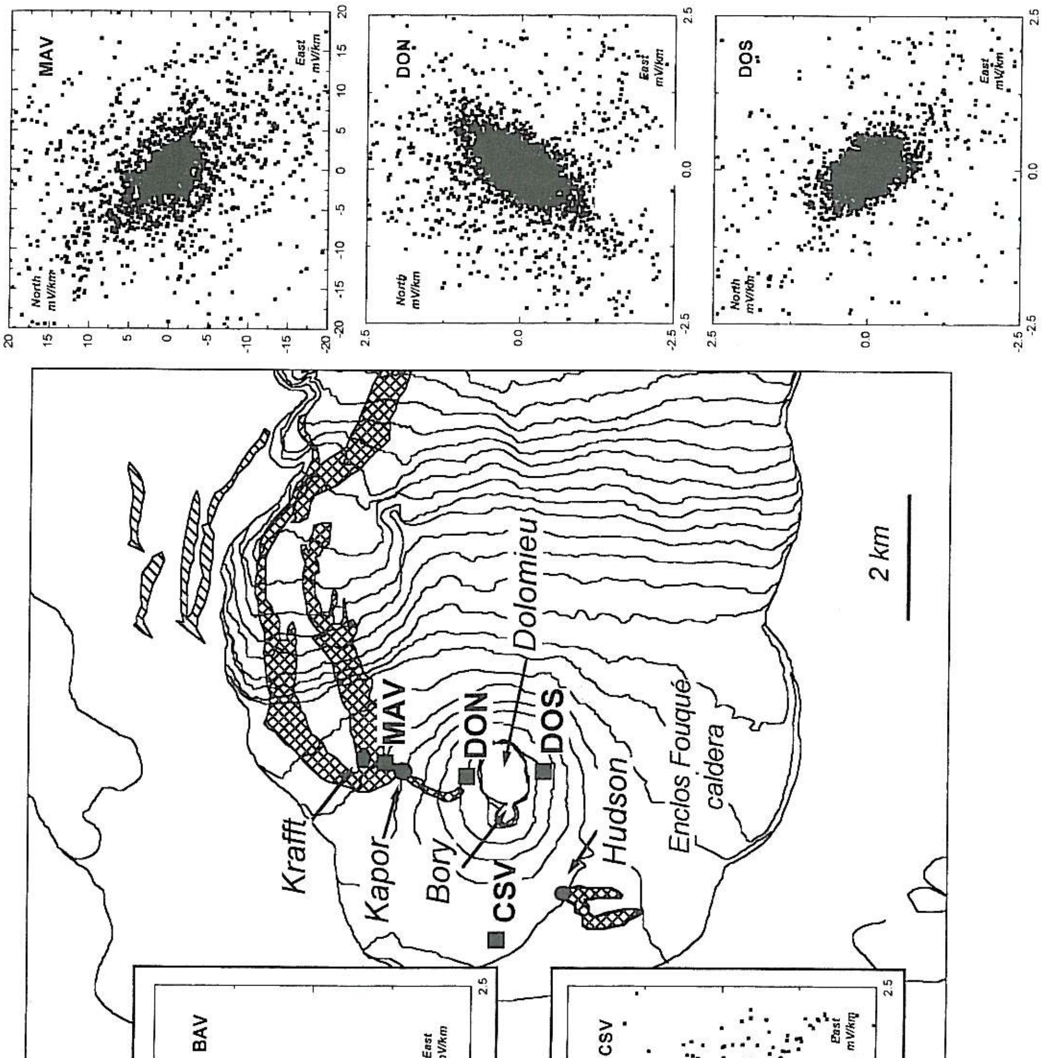

Fig. 12. Polarisation of one hour high pass filtered data of the electric field on day 68, 1998 at the five stations.

BAV, DOS, DON, and MAV, the polarity is about N150°E, N140°E, N40°E, and N140°E, respectively. There is almost no polarity at CSV. These values are not far from those we previously called normal. This supports the geological meaning of those sharp period oscillations which belong to the so-called ULF band.

5. Discussion

Whatever the volcanic activity is, La Fournaise volcano is the site of large scale long-standing SP anomalies. One of them is positive and centred on the cone. This anomaly is generated by the hydrothermal activity beneath the cone. Data between 1981 and today show that the pattern and the amplitude of this positive anomaly are more or less constant; which supposes an equilibrium between the refilling of the hydrothermal system by rainfall and the heat transfers generated by dike or sill complexes which induce convective water circulations.

These long-standing anomalies present seasonal variations attributed to the combination of seasonal temperature and rainfall variations. The seasonal variations can be wide in the vicinity of faults (*i.e.* the MFZ) and along highly permeable interfaces. When structural heterogeneities are present, the larger the anomalies are, the larger the amplitude of seasonal variations. Such information has to be taken into account when SP surveys are made during several years.

Superimposed onto the long standing SP anomalies with their seasonal variations are SP signals generated by the volcanic activity; the latter modify the pressure field, the permeability of the medium and then the associated ground water circulations. In 1981, smooth anomalies are observed north of La Fournaise cone (Lénat, 1987). A positive peak, about 400 mV in amplitude, 750 m wide, is centred on the western border of the MFZ which was activated by the 1981-1992 eruptions. In 1992, large SP anomalies delineate again the MFZ on which eruptions took place. Superimposed on a large scale feature, 2500 m wide, two smaller ones coincide with two main fissural axes (N5°E and N35°E) on which most of the eruptions took place. The comparison between the 1981 and 1992 SP mappings show that (i) the pattern of the SP anomalies can change in a decade, scales reaching several kilometers and with amplitudes up to 750 mV, and (ii) the location of the structures involved in the ground water channelling can shift.

When SP profiles are regularly measured over several year time spans, the stability of the potential at the reference point must be assessed. It should be taken outside the areas where SP anomalies can change with the volcanic activity, as on the cone, and in places where seasonal changes are weak. The profile, crossing Enclos Fouqué caldera to the north, measured in 1992, 1997, and 1998, respects these conditions. Therefore major information can be outlined.

– The 1981 positive anomaly delineates a small fracture zone, which is located at the western edge of the large MFZ described in the 1992 SP mapping (Michel and Zlotnicki, 1998). In 1981 no fissural axis exists along the N35°E direction.

– The anomalies developed between 1981 and 1992 and associated with the MFZ took place to the east o f the 1981 fracture zone. The width and the amplitude of MFZ anomalies are large, 2500 m and 750 mV, respectively.

– After five years of quietness of the volcano (1992-1997 period), the decay of the positive anomaly associated with the MFZ reaches 625 mV. Small scale anomalies have disappeared.

– The 1998 eruption enhanced the general anomaly measured in 1997. Now SP anomalies recover the pattern of those of 1992. Short wavelength anomalies are well correlated with the 1998 fissures, the amplitude of which reaches 750 mV.

– The 1992, 1997, and 1998 surveys show that the SP anomalies associated with the MFZ always appear in the same area of the volcano. This observation implies two different structures, of high permeability contrast, of north-south direction, with a larger permeability within the MFZ. When highly permeable structures are generated by the volcanic activity, they channelled ground water circulations at the expense of other existing structures of lower permeability.

– The displacement of the positive SP anomalies between 1981 and 1992 points out: i) a shift to the east of the volcanic activity, and

ii) the formation of a new fissural axis, of N35°E direction and of small width, which could be associated with the possible collapse of the east flank of the volcano (*i.e.* Sigmundsson *et al.*, 1999).

Regular SP mappings and SP surveys on volcanoes give valuable information on the geometry of hydrothermal circulations and their changes over a long time span. But they cannot give information on the genesis of the SP signals during the preparation of an eruption. Continuous recordings at several sites in two directions are necessary.

For the first time, oscillations belonging to the ULF band have been observed on a volcano. The periods are less than several tens of minutes with characteristic values of about 40-50 s, 70-80 s, and 120-140 s. The 20 s sampling prevents detection of smaller periods. Amplitudes range between a few mV/km to several tens of mV/km. Some of these oscillations were recorded five days at least before the March 9, 1998 eruption. A few of them were recorded 9 km away of the volcano summit, when the most energetic oscillations occurred. Oscillation trains can be delayed up to ten minutes from one site to another one. Displacement of the energy of the oscillations is in accordance with the location of future effusive vents. More examples are needed to validate this first result. The oscillations are well polarised and the polarisation seems to depend on the location of the recording station with respect to the structural heterogeneity and the local resistivity.

In the case of the March 9, 1998 eruption of La Fournaise, oscillations are followed by the appearance of large variations of 1-2 h periods. Their polarisation remains similar to the polarisation of the oscillations. This result indicates that there is some consistency between all these variations with periods less than a few hours.

The mechanism which could give rise to these oscillations could be similar to those proposed for ULF emissions along active faults (Dobrovolsky *et al.*, 1989; Fraser-Smith *et al.*, 1990; Draganov *et al.*, 1991; Fenoglio *et al.*, 1995). In an hydrothermal system in equilibrium, SP anomalies are representative of large and stable ground water circulations on which seasonal changes are superimposed. When the stress field increases within the volcano due to some renewal of activity (a magma batch for instance), the pore pressure distribution changes, and overpressures concentrate along mechanical weakness axes where pre-existing cracks or fissures exist. When a threshold value corresponding to opening of cracks is reached they open and propagate. The fluids contained in the pores before disruption quickly flow into the propagating cracks in which the pore pressure is weak. The fluids fill the new cracks until the propagation stops. Such fracturing could imply oscillatory phenomena in the fluid flow until the pore pressure recovers the hydrostatic equilibrium. These oscillatory phenomena could be controlled by the geometry and permeability of the activated fissures (Fenoglio *et al.*, 1995). A time delay is then necessary to open further cracks and this time span could correspond to periods where no oscillations are recorded. The roughly constant durations of lack of oscillation periods could be associated with the time needed for the loading to reach the threshold value necessary to re-open new cracks. This mechanism would exist only if the medium is not extremely fractured.

The opening of small cracks most likely participates in the progressive opening of large fissural axes. This could explain the homogeneity of the polarisation of the electric field for a large range of periods (40 s to several hours) in accordance with the structural heterogeneity. The mechanism described above reflects non homogeneous phenomena. It favours the genesis of oscillations in areas where pre-existing fractures already exist and where the permeability is high. In the La Fournaise, case of all main active fissural axes like those described in Michel and Zlotnicki (1995, 1998) are good candidates as the site of electric oscillations. For the 1998 eruption the MFZ, and the N225°E axis were preferentially activated by the renewal of activity. This observation could well explain that oscillations and 1-2 h periods variations both have their polarisation controlled by the same structural heterogeneities. The disappearance of most oscillations when the activity is growing could be due to the opening of cracks or fissures, too large to generate oscillatory phenomena.

The large changes in the polarisation and in the amplitude of the electric field prior to the opening of the effusive vents at the ground surface are controlled by the same structural heterogeneities. The polarisation of the electric field becomes a marker of the resistivity variation associated with the lava migration inside the driving heterogeneity, mainly the N5°E axis in the case of the March 9, 1998 eruption. The electric field direction seems to clearly point out the emplacement of the vents. The amplitude became larger and larger, from DOS and DON toward MAV, where most active vents have appeared.

6. Concluding remarks

One of the efficient methods to obtain information on the existence, geometry, strength and time variation of a hydrothermal system is the electric self-potential method.

SP mappings are useful to disclose contours of a hydrothermal system and associated upward and downward ground water circulations. The central part of a volcano is generally submitted to convective cells maintained by the interaction between the infiltration of meteoric water and the upward dissipation of heat issued from the magma complex. On the flanks, ground water is driven by structural heterogeneities like faults, fissures and highly permeable media. Therefore, the most active faults are the site of positive anomalies which wane far away from the summit. SP mappings regularly made in the course of years can follow the migration of the activity. On La Fournaise, a new N35°E axis formed after the 1981 eruption and contributes to the long-term tendency to destabilise the east flank of the volcano. SP profiles regularly sampled give detailed information over several kilometers if the potential reference is taken with great care. This reference has to be outside faulted zones where seasonal changes are weak, and of course outside the central part of the volcano where positive anomalies are high. With such caution, time constants and spatial scale of SP variations reflect phases of activity or rest. On La Fournaise, a decay of several hundred mV in amplitude was observed between 1992 and 1998 on the northern flank. The 1998 eruption emphasised the same large scale anomaly as in 1992, 2500 m wide and with an amplitude up to 625 mV, on which short wavelength anomalies, 250 mV wide and 750 mV in amplitude, are superimposed.

Continuous SP recordings at several locations on a volcano are a powerful tool to monitor the volcanic activity. Oscillations belonging to the ULF band are well observed several days before La Fournaise eruption. The presence and lack of oscillations can be explained by successive openings of cracks in which ground water flows. This start-stop process can generate oscillatory electric phenomena by electrokinetic effect. The energy of these oscillations evolves with time and seems to concentrate along the structural heterogeneities where effusive vents take place. A complete theory of these oscillations remains to be made.

Lastly, continuous SP measurements in several directions seem to give valuable information on the migration of the magma just prior to the opening of fissures at the ground surface.

Acknowledgements

This study was supported by the District of Orléans and by the Laboratoire de Géophysique d'Orléans (LGO-CNRS). The research was made in the framework of the International Scientific Program of Cooperation 470. We are greatly indebted to the Régiment de Parachutisme et d'Infanterie de Marine of Réunion Island, in particular Colonnel Helly, Commander Bertrand, Lieutenant Ginon, Capitain Pottier, Adjudant Tessier, and the groups who helped us to do field work in the best conditions.

REFERENCES

ADLER, P.,. J.L. LE MOUËL and J. ZLOTNICKI (1998): Electrokinetic and magnetic fields generated by flow through a fracture zone: a sensitivity study for La Fournaise volcano, *Geophys. Res. Lett.*, **26** (6), 795-798.

BALLESTRACCI, R. and Y. NISHIDA (1987): Fracturing associated with 1977-1978 eruption of Usu volcano, North Japan, as revealed by geophysical measurements, *J. Volcanol. Geotherm. Res.*, **34**, 107-121.

BRIOLE, P. (1990): Étude des déformations de zones sismiques et de volcans. Interaction mesure-modélisation, *Thesis*, University Paris VI, France.

CAYOL, V. and F.H. CORNET (1998): Three-dimensional modeling of the 1983-1984 eruption at Piton de la Fournaise, Réunion Island, *J. Geophys. Res.*, **103**, 18025-18037.

CORWIN, R.F. and D.B. HOOVER (1979): The self potential method in geothermal exploration, *Geophysics*, **44** (2), 226-245.

DELORME, H. (1997): *Apport des Déformations à la Compréhension des Mécanismes Eruptifs: Le Piton de la Fournaise*, Univ. Pairs VII, France, pp. 613.

DOBROVOLSKY, I.P., N.I. GERSHENSON and M.B. GOKHBERG (1989): Theory of electrokinetic effects occurring at the final stage of in the preparation of a tectonic earthquake, *Phys. Earth Planet. Int.*, **57**, 144-156.

DRAGONOV, A.B., U.S. INAN and Y.N. TARANENKO (1991): ULF magnetic signatures at the Earth due to groundwater flow: a possible precursor to earthquakes, *Geophys. Res. Lett.*, **18**, 1127-1130.

FENOGLIO, M.A., M.J.S. JOHNSTON and J.D. BYRLEE (1995): Magnetic and electric fields associated with changes in high pore pressure in fault zones: application to the Loma Prieta ULF emissions, *J. Geophys. Res.*, **100** (B7), 12951-12958.

FITTERMAN, D.V. (1978): Electrokinetic and magnetic anomalies associated with dilatant regions in layered Earth, *J. Geophys. Res.*, **83,** 5923-5928.

FITTERMAN, D.V. (1982): Self-potential measurements and interpretation at Rivière Langevin and Cirque de Salazie, Ile de la Réunion, *U.S. Geol. Surv. Open-file Rep., 82-580*, pp. 50.

FRASER-SMITH, A.C., A. BERNADI, P.R. MCGILL., M.E. LADD, R.A. HELLIWELL and O.G. VILLARD Jr. (1990): Low-frequency magnetic field measurements near the epicenter of the M_S 7.1 Loma Prieta earthquake, *Geophys. Res. Lett.*, **17** (9), 1465-1468.

ISHIDO, T. (1989): Self potential generation by sub surface water flow through electrokinetic coupling, *Lect. Notes Earth. Sci.*, **27**, 121-131.

ISHIDO, T. and H. MITZUTANI (1981): Experimental and theorical basis of electrokinetic phenomena in rock-water systems and its applications to geophysics, *J. Geophys. Res.*, **86**, 1763-1775.

LÉNAT, J.F. (1987): Structure et dynamique internes d'un volcan basaltique intraplaque océanique: Le Piton de La Fournaise (Ile de la Réunion), *Thèse d'État*, Univ. Clermont II, Clermont-Ferrand, France.

MALENGREAU, B., J.L. LÉNAT and A. BONNEVILLE (1994): Cartographie et surveillance temporelle des anomalies de Polarisation Spontanée (PS) sur le Piton de La Fournaise, *Bull. Soc. Géol. France*, **165**, 221-232.

MASSENET, F. and V.N. PHAM (1985): Mapping and surveillance of active fissure zones on a volcano by the self-potential methods, Etna, Sicily, *J. Volcanol. Geotherm. Res.*, **24**, 315-338.

MICHEL, S. and J. ZLOTNICKI (1995): Le dynamisme de la Fournaise est-il contrôlé par l'anisotropie structurale lithosphérique N120° située sous l'île de la Réunion?, *C.R. Acad. Sci. Paris*, **321**, Série II, 643-650.

MICHEL, S. and J. ZLOTNICKI (1998): Self potential and magnetic surveys. Tools to investigate faulting, fluid circulation and eruptive dynamism of volcanoes: example of La Fournaise (Réunion Island), *J. Geophys. Res.*, **103**, 17845-17857.

MORGAN, F.D., E.R. WILLIAMS and T.R. MADDEN (1989): Streaming potential properties of Werterly granite with applications, *J. Geophys. Res.*, **94**, 12449-12461.

POZZI, J.P., C. PHILIPPE, J.L. LE MOUËL, J.C. ROSSIGNOL and J. ZLOTNICKI (1983): Anomalies magnétiques et déformations associées à l'activité de volcans andésitiques. Exemple de la Soufrière de Guadeloupe, *Bull. PIRPSEV*, **79**, pp. 31.

SASAI, Y. (1979): The piezomagnetic field associated with the Mogi model, *Bull. Earthquake Res. Inst.*, **54**, 1-29.

SASAI, Y. (1991): Piezomagnetic field associated with the Mogi model revisted: analytic solution for finite spherical source, *J. Geomagn. Geoelectr.*, **43**, 21-64.

SATO, M. and H.M. MOONEY (1960): The electrochemical mechanism of sulfide Self Potentials, *Geophysics*, **35**, 226-249.

SEAN (1998): Smithonian Institution, Global Volcanism Network, *Piton de la Fournaise*, **23** (3), 2-4.

SIGMUNDSSON, F., P. DURAND and D. MASSONET (1999): Opening of an eruptive fissure and seaward displacement at Piton de la Fournaise volcano measured by RADARSAT satellite radar inerferometry, *Geophys. Res. Lett.*, **26** (5), 533-536.

SYKIOTI, O. (1991): *Application à la Télédétection à l'Étude du Bilan Hydrique et du Fonctionnement Hydrogéologique d'un Volcan Actif: Le Piton de La Fournaise, Ile de La Réunion, Océan Indien*, DEA National d'Hydrologie, Univ. Paris VII, Paris, France.

VIOLETTE, S. (1993): Modélisation des circulations d'eaux dans le volcan de La Fournaise: approche du bilan hydrologique et des échanges thermiques, *Thèse d'Univ.*, Univ. Paris VII, Paris, France, pp.163.

ZABLOCKI, C.J. (1976): Mapping of thermal anomalies on an active volcano by self potential method, Kilauea, Hawaii, in *Proceedings of the Second United Nations Symposium on the Development and Use of Geothermal Resources*, Lawrence Barkeley Lab., Univ. California, 1299-1309.

ZLOTNICKI, J. and J.L. LE MOUËL (1988). Volcanomagnetic effects on Piton de la Fournaise Volcano (Réunion Island), *J. Geophys. Res.*, **93**, 9157-9171.

ZLOTNICKI, J. and J.L. LE MOUËL (1990). Possible electrokinetic origin of large magnetic variations at la Fournaise volcano, *Nature*, **343**, 633-636.

ZLOTNICKI, J., J.C. RUEGG, P. BACHELERY and P.A. BLUM (1990): Eruptive mechanisms on Piton de la Fournaise volcano associated with December 4, 1983, and January 18, eruptions from ground deformation monitoring and photogrammetric surveys, *J. Volcanol. Geotherm. Res.*, **40**, 197-217.

ZLOTNICKI, J., J.L. LE MOUËL., J.C. DELMOND, C. PAMBRUN and H. DELORME (1993): Magnetic variations on Piton de la Fournaise volcano: volcano-magnetic signals associated with the November 6 and 30, 1987, eruptions, *J. Volcanol. Geotherm. Res.*, **56**, 281-296.

ZLOTNICKI, J., S. MICHEL and C. ANNEN (1994): Anomalies de polarisation spontanée et systèmes convectifs sur le volcan du Piton de la Fournaise (Ile de la Réunion, France), *C.R. Acad. Sci. Paris*, **318**, Série II, 1325-1331.