

Geomagnetic anomalies in the area of Popocatepetl volcano, Mexico

A. Kotsarenko, V. Yutsis*, V. Grimalsky, S. Koshevaya and Yu. Kotsarenko

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Resumen

Las anomalías geofísicas de diferente naturaleza observadas en el área del volcán Popocatepetl se presentan y analizan en este artículo. Las anomalías encontradas son de origen volcánico. El ambiente electromagnético en las cercanías del volcán resultaron tener más ruido que las estaciones de referencia; una fuerte actividad geomagnética similar al ruido fue observada en la componente H; además solamente se detectaron pulsaciones geomagnéticas en la estación Tlamacas (localizada a 4 km del volcán). Algunos cambios notables en la evolución del índice fractal calculado para el campo geomagnético pueden estar conectados a la presencia de procesos críticos, los cuales pueden estar ocurriendo en la dinámica del volcán.

Palabras clave: actividad volcánica, anomalía geomagnética, índice fractal, Popocatepetl.

Abstract

Geomagnetic anomalies of different nature observed in the area of Popocatepetl volcano are presented and analyzed in the current paper. The analysis reveals some anomalies considered to be of local volcanic origin: the EM background in the vicinity of the volcano was found to be significantly noisier than other reference stations; sporadic strong noise-like geomagnetic activity was observed in the H-component; some geomagnetic pulsations were observed only at Tlamacas station (located 4 km near the volcano). Some noticeable changes in the evolution of the fractal index calculated for geomagnetic field may be connected to the presence of critical processes in the volcano dynamics.

Key words: volcano activity, geomagnetic anomaly, fractal index, Popocatepetl.

A. Kotsarenko
Facultad de Ingeniería
Universidad Autónoma del Carmen
Cd. del Carmen, Campeche, México

V. Yutsis*
División de Geociencias Aplicadas
Instituto Potosino de Investigación Científica
y Tecnológica, A.C.
San Luis Potosí, 78216
S.L.P., México

*Corresponding author: vsevolod.yutsis@ipicyt.edu.mx

V. Grimalsky
S. Koshevaya
Centro de Investigación en Ingeniería
y Ciencias Aplicadas
Universidad Autónoma del Estado de Morelos
Cuernavaca, Morelos, México

Yu. Kotsarenko
Independent Researcher
Cuernavaca, Morelos, México

Introduction

The object of our interest, Popocatepetl volcano (nicknamed El Popo, Figure 1, top left), is located in Central Mexico (19.0N, 98.6W) at 5465 m altitude. It is one of several active volcanoes that form the Trans-Volcanic Belt of Mexico (also known as Neo-Volcanic Axis) and its existence is related to the geodynamics of the North American and Cocos plates. El Popo is one of the major geological hazards in Mexico, if a sudden eruption would take place (Figure 1, top right), it may result in one of the most dramatic natural disasters in contemporary Mexican history due to the fact that El Popo is situated near one of the world's most populated areas (Figure 1, bottom left) : Mexico City (about 70 km southeast) and the nearby populations of Puebla (about 45 kilometers west) and Cuernavaca (about 60 kilometers northeast) among others. More than 30 million people live in the view distance of the volcano and hundreds of thousands of people would be endangered by hazards associated with a large explosive eruption of the volcano (Macías Vázquez *et al.*, 1995). A major eruption would have serious consequences for people living in communities on the flanks of the volcano, and ash from such an eruption could also endanger aircraft using Mexico City international airport.

About 30 eruptions have been reported in historical time (although documentation is poor), the latest significant activity took place from 1920-22. During the eruptive activity from December 2000 (Figure 2) more than 56,000 people were evacuated from the surrounding area and more than hundred civilian air flights departing and landing at Mexico City airport were cancelled. Besides of that, El Popo is a permanent source of the ash periodically polluting nearby metropolitan areas (Juárez *et al.*, 2005). Due to its recent activity Popocatepetl volcano is the object of constant seismic and volcanic monitoring by CENAPRED (National Mexican Center for Disasters Prevention) and also the actual interest to establish a station for permanent geomagnetic monitoring of the volcano. Present activity of Popocatepetl volcano can be briefly summarized as follows.

Light eruptions occur everyday: from several to tens of eruptions of gas and water can be daily observed during quiet volcano phases, up to 50-100 eruptions occurred in the active phases (González-Pomposo, 2004; Arámbula-Mendoza *et al.*, 2010). In several months moderate eruptions of gases and volcano ash take place from one to several times per day for quiet and active phases, respectively. Moderate eruptions can also be

accompanied by explosive elements (rocks injection), with a frequency from several to dozens of events per year in recent times. Major eruptive activity is not so frequent. The last time such activity occurred it lasted from December 2000 to January 2001. At this stage intensive rock expulsions, lava eruptions and pyroclastic flows take place in addition to the above mentioned phenomena. Tectono-volcanic micro-seismic events with magnitudes up to $M_s=2-3$ and high frequency tremors are also part of the volcano activity.

Geomagnetic anomalies observed in the area of Popocatepetl volcano in the period 2003-2009 during constant monitoring of magnetic field in Tlamacas station are presented in this paper.

Different long-term observatories all over the world collected in monographs (Hayakawa, 1994, 1999, and Hayakawa and Molchanov, 2002) points the ULF EM (Ultra Low Frequency Electro-Magnetic) band as very promising for EM emission monitoring generated in the period preceding strong seismic events. The number of volcano-related EM studies is quite smaller but some of them deserve a particular interest (Currenti, *et al.*, 2005, Enomoto, *et al.*, 2006, Fujinawa *et al.*, 2006) proving the possibility of generation of similar signals associated with a volcanic activity.

Geological setting

Popocatepetl is a Pliocene-Quaternary stratovolcano situated 65 km SE of Mexico City and 45 km to the west of the city of Puebla, in the frontal part of the Trans-Mexican Volcanic belt (TMVB) (Figure 1 and 2) on a basement of Paleozoic metamorphic and Cretaceous sedimentary rocks (Macías *et al.*, 2005; Espinasa-Pereña and Martín-Del Pozo, 2006). The volcano forms the southern end of the Sierra Nevada volcanic range. Its stratigraphic column consists of pyroclastic deposits (sandy ash, pumice, ash flow, lithic clasts of granodiorite, hornfels, arenite and other xenolites) erupted during the past 23,000 yr. BP (Siebe *et al.*, 1995, Siebe and Macías, 2006). Mooser *et al.* (1996) report the existence of three units differentiated by their lithology. The first corresponds to the Popocatepetl volcano, composed of andesitic, dacitic and rhyolitic lavas alternating with pyroclastic materials. The second corresponds to the foothills of the volcano, and is composed of pyroclastic potent layers as ash and pumice, plus materials such as lahar, fluvial and fluvio-glacial deposits. This whole set is called the Tarango Formation. The third unit consists of a different type of

monogenetic volcanoes that are located in the SW sector of the volcano on its piedmont. These form part of the Chichinautzin Group, where cones of scoria with extensive lava flows of basic and intermediate composition, i.e., where basalts and andesites, are dominating.

Data collection and processing

Geomagnetic monitoring of Popocatepetl volcano was established on March 8, 2002, as a complimentary part of the Tlamacas seismic station (CENAPRED, $98^{\circ} 37' 41''$ W, $19^{\circ} 04'$



Figure 1. Popocatepetl. Quiet volcano, January 2005 (a). Eruption of Popocatepetl, December 2000 (b). Map of the volcano Popocatepetl (red circle) and Tlamacas station (blue arrow) (c). Gas eruptions as seen from the Tlamacas station (d).



Figure 2. Popocatepetl eruption, December 19, 2000. Photo courtesy of Mexico National Center of Prevention of Disasters (CENAPRED).

01'' N) located 4 km near the volcano crater (Figure 1, bottom right). First data collected by Torsion type 3-axial magnetometer (GPS-synchronization, 50 Hz sample frequency, designed at St-Petersburg IZMIRAN Dept.) appeared to be contaminated by an intensive periodical multi-band noise coming from the near-buried seismograph cables, as well as the precision of the instrument went down. Recording of the data was renewed in 2003 with a 3-coordinate fluxgate magnetometer (GPS, 1 Hz, designed at UCLA). The results from 2003-2004 (Kotsarenko *et al.*, 2005a) due to the numerous power cuts frequently occurred in the observation spot cover an unlucky short time intervals and therefore are considered not very reliable. The powerful USP system established in the 2005 permitted to collect a 5 month constant monitoring data (March-July, 2005) which are analyzed in this study.

The study includes the analysis of dynamic spectra as part of a traditional analysis for the continuous component of the magnetic field and the analysis of geomagnetic micro-pulsations for the pulse component. Temporal intervals with a high geomagnetic activity (estimated by equatorial Dst index) are normally discarded from the analysis. In order to distinguish the local character of the observed phenomena from the global ones compared our results where compared with those calculated from reference stations: the closest Mexican station Juriquilla (JU2 and other geomagnetic stations integrated to the Mid-Continent Magneto-seismic Chain (McMAC, Chi *et al.*, 2005) network are equipped with the same instrument (Table 1).

Another subject of study was the geomagnetic fractal dynamics which emphasize the character of the criticality of the SOC (Self Organized Critical) processes contributed to the geomagnetic field (Gotoh *et al.*, 2004; Kotsarenko *et al.*, 2004 and 2005b).

As the SOC processes emphasize tendency $S(f) \sim f^{-\beta}$ (where S is a spectral density of the signal and f is the frequency), the FFT (Fast Fourier Transform) was used for calculation of tectono-volcanic events β as the slope of the line that best fits $\log(S)$ -vs- $\log(f)$.

Results

The analysis of the obtained results shows the following tendencies:

1. The general EM background in the vicinity of the volcano is significantly noisier than in the Juriquilla or the other reference stations (Figure 3). In the very low frequency range, up to 0.01-0.02 Hz, both TLA and JU2 are characterized by rather similar noise intensity, with some "flares" at 2:00 and 6:00. For larger frequency bands, TLA is on the average noisier than JU2. The observed feature has a mostly permanent character.

2. The strong noise-like geomagnetic activity in the H-component of magnetic field with intensity up to tens of gammas and duration from several hours (Figure 4) up to several days (Figure 5) was detected only in the TLA geomagnetic data 13 times during the observations time. These events sometime accompanied by a weak and moderate eruptive activity (mostly gas or water) of the volcano and local seismic events, but at all other times it occurs without any observed activity.

3. Some geomagnetic pulsations observed at LA station (Figure 6) were not detected at the reference station, and use to be locally generated in the volcano area. The observed pulsation do not reveal any dominant direction (arbitrary polarization). Observed phenomena have similarity with seismo-related effects (Kotsarenko *et al.*, 2004).

Table 1. Description (Geographic Coordinates) for Tlamacas and reference stations.

Station name	Abbreviation	Latitude N	Longitude E
San Gabriel Dam	SGD	40.7	242.2
Boulder	BLD	40.1	254.8
Juriquilla	JU2	20.6	259.6
Tlamacas	TLA	19.0	261.4
Jicamarca	JIC	-12.0	283.1

05-Mar-2005, SIGNAL. TLAMACAS (volcano station, in color) and JURIQUILLA (referring station, black lines)

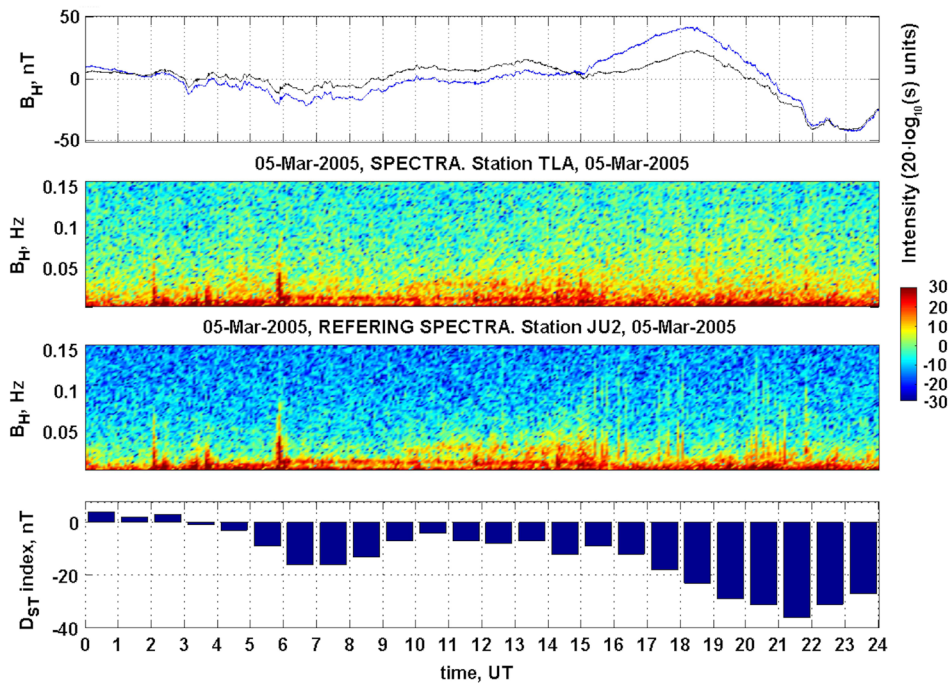


Figure 3. Top panel. H-component signals, Tlamacas (blue line) and Juriquilla (black line). 2nd and 3rd panels: Tlamacas and Reference spectrogram accordingly. Bottom panel: Dst index of geomagnetic activity. The spectral intensity of the noise background is higher in the Tlamacas (2nd panel); domination of more intensive orange colors in contrary to the weaker green and blue seen at the 3rd panel, Juriquilla, the reference station.

16-Mar-2005, SIGNAL. TLAMACAS (volcano station, in color) and JURIQUILLA (referring station, black lines)

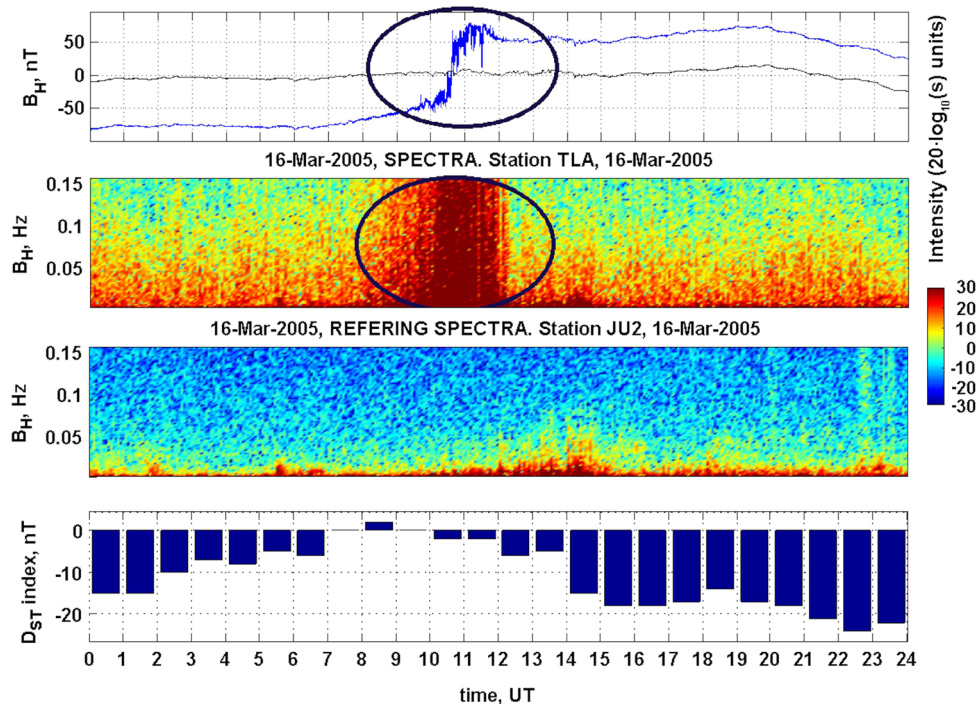


Figure 4. The intensive (100 nT change of the base value, up to 50 nT in the noise amplitude) perturbation observed in the signal at Tlamacas station (blue line) in compare with a referent Juriquilla signal (back line) (top panel); and its spectra (2nd panel). Referent (not-perturbed) Juriquilla spectra (3rd panel) observed under geomagnetically quiet period. Dst index of geomagnetic activity (bottom panel).

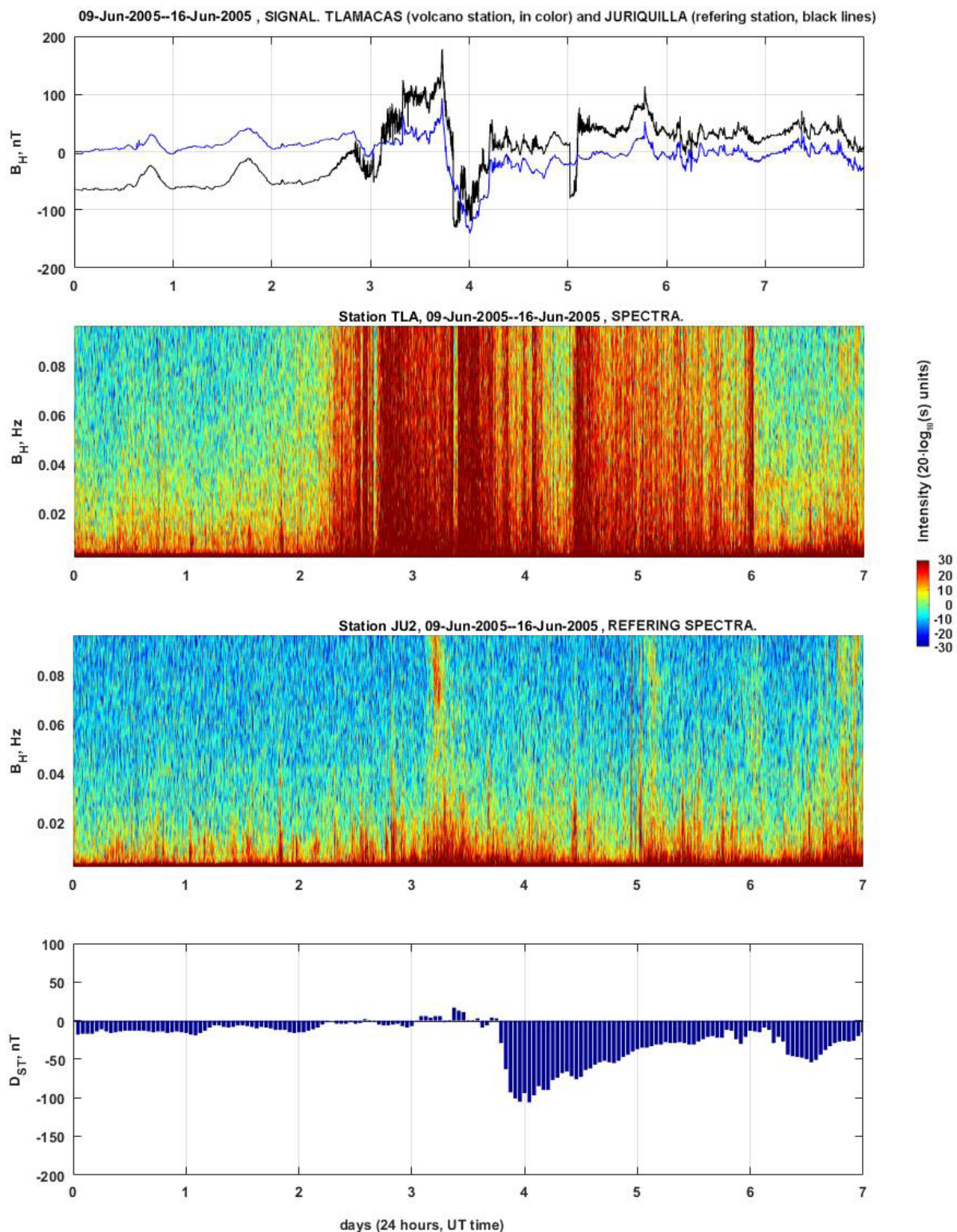


Figure 5. Top panel. Noise-like geomagnetic behavior observed several days in the signal of Tlamacas station (blue line) in compare with a referent Juriquilla signal (back line), and its spectra (2nd panel). Referent (not-perturbed) Juriquilla spectra (3rd panel). Bottom panel: Dst index of geomagnetic activity.

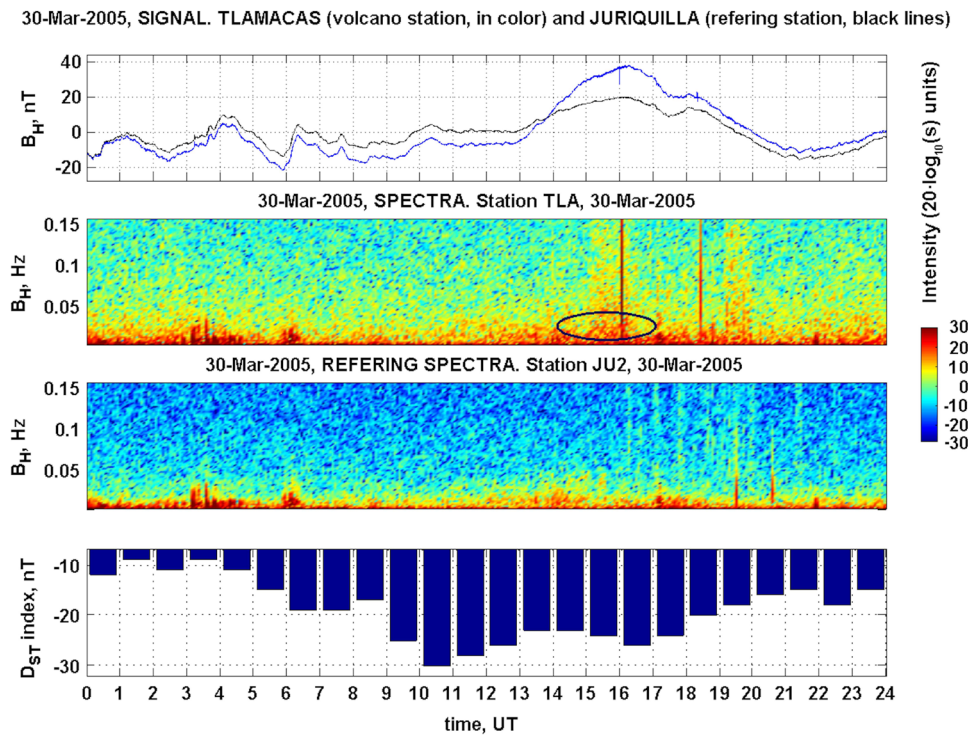


Figure 6. The example of locally generated PC4-like geomagnetic micro-pulsation is marked by ellipse. In the presented case the pulsation intensity is more expressed in the H-component. The table of symbols is the same as in Figures 4-5.

4. The dynamics of the fractal index for the LA station, in comparison with the reference station, show 1-2 days drops during geomagnetically quiet days (marks 1-4, Figure 7) whereas at the other stations results are rather comparable (especially for the northern stations, the Jicamarca station is located at Zero magnetic latitude). Events 1-3 may indicate the increase of the level of criticality in the processes that contributed to the signal (also see Kotsarenko *et al.*, 2004, 2005b,) while event 4 is probably related to the effect of a geomagnetic storm.

Discussion

As the observed phenomena have occurred in an electromagnetically calm place as a volcano, the following provisional models that could possibly explain the mentioned anomalies are presented:

1. As the magma has good conductive properties, convective circular motion in the magmatic reservoir may create a perturbed magnetic field due to the effect of self-induction.

2. The thermal heating may induce re-magnetization processes in the rock medium.

3. The different mechanisms of micro-fracturing (already developed) may be enhanced by the conductive currents in the lava.

4. The effect of the magneto-striction simulated by stressed rock movement may also be possible source of the generated emission (in analogy to the electro-striction).

Among the observed anomalies one (the highly perturbed H-component, Figures 4 and 5) is a subject of special interest and should be discussed separately. Similar links to the observed phenomena were presented in Martin-Del Pozzo *et al.* (2002). The significant differences between these results and the presents one are that the firsts authors used a total field magnetometer system and, therefore, could not distinguish the polarization of the observed signals. The actual polarization of the perturbations, mostly expressed in the horizontal component, makes the recently obtained result important because it indicates

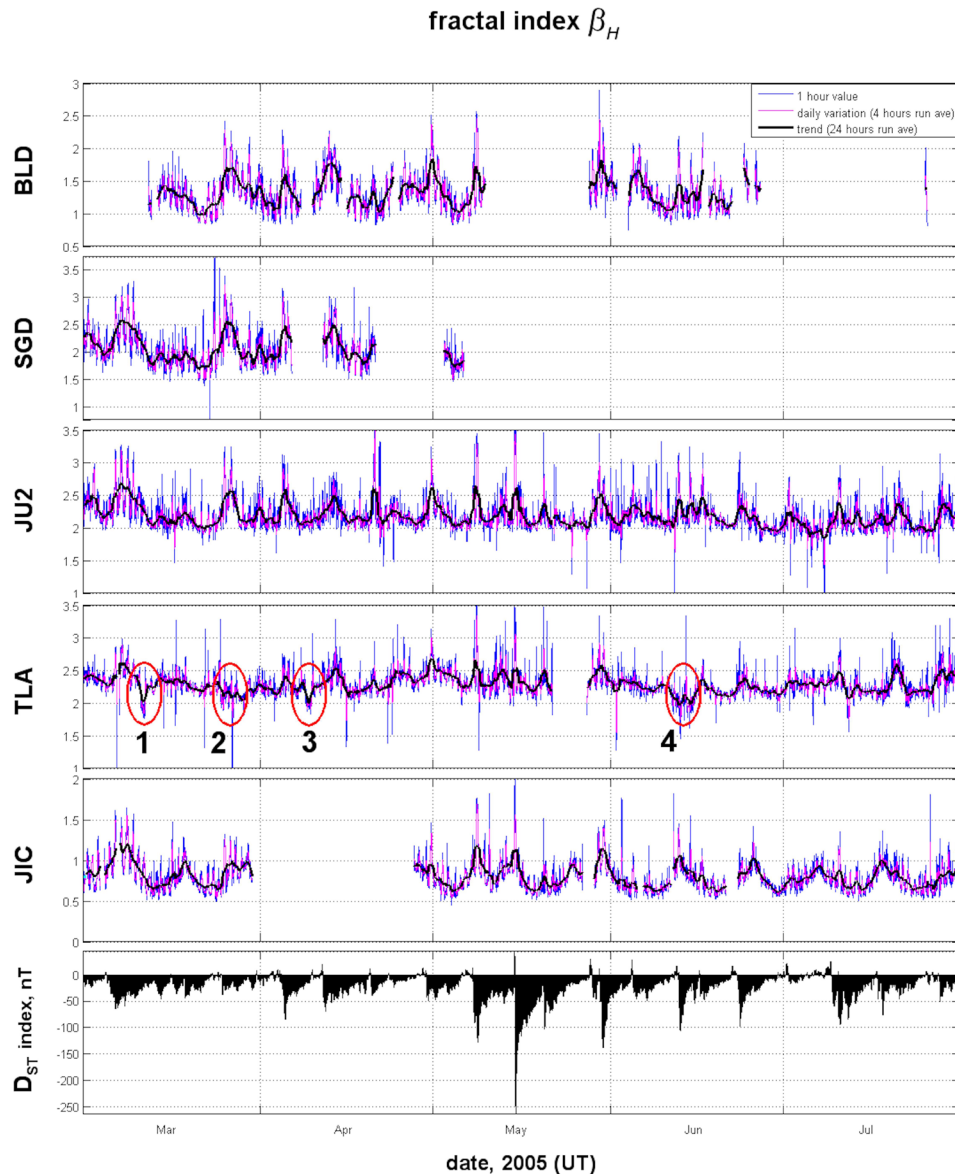


Figure 7. Dynamics of the fractal index β calculated for geomagnetic field at Tlamacas and referring stations (see for description Table 1). Local drops in geomagnetic fractal dynamics (marked by ellipses 1-4) may indicate some critical processes occurred in the region of volcano.

certain anisotropy in their generation, or a specific geometry of the source system. The majority of natural physical mechanisms capable of producing similar perturbations, such as the already mentioned re-magnetization and magmatic flows, are in general, isotropic. Another suitable mechanism, magnetostriction, implies friction in the rock medium, i.e. tectono-volcanic events and therefore does not match the evidence, because most of the observed perturbations occur under seismically quiet periods.

In the present study original mechanism of the generation, can theoretically explain the strict polarization of the perturbations is shown. It is based on the specific geometry of the source. The possible existence of an additional lateral magmatic camera (or broad magmatic channel) besides the main magmatic reservoir is proposed. This camera should have *flat* geometry and be oriented strictly perpendicular to the line S-N, which almost coincides with the axis LA – Popocatepetl Crater with a very small deviation. From this, circular

motions in that hypothetical flat camera will produce manifestations of the H-component of the geomagnetic signal only.

To estimate a possible current configuration that could yield the measured values and directions of the magnetic field, let us consider the simplest circular closed loop with current (Figure 8). It is well-known (Batygin and Topygin, 1978) that the magnetic field of the loop with electric current is given by the formula:

$$\begin{aligned} B_\rho &= \frac{\mu_0 I}{2\pi} \frac{y}{\rho[(R+\rho)^2 + y^2]^{1/2}} \times \left[-K(k) + \frac{R^2 + \rho^2 + y^2}{(R-\rho)^2 + y^2} E(k) \right]; \\ B_y &= \frac{\mu_0 I}{2\pi} \frac{1}{[(R+\rho)^2 + y^2]^{1/2}} \times \left[K(k) + \frac{R^2 - \rho^2 - y^2}{(R-\rho)^2 + y^2} E(k) \right]; \\ B_\varphi &= 0; \quad k^2 = \frac{4R\rho}{[(R+\rho)^2 + y^2]} \end{aligned} \quad (1)$$

Here I is the value of the electric current, $K(k)$ and $E(k)$ are the elliptic integrals of the first and second kinds. That the volcanic rocks are assumed nonmagnetic. In the present case, the magnetic component in one specified direction dominates. A possible origin of such a field can be the loop with electric current oriented in the vertical direction, when the normal vector to the area of the loop is directed along the line S-N. Under conditions $\rho \ll R$, $y \sim R$ we have:

$$B_\rho \approx 0; \quad B_y \approx \frac{\mu_0 R^2 I}{2(R^2 + y^2)^{3/2}} \quad (2)$$

In this configuration, the measured magnetic field is directed along the y-axis. For

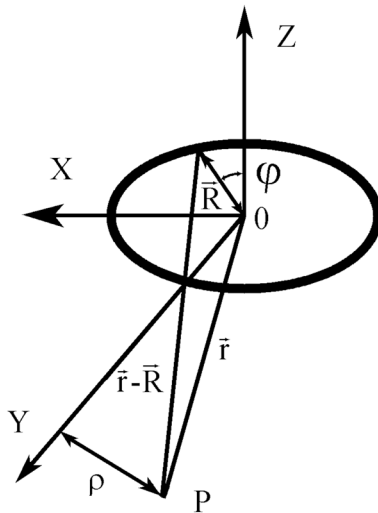


Figure 8. Schematic source configuration for the flat magmatic camera (ring) for the calculation of the magnetic field in the observation point (P).

the estimations, $R = 2$ km (a possible size of current loop within the volcano's body), $y = 2$ km, $B_y = 100$ nT are used. From (2), one can get $I \approx 10^3$ A.

Assuming the shape of the ring as a torus with the radius of its internal cross-section $a \ll R$, it is possible to estimate a density of the current within such a torus:

$$i \approx \frac{I}{\pi a^2} \quad (3)$$

The estimations for realistic values of such a radius are $a = 200$ m give $j \approx 0.01$ A/m².

This model is still very hypothetic. However, on the basis of the results by Zúñiga and Valdés (2007) analysis of the spatial distribution of magnitudes of the local seismicity in the vicinity of Popocatepetl volcano points out a possible existence of a new magma chamber. Eventually, to prove this hypothesis, permanent simultaneous observations at different points (at least 4) separated by distances of 1- 10 km and situated at different heights are desirable. A more solid confirmation can be obtained from geophysical and geological studies in the area of the volcano.

Finally, geomagnetic micro-pulsations with arbitrary elliptical polarization was detected, locally generated in the vicinity of the volcano, not observed in the reference station. The event presented in Figure 6 was observed during an intense and long-duration volcano eruption (it started at 11:21 UT, and the cloud raised up to 1.5 km moving in the N-W direction). Their possible sources could involve collective properties of the extending aerosol (dusty) plasma like the generation of different plasma instabilities due to the motion of the ionized (and metallic) particles erupted from the crater.

Unfortunately, the precision of the instrument (noise power is 10^{-3} nT²/Hz at 1 Hz) prevent to confidently resolve them from the enhanced noise level, especially at the time when the eruption began.

Conclusions

A series of anomalies of different geophysical nature were presented in the current paper. Description of the geomagnetic anomalies observed at Popocatepetl volcano were shown have a discussion of the possible mechanisms of their generation. The first two phenomena observed, EM noisy background and strong

burst-like activity, reveal manifestations of the internal dynamics of the volcano related to the local geomagnetic field, and, therefore, their future analysis could be useful to obtain some latent processes at the body of the volcano, which are difficult to locate by traditional methods. The last phenomena, the locally generated magnetic pulsations, can also serve as a marker for the direction and velocity of the motion of eruptive clouds (using triangulation technique in case the geomagnetic station set is greater than 4) and, therefore, can also be useful for an efficient prevention of the pollution in the air and nearby populated lands.

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References

- Arámbula Mendoza R., Valdés González C., Martínez Bringas A., 2010, Temporal and spatial variation of the stress state of Popocatepetl volcano, Mexico. *J. Volcanol. Geotherm. Res.*, 196, 156–168.
- Batygin, V. and Toptygin, I., 1978, Problems in Electrodynamics, Academic Press, N.Y., 574 pp.
- Chi P.J., Engebretson M.J., Moldwin M.B., Russell C.T., Mann I.R., Samson J.C., López
- Cruz-Abeyro J.A., Yumoto K. and Lee. D.-H., 2005, Mid-continent Magnetoseismic Chain (McMAC): A Meridional Magnetometer Chain for Magnetospheric Sounding, Proceedings of the Environment Modeling Workshop, June 17-22, 2005, Snowmass, Colorado, USA.
- Currenti G., Del Negro C., Lapenna V. and Telesca L., 2005, Multifractality in local geomagnetic field at Etna volcano, Sicily (southern Italy). *Nat. Hazards Earth Syst. Sci.* (NHES), 5, 555–559.
- Enomoto Y., Hashimoto H., Shirai N., Murakami Y., Mogi T., Takada M., Kasahara M., 2006, Anomalous geoelectric signals possibly related to the 2000 Mt. Usu eruption and 2003 Tokachi-Oki earthquakes. *Physics and Chemistry of the Earth*, 31, 319–324.
- Espinasa-Pereña R., Martín-del Pozzo A.L., 2006, Morphostratigraphic evolution of Popocatepetl volcano, México, in: Siebe, C., Macías, J.L., Aguirre-Díaz, G. (eds.), Neogene-Quaternary continental margin volcanism: a perspective from México, Boulder, Colorado, Geol. Soc. of America, *Special Paper*, 402, 115–138.
- Fujinawa Y., Matsumoto T., Iitaka H., Takahashi K., Nakano H., Doi T., Saito T., Kasai N., Sato S., 2006, Earliest detection of magma movements by measuring transient streaming potential. *Physics and Chemistry of the Earth*, 31, 223–233.
- González-Pomposo G.J., 2004, Análisis de la sismicidad asociada a la actividad del volcán Popocatepetl y determinación de su estructura por medio de tomografía sísmica, PhD Thesis, Instituto de Geofísica, National University of Mexico, Mexico.
- Gotoh K., Hayakawa M., Smirnova N. and Hattori K., 2004, Fractal analysis of seismogenic ULF emissions. *Phys. Chem. Earth*, 29, 419–424.
- Hayakawa, M. and Fujinawa, Y. (Eds.), 1994, Electromagnetic Phenomena Related to Earthquake Prediction, Terra Sci. Pub. Co., Tokyo.
- Hayakawa, M., (Ed.), 1999, Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes, TERAPPUB, Tokyo.
- Juárez A., Gay C., Flores Y., 2005, Impact of the Popocatepetl's volcanic activity on the air quality of Puebla City, Mexico. *Atmósfera*, 57–69.
- Kotsarenko A., Pérez Enríquez R., López Cruz-Abeyro J.A., Koshova S., Grimalsky V., 2004, Analysis of the ULF electromagnetic emission related to seismic activity, Teoloyucan geomagnetic station, 1998–2001. *Natural Hazards and Earth System Sciences (NHES)*, Vol.4, P. 679–684.
- Kotsarenko A., Valdez-Gonzalez C., López Cruz-Abeyro J.A., Pérez Enríquez R., Koshevaya S., Grimalsky V., 2005a, Seismogenic ULF EM emissions of volcano origin, observed at Tlmacas seismo-geomagnetic station, volcano Popocatepetl, Mexico, 2001–2004. International Workshop on Seismo Electromagnetics IWSE 2005, Programme and Extended Abstracts, 217–218.
- Kotsarenko A., Molchanov O., Perez Enriquez R., Lopez Cruz-Abeyro J. A., Koshevaya S., Grimalsky V., and Kremenetsky I., 2005b, Possible seismogenic origin of changes in the ULF EM resonant structure observed at

- Teoloyucan geomagnetic station, Mexico, 1999– 2001. *Natural Hazards and Earth System Sciences (NHES)*, 5, 711–715.
- Kotsarenko A., 2005c
- Macías J.L., 2005, Geología e historia eruptiva de algunos de los grandes volcanes activos de México, *Boletín de la Sociedad Geológica Mexicana*, Tomo LVII, núm. 3, 379-424.
- Macías Vázquez J.L., Carrasco Núñez G., Delgado Granados H., Martín Del Pozzo A.L., Siebe Grabach C., Hoblitt R.P., Sheridan M.F., Tilling R.I., 1995a, Mapa de peligros del volcán Popocatepetl, Instituto de Geofísica, UNAM, Mexico, 1995. http://tornado.cenapred.unam.mx/es/Instrumentacion/InstVolcanica/MVolcan/ImagenesMV_olcan/mapaPeligrosA.jpg
- Martin-Del Pozzo A.L., Cifuentes-Nava G. Cabral-Cano E., 2002, Volcanomagnetic signals during the recent Popocatepetl (Mexico) eruptions and their relation to eruptive activity. *J. Volc. Geoth. Res.*, 113, 415-428.
- Mooser F., Montiel A., Zúñiga Á., 1996, Nuevo mapa geológico de las cuencas de México, Toluca y Puebla: México, D.F., Subdirección de Construcción, Comisión Federal de Electricidad México, D.F.
- Siebe C., Macías J.L., Abrams M., Rodríguez-Elizarrarás R.S., Castro R., Delgado H., 1995, Quaternary Explosive Volcanism and Pyroclastic Deposits in East-Central México: Implications for Future Hazards. *Geol. Soc. of America*, 1, 1-48.
- Siebe and Macías, 2006
- Zúñiga R.D.M. and Valdés C., 2007, Se está formando una segunda cámara magmática en el Popocatepetl? Análisis de la variación espacial de los valores B bajo el edificio volcánico, *Geos*, 27 (1), 113, 2007, <http://www.ugm.org.mx/raugm/docs/geos27-1b.pdf>.