# GEOFISICA INTERNACIONAL

REVISTA DE LA UNION GEOFISICA MEXICANA, AUSPICIADA POR EL INSTITUTO DE GEOFISICA DE LA UNIVERSIDAD NACIONAL AUTONOMA DE MEXICO

Vol. 24 México, D. F., 1o. de octubre de 1985 Núm.4

## *FIRST ESTIMATIONS OF TERRESTRIAL HEAT FLOW IN THE TMVB AND ADJACENT AREAS BASED ON ISOTOPIC COMPOSITION OF NATURAL HELIUM*

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RESUMEN

El Cinturón Volcánico Transmexicano (CVM) es la zona que en la actualidad presenta la mayor actividad volcánica en la región sur de México. En este trabajo se emplea un método no tradicional para calcular el flujo de calor por medio de la razón de $^{3}He/^{4}He$ en gases de origen geotermal. Los datos obtenidos trazan los principales sistemas volcánicos y los límites del CVM .

ABSTRACT

The Transmexican Volcanic Belt is the most active zone of recent volcanism in Southern Mexico. However, only a few heat flow data have been collected in the region. In the present work a non-traditional approach is used to calculate terrestrial heat flow by means of the $^{3}He/^{4}He$ ratio in gases of geothermal origin. The data obtained delineate the main volcanic systems of the Belt and its limits.

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## INTRODUCTION

México has achieved considerable progress in the development and use of geothermal resources. The first geothermal power plant at Cerro Prieto produced industrial energy as early as 1971. In November 1983, the installed capacity of this plant was of 180 MW and is planned to bring it up to 520 MW by the end of 1985. Cerro Prieto is located at the junction of the Californian segment of the oceanic rift and the structures of the American continent along the San Andrés-San Jacinto fault systems. However, most manifestations of recent geothermal activity are concentrated in the Transmexican Volcanic Belt (TMVB), which crosses the country along 20°N from the Pacific Ocean to the Gulf of Mexico.

The TMVB is traced by the Plio-Quaternary volcanics and is considered as the most recent geological feature superimposed on older structures which are mainly composed of volcanic rocks too (Demant, 1978; Negendank *et al.*, 1982). The TMVB encompasses many local geothermal anomalies. Most of the active stratovolcanoes of Mexico are situated here as well as a host of recent monogenetic scoria cones. A great number of hot and warm springs are discharged within the TMVB and in adjacent areas. Three large high-temperature hydrothermal systems stand out particularly sharp against this background because of their sizes and thermal potentials: Los Humeros, Los Azufres and La Primavera. These systems are intensively studied now by means of drilling, geological, geophysical and geochemical methods. Some other areas of hydrothermal discharge (Pathé, Ixtlán de Los Hervores and San Bartolomé) have also been studied partly by shallow wells, hydrogeochemical sampling, geoelectrical and geotemperature surveys.

However, the background conductive heat flow, which is the most important component of the geoenergetic budget, has hardly been studied in this part of Mexico. There have been only 8 measurements of this parameter along the 99.5°W longitude profile from the Pacific Ocean to approximately 100 km north of Mexico City (Blackwell *et al.*, 1977). According to the work cited, within the TMVB the terrestrial heat flow values average about 100 $mW/m^2$, whereas the low heat flow zone is located between the edge of the TMVB and the Pacific Coast, where a minimum surface heat flow average value of 30 $mW/m^2$ was obtained.

The determination of heat flow values and the elucidation of their spatial pattern are very important to solve both the basic problems of geodynamics and the task of

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locating the most favorable areas for prospection and use of geothermal resources. But the evaluation of terrestrial heat flow in the traditional way (through the determination of geothermal gradient and thermal conductivity of rocks) is very difficult in the TMVB region because of the lack of deep drill-holes outside of the prospected hydrothermal systems, which are the thermal anomalies. Therefore, in the framework of the Mexican-Soviet scientific-technological cooperation, a project has been undertaken to estimate the background heat flow in the TMVB and adjacent areas by means of a new approach developed in the USSR. This approach is based on the study of the isotopic composition of helium contained in underground fluids.

## RELATION BETWEEN HELIUM ISOTOPIC COMPOSITION AND HEAT FLOW

Studies of underground fluids carried out in the USSR showed that within a single geotectonic unit, these fluids contain helium with identical isotopic composition, i. e., with a constant value of $R = {}^3He/{}^4He$ (Polak *et al.*, 1979). In this respect the fluids of any type are uniform independently of their general hydrochemical and other peculiarities (Kamensky *et al.*, 1976; Polak *et al.*, 1976; Matveeva *et al.*, 1978). The comparison of the R values that characterize the different tectonic structures showed a general relation between the helium isotopic composition and the age of tectono-magmatic activity in the regions studied: the younger this activity, the greater the values of R. Heretofore, an analogous trend was established for the heat flow variations on the continents (Polak and Smirnov, 1968). The comparison of these parameters (heat flow and helium isotopic composition), using their values measured in the USSR (Polak *et al.*, 1979), showed a correlation between them, which may be approximated by the following equations within certain limits:

$$R = e^{6q-5.3} \quad (1)$$

$$\text{or: } q = 0.166 \ln R + 3.95 \quad (2)$$

where q - background heat flow density* given in "Heat Flow Units" (HFU = 1 x $10^{-6}$cal/s·cm² = 41.868 mW/m²). Such an approximation allows to estimate heat flow values from the helium isotopic composition in underground fluids in regions where there are no drill holes.

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* The term heat flow density is used to denominate the magnitude of terrestrial heat flow in accordance with the decision of the International Heat Flow Commission, Liblice, 1982.

The validity of this approach was tested by special studies carried out in Czechoslovakia where heat flow is well known. "Isotope-helium" based heat flow values agree well with those obtained by the traditional method (Polak *et al.*, 1982 (a)). This relation was confirmed by Japanese scientists who studied methane-rich gases in Honshu island (Sano *et al.*, 1982).

The concepts behind the relationship between terrestrial heat flow and helium isotope composition are considered in detail by Polak *et al.* (1979) and Polak and Tolstikhin (1985). They showed that this correlation is caused by the participation of heat-mass flux from the mantle in the creation of the continental crust. The correlation of these parameters is the result of the combined effect of the cooling of mantle material transported to the Earth's surface, and of the gradual substitution of mantle helium ($R_m \simeq 10^{-5}$) by radiogenic one ($R_r \simeq 10^{-8}$). Since the regression equation (eq. (1), (2)) was obtained on data from a vast territory of Northern Eurasia, it must be of global character. Therefore it is reasonable to use the corresponding regression equation (eq. (2)) for the estimation of heat flow in the American continent as well. With this aim in mind, 26 samples of gases contained in thermal fluids were collected from 22 areas of hydrothermal discharge in Southern Mexico during two field trips (November-December, 1979 and March-April, 1982).

## ANALYTICAL METHODS

The samples under study are gases bubbling through water of thermal springs or included in a steam-water mixture emitted from a drill hole. These gases were collected by the water displacement technique with inverse funnel.

A combination of volumetric and mass spectrometric techniques was used to study abundance and isotopic compositions of noble gases in each sample. Pre-cleaning of samples was made by two Ti-getters in order to absorb the active gases. Noble gases were subdivided by activated charcoal at a temperature of $-196^{\circ}C$ into two fractions, He + Ne and Ar + Kr + Xe, collected in separate glass ampules. The amount of each fraction was determined volumetrically with an experimental error of 3-10% at $1\sigma$. The He/Ne, Kr/Ar and Xe/Ar ratios were measured with a mass-spectrometer (experimental error is 10% at $1\sigma$), the atmospheric noble gases being used as a standard. The measurements of abundances and isotopic compositions of noble gases enable us to determine fractions of atmospheric noble gases in the samples. Based on these data the $^3He/^4He$ ratio can be calculated for non-atmospheric

He. The procedure of such calculations was described earlier (Kamensky *et al.*, 1976; Mamyrin *et al.*, 1969, and the review by Mamyrin and Tolstikhin, 1984). The magnitude of correction for the admixture of atmospheric He is negligible in most samples. Data on abundance and isotopic composition of all noble gases are not presented in this paper; they will be discussed in detail in future publications.

The $^3He/^4He$ values obtained were used to estimate the density of terrestrial heat flow in the sampling points according to the equation given above (eq. (2)). This equation corresponds to the regression line obtained by statistical treatment of the data known until 1979. Continuous accumulation of data changes slightly the numerical expression of the relationship established, but the difference between heat flow estimations for the same R values does not exceed 10% and it is usually less. In connection with this, it is worthwhile to remember that experimental error of determination of the heat flow density by the traditional method is usually evaluated as ± 10%. Therefore the $q_R$ values can be considered as a quite satisfactory approximation to reality.

## RESULTS

The results of isotopic analysis of helium and the calculated heat flow density are given in Table 1. When comparing both parameters, it can be observed that their variability in the regions under study is very different: the R values vary about a factor of 20, while the heat flow values vary no more than 30%. It demonstrates the high sensitivity of helium isotopic composition as an indicator of geothermal activity. The calculated $q_R$ values agree with the background heat flow values obtained in other volcanic belts of the globe (Polak and Smirnov, 1968; Uyeda, 1972; Smirnov, 1980).

It is the background (regional) heat flow that is characterized by the calculated values, although the analyzed samples were collected in local positive thermo-anomalous areas caused by hydrothermal discharge. As it is known, the specific heat output within such areas is 1-3 orders of magnitude higher than the background heat losses of the Earth, and the conductive heat flow is sharply disturbed by water circulation, not corresponding with the background (regional) value out of anomalous areas. Besides water circulation, there are many other factors that influence the estimations of heat flow by the traditional method. These are: *i)* topography, *ii)* climate variations (changes of surface temperature connected with glaciation, etc.), *iii)* the morphology of geological bodies having a contrasting thermal conductivity,

TABLE 1

Isotopic composition of helium and terrestrial heat flow in the TMVB and adjacent areas

| N N points on Fig.1 | N N samples | Thermal manifestation | $R = \frac{^3He}{^4He}$, x $10^6$ X (see footnotes) | Heat flow values calculated from R (see text) | |
|---|---|---|---|---|---|
| | | | | HFU | mW/m$^2$ |
| 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | 7901 | Azufres Alcaparroza (Cuatelolulco) | 8.8 (3)[1] | 2.01 | 84.2 |
| | 7902 | Los Azufres, Barranca del Agua Fría | 7.1 (2)[2] | | |
| | 7904 | Los Azufres, P. # 6 | 8.3 (2) | | |
| | 8203 | Los Azufres, P. # 6 | 9.5 (3) | | |
| | 8204 | Los Azufres, P. # 1 | 8.2 (2) | | |
| 2 | | mean value for Los Azufres | 8.3[3] | 2.01 | 84.1 |
| 3 | 7905 | Araró | 6.3 (2)[4] | 1.96 | 82.0 |
| 4 | 7906 | Ixtlán de los Hervores | 5.6 (2) | 1.94 | 81.5 |
| 5 | 7907 | Hervores de la Vega | 1.85 (2) | 1.76 | 73.6 |
| 6 | 7908 | Comanjilla | 0.85 (2) | 1.63 | 68.2 |
| 7 | 7909 | San Bartolomé | 2.3 (2) | 1.79 | 75.2 |
| 8 | 8201 | Ajacuba | 4.1 (3) | 1.89 | 79.1 |
| 9 | 8202 | Ixtapan del Oro | >9.0 (2)[5] | >1.99 | >83.2 |
| 10 | 8205 | Puruandiro | 4.0 (2) | 1.89 | 78.9 |
| 11 | 8206 | La Huacana | 3.2 (2) | 1.85 | 77.4 |
| 12 | 8207 | La Primavera, P. # 1 | 8.6 (4) | 2.01 | 84.3 |
| | 8208 | Barreno El Rancho | 7.2 (2)[6] | | |
| | 8209 | San Marcos | 4.2 (3) | | |

and *iv)* neotectonic movements accompanied by sedimentation in subsided blocks and erosion of uplifting ones. Therefore, the "observed" values of heat flow density determined by the traditional methods in the uppermost part of the Earth crust al-

Cont. Table 1

| 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| 13 | | mean value for San Marcos-Barreno el Rancho | 5.7 | 1.94 | 81.4 |
| 14 | 8210 | Agua Caliente de Colima | 5.6 (2) | 1.94 | 81.3 |
| 15 | 8211 | Agua Caliente del Molote | 4.4 (2) | 1.90 | 79.6 |
| 16 | 8212 | Volc. Ceboruco | 7.9 (3)[7)] | 1.96 | 82.2 |
| 17 | 8214 | Lourdes | 4.6 (2)[8)] | 1.91 | 80.0 |
| 18 | 8215 | Agua Hedionda | 3.5 (2) | 1.86 | 78.1 |
| 19 | 8216 | Agua Caliente "El Tamarindo" | 0.52 (2) | 1.55 | 64.8 |
| 20 | 8217 | Agua Caliente "Guerrero" | 0.62 (1) | 1.58 | 66.0 |
| 21 | 8219 | Los Humeros P. # 1 | 8.9 (2) | 2.02 | 84.6 |
| 22 | 8220 | Estación "El Carrizal" | 3.2 (2) | 1.85 | 77.4 |

low the estimation of background (or deep) heat flow only if the influence of all disturbing factors has been quantitatively accounted for. In many cases, however, it is quite difficult to estimate precisely this influence. Fortunately, such disturbing factors practically do not influence the isotopic composition of helium contained in thermal fluids. The large amount of data used in the statistical analysis of the relation between q and R compensates the opposite influences of the above mentioned factors in different regions. Therefore, using the numerical expression (eq. (2)), it is possible to obtain estimations which are nearer to the regional mean of heat flow density (i.e., "deep" values of this parameter) than its individual determiation by the traditional method.

## DISCUSSION

The location of the points of geochemical sampling for determining "helium-isotope" estimations of heat flow is shown in Fig. 1. Comparison of these data with the geological map of Mexico (López-Ramos and Sánchez-Mejorada, 1976) shows that the highest $q_R$ values (greater than 80 mW/m²) trace out the Transmexican Volcanic Belt, i.e. the main zone of location of Upper Pliocene-Quaternary volcanics ("Superior Volcánico"). The maximum $q_R$ values have been established in the most powerful hydrothermal systems: Los Humeros, Los Azufres and La Primavera (Table 1). This fact is not only of geological but of applied significance as well. It is remarkable that the $q_R$ value obtained in the Colima graben is as high as those in the TMVB (point 14). In the western part of the TMVB near the "Hervores de la Vega" hot springs (point 5) a local decrease of the $q_R$ value is observed. According to the geological map, the zone of location of recent volcanics is interrupted here by a zone of older volcanic rocks of Oligocene-Lower Pliocene age ("Medio Volcánico"). The spatial distribution of the available heat flow values enables us to assume the presence of less drastic geothermal minimae inside the TMVB, particularly in the Valle de México and to the west of Lago Cuitzeo. Yet, additional data are necessary to prove the existence of these minimae.

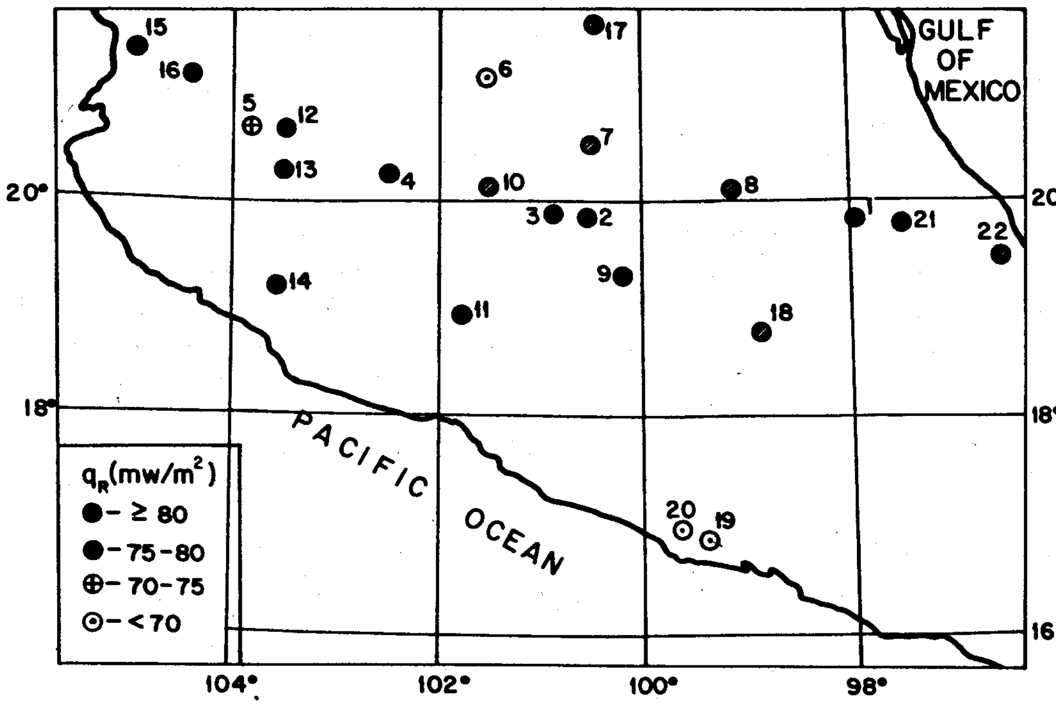


Fig. 1. "Helium" heat flow values in TMVB and adjacent areas. Circles denote the sampling points (see Table 1).

The "helium-isotope" values of heat flow on the periphery of the TMVB decrease as well as in the northern branch of "Superior Volcánico" (point 17). The same values established in the western-and easternmost sampling points may imply that the zone of maximum heat flow is closed in both directions. But this conclusion must be checked by further studies, because the "Estación El Carrizal" warm springs (point 22) are located in "Superior Volcánico" according to the geological map. On the contrary, the "Agua Caliente del Molote" hot springs (point 15) are located near the Jurassic intrusive massif and it is possible that the heat flow in this area is lower than in the zone of active volcanism.

Outside the TMVB a heat flow decreasing tendency is observed with increasing distance from the zone of "Superior Volcánico". This is evidenced by heat flow values at points 6 and 7 located in the area of "Medio Volcánico" between TMVB and its northern branch, and it is still more evident as the distance from the belt axis increases southwards. The minimum "helium-isotopic" values were obtained within Sierra Madre del Sur (points 19, 20) formed mainly by Paleozoic and Precambrian metamorphic rocks. In some places they are cut by Mesozoic intrusions. According to the general "heat flow-tectonic age" dependence, a heat flow minimum should be expected in this area.

## CONCLUSIONS

The pattern of heat flow distribution in Southern Mexico, which follows from the data on helium isotopic composition generally agrees with the inferences based on a few traditional determinations of this parameter (Blackwell *et al.*, 1977) although the numerical values in that work are somewhat different. It is interesting to point out the good agreement between values and distribution patterns of heat flow in the studied parts of Mexico and Honshu island (Japan), where the maximum values of q and R trace active volcanic belts, whereas the minimum values of both parameters are observed in older formations near the oceanic trench (Uyeda, 1972; Nagao *et al.*, 1981; Sano *et al.*, 1982).

Summing up, we can conclude that the present "helium-isotopic" heat flow estimations agree well with the geological setting in Southern Mexico, as well as with the global geothermal regularities. In order to refine the heat flow pattern in this area, the hydrogeochemical sampling was continued during November, 1983, within the TMVB and in adjacent areas including the southern part of the Sierra Madre Occidental as well as the Sierra Madre Oriental. Eighteen new samples were collected in thermal springs, and several control samples were collected again from a few points. Coupled with the data presented in this paper, they will enable us to elaborate an estimated heat flow map for the southern part of Mexico.

The study of noble gases has many applications and the "helium-isotope" estimation of terrestrial heat flow is only one of them. As it is known, the helium isotopic composition gives us very important information concerning mantle degassing (see the review by Mamyrin and Tolstikhin, 1984) and the origin of hydrothermal systems of different types (Kononov and Polak, 1975; Kononov, 1983). An integral study of concentrations and isotopic compositions of all noble gases enables us to identify the atmospheric component in thermal fluids and to estimate the probability and degree of their preceding sub-surface degassing. From this point of view the results obtained have already been partly discussed by Polak *et al.* (1982b) and Prasolov *et al.* (1982.) Such researches will be continued and described in further papers.

ACKNOWLEDGEMENTS

We wish to thank CONACYT, Instituto de Geofísica (UNAM) and Comisión Federal de Electricidad (México) for their logistic support. We are grateful to Drs. I. N. Tolstikhin and I. L. Kamensky for assistance in analyzing the samples and helpful discussion of the data. Mr. Gerardo Juárez M. is acknowledged for his assistance in the preparation of the English version of this paper. We are also indebted to two anonimous reviewers for critical comments and suggestions concerning some improvements which were accepted by us with sincere gratitude.

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* Asterisks denote works published in Russian.

*(Received: January 26, 1984)*
*(Accepted: October 22, 1984)*

It is recommended that reference to this paper be made as follows:

B. G. Polak, V. I. Kononov, E. M. Prasolov, I. V. Sharkov, R. M. Prol-Ledesma, A. González, A. Razo y R. Molina-Berbeller. First estimations of terrestrial heat flow in the TMVB and adjacent areas based on isotopic composition of natural helium. *Geofis. Int.* Special Volume on Mexican Volcanic Belt - Part 2 (Ed. S. P. Verma), *Vol. 24*-3, pp. 465-476.