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Aeromagnetic anomalies and structure of the Iztaccíhuatl-Popocatépetl volcanic region in Central Mexico

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RESUMEN

Se reportan los resultados del estudio aereomagnético de la región volcánica del Iztaccíhuatl y Popocatépetl, en el centro de México. El volcán Popocatépetl está caracterizado por una anomalía dipolar de gran amplitud y polarización normal centrada sobre el cono. La anomalía muestra una correlación con la topografía y los lineamientos mayores (zonas de falla). Las anomalías sobre el volcán Iztaccíhuatl muestran características similares con una anomalía dipolar normal y anomalías sobrepuestas de menor amplitud, aunque la anomalía es compuesta y de mayor complejidad. El estudio aereomagnético en las regiones adyacentes muestra anomalías de alta frecuencia y mayor amplitud en los terrenos volcánicos y de menor amplitud y baja frecuencia sobre los depósitos sedimentarios. Las anomalías magnéticas sobre los dos volcanes incluyen efectos superficiales de la estructura topográfica y de efectos profundos. Los resultados de este estudio ilustran el alto potencial del método aereomagnético para investigar estructuras volcánicas con topografía abrupta y de difícil acceso.

PALABRAS CLAVE: Estudio aeromagnético, estructura volcánica, volcán Popocatépetl, centro de México.

ABSTRACT

Popocatépetl volcano is characterized by a high amplitude dipolar anomaly that is normally polarized and centered on the summit cone. The anomaly shows the effects of topographic relief and of major fault zones. Similar characteristics are documented over the Iztaccíhuatl volcanic complex, where a large composite dipolar anomaly is correlated with topography and with effects of deeper-seated source bodies. The dipolar anomaly is normally polarized over the summit elevations, with superimposed lower amplitude anomalies over the volcano flanks. An aeromagnetic survey over the adjacent volcanic and sedimentary terrains to the east and south of the Iztaccíhuatl-Popocatépetl complex also reflect the surface and deep geological features, with high-amplitude, high-frequency anomalies over the volcanic units and small volcanoes and low-amplitude, long-wavelength anomalies over the volcano-sedimentary deposits. The aeromagnetic survey illustrates the potential of aerogeophysical methods in studying volcanic structures over abrupt topography and undergoing active eruptive phases.

KEY WORDS: Aeromagnetic survey, volcanic structure, Popocatépetl volcano, Central Mexico.

INTRODUCTION

Magnetic surveys have long been conducted over volcanic regions (e.g., Finn and Williams, 1987; Okuma *et al.*, 1994; Nakatsuka, 1994; Gibson and Milligan 1998), where they have demonstrated their usefulness for delineating volcanic structure and potential for further development. Recently, aerogeophysical methods are undergoing rapid development with new high-resolution instrumentation and methodologies (e.g., Mouginis-Mark *et al.*, 2000; Finn *et al.*, 2001).

After decades of quiescence the Popocatépetl volcano reawakened in late 1994. Background seismicity showed a sharp increase by October 1994, followed a few weeks later by a swarm of volcano-tectonic events and tremor accompanying a large ash plume on December 21, 1994. Activity at first was characterized by emission of ash rich in non-juvenile material and volatiles, with tremor, volcano-tectonic and long-period earthquakes (Arciniega-Ceballos *et al.*, 1999, 2000). Ash and gas columns from some events distributed ash over Mexico City and surrounding areas, with lapilli and blocks falling over the volcano flanks. In March 1996, a dacitic dome built up within the summit crater; magmatic activity to the present has been characterized by episodes of dome growth and destruction. Activity during December 2000 – January 2001 was particularly intense, and on January 21 a major explosive event resulted in the collapse of the eruptive column and formation of small pyroclastic flows. Studies of seismicity, deformation employing GPS, tilt systems and other components of the monitoring network require an improved knowledge of the shallow and deep structure.

In this paper, initial results of an aeromagnetic survey over the Iztaccíhuatl and Popocatépetl volcanoes and surrounding volcanic terrain in central Mexico are presented.

POPOCATÉPETL VOLCANO

Popocatépetl volcano lies in the central sector of the Plio-Quaternary Trans-Mexican volcanic belt (TMVB) (Figure 1). The TMVB is a continental arc associated with subduction of the Cocos and Rivera plates along the Middle American trench, and oriented almost E-W from the Pacific ocean to the Gulf of Mexico (Urrutia-Fucugauchi and Del Castillo-García, 1977). Central Mexico is heavily populated, and includes the major cities of Guadalajara, Morelia, Toluca, Mexico, Puebla and Xalapa. Volcanic activity has exerted a major influence in the development of the Prehispanic settlements, often located close to volcanoes.

Popocatépetl is at the southern end of a north-south trending volcanic range formed by three large volcanic structures (Figure 2). Popocatépetl andesitic stratovolcano has evolved in alternating periods of cone formation and destruction, with major cataclysmic events that destroyed ancient cones followed by formation of dome complexes and new summit cones (Carrasco-Núñez *et al.*, 1986; Robin and Boudal, 1987).

Magnetostratigraphic and rock-magnetic investigations have been undertaken in the Iztaccíhuatl and Popocatépetl (e.g., Carrasco-Núñez *et al.*, 1986; Urrutia-Fucugauchi, 1995). This data are useful in modeling aeromagnetic anomalies, providing constraints on the physical property contrasts and remanent magnetization directions. Rock-magnetic data also provide information on hydrothermal activity and in mapping of alteration zones. Ground magnetic surveys are being conducted, which document fault zones and shallow structures. Repetitive measurements taken at different times along selected profiles and locations (López-Loera *et al.*, 1999) are being used to study temporal variations in the magnetic field associated with the eruptive activity (thermal state of magmatic system, fluid effects, piezomagnetic effects, etc). A permanent magnetic station has been in operation in the northern volcano flank of Popocatépetl, south of Cortés Pass (Cifuentes-Nava *et al.*, 1998). This station provides necessary information on diurnal and secular variation of geomagnetic field (and mag-

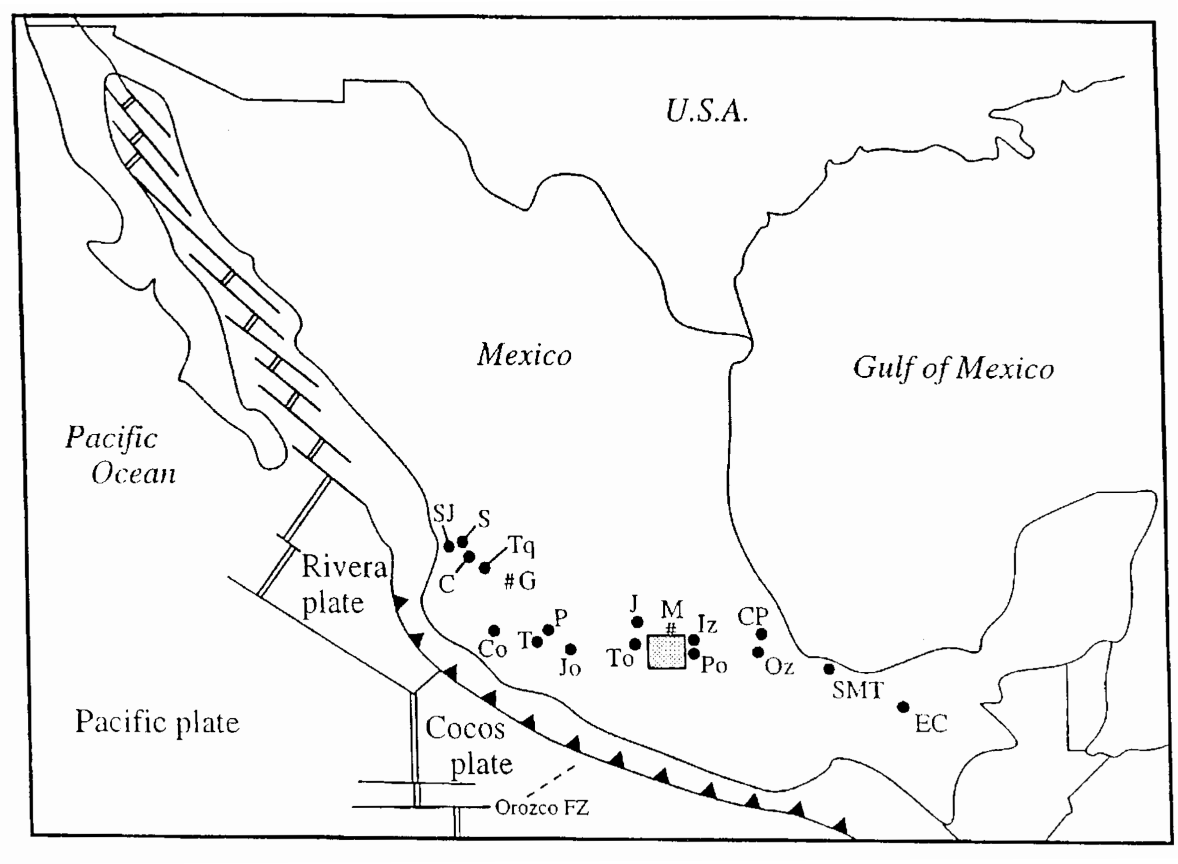


Fig. 1. Schematic map showing some of the volcanoes (black dots) in the Trans-Mexican volcanic belt (TMVB) and Chiapas magmatic arc. Location of the basin of Mexico is shown by the square (M). The eastern basin limit is formed by the volcanic range of the Iztaccíhuatl (Iz)-Popocatépetl (Po) complex (taken from Wallace and Carmichael, 1999).

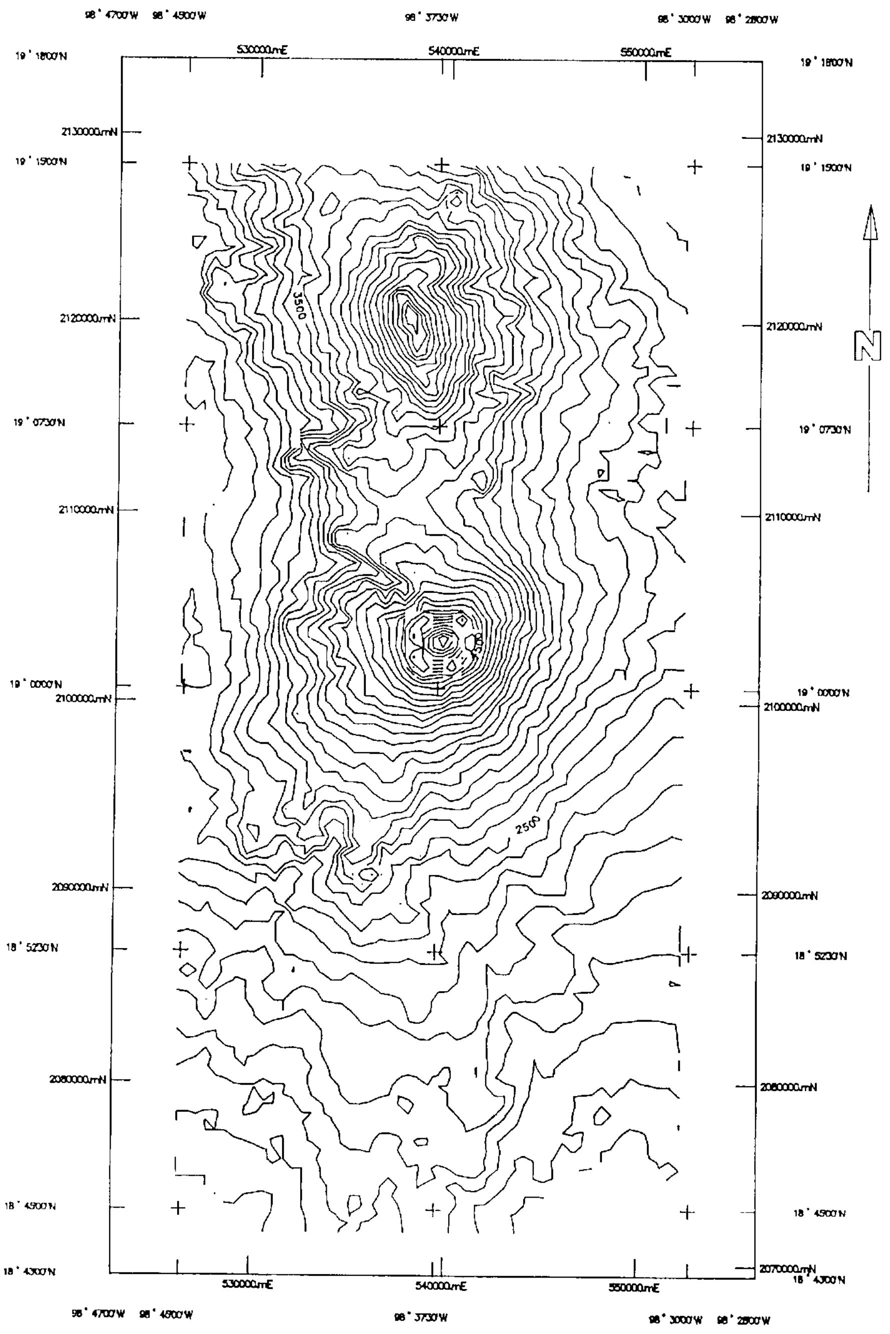


Fig. 2. Simplified contour map of the topography over the Iztaccíhuatl-Popocatépetl volcanic range. Contour map constructed from the elevation data acquired during the aeromagnetic survey.

netic storms), as well as data on the short-term anomaly changes due to volcanic events.

Analyses of seismicity are restricted by the lack of a detailed velocity model. Volcano-tectonic earthquakes help delineating fractured regions through which magmatic fluids move and stress readjustment zones. Tremor and long-period events document fluid movement, pressure and volumetric changes and dynamic conditions through the conduits at shallow depths (Chouet, 1996). Petrographic and chemical studies, focused in the origin of melt components, elemental budgets, differentiation and fractionation processes, interactions in deep crust and shallower conduits, metamorphic processes and hydrothermal systems, may profit from an understanding of volcanic structure. The tectonic and structural setting of the volcano is important, and models of its

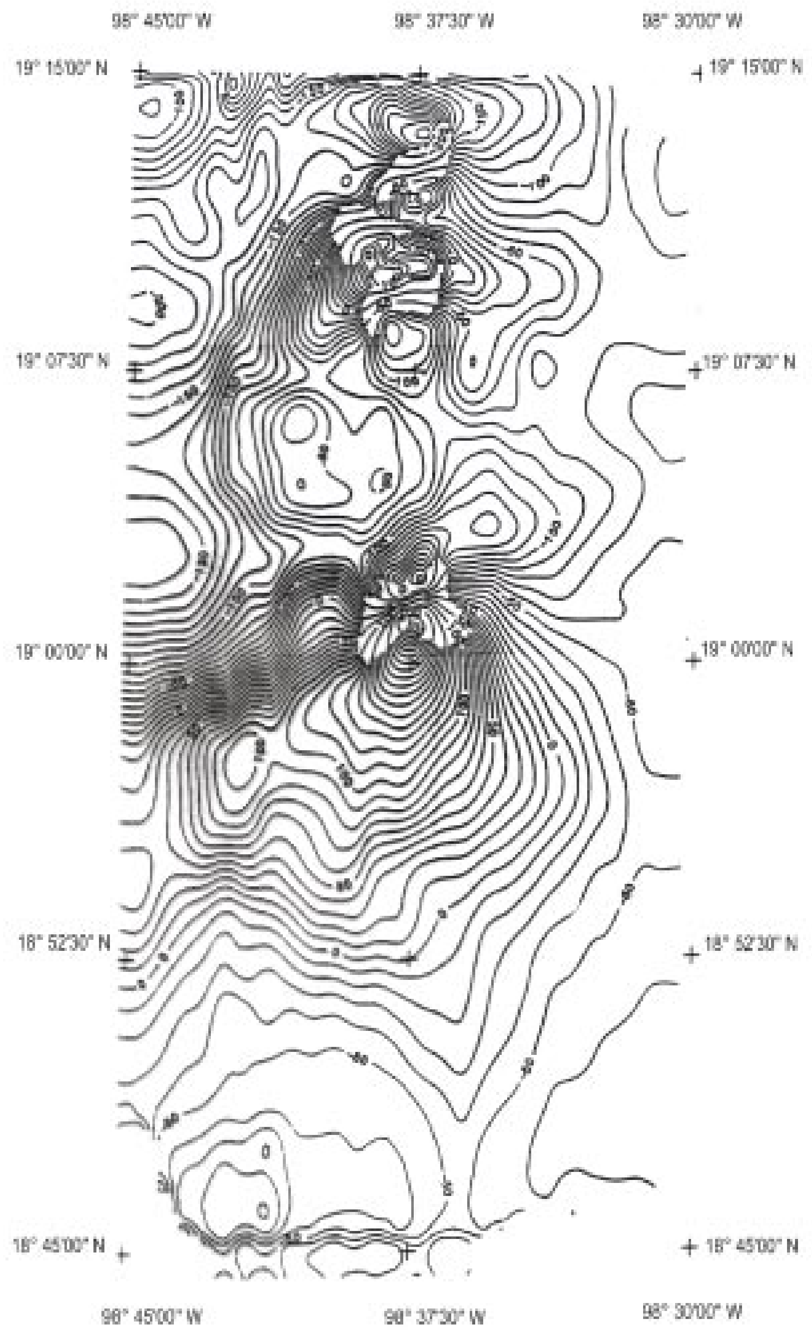


Fig. 3. Contour map of the aeromagnetic anomaly observed over the Iztaccíhuatl-Popocatépetl volcanic complex. Note the dipolar anomaly over the Popocatépetl and the more complex form of the anomaly over the Iztaccíhuatl. Contours every 10 nT.

subsurface give information on faults and zones of fracturing and hydrothermal alteration (Finn *et al*., 2001). These studies help investigate tectonic controls of magmatic activity, and also potential collapse of portions of the volcanic edifice and the formation of debris avalanches.

AEROMAGNETIC SURVEY

The aeromagnetic survey was planned as a part of the active volcano research program, to investigate on the internal structure of the volcano, occurrence of faults, fractures and alteration zones and the on-going active eruptive phase. Total-field magnetic data have been collected by using an optically-pumped cesium magnetometer installed in a Britten Norman BN-2 Islander aircraft. Positioning was with video navigation and global positioning system (GPS). The area surveyed was divided into several separate zones according to topography and surface geology; with the zone over the

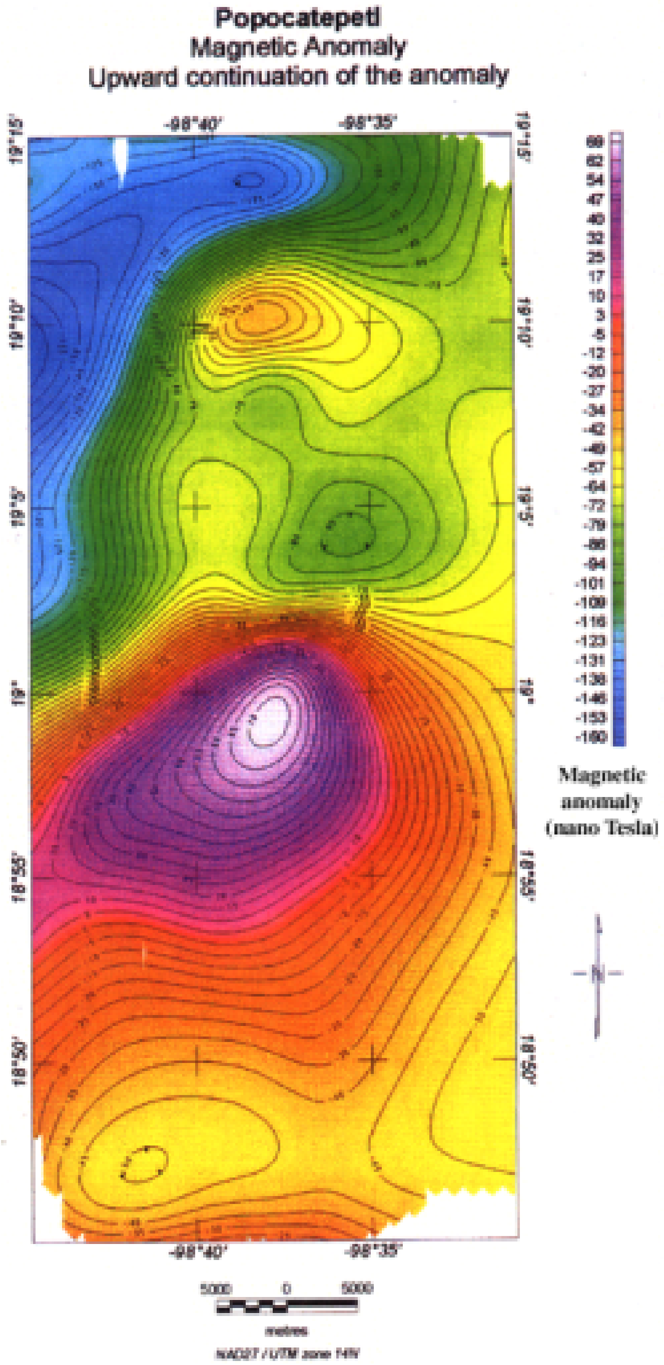


Fig. 4. Upward analytical continuation of the aeromagnetic anomaly over the Iztaccíhuatl and Popocatépetl volcanoes.

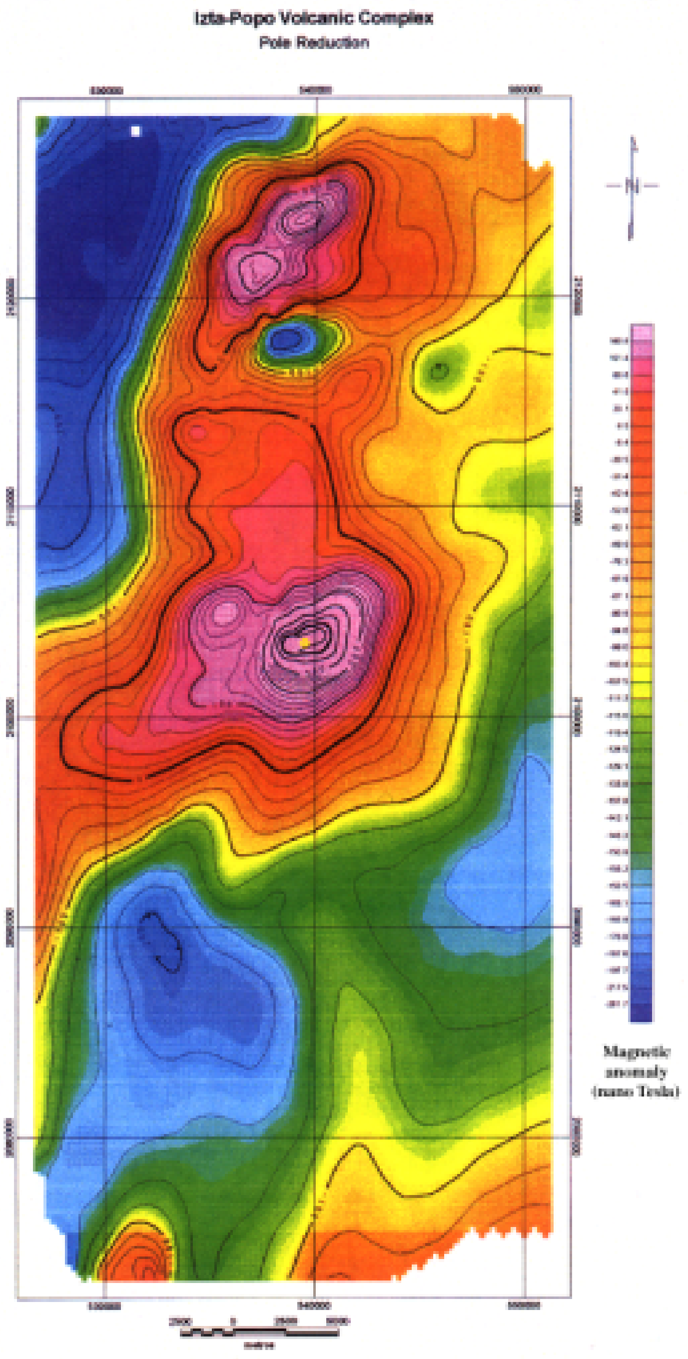


Fig. 5. Reduced to the pole anomaly map of the aeromagnetic data over the Iztaccíhuatl-Popocatépetl volcanic complex.

high elevation Iztaccíhuatl and Popocatépetl volcanoes flown separately at an elevation of 5500 m a.s.l. Twenty-five north-south lines and five east-west control lines formed the survey grid. Flight lines crossed the summit crater some 100 m above the crater rim. Some eruptive events occurred at the time of the magnetic survey, with emission of ash and gas clouds. The survey grid over the adjacent areas east and south of the Iztaccíhuatl-Popocatépetl range was formed by north-south and east-west lines at a terrain clearance of 300 m and line spacing of 1000 m.

Aeromagnetic and position/elevation data were initially processed at the Consejo de Recursos Minerales. Further data processing and modeling is being done at the National University using Geosoft software (Oasis Montaj data processing and analysis system) for data contouring and display (Fig-

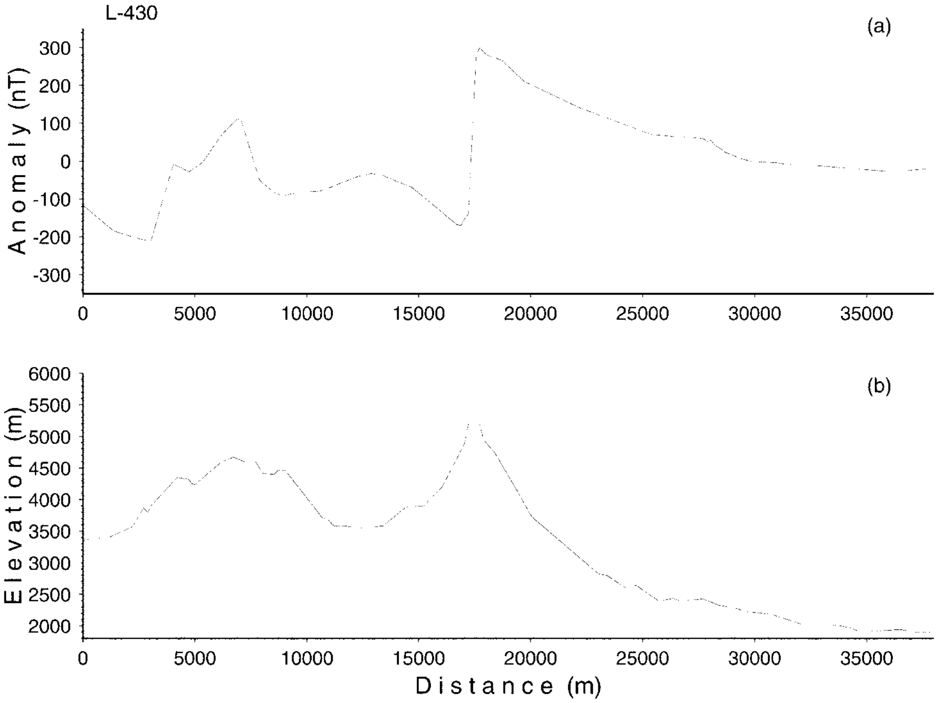


Fig. 6. (a) Aeromagnetic and (b) elevation data for line L-430 within the group of the central profiles (south to north), crossing the Popocatépetl and Iztaccíhuatl volcanic complexes. Note the high amplitude dipolar anomaly over the Popocatépetl volcano and the composite dipolar anomaly over the Iztaccíhuatl volcano.

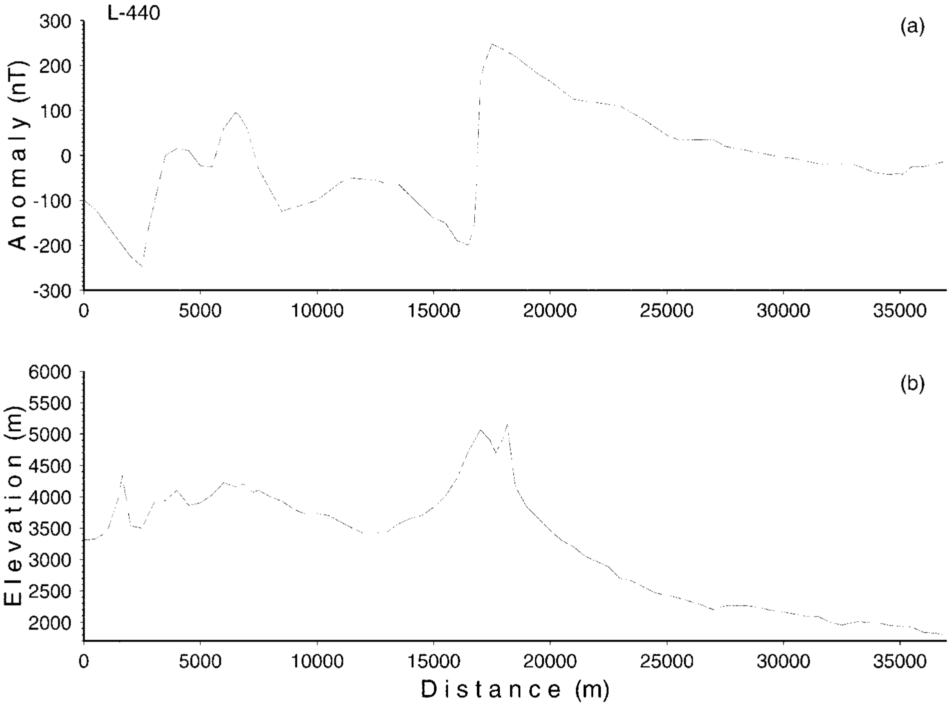
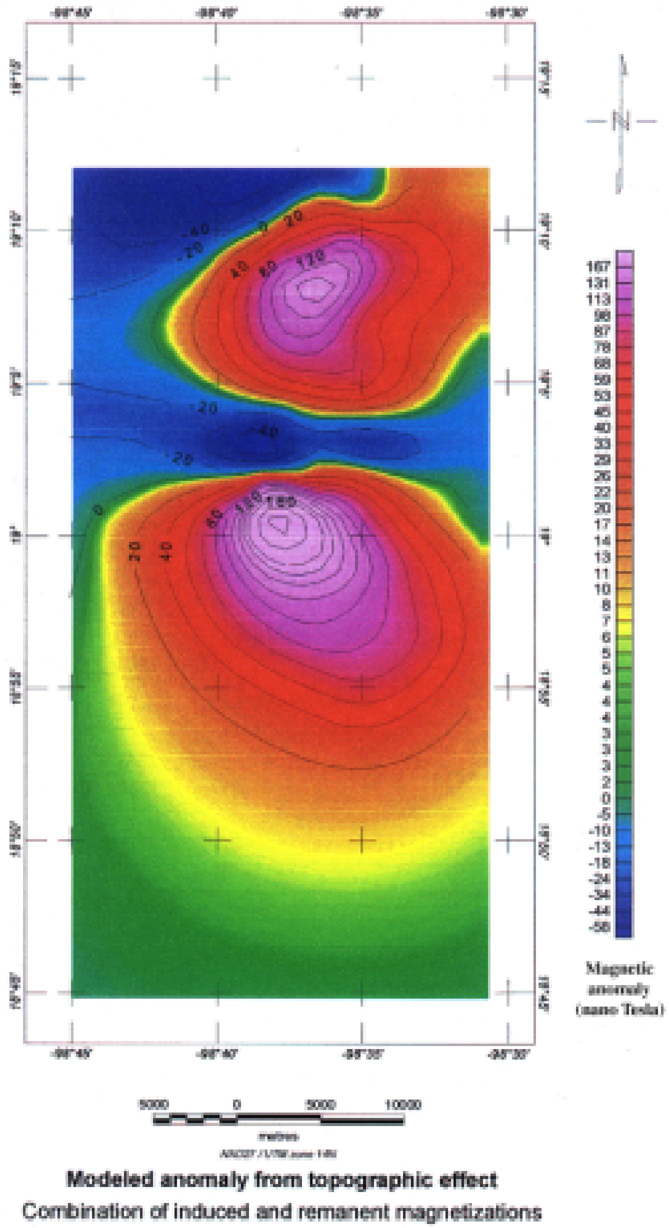


Fig. 7. (a) Aeromagnetic and (b) elevation data for line L-440 within the group of the central profiles (south to north), crossing the Popocatépetl and Iztaccíhuatl volcanic complexes. Note the high amplitude dipolar anomaly over the Popocatépetl and the composite dipolar anomaly over the Iztaccíhuatl volcano.



Modeled anomaly from topographic effect

Combination of induced and remanent magnetizations

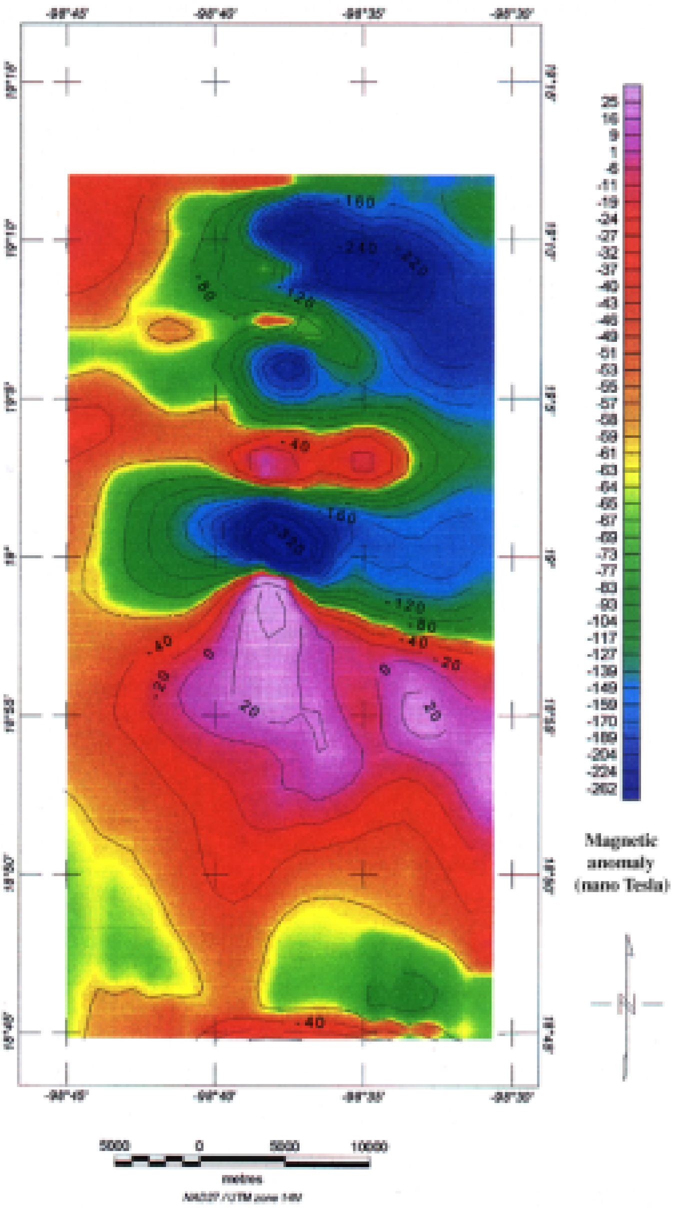


Fig. 8. Synthetic magnetic anomaly over the Iztaccíhuatl and Popocatépetl volcanoes constructed from a prismatic assemblage approximating the topography of the volcanic range.

Fig. 9. Difference field calculated by subtracting the synthetic topographic magnetic field from the observed aeromagnetic field.

ure 3). First and second vertical derivatives, reduction to the pole, and upward and downward analytical continuations have been calculated (Figures 4 and 5).

Digital elevation maps have been constructed for the Iztaccíhuatl-Popocatépetl complex and for the surrounding regions. Popocatépetl (Figure 2) shows a simple conical shape slightly elongated towards the southwest with a steeper flank on the east and a major canyon scarp to the NW. This corresponds to the older caldera rim of the Nexpayantla volcano. Iztaccíhuatl volcano shows a NS elongated shape (Figure 2) with three major structures forming the elevated portions corresponding to the "head", "breast" and "feet" of the mountain. It also shows a steep scarp west of the southern sector. The two volcanic edifices are separated by Cortés Pass (Figure 2).

TOPOGRAPHIC EFFECTS

Aeromagnetic studies over volcanic terrains with abrupt topography present special challenges, since there are large effects due to the rapidly varying distance between the ob-

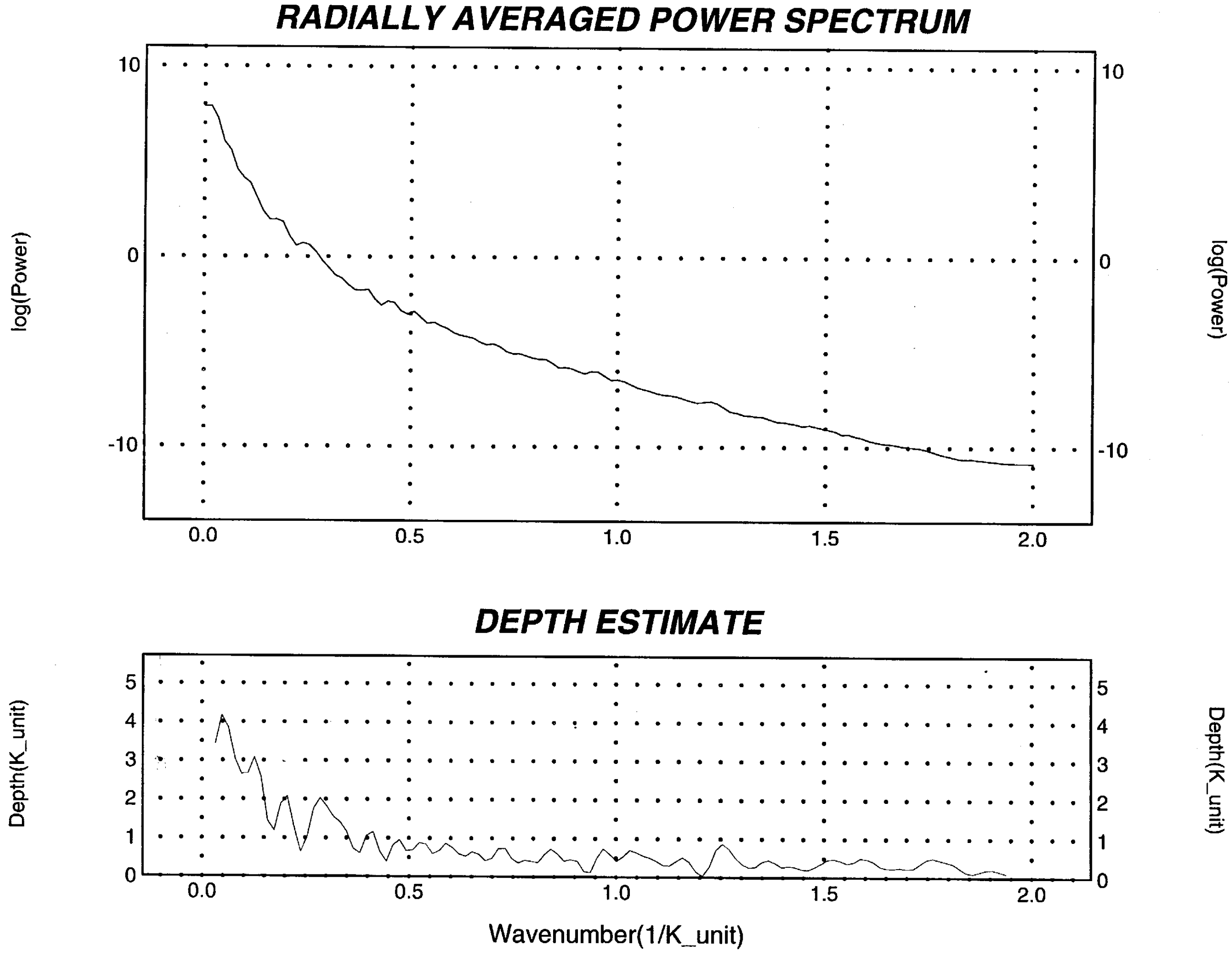


Fig. 10. Radial power spectrum of the aeromagnetic anomaly data plotted as a function of the wavenumber. The average depths estimated from the slope of the semi-logarithmic plot of the power spectrum are summarized in the bottom diagram.

servation point and the shallow magnetic sources. The effects are enhanced by the strong magnetic susceptibility and remanent magnetization contrasts of basic and intermediate volcanic rocks. The topographic effect in aeromagnetic data has been discussed in several studies (e.g., Blakeley, 1985; Cordell, 1985), and different methods have been employed for modeling and interpretation. Analytical continuation upward and downward methods between a level surface and an uneven surface (Cordell, 1985) and between uneven profiles have been developed (e.g., Huestis and Parker, 1979). The topographic effect can be evaluated as a forward problem by construction of geometric models based on the topography.

Total-field magnetic anomalies and topographic relief for three of the central lines across the volcanic complex are summarized in Figures 6 and 7. A first-order horizontal plane at 41 900 nT was used as an initial estimate of regional field. The high amplitude dipolar anomaly over the Popocatépetl summit cone and the lower amplitude composite anomaly over the Iztaccíhuatl are clearly shown. The residual anomaly shows a maximum value of the magnetic high of 250 nT and the minimum is –250 nT; maximum elevation on the side of the crater rim is 5165 m a.s.l.

To evaluate the effect of the topographic mass of Popocatépetl and Iztaccíhuatl volcanoes, we have constructed a geometric model consisting of an assemblage of prismatic bodies. The model considers a set of 22 200-m-thick prismatic bodies that follow the topography of the volcanic range above 2600 meters a.s.l. We used the method developed by Plouff (1976) with the following geomagnetic field parameters: declination=6°, inclination =47° and intensity = 43 000 nT. As a first approximation the rock-magnetic properties are treated as homogeneous; however, a complex assemblage of lava flows, pyroclastic flows, dikes, and lahars likely builds the volcanoes. We consider various data sets using the available paleomagnetic data for the Iztaccíhuatl and Popocatépetl volcanoes (Urrutia-Fucugauchi, 1995; Conte *et al*., 2002). Results of the synthetic models are shown in Figure 8. We have used average magnetic susceptibilities of 3 10^{-3} SI and 5 10^{-3} SI, and a remanent magnetization of 0.5 A/m. As expected, the synthetic field shows a large high-amplitude dipolar anomaly over the Popocatépetl volcano. The dipolar anomaly is however located to the north with respect to the observed anomaly field, which results in a difference between the synthetic and observed fields (Figure 9). Further modeling is required to evaluate the topographic effect on the aeromagnetic data. Forward models are limited by the lack of rock-magnetic data on the volcanic rocks at surface and at deep in the range. An alternative is use of inverse models for three-dimensional assemblages in the presence of topography (e.g., Parker and Huestis, 1974).

AEROMAGNETIC ANOMALIES

Popocatépetl is characterized by a large amplitude dipolar magnetic anomaly centered over the summit crater (Figure 3), with the high on the south and the low towards the north. The anomaly is slightly elongated along a SW-NE trend following the topography. The effects of the relief are also noted by the change in trend corresponding to the Nexpayantla canyon with a change in the anomaly shape to the NW of the dipole low. Other large feature is a SW-NE trend passing trough the center of the magnetic dipole, which is reflected in an elongation of the dipole low. This trend is interpreted as a major fault zone.

The Iztaccíhuatl volcano shows a composite elongated dipolar anomaly, more complex than over Popocatépetl, which correlates with the topography of the summit area and the structure of the summit peaks. Regional fault zones are also noticeable in the shape of anomalies and trends. The regional field is approximated with a first order horizontal surface of 41 900 nT.

The residual anomaly shows a maximum for the magnetic high of about 250 nT and a minimum of about –250 nT. Spectral analysis developed by Spector and Grant (1970) was used to estimate depths to magnetic source bodies. Preliminary results for transect L-400 gives average depth estimates of 690 m and 1000 m below the reference survey flight line. Results for the four neighbor profiles across the summit cone give similar estimates, ranging from 580 m to 710 m and 1000 m to 1270 m, respectively for the two source assemblages. The radial power spectrum calculated for the aeromagnetic anomaly map is shown in Figure 10. Depths estimated from the slope of the semi-logarithmic relation of power spectrum plotted as a function of the wavenumber are summarized in the bottom diagram. Initial analyses of volcano-tectonic earthquake hypocenters show a diffuse cluster between about 1 km above sea level and 6 km below sea level, which suggest possible features in the local basement like the Mesozoic carbonates-volcanics contact and brittle-ductile deep transition (Arciniega-Ceballos *et al*., 2000).

Magnetic field anomalies over the volcanic areas east and south of the Iztaccíhuatl and Popocatépetl volcanoes are characterized by high amplitudes and short wavelengths; whereas the sedimentary sequences, mainly in the south-eastern sector, show low amplitudes and long wavelengths. The volcanic areas are at around 1800 m a.s.l., with the elevation decreasing to the south. Upward continuation of the magnetic anomalies up to the reference plane used over Iztaccíhuatl-Popocatépetl shows a simple pattern with a large dipolar anomaly farther south of Popocatépetl (Figure 6). The large dipolar anomaly is slightly oriented NNE-SSW, suggesting a deep intrusive body. The dipole is also normally polarized with a high to low difference of some 160 nT. The long wavelength anomaly is over volcano-clastic deposits (including thick lahars) of Popocatépetl, with no surface indications of large intrusive bodies. Examination of the low elevation data shows a high frequency more complex pattern, pointing to a composite anomaly with sources at various depths, whose effects are integrated in the upward continuation field. Further studies are required to interpret the aeromagnetic anomaly and its geological implications.

CONCLUSIONS

Popocatépetl volcano shows a high amplitude dipolar anomaly that is normally polarized and centered over the summit cone (Figure 3): it reflects the effects of the topographic relief and major fault zones (Figure 2). A similar situation is observed over the Iztaccíhuatl volcanic complex, with a large composite dipolar anomaly (Figure 3). The dipolar anomaly is normally polarized over the summit elevations, with superimposed lower amplitude anomalies over the volcano flanks. Aeromagnetic survey data over the adjacent volcanic and sedimentary terrains to the east and south of the Iztaccíhuatl and Popocatépetl volcanoes also document the surface and deep geological features, with high- amplitude high-frequency anomalies over the volcanic units and small volcanoes and low- amplitude long wavelength anomalies over the sedimentary deposits. The study also documents a large dipolar anomaly over a deep-seated intrusive body, located farther south of Popocatépetl volcano.

Information of internal structure is critical to understand volcanoes and volcanic processes. Detailed models of tall stratovolcanoes are difficult to obtain because of abrupt topography, high elevation, difficult weather and working conditions and complex non-horizontal lithologic contacts, heterogeneous physical properties, and alteration zones. For volcanoes undergoing explosive phases, difficulties increase because of risks involved in field activities. Aerogeophysical methods, altimetry, remote sensing, GPS and radar interferometry satellite systems are offering new opportunities for high-resolution studies of active volcanoes.

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BIBLIOGRAPHY

ARCINIEGA-CEBALLOS, A., B. CHOUET and P. DAWSON, 1999. Very long-period signals associated with vulcanian explosions at Popocatépetl volcano, Mexico. *Geophys. Res. Lett., 26,* 3013-3016.

ARCINIEGA-CEBALLOS, A., C. VALDÉS and P. DAWSON, 2000. Temporal and spectral characteristics of seismicity observed at Popocatépetl volcano, central Mexico. *J. Volc. Geoth. Res., 102,* 207-216.

BLAKELEY, R. J., 1985. The effect of topography on aeromagnetic data in the wavenumber domain. *In:* Proceed. Int. Meeting Potential Fields in Rugged Topography, Univ. Lausanne Inst. Geophys. Bulletin, 7, 102-109.

CARRASCO-NÚÑEZ, G., SILVA, H. DELGADO and J. URRUTIA-FUCUGAUCHI, 1986. Geología y paleomagnetismo del Popocatépetl. Publ. Inst. Geofísica, UNAM, Ser. Inv., 33.

CHOUET, B., 1996. Long-period volcano seismicity: its source and the use in eruption forcasting. *Nature, 380,* 309-316.

CIFUENTES-NAVA, G., E. HERNÁNDEZ, E. CABRAL, F. CORREA-MORA, R. CHÁVEZ, J. URRUTIA-FUCUGAUCHI and A. L. MARTIN DEL POZZO, 1998. Simultaneous magnetic observations at Teoloyucan magnetic observatory and Popocatépetl volcano, Mexico. *Geofísica, 48,* 149-159.

CONTE, G., J. URRUTIA-FUCUGAUCHI, A. GOGUITCHAICHVILI, A. M. SOLER and A. INCORONATO, 2002. Paleomagnetic and paleointensity study of lava flows from the Popocatépetl volcanic region in central Mexico. (submitted).

CORDELL, L., 1985. Applications and problems of analytical continuation of New Mexico aeromagnetic data between arbitrary surfaces of very high relief. *In:* Proceed. Int. Meeting Potential Fields in Rugged Topography, Univ. Lausanne Inst. Geophys. Bulletin, 7, 96-101.

FINN, C. T. W. SISSON and M. DESZCZ-PAN, 2001. Aerogeophysical measurements of collapse-prone hydrothermally altered zones at Mount Rainier volcano. *Nature, 409,* 600-603.

FINN, C. and D. WILLIAMS, 1987. An aeromagnetic study of Mount St. Hellens. *J. Geophys. Res., 92,* 10,194-10,206.

GIBSON, R. I. and P. S. MILLIGAN (Eds), 1998. Geologic Applications of Gravity and Magnetics: Case Histories. Soc. Expl. Geophys., Geophys. Ref. Series 8, 162 pp.

HUESTIS, S. P. and R. L. PARKER, 1979. Upward and downward continuation as inverse problems. *Geophys. J. Roy. Astr. Soc., 57,* 171-188.

LÓPEZ-LOERA, H., J. URRUTIA-FUCUGAUCHI, L. M. ALVA-VALDIVIA, O. DELGADO-RODRÍGUEZ and F. GARCÍA-PÉREZ, 1999. Variaciones vulcanomagnéticas asociadas al complejo volcánico Popocatépetl-Iztaccíhuatl. *In:* Simposio Internacional Volcán Popocatépetl, Mexico City, Abstract and Program Volume, p. 22.

MOUGINIS-MARK, P. J., J. A. CRISP and J. H. FINK (Eds), 2000. Remote Sensing of Active Volcanism. Geophys. Monograph Series 116. American Geophysical Union, 272 pp.

NAKATSUKA, T., 1994. Aeromagnetic anomalies over the area of Unzendake volcano. *J. Geomagn. Geoelectr., 46,* 529-540.

OKUMA, S., M. MAKINO and T. NAKATSUKA, 1994. Magnetization intensity mapping in and around Izu-Oshima volcano, Japan. *J. Geomagn. Geoelectr., 46,* 541-556.

PARKER, R. L. and S. P. HUESTIS, 1974. The inversion of magnetic anomalies in the presence of topography. *J. Geophys. Res., 79,* 1587-1593.

PLOUFF, D., 1976. Gravity and magnetic fields of polygonal prisms and application to magnetic terrain corrections. *Geophysics, 41,* 727-741.

ROBIN, C. and C. BOUDAL, 1987. A gigantic Bezymianny-type event at beginning of modern volcan Popocatépetl. *J. Volcanol. Geoth. Res, 31,* 115-130.

SPECTOR, A. and F. S. GRANT, 1970. Statistical models for interpreting aeromagnetic data. *Geophysics, 35,* 293-262.

URRUTIA-FUCUGAUCHI, J., 1995. Constraints on Brunhes low-latitude paleosecular variation-Iztaccíhuatl stratovolcano. *Geofís. Int., 34,* 253-262.

URRUTIA-FUCUGAUCHI, J. and L. DEL CASTILLO-GARCÍA, 1977. Un modelo del Eje Volcánico Mexicano. *Bol. Soc. Geol. Mex., 38,* 18-28.

WALLACE, P. J. and I. S. E. CARMICHAEL, 1999. Quaternary volcanism near the Valley of Mexico: Implications for subduction zone magmatism and the effects of crustal thickness variations on primitive magma compositions. *Contrib. Mineral Petrol., 155,* 291-314.

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