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# 32. *Geothermal and Magnetic Survey off the Coast of Sumatra.*

## 2. *Interpretation and Discussion of the Results.*

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### Abstract

The geothermal and magnetic data presented in Part 1 are interpreted in relation to other geological and geophysical data of Sumatra. Sedimentation-erosion, seismicity, thermal conductivity refraction, and geothermal convection currents are proposed and evaluated in order to account for the observed large-scale geothermal feature. Geothermal convection currents are proposed as the most likely source of the major geothermal anomaly.

### 1. Introduction

The heat-flow pattern shown in Figure 1, Part 1, has three distinct features. First of these is the high heat flow found across the 90° East ridge. As only one heat-flow profile was made across this feature, the results were considered too few to interpret. The second large geothermal feature, running roughly east-west along 04°30′S latitude, is an area of high heat flow. In this area are found the highest heat-flow values measured off Sumatra. Associated with this east-west area of high heat flow is a zone of high magnetic field intensity (see Part 1). A band of high heat flow ($>1.5\,\mu$cal/cm$^2$sec) parallel to Sumatra and flanked by areas of low heat flow ($<1.0\,\mu$cal/cm$^2$ sec) is the third and most dominant feature of Figure 1. The second and third heat flow features of Figure 1 will be discussed in this paper in some detail.

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## 2. Interpretation of the second geothermal feature

There is a large heat-flow anomaly associated with a high magnetic anomaly running east-west along 04°30′S latitude. Two possible causes were considered to explain the associated magnetic and heat-flow anomalies. The first was that of volcanism; the second, serpentinization.

For volcanism to be the source of the associated magnetic and thermal anomalies in the region of 04°30′S, then it would be necessary that recent, shallow, basic igneous activity occurred in this region. The higher than ambient temperature of the igneous rock would produce the thermal anomaly and the above average magnetic susceptibility of the basic igneous intrusion would act as the source for the magnetic anomaly. Igneous activity can be postulated as a source for the magnetic anomalies as long as the igneous rocks are at a temperature lower than their Curie point.

The second possibility is that the related magnetic and thermal flux anomalies are due to serpentinization. The idea of serpentinization in the region of submarine trenches has been considered by others [Fisher and Hess, 1963]. Serpentine has a greater magnetic susceptibility than peridotite, and the process of serpentinization is exothermic, so that serpentinization affects both the magnetic and thermal fields. It is significant that the nonvolcanic island arc is composed mainly of ophiolitic rocks, among which serpentine predominates [*van Bemmelen*, 1954]. While analyzing the possibility of serpentinization, two alternatives were considered. The first was that the serpentinization has occurred in the past and is no longer in progress. All the thermal energy released by the now extinct serpentinization would not yet have been dissipated. This thermal lag would be the result of the low thermal conductivity of the earth's crust. An alternative possibility is that the serpentinization is now in progress. This would imply movement of mantle material past the 500°C isotherm [*Hess*, 1962]. Movement of material in the upper mantle implies convection currents in this region, where the serpentinization is occurring.

Based upon the limited amount of magnetic and geothermal data, the author believes that it is impossible to determine uniquely which of the two hypotheses concerning the associated magnetic and thermal anomalies is correct.

## 3. Interpretation of the third geothermal feature

Several causes of the band of high heat flow flanked by areas of lower heat flow were considered. Among those postulated were sedimentation-erosion, seismicity, thermal conductivity refraction, and geothermal convection currents. Each of these possible sources of the heatflow anomaly will be considered separately.

## 4. Sedimentation-erosion

Where the sea floor is being actively eroded, it will appear as a heat flow high because rapid erosion of a layer of material will increase the geothermal gradient. The eroded material, when deposited, will absorb heat flowing from the interior and be represented as an area of low heat flow [*Von Herzen and Uyeda*, 1963]. The distribution of the heat-flow anomaly in the Sumatra region was such as to suggest that the anomaly was due to erosion and sedimentation. This hypothesis was, however, considered doubtful because it has been shown that the sedimentation rate in submarine trenches is quite small [*Menard*, 1964] and evidence of a mechanism for erosion was not found. *Goldberg and Koide* [1963] found the sedimentation rate in the Indian Ocean to be of the order of a few millimeters per thousand years. This rate is much lower than the value of $10^{-2}$ to $10^{-1}$ cm/yr which is necessary to effect the heat flow [*Von Herzen and Uyeda*, 1963]. Goldberg and Koide's measurements, however, were not in the immediate vicinity of the survey.

## 5. Seismicity

The Indonesian island arc is a seismically active region. A study was made to determine whether or not the major heat-flow pattern observed off Sumatra showed evidence of being seismically controlled. That is, it was postulated that the heat flow high, parallel to the island of Sumatra, might be the product of seismically released energy. This idea was readily rejected after the epicenter in the region of the survey had been plotted (see Figure 5).

It was further thought that the heat flow high was related to the regional tectonic shear pattern outlined by the increasing depth to earthquake foci with incresing distance landward across the continental-oceanic boundary, which was first illustrated by *Gutenberg and Rich-*

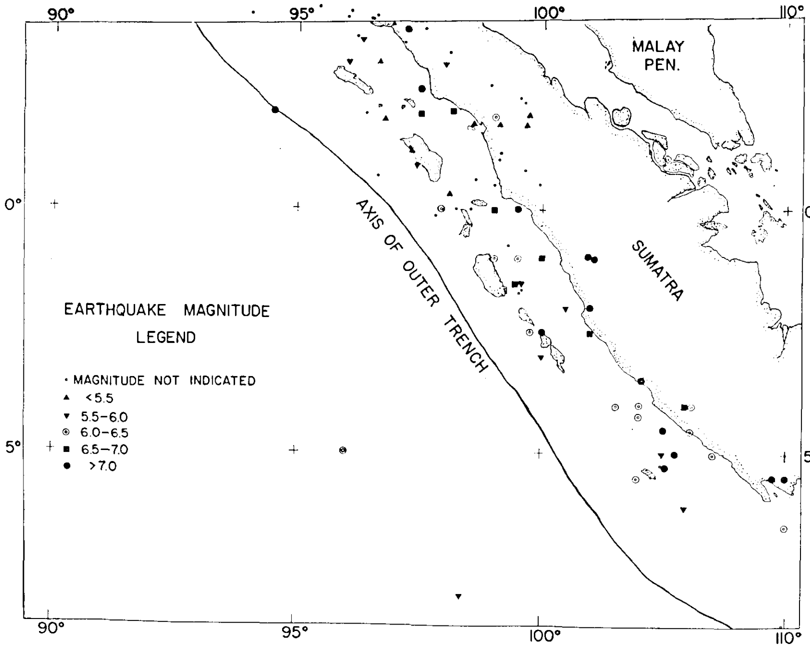


Fig. 5. Seismicity map for the Sumatra region.

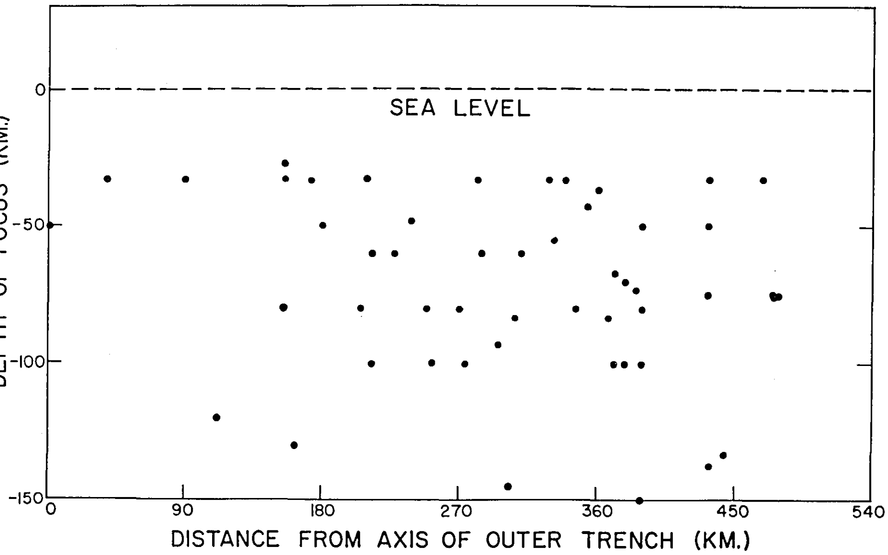


Fig. 6. Seismicity cross section for the Sumatra region.

*ter* [1949]. However, it was found (see Figure 6) that a depth to earthquake focus relation such as observed in Japan, Chile, and the

Tonga trench was not present in the area of Sumatra.

From the seismicity study, it was concluded that the heatflow patterns were not the result of seismic activity. *MacDonald* [1963] has shown that seismicity in the continental-oceanic tectonic region may be related, via thermoclastic stress, to the disparity in number of radioactive heat sources across the continental-oceanic boundary, the oceanic mantle being enriched in radioactive heat sources as compared with the continental mantle.

## 6. Thermal conductivity refraction

It has been shown [*Coster*, 1947] that a varying heat-flow pattern may be produced by constant thermal energy being refracted by a horizontal change in thermal conductivity. That is, a heat-flow anomaly might be the result not of an anomalous pattern of thermal energy in the mantle or lower crust but of a laterally varying thermal conductivity which acts as either a converging or diverging lens to the incident thermal energy. More recently, *McBirney* [1963] has developed the idea that the heat-flow pattern over the East Pacific Rise is the result of a thermal conductivity anomaly, at depth, and the intrusion of a magma.

It is possible that the heat-flow pattern measured off the coast of Sumatra may be the result of thermal conductivity refraction. Charles Cox of the Scripps Institution of Oceanography has developed solutions

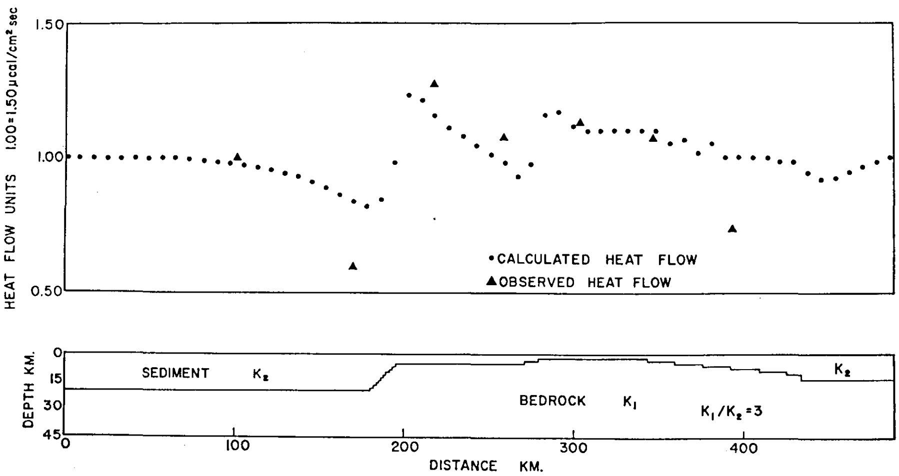


Fig. 7. Observed heat-flow profile and computed heat-flow profile resulting from varying thermal conductivity.

for heat-flow patterns caused by lateral variations of thermal conductivity which might result, for example, from sediments in a basin (the sediments and basin material having different values of conductivity). Using this method, we attempted, with a computer, to match a representative heat-flow profile from the Sumatra area with a sedimentary basin or thermal conductivity contrast (the contrast being 3 to 1). A reasonable match was obtained for the shape of the observed heat-flow profile and that computed for a thermal conductivity contrast. The match, however, failed to show the amplitude for the observed low values. The observed and computed heat-flow profiles are shown in Figure 7. The basin used to provide the thermal conductivity contrast for the computer program required to produce the theoretical heat flow profile was 20 km thick. It is extremely doubtful that sediments or a variation in thermal conductivity 20 km thick lie off Sumatra. The thermal conductivity contrast of 3 to 1 would have to be maintained throughout the 20 km of its depth in order to produce the heat-flow pattern. At such a depth, the sediments or thermal conductivity contrast would be in the upper mantle. It was now thought that the heat-flow pattern of the Sumatra area is not the result of a thermal conductivity contrast.

## 7. Geothermal convection currents

A central heat flow high flanked by areas of low heat flow suggested the idea of geothermal convection currents as one of the main hypotheses of the interpretation. The idea of convective heat transfer in the earth is one of the basic problems of solid earth geophysics.

*Pekeris* [1935] and Hales [1936] made the first serious attempts to describe the thermal convective process as acting within the earth. Others have since postulated convection currents to account for certain solid earth dynamic processes [*Griggs*, 1939; *Heiskanen and Vening Meinesz*, 1958; *Orowan*, 1964]. The existence of convection currents in the earth has been extensively treated by *Knopoff* [1964], who concluded that, given the proper physical conditions in the earth, laminar convective heat transfer is possible in the upper mantle.

From direct measurements of the width of the heat-flow anomaly, and the graphical results calculated by *Rikitake and Horai* [1960], it is postulated that the convection cell has a width of 200 km. Since Rikitake and Horai assume a square convection cell, the cell, postulated to exist off Sumatra is at a depth of approximately 200 km below the crust. Although the measured width of the heat flow anomaly, from Figure 1, varies from 150 to 200 km, 200 km was established as the proposed depth for the postulated convection cells. At a depth of 200 km, the convection cells would be located in the upper mantle.

Geological and geophysical evidence indicates that tectonic activity is occurring at present along the continental-oceanic interface of the Pacific Ocean and parts of the Indian Ocean. On the basis of radioactive element distribution, *MacDonald* [1964] calculates that there is a significant lateral temperature gradient, up to 100°C at depth, across the continental-oceanic interface, the oceanic mantle being hotter than the continental. It is possible that there is a direct connection between the lateral thermal gradient and the geologic activity. This connection could be made by postulating the existence of convection currents in the upper mantle. The temperature gradient across the continental-oceanic interface could act as a starting mechanism and it would direct the rising convection cell to sink under the continent.

It has, however, been suggested that the major heat-flow anomaly observed off Sumatra might be the result of the thermal edge effect caused by the lateral variation of radioactive heat sources across the oceanic-continental boundary. Since the oceanic mantle is at a higher temperature than the continental mantle, at a given depth, heat would flow across the oceanic-continental boundary from the oceanic side to the continental. This flow pattern would produce a higher than average heat flow over the continental edge and a lower than average heat flow across the oceanic side of the boundary. *MacDonald* [1963], however, has shown that this effect would only be of the order of 3%, for MacDonald's model of a continent formed 3.5 billion years ago.

In a report of his investigation of the heat flow in the Pacific basin, *Von Herzen* [1960] states, while commenting on the heat flow pattern of the South and Central American trenches, that the horizontal forces produced by lateral spreading of the upper part of the convection cell may cause the crustal material which abuts the continents to be thrust underneath the continental massif. A similar hypothesis is suggested for the Sumatra Trench.

In summary, it is proposed that the dominant heat-flow pattern observed off Sumatra is due to the rising and sinking of thermal convection cells in the earth's upper mantle. The mechanism of convection involves laminar double-roller cells which diverge under the heat flow high and sink to either side. This doubleroller convection cell interpretation is illustrated in Figure 8. The structure cross section shown in Figure 8 was taken directly from the work done by *Raitt and Shor*

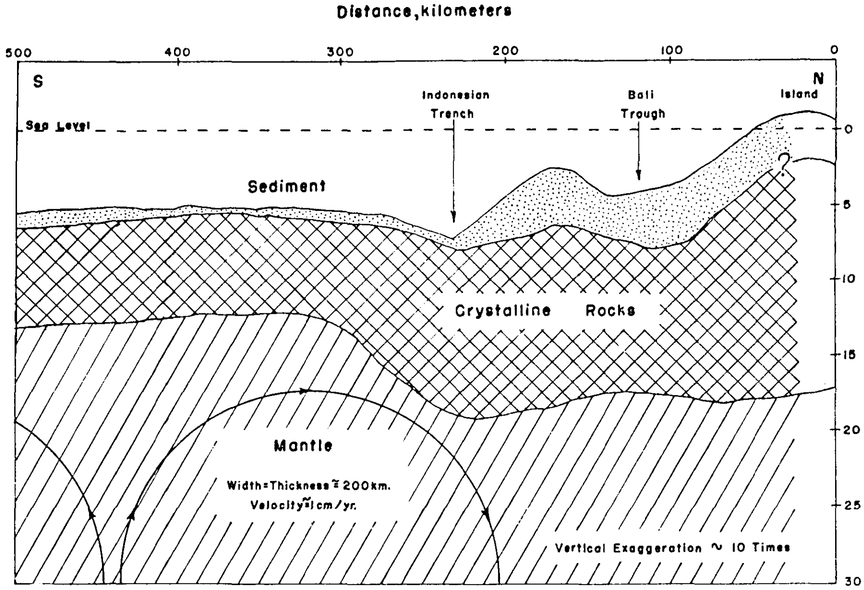


Fig. 8. Structure section of the Indonesian island arc [Raitt and Shor, 1964].

[1964]. The data are in preliminary form. This cross section if for the Java trench, which may be geographically close enough to be representative of the Sumatra Trench.

As mentioned earlier, a thermal convective process might be operating in the region of the second geothermal feature of the area, the east-west band of high heat flow. It is not obvious how this thermal convection is related to the larger-scale thermal convection process postulated to be the cause of the long, narrow heat flow high and low observed above.

## 8. Acknowledgments

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The thermal conductivity refraction computer program was developed by C. Cox of the Scripps Institution of Oceanography. The U. S. Coast & Geodetic Survey was most helpful in supplying the latest seismicity results in the Sumatra region.

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# 32. スマトラ島沖の地熱及び地磁気調査

## 2. 観測結果の解釈

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第1部に報告された，熱的および磁気的観測結果を，スマトラ島に関する他の，地質学的および地球物理学的データとの関連において解釈した．堆積，侵食，地震，熱伝導度分布，マントル内部熱対流などが，観測された大規模な熱流量分布の機構として考慮された．これらの可能性のうち，対流仮説がもつとも有望と結論された．