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A PRELIMINARY THERMAL MODEL OF THE MEXICAN SEISMOVOLCANIC BELT AS A RESULT OF SUBDUCTION

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RESUMEN

Se desarrolla un modelo término de la faja volcánica mexicana. Los datos geofísicos y los datos geológicos se toman en cuenta en el desarrollo de este modelo (generación de calor, flujo de calor, volcanismo, patrón de falla y parámetros geométricos de la supuesta zona de Zavaritsky-Benioff) y además se supone una fuente adicional de calor debida a fricción.

Se introduce en la discusión un transporte de calor efectivo e incrementado de acuerdo con la región estudiada altamente fracturada.

Con el empleo de este modelo puede determinarse la distribución de la temperatura según el flujo calórico profundo y superficial. El perfil calculado para Acapulco-Tuxpan muestra que el flujo de calor aumenta desde un valor muy bajo (33.3 mW/m^2) cerca de la trinchera, hasta valores de 58.2 mW/m^2) en las áreas geotérmicamente activas y hasta 108 mW/m^2, en la región de reciente volcanismo.

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ABSTRACT

A two-dimensional numerical thermal model of the Mexican Volcanic Belt (MVB) is developed. In this model geophysical and geological data are taken into account (heat generation, heat flow, volcanism, fault pattern and geometrical parameters of the assumed Zavaritskiy–Benioff zone), and an additional heat source due to friction is assumed.

An increasing effective heat transport is introduced, coinciding with the observed highly faulted region.

Using this model the temperature distribution with depth and surface heat flow are determined. The calculated profile Acapulco-Tuxpan shows that heat flow increases from a very low value (33.3 mW/m^2) near to the trench, to values of 58.2 mW/m^2 in the geothermally active areas, and 108.2 mW/m^2 in the region of recent volcanism.

INTRODUCTION

Data on deep seismicity distribution, focal mechanisms, volcanism geothermal activity and geomorphology for the MVB suggest that a downgoing slab structure exists between the Cocos and North-American plates (Molnar and Sykes, 1969). This structure may be related with the remnants of the Farallon plate (Atwater, 1970), a large plate that subducted the American plate and broke when its rift colided with the continent. The Cocos plate is assumed to be thrusted down by the Caribbean and North-American plates, and the observed geothermal and volcanic manifestations in the MVB zone seem to be related to the subduction process (Turcotte and Oxburgh, 1969). Nevertheless, until now no quantitative thermal analysis has been made, which could support the assumption of the island-arc structure of the MVB, in this paper an attempt is made to give such a thermal model.

GEOPHYSICAL AND GEOLOGICAL EVIDENCES

The MVB is located in the central part of Mexico (Fig. 1), between 19° and 20° N (Mooser, 1972) in the same direction of the Clarion fault system.

In the Pacific Ocean, at approximately 75 km from the west coast of Mexico, the Central-American trench is located; in the part we study it is called Acapulco Trench and has a maximum depth greater than 5000 m (Fisher, 1961). Topographic (Fisher, 1961) and reflection (Ross and Shor, 1965) profiles in the eastern part of the Pacific Ocean show that the trench bottom relief is smoother in the northern part than in the southern, so to the north from the Tehuantepec Ridge the trench may be older than to the south, where the rift walls are very steep and the bottom has a very thin sediment cover, it may be due to high tectonic activity in this region of the trench. Hereafter it is possible to define this southern region as a typical island arc (Turcotte and Schubert, 1973), the Zavaritskiy-Benioff (Z-B) zone here is more clearly located, seismicity is not so diffusive and volcanism is concentrated in a belt, parallel to the trench axis.

In the MVB the following active volcanoes are located: Ceboruco, Colima, Paricutín, Jorullo, Popocatepetl, Pico de Orizaba and Tuxtla (Fig. 1). Their location is closely related to the fault pattern of the region. These faults form two systems almost perpendicular to each other, with direction NW-SE and SW-NE. Satellite images data indicate that the volcanoes and geothermal fields are located in the crossing points of the faults (Del Río, in prep.).

Seismic activity shows maximum values of 6-7 degrees for magnitude of earthquakes and 200-300 km for focus depth. Molnar and Sykes (1969) calculated focal mechanisms for 21 earthquakes in the Middle-American Arc region, northwest of the continental extension of the Cayman Trough. Results for 16 of them indicate that Cocos place underthrusts the North American plate with a direction between N35°E and N45°E. Nevertheless, the Z-B zone has very particular features, that have not been explained because data are insufficient. Hanuš and Vaněk (1977) used seismological data and proposed mean values for geometrical parameters of the subducting plate in the zone located between 11°–21°N and 90°–110°W, and assumed that the maximum depth reached by the cold slab is 300 km, they proposed that the dip-angle changes from approximately 20° in the northern part to 45° to the south from the Tehuantepec ridge. Several calculations of the subduction rate have been made that yield values of 1.5-2, 4-5 and 10 cm/yr (Molnar and Sykes, 1969).

Large gravity anomalies are associated with island-arc structures, free-air anomalies are located on the trench axis and Bouguer anomalies are related with the volcanic areas (McKenzie *et al.*, 1973). Gravimetric profile Acapulco-Tuxpan shows that the Bouguer anomaly reaches a value of -200 mgal on the MVB region (Monges and Mena, 1973).

In the region occupied by the MVB there are numerous geothermal fields with hot springs that have water temperature from 140°–300°C, as in the fields of Tula, Los Hervores, Los Negritos, Agua Caliente, Ixtapan and Los Azufres, where the temperature reaches 300° C at a depth of 1500 m, and it is planned to use these hot springs to obtain electricity, as in the field "Cerro Prieto" in northern Baja California, Mexico, where a geothermoelectrical station with power 140 MWatts is successfully working.

In the oceanic regions of the ABCDE profile (Fig. 1), heat flow has approximately the same value as in the Acapulco trench (33.3 mW/m^2) (McKenzie and Sclater, 1969), and it has been observed by recent measurements (Blackwell *et al.*, 1977) that in the continent heat flow increases with distances from the trench axis from a value of 33.3 mW/m^2 at Tierra Colorada to 100 mW/m^2 at 300 km from the trench axis.

PARAMETERS

Let us consider a transversal section of the MVB approximately perpendicular to the trench axis, in Fig. 1 it is denoted as ABCDE. We chose that profile because it intersects the MVB, near the active volcano Popocatepetl, and the gravity anomalies profile and some heat flow data are known (Monges and Mena, 1973; Blackwell *et al.*, 1977). The profile begins in the Pacific Ocean, at 400 km west from the trench axis goes through Acapulco and Tuxpan and ends in the Gulf of Mexico at 180 km from the coast, thus right and left boundary conditions (points A, E) are approximately equivalent, and for these we use the mean oceanic temperature distribution with depth, as given by Fujisawa (1968), at 500 km depth the temperature equals 1400° C.

The heat generation in the upper part of the continental crust was determined from the mean concentration of the radioactive elements (U, Th, K) observed in rocks from the south of Mexico (Pal *et al.*, 1976): U–1.17-2.42 ppm; Th–5.45-7.97 ppm; K–1.23-191%: thus heat generation in the upper part of the continental crust has values between 0.93-2.03 W/m^{-3}. In the model mean values are used for the heat generation (H) and the thermal conductivity (λ): $\lambda_1 = 2.5$ W/m K, $H_1 = 0.46$ $\mu W/m^3$; $\lambda_2 = 3.4$ W/m K, $H_2 = 0.1$ $\mu W/m^3$ and $\lambda_3 = 4.2$ W/m K; $H_3 =$

0.1 $\mu W/m^3$, for the oceanic crust, oceanic lithosphere and astenosphere respectively (Hasebe *et al.*, 1970, Minear and Toksöz, 1970).

An additional heat source due to friction is assumed in the upper surface of the subduction slab (McKenzie and Sclater, 1968). A constant heat generation is considered to a given depth, then the value of viscosity suddenly decreases when melting temperature is reached, hereafter heat generation is assumed to decrease to a much lesser value. So we divided the assumed friction zone in two sections parallel to the slab and located on its upper surface with an upper section with thickness 10 Km from 100 to 180 Km depth with high heat generation as calculated for instance by Hasebe *et al.* (1970): 6:24 $\mu W/m^3$; and a lower section with heat generation approximately 10 times less than the upper one.

The cold subducting slab is modelled as a heat sink, so we introduced heat absorption in the region occupied by the slab, with a value of -0.65 $\mu W/m^3$. Assuming that the cold slab absorbs heat, it is possible to study how it perturbes the upper mantle thermal region.

A special characteristic of our model is the assumption of a high value for the heat transfer by mass-transport, that is represented by a high effective thermal conductivity, that has a value of 42 W/m K, approximately 10 times larger than that in the asthenosphere. The high thermal conductivity zone is located in highly faulted regions of the lithosphere, over partially molten areas of the asthenosphere to represent the heat transfer due to the ascending movement of the magma through the fractures.

NUMERICAL MODEL

As a first approximation one can consider the temperature field as quasistatic. Thus the elliptical differential equation in finite differences form is simpler and the boundary conditions are of the first type (Tikhonov and Samarskiy, 1972). The lithosphere is assumed to have upper and lower boundaries given by the isotherms T_i $(i = 1, 2)$ that represent piece-wise continuous surfaces. The linear temperature distributions for points A and E of the profile in the oceanic lithosphere are solutions of the border differential equation: $\frac{d}{dy} \cdot \lambda \frac{dT}{dy} = -f$ for the above mentioned border conditions at the upper and lower boundaries.

Attention is mainly paid to the temperature distribution with depth and horizontal distance, and to the surface heat flow in the subduction zone. It has been shown that to solve this problem it is possible to use the finite difference method (Lubimova and Luboshits, 1975; Lubimova *et al.*, 1976; Luboshits, 1976, 1978). When using exact boundary conditions and after 64 steps on each direction the error in the calculated value for q by the Runge's principle (Berezin and Zhidkov, 1962) is less than 0.5%.

The calculations were made using a net $79h_x \times 50h_y$, where the horizontal step $h_y = 20$ km and the vertical step $h_y = 10$ km, thus the angle of the diagonals coincides with the dip of the descending slab: approximately 23°. Calculations were carried out for different parameters sets, and the best correlation was obtained using the parameters presented below. The MVB geothermal section is represented by a horizontal layered section (H) with local buried bodies (L). The parameters λ and f for the layers, normalized to the asthenosphere parameters given in section 3 are expressed as: $\lambda^H_1 = 0.59$, $f^H_1 = 44$; $\lambda^H_2 = 0.80$, $f^H_2 = 40$; $\lambda^H_3 = 1$, $f^H_3 = 2$, and the layer thickness is given as $l_1 = 10$ km, $l_2 = 90$ km and $l_3 = 400$ km.

In the upper layer there is a buried rectangle with $\lambda^L_1 = 0.3$ and $f^L_1 = 100$.

In the middle layer, there are two buried rectangle with: $\lambda^L_{2,3} = 10$ and $f^L_{2\,3} = 40$.

The subduction zone is represented by two local intrusions, each comprises two zones with parameters: $\lambda^L_4 = 0.80$, $f^L_4 = -40$; $\lambda^L_5 = 0.59$,

$f^L_5 = 1000$; $\lambda^L_6 = 0.80$, $f^L_6 = -40$; $\lambda^L_7 = 0.59$, $f^L_7 = 100$.

RESULTS

Basic results, obtained using geophysical data for the MVB and surrounding regions are shown in Fig. 2, where temperature distribution for the inner section of the ABCDE profile and calculated surface heat flow are plotted.

Calculated heat flow has a minimum value of 33.3 mW/m^2 in the ocean, at the left side of the trench axis, and grows with distance from the trench axis in the continental side of the profile, reaching a value of 83.2 mW/m^2 on the hydrothermally active region Atotonilco, and a mean of 108.2 mW/m^2 in the quaternary volcanism region. Then heat flow decreases but still has a high value 74.9 mW/m^2 to a distance of 600 km from the trench axis in the hydrothermal area Zacatlán. Finally heat flow abruptly decreases to 4.16 mW/m^2 in the Gulf of Mexico.

Temperature distribution with depth shows the presence of a partially molten region with temperature greater than 1400°C in the asthenosphere, at 180 km under the quaternary volcanism region. As it is shown from seismological data, a low velocity layer (7.5 km/sec) has been discovered under the central part of Mexico (Shurbet, 1972), that is approximately located from 80–170 km depth. According to our calculated temperature distribution, the 1400°C isotherm ascends to a depth of 180 km, thus it yields a partially melted region coincinding with the data.

The subducting plate remains cold at deep regions; the 800° C isotherm descends to 280 km depth at a distance of 300 km from the trench, and the 600°C isotherm goes to a depth of 200 km in the cold slab and on the high conductivity zone it rises to less than 10 km depth. Thus the slab until that depth (280 km) maintains brittle properties, so it determines a maximum for deep earthquakes focus, as observed in the studied profile.

The 600°C isotherm behaviour shows the two different thermal regimes, typical of subduction zones. In the cold slab it deepens and ascends under volcanic areas. Analyzing the temperature distribution with depth (Fig. 3) it is clear the difference of the temperature variation with depth depending on the horizontal distance from the trench. These different thermal regimes determine zones appropriated for different metamorphic processes (Miyashiro, 1961; Oxburgh and Turcotte, 1971; Glebovitsky, 1973). From our results it yields that the glaucophan-schists metamorphism may occur up to a distance of 100 km from the trench, and the andalusite-sillimanite metamorphism only from 300 km. These results agree with the typical thermal regime for subduction zones.

DISCUSSION

Subduction mechanism has not been well explained. Particularly it is difficult to make a proper model for the friction zone between the subducting plate and upper mantle. The heat generated by friction has not been well determined, as it depends on parameters that are not easy to measure; it depends on stress, and the values of stress in subduction zones are calculated between 0-2.5 Kbar (Andrews and Sleep, 1974; Toksoz *et al.*, 1971), but it has been shown that to produce processes of dehydration and partial melting of the slab material, the stress has to reach values greater than 1 Kbar (Anderson *et al.*, 1976). Here we use this minimum value, but it will be possible to obtain better results using more accurate values from seismological data. Even if allowing the stress to have a fixed value the quantity of generated heat is not completely determined because it also depends on the width of the friction area, that usually is taken to be a constant (Turcotte and Schubert, 1973), but if it is allowed to vary, it has been obtained that its value grows with depth and depends on the initial temperature and the subduction velocity (Yuen *et al.*, 1978; Jischke, 1975); so it introduces large uncertainty to the value of the heat generated by friction, but the chosen value is justified by the results.

It is well known that very deep temperature anomalies cannot give the observed heat flow anomalies over subduction zones if heat is transported only by conduction (McKenzie and Sclater, 1968). So in our model we introduced a high effective conductivity zone of 140 km width, corresponding to the faulted region of the MVB (a, a' in Fig. 1). The parameters of this zone are very important in our model because they basically determine the large positive heat flow anomalies in the surface, and they are determined according to the fault pattern of the region.

CONCLUSIONS

The results obtained from the presented numerical thermal model of the MVB agree with the observed geophysical and geological data. It is shown that the calculated large positive anomalies of heat flow on the surface are related with observed geothermal and volcanic activity phenomena. The calculated temperature distribution with depth gives the location of zones with high and low relative temperature, coinciding with seismic waves absorption zones and low heat flow anomalies.

Surface heat flow and temperature distribution calculations were carried out on the described simple model for the assumed values for the parameters of: heat generation due to friction, heat absorption and effective thermal conductivity, and the obtained results agree reasonably well with the typical features of subduction zones.

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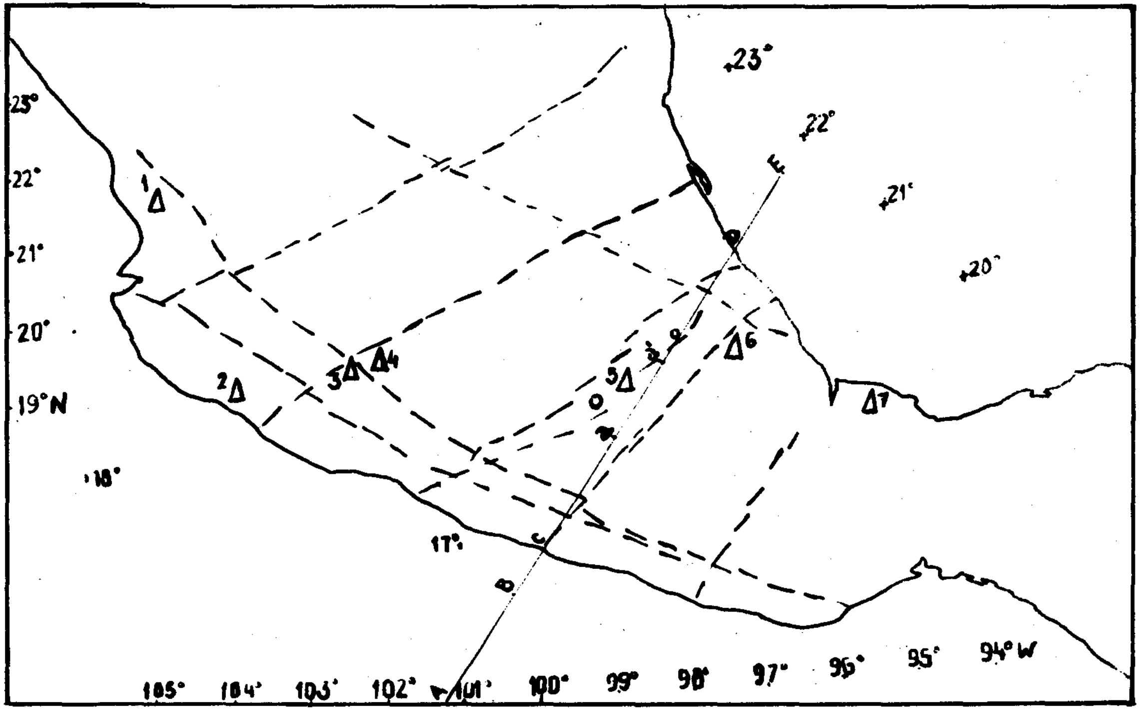

Figure 1. Location of the volcanoes and main faults (after Del Río, in prep.): 1) Ceboruco, 2) Colima, 3) Jorullo, 4) Paricutin, 5) Popocatepetl, 6) Pico de Orizaba, 7) Tuxtla. ABCDE – geothermal profile: A, E – left and right boundaries of the profiles; B – trench axis; C, D – coasts of the Pacific Ocean and Gulf of Mexico respectively. a-a′ high effective conductivity area.

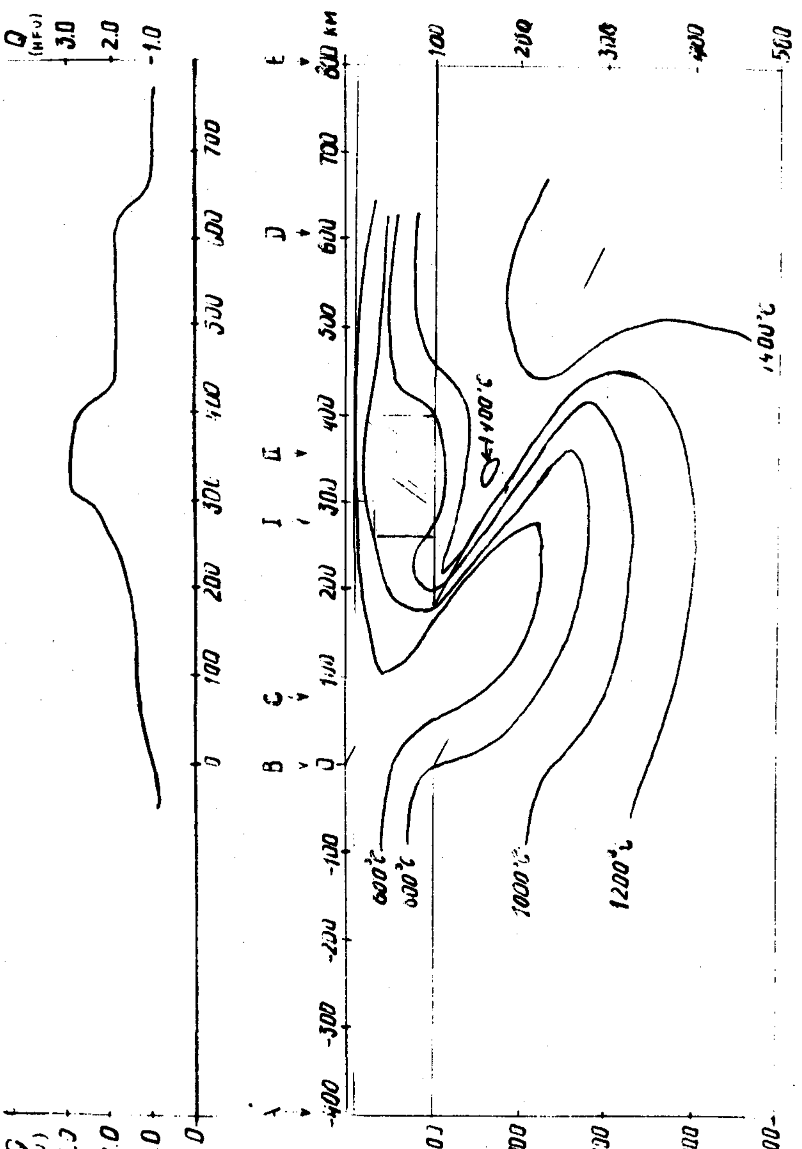

Figure 2. Calculated temperature distribution and surface heat flow through the profile ABCDE from Fig. 1. I – geothermal zone; II – active volcanism.

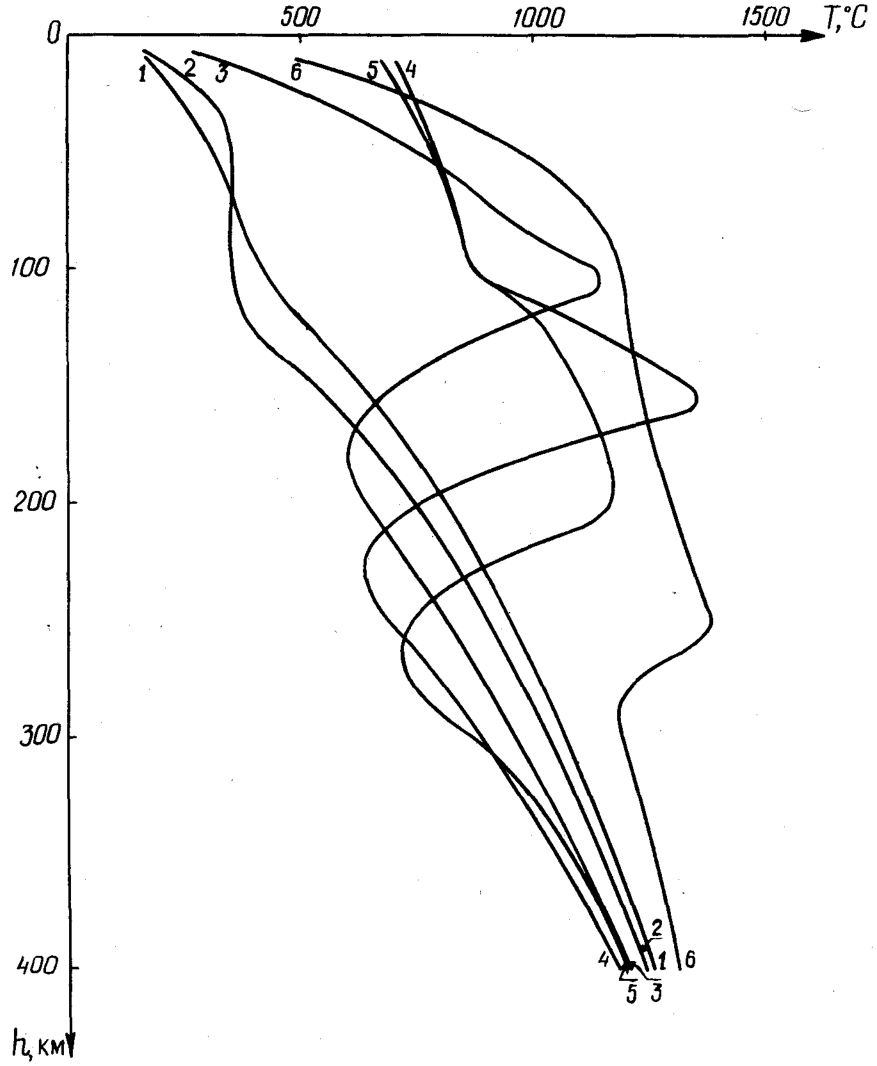

Figure 3. Graphs Tvsh for the calculated temperature distribution at different distances from the trench axis: 1 – 60 km, 2 – 100 km, 3 – 200 km, 4 – 300 km, 5 – 400 km, 6 – 500 km.

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