Geofísica Internacional (2012) 51-2: 129-142

Original paper

2 ¾ dimension modeling of the aeromagnetic anomaly of Volcán de Colima, western Mexico

Héctor López-Loera

Received: January 20, 2011; accepted: October 20, 2011; published on line: March 30, 2012

Resumen

Se presentan los resultados de un modelo 2 ¾ 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 de 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 ¾ 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.

H. López-Loera
División de Geociencias Aplicadas
Instituto Potosino de Investigación Científica y Tecnológica, A.C.
Camino a la Presa San José # 2055
Lomas 4ª Sección, C. P. 78216
San Luis Potosí, S.L.P., México.
Corresponding author: hlopezl@ipicyt.edu.mx

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 volcanomagnetics 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 withan 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 km^3 (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 cost 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 Prestegaard (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.

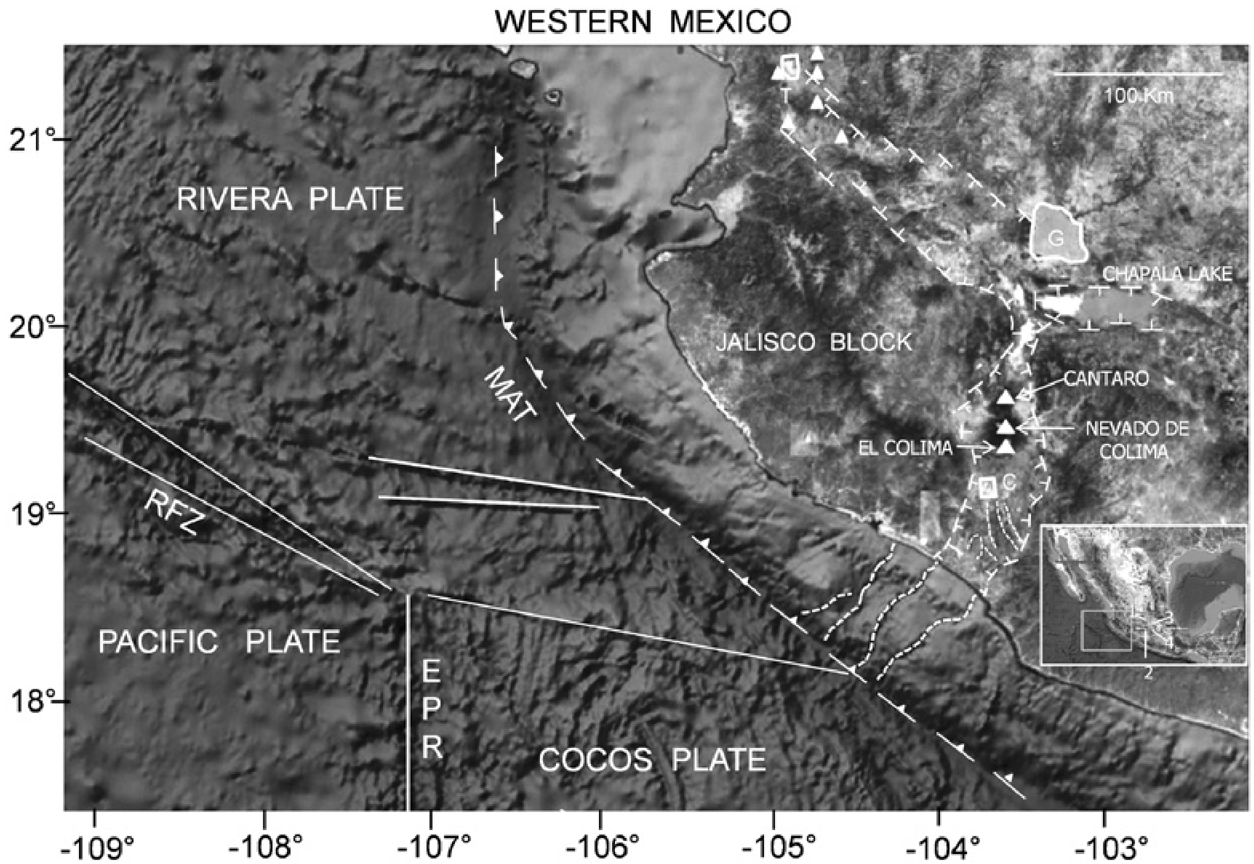

Figure 1. Satellite image of western México, showing the Colima Volcanic Complex and the interaction between different existing tectonic plates. White triangles represent major volcanic centers in the area. Major structural lineaments mark the tectonic depressions of the Colima Rift, Tepic-Zacoalco Rift 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); Popocatépetl (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-SYS™ 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 canyons 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).

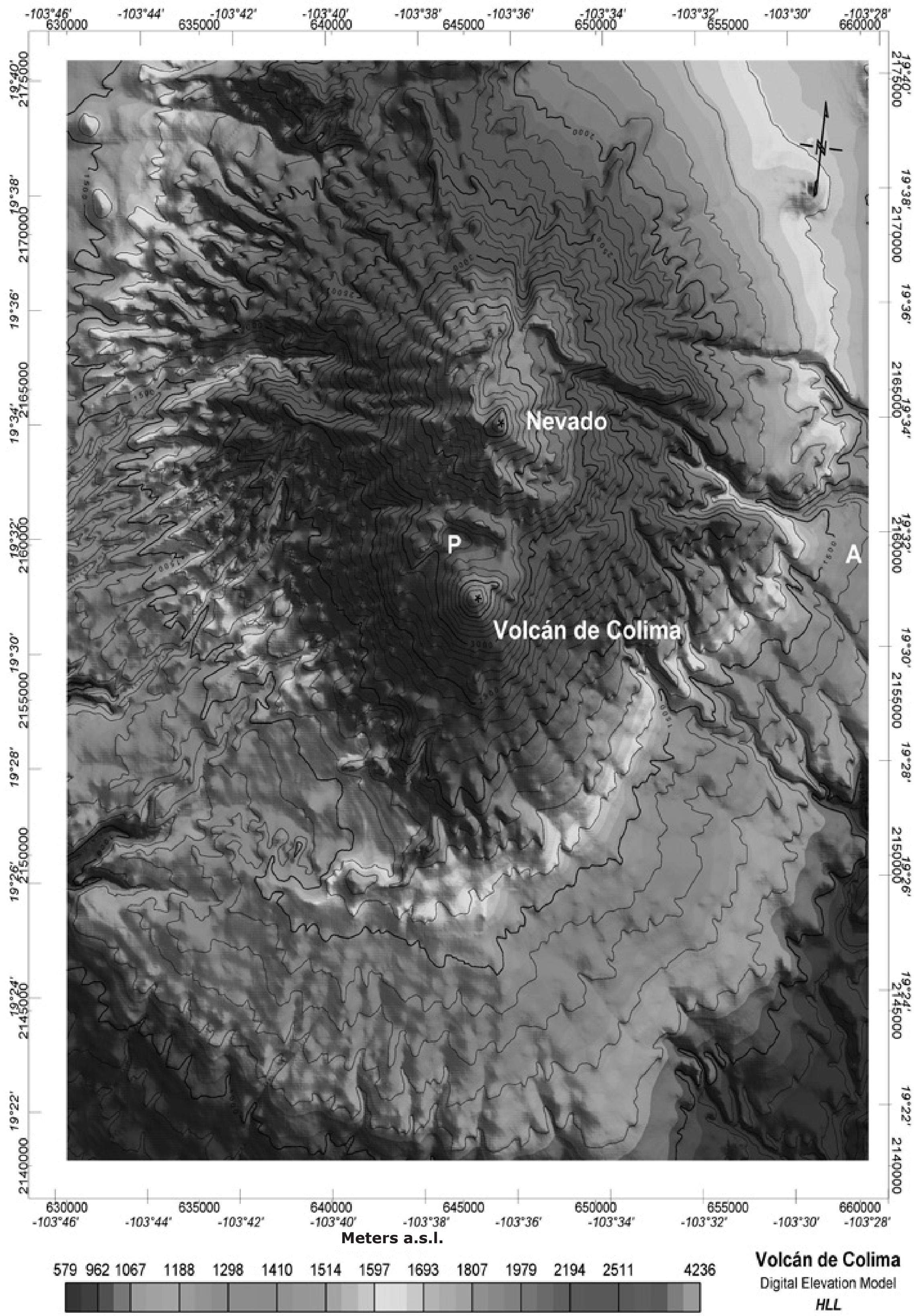

Figure 2. Map of the digital terrain model of the southern portion of the Colima Volcanic Complex. To the north of the Volcán de Colima flank there is a vertical corresponding to a ring portion of the old caldera called Colima protovolcano. Samples for the measured of magnetic properties were collected 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 Urrrutia-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 x 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 x 10^{-5} SI, with an average of 7.23 x 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 x 10^{-5} SI and 5.35 x 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 x 10^{-5} SI and 6.2 x 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 x 10^{-5} SI and 5.8 x 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 ¾ 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

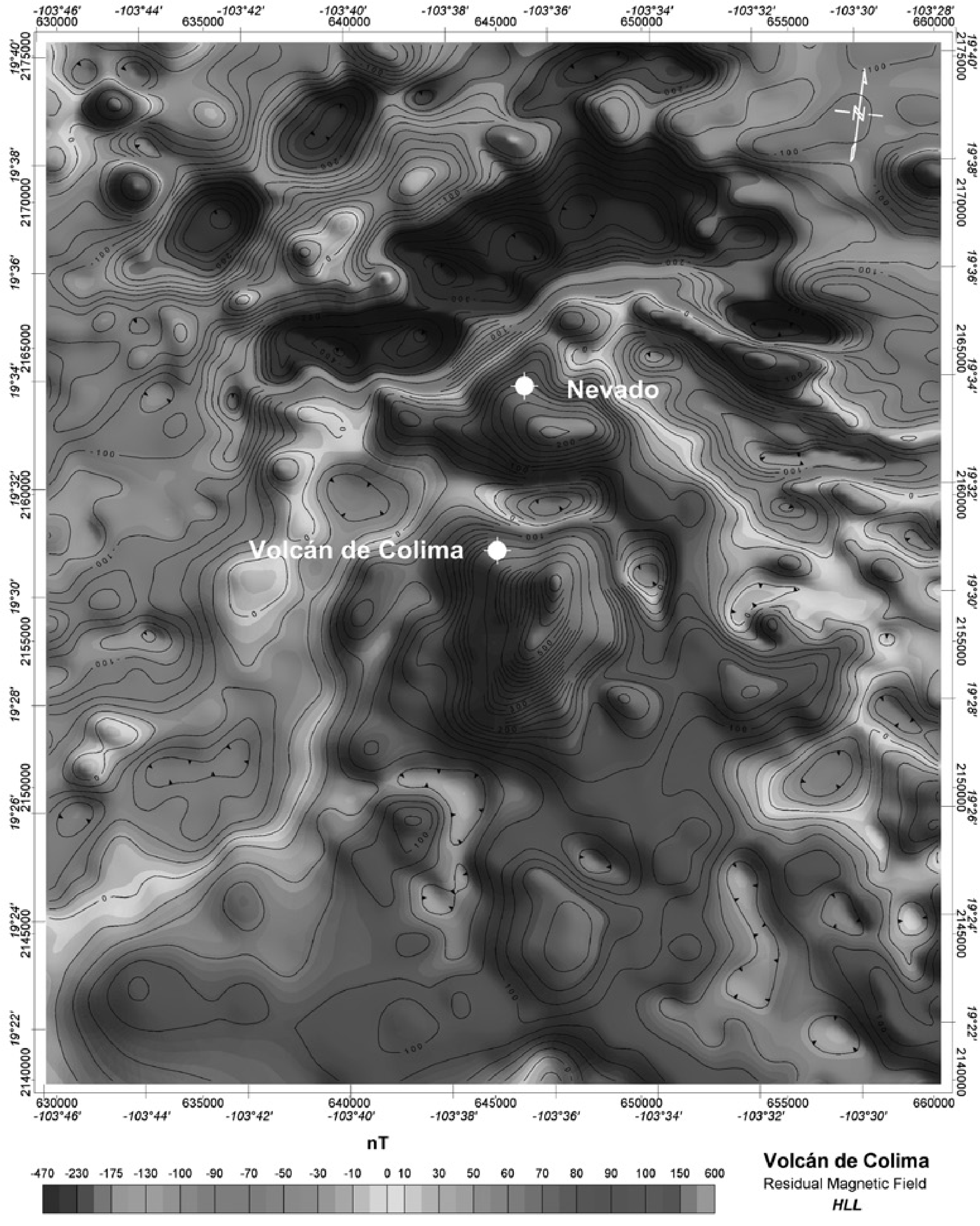

Figure 3. Contour map of the Residual Magnetic Field from the center and south of the Colima Volcanic Complex. The location of Volcán de Colima crater is shown (~200m x 200m).

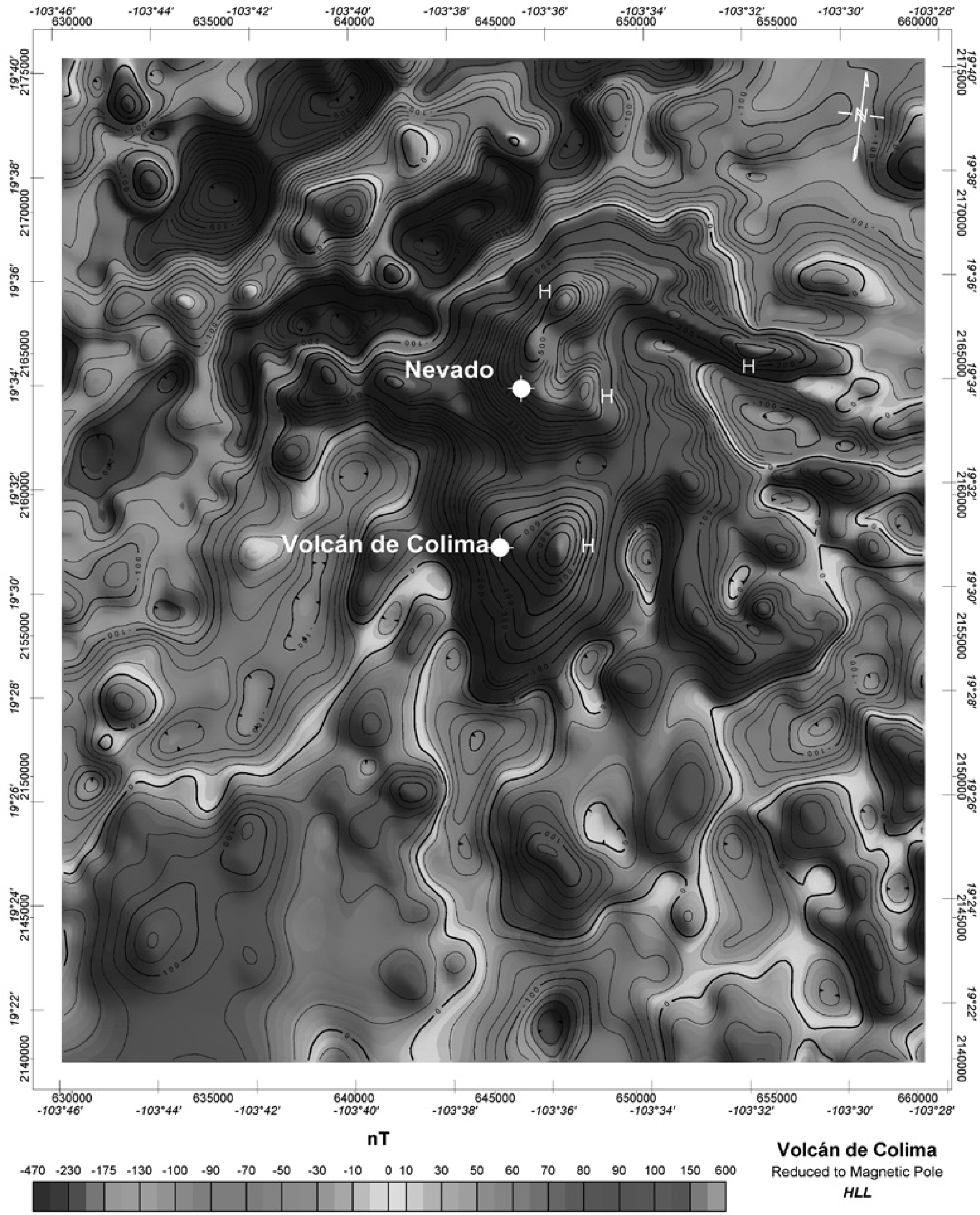

Figure 4. Contour map of the Reduce to Magnetic Pole of the center and southern portion of the Colima Volcanic Complex.

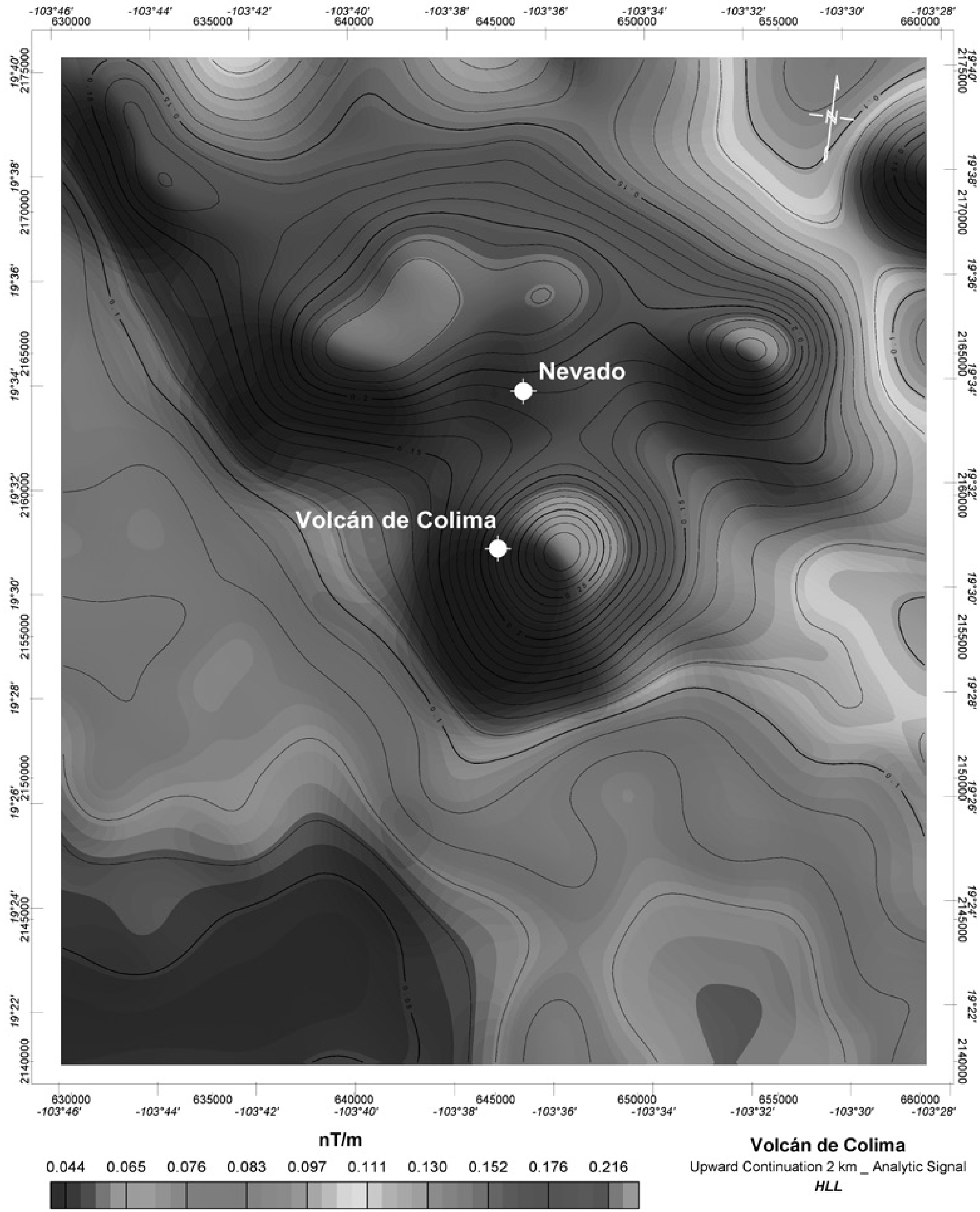

Figure 5. Contour map of the Analytic Signal upward continued 2 km of the Reduce to Magnetic Pole Field.

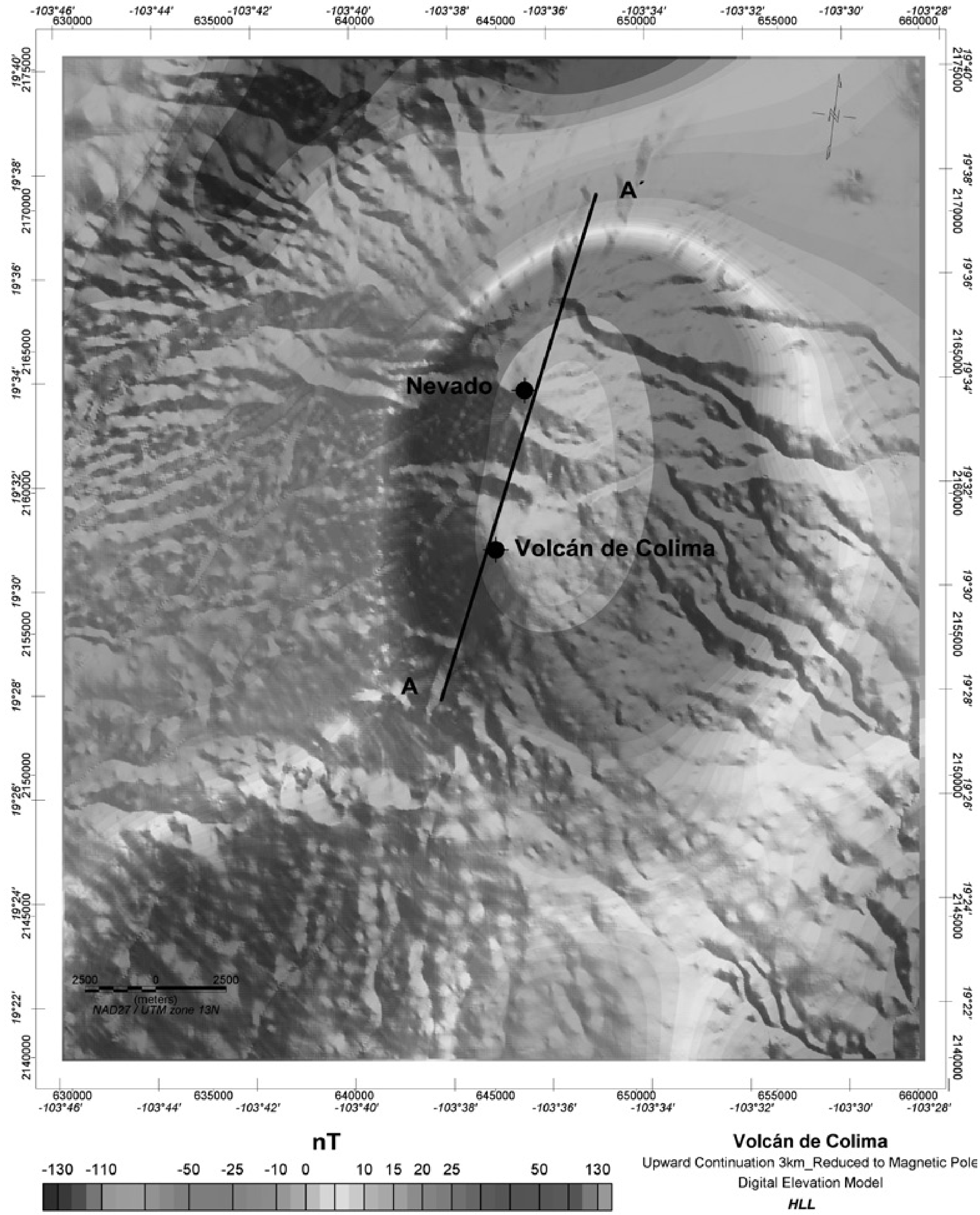

Figure 6. Contour map of the Reduced to Magnetic Pole field upward continued 3km and Terrain Digital Model and Modeling section.

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.

	MAGNETICS		REMANENCE	
Rocks Type*	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.

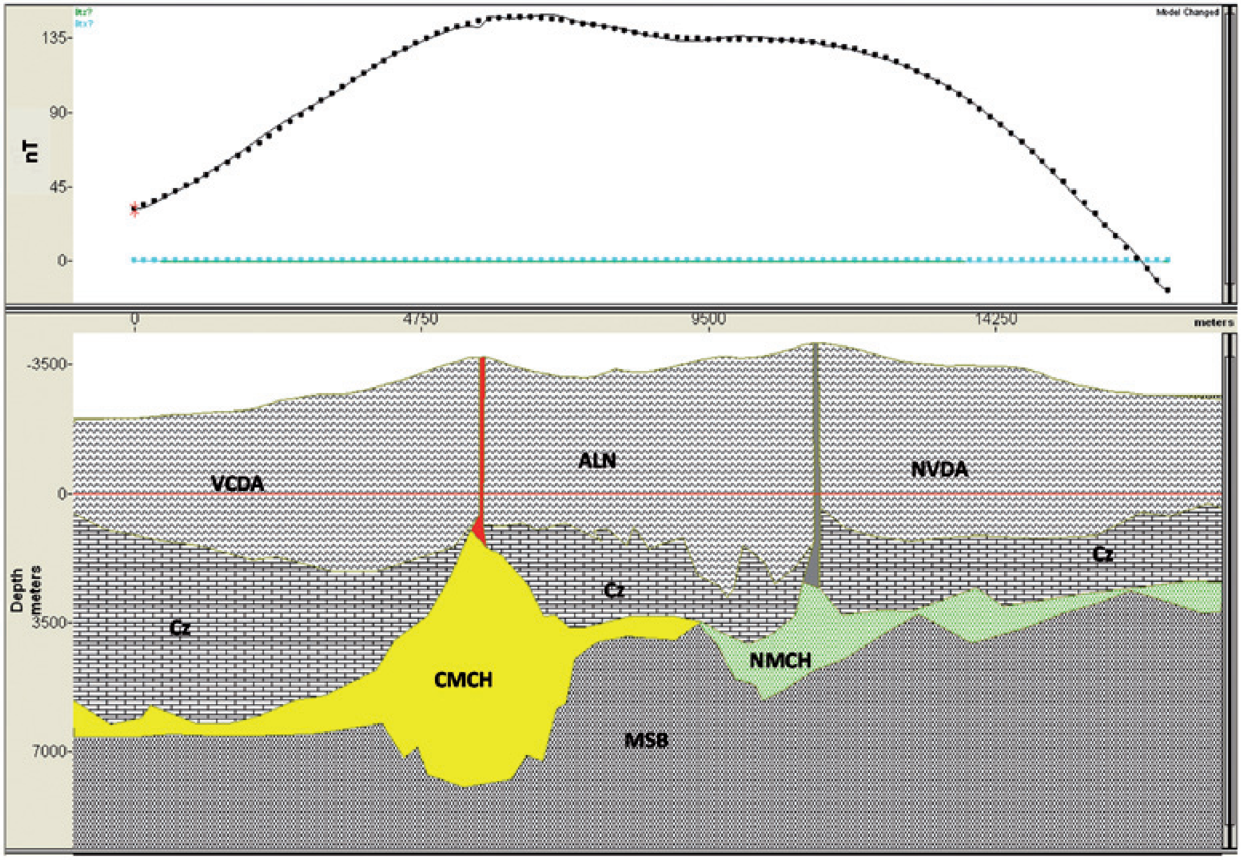

Figure 7. 2 ¾ D aeromagnetic model of the section A-A´. The dotted section is the Reduced to Magnetic Pole 3km upward continued. VCDA, Volcán de Colima debris avalanche; VC, Volcán de Colima; ALN, andesitic lavas from Nevado; NV, Nevado volcano; NVDA, Nevado volcanic debris avalanche; Cz, Limestones; 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; Popocatépetl-Izztacihuatl-Telapón; Pico de Orizaba (Citlaltepetl)–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 Iztaccihuatl 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-Gutierrez 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.

Acknowledgments

This project has been supported by a scholarship for Ph.D. studies from Consejo Nacional de Ciencia y Tecnología (CONACYT) to the author. Special thanks to Dr. Tonatiuh Dominguez, from Red Sísmica de Colima (RESCO) at the Universidad de Colima, for his kindness in providing the seismic events of 1997-1998. I gratefully acknowledge comments and useful suggestions by anonymous journal reviewers on earlier versions of the paper. Thanks are also given to Dr. Jaime Urrutia-Fucugauchi and Dr. Andrea Pavlick for comments that resulted in a more comprehensible, appropriate and improved manuscript.

Bibliography

Bandy W., Mortera-Gutiérrez C., Urrutia-Fucugauchi J., 1993, Gravity field in the southern Colima graben. Mexico. Geofísica Internacional, 32, 561-567.

Bandy W., Mortera-Gutiérrez C., Urrutia-Fucugauchi J., Hilde T.W.C., 1995, The subducted Rivera-Cocos plate boundary-where is it, what is it and what is it its relationship to the Colima rift? Geophys. Res. Lett. 22, 3075-3078.

Baranov V., Naudy H., 1964, Numerical calculation of the formula of reduction to the magnetic pole. Geophysics, 29, 67-79.

Barton C.E., Balwin R.T., Barraclough D.R., Bushati S., Chiappini M., Cohen Y., Coleman R., Hulot G., Kotze P., Golovkov V.P., Jackson A., Langel R.A., Lowes F.J., McKnight D.J., Macmillan S., Newitt L.R., Peddi N.W., Quinn J.M., Sabaka T.J., International Geomagnetic Reference Field, 1995, revision, 1996, Presented by IAGA Division V, Working Group 8, Physics of Earth and Planetary Interiors, Vol. 97, DOI: 10.1016/0031-9201(96)03139-1.

Blakely R.J., 1995, Potential Theory in Gravity and Magnetic Applications. Cambridge University Press, 441 pp.

Blanco-Montenegro I., Miquel Torta J., García A., Araña V., 2003, Analysis and modeling of the aeromagnetic anomalies of Gran Canaria (Canary Islands). Earth and Planetary Science Letters 206, 601-616.

Blanco-Montenegro I., Nicolasi I., Pignatelli A., García A., Chiappini M., 2011, New evidence about the structure and growth of ocean island volcanoes from aeromagnetic data: The case Tenerife, Canary Islands. J. Geophys. Res., 116, B03102, doi:10.1029/2010JB007646.

Bournas N., Galdeano A., Hamoudi M., Baker H., 2003, Interpretation of the aeromagnetic map of Eastern Hoggar (Algeria) using Euler deconvolution, analytic signal and local wavenumbers methods. Journal of African Earth Sciences. 37, 191-205.

Cabrera-Gutiérrez R., Espindola J.M., 2010. The 1998-1999 eruption of Volcán de Colima, Mexico: an application of Maeda's viscoelastic model. Geofísica Internacional 49 (2), 83-96.

Cantagrel J.M., Robin C., 1979, K-Ar dating on Eastern Mexican volcanic rocks; relations between the andesitic and the alkaline provinces. Journal of Volcanology and Geothermal Research. 5, 99-114.

Capra P. L., 2000, Colapso de edificios volcánicos: transformación de avalanchas de escombros en flujos de escombros cohesivos, los casos del monte Santa Elena (EE.UU.), Nevado de Toluca y Nevado de Colima (México). Inst, de Geofísica, UNAM, Tesis Doctoral, 120 pp.

Coonor C.B., Lane S.B., Clement B.M., 1993, Structure and thermal Characteristics of the summit dome, March, 1990-March, 1991; Volcan Colima. Geofísica Internacional, 32, p 643-657.

De Ritis R., Ventura G., Chiappini M., 2007, Aeromagnetic anomalies reveal hidden tectonic and volcanic structures in the central sector of the Aeolian Islands, southern Tyrrhenian Sea, Italy. J. Geophys. Res., 112, B10105, doi: 10.1029/2006JB004639.

De Ritis R., Dominici R., Ventura G., Nicolasi I., Chiappini M., Speranza F., De Rosa R., Donato P., Sonnino M., 2010a, A buried volcano in the Calabrian Arc (Italy) reveled by high – resolution aeromagnetic data. J. Geopys. Res., 115, B11101, doi:10.1029/2009JB007171.

De Retis R., Ventura G., Chiappini M., Carluccio R., Von Frese R., 2010b, Regional magnetic and gravity anomaly correlations of the Southern Tyrrhenian Sea. Phys. Earth Planet. Int., Vol. 181, doi:10/1016/j.cageo.2010.10.003.

Fedi M., Florio G., Rapolla A., 1998, A 2.5 modeling of Somma-Vesuvius structure by aeromagnetic data. Journal of Volcanology and Geothermal Research. 82, 239-247.

Finn C., Williams D.L., 1987, An Aeromagnetic Study of Mount St. Helens. J. Geophys, Res., 92, 10,194-206.

Finn C.A., Morgan L.A., 2002, High-Resolution aeromagnetic mapping of volcanic terrain, Yellowstone National Park, 2002. Journal of Volcanology and Geothermal Research 115, 207-231.

Flanagan G., Williams D.L., 1982, A magnetic investigation of Mount Hood. Oregon, Journal of Geophysical Research B, 87, 4, 2804-2814.

Garcia A., Chiapini M., Blanco-Montenegro I., Carluccio R., D´Ajello-Caracciolo F., De Ritis R., Nicolasi I., Pignatelli A., Sánchez N., Boschi E., 2007, High resolution magnetic anomaly map of Tenerife, Canary Islands. AnnalGeophysics; Eds. M. Chiappini, A. García, v. 50, no. 5, 689-697.

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

Hagiwara Y., 1965, Analysis of the Results of the Aeromagnetic Surveys over Volcanoes in Japan (I). Bull. Earth. Res. Inst., 43, 529-547.

Hasenka T., Carmichael I.S.E., 1985, The cinder cones of Michoacán-Guanajuato, central Mexico; their age, volume and distribution, and magma discharge rate. Journal of Volcanology and Geothermal Research 25, 105-124.

Henderson R.G., 1970, On the validity of the use of the upward continuation integral for total magnetic intensity data. Geophysics, 35, 916-919.

Henderson R.G., Zietz I., 1949, The upward continuation of anomalies in total magnetic intensity fields. Geophysics, 14, 517-534.

Hildenbrand T.G., Rosenbaum J., Kauahikaua J.P., 1993, Aeromagnetic Study of the Island of Hawaii. J. Geophys. Res., 98, 4099-4119.

Honkura Y., 1991, A Magnetic Anomaly Map in the Japanese Region with Special Reference to Tectonic Implication. J. Geomagn. Geoelectr., 43, 71-83.

Komorowski J.C., Cortés A., Navarro C., Gavilanes J.C., Siebe C., Rodríguez S., 1996, Edifice collapse and debris avalanches deposits at Colima volcanoes, México- a review with new variations on a recurrent theme: Univ. de Colima. Reunión Inter. Volcán de Colima. 5ª, Colima, Col. (large abstract, electronic format).

López-Loera H., Gutiérrez C., 1977, Pseudosecciones Geo-eléctricas e Implicaciones Geohidrológicas en el Valle de Colima. Geofísica Internacional, 17, 2, 127-150.

López-Loera H., Urrutia-Fucugauchi J., 1999, Spatial and temporal magnetic anomalies of Colima volcano, western Mexico. Geofisica Internacional, 39, 3-16.

López-Loera H., Aranda-Gómez J.J., Arzate J.A., Molina-Garza R.S., 2008, Geophysical surveys of the Joya Honda mar (México) and surroundings; volcanic implications. Journal of Volcanology and Geothermal Research 170, 135-152.

López-Loera H., Urrutia-Fucugauchi J., Alva-Valdivia L.M., 2010, Magnetic characteristics of fracture zones and constraints on the subsurface structure of the Colima Volcanic Complex, western Mexico. Geological Society of America, Geosphere 6, 1, 35-46.

Luhr J.F., Carmichael I.S.E., 1980, The Colima Volcanic Complex, Mexico. Part I, Post-caldera andesites from Volcan Colima. Contrib. Mineral. Petrology, 71, 343-372.

Luhr J.F., Carmichael I.S.E., 1981, The Colima Volcanic Complex, Mexico. Part II, Late Quaternary cinder cones: Contrib. Mineral. Petrology, 76, 127-147.

Luhr J.F., Carmichael I.S.E., 1982, The Colima Volcanic Complex, Mexico. Part III. Ash and scoria-fall deposits from the upper slopes of Volcan Colima: Contrib.Mineral. Petrology, 80, 262-275.

Luhr J.F., Carmichael I.S.E., 1990, Geology of Volcan de Colima. Bol. Inst. Geol:, UNAM, 107, 101p.

Luhr J.F., Prestegaard K.L., 1988, Caldera formation at Volcan Colima, Mexico, by a large Holocene volcanic debris avalanche. J. Volcanol. Geotherm. Res., 35, 335-348.

Malahoff A., 1969, Magnetic Studies over Volcanoes in the Earth’s Crust and Uppermantle. Geophys. Monograph 13, edited by J. H. Pernbroke, Am. Geophysical Union 436-446.

Marquardt D.W., 1963, An algorithm for least-squares estimation of non-linear parameters. J. SIAM, 11, 431-441.

Medina F., Espindola J.M., De la Fuente M., Mena M., 1996, A Gravity model of the Colima, Mexico region. Geofisíca Internacional 35 (4), 409-414.

Meridee J.C., 1995, Structural controls of Holocene reactivation of the Meer fault, Southwestern Oklahoma, from magnetic studies. Geological Society of America, Bulletin, 107,1, 98-112.

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

Nakatsuka T., Utsugi M., Okuma S., Tanaka Y., Hashimoto T., 2009, Detection of aeromagnetic anomaly change associated with volcanic activity: An application of the generalized mis-tie control method. Tectonophysics. 478, 3 -18.

Okubo A., Kanda W., Tanaka Y., Ishihara K., Miki D., Utsugi M., Takayama T., Fukushima M., 2009, Apparent magnetization intensity map on Sakurajima Volcano, Kyushu, Japan, inferred from low-altitude, high density helicopter-borne aeromagnetic surveys. Tectonophysics. 478, 34-42.

Okuma S., Stotter Ch., Supper R., Nakatsuka T., Furukawa R., Motschka K., 2009, Aeromagnetic constrains on the subsurface structure of Stromboli Volcano, Aeolian Islans, Italy. Tectonophysics 478, 19-33.

Pascacio R.P., 2001, Texto Guía Carta Magnética "Colima" E13-3, Consejo de Recursos Minerales, 12p.

Pignatelli A., Nicolosi I., Carluccio R., Chiappini M., vonFrese R., Chiappini M., 2011, Graphical interactive generation of gravity and magnetic fields. Computers and Geosciences, doi:10.1029/2010JB007646.

Reynolds R.L., Rosenbaum J.G., Hudson M.R., Fishman N.S., 1990, Rock magnetism, the distribution of magnetic minerals in the Earth´s crust, and aeromagnetic anomalies, in Geologic Applications of Modern Aeromagnetics Surveys, U.S. Geol. Surv. Bull., 1924, 24-45.

Robin C., Mossand P., Camus G., Cantagrel J.M., Vincent P., 1987, Eruptive history of the Colima volcanic complex (Mexico). J. Volcanol. Geotherm. Res., 31, 99-113.

Robin C., Komorowsi J.C., Boudal C., Mossand P., 1990, Mixed magma pyroclastic surge deposits associated with debris avalanche deposits at Colima Volcanoes, Mexico. Bull. Vulcanol., 52, 391-403.

Robin C., Camus G., Gourgaund A., 1991, Eruptive and magmatic cycles at Fuego de Colima (Mexico). J. Volcanol. Geotherm. Res., 45, 209-225.

Stoopes G., Sheridan M.F., 1992, Giant debris avalanches from the Colima volcanic complex, Mexico – implications for long-run out landslides (> 100 km) and hazard assessment. Geology, 20, 299-302.

Ueda Y., 2007, A 3D magnetic structure of Izu-Oshima Volcano and their changes after the eruption in 1986 as estimated from repeated airborne magnetic surveys. Journal of Volcanology and Geothermal Research 164, 176-192.

Ueda Y., Nakagawa H., Kumagwa K., 1990, Aeromagnetic Anomaly and Derived Structure of Izu-Oshima Volcano after the eruption in November, 1986. J. Geomag. Geoelectr., 42, 355-363.

Urrutia-Fucugauchi J., Del Castillo L., 1977, Un modelo del Eje Neovolcánico Mexicano. Bol. Soc. Geol. Mex., 38, 18-28.

Urrutia-Fucugauchi J., Martín del Pozzo A.L., Alva-Valdivia L., López-Loera L., Ponce R., 1997, Paleomagnetic estimates of emplacement temperatures of pyroclastic deposits from the Colima volcanic complex. Intern, Assoc. Volcanol. Geochem. Earth Inter., IAVCEI General Assembly, January 1997, Puerto Vallarta, Mexico, Abstr. P.12.

Urrutia-Fucugauchi J., Martínez-Pepin N., Hernández-Pérez I., Arciniega-Ceballos A., López-Loera H., Flores-Ruiz J.H., Anaya C., 2002, Aeromagnetic anomalies and structure of the Iztaccíhuatl-Popocatépetl volcanic region in Central Mexico. Geofísica Internacional, 41,2, 121-131.

Webring M., 1985, SAKI: a FORTRAN program for generalized inversion of gravity and magnetic profiles. USGS Open File Report 85-122, 29p.

Williams D.L., Finn C., 1987, Evidence for shallow pluton beneath the Goat Rocks Wilderness, Washington, from gravity and magnetic data: Journal of Geophysical Research, 92, 4867-4880.

Zobin V.M., Luhr J.F., Taran Y.A., Breton M., Cortés A., De La Cruz-Reyna S., Dominguez T., Galindo I., Gavilanes J.C., Muñiz J.J., Navarro C., Ramírez J.J., Reyes G.A., Ursua M., Velasco J., Alatorre E., Santiago H., 2002, Overview of the 1997-2000 activity of Volcán de Colima, México. Journal of Volcanology and Geothermal Research. 117, 1-19.