Magnetic Observations on La Soufrière Volcano (Guadeloupe; F.W.I.) over a Quiet Period; Background Estimation

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Since 1978 the routine surveillance of La Soufrière volcano (Guadeloupe, F.W.I.) is performed using measurements of the total intensity ($B$) of the Earth magnetic field made at 3 stations radio-transmitted to the Fort Saint-Charles observatory. Differences $\Delta B$ between values of $B$ measured at two of these stations and the one simultaneously measured at the third one (Matouba, the reference station) are computed; values of $\Delta B$ recorded around 2:00 a.m. are used to monitor the volcano-magnetic field. These 3 stations are installed in areas where (1) the reduction and projection errors are as weak as possible (2) the volcano-magnetic signal is expected to be noticeable during a volcanic crisis.

The observations made using this network during the years 1979 to 1981 are presented. During these 3 years of no abnormal volcanic activity, the volcano-magnetic field, if any, remains below the experimental noise level.

1. Introduction

Magnetic effects clearly related to volcanic activity have so far been isolated in only a few examples. Among them, after the first works in Japan on Oshima volcano (Rikitake, 1951; Yokoyama, 1955; Uyeda, 1961), one can mention measurements on Ruapehu and Ngauruhoe volcanoes (New Zealand) (Johnston and Stacey, 1969a, 1969b), on Kilauea (Hawai) (Davis et al., 1979), and on Mount St-Helens (Washington USA) (Johnston et al., 1981). Results were obtained during the 1976-1977 seismo-volcanic crisis of La Soufrière Volcano of Guadeloupe (F.W.I.) using a network of repeat stations settled on the volcanic dome (Le Mouël, 1976; Pozzi et al., 1979).

The network was made of about 16 repeat points and a permanent recording station (Fig. 1). Differences $\Delta B(P_i)$ between the intensities of the field at point $P_i$ and at the recording station were measured on a daily basis. Significant variations in $\Delta B$ differences were observed, the amplitude of which reached 10 nT in some stations; the main time constant of the variations was on the order of a few days, their amplitude decreased to the noise level at the end of the crisis (Pozzi et al., 1979).
Such a network of repeat points is difficult to maintain on a permanent basis. For the routine surveillance of the volcano and following the recommendations of the international committee on La Soufrière held in Paris in November 1976, a set of automatic proton magnetometers radio-linked to the central station Fort St-Charles (Fig. 1) was installed in 1978. We will first give some considerations which prevailed for setting out the network, then present the results obtained from it.

2. Discussion of the Difference $\Delta B$

Following Le Mouël (1976), we will write the geomagnetic field measured at time $t$ and point $P$ under the form:

$$B(P, t) = B_r(P, t) + B_a(P) + B_v(P, t) + B_t(P, t). \quad (1)$$

$B_r$ is the regular field, $B_a$ the static anomalous field due to magnetic rocks in the crust, $B_t$ the transient magnetic field (the origin of which is primarily external), and $B_v$ the volcano-magnetic field (if any) related to changes in magnetization of the rocks due to the activity of the volcano (in other words, $B_v$ is the rapidly varying component of the sum $(B_a + B_t)$, which cannot of course be split unambiguously). Then we can write (Le Mouël, 1976; Pozzi et al., 1979):

$$\Delta B(P, 0, t) = B(P, t) - B(0, t) = (B_v(P, t) - B_v(0, t)) u(0) + (B_t(P, t) - B_t(0, t)) u(0) + B_t(P, t) (u(P) - u(0)) + k \quad (2)$$

where $u$ is the unit vector of $B_r + B_a$ and $k$ a scalar constant with respect to time.

We call the third term of the right-hand side of (2) the projection error. The projections of $B_v$ and $B_t$ (1st and 2nd terms of (2)) are along $u(0)$ while $u(P)$ can be different from $u(0)$: the projection error arises from that angular difference. For the repeat points $P$ an estimation of the upper bound of $\|u(P) - u(0)\|$ was taken as $\max(\|B(P) - B(0)\|/B(0))$; for the stations of the radiolinked array, $u(P)$ has been measured and $u(P) - u(0)$ computed for each one of the 2 stations (Table 1) (Zlotnicki, 1979).

The second term of the right-hand side of (2) is what we call the reduction

<table>
<thead>
<tr>
<th>Station</th>
<th>Altitude</th>
<th>Longitude</th>
<th>Latitude</th>
<th>$B(\gamma)$ 1976.5</th>
<th>Gradient moyen $\gamma$/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matouba</td>
<td>825 m</td>
<td>60°40'56&quot;</td>
<td>16°03'12&quot;</td>
<td>39480</td>
<td>3.5</td>
</tr>
<tr>
<td>Savane à Mulets</td>
<td>1080 m</td>
<td>61°39'42&quot;</td>
<td>16°02'24&quot;</td>
<td>39260</td>
<td>19</td>
</tr>
<tr>
<td>Palmiste</td>
<td>640 m</td>
<td>61°39'47&quot;</td>
<td>16°00'45&quot;</td>
<td>39760</td>
<td>26.5</td>
</tr>
</tbody>
</table>

$e_p$ is the projection error.
error $E_r(P, t)$. It comes from the non homogeneity of the transient field $B_t$ in the area of the survey. Of course the external part of $B_t$ is homogeneous, but not its internal part due to electric currents circulating in the heterogeneous crust. In order to get an estimation of this reduction error, we have performed recordings of $B$ variations in a number of stations (Fig. 1). Then we have determined the quantities $(B_t(P, t) - B_t(0, t))\cdot u(0)$ (the recordings were performed during a period of volcanic quiescence): if we take into account the particular characteristics of the anomalous transient field (Pozzi et al., 1979), we can show that the reduction error may be expressed in first approximation as:

\[ E_r(P, t) = \beta(P) \cdot B_t(0, t) \cdot u(0). \]  

(3)

$\beta(P)$ being a real coefficient characteristic of station $P$ which can be computed from:

\[ \beta(P) B_t(0, t) \cdot u(0) = (B_t(P, t) - B_t(0, t)) \cdot u(0). \]

Such a determination of the reduction error is similar to the one proposed by Rikitake (1966).

Values of $\beta(P)$ have been reported on Fig. 1. Equation (3) was first checked for variations with periods smaller than some hours; it can be extended, with lesser accuracy, to the diurnal variation itself (see Section 4).

The map of Fig. 1 evidences a short wavelength anomaly of transient variations; the anomalous transient field may reach in some places 25% of the transient field recorded at Matouba and it is noticeable that long period variations are observed in the anomalous field (e.g., 24h; see Section 4). The anomalous transient field observed near Dolé and l’Hermitage stations is obviously related to the channelling of currents in a superficial conducting channel separating the Soufrière Massif from Monts Caraïbes. This anomalous field is superimposed to the well known island effect.

As a conclusion, it appears that near the central part of La Soufrière Massif, in an area of roughly elliptic-shape (hatchured area on Fig. 1), the reduction error remains less than 10% of the transient field simultaneously recorded at Matouba.
Fig. 1. Map of the southern part of Basse Terre (Guadeloupe, F.W.I.). The dashed area is the central part of La Soufrière Massif, where altogether the reduction error is weak and the volcanic effect is expected to be noticeable.
3. The Area Affected by the Volcano-Magnetic Effect

We have considered the volcano-magnetic field observed at the repeat stations during the 1976–1977 seismo-volcanic crisis (in fact the difference between the actual volcano-magnetic field at the varying point and the one at Matouba). Pozzi et al. (1979) have shown that this differential field was small (in any case smaller than 5 nT) in the summit area (Bains Jaunes, Savane, Carbet), but could reach 10 nT in some more remote stations after taking into account the reduction error (Palmiste, l’Habituée, Grand Maison, Dolé, for instance). A model has been computed on the basis of a pure piezomagnetic anomaly (Pozzi et al., 1983). The volcano has been supposed to start activity when a sufficient over-pressure arise in a magmatic chamber situated at 6 km depth. The volcanic structure is considered to have elastic behaviour. The piezomagnetic coefficients have been derived from laboratory experiments using rocks sampled on the volcano (Zlotnicki et al., 1981). The results show that differences $\Delta B$ could arise between the stations Bains Jaunes, Savane, Carbet, Matouba, located near the summit and more distant stations of Palmiste, l’Habituée, Grand Maison, Dolé; among the latter Palmiste is the only one situated in the hatchured area (Fig. 1).

4. The Radio-Linked Surveillance Network

Finally, a permanent network made up of three measurement stations (Matouba, Savane à Mulets, Palmiste) was located in the central area defined above and radio-linked to the Fort Saint Charles observatory. Figure 1 gives the location of these 3 stations.

The geographic and magnetic characteristics of the measurement stations are given in Table 1. Matouba is still the reference station and the routine surveillance of the volcano is performed using the variations of the two differences $B(S_1, t) - B(0, t)$ and $B(S_2, t) - B(0, t)$, $S_1$, $S_2$ and 0 being, respectively, Savane à Mulets, Palmiste and Matouba.

5. The Diurnal Variation

It has been noted that the $\beta(P)$ values plotted in Fig. 1 were first determined for variations with periods smaller than some hours. Using the recording of the telelinked network, we have also computed the $\beta(P)$ values at the stations of Palmiste and Savane à Mulets for the regular daily variation ($S_R$). For that, hourly mean values of $B(S_1, t) - B(0, t)$, $B(S_2, t) - B(0, t)$ and $B_0(0, t)$ have been computed for each season (D: November, December, January, February; E: September, October, March, April; J: May, June, July, August) during the year 1980. Both differences clearly exhibit a diurnal variation and the anomalous $S_R$ field does appear to be, in a first approximation, proportional to the $S_R$ recorded at Matouba (Fig. 2). In both cases, the value of the multiplicative factor is not significantly different from the $\beta(P)$ value determined by Pozzi et al. (1979). Thus, for the
two telelinked stations, formula (3) is valid for most of the transient field components.

As said before, the main characteristic time constants of the variations of the volcano-magnetic field as observed during the 1976-1977 crisis are on the order of a few days (Pozzi et al., 1979). This phenomenon can then be monitored using daily values; in order to avoid the errors due to $S_R$ variations, we use the values recorded each night around 2:00 local time.

Table 2 shows that for both stations Palmiste and Savane, the sum of projection and reduction errors does remain smaller than 10% of $B_t(0,t)$.

6. The Results

Figure 3 shows the variations of the differences observed during the years 1979 to 1981. Plotted points represent daily values (obtained as described early), averaged over 5 days. For both differences the values remain within ±1 nT around the annual mean value (Table 3). This scattering can be accounted for by the sum of experimental, projection and reduction errors (Table 2). So the signal due to the volcano, if any, generally remains below the noise level during these three years (which were, indeed, quiet years for La Soufrière volcano). Straight lines correspond to the annual mean values. Notice that the mean values for 1979 and 1980 are equal whereas the one for 1981 is slightly smaller. That should correspond to a seismic crisis which occurred in January 1981.
Table 2. Statistical study of the 2:00 values of the differences recorded using the tele-liked network during the year 1981: comparison between the observed standard deviation —\(\sigma\)— and the computed one (\(\sigma(\delta B)^2 + \sigma_e^2\)).

<table>
<thead>
<tr>
<th>Period</th>
<th>Différence</th>
<th>(\sigma(\delta B)) nT</th>
<th>(\sigma(B_t)) nT</th>
<th>(\sigma_e = \sigma(B_t)(\beta + \varepsilon)) nT</th>
<th>(\sigma(\delta B)^2 + \sigma^2_e) (1/2)</th>
<th>(\sigma) nT</th>
<th>(m(\Delta B)) nT</th>
<th>Nbre de mesures</th>
</tr>
</thead>
<tbody>
<tr>
<td>January–March</td>
<td>(\Delta B) (SAV-MAT)</td>
<td>0.18</td>
<td>5.5</td>
<td>0.46</td>
<td>0.49</td>
<td>0.71</td>
<td>169.31</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td>(\Delta B) (PAL-MAT)</td>
<td>0.15</td>
<td>6.4</td>
<td>0.60</td>
<td>0.62</td>
<td>0.57</td>
<td>215.94</td>
<td>47</td>
</tr>
<tr>
<td>April–June</td>
<td>(\Delta B) (SAV-MAT)</td>
<td>0.14</td>
<td>7.8</td>
<td>0.65</td>
<td>0.67</td>
<td>0.92</td>
<td>169.95</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>(\Delta B) (PAL-MAT)</td>
<td>0.12</td>
<td>7.0</td>
<td>0.66</td>
<td>0.67</td>
<td>0.64</td>
<td>215.69</td>
<td>67</td>
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<tr>
<td>July–September</td>
<td>(\Delta B) (SAV-MAT)</td>
<td>0.13</td>
<td>4.8</td>
<td>0.40</td>
<td>0.41</td>
<td>0.62</td>
<td>169.12</td>
<td>60</td>
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<tr>
<td></td>
<td>(\Delta B) (PAL-MAT)</td>
<td>0.13</td>
<td>5.8</td>
<td>0.54</td>
<td>0.56</td>
<td>0.75</td>
<td>215.56</td>
<td>63</td>
</tr>
<tr>
<td>October–December</td>
<td>(\Delta B) (SAV-MAT)</td>
<td>0.15</td>
<td>7.2</td>
<td>0.60</td>
<td>0.62</td>
<td>0.60</td>
<td>169.63</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>(\Delta B) (PAL-MAT)</td>
<td>0.16</td>
<td>7.3</td>
<td>0.69</td>
<td>0.71</td>
<td>0.60</td>
<td>215.46</td>
<td>39</td>
</tr>
</tbody>
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\(\sigma(\delta B)\) is the standard deviation related to the measurement error; \(\sigma_e\) the one related to the reduction and projection errors, computed using the 2:00 value of the transient field \(B_t\) at Matouba (see text and Table 1 for further explanations).
Fig. 3. The magnetic monitoring of La Soufrière volcano activity during the years 1979–1981. For each difference $B$, the plotted values are the average over 5 days of the corresponding daily 2:00-differences and the straight lines represent the annual mean-values.
Magnetic Observations on La Soufriere Volcano

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<tbody>
<tr>
<td>1979</td>
<td>215.7</td>
<td>215.6</td>
<td>215.9</td>
<td>215.7</td>
<td>216.5</td>
<td>216.0</td>
<td>216.1</td>
<td>216.2</td>
<td>216.3</td>
<td>216.3</td>
<td>216.5</td>
<td>216.5</td>
</tr>
<tr>
<td>1980</td>
<td>215.1</td>
<td>215.6</td>
<td>215.2</td>
<td>215.5</td>
<td>215.3</td>
<td>215.1</td>
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<td>215.4</td>
<td>215.4</td>
<td>215.4</td>
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<td>215.4</td>
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Table 3. Monthly mean values of the 2,000-values of the difference $\Delta B$ (Palmiste-Matourba).

Fig. 4. Observations made at the stations of the telelinked network during summer 1981. Each plotted value of the differences $B$ is an individual 2,000-difference; the plotted value of the transient field at Matourba is also estimated each day around 2:00 local time (see text Section 4 for further explanations).
7. Estimation of Accuracy

Figure 4 displays the values of the individual 2:00-differences recorded during the months of July, August and September 1981. For both signals, the observed values are constant within ±1.5 nT. Figure 4 also shows the transient field simultaneously recorded at Matouba, defined as the difference between the field observed around 2:00 local time and the corresponding night level. The observed dispersion can be quite satisfactorily explained by the sum of the measurement (±0.5 nT at each station), reduction and projection error. Furthermore, all the 2:00-differences measured in 1981 have been statistically studied. For both differences, the standard deviation has been computed and compared to the standard deviation corresponding to the three errors mentioned above. Again, the agreement is satisfactory (Table 2).

8. Conclusion

Despite very unfavourable conditions (large static anomalies with gradients up to 1000 nT/m in many places, presence of a strong conductivity anomaly and a difficult rainy climate), it appears to be possible to get the difference in the intensity of the geomagnetic field between two points some kilometers apart, with an accuracy of about 1 nT. The stability of the mean differences over a three year period is also within 1 nT. If, as argued by Pozzi et al. (1979), variations in ΔB differences up to 10 nT may occur during a crisis, the magnetic network settled on La Soufrière volcano seems to be adequate for monitoring the volcano activity.

Y. Martin had with G. Simon the charge of the installation of the radio-transmitted network; we thank him for his efficient contribution to the success of this experiment. We are also grateful to M. Feuillard, director of the Soufrière Observatory, for his help. We thank B. Figaro, Y. Bernabé, G. Brandeis and C. Sotin who took part in the data-gathering process.

REFERENCE


