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2 ³/₄ dimension modeling of the aeromagnetic anomaly of Volcán de Colima, western Mexico

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Resumen

Se presentan los resultados de un modelo 2 ³/₄ D de la anomalía aeromagnética del Volcán de Colima ubicado en la porción sur del Complejo Volcánico de Colima. El modelo estructural documenta la presencia de una cámara magmática de forma alargada con una longitud mayor a los 10 km en la dirección norte-sur y que se extiende más de 6.6 km al sur del Volcán de Colima. El máximo espesor de la cámara magmática está hacia el ESE del cráter del Volcán de Colima y tiene una extensión del orden de los 6.9 km. Hacia los bordes la cámara magmática presenta espesores del orden de los 820 m a 620 m al sur y norte respectivamente. Bajo el Volcán de Colima se localiza a una profundidad entre 4.9 y 1.2 km bajo el nivel del mar. El modelo geofísico es consistente con las propuestas de la migración norte-sur de la actividad en el Complejo Volcánico de Colima.

Palabras clave: Volcán de Colima, anomalía magnética, modelo magnético, cámara magmática, magnetismo.

Abstract

Results of 2 ³/₄ D modeling of the aeromagnetic anomaly of Volcán de Colima, in the southern sector of the Colima Volcanic Complex are presented. The structural model documents the presence of a magma chamber with an elongated shape and a length greater than 10 km in a north-south direction extending over 6.6 km south of Volcán de Colima. The maximum thickness of the magma chamber, around 6.9 km, is located to the ESE of the volcano. The edges of the magma chamber have thicknesses ranging from 820 m to 620 m to the south and north, respectively. The magma chamber under Volcán de Colima is located at depths of 4.9 and 1.2 km below sea level. The geophysical model is consistent with a proposed north-south migration of activity in the Colima Volcanic Complex.

Key words: Volcán de Colima, magnetic anomaly, magnetic model, magmatic chamber, magnetism.

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Introduction

The study of magnetic fields from the air has been extensively used in volcanic areas worldwide where it has proven its usefulness and potential in studying structural features (e.g., Hagiwara, 1965; Finn and Williams, 1987; Ueda *et al.*, 1990; Hildenbrand *et al.*, 1993; Nakatsuka, 1994; Gibson and Milligan, 1998; Fedi *et al.*, 1998; Lopez-Loera and Urrutia-Fucugauchi, 1999; Garcia *et al.*, 2007; Okuma *et al.*, 2009; De Ritis *et al.*, 2007, 2010a; Blanco Montenegro *et al.*, 2011). In recent years aeromagnetometry has developed significantly with new instrumentation, survey methodologies, data processing and interpretation (e.g., Urrutia-Fucugauchi *et al.*, 2002; Finn and Morgan, 2002; Blanco-Montenegro *et al.*, 2003; Bournas *et al.*, 2003; Ueda, 2007; Okuma *et al.*, 2009; Okubo *et al.*, 2009; Nakatsuka *et al.*, 2009; De Ritis *et al.*, 2010b; Pignatelli *et al.*, 2011).

The effectiveness of aeromagnetic methods for determining the nature of surface and subsurface rocks is well established (Malahoff, 1969). An aeromagnetic anomaly reflects the spatial variation in the total magnetization of rocks measured by a magnetometer. Knowledge of the possible range of magnetization, and the recognition of factors that control magnetization, are essential for the interpretation of the geological significance of aeromagnetic data. The total magnetic intensity observed at a given point, is the vector sum of contributions of the natural remanent magnetization (NRM) and the induced magnetization (IM). At volcanic complexes in general, changes in quantity, grain size and composition of titanomagnetites produce most of the variations in the magnetization magnitude (Reynolds *et al.*, 1990).

Aeromagnetometry has enabled the study of faults reactivation (Meridee, 1995), the evaluation of magnetic properties before and after volcanic eruptions (Finn and Williams, 1987; Nakatsuka *et al.*, 2009), the establishment of the existence of volcanomagnetites belts (Honkura, 1991) and the study of the relationship with topography (Flanagan and Williams, 1982; Urrutia-Fucugauchi *et al.*, 2002; Okuma *et al.*, 2009). Airborne magnetic methods have allowed the delineation of the lateral extent of structures such as rifts, caldera peaks, craters, fissures and ventilation fissures (Hildenbrand *et al.*, 1993; López-Loera *et al.*, 2008, 2010). They have also allowed the investigation and identification of intrusive in the underground with no surface manifestations (Williams and Finn, 1987; De Ritis *et al.*, 2010a).

The aeromagnetic research presented here aims to show the main magnetic elements that

support magmatism migration from north to south in the Mexican Volcanic Belt, through a model that is based on an aeromagnetic survey conducted by the Mineral Resource Council (now the Mexican Geological Survey) covering the Colima Volcanic Complex.

Volcán de Colima

The Fire volcano or Volcán de Colima (Latitude 19° 30'50" N, Longitude 103° 37'0" W) is a composite volcano located in western Mexico, approximately 30 km north of the city of Colima (Figure 1). It has an elevation of 3,850 m above sea level and its located 175 km north the Middle American trench. Volcán de Colima is the youngest volcano in quaternary volcanic complex formed by the volcanoes Nevado and El Cántaro. The Colima Volcanic Complex and the Colima Rift have often been the focus of scientific research; examples include Luhr and Carmichael (1980, 1981, 1990), Robin *et al.*; (1990, 1991), Urrutia Fucugauchi *et al.*, (1997), Bandy *et al.*, (1993, 1995), López-Loera and Gutiérrez (1977), López-Loera *et al.*, (1999, 2010).

Volcán de Colima is 5.5 km south of the volcano Nevado. It most likely became active when activity in Nevado ceased. The activity of Nevado de Colima with an old volcano called Paleo-Fire within an estimated age of 50 ka (Robin *et al.*, 1987) was characterized by the collapse of the cone in an avalanche type similar to Mt. St. Helens, with a volume of 22-33 km³ (Stoopes and Sheridan, 1992). The Colima avalanche extended 120 km to the south, reaching the Pacific coast. Recent studies (Capra, 2000) consider that these deposits did not reach the coast as primary deposits, but are instead the product of a secondary lahar. Volcán de Colima is characterized by major explosions and avalanche events, including volcanic debris of the Mt. St. Helens type, which formed a caldera 5 km in diameter in the form of horseshoe. For the Volcán de Colima avalanche, Robin *et al.* (1987) reported radiocarbon dates of 9,370 ± 400 years BP, for a sample of charcoal from a pyroclastic deposit above the avalanche. Luhr and Prestegard (1988) found an age of 4,280 ± 110 years BP for a sample of coal underlying the debris avalanche deposit. Komorowski *et al.* (1996) suggest an age of 2.5 ka for the last collapse of the volcano. This author and colleagues consider that the Colima volcanoes have collapsed at least 12 times in the last 45 ka and that probably 9 events have been to the south. Komoroswski *et al.* (1996), dated five well-defined avalanches with ages ranging from 18,553 to 2,565 BP. After the last avalanche, an andesitic cone began to grow within the caldera. This cone has become Volcán de Colima.

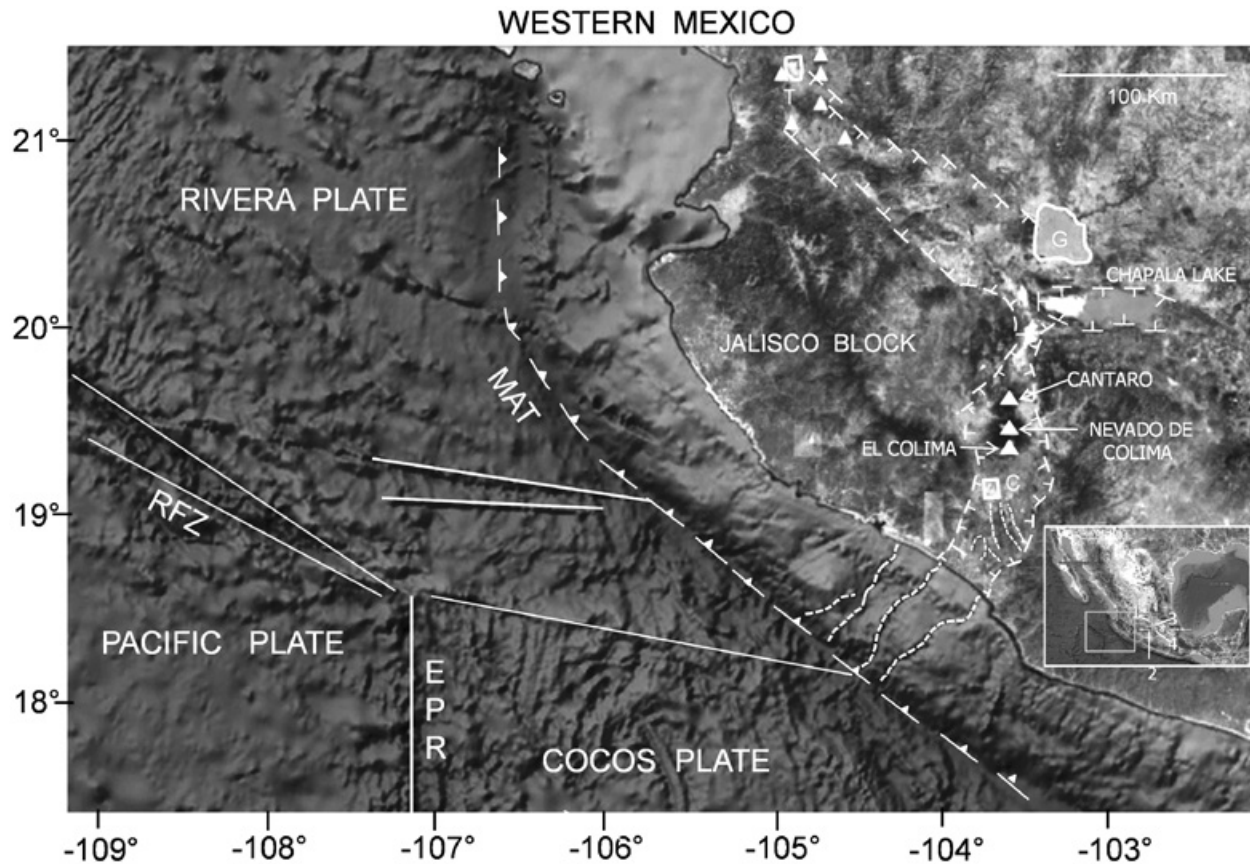


Figure 1. Satellite image of western México, showing the Colima Volcanic Complex and the interaction between different existing tectonic plates. White triangles represent major volcanic centers in the area. Major structural lineaments mark the tectonic depressions of the Colima Rift, Tepic-Zacoalco Rift and Chapala Rift. G, Guadalajara City; T, Tepic; C, Colima; PV, Puerto Vallarta; MAT, Mesoamerican Trench; EPR, East Pacific Rise and RFZ, Rivera Fracture Zone. In the small rectangle within the image shows the location of volcanoes: Iztaccihuatl (1); Popocatepetl (2); Cofre de Perote (3) and Pico de Orizaba (4).

Aeromagnetic Survey

The aerial survey was conducted by the Mineral Resources Council in 1999 as part of a research program to understand geological and structural conditions, mainly for the selection of prospective mining areas. The study was conducted with flight lines every 1,000 m with an N-S direction and with an average height of 300 m above ground level. The aircraft was a B-27 BN2 Islander, using a CS-2 cesium magnetometer with a resolution of 0.001 nT with fixed sensor. Digital compilation was performed with aircraft motion correction (magnetic compensation), diurnal variation correction and subtraction of the International Geomagnetic Reference Field (IGRF 1995) (Barton *et al.*, 1996). The digital information obtained by this survey was integrated and processed by generating a data grid with a cell size of 200m x 200m (Pascacio, 2001).

Further processing and modeling were performed in our lab using Geosoft software Oasis Montaj data processing and GM-SYST[™] magnetic modeling software. Mathematical algorithms were applied to calculate reduced to magnetic pole (Baranov and Naudy, 1964) and analytical upward continuations (Henderson and Zietz, 1949; Henderson 1970; Blakely, 1995).

A digital elevation map of the Nevado and Colima volcanoes shows that Nevado is a larger volcanic structure than Volcán de Colima. There are wide areas of cañón and the zone of the Colima protovolcano is characterized by remnants of a crater rim that can be seen north of the volcanic structure (Figure 2).

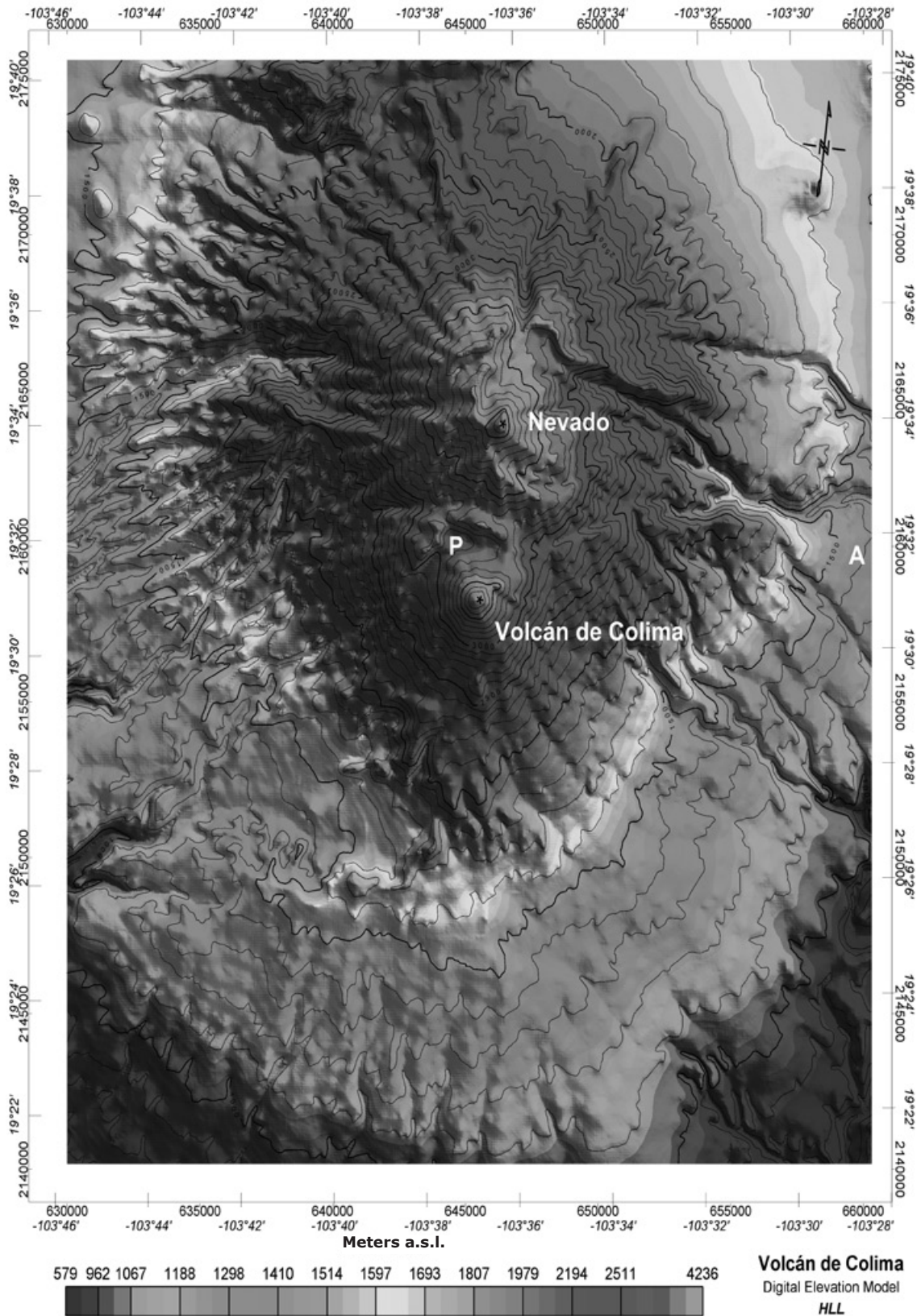


Figure 2. Map of the digital terrain model of the southern portion of the Colima Volcanic Complex. To the north of the Volcán de Colima flank there is a vertical corresponding to a ring portion of the old caldera called Colima protovolcano. Samples for the measured of magnetic properties were collected along the transect E-W, between Atenquique (A) and El Playón (P), respectively.

Aeromagnetic anomaly

Volcán de Colima is characterized by a residual magnetic field configuration associated with a normal dipolar anomaly, i.e., the magnetic high is located to the south and the magnetic low to the north (Figure 3). The contour map of the reduced to the magnetic pole of Volcán de Colima shows an elongated anomaly of triangular shape prolonged in the NNE-SSW direction and reaching maximum amplitude on the order of 1,000 nT (Figure 4). The crater is 1,450 m towards the WNW of the maximum magnetic amplitude. Nevado shows a magnetic anomaly in the L form, which has changed its direction from NNE-SSW to EW to the south. The anomaly consists of three magnetic highs with amplitudes of 466 nT, east of the crater, 505 nT to the NW of the crater and 545 nT to the north of the volcano summit. The Colima and Nevado volcanic structures form a single aeromagnetic domain differentiated by an ENE-WSW alignment, which correlates with a fault zone that should exist between these two volcanoes (López-Loera *et al.*, 2010).

The map generated by the analytic signal and upward continued 2 km of the reduced to the magnetic pole, shows three magnetic anomalies. One of them is clearly associated with the circular structure of Volcán de Colima, placing the crater towards the west portion of maximum intensity. The other two anomalies seem to be closely related and are elongated in the E-W direction. The remnant crater of Nevado is located south of these anomalies at a distance greater than 3 km (Figure 5).

Magnetic properties

The magnetic properties in the Colima volcanic complex have been reported by Urrutia-Fucugauchi *et al.* (1997), Coonor *et al.* (1993) and López-Loera and Urrutia-Fucugauchi (1999). The Coonor *et al.* (1993) study includes samples of the crater dome. Magnetic susceptibilities of five representative samples are reported in the range between 2.61 and 8.16 $\times 10^{-5}$ SI. Data for remanent magnetization intensities range from 1.08 to 3.84 A/m. Three samples show a discrete blocking temperature higher than 450 to 575° C, and two samples show a narrow range of unlocked temperatures.

López-Loera and Urrutia-Fucugauchi (1999) measured the magnetic properties of 50 samples collected along a transect between Atenquique and El Playón. This section runs along a general direction from the east (Atenquique) to the west (El Playón) and reaches the central portion of the Volcán de Colima. The natural remanent magnetization was measured with a Molspin spinner magnetometer. Low field

magnetic susceptibilities were measured with a MS2 Bartington susceptibilimeter. López-Loera and Urrutia-Fucugauchi (1999) found that the magnetic properties of fragments in the volcanic debris avalanche of Nevado de Colima and Colima have a great range of variation. The magnetic susceptibilities of the avalanche of Nevado de Colima vary between 3.66 and 10.64 $\times 10^{-5}$ SI, with an average of 7.23 $\times 10^{-5}$. Remanent magnetization intensities range from 0.55 to 1.86 A/m. Samples of the recent avalanche of Volcán de Colima show ranges and averages for the magnetic susceptibility and intensity of remanence of 1.28-8.36 $\times 10^{-5}$ SI and 5.35 $\times 10^{-5}$ SI and 0.73-3.69 A/m with an average of 2.52 A/m, respectively.

Samples of andesitic lava from Nevado de Colima have remanence and susceptibilities intensities of 2.5 -10 $\times 10^{-5}$ SI and 6.2 $\times 10^{-5}$ SI and 0.37-7.33 A/m with an average of 0.56 A/m respectively. Historic lava samples from the east wall of the Volcán de Colima caldera, show susceptibilities and remanence intensities of 4.2-9.8 $\times 10^{-5}$ SI and 5.8 $\times 10^{-5}$ SI and 0.8-1.0 A/m with an average of 0.88 A/m respectively.

The magnetic polarity of all units is normal, and in accordance with the age of the Colima Volcanic Complex. Therefore, the remanent magnetization direction remains constant and close to the dipole value with an inclination of 45 degrees and declination towards the north.

Aeromagnetic model

In order to document the magmatism migration from north to south across the volcanic complex of the Mexican Volcanic Belt (Luhr and Carmichael, 1990) an attempt has been made to model the magnetic response of the southern Colima Volcanic Complex and to determine if there could be magnetic elements to support such migration.

A 2 $\frac{3}{4}$ D model of the magnetic anomaly reduced to magnetic pole and upward continued 3 km, including Volcán de Colima and Nevado de Colima (Figure 6) was constructed. The anomaly was modeled by polygonal bodies with different magnetizations. The geometry and the magnetic properties of the sources associated with the anomaly were modeled using the GM-SYS™ software; this inversion routine utilizes a Marquardt inversion algorithm (Marquardt, 1963) to linearize and invert the calculations. GM-SYS™ uses an implementation of this algorithm for magnetic data processing developed by the USGS in the computer program SAKI (Webring, 1985).

Rock samples for magnetic studies were obtained from different lithological units: andesitic flows and breccias, as well as pyroclastic

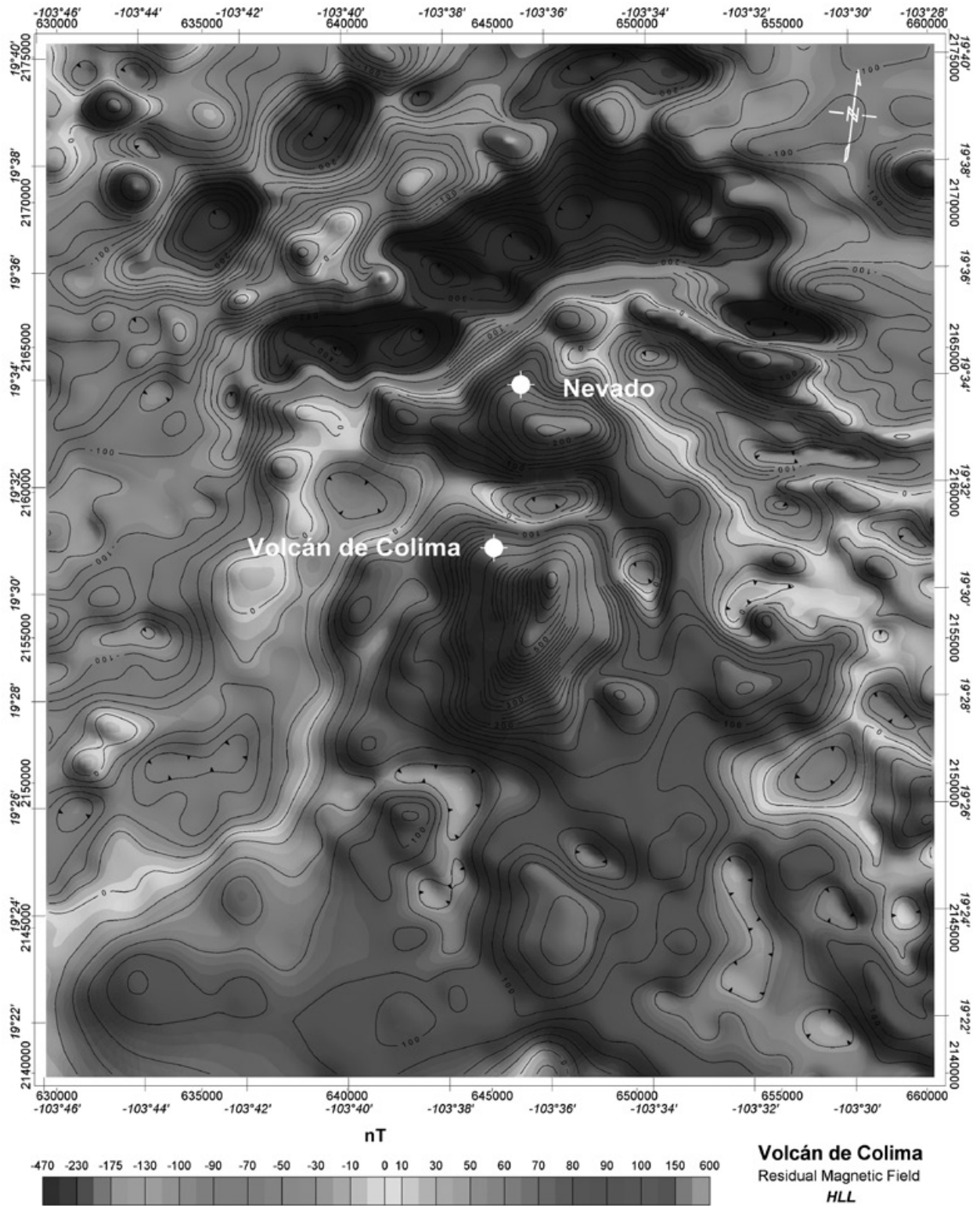


Figure 3. Contour map of the Residual Magnetic Field from the center and south of the Colima Volcanic Complex. The location of Volcán de Colima crater is shown (~200m x 200m).

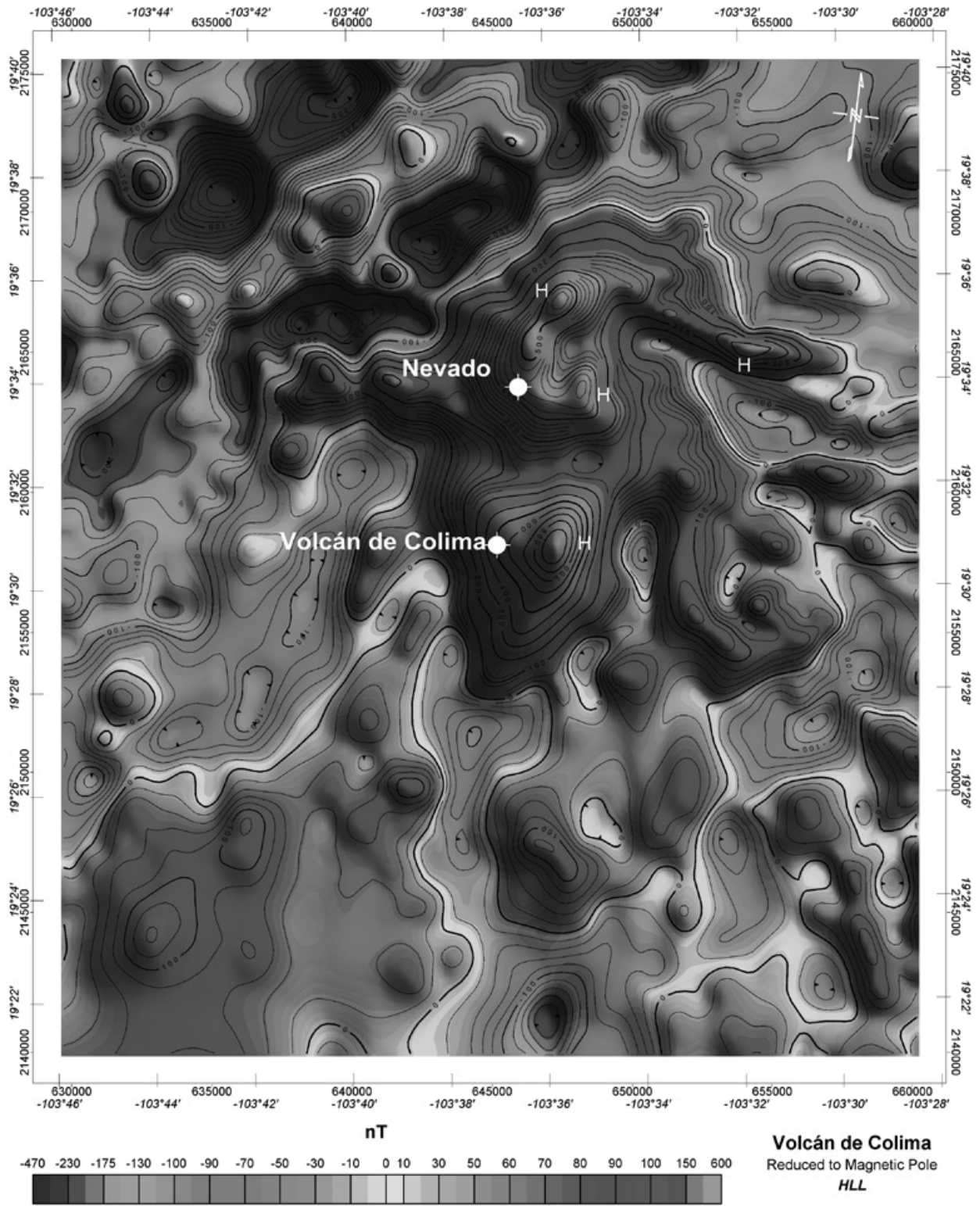


Figure 4. Contour map of the Reduce to Magnetic Pole of the center and southern portion of the Colima Volcanic Complex.

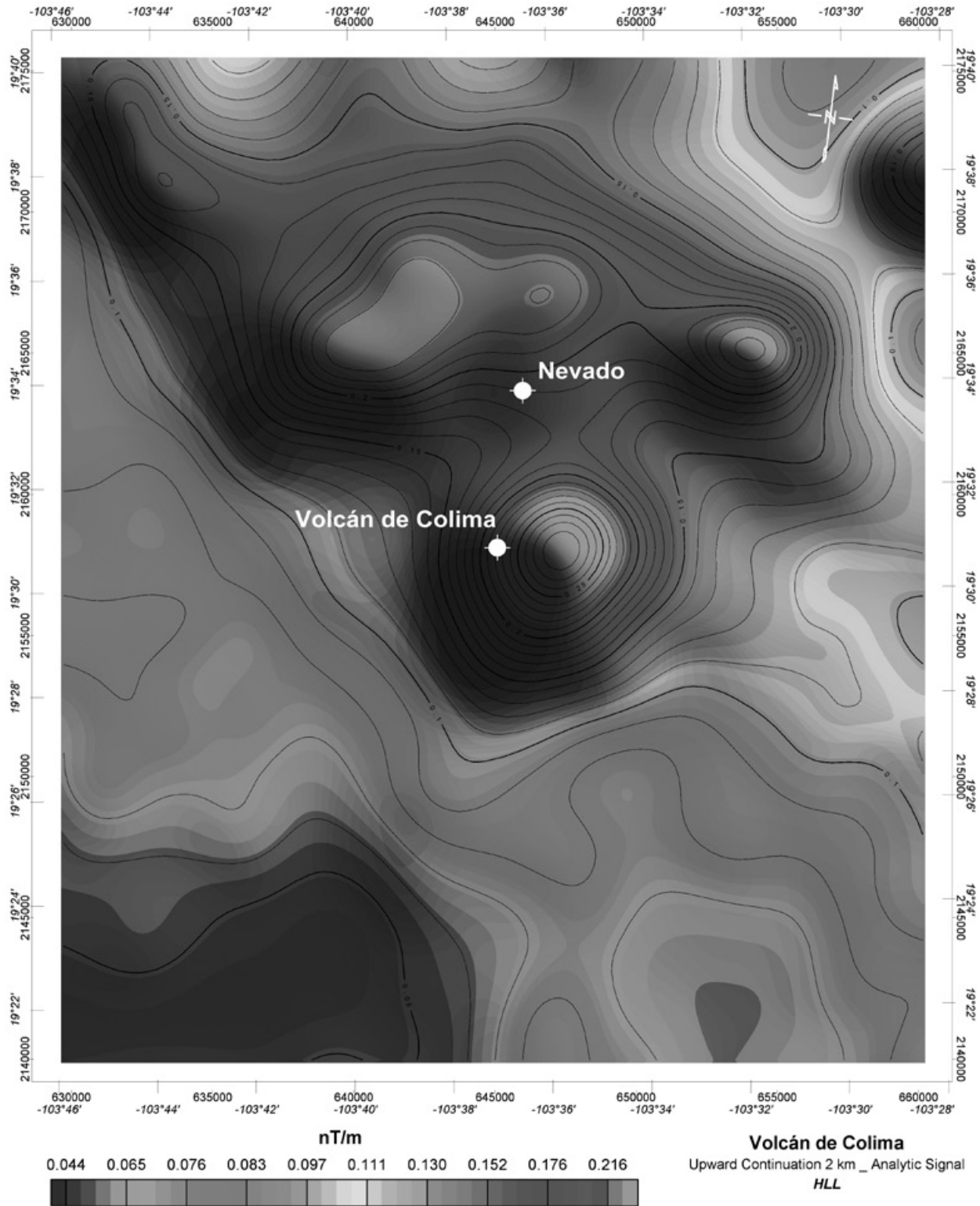


Figure 5. Contour map of the Analytic Signal upward continued 2 km of the Reduce to Magnetic Pole Field.

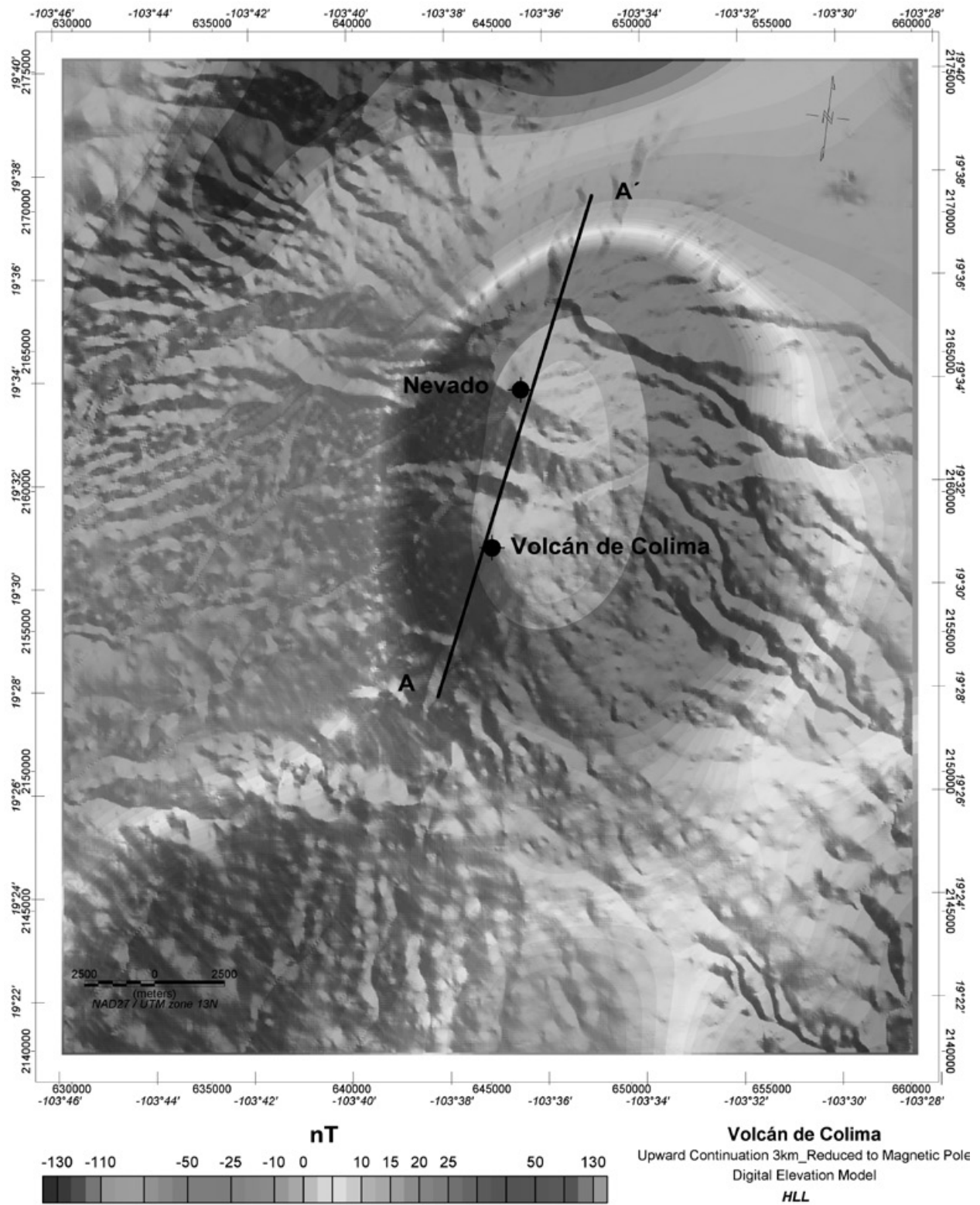


Figure 6. Contour map of the Reduced to Magnetic Pole field upward continued 3km and Terrain Digital Model and Modeling section.

deposits of volcanic debris avalanches (Coonor *et al.*, 1993; Urrutia-Fucugauchi *et al.*, 1997; Lopez-Loera and Urrutia-Fucugauchi, 1999). Average values for the susceptibilities and remanent magnetization intensity were used as initial values in the model. While the magnetic polarity of all units is normal, according to the age of the Colima Volcanic Complex. A major limitation in the analysis is the lack of information related to the variation of the magnetic properties with depth.

Results and discussion

The model of the reduced to magnetic pole and upward continued 3 km (Figure 7), shows the existence of a magmatic chamber of elongated shape with a length greater than 10 km in the NS direction. The edges of this chamber have thicknesses ranging from 820 m to 620 m to the south and north respectively. To the ESE of the summit of Volcán de Colima the magmatic chamber has a maximum thickness of about 6.9 km. Therefore the conduit may have a length of about 4.9 km. Values of magnetic susceptibility and remanence do not exist for the magma chamber since by definition it must have temperatures higher than the Curie point (Table 1).

Although numerous papers have been published on the Colima volcanic complex, the issue of the magma chamber has hardly been addressed. Based on the distribution of located epicenters of earthquakes during the seismic crisis of 1997-1998, Zobin *et al.* (2002), mentioned that the free zone of earthquakes may be associated with the magma storage area and that this area is set at a depth on the order of 3.3 km. Existing charts tend to give a triangular

shape to the magma chamber underlying Volcán de Colima. However Medina-Martínez *et al.* (1996) modeled the magma chamber of the Volcán de Colima using gravimetric data and determined the magmatic chamber to have rectangular shape more than 2 km wide, 5 km length and located about 1.5 km below sea level.

To place appropriated limits on the model, the Maeda viscoelastic model by Cabrera-Gutierrez and Espindola (2010) was also analyzed. They modeled the Volcán de Colima eruption of 1998-1999. Based on observed data for the volume of material produced during the eruption, they reported a magmatic chamber of approximately 1.93 km in radius centered at ~1.7 km below sea level which is ~5.6 km beneath the crater. The roof of the magma chamber generated by the model in the magnetic study presented here has a maximum depth of 4.9 km. Based on the model used in this research, the chamber is about a 1.4 km below sea level, and has a maximum length of 6.9 km to depth.

The magnetic model of the internal structure of Volcán de Colima, has some limitations due primarily to the fact that the magma chamber itself does not generate any magnetic response because in principle within it magnetic properties are undefined, so the principal magnetic response comes mainly from the overlying geologic units. The contact zone between the magma chamber and the host rocks becomes very susceptible to any small change in the magma chamber - host rock configuration, creating contrasting changes between measured field and the calculated field. In addition, the lack of magnetic properties at depth means that the magnetic response

Table 1. Magnetic properties of the sources associated to the modeled anomaly.

Rocks Type*	MAGNETICS		REMANENCE	
	Susceptibility (SI)	Magnetization (A/m)	Inclination	Declination
VCDA	0.0000125	0.351	87	15
Volcanic conduct VC	0.000125	0.001	47	20
ALN	0.0000125	1.4	90	15
Volcanic neck NV	0.0001633	1	90	20
NVDA	0.0006408	2.001	90	22
Limestone ¿? (Cz)	-0.0000754	3	86	22
VC Magmatic Chamber	0	0	0	0
NMCH	0.00010005	1.051	65	22
MSB	0.0000125	4.2	78	20

* VCDA = Volcán de Colima debris avalanche; VC = Volcán de Colima; ALN = Andesitic lavas from Nevado; NV = Nevado Volcano; NVDA = Nevado volcanic debris avalanches; NMCH = Nevado magma chamber; MBS = Marine sedimentary basement.

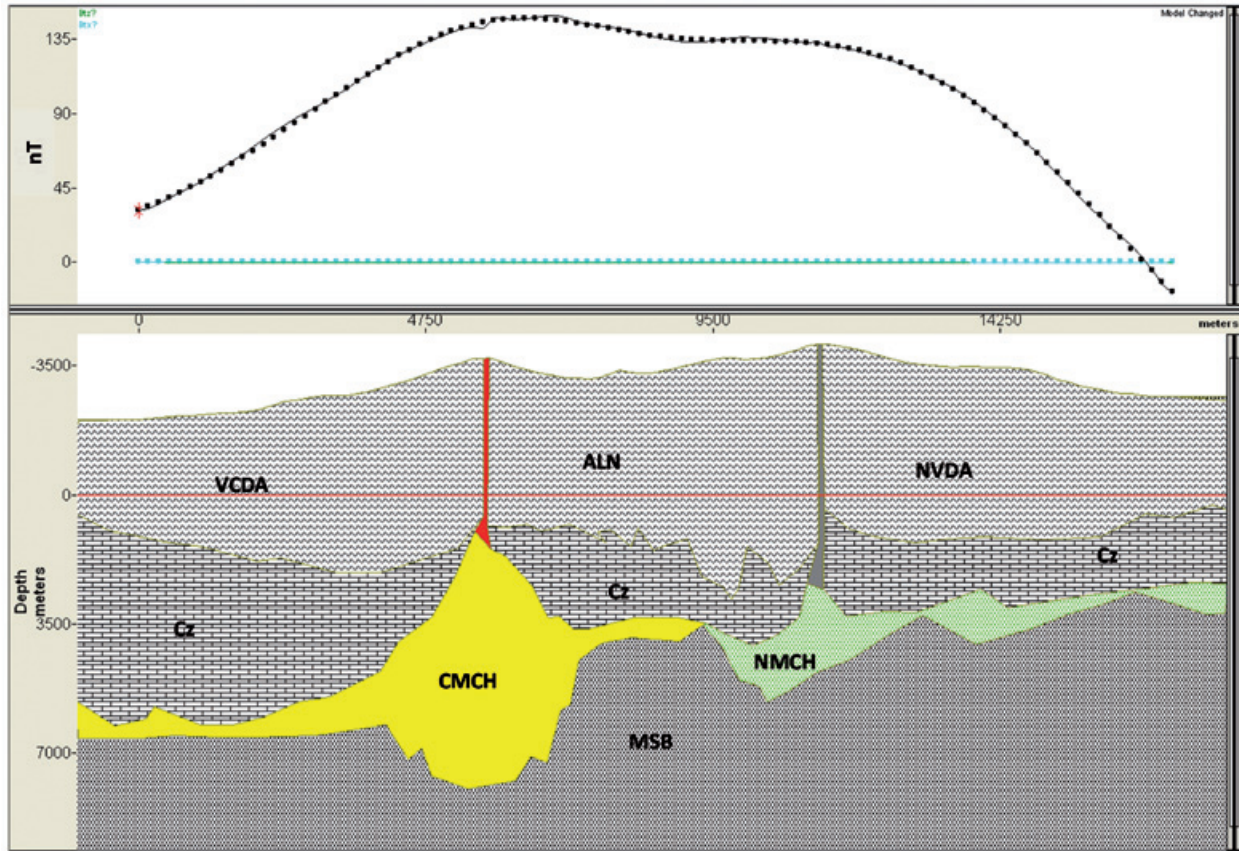


Figure 7. 2 $\frac{1}{4}$ D aeromagnetic model of the section A-A'. The dotted section is the Reduced to Magnetic Pole 3km upward continued. VCDA, Volcán de Colima debris avalanche; VC, Volcán de Colima; ALN, andesitic lavas from Nevado; NV, Nevado volcano; NVDA, Nevado volcanic debris avalanche; Cz, Limestones; CMCH, Colima magma chamber; NMCH, Nevado magma chamber; MSB, marine sedimentary basement.

mainly comes from the underlying geologic unit. Therefore, the process of modeling is difficult and has to be refined with respect to the contour of the chamber-host rock contact to achieve an acceptable fit.

The migration of magmatism from north to south appears to be one of the main features of the Mexican Volcanic Belt (MVB). Evidence of migration of eruptive activity to the south may be found in the elongated volcanic chains at three major volcanic complexes (Volcán de Colima-Nevado-Cántaro; Popocatepetl-Iztacihuatl-Telapón; Pico de Orizaba (Citlalpetel)-Cofre de Perote) in the MVB, where older stratovolcanoes are located to the north and young active volcanoes are located to the south (Luhr and Carmichael, 1990). Thus Cofre de Perote is older than Pico de Orizaba and Iztacihuatl is older than Popocatepetl, and Cántaro is older than Nevado and the Volcán de Colima. Towards the eastern portion of the MVB, Cantagrel and Robin (1979) using found that the migration of volcanism dates to the Pliocene using K-Ar dating. Hasenka and Carmichael (1985) investigated the ages of numerous cinder cones

of the Michoacán-Guanajuato volcanic field, in the middle portion of the MVB. Most of the cinder cones dated by Hasenka and Carmichael (1985) thought to be less than 40 thousand years old. All of these cones were located in the south. Cones located to the north were found to be older and are more eroded (Luhr and Carmichael, 1990). In addition, some researchers suggest that the MVB magmatism migration may reflect a change in subduction angle of the Cocos Plate (e.g., Urrutia Fucugauchi and Del Castillo, 1977).

Conclusions

The model of reduced to the magnetic pole field and upward continued 3 km described in this paper, shows elements that support the migration of magmatism from north to south in the Mexican Volcanic Belt and particularly in the Colima Volcanic Complex. The aeromagnetic model supports migration to the south of the Volcán de Colima (from the center of the body that simulates the magma chamber) of around 6.6 km.

The Volcán de Colima magma chamber model generated in this study has certain similarities with the gravity model of Medina-Martínez *et al.* (1996) and with the viscoelastic model by Cabrera-Gutiérrez and Espindola, differs from the conception described by Zobin *et al.* (2002), they have a classic pattern in terms of shape and position of the magma storage area, and the model shows no traces of magmatism migration, although their study was designed to investigate the seismic activity, and not to interpret the magma chamber.

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