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AEROMAGNETIC STUDIES, LOS AZUFRES GEOTHERMAL AREA, MICHOACAN

by

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ABSTRACT

Detailed and regional aeromagnetic surveys were completed over the Los Azufres geothermal area in central Mexico. Many mapped faults are clearly expressed in the detailed magnetic data because these faults penetrate to the surface and many are reflected in the topography. East-trending faults are often cut by younger north- to -northwest trending structures which can be interpreted from the magnetic data. A large zone of mapped hydrothermal alteration is apparent in the magnetic data as an area of unusually low (0-50 nT) magnetic relief. Interpreted structures trend NW into this area and are weakly expressed within the alteration zone. The regional survey records several major volcanic - intrusive complexes as large, positive magnetic anomalies, including the Los Azufres area. The source of the Los Azufres magnetic high appears to be bounded by northwest- and north-trending regional structures.

INTRODUCTION

As part of a cooperative agreement between the United States Department of Energy (DOE) and the Mexico Comisión Federal de Electricidad (CFE), two aeromagnetic surveys were completed over the Los Azufres geothermal area in Michoacan, central Mexico. The goals of this work were to determine the effectiveness of specialized aeromagnetic surveys for determining structural control and alteration areas in geothermal resources related to fractured volcanic systems. Other data obtained in support of the aeromagnetic surveys included the collection of magnetic susceptibility data for geologic units at Los Azufres and recording the diurnal variation of the earth's magnetic field.

DATA ACQUISITION

The aeromagnetic surveys are classified as detailed (low-altitude survey) and regional (high-altitude survey). The detailed survey was completed over the Los Azufres geothermal area using a Llama helicopter operated by CFE. Approximately 527 line-km were flown in an area of 96 sq km, for an average line spacing of 0.18 km. Survey lines were flown northwest-southeast at an attempted terrain clearance of 100 m. The recording equipment included a Geometrics Model G-803 Airborne (proton) Magnetometer, a Bonzar Mark 10X radar altimeter, a Panasonic color TV camera, and a Panasonic VHS Portable Video Cassette Recorder. Both analog and digital magnetic and altimeter data were recorded.

The high-altitude survey covered an area of approximately 1500 sq km in which the Los Azufres geothermal field was centrally located. Approximately 1590 line-km were flown north-south at a nearly constant altitude of 11,300 ft (3,444 m) except over parts of San Andres volcano where altitude reached 12,500 ft (3,810 m). This survey was flown in a Piper Cherokee fixed-wing airplane chartered by CFE. Dense smoke and haze resulting from numerous fires restricted flying and complicated navigation, resulting in non-uniform survey data coverage.

Both surveys were completed in May, 1988 by a four man-crew which included a pilot and navigator from CFE, and a magnetometer operator and video system/recorder operator from UURI. The variation of the earth's magnetic field was recorded with a Scintrex Base-Station Magnetometer, Model MBS-2 for the period 19 April to 26 May 1988. These variations, which have a normal distribution, have a mean value of

42,740 gammas. The goal of this magnetic field monitoring was to determine the diurnal corrections to be applied in the reduction of the aeromagnetic data. Significant diurnal variations did occur during the low-altitude survey.

DATA COMPILATION AND PROCESSING

The flight-path recovery utilized VHS tapes of the flight path which were replayed many times to locate points identifiable on aerial photos, photomosaics, and topographic maps. The predominance of forest cover and incomplete photographic coverage limited the number of recovered points on both surveys.

A first-generation magnetic map of the low-altitude data was completed by removing a base level of 42,000 nanoteslas (nT) from all observed values and applying diurnal corrections to each flight line. The diurnal adjusts all recorded data to the "normal" value of 42,740 nT observed at the CFE monitor station during the survey period, (Campos E. and Herrera B., 1988). The final magnetic map includes additional corrections to entire lines or portions of lines based on tie-line intersections and altitude variations. This map of total magnetic intensity also incorporates smoothing to reduce flight-line effects and to emphasize geologic information.

During the initial qualitative interpretation it became evident that additional computer processing would reduce the effects of terrain clearance variation, remaining flight position errors and other high-frequency noise. The aeromagnetic map was manually digitized by CFE for a square grid of 250 m interval. With digital data the following processes could later be employed: reduction to the pole; upward continuation; second vertical derivative; and downward continuation. Depending on the results obtained two-dimensional and three-dimensional modeling will be completed at a later date.

Compilation of the high-altitude data included diurnal corrections (generally less than 10 nT according to Campos E. and Herrera B., 1988) and removal of a 42,000 nT base level. Because the diurnal changes were small and well-located tie-line intersections were generally less than +/- 10 nT, no further tie-line adjustments were made. Nonconforming data for poorly located portions of several flight lines were ignored in contouring the final map.

INTERPRETATION - LOW-ALTITUDE SURVEY

An initial qualitative interpretation of the low-altitude map was completed by the correlation of geological and geophysical data, including; lithology, structure, susceptibility samples, paleomagnetic data, gravity, and ground magnetics. Linear magnetic trends and dipolar magnetic anomalies resulting from distinct sources with induced magnetization were identified from these data. In general, the detailed map (Plate I) shows well-defined regional trends with an E-W orientation which predominate in the northern sector, and NW-SE trends which predominate in the south and west portions of the area. Other trends of minor importance, with an approximate N-S orientation, occur in the eastern sector. These magnetic trends correspond to orientations associated with a system of structures observed at the surface. The NW-SE trends may be of major importance as they coincide with trends observed in the regional gravity map. The detailed (1:10,000) geologic mapping (CFE, 1986) provides a basis for evaluation of the magnetic data.

Inspection of the low-altitude survey map, Plate I, reveals several interesting features.

1. Numerous short-wavelength highs and lows, less than 0.5 km in long dimension, occur on portions of the periphery of the surveyed area. Many of the small closed anomalies result from data acquisition or compilation problems (i.e. terrain clearance variation, flight path recovery inaccuracies). Terrain clearance variations are most severe when the magnetometer is less than 100 m above the ground surface. Many anomalies result as the irregular topography rises to, or falls away from, the smoother flight path. Anomalies of this type can be evaluated by correlation with topographic maps and review of the radar altimeter data.

2. There is a northwest-southeast elongation of contours, some of which may result from flight-line position and data leveling errors. Manual smoothing has reduced these compilation effects. Much of the remaining NW-SE elongation results from the topographic grain and magnetization contrasts due to northwest-trending faults, fractures, and geologic contacts. Discrimination between compilation errors and valid geologic contrasts is difficult, and interpreted NW-SE structures must be regarded as somewhat uncertain.

3. Magnetic field variations of 300 nT to more than 1200 nT per kilometer are common along all borders of the survey. An area of perhaps 5 km (N-S) by 1-3 km (E-W) in the center of the survey, and largely coincident with the zone of hydrothermal alteration between the north and south production zones, is characterized by only long-wavelength variations between 640 nT and 750 nT. This limited variation indicates very minor magnetization contrasts in near-surface rocks (0-1000 m depth) which may arise from different geologic models.

4. Numerous positive anomalies are associated with the San Andres dacite (Qdp) to the east, the Mil Cumbres andesites (Tma) and dacite cinders (Qvc) in the north.

5. Several negative anomalies occur over rhyolitic rocks (Qrf). The near-surface depth estimates to the source rocks along with correlation with hilltop topography and reduced terrain clearance (from the radar altimeter) suggest reversely polarized units within these Quaternary rhyolites. Several of these reversed sources are identified by (R) on the interpretation map, Plate II. Additional reversely polarized volcanic sources may be present but have not been positively identified. Flux-gate magnetometry measurements by Dobson and Mahood (1985) document reversed magnetizations in "basement rocks" and in the Agua Fria rhyolites at Los Azufres.

Interpretation of the low-level data to date has focused upon: 1) an evaluation of the utility of this detailed, low-level survey in helping to map this volcanic-hosted, fracture-dominated geothermal system; and 2) a preliminary magnetic/geometric model of the production zones and adjacent areas of the geothermal system. A more complete interpretation of the survey will result from subsequent CFE processing and numerical modeling. The results of the present interpretation are summarized on Plate II, an overlay to the magnetic data or geologic maps, and are discussed below.

Fault and Fracture Delineation

The magnetic contour map is dominated by the expression of faults and fractures. These structures are well expressed for several reasons. Many faults penetrate to the surface and are reflected in the surface topography. The faults place volcanic rocks of different magnetization in lateral contact, providing the necessary magnetization contrasts. Magnetic susceptibility contrasts within the Los Azufres area have been documented by Campos and Abad (1988) and confirm a substantial range of susceptibility variation (10 E-6 to 2047 E-6 cgs for individual measurements). The variation in remanent magnetization is probably greater. The low level of the helicopter flight provided a small distance between the magnetization contrasts and the sensor, enhancing the anomalies.

Major portions of more than 18 mapped faults and several second-order structures are expressed in the magnetic data (Plate II, Table I). Figure 1 illustrates the form of magnetic anomalies for two characteristic models as computed for the magnetic-field parameters of the Los Azufres area. The faults and fractures are expressed in various ways. A linear gradient 0.5 to several km long (e.g. Falla La Presa, Falla Maritaro) is the most obvious expression. More common in these data are truncation of magnetic highs and lows and changes in anomaly amplitudes along a linear alignment. Many known faults are revealed by combinations of the above.

Not all faults are well expressed in the magnetic data, and only rarely can the entire fault be interpreted from the magnetic data. Because the surface geology has been mapped in detail and many drill holes have been completed, the opportunity for identifying major new features from the magnetic data is somewhat limited. Using the criteria discussed earlier, and in conjunction with the CFE geologic map, several mapped faults may be extended with some confidence based on the magnetic data. These include Falla Laguna Verde, Falla La Hiobba, Falla El Chinapo, and other unnamed features.

More than 12 previously unmapped structures are also interpreted from the magnetic data, as shown on Plate II. Several of these interpreted structures trend N60W to N20W, at a relatively small angle to the flight lines and hence could arise from compilation problems in areas of poor flight path recovery, or a coincidental alignment of magnetic gradients of anomalies. Perhaps the most important of these trends northwest near the eastern margin of the South Production Zone. The recognition of these NW-SE structures is a useful contribution to the knowledge of Los Azufres at this stage of qualitative interpretation. These interpreted features should be verified by geological mapping or surface geophysical

Table I
Magnetic Expression of Known Faults

Falla	Magnetic Expression	*Type of Expression	Length(Km) Expressed	Trend Direction
Falla Fio Agrio	Weak	GR + AD	1	NNW
Falla Maritaro	Strong	GR + AD	6	E
Falla Nopalito	Weak	AD	0.5	NE
Falla Espinazo del Diablo	None	---	--	E
Falla Los Coyotes	Moderate	AD	3	E
Falla La Presa (N)	Moderate	GR + AD	3	NNW
Falla Laguna Verde (N)	Moderate	GR + AD	3	NNW
Falla La Cumbre	Weak	---	1	E
Falla La Hiobba	Moderate	GR + AD	1	N;NNE
Falla La Presa (S)	Strong	GR	3	NNW
Falla Dorada	None	---	--	NE
Falla El Chino	Weak	AD	0.7	E
Falla Laguna Larga	Moderate	AD	2.5	E
Falla San Alejo	Weak	GR + AD	0.7	E
Falla Agua Fria	Moderate	GR + AD	3.5	E
Falla El Vampiro	Weak	AD	0.8	NE
Falla El Viejon	Moderate	GR + AD	2	NE
Falla Ejamaniles	Moderate	GR + AD	2	SE;E
Falla Los Azufres	Moderate	GR + AD	0.8	E
Falla Agua Ceniza	Moderate	GR + AD	1	NE
Falla El Chinapo	Strong	GR + AD	2.5	E
Falla Laguna Verde (S)	Moderate	GR + AD	1.7	NNW

* Magnetic expression type: GR = gradient; AD = alignment of discontinuities

surveys before being accepted as faults.

Los Azufres Geothermal System

A preliminary interpretation of the Los Azufres area, is shown on Plate II. This interpretation, supported by numerical modeling of the high-altitude survey, Figure 2, indicates that a large body of relatively uniform bulk magnetization extends from Falla El Chinapo on the south to Falla Los Coyotes on the north. The body is truncated by Falla Laguna Verde and Falla La Presa on the east, and extends west beyond Presa Laguna Larga. This broad, positive source appears to be the 1000 m plus thickness of andesites contrasting with San Andres dacite and La Yerbabuena rhyolite domes on the east, and La Yerbabuena rhyolite domes on the west. Superimposed on this dominantly low-relief feature are minor anomalies due to topographic effects, faulting, and locally, reversely magnetized rhyolites which may outcrop.

Thin, layered rhyolites overlie andesites in the central portion of the positive source body. A broad area of hydrothermal alteration is expressed by subdued magnetic variations, and appears to be oriented along the trend of two poorly defined structures interpreted from the magnetic data. We do not observe a detailed correlation between the diverse lithologic units and the magnetic contours, except that in the areas of high susceptibility (andesites and dacites) the magnetic relief is much more irregular than where the surface cover are tuffs, rhyolites and altered rocks, even though the average value of the field is approximately the same.

The structures indicated may have some significance as controls for the South Production Zone. The significance of structures and magnetic sources near the North Production Zone is unclear at present.

INTERPRETATION - HIGH ALTITUDE SURVEY

The high altitude residual magnetic intensity map is presented as Plate III. The interpretation of this survey will be somewhat limited by flight-path recovery problems, principally in the southern third of the survey area, and by several wide gaps in flight line separation. In four areas, the spacing between flight lines exceeds three km. In these areas the frequency content of the mapped data is lower than that of the true magnetic field at this elevation, and anomaly shapes may be somewhat incorrect.

Several major west and west-northwest trending structures can be inferred from the contour map. Positive magnetic sources, 4 to 20 sq km in aerial extent, suggest major volcanic-intrusive complexes. Some of the more prominent sources occur at the eastern end of Laguna Cuitzeo, north of Presa Pucuato, near Mesa El Cantor, and at Uripitio. Geothermal fields are associated with two of these large sources: Araro, southeast of the Cuitzeo source, and Los Azufres. The volcano San Andres, less than 400 m below the flight altitude, occurs as a positive magnetic anomaly with amplitude 300 nT above background. The inferred source position includes an area of approximately 12 sq km, much of which is above 3000 m in elevation.

The low-frequency magnetic anomalies, and the magnetic sources which can be inferred from these anomalies, form a large somewhat-circular area perhaps 25 km in diameter in the southeastern portion of the survey area. Any interpretation relating this near-circular appearance to a caldera complex will require more interpretation and considerable geologic input.

The only specific interpretation of the high-altitude data reported here is first-pass modeling of a low-amplitude positive anomaly which encompasses 20 sq km and is centered over the Los Azufres geothermal area. A simplified model of this source (Figure 2) corresponds to the broad magnetic source identified from the low-altitude survey which includes the Los Azufres geothermal system. The interpreted susceptibility contrast for this body, contrasted with bordering, less magnetic blocks, is approximately 1000 E-6 cgs, assuming a finite depth extent of the order of 2300 m, for this magnetization contrast. This may relate to a thicker section of andesites downfaulted with respect to surrounding dacites, rhyolite domes and other rocks and/or intrusive rocks beneath the andesite units.

CONCLUSIONS

The high-altitude aeromagnetic survey maps an arcuate area of over 500 sq km which includes several large magnetic sources suggestive of volcanic-intrusive complexes. One of these sources includes the entire area of the Los Azufres geothermal system. This source is bordered on three sides by major mapped faults. The positive magnetic source may correspond to a thicker section of Mil Cumbres andesites, and/or intrusives at depth, and contrasts with rhyolite and dacite domes to the west and east. Several regional structures may be inferred from this survey but they have not yet been studied in detail.

On the basis of the preliminary interpretation, it appears that the low-altitude survey is only partially successful for reflecting the known geologic characteristics at Los Azufres, but contributes indications of a regional kind which shed new information and permit making hypothesis for later studies. The most important are the possible relation of the Los Azufres volcanic complex with the intersection of a NW-SE structural system (Basing and Range?) with more recent E-W structures. These data also suggest that the hydrothermal alteration observable at the surface is largely restricted to shallow units and decreases notably with depth.

The detailed, low-level magnetic survey shows numerous linear magnetic trends and discontinuities not present on the high altitude data, at least 18 of which correlate with mapped faults and other probably structures. Several mapped faults may be extended with an interpretation of the magnetic data, and more than 12 previously unmapped structures are interpreted from these data. Some of these structures may be important to a better understanding of structural controls for the South Production Zone. With more study, this structural information will lead to a better understanding of this fracture-controlled geothermal system. The cost-effectiveness of the regional survey is still being evaluated.

Magnetic surveys of similar structurally controlled volcanic geothermal systems should utilize a close flight line spacing (200-300 m) and a smoothly draped flight path somewhat higher than the minimum and mean terrain clearance of this survey. Depending on local relief and helicopter performance, a mean terrain clearance of 100 to 200 m should be considered.

Further interpretation of the detailed survey may benefit from low-pass digital filtering to reduce noisy data due to varying terrain clearance and flight-line position errors. Additional numerical modeling of the geothermal area should then be completed. Numerical modeling and structural interpretation of the high-altitude survey can be completed on a lower priority basis.

ACKNOWLEDGEMENTS

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ILLUSTRATIONS

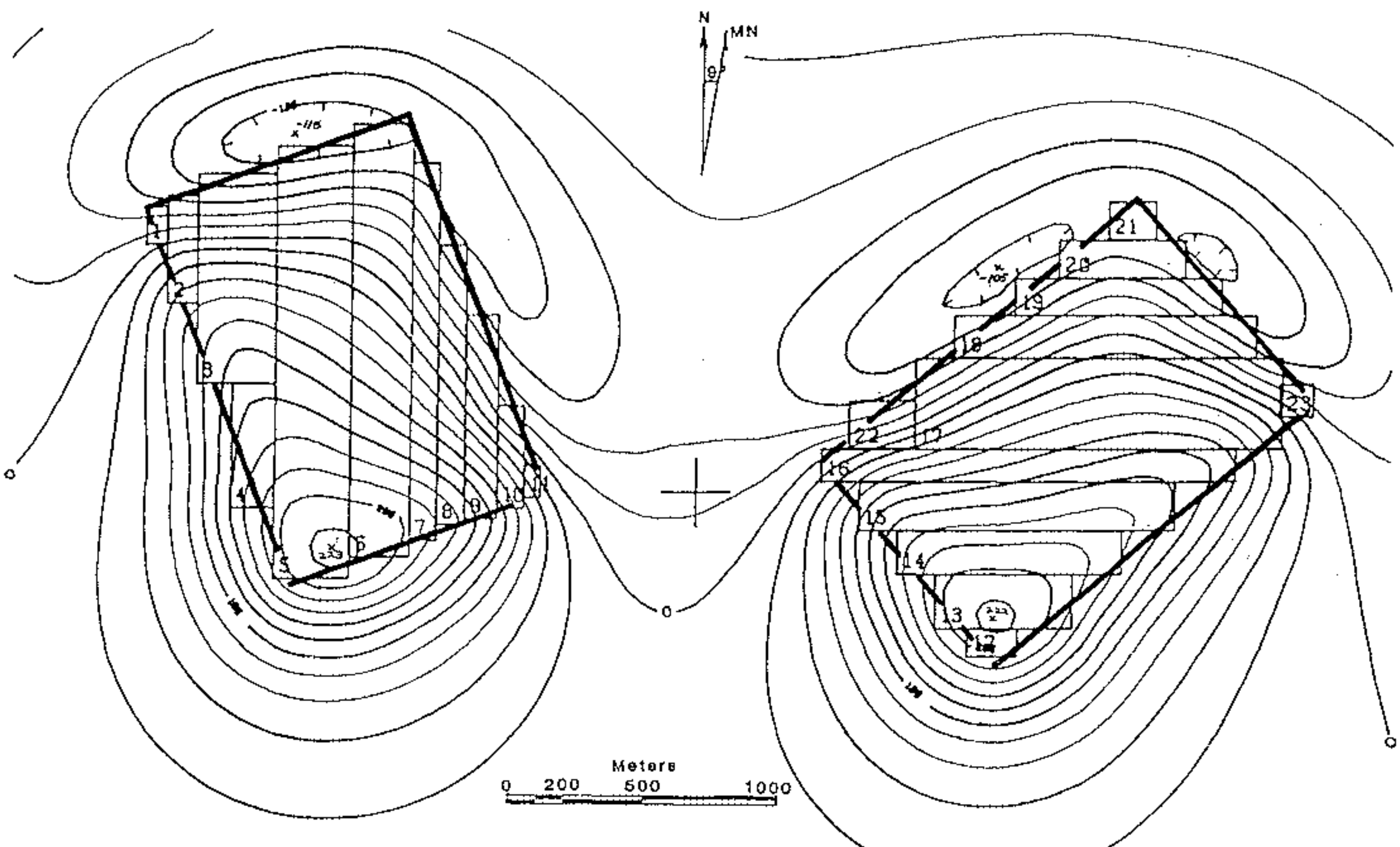

Figure 1. Characteristic magnetic model responses, Los Azufres, Michoacan area. Rectangular bodies 1 x 1.5 km trending N20W and N50E. Susceptibility contrast 0.002 cgs, depth to top 200 m, thickness 600 m. Declination 9°E, inclination 48°. TF=42,740 nT. Contour interval 20 nT.

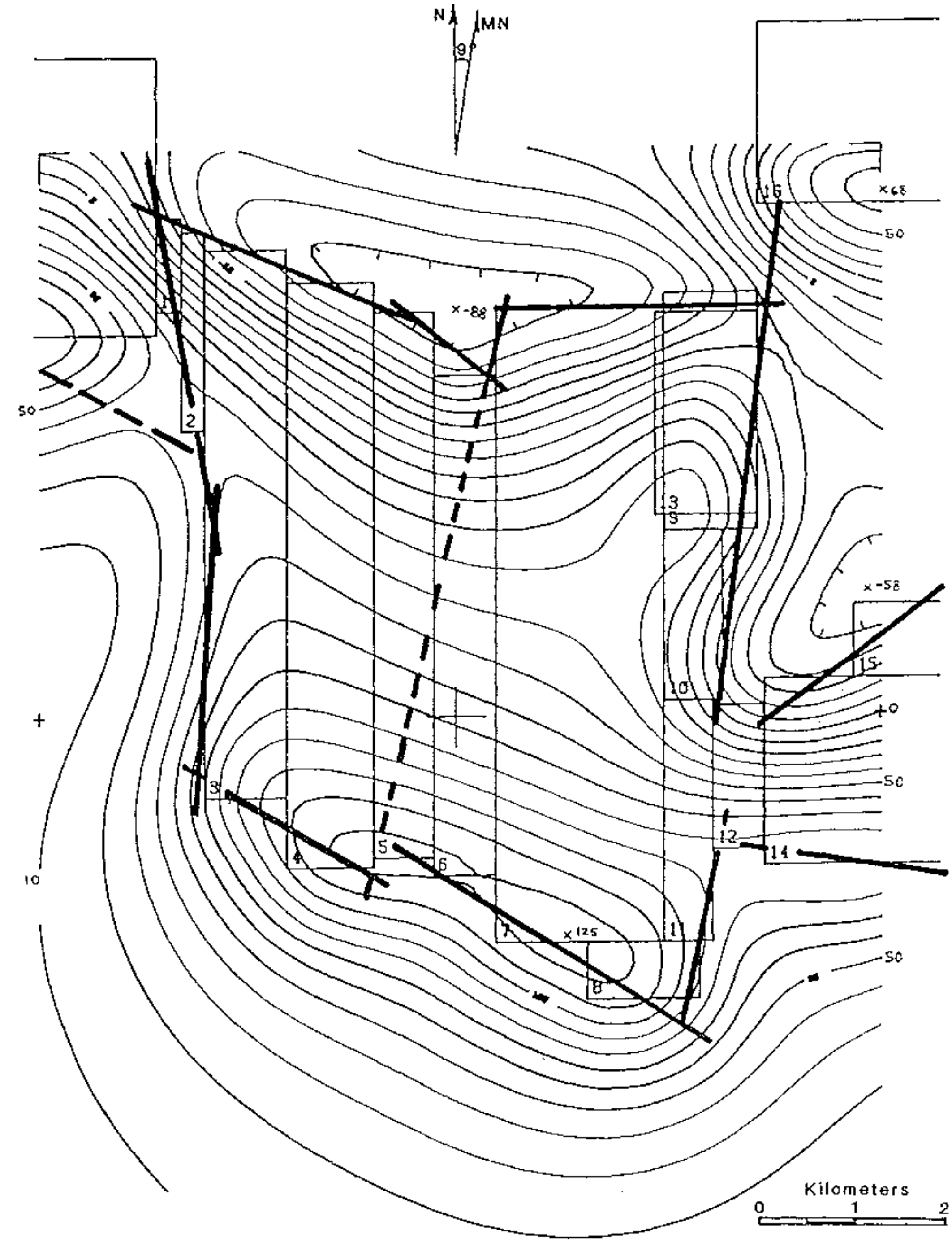

Figure 2. Preliminary magnetic model for Los Azufres geothermal area, from high altitude data. Major source body with susceptibility contrast 0.001 cgs, outcropping, with thickness of 2300 m. Body borders are probably defined by regional structures. Contour interval 10 nT.