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Signals recorded by DEMETER satellite over active volcanoes during the period 2004 August–2007 December

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SUMMARY

More than 1500 volcanoes can potentially enter into eruption but only some tens of them are equipped with monitoring networks. Most of volcanic eruptions can be predicted by the integration of continuous real time observations, data processing and analysing. In the electromagnetic field (EM), a long history of ground observations shows that electric, magnetic and electromagnetic signals may precede and accompany volcanic eruptions. The possibility that volcanic eruptions may also be preceded by transient electromagnetic anomalies in the ionosphere can be analysed on the basis of DEMETER mission. This microsatellite, launched by CNES in 2004, covers 14 orbits per day over seismic and volcanic regions of the Earth. Two complementary and systematic studies are presented. Over the time period 2004 August–2007 December, the first study shows that three types of electric and/or magnetic anomalies can be observed in the time window of 30 d preceding an eruption and 15 d after. On the 74 eruptions occurring on 50 volcanoes under consideration, 48 anomalies are recognised along 30 eruptions. 41 per cent of the eruptions were accompanied by EM signals on board of the satellite. 81 per cent of the anomalies are observed before the eruptions for the period (−30 d, +15 d) and 69 per cent for the period (−15 d, +15 d). In the second study, the anomalies above three nearby volcanoes (Lopevi, Ambrym and Aoba) are systematically looked for all orbits between 2004 August and 2006 December. Anomalies are only observed during periods of larger activity on each of them. Taking into account that no anomaly is observed a long time before an eruption, one can allocate the anomalies to each volcano. Although the database is still limited, the study shows that volcanic activity may be preceded by EM perturbations of the ionosphere.

Key words: Time series analysis; Ionosphere/atmosphere interactions; Remote sensing of volcanoes; Volcano monitoring.

1 INTRODUCTION

During the last decades, number of studies stand on the possibility to identify precursory signals to natural disasters as volcanic eruptions and earthquakes.

On active faulting more and more encouraging electromagnetic observations on land and on board of satellites, indicate that pre-seismic signals may appear before earthquakes (i.e. Parrot & Mogilevsky 1989; Fraser-Smith *et al.* 1990; Gokhberg *et al.* 1995; Hattori *et al.* 1999; Hayakawa 1999; Uyeda *et al.* 2002; Hayakawa *et al.* 2004b; 2004a; Varotsos 2005; Ouzounov *et al.* 2006; Nêmec *et al.* 2008) while different models of EM sources are proposed (i.e. Parrot & Johnston 1993; Hayakawa & Molchanov 2002; Molchanov *et al.* 2004; Pulinets *et al.* 2006; Tronin 2006).

On volcanoes, observations on the ground of pre-eruptive signals appear more reliable. A number of observations show unambiguous electromagnetic signals before volcanic eruptions as resistiv-

ity changes, long time evolution of the magnetic field, transient magnetic and electric signals (i.e. Yukutake *et al.* 1990a, 1990b; Hashimoto & Tanaka 1995; Tanaka 1995; Zlotnicki *et al.* 2000, 2001, 2006; Sasai *et al.* 2001, 2002; Del Negro & Currenti 2003; Del Negro *et al.* 2004). Mechanisms of these electric and magnetic signals can be found in review papers (i.e. Johnston 1997; Zlotnicki & Nishida 2003).

However, only some tens of volcanoes in the world are monitored by complex geophysical equipments, whereas hundreds of volcanoes remain without any adequate observations and real time monitoring systems. On the other hand, some studies have shown that the ionosphere could be disturbed by the volcanic activity (i.e. Cheng & Huang 1992; Igarashi *et al.* 1994; De Ragone *et al.* 2004; Heki 2006). Therefore, multiplatform satellites could partly contribute to the mitigation of volcanic hazards and trap some of the pre-eruptive signals, even if the data sampling over a volcano is of several hours or more between consecutive orbits. The

microsatellite DEMETER, launched in 2004 June by the French National Space Agency (CNES), is devoted to the detection of electromagnetic (EM) perturbations of the ionosphere caused by earthquakes, volcanic eruptions and human activities (Berthelier *et al.* 2006; Colin *et al.* 2006; Lebreton *et al.* 2006; Parrot *et al.* 2006a; Sauvaud *et al.* 2006; Zlotnicki *et al.* 2006). This paper is an attempt to recognize EM signals related to volcanic activity in the data recorded on DEMETER satellite.

2 DEMETER MISSION AND DATABASE

DEMETER satellite is the first microsatellite developed by CNES. The scientific payload weight is only 20 kg on a total of 130 kg (Cusac *et al.* 2006). The satellite was launched by a Russian DNEPR rocket and placed on a sun-synchronous polar orbit at 710 km in altitude till 2005 December. Then, the altitude was reduced to 660 km. The satellite covers 14 orbits per day. At the equator, the shift in longitude between two orbits is about 2860 km.

2.1 DEMETER instrumentation

To study the disturbances of the ionosphere generated by seismo- and volcano-electromagnetic effects, and anthropogenic activities, a specific instrumentation is operating for measuring the electromagnetic field and the plasma characteristics.

- (1) A three-components search coil magnetometer ('IMSC') whose frequency band extends from 20 Hz to 20 kHz;
- (2) A three-components electric field sensor ('ICE') whose frequency band lies from dc to 3.5 MHz;
- (3) A Langmuir probe ('ISL') which measures the electrons density from 100 to 5×10^6 particules cm^{-3} and the electron temperature between 500 and 3000°K;
- (4) A plasma analyser ('IAP') of the ion density, temperature and energy distribution in the ionosphere;
- (5) An energetic particle analyser of electrons between 60 keV and 2 MeV.

Data are recorded in two modes depending on the location of the satellite. Above active faults and main active volcanic areas, data are recorded in a burst mode and waveforms, up to 20 kHz, are saved. For one electric channel, data are recorded up to 3 MHz. Anywhere else, only spectrograms are kept for the same frequency range (Berthelier *et al.* 2006; Lebreton *et al.* 2006; Parrot *et al.* 2006a; Sauvaud *et al.* 2006).

2.2 Database

The objective of this first study of EM signals related to volcanic activity is to analyse DEMETER data around the time of volcanic eruptions over a period of several years. Therefore, a database is built as follows:

- (1) The period under study starts in 2004 August when DEMETER is fully in operation and ends in 2007 December.
- (2) Only volcanoes located between latitudes -50° and $+50^\circ\text{N}$ are taken into account. Beyond these latitudes, auroral phenomena prevail in DEMETER records and could hide small EM anomalies associated with ground phenomena.
- (3) Volcanoes characterized by a Volcanic Explosivity Index (VEI) ≥ 1 are considered, independently of their location and eruptive behaviour (see <http://www.volcano.si.edu/world/>

eruptioncriteria.cfm#VEI). However, volcanoes for which the activity is mainly effusive are disregarded.

(4) The database is produced by observations from downward (north to south) and upward (south to north) orbits. Downward orbits correspond to daytime whereas upward orbits correspond to nighttime. In the first study a time window beginning 30 d before the eruption and ending 15 d after has been chosen, because most of the transient EM signals recorded on the ground occur during this time lapse.

(5) For any orbit data are analysed if the maximum distance between the footprint of the satellite and the volcano under study is less than 500 km for $\text{VEI} \leq 3$, and 900 km for $\text{VEI} > 3$. These distances were chosen after (i) recognition of anomalies which can last 20 s to about 1 mn (see text hereafter), (ii) taking into account the spatial distribution of thermal anomalies or ashes ejecta in the atmosphere during eruptive events and (iii) the estimation of background EM environment beyond these threshold distances. These thresholds correspond to about 70 and 110 s of satellite records above volcanoes (satellite velocity of 7 km s^{-1}).

In a first step, the data collection is used for analysing the different types of anomalies encountered in the vicinity of volcanoes. 74 volcanic eruptions have respected the previous criteria and about 6600 orbits were systematically analysed.

In the second step, we thoroughly investigate anomalous signals on all DEMETER orbits between 2004 August and 2006 December above Lopevi, Aoba and Ambrym volcanoes. Day-to-day analysis is processed, corresponding to the examination of 1750 orbits.

3 SIGNALS RECORDED AROUND THE TIME OF ERUPTIONS

3.1 Method

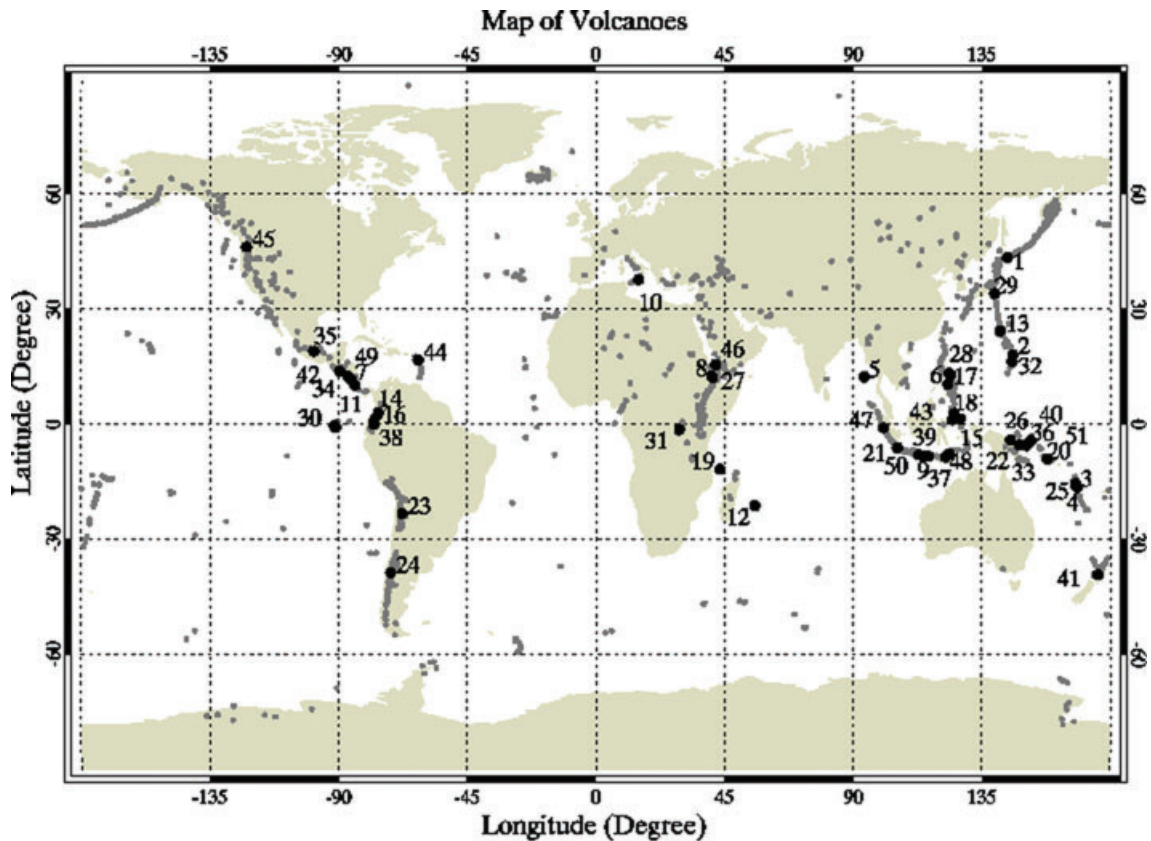
For the 74 volcanic eruptions occurring on 50 volcanoes, each orbit filling the database requirements is scrutinized (Fig. 1). Automatic visualization of the course of DEMETER, the location of the volcano and the magnetic points are performed (Lagoutte *et al.* 2006). The distance between the footprints of the satellite and the volcano, and the magnetic conjugate points are computed along each flight path. If the distance between the footprint and the volcano becomes less than 500 or 900 km depending of the database requirements, the minimum distance is determined and a centred 5 min data set is extracted to evaluate the background EM noise level, too.

Anomalous changes in DEMETER parameters are found before and during 30 eruptions. The EM anomalies can be classified in three types.

3.2 Anomalies

3.2.1 Type 1

Let us consider the electric anomalies recorded on ICE sensors (Figs 2a–c). These anomalies are characterised by a high energetic content spreading from dc to several hundreds of Hertz. No corresponding IMSC magnetic anomaly is observed. ISL and/or IAP anomalies may exist with the electric anomalies. The duration of the EM anomalies on the records, up to 20 s, supposes that the signal may cover a regional scale or that its strength is large enough to be seen over large distances. It also confirms the necessity to look for anomalies over large distances (i.e. 500 km).



- | | | |
|------------------------|----------------------|-----------------------------|
| 1 - Akan | 2 - Anatahan | 3 - Ambrym |
| 4 - Aoba | 5 - Barren Island | 6 - Bulusan |
| 7 - Concepción | 8 - Dabbahu | 9 - Egon |
| 10 - Etna | 11 - Fernandina | 12 - Fournaise, Piton de la |
| 13 - Fukutoku-Okanoba | 14 - Galeras | 15 - Gamkonora |
| 16 - Huila, Nevado del | 17 - Kanlaon | 18 - Karangetang [Api Siau] |
| 19 - Karthala | 20 - Kavachi | 21 - Krakatau |
| 22 - Langila | 23 - Lászar | 24 - Llaima |
| 25 - Lopevi | 26 - Manam | 27 - Manda Hararo |
| 28 - Mayon | 29 - Miyake-jima | 30 - Negra, Sierra |
| 31 - Nyamuragira | 32 - Pagan | 33 - Pago |
| 34 - Poás | 35 - Popocatepetl | 36 - Rabaul |
| 37 - Raung | 38 - Reventador | 39 - Rinjani |
| 40 - Ritter Island | 41 - Ruapehu | 42 - Santa Ana |
| 43 - Soputan | 44 - Soufrière Hills | 45 - St. Helens |
| 46 - Tair, Jebel at | 47 - Talang | 48 - Tara, Batu |
| 49 - Telica | 50 - Tengger Caldera | 51 - Ulawun |

Figure 1. Small grey dots: location of active volcanoes in the world. Large black dots: location of volcanoes for which anomalies have been recorded between 2004 August and 2007 December, according to the database requirements (see text).

Figs 2a–c illustrate these anomalies, called type 1 anomalies, observed above Lascar and Aoba volcanoes. On Lascar volcano, 1 week before 2005 May 4 eruption, the electric field (ICE) shows a sharp anomaly the energy of which is concentrated between dc and about 200 Hz (Figs 2a and b). The ICE anomaly is also recorded at the magnetic conjugate point. No magnetic anomaly is detected during this period. On Aoba volcano, 6 d before 2005 November 27 eruption, an ICE anomaly appeared above the edifice (Fig. 2c). As for most of anomalies of type 1, Aoba volcano shows an electric field anomaly associated with an increase of the electron density and a decrease of the electron temperature. At

the same time, anomalies of the ion density and temperature are recorded.

On Aoba volcano, anomalies of type 1 are observed only twice during the three years data set, just before the 2005 November 27 eruption (see Paragraph 4). On Lascar volcano, anomalies of type 2 and 3 are also observed before the 2005 May 4 eruption (see hereafter).

Finally, 22 anomalies were found between 2004 August and 2007 December (Table 1a).

These anomalies of type 1 for which no magnetic anomaly is recorded, are also observed on DEMETER in the vicinity of

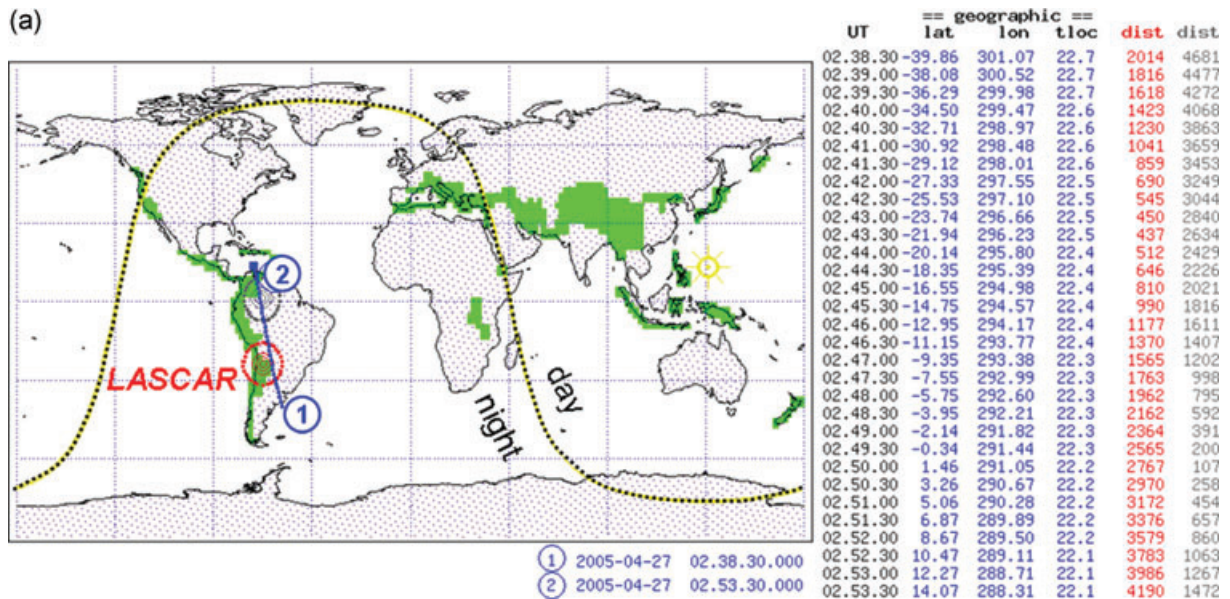


Figure 2. (a) Trajectory of DEMETER satellite on 2005 April 27 in the vicinity of Lascar volcano (blue line). Right-hand side: UT time, geographical coordinates of DEMETER, local time, distance of the footprint of the satellite and Lascar volcano, and associated distance of the conjugate magnetic point (black circles). Dash line delimits day and night sectors. (b) Anomaly of type 1 observed above Lascar volcano 7 d before 2005 May 4 eruption. From top to bottom: Spectrogram of electric and magnetic fields (ICE and IMSC sensors), electron density and temperature (ISL sensor), ion density and temperature (IAP sensor) and earthquakes occurring along the path of the orbit; symbols on the bottom right-hand side indicate magnitude and time of earthquakes along the path of the satellite. Time window: 2005 April 27, from 02:42 to 02:53 UT time. (c) Left-hand side: Anomaly of type 1 observed above Aoba volcano 6 d before 2005 November 27 eruption. From top to bottom, spectrogram of electric and magnetic fields (ICE and IMSC sensors), electron density and temperature (ISL sensor), ion density and temperature (IAP sensor) and earthquakes occurring along the path of the orbit; symbols on the bottom right-hand side indicate magnitude and time of earthquakes along the path of the satellite. Time window: 2005 November 21, from 10:55 to 11:06 UT time.

earthquakes (Figs 3a and b, i.e. Parrot *et al.* 2006b; Bhattacharya *et al.* 2007; Sarkar *et al.* 2007). This phenomenon is known as ionospheric electrostatic turbulence (Hobara *et al.* 2005). Several mechanisms are proposed to explain these anomalies. One is based on gas release from the ground generating thermal anomalies, which give birth to acoustic gravity waves which penetrate into the ionosphere (i.e. Pulinets 2004; Molchanov *et al.* 2004). Another interpretation is based on gas emission generating electrical charge separation in the atmosphere, which produces high electric fields which disturb the ionosphere (i.e. Ouzounov *et al.* 2006; Pulinets *et al.* 2006).

3.2.2 Type 2

Anomalies of type 2 are defined by simultaneous electric and magnetic anomalies of spike shape (Fig. 4). The frequency content can be spread between dc and 20 kHz. There is no shift of the frequency with time. These anomalies appear in the close vicinity of volcanoes. Generally, no change in electron and ion densities and temperatures are recorded (Table 2). 22 anomalies of type 2 were found in the database between 2004 August and 2007 December.

An example is given by Pagan volcano (Fig. 4). Electric and magnetic anomalies are observed 26 d before the 2006 December 4 eruption.

These anomalies of type 2 formed by high energetic electric and magnetic signals are defined as whistlers (Inan *et al.* 2007). They correspond to atmospheric lightning discharges (see Volland 1995; Hayakawa *et al.* 2003). They are generated by the accumulation of electric charges between the ground surface and the atmosphere, and the sudden discharge of these charges into the atmosphere (Singh *et al.* 2005). Whistlers can propagate to the ionosphere and generate an electromagnetic turbulence without either large

attenuation or frequency drift. These EM anomalies of impulse behaviour have already been recognised above seismic areas (Fig. 5, Parrot *et al.* 2006b). Whistlers occurring during daytime can more easily propagate into the ionosphere if the latter is already disturbed. 20 anomalies of the type 2 are observed during daytime. This would mean that the volcanic activity can sufficiently disturb the ionosphere to allow whistlers to be recorded by DEMETER when passing over the volcano.

It is also well known that electric storms may occur at the summit of volcanoes before or during the eruptive phases (McNutt & Davis 2000; Matter & Harisson 2006; Thomas *et al.* 2007; James *et al.* 2008). However, these phenomena are produced by high electric charges carried out by dust clouds, plumes or pyroclastic flows.

3.2.3 Type 3

Till now, this type of anomaly was unknown (Figs 6a and b). Both electric and magnetic anomalies appear simultaneously. The frequency content is spreading over a few hundreds of Hertz with a maximum of energy in the middle of the frequency domain. These anomalies disappear before 1 kHz. They can be recorded during 2 min, which correspond to a distance covered by the satellite of about 840 km. They appear during either day- or nighttime. There is no relationship between the observed anomalies and the magnetic storms, as inferred from the DST indices (i.e. http://web.dmi.dk/fsweb/cgi-bin/webin_wdget.sh?objtype=idxsrch&data_type=dst_index).

Anomalies of type 3 can be described through two cases (Figs 6a and b). At Fernandina and Lascar volcanoes, electric and magnetic anomalies progressively appear, respectively, 5 and 18 d before their respective eruptions (2005 May 13 and 2006 April 18). The anomalies cover a relatively narrow frequency band of a few hundred Hertz with a maximum of energy between 500 and 600 Hz. The

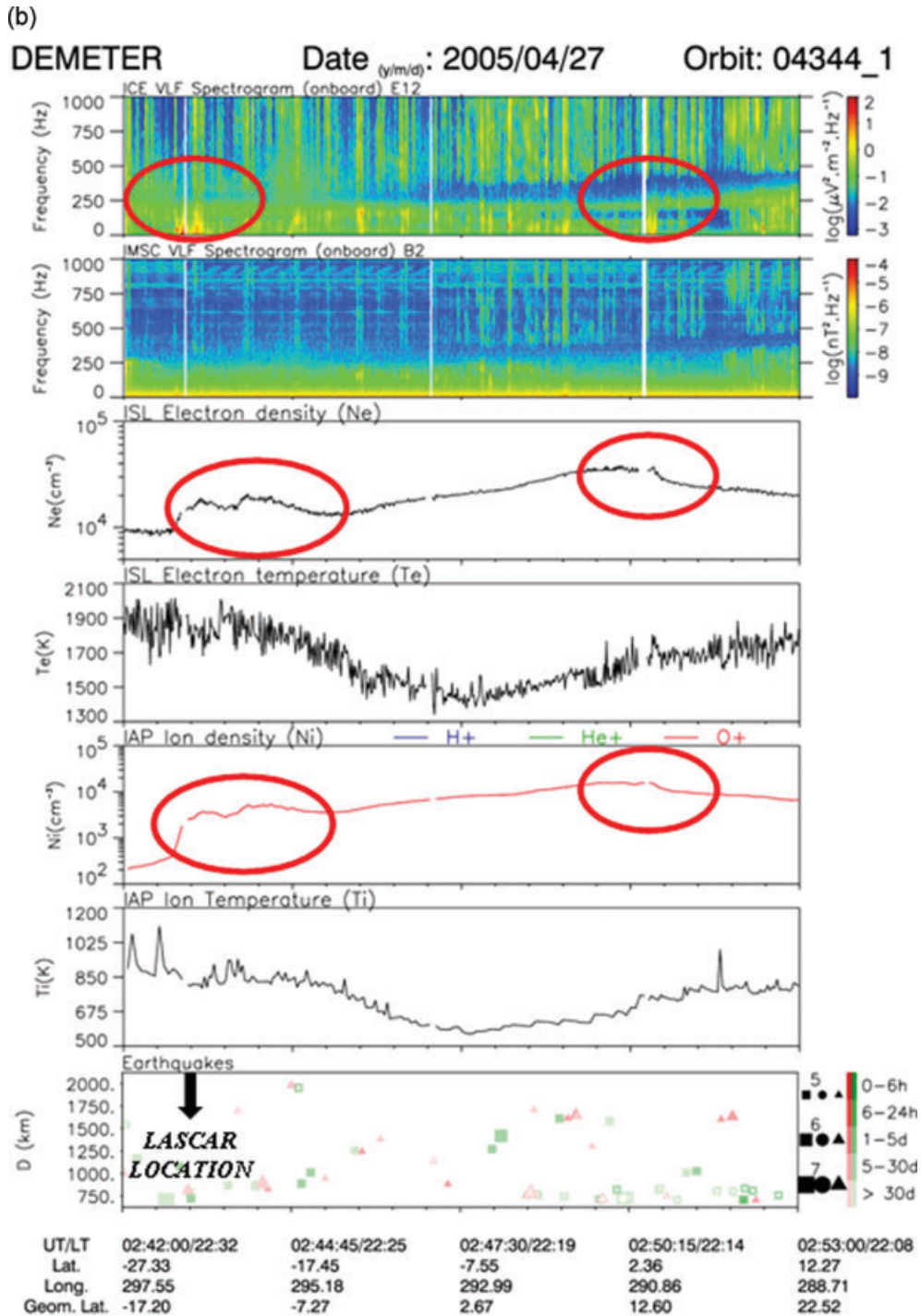


Figure 2. (Continued.)

anomalies last about 60 s. No other anomaly is observed in DEMETER records during that period. On Fernandina volcano, a similar anomaly is found 4 d after the beginning of the only eruption (2005 May 13) occurring between 2004 August and 2007 December. Only four anomalies of type 3 were found in the database (Table 3).

3.3 Analysis

Following the database requirements, 74 eruptions on 50 volcanoes have occurred during the 3.5 years of records. 30 eruptions are accompanied by 48 anomalies during the time window starting

30 d before the eruption and ending 15 d after (Fig. 7). Although the database is still small (74 events), some important characteristics can be outlined.

- (1) 41 per cent of the eruptions were accompanied by anomalies;
- (2) 81 per cent of the anomalies are observed before the eruptions if we consider the time window $[-30 \text{ d}, +15 \text{ d}]$ and 69 per cent for the period $[-15 \text{ d}, +15 \text{ d}]$;
- (3) Most of the anomalies are of type 1 or 2. Anomalies of type 1, 2 and 3 represent 46 per cent, 46 per cent and 8 per cent of cases, respectively.

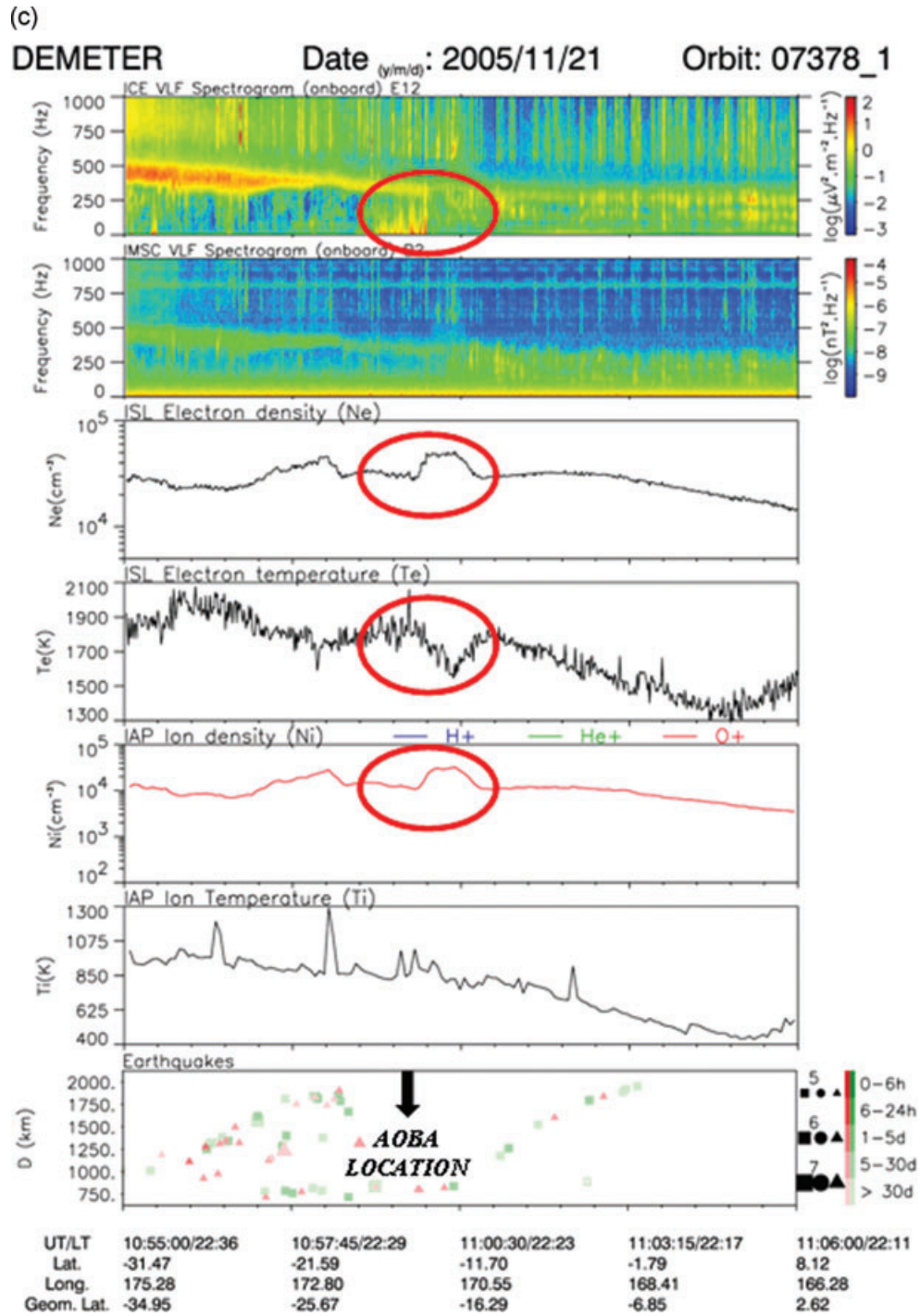


Figure 2. (Continued.)

(4) Several anomalies, even of different types, can be recorded above the same volcano. Anomalies seem to appear independently of the characteristics of the volcano (i.e. dynamism, VEI index, location and regional setting);

(5) It is still difficult to attribute a relationship between the characteristics of the anomalies (i.e. amplitude, duration and frequency content) and the strength of the future volcanic activity. However, one can note that the number of recognised anomalies is at most three for four volcanoes, the VEI of which is ≥ 2 (Lascar, VEI = 3; Lopevi, VEI = 2; Kartala, VEI = 2; Fernandina, VEI = 2). Exten-

sion of the database and the analysis will be achieved along the life of satellite for defining more clearly these relationships.

The previous statements should be considered with the following remarks:

Every day, the daily shift in longitude by DEMETER satellite is about 2860 km at the equator. Therefore, the distance between the footprint of the satellite and the volcano under study, along two consecutive 24 h revolutions becomes larger than the distance threshold of 500 and 900 km for which the analysis is performed. Therefore,

Table 1. Anomalies of type 1. Name of volcanoes, latitude, longitude, time of appearance of anomaly, frequency band of the anomaly, time of eruption and volcanic explosivity index (VEI), density (*D*) and temperature (*T*) anomalies.

Volcano	Latitude (degree)	Longitude (degree)	Anomaly		Eruption		ISL		IAP	
			Occurrence (day)	Frequency (Hz)	Date	VEI	D	T	D	T
Aoba	−15.4	167.83	−10	DC-150	2005 November 27	2	X	X	X	X
			−6	DC-200			X	X		
Akan	43.384	144.013	0	DC-250	2006 March 21	1	X	X	X	X
			+2	DC-150						
Bulusan	12.77	124.05	−4	DC-150	2006 October 10	2	X	X		X
Kanlaon	10.412	123.132	−8	DC-700	2006 June 03	2				
Concepcion	11.538	274.378	−17	DC-150	2007 February 09	1				X
Huila-Nevadodel	2.93	283.97	−25	DC-300	2007 February 19	3				
Lascar	−23.37	292.27	−7	DC-200	2005 May 04	3	X			X
Llaima	−38.692	288.271	−16	DC-350	2007 May 26	2				X
Lopevi	−16.507	168.346	0	DC-150	2005 January 30	2	X			
Manam	−4.08	145.037	−28	DC-500	2004 October 24					
Miyakejima	34.079	139.529	−20	DC-100	2006 August 23	1				
Pago	−5.58	150.52	+6	DC-250	2007 August 28	1				
			+9	DC-200			X	X	X	
Rabaul	−4.271	152.203	−3	DC-350	2005 January 25	2				
			+11	DC-180	2006 August 11	4	X	X		
Ritter Island	−5.52	148.121	−1	DC-500	2007 May 19	1	X	X		
Santa Ana	13.853	270.37	−28	DC-180	2005 June 16	1	X	X	X	X
Soputan	1.108	124.73	−29	DC-500	2005 April 19	2	X	X		X
Ulawun	−5.05	151.33	−24	DC-250	2007 May 1	2	X	X	X	
			−17	DC-300						

the number of recognised anomalies can be underestimated due to the loose satellite data coverage over a particular volcano.

Moreover, during pre-eruptive period (i.e. weeks), the volcanic activity may present episodic transient signals of a few minutes durations which have a great probability to occur outside the 70 to 110 s of satellite records above the volcano. This observation leads to assume that anomalous EM signals in the ionosphere might be more numerous than those trapped by DEMETER satellite.

No anomaly is also observed on two consecutive records filling the threshold distance of 500 or 900 km, which outlines that the observed anomalies are transient signals of less of few days duration.

4 LONG-TERM STUDY: 2004 AUGUST AND 2006 DECEMBER

4.1 Anomalies

To check if anomalous signals are observed outside the time window of 45 d bracketing an eruption, we now consider all orbits above Ambrym, Aoba and Lopevi volcanoes between 2004 August and 2006 December (see Fig. 8a for location). These volcanoes are located at mid-latitude where the ionospheric disturbances and seasonal variations of magnetic disturbances are weak (Stolle *et al.* 2006). We consider only anomalies for which the distance between the footprint of DEMETER and the volcano is less than 500 km.

No anomaly is recorded outside the period of activity of the three volcanoes and 11 anomalies of type 1 or 2 appear during the periods of activity (Fig. 8b). Unfortunately, these edifices are less than 200 km away from each other and it is difficult to attribute each anomaly to a specific volcano without taking into account results obtained in the first study and the volcanic activity in the area.

4.2 Volcanic activity

Lopevi volcano. Lopevi is a basaltic-to-andesitic volcano (16.507°S, 168.346°E), which forms an island of about 7 km in diameter above sea level (s.l.). The summit culminates at 1450 m in altitude and at 3500 m above the seafloor. Lopevi is one of the most active volcanoes of the Vanuatu archipelago. Eruptive activity occurs every ~15–20 yr. Significant plinian eruptions, pyroclastic flow, strombolian activity, lava flow as well as fumarolic and gas emissions are observed during eruptive activity.

On 2003 June 8 and 9, a thick ash plume rose up to 12 km in altitude and was followed by other ash clouds which extended to 18 km in size during the next weeks. Numerous thermal anomalies were detected by MODIS satellite at Lopevi during 2003 July to 2005 March [2003 June (BGVN 28:06); 2007 February (BGVN 32:02), http://www.volcano.si.edu/world/volcano.cfm?vnum=0507-05=&volpage=var#bgvn_2806]. During 2004 September thermal anomalies were detected four times. Ongoing eruptive activity at Lopevi was large again between 2005 January and February. After 11 months of quietness, a small vertical plume rising to about 2.7 km was observed on 2006 January 24 and was followed by a lava flow. After 2006 May 7 a small ash plume was again visible during the next days (altitude <3 km) and a lava flow was observed. A new eruptive episode started on June 27, but no plume was reported after 2006 July 10.

Aoba volcano. Aoba is the largest basaltic shield volcano of the Vanuatu archipelago (15.40°S, 167.83°E). The base of volcano is at about 2400 m depth below s.l. and the summit culminates at 1500 m above s.l. One of the two summit calderas is filled by the 2 km in diameter Vouli Lake. The general activity is figured out by a hydrothermal activity. During 2000 March–June, the temperature of the lake increased by 7°C [2000 August (BGVN 25:08), 2005 November (BGVN 30:11); <http://www.volcano.si.edu/world/volcano.cfm>]

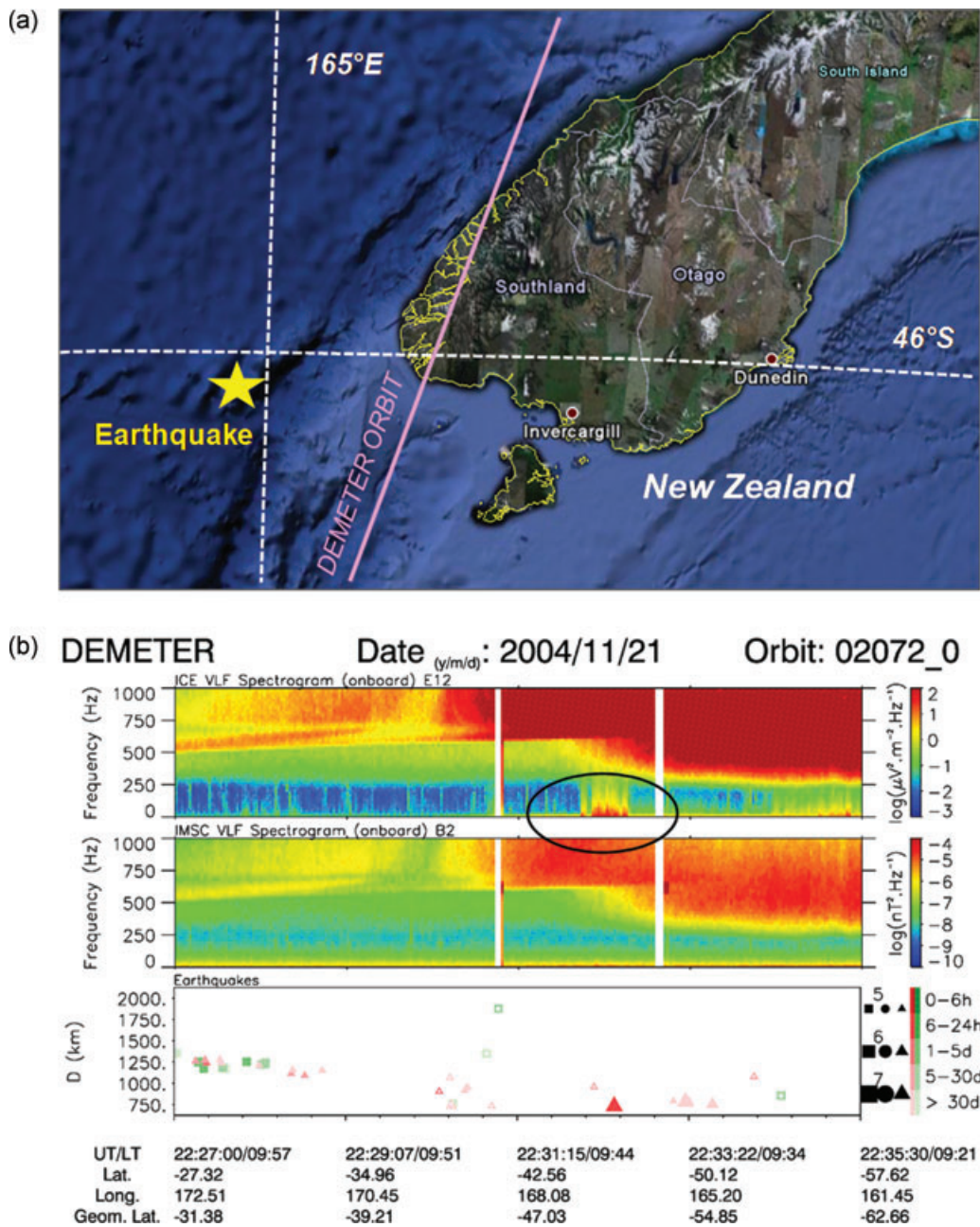


Figure 3. (a) Location of 2004 November 22 New Zealand M 7.3 earthquake (20:26 UT). (b) Data recorded by DEMETER on 2004 November 21 between 22:27 UT and 22:35 UT. From top to bottom: spectrogram of electric and magnetic fields (ICE and IMSC sensors), distance from the satellite to earthquakes. Symbols on the bottom right-hand side indicate magnitude and time of earthquakes along the path of the satellite. The horizontal scale shows Universal (UT) and Local (LT) Time, latitude and longitude of earthquakes and latitude of the magnetic field.

vnum=0507-03=&volpage=var#bgvn_2508]. The activity resided after.

An eruption began on 2005 November 27 accompanied by vapour plumes and ash columns originating from Lake Vouli. White steam reached 1500 m above the summit and 2000 tons of ash per day felt on the island. Ashes plume was observed on 2006 January 31. The volcanic eruption continued till 2006 February, with SO_2 degassing. The Aura/OMI satellite detected elevated SO_2 concentrations above Aoba during 2006 July–August at the end of eruption [2006 December (BGVN 31:12), http://www.volcano.si.edu/world/volcano.cfm?vnum=0507-03=&volpage=var#bgvn_3112].

Ambrym volcano. Ambrym is a pyroclastic basaltic shield volcano (16.25°S, 168.12°E), 1334 m in altitude above s.l.. A 12-km-wide caldera cuts the summit. The caldera was formed during a major plinian eruption with dacitic pyroclastic flows about 1900 years ago. Younger eruptions have partly filled the caldera and have also taken place along a fissure system oriented ENE–WSW. In the historical time, almost one eruption has occurred every year.

In 2004 March, a lava lake became weakly active in a summit crater, and only SO_2 gas was emitted [2004 March (BGVN 29:03; http://www.volcano.si.edu/world/volcano.cfm?vnum=0507-04=&volpage=var#bgvn_2903)]. Thermal anomalies disappeared on 2005 June 1. After a long period of quietness, thermal anomalies

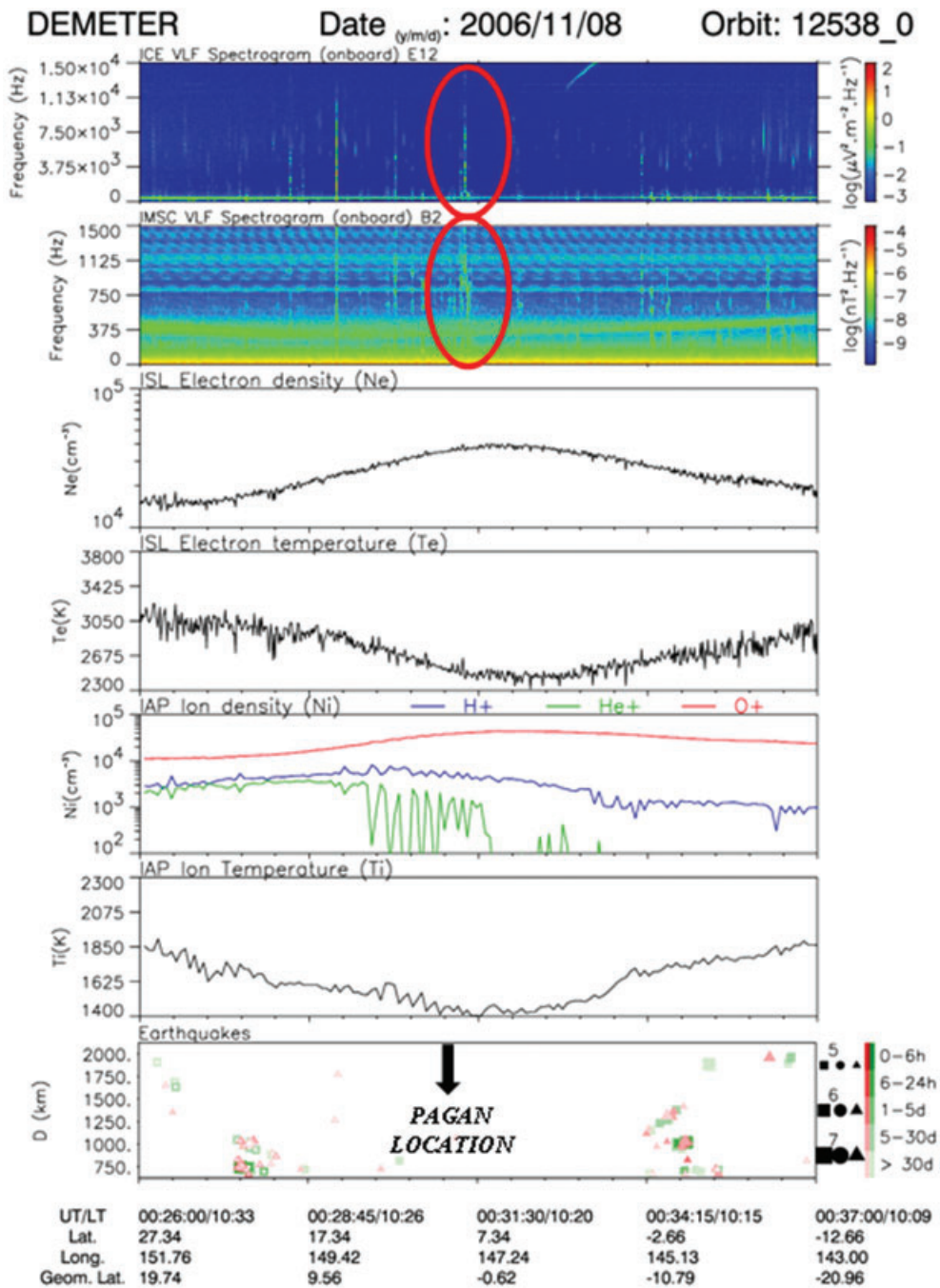


Figure 4. Anomaly of type 2 above Pagan volcano recorded 26 d before 2006 December 4 eruption. From top to bottom: spectrogram of electric and magnetic fields (ICE and IMSC sensors), electron density and temperature (ISL sensor), ion density and temperature (IAP sensor) and earthquakes occurring along the path of the orbit; symbols on the bottom right-hand side indicate magnitude and time of earthquakes along the path of the satellite. Time window: 2006 November 8 from 00:26 to 00:37 UT time.

were episodically observed in 2006 April, on 2006 November 8–15, on 2007 January 11–15 and during 2007 February 3–19, and daily later [2005 May (BGVN 30:05)]. A new activity with 2.4 km high ashes plume started in 2007 April and continued up to the end of the year.

4.3 Discussion

The short distance between Aoba, Lopevi and Ambrym volcanoes (less than 200 km) compared to the threshold distance

of the footprint of the satellite to these volcanoes (less than 500 km) and to the altitude of the satellite (660 km) makes difficult to distinctively attribute the anomalies observed on DEMETER to a particular volcano without considering simple statements.

If we take into account that no anomaly was observed on any volcano in the database 1.5 yr before an eruption, we can assume that the anomalies observed in 2004 and early 2005 should be related to Lopevi volcano. Lopevi volcano is also the only active volcano during this period.

Table 2. Anomalies of type 2. Name of volcanoes, latitude, longitude, time of appearance of anomaly, frequency band of the anomaly, time of eruption and volcanic explosivity index (VEI).

Volcano	Latitude (degree)	Longitude (degree)	Anomaly		Eruption	
			Occurrence (day)	Frequency (Hz)	Date	VEI
Egon	-8.67	122.45	+14	DC-15000	2005 February 6	1
Fernandina	-0.37	268.45	-1	DC-6000	2005 May 13	2
Huila-Nevadodel	2.93	283.97	-10	DC-6000	2007 February 19	3
Karthala	-11.75	43.38	-29	DC-6000	2007 January 12	2
			-16	DC-8500		
			-4	DC-15000		
			-13	DC-20000		
Kavachi	-9.02	157.95	-13	DC-20000	2007 April 2	1
Krakatau	-6.102	105.423	-5	DC-12000	2007 October 23	2
			+2	DC-6000		
Lascar	-23.37	292.27	-1	DC-10000	2005 May 4	3
			-17	DC-20000		
Lopevi	-16.507	168.346	-30	DC-15000	2005 January 30	2
				DC-20000		
				DC-7500		
				DC-20000		
Mayon	13.257	123.685	-29	DC-10000	2006 July 13	1
			-12	DC-17000		
Pagan	18.13	145.8	-26	DC-12000	2006 December 4	1
Rabaul	-4.271	152.203	-8	DC-20000	2005 January 25	2
Soputan	1.108	124.73	+12	DC-13000	2004 October 18	3
Talang	-0.978	100.679	-13	DC-13000	2007 November 27	2
Tara-Batu	-7.792	123.579	-26	DC-20000	2007 January 17	2
			-23	DC-20000		
Telica	12.602	273.155	-11	DC-15000	2007 January 9	1

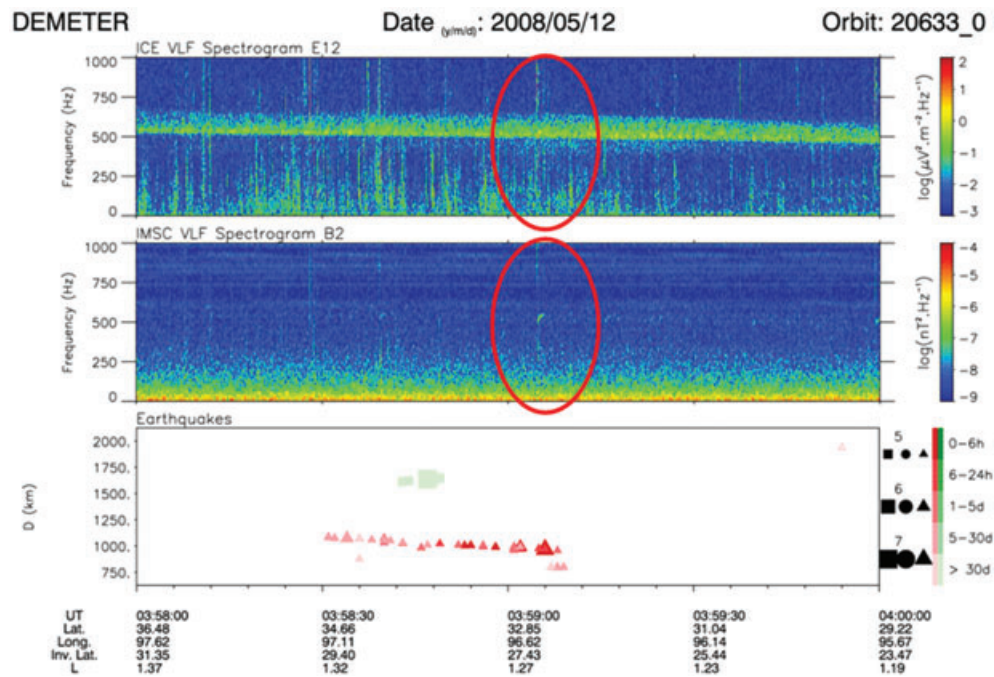


Figure 5. Example of type 2 anomaly recorded by DEMETER 2.5 hr before the devastating Wenchuan earthquake ($M = 7.9$) on 2008 May 12. From the top to the bottom: the electric field spectrogram, the magnetic field spectrogram and the earthquake occurrence along the orbit. The closest approach to the main epicentre is at 03:59:06 UT. All other red triangles are related to numerous aftershocks. In addition to the whistlers, the reader will also note in the top panel the electrostatic turbulence being all along the fault which is almost in the direction south–north.

Between 2005 November and 2006 February, Lopevi activity resides in a smooth lava flow which progressively vanishes. During the same period of time, Aoba volcano becomes active with phreatic explosions and ashes plumes. Therefore, the three anomalies observed during this three months period can be more logically attributed to Aoba volcano.

After 2006 February, the activity at Aoba vanished and the one at Lopevi weakened after 2006 February. Therefore, with the same assumption on the anomalies observed after volcanic eruptions or during a decreasing activity, we can suppose that the anomalies observed in 2006 September and later are most probably due to Ambrym activity.

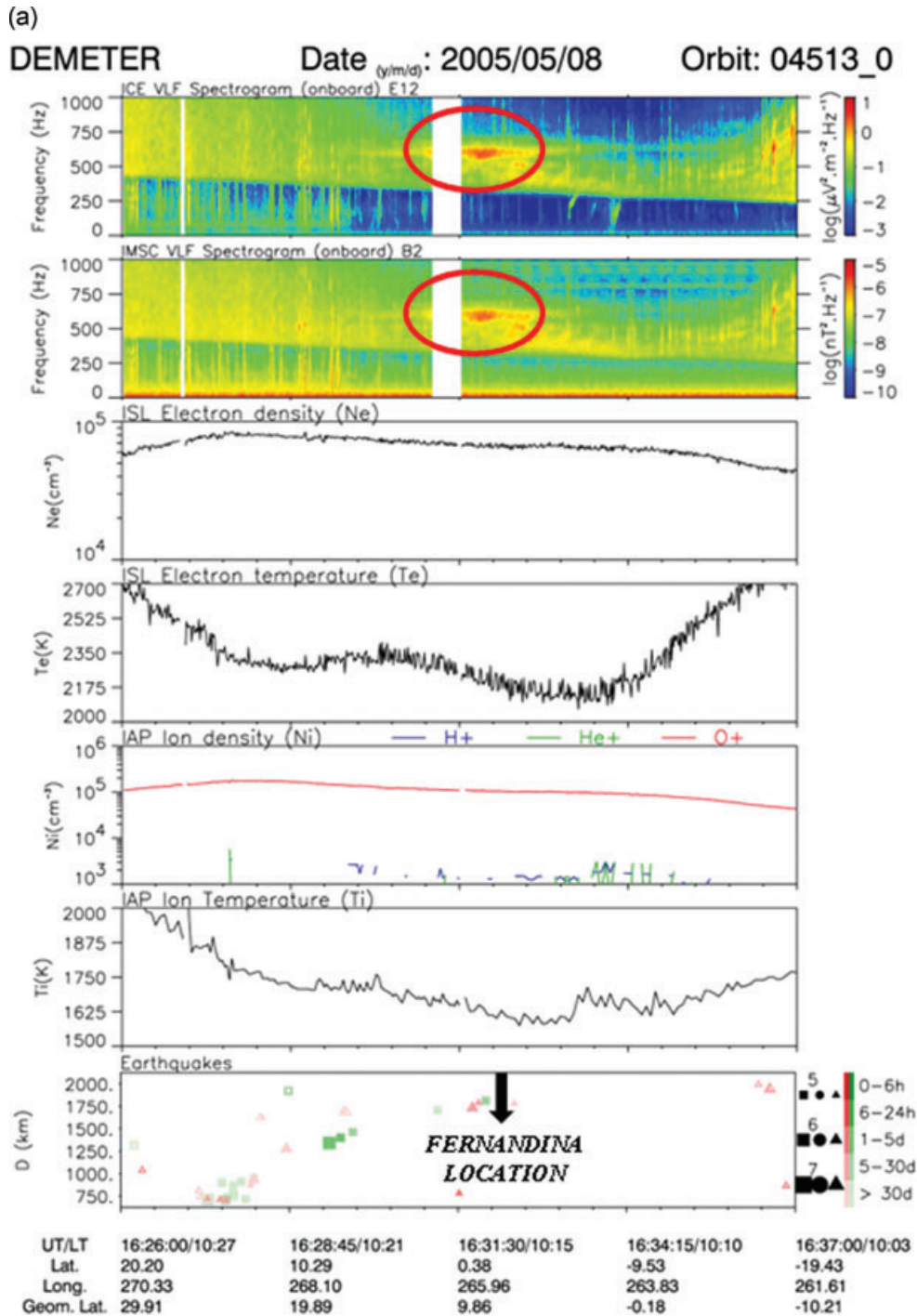


Figure 6. (a) Anomaly of type 3 on Fernandina volcano recorded 5 d before 2005 May 13 eruption. From top to bottom: spectrogram of electric and magnetic fields (ICE and IMSC sensors), electron density and temperature (ISL sensor), ion density and temperature (IAP sensor) and earthquakes occurring along the path of the orbit; symbols on the bottom right-hand side indicate magnitude and time of earthquakes along the path of the satellite. Time window: 2005 May 8 from 16:26 to 16:37 UT time. (b) Anomaly of type 3 on Lascar volcano recorded 18 d before 2006 April 18 eruption. From top to bottom: spectrogram of electric and magnetic fields (ICE and IMSC sensors), electron density and temperature (ISL sensor), ion density and temperature (IAP sensor) and earthquakes occurring along the path of the orbit; symbols on the bottom right-hand side indicate magnitude and time of earthquakes along the path of the satellite. Time window: 2006 March 31 from 14:39 to 14:50 UT time.

Although the interpretation is based on the volcanic activity of the three volcanoes, the study shows that EM signals observed on DEMETER satellite could be related to a simple scheme related to the volcanic activity. A larger number of cases in the future will clarify these relationships.

5 CONCLUSION

On land, magnetic and electric signals may precede volcanic eruptions. Transient signals are mostly observed during pre-eruptive periods, which can be roughly on the order of weeks

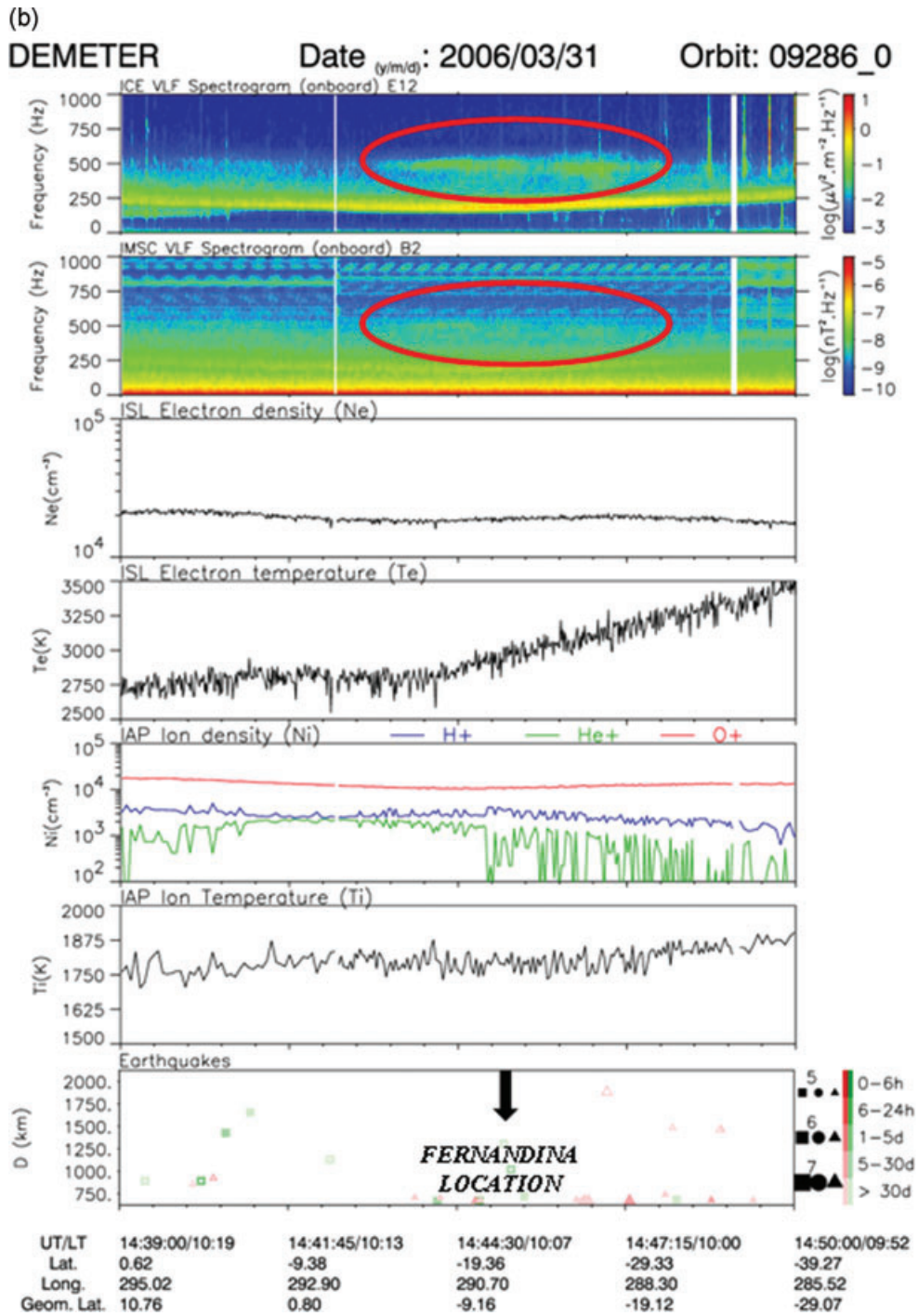


Figure 6. (Continued.)

Table 3. Anomalies of type 1. Name of volcanoes, latitude, longitude, time of appearance of anomaly, frequency band of the anomaly, time of eruption, density and temperature anomalies and volcanic explosivity index (VEI).

Volcano	Latitude (degree)	Longitude (degree)	Anomaly		Eruption		ISL		IAP	
			Occurrence (day)	Frequency (Hz)	Date	VEI	D	T	D	T
Fernandina	-0.37	268.45	-5	600	2005 May 13	2				
Lascar	-23.37	292.27	+4	750	2006 April 18	3				
Manda-Hararo	12.17	40.82	+8	DC-170	2007 August 12	2				

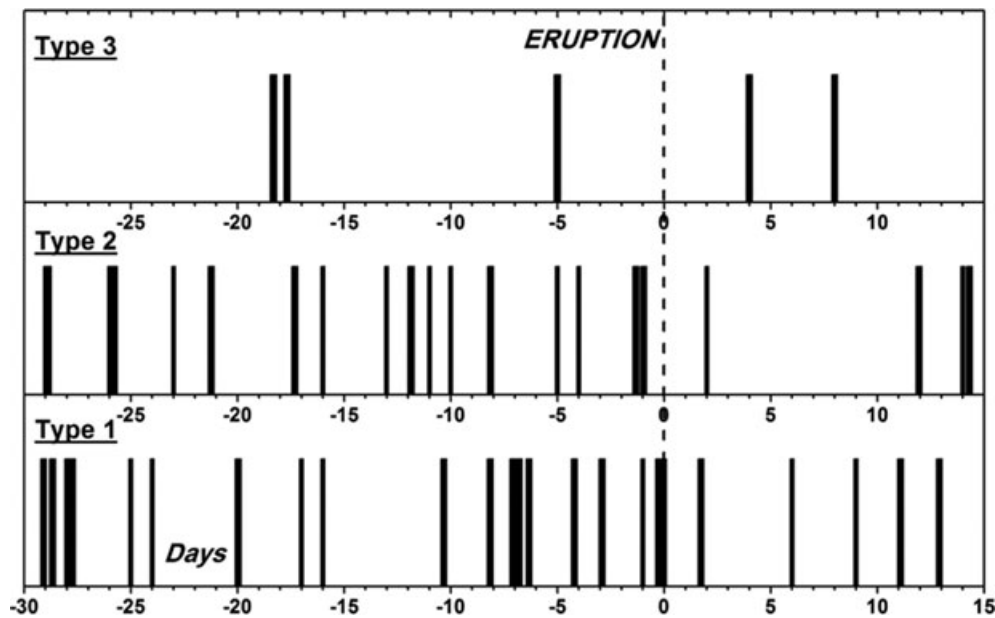


Figure 7. Anomalies of type 1, 2 and 3 observed within the time window 30 d before and 15 d after the eruptions, between 2004 August and 2007 December.

depending on the dynamism of the volcano (see references herein).

Satellite observations allow a global analysis of the perturbations of the ionosphere induced by the volcanic activity. The advantage of satellites coverage is to track anomalies in large areas of the Earth where ionospheric disturbances are not too large (latitude between 50°S and 50°N). On the other hand, for a non geostationary satellite as DEMETER, the drift in longitude between two consecutive orbits is generally too large (few thousand kilometres) for continuously evaluating the persistence of anomalies with time.

Nevertheless the study of the perturbation of the ionosphere by erupting volcanoes between 2004 August and 2007 December shows that electric or electric and magnetic anomalies may be observed above volcanoes for distances at the ground surface less than 500 or 900 km. Beyond these distances, the background EM environment may concern other ionospheric phenomena like hisses or high latitudes auroral activity.

Three types of anomalies have been recognised and for two of them the origin is known to be electrostatic turbulences and whistlers phenomena. These two types of anomalies are also observed in the vicinity of impending earthquakes. The third type of anomaly was unknown and further investigations will be led on its origin.

In the time period of 30 d before to 15 d after an eruption, the three types do not appear systematically on all volcanoes. On the 50 volcanoes, which have erupted between 2004 August and 2007 December, DEMETER was only tracking anomalies, at most every day, during a time window of 70–110 s above each active volcano. Nevertheless, 48 anomalies in the ionosphere were recognised and associated with 30 eruptions on a total of 74. No clear relationship is found between the features of the volcanoes (geological setting, dynamism and explosivity index) and the type or the recurrence of the anomalies. The number of cases will be increased in the future to secure these observations.

The other systematic study of existing anomalies between 2004 August and 2006 December was led on Lopevi, Aoba and Ambrym

volcanoes, whatever the volcanic activity was. The outstanding result shows that anomalies are only recorded before and during the activity of the three volcanoes. The vicinity of the three volcanoes (distance <200 km) does not allow to immediately associate the anomalies to a particular volcano. However, based on the simple assumption that no anomaly caused by volcanic activity appears long time before an eruption, it is possible to attribute logically each anomaly detected by DEMETER to the different volcanoes, giving rise to a logical pattern between anomalies and volcanic activity.

From these two complementary and systematic studies, we can assume that eruptions of volcanoes may be preceded by the appearance of electric, magnetic and electric anomalies, and in electron and ion temperature and density as well. For the volcanoes, which are not systematically monitored by ground real time devices, DEMETER satellite observations can be an additional tool for detecting and analysing anomalies in regard with a future surface activity.

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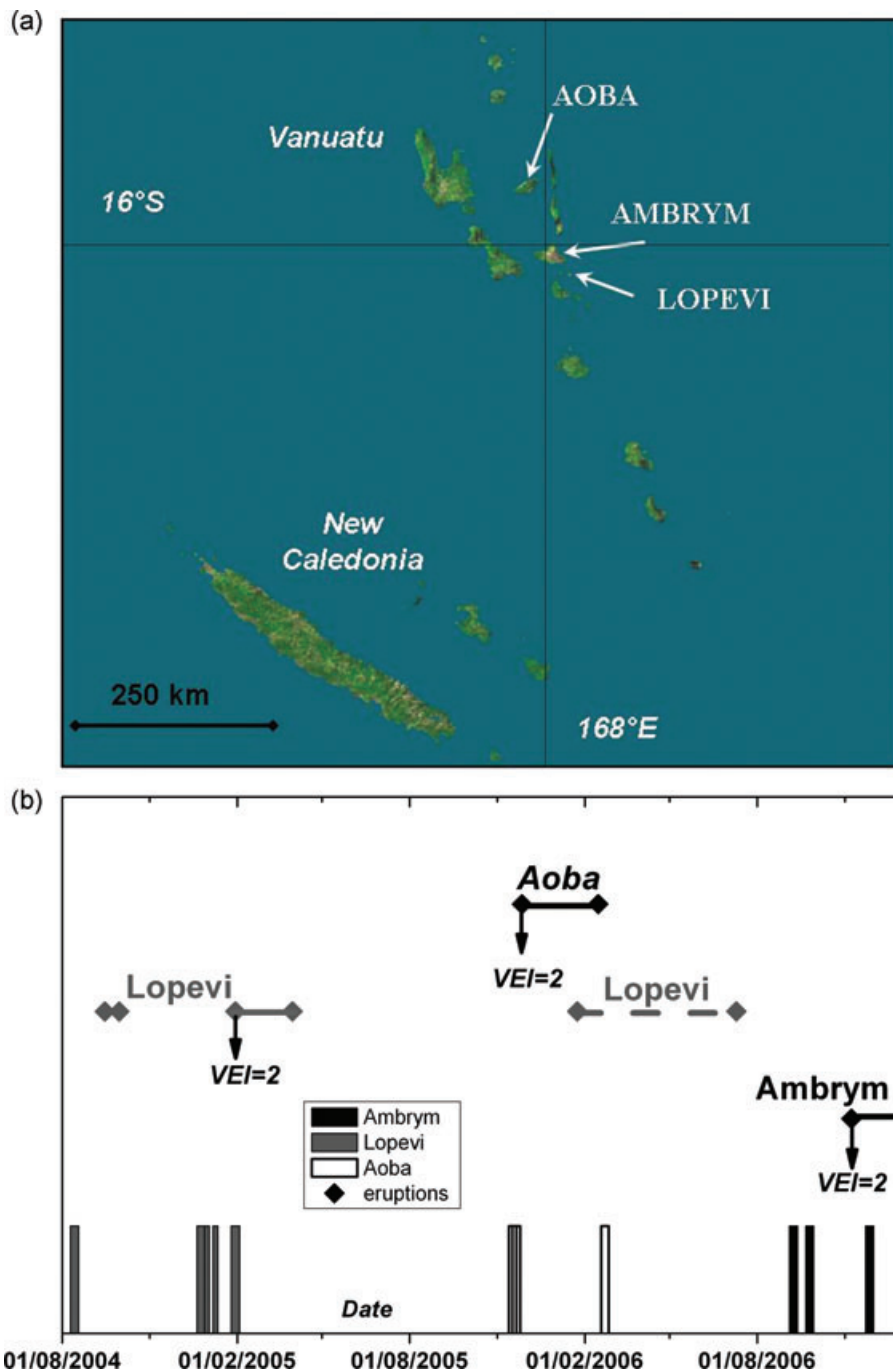


Figure 8. (a) Location of Lopevi, Aoba and Ambrym volcanoes in Vanuatu archipelago. (b). Anomalies observed above Ambrym (black bars), Aoba (empty bars) and Lopevi (grey bars) volcanoes between 2004 August 1 and 2006 December 31.

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