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# A Review on Indirect Measurement of Heat Flow from Integrated Geophysical Modeling: Insights into Petroleum E&P and Geothermal Resource Exploration

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## ABSTRACT
Knowledge of heat flow helps to gain insights about the Earth's interior in terms of its thermal structure and temperature distribution. In addition to the study of geodynamics, heat flow data are also of great use in the petroleum and geothermal industries. In the oil and gas industry, heat flow reveals information about oil generation, rock quality, migration and entrapment mechanism. Indirect measurement of heat flow takes advantage of its intrinsic relationship with petro-physical parameters such density, seismic velocity, heat production and electric conductivity. Such parameters can be studied using their corresponding geophysical observable.
**Keywords:** Heat flow, Petroleum E&P, Geothermal resources, Thermal gradient

## INTRODUCTION
The Earth's heat originates from the original formation of the planet and from radioactive decay of materials. A portion of the heat conducted through the earth's crust is contributed to drive the chemical reactions which transform organic matter contained in sedimentary rocks into petroleum. Recognition of the heating system and its variations with time, leads to a better understanding of hydrocarbon generation, separation of source rocks, immigration and the mechanism of entrapment. Also, heat flow can be used in the process of designing of the drilling mud composition, cement, rubber downhole tools, well logging tools, downhole electronic devices and drilling pipes.
Another application of temperature distribution studies is in identifying geothermal resources. Geothermal power is cost-effective, reliable, sustainable, and environmentally friendly. There are various geothermal power applications which can be distinguishes according to the hydrothermal temperatures, however, they can be divided into two categories: direct and indirect. Direct usages such as heating or cooling of space, agricultural, animal husbandry, industrial, hydrotherapy and melting the snow and ice of roads and indirect usage for converting geothermal into electricity.
Heat flow is a key parameter for investigate these issues. In order to determine the present heat flow, it is necessary to know about the heat generation, thermal gradient and thermal conductivity. Moreover, to establish a clear image of the past heat flow, additional information about Palaeo-temperatures is required.
Thermal gradient is a vector quantity depending on the distribution of temperature in three dimensions. Generally, it is assumed that the direction of maximum gradient within the upper crust is vertical, thus the gradient is the derivative of temperature with respect to depth *(dT/dz).*
Only a few methods are available for estimating the temperature in the deep crust without requiring direct access. The Curie depth is the depth at which minerals lose their magnetic properties (580°C isotherm in most continental regions); this can be estimated through spectral analysis of regional aeromagnetic data. A xenolith is a piece of country rock picked up by magma as it rises through the crust. The pressure-temperature stability conditions indicated by a xenolith's mineral assemblage provide information about the depth and temperature of its original location. The Magnetotelluric method can yield deep variations of electrical conductivity down to the upper mantle, which is strongly dependent on temperature.
Because of the dependence of most petro-physical parameters on heat (or temperature), heat flow data can be readily correlated with other geophysical and geological observables. In particular, there are clear associations between heat flow and surface heat production, geologic age, seismic velocity and electrical conductivity. Expected correlations between heat flow and crustal thickness, however, are difficult to establish.

## METHODOLOGY
### 1. Heat Flow and Heat Production
An empirical linear relationship between surface heat flow and heat generation in local basement rocks is demonstrated by Roy et al. (1968) (Figure 1). According to the following expression, simple statistical measures can be applied to local data to define a heat flow province:

$$Q = q + A_0 D \qquad (1)$$

where Q is surface heat flow ($mW/m^2$), q is residual heat flowing into the crust from mantle sources ($mW/m^2$), $A_0$ is surface heat generation ($\mu W/m^3$) and $D$ is a depth (km) characteristic of the province. Assumed radioactivity measured at the surface is constant to depth D. Values for the residual, q, (generally 25—

$35\,mW/m^2$) indicate the minimum contribution to crustal heat due to global accretion, segregation, and mantle heat generation. Trends of this type have been directly observed in limited areas with sufficient geological exposure (e.g. Lachenbruch and Bunker, 1971; Hawkesworth, 1974). However, in regions of complex geology typical of continental crust, simple mathematical expressions are rarely sufficient (e.g. Smithson and Decker, 1974).

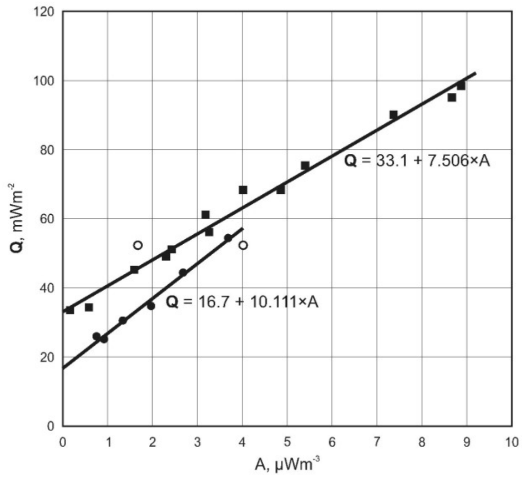


**Figure 1. Plot of surface heat flow, Q ($mW/m^2$), versus heat generation, A ($\mu W/m^3$), for the Sierra Nevada (circles) and the New England/Central Stable Region of the United States (squares). Linear relationships are apparent. Data from Roy et al. (1968).**

## 2. Heat Flow and Seismic Data

We may expect a correlation between crustal heat flow, Q ($mW/m^2$), and upper mantle P-wave velocity, $V_p$ (km/s), as the seismic velocity varies with temperature (e.g. Anderson et al. 1968). Cull and Denham (1979) demonstrated such a correlation for Australia, which they described by a linear expression:

$$Q = 1150 - 135 \times V_p \tag{2}$$

Tomography concepts can make correlations between heat flow and seismic travel time in a more direct way. Drummond et al. (1989) presented detailed contours of travel time residuals for Australia (Figure 2). Systematic trends are evident with early arrivals in the relatively cold Precambrian crust and later arrivals along the warmer east coast, consistent with the heat flow domains in Figure 3 (Sass and Lachenbruch, 1979). Cull and Denham (1979) suggested a linear relationship:

$$Q = 21.45 \times t_r + 65.3 \tag{3}$$

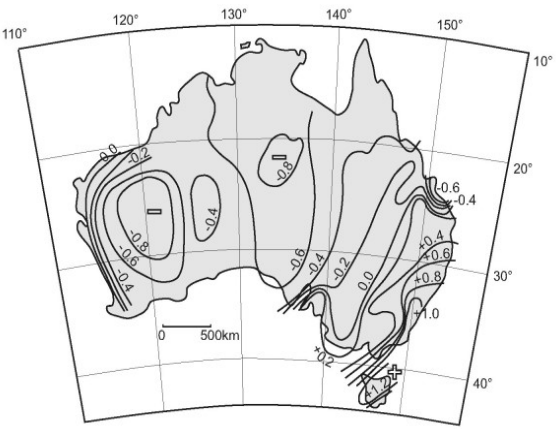


**Figure 2. Teleseismic travel time residuals for Australia. Contour interval is 0.2 s. Modified after Drummond et al. (1989).**

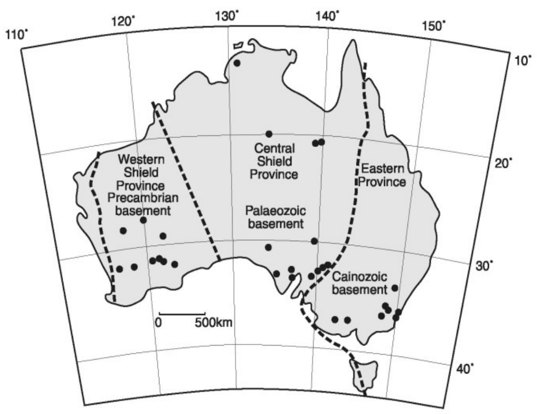


**Figure 3. The three major Australian heat flow provinces, as defined by Sass and Lachenbruch (1979). Circles indicate locations of heat flow-heat production pairs.**

Where Q ($mW/m^2$) is the surface heat flow and $t_r$ (s) is the travel time residual defined by Drummond et al. (1989). For most sedimentary rocks, Houbolt and Wells (1980) observed that the ratio of sound velocity to thermal conductivity increases linearly with temperature. They used one-way travel time logs in combination with bottom-hole temperatures to derive a relationship for heat flow:

$$Q^* = ln\frac{T_L + c}{T_U + c} \times \frac{1}{a(T_L - T_U)} \quad (4)$$

where Q* is heat flow in relative Bolderij units, BU (1 BU ≈ $77\,mW/m^2$), $T_L$ and $T_U$ are the temperatures (°C) at the bottom and top of a sub-surface interval, $T_L$ and $T_U$ are the one-way sonic travel times (s) to the bottom and top of the interval, a = 1.039 and c = 80.031.
Houbolt and Wells (1980) concluded that their method works with an acceptable accuracy for siliciclastic and carbonate rocks.

## 3. Heat Flow and Electrical Conductivity

Adam (1978) correlated heat flow with the depths of electrically conducting layers in the crust and upper mantle. Adam's 'first conducting layer' (FCL) is assumed to coincide with the onset of granitisation and melting in the crust, and the boundary between amphibolite and granulite facies. The 'intermediate conducting layer' (ICL) is apparently related to partial melting at the top of the asthenosphere. Adam suggested that the depth, h, of each layer be related exponentially to regional heat flow, q ($mW/m^2$):

$$h = h_0 \times q^{-a} \quad (5)$$

where

$h_0 = 4493\,km$ , a=1.30 for the FCL

$h_0 = 36.167\,km$ , a=1.46 for the ICL

Magnetotelluric sounding techniques may reveal both $h_{FCL}$ and $h_{ICL}$ at a single locality, giving two constraints for heat flow where no other data may be available.

## 4. Temperature and Density

Parsons and Sclater (1977) proposed a relationship between temperature and density. Increasing temperature results in decreasing density through the following relation:

$$\rho(T) = \rho_0\left(1 - \alpha\left(T - T_0\right)\right) \quad (6)$$

where $\rho(T)$ is the density at a given temperature T (°C), $\rho_0$ (kg/m$^3$) is the density at a reference temperature $T_0$, and $\alpha$ is the thermal expansion coefficient. This relation is the base of various studies for regional lithospheric section and temperature distribution modeling (Motavalli-Anbaran et al. 2016 and Entezar-Saadat et al. 2017). Temperature gradient together with thermal conductivity and radiogenic heat production data, can be used to derive heat flow.

## 5. Heat Flow and Continental-Oceanic Crust Age

There are also correlations between heat flow and the age of continental and oceanic crusts. In general, radiogenic elements in older crust are depleted through natural decay, and as a direct consequence older crust typically exhibits lower surface heat flow (e.g. Sass and Lachenbruch, 1979; Teichmuller and Teichmuller, 1986) and lower thermal gradients. Likewise, the volume of heat-producing material is directly proportional to the thickness of the crust. Therefore, thicker crusts contribute more heat than thinner crusts of the same age. There are clear correlations between oceanic age and surface heat flow related to the cooling of oceanic lithosphere. Specifically, heat flow increases with the inverse square root of the age of oceanic crust.

## CONCLUSION

Indirect measurement of heat flow is made possible due to the existing intrinsic relationship between petro-physical parameters and temperature. As such, there are clear associations between heat flow and surface heat production, geologic age, seismic velocity, density and electrical conductivity. Empirical linear relationships between surface heat flow and heat generation in local basement rocks have been established for numerous regions around the globe. There is a reverse relationship between temperature and density, wherein the increase of temperature results in the decrease of density. Linear relationships have been identified between crustal heat flow and upper mantle P-wave velocity, and between crustal heat flow and seismic travel time residuals. Mean surface heat flow progressively decreases with the age of basement rocks in both continental and oceanic settings. The depth to electrically conducting layers in the crust and upper mantle is related exponentially to crustal heat flow.

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