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Spatial and temporal magnetic anomalies of Colima volcano, western Mexico

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RESUMEN

Se presentan resultados iniciales de un proyecto de largo plazo relacionados con los cambios temporales de las anomalías magnéticas sobre el Volcán de Colima. Este volcán se ha caracterizado por eventos eruptivos frecuentes en tiempos históricos. La actividad presente incluye el crecimiento de un domo de lava en la cima del cráter. Medidas del campo magnético total se tomaron en estaciones espaciadas cada 0.5 km a lo largo de una sección de 35 km que cubre el flanco este y parte de la cima entre Atenquique y El Playón, en un periodo que cubre del 27 de abril de 1995 al 16 de mayo de 1996. Se han reconocido 3 diferentes zonas con características magnéticas anómalas a lo largo de la sección. (1) La zona asociada a avalanchas de escombros del Nevado de Colima y depósitos volcano-conglomeráticos de la Formación Atenquique, entre las estaciones km 10 y 23, caracterizados por anomalías de amplitudes y frecuencias bajas sin cambios magnéticos temporales. (2) La zona de lavas y brechas andesíticas del Nevado de Colima entre las estaciones km 23 y 35, caracterizado por un conjunto de anomalías de baja frecuencia superpuestas a anomalías de altas frecuencias y amplitud variable. Está caracterizado por cambios magnéticos temporales de baja amplitud. (3) La zona entre las estaciones km 35 a 45, caracterizada por anomalías de baja frecuencia y altos y bajos magnéticos de alta amplitud con variaciones temporales de amplitud grande. Esta cruza la cima del Volcán de Colima y la caldera de avalancha, asociado a lavas y brechas andesíticas. Un modelado del campo magnético anómalo indica que los cuerpos fuente pueden extenderse cientos de metros a profundidad, más sin embargo existe una incertidumbre considerable en la variación en las propiedades magnéticas a profundidad. Los datos magnéticos anómalos sugieren que las variaciones temporales en la magnetización en el volcán son causadas por cambios en la temperatura. En particular, los procesos de magnetización/ desmagnetización bajo el área del cono relacionados a la actividad eruptiva pueden ser importantes para los cambios magnéticos. Mecanismos potenciales para los procesos de calentamiento-enfriamiento pueden incluir movimientos de magma y sistemas hidrotermales activos con actividad fumarólica fuerte e interacciones de agua subterránea. Un bajo magnético de 1500-2500 nT caracteriza a la cima del cono y a la caldera de avalancha. Se han observado cambios temporales superpuestos sobre estas anomalías magnéticas de alta amplitud y baja frecuencia, los cuales muestran efectos térmicos asociados a la actividad volcánica.

PALABRAS CLAVE: Anomalías magnéticas, domo, estado térmico, Volcán de Colima, occidente de México

ABSTRACT

Colima volcano has erupted frequently in historic times. Present activity includes the episodic growth of a lava dome within the summit crater. Total magnetic field at stations spaced every 0.5 km along a 35 km long transect was measured across the eastern flank and the summit, between Atenquique and El Playón, from April 27, 1995 to May 16, 1996. Three distinct sectors were recognized. (1) The Nevado de Colima debris avalanche and volcanic conglomerates of the Atenquique Formation, between stations 10 and 23 km, characterized by low-amplitude, low-frequency anomalies and no temporal changes. (2) Andesitic lavas and breccias between stations 23 and 35 km, characterized by low-frequency anomalies with superimposed high-frequency anomalies of varying amplitude, and low-amplitude temporal changes. (3) Between stations 35 and 45 km, characterized by low-frequency, high-amplitude anomalies and large-amplitude temporal variations, across the summit and avalanche caldera, in andesitic lavas and breccias. Modeling indicates that source bodies may extend several hundred meters deep, depending on the variation of magnetic properties with depth. Temporal variations in the magnetization within the volcano may be caused by temperature changes. Magnetization/demagnetization beneath the summit may be associated with the eruptive activity. Potential mechanisms for heating/cooling processes may include magma movement, an active hydrothermal system with strong fumarolic activity and groundwater interactions. A 1500-2500 nT composite magnetic low was found at the present cone summit and the avalanche caldera. Temporal changes superimposed over the high-amplitude, low-frequency magnetic anomalies, are associated with the ongoing volcanic activity.

KEY WORDS: Magnetic anomalies, dome, thermal state, Colima volcano, western Mexico

INTRODUCTION

Volcanic rocks are usually characterized by strong remanent and induced magnetizations, because of their high contents of iron oxide minerals including magnetite, titanomagnetites and hematite (Tarling, 1983; Grant, 1985). These iron oxides represent a few weight percent or less of the mineral assemblage (Haggerty, 1976), but they are capable of acquiring strong thermo-remanent magnetizations (TRM) on cooling through the corresponding Curie temperature. The TRMs are stable for long periods, because of the large relaxation times of fine-grained titanomagnetites and magnetites in volcanic rocks. Magnetic field measurements over volcanoes have been widely used to investigate the internal structure (e.g., Nishida and Miyajima, 1984), and to monitor temporal changes associated with volcanic eruptions (e.g., Rikitake and Yokoyama, 1955; Yokoyama, 1969; Zlotnicki and Le Mouel, 1990; Tanaka, 1995; Johnston, 1997). Both approaches may be integrated in order to investigate the spatial and temporal variation patterns of the magnetization associated with the subsurface structure, magmatic activity, heating and cooling processes and the thermal structure of volcanoes (Dzurisin *et al.*, 1990).

We report some initial results of a long-term study to investigate the spatial and temporal changes of the magnetic field over Colima volcano (Figure 1). This volcano has produced frequent eruptive events in historic times (e.g., Medina-Martínez, 1983; Robin *et al.*, 1987, 1991; Luhr and Carmichael, 1990). Activity since the 16th century shows a characteristic pattern of Plinian ash falls and pyroclastic flows followed by quiet intervals, the formation of a lava dome that fills the crater, and eventual lava flows and explosive events. Activity in the past 40 years has generated lava flows, pyroclastic flows and (since 1913) the steady growth of a lava dome that may signal the end of the effusive cycle. Possible future explosive activity has increased the interest in documenting the thermal structure of the volcano and temporal and spatial changes of the Colima magmatic system. Connor *et al.* (1993) reported a study of the thermal characteristics and magnetic anomaly of the summit dome from March 1990 to March 1991. The magnetic anomaly low over the dome was interpreted in terms of a shallow body heated by ascending magma.

COLIMA VOLCANO

Colima volcano is located at 19.51°N and 103.62°W, in western Mexico (Figure 1). It is the youngest cone in a major Quaternary volcanic complex that comprises the Neva-

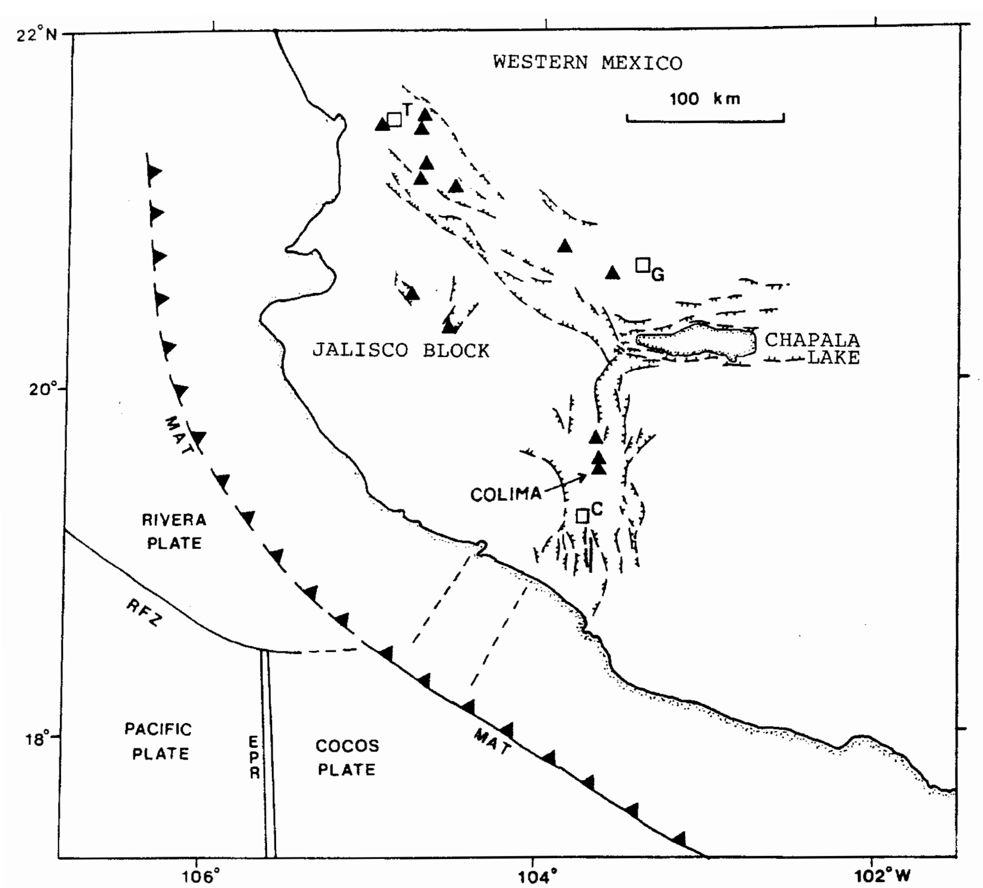

Fig. 1. Schematic map of western Mexico showing location of the Colima volcanic complex with, from south to north, Colima volcano, Nevado de Colima and volcán Cántaro. Triangles indicate major Quaternary volcanic centers. Structural features that define the Colima, Tepic-Zacoalco and Chapala rifts are indicated by the broken curves. MAT, Middle American trench; EPR, East Pacific rise; C, Colima city, G, Guadalajara city; T, Tepic city; and RFZ, Rivera fracture zone (adapted from Luhr and Carmichael, 1990).

do de Colima and the Cántaro volcanoes. It has an elevation of about 3820 m above sea level and it lies some 175 km north of the Middle America trench (MAT). Cántaro volcano is an eroded andesite-dacite cone found some 16 km north of Nevado de Colima. K-Ar dates for lava flows and domes on the northern flank of the Cántaro yield 0.95 ± 0.17 Ma, 0.99 ± 0.01 Ma, 1.33 + 0.2 Ma and 1.66 ± 0.24 Ma (Allan, 1986). The evolution of Nevado de Colima has been divided into three stages, marked by caldera-forming events (Robin *et al*., 1987). The stage-2 cone collapsed in a Mount St. Helens-type avalanche, with a volume of about 22-23 km (Stoopes and Sheridan, 1992). This giant debris avalanche extended some 120 km southwards, to the Pacific ocean coast. The present andesitic cone formed in the avalanche caldera; it is slightly eroded, with an elevation of 4260 m. The active cone of Colima volcano is located 5.5 km south of Nevado de Colima. The onset of activity probably took place during stage-2 of Nevado de Colima (Robin *et al*., 1987). Colima volcano has also featured major explosive and avalanche events, including a Mount St. Helens debris avalanche that formed a 5 km diameter horseshoe-shaped caldera. Robin *et al*. (1987) reported a radiocarbon date of 9370 ± 400 yr B.P. for charcoal from a pyroclastic deposit above the avalanche, whereas Luhr and Prestegaard (1988) found 4280 ± 110 yr B.P. for charcoal from beneath the debris avalanche deposit. After the avalanche the andesitic cone has been growing inside the summit caldera.

Colima volcano has been active during historic times, with several major eruptions since 1580 (Medina-Martínez, 1983; Luhr and Carmichael, 1990). Activity in the past two centuries has been characterized by two major Plinian eruptions in 1818 and 1913, both followed by progressive emplacement of a summit lava dome and minor explosive events and lava flows. The summit dome has now completely filled the crater. Explosive events and lava flows have occurred in 1961, 1975-1976, 1981-1982 and 1991. The 1991 activity included the formation of a lobe in the summit dome and a lava flow that descended on the steep southern flank. These events caused major deformation of the cone summit and triggered rock avalanches on its flanks (Connor *et al*., 1993).

Magnetic properties in the Colima volcanic complex have been measured by Urrutia-Fucugauchi *et al*., (1997), and Connor *et al*., (1993). The latter work included samples from the summit dome. Magnetic susceptibilities for five samples that they considered representative range between 2.61 and 8.16 10^{-5} mass-corrected SI units. Corresponding data for remanent magnetization intensity yield 1.08 to 3.84 A/m. Three samples present discrete unblocking temperatures higher than 450° to 575° C, and two samples present a wide and lower range of distributed unblocking temperatures.

We have measured the magnetic properties of 50 samples collected along the transect between Atenquique and El Playón. Natural remanent magnetization was measured with a Molspin spinner magnetometer. Low-field magnetic susceptibility was measured with the Bartington MS2 susceptibility meter. Magnetic properties of the volcanic fragments in the debris avalanche deposits from Nevado de Colima and Colima volcano present wide ranges of variation. Magnetic susceptibilities from the Nevado de Colima avalanche vary between 3.66 and 10.64 10^{-5}, with a mean of 7.23 10^{-5}. The remanent magnetization intensities vary from 0.55 to 1.86 A/m, with a mean of 1.2 A/m. Samples from the younger Colima volcano avalanche show a range and mean for the susceptibility and remanence intensity of 1.28-8.36 and 5.35 10^{-5}, and 0.73-3.69 and 2.52 A/m, respectively. Samples from andesitic lavas of the Nevado de Colima yield susceptibility and remanence intensities of 2.5-10 and 6.2 10^{-5}, and 0.35-7.33 and 0.56 A/m, respectively. Samples from historic andesitic lavas in the Colima volcano eastern caldera wall show susceptibility and remanence intensities of 4.2-9.8 and 5.8 10^{-5}, and 0.8-1.0 and 0.88 A/m, respectively.

The magnetic polarity for the andesitic lava flows of the Nevado de Colima and Colima volcano is normal. Remanence directions for volcanic clasts of the old and young debris avalanche deposits show scattered distributions. An air fall ash deposit also showed a scattered directional distribution. Some results on the different lithologies are summarized in Figure 3. The vectorial composition and directional stability of samples were investigated by alternating field and thermal demagnetizations. Alternating field demagnetization was completed with an AF demagnetizer up to maximum fields of 100 mT. Thermal demagnetization was completed in steps up to 400°-500° C. Examples of vector demagnetization plots are given in Figure 4. Examples of unblocking temperature spectra are included in Figure 5. Magnetic carriers are members of the titanomagnetite and titanohematite series, with low and intermediate coercivity and distributed and discrete unblocking temperature spectra. In general, samples show high magnetic stability upon alternating field and thermal demagnetization, with mainly univectorial or in some cases multicomponent magnetizations. Unblocking temperatures for some samples are in the range 400°-500° C (Figure 5), characteristic of magnetites.

MAGNETIC FIELD OBSERVATIONS

The magnetic field observations have been made along a 35 km long profile between Atenquique and El Playón, on the eastern flank of the volcano across its summit and the avalanche caldera (Figure 2). El Playón represents the floor of the summit horseshoe-shaped avalanche caldera. Magnetic field observations have been made every 500 meters, and stations have been marked for accurate periodical re-occupation. Diurnal variation effects have been subtracted from the magnetic readings (base station 10 km). Total magnetic field measurements have been taken with a Geometrics G-

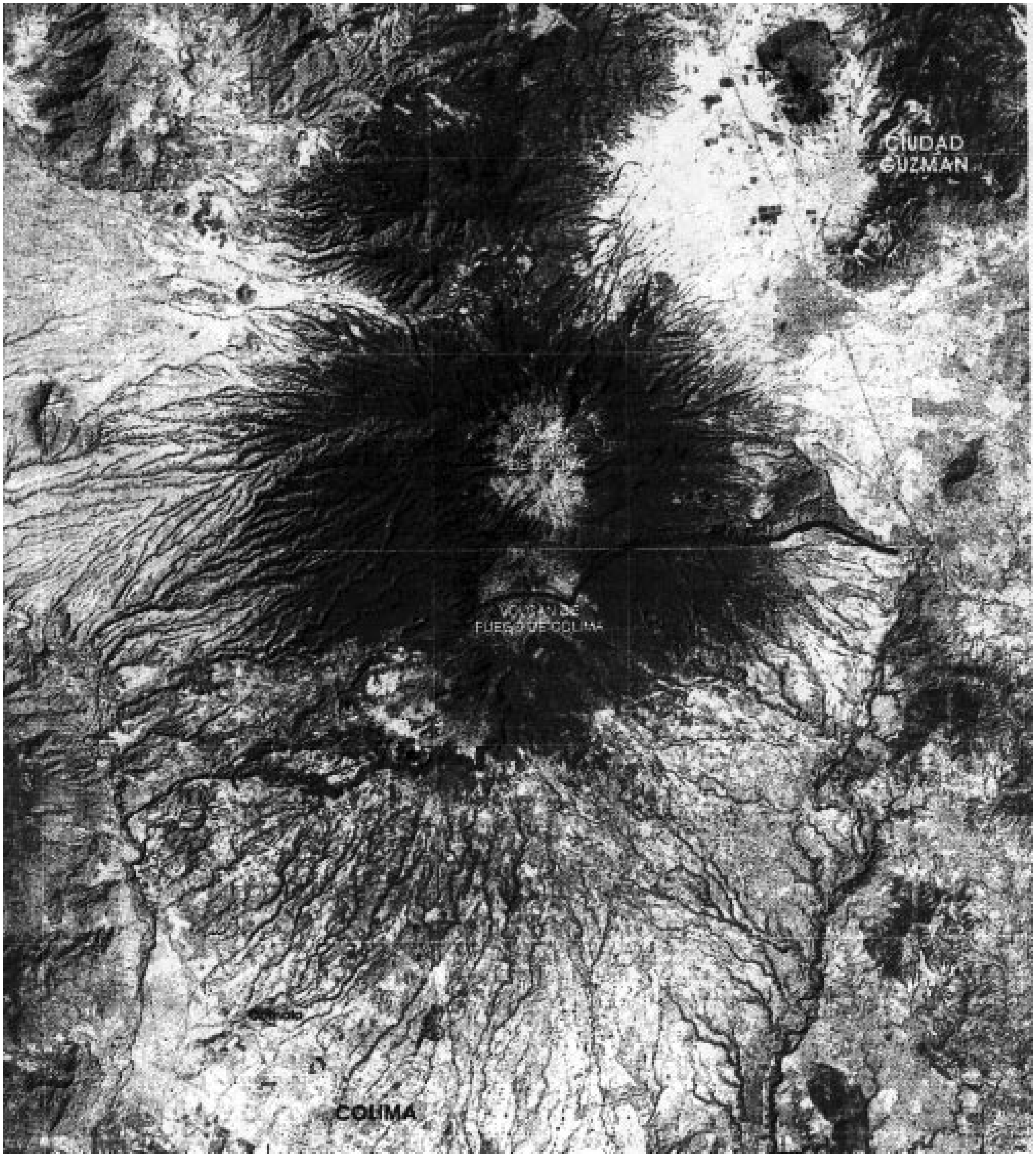

Fig. 2. Location of study transect along the eastern flank of the Colima volcanic complex and summit cone and avalanche caldera of Colima volcano. The transect is 35 km long and extends from Atenquique to El Playón. Magnetic field measurements were taken at four different times at stations spaced every 0.5 km. Base map is a Landsat thematic mapper image of the area taken from INEGI.

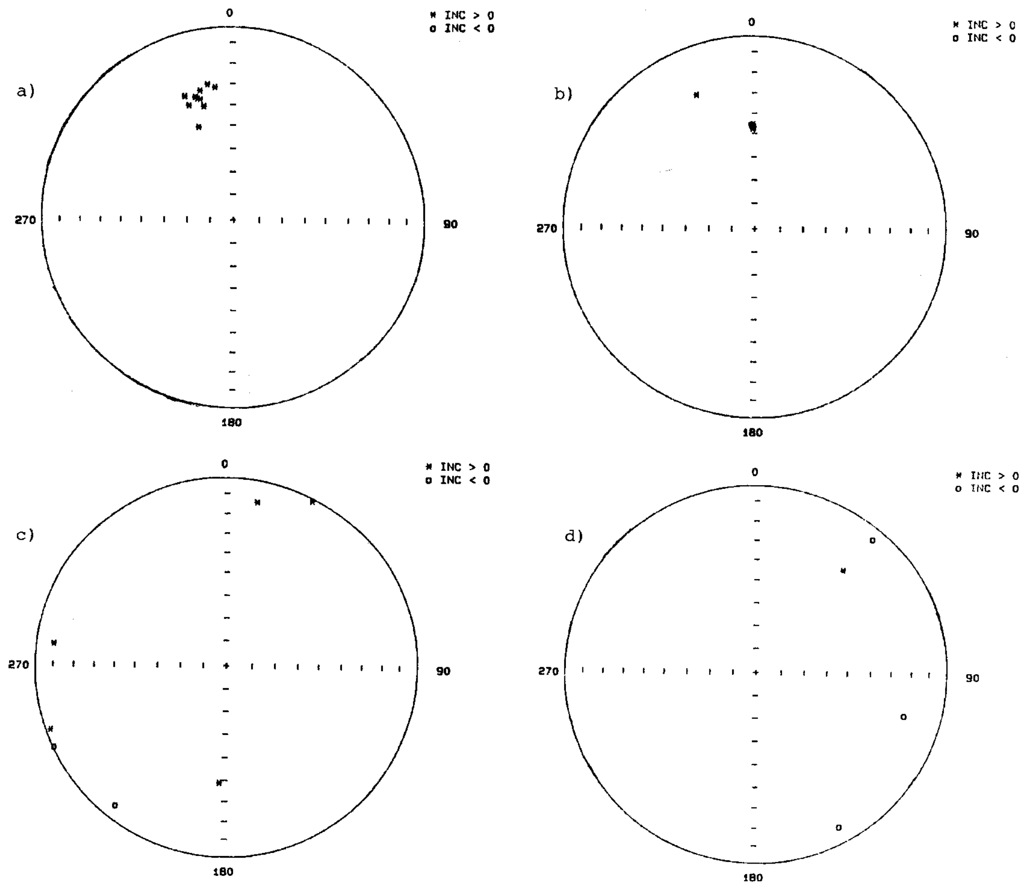

Fig. 3. Examples of natural remanent magnetization directional distributions for sites collected in the andesitic lava flows of Nevado de Colima (a), Colima volcano (b), and volcanic clasts of the debris avalanche deposits of Nevado de Colima (c) and Colima volcano (d).

826 proton-precession magnetometer. The profile starts at Atenquique on the road junction of the Federal Colima-Guadalajara highway with the access road to the volcano summit; it ends at the region of El Playón. The profile starts at 1120 m asl, reaches the 3050 m asl at the cone summit, and ends at 2720 m asl on the summit caldera floor (Figure 6).

Magnetic field measurements have been taken at four different times, on April 27, 1995, January 15, 1996, March 27, 1996 and May 16, 1996. The magnetic anomaly observations are summarized in Figure 6. For comparison, the data points for each transect measurement are shown in Figure 7. There is overall agreement between the four sets of measurements; a sector at the flank of the volcanic complex shows no changes and the sectors towards the summit shows larger changes. These four sets of measurements are discussed in the next section, in terms of temporal variation patterns. The following notes concern the spatial changes and relate mainly to the initial field survey, which addressed the magnetic anomaly characteristics of the volcano. The magnetic field measurements start at about 42 000 nanoTeslas (nT); they reach a maximum of about 42 700 nT at station 37.5 km, and a minimum of about 40 730 nT at station 44 km (Figure 6). The cone summit and caldera region is characterized by a 2000-2500 nT anomaly low.

Three distinct sectors with characteristic magnetic anomaly domains may be recognized along the profile. The first domain in the volcano complex flank (sector A), between stations 10 km and 23 km, is characterized by low amplitude, low-frequency changes. It is associated with weakly magnetized lithologies corresponding at the surface to a sequence of volcanic breccias, conglomerates, pyroclastic deposits and sands of the Atenquique Formation and the Nevado de Colima debris avalanche (Robin *et al.*, 1987; Stoopes and Sheridan, 1992; Luhr and Carmichael, 1990). There is a good agreement among the various sets of measurements in this sector, indicating the absence of significant temporal magnetic field variations. The second domain (sector N), between stations 23 km and 35 km, is character-

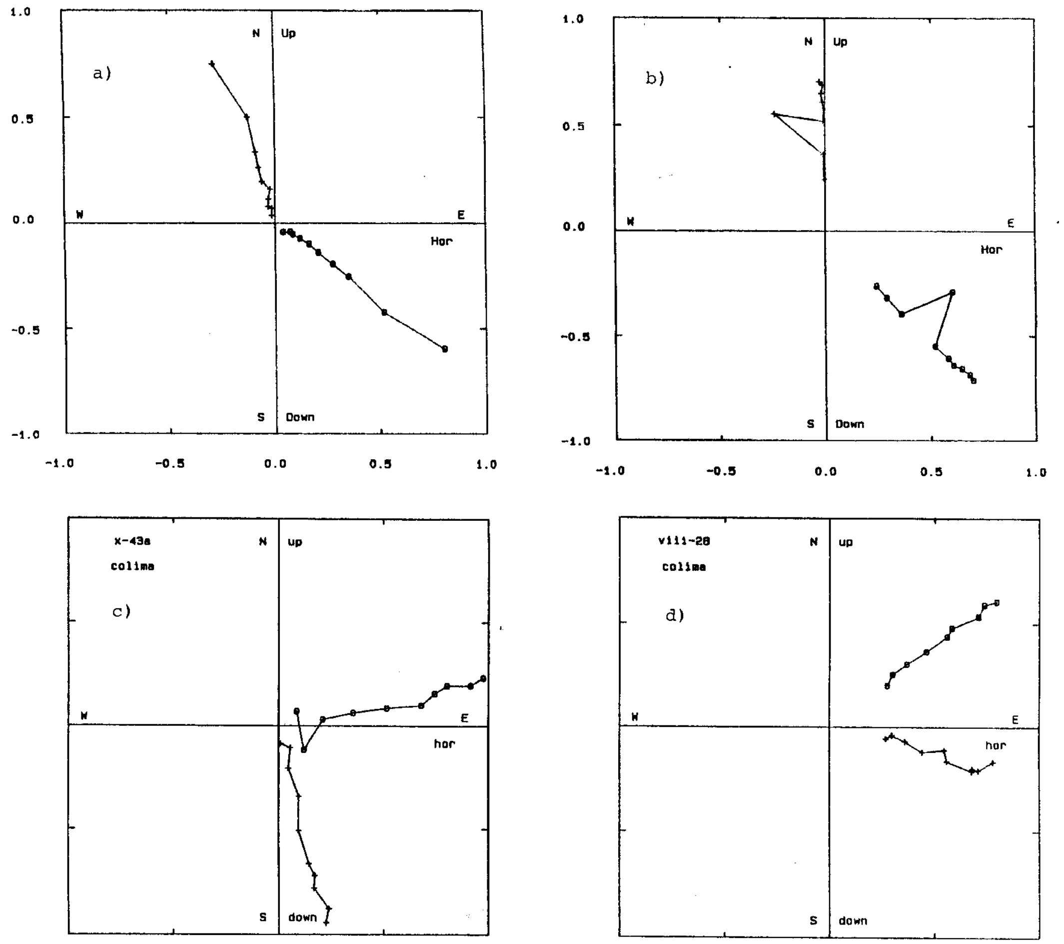

Fig. 4. Examples of vector demagnetization plots for samples of andesitic lava flows from Nevado de Colima (a) and Colima volcano (b) and for clasts of the debris avalanche deposits of Nevado de Colima (c) and Colima volcano (d). Crosses and circles indicate the horizontal and vertical components, respectively.

ized by low-frequency magnetic anomalies (particularly a low and a high between stations 23 km and 30 km), with superimposed higher frequency anomalies of varying amplitude. This sector of the profile is over andesitic lavas and breccias of the Nevado de Colima volcano, with low-amplitude temporal variations. The third domain (sector C), between stations 35 km and 45 km, is characterized by low-frequency, high-amplitude highs and lows. This sector crosses the Colima volcano summit over andesitic lavas and breccias. Sector C is the only one which features large-amplitude temporal variations, in contrast with the sector A at the flank of the volcano. The separation of the magnetic domains correlates approximately with the presence of regional faults crossing the profile. Three possible fault zones were recognized, at station 25 km, at station 30.5 km and at station 34 km. The fault near the summit appears to represent the continuation of the Remate-La Lumbre fault that is associated with the summit cone of Colima volcano and Volcancito.

MAGNETIC FIELD TEMPORAL VARIATIONS

The period covered by the magnetic field measurements extends over little more than one year, from April 27, 1995 to May 16, 1996 (Figure 6). The second set of measurements was completed about 8.5 months after the first survey. The later surveys were made at intervals of about 2.5 months. The magnetic field observations over the profile at different measurement periods display overall similar characteristics (Figure 6). These similarities in the spatial magnetic anomaly field can be observed by comparing the individual transect measurements (e.g., Figure 7). To investigate the temporal changes, subtraction of the magnetic field measurements from one observation to another was used. Figure 8 summarizes the results for the temporal changes between sequential data sets.

The magnetic field difference between the first and sec-

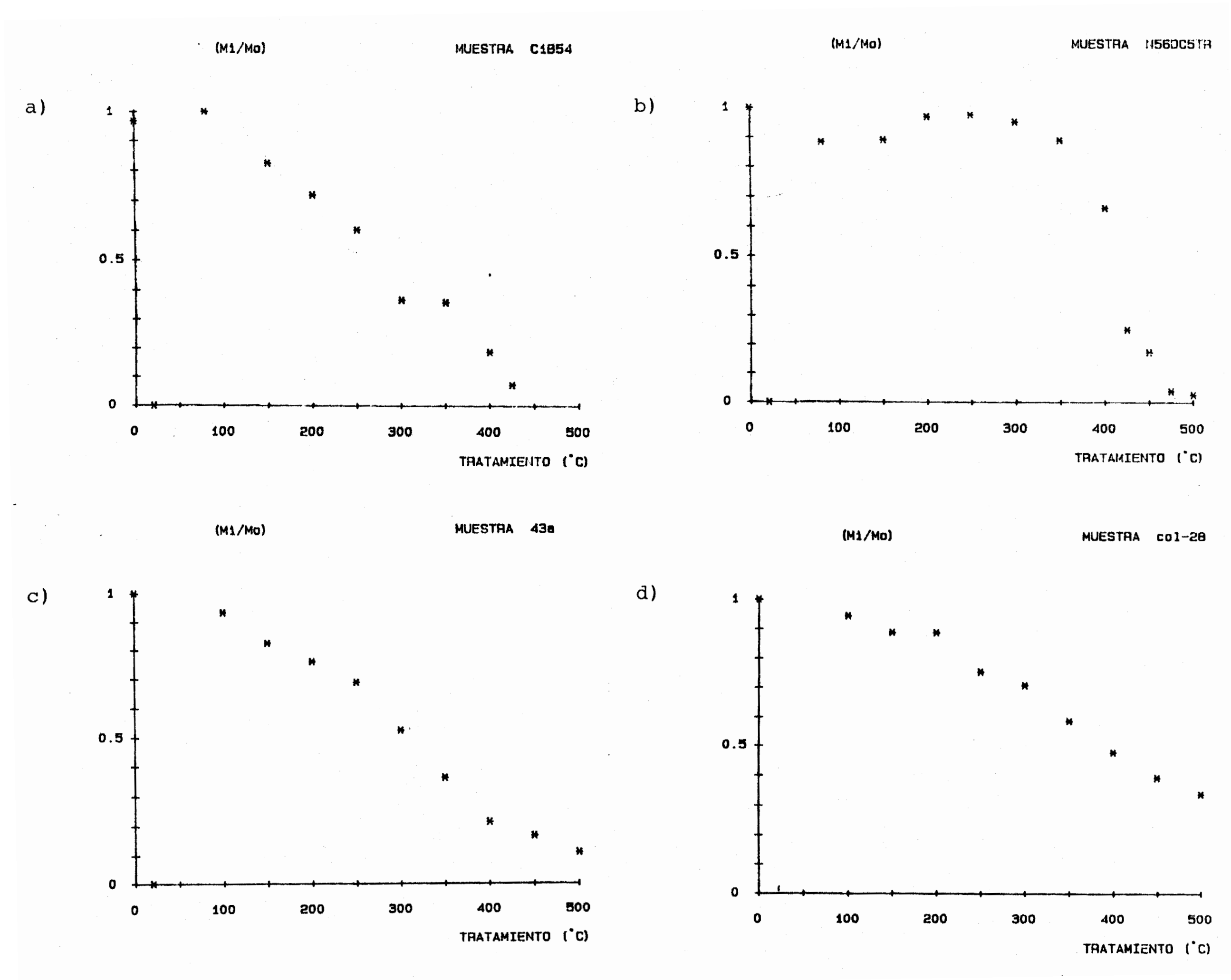

Fig. 5. Examples of normalized intensity diagrams for thermal demagnetization of samples showing the different unblocking temperature spectra characteristics.

ond sets shows a sector between stations 10 km and 23 km with no changes (sector A), a sector between stations 23 km and 35 km with low-amplitude changes (sector N), and a sector between stations 35 km and 45 km with larger changes (sector C) (Figure 8a). This pattern is also observed for the field differences between the second and third sets (Figure 8b) and between the third and fourth sets (Figure 8c). Note that the larger differences occur between the second and third data sets (Figure 8b). Smaller differences are observed between the third and fourth data sets (Figure 8c).

Figure 9 shows the field differences between data sets using the first set as reference. Notice that the field differences of data sets third (Figure 9b) and fourth (Figure 9c) display a similar pattern. Major changes can be observed for the sector between stations 35 km and 45 km that crosses the volcano summit and avalanche caldera. The main features of the time-varying field may be summarized as follows: (a) the low at 37.5 km increases its amplitude; (b) the low at station 39.5 km decreases its amplitude; (c) a high at station 43 km develops and grows; and (d) a set of highs and lows develops between stations 35 km and 45 km.

DISCUSSION

Geomagnetic field measurements allow us to investigate the structure and magmatic activity of the active Colima volcano. Measurements were taken along a 35 km long profile across the eastern side of the Colima volcanic complex. Temporal variations are investigated by performing measurements at four different times, between April 27, 1995 and May 16, 1996. Approximate intervals between measurements are about 8.5 months for the first and second set of measurements, and about 2.5 months between the second and third, and the third and fourth sets of measurements. Three distinct sectors along the transect feature different spatial and tem-

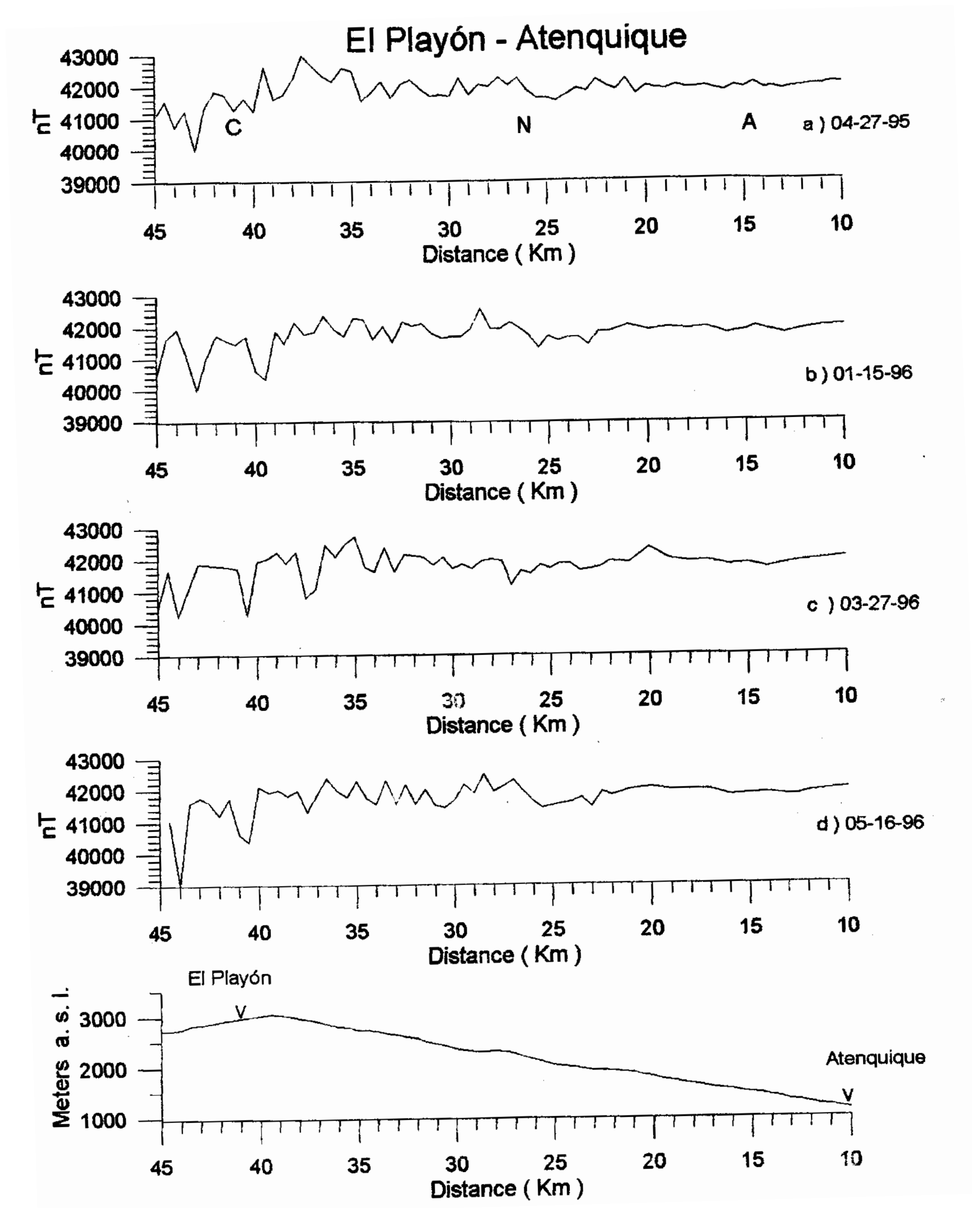

Fig. 6. Summary of the magnetic field measurements taken along the Atenquique-El Playón transect on the eastern flank of the Colima volcanic complex (see Fig. 2). (A) Magnetic anomaly field measurements taken on April 27, 1995. (B) Magnetic anomaly field measurements taken on January 15, 1996. (C) Magnetic anomaly field measurements taken on March 27, 1996. (D) Magnetic anomaly field measurements taken on May 16, 1996. The topography along the flank of the Colima volcanic complex is shown at the bottom figure. Note that for the sector between 10 km and 23 km, the field shows low-amplitude, low-frequency anomalies. This sector named A runs over weakly magnetized volcano-sedimentary deposits of the Atenquique Formation and the Nevado de Colima debris avalanche. The sector between 23 km and 35 km is characterized by larger amplitude, low-frequency anomalies, and lies over andesitic lavas and breccias of the Nevado de Colima volcano (sector N). The sector near the summit between 35 km and 45 km is characterized by high amplitude anomalies (sector C). The summit and avalanche caldera is marked by 1500-2500 nT anomaly lows.

poral magnetic field anomalies (Figures 7, 8 and 9). Sector C, over the avalanche caldera and cone summit between stations 35 km and 45 km, is characterized by a 1500-2500 nT composite low and superimposed high-amplitude temporal changes in the magnetic field. Sector N, over lavas and pyroclastics on the flank of the Nevado de Colima between stations 23 km and 35 km, is characterized by a series of lows and highs with superimposed high-frequency anoma-

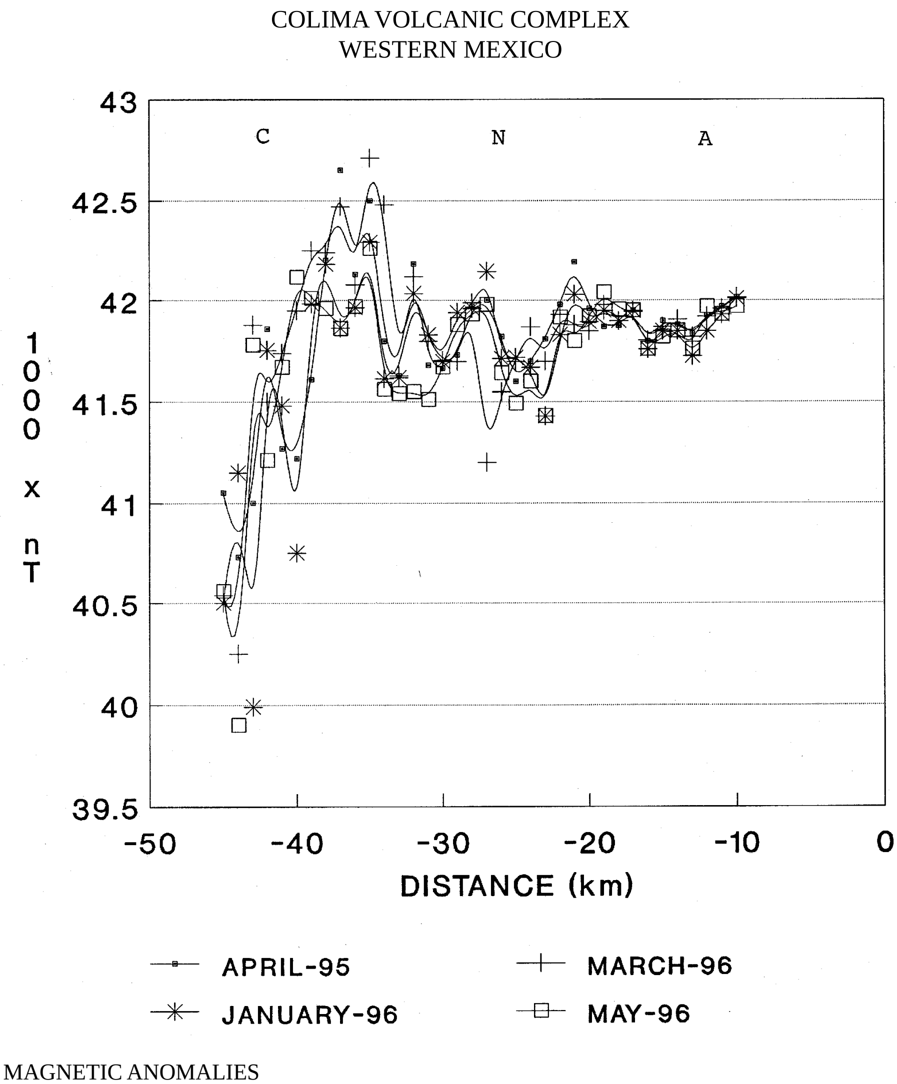

Fig. 7. Comparison of the magnetic field data collected for the four different transects at April 1995, January 1996, March 1996 and May 1996. Note that for the sector between approximately 10 km and 23 km (sector A), the measurements show no temporal changes. In contrast, for the sector near the cone summit and avalanche caldera, approximately between 35 km and 45 km (sector C), large changes can be observed among the different transect measurements. For the intermediate sector approximately between 23 km and 35 km (sector N), smaller amplitude differences can be observed. See text for discussion.

lies of varying amplitude, with low-amplitude temporal variations. Sector A, at the flank of the volcanic complex over volcano-sedimentary deposits of the Atenquique Formation and Nevado de Colima debris avalanche between stations 10 km and 23 km, is characterized by low-amplitude, low-frequency anomalies and no temporal variations. The contrast in behavior of the time-varying field between sectors C at the summit and sector A at the base suggests that the temporal magnetic field changes are likely associated with the magmatic activity (see Figures 7, 8 and 9).

In an attempt to investigate the geometry and magnetic properties of the anomaly source bodies, we have modeled the magnetic field anomalies using a Talwani algorithm (Talwani *et al.*,1964) and the MagPoly PC-version computer program. Anomalies are modeled by a set of polygonal bodies with varying magnetization (Figure 10). A major limitation in the analysis is the lack of information concerning magnetic property variations with depth. Samples for paleomagnetic studies have been collected from the various lithological units, including the andesitic flows, pyroclastic deposits, and avalanches (e.g., Connor *et al.*, 1993; Urrutia-Fucugauchi *et al.*, 1997). Averages for the magnetic susceptibility and intensity of remanent magnetization have been used as initial values for the modeling. The magnetic polarity of all units is normal (Figure 3), in agreement with the age of the Colima volcanic complex. Thus, direction of remanent magnetization remained constant, close to the dipo-

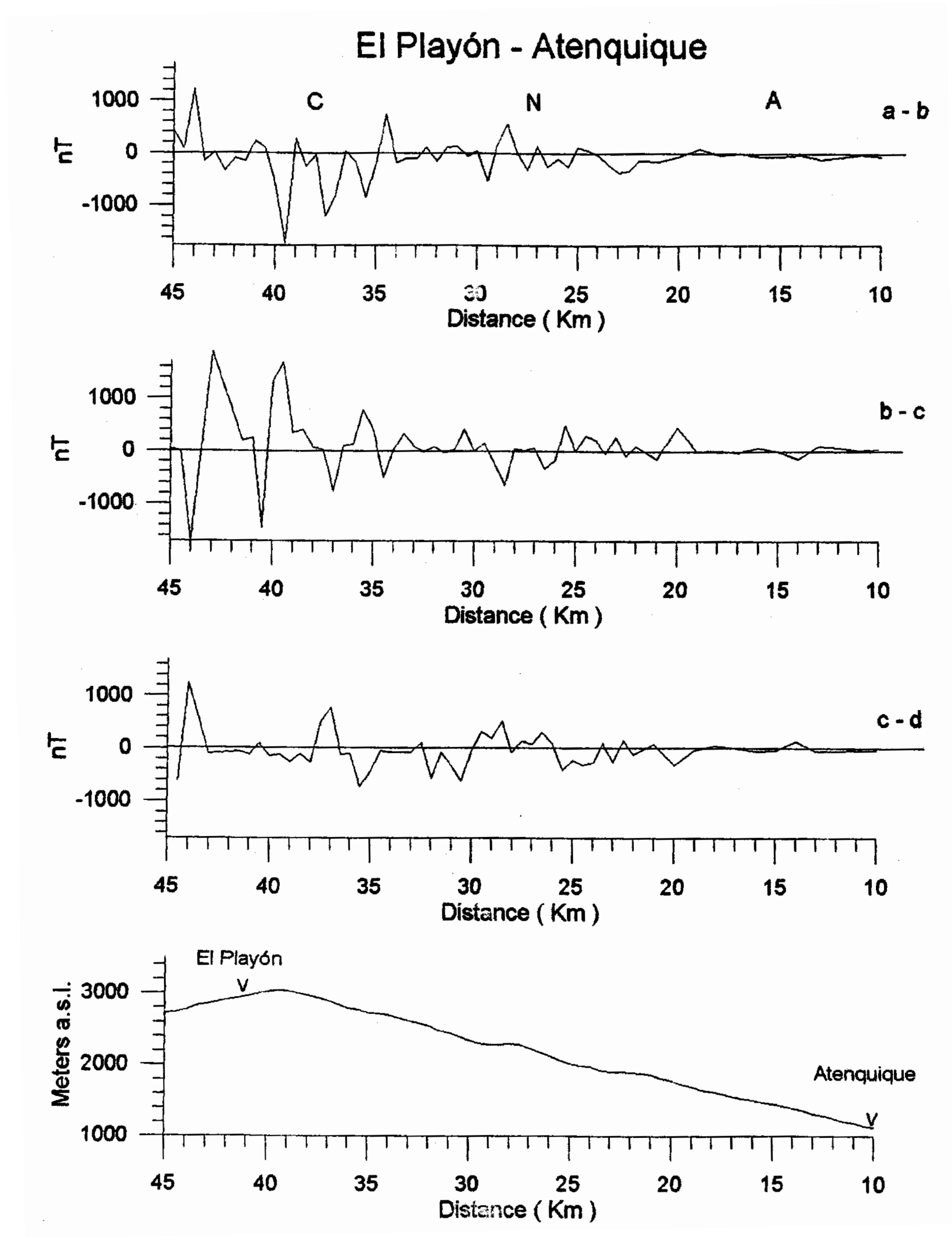

Fig. 8. Summary of temporal differences in the magnetic anomalies. Differences are calculated by subtraction between measurements taken at the different times. See Fig. 3 for explanation. Time span between sets of measurements A and B is about 8.5 months, between B and C about 2.5 months, and between C and D about 2.5 months. Note the contrast in temporal behavior along the profile, with large differences observed in the region near the summit, between approximately 35 km and 45 km. In contrast, no differences were found at the flank of the volcanic complex.

lar value with an inclination of 45 degrees and a northward declination. However, large variations in magnetic susceptibility and remanence intensity were expected because of hydrothermal alteration, degree of weathering, etc (Grant, 1985; Tarling, 1983; Dzurisin *et al*., 1990). Within these uncertainties, we found that the source bodies used to fit the magnetic anomaly extended to a considerable depth, though the depth of source bodies is generally poorly constrained by magnetic modeling. The summit polygons have a relative negative magnetic property contrast. Additional geophysical data, including gravity data along the transect, should help constrain the shallow structure of the volcanic complex.

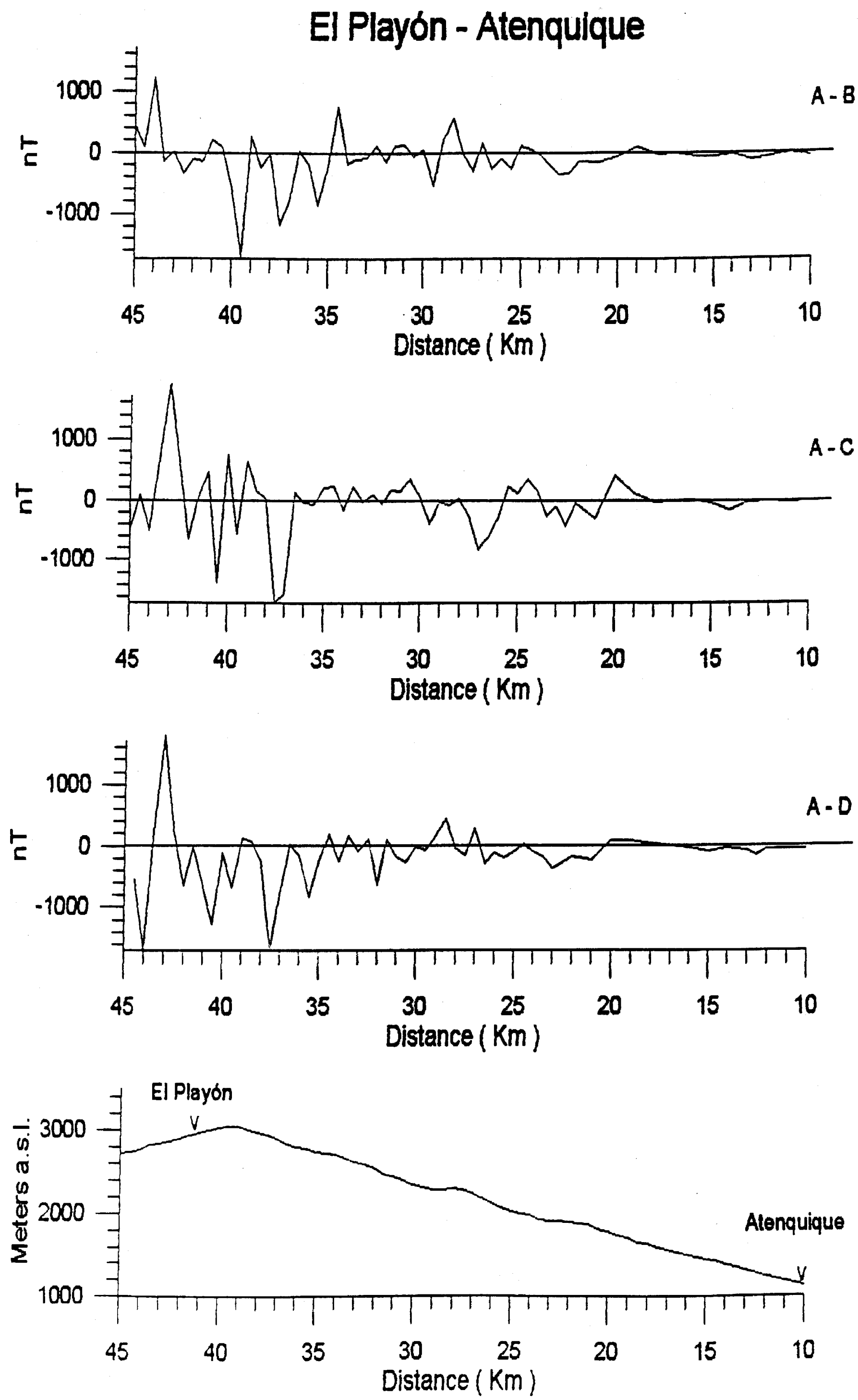

Fig. 9. Summary of temporal differences in the magnetic anomalies, referred to measurements collected on April 1995. See Fig. 6 for explanation.

Joint inversion of magnetic and gravity anomalies may improve the model for the shallow structure. The model for the summit area of Colima volcano features a large tabular body and relative negative contrast as for other active volcanoes. Sasai *et al*. (1990) modeled the magnetic low at Izu-Oshima volcano with a 200 m wide tabular body of demagnetized

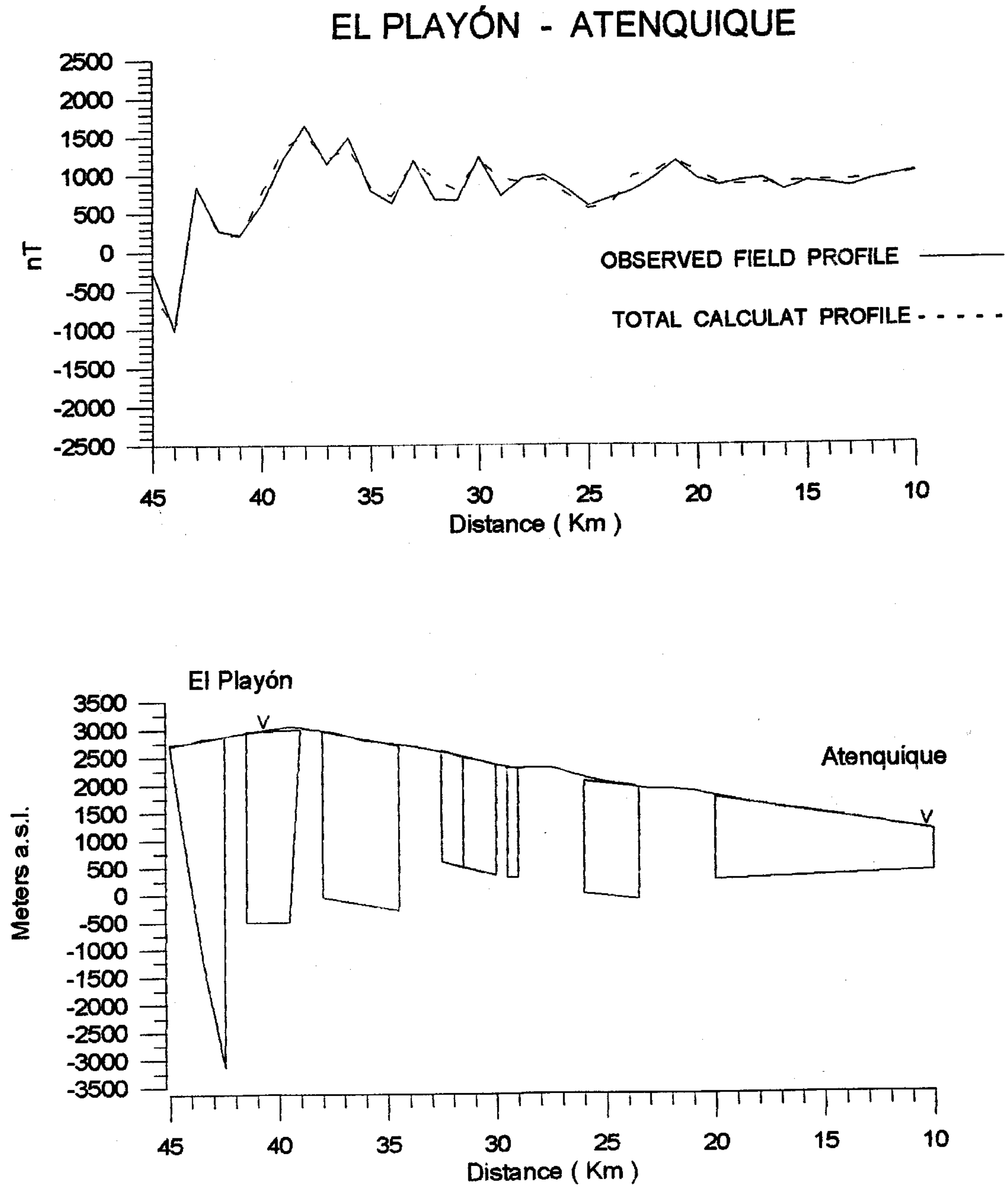

Fig. 10. Preliminary magnetic model for Atenquique–El Playón transect. Magnetic modeling used a Talwani-type algorithm. (a) Observed and calculated magnetic anomalies. (b) Preliminary model with eight polygonal source bodies. See discussion in text.

material. Nishida and Miyajima (1984) observed a high and low over Mount Showa-Shinzan of Usu volcano. Their preferred model for the magnetic anomaly features a 100 m-wide tabular body with negative contrast, embedded in a 300 m wide body at the summit area of the volcano.

Connor *et al.* (1993) measured a 120 m long magnetic traverse across the dome in the high-temperature fumarole field (350°–575° C) during December 1990. They detected a 2000 nT anomaly low, with a wavelength of about 100 m. For the magnetic model, they assumed blocks of varying sizes and shapes and thin layers of clastic material forming the surface of the dome, with no coherent magnetic response apart from short-wavelength anomalies. The magnetized rock was assumed to lie some 5 or 10 m deeper, based on observations at other lava domes. They interpreted the anomaly in terms of a shallow body corresponding to the dome interior that was heated above the unblocking temperatures. They assumed that this body is elongated in a NNW direction, corresponding to the scarp formed by the extrusion of the new dome lobe. They also presented an analysis of the thermal state of the dome, based on the thermal monitoring of the fumaroles and the magnetic study.

Long-period magnetic anomaly changes related to ongoing magmatic activity have been observed at various volcanoes. Examples include: Oosima volcano (Yokoyama, 1969), Piton de la Fournaise volcano (Zlotnicki and Le Mouel, 1988), Izu-Oshima volcano (Sasai *et al*., 1990), dome of Mount St. Helens (Dzurisin *et al.,* 1990), Aso volcano (Tanaka, 1993), and Unzen volcano (Tanaka, 1995). These long-term changes have been associated with changes in the thermal regime of the volcano that affect the remanent magnetization. Several different mechanisms could account for temporal changes in the magnetic field. Some workers have associated them with different stages in the volcanic activity (e.g., Sasai *et al*., 1990; Tanaka, 1995; Johnston, 1997). Possible mechanisms include:

(1) thermal effects that induce magnetization/demagnetization in the rocks,

(2) rotation and displacement of rock fragments e.g., due to explosions and volcano deformation,

(3) loss/addition of magnetized material,

(4) piezomagnetic effects due to stress changes,

(5) chemical changes on magnetic minerals due to oxidation/reduction reactions, and

(6) electrokinetic effects due to ground water interactions.

Long term processes with characteristic time scales of weeks to months include mechanisms 1 to 4. Short-term processes with characteristic time scales of seconds to days include mechanisms 4 and 6 (Johnston, 1997). Thermal effects are in general important because of the temperature changes associated with volcanic activity, i.e., fumarolic activity, hydrothermal activity, ejection of ash, pyroclastic flows and lavas, and magma ascent. Relatively rapid heating and cooling processes can affect the summit area of active volcanoes, where strong hydrothermal and hydrologic systems are active. This might be the preferred mechanism capable of accounting for the temporal changes observed over the Colima volcano summit region. The changes in the thermal state are associated with the episodic emplacement of the lava dome in the summit area. The high temperatures originating from the magma ascent and the strong hydrothermal system that sustains the fumarolic activity and degassing heat the surface rocks. Heating and cooling mechanisms may be acting as a result of the volcanic activity and hydrologic interactions (Connor *et al*., 1993). Additional mechanisms due to rotation/translation of magnetized material and piezomagnetic effects may also contribute to the observed changes in the magnetic anomaly field.

The present preliminary study of the Colima volcanic complex documents geomagnetic anomaly changes with time scales of months in the summit area of the active Colima volcano. No temporal anomalies were observed over the flanks of the volcanic complex. Large temporal anomalies do occur over the summit cone and avalanche caldera, where they are superimposed over the high-amplitude low-frequency high and low that characterize the volcano summit area. The magnetic anomalies show an apparent systematic variation that is likely associated with the ongoing volcanic activity of Colima volcano. Further studies should involve a permanent network of magnetic recording stations to investigate the nature of the geomagnetic anomaly changes and their relation to eruptive activity in Colima volcano.

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