AAPG International Conference & Exhibition '94
August 21-24, 1994, Kuala Lumpur, Malaysia

Determination of heat flow in some exploration wells in the northern part of the South China Sea

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Abstract: As a part of the crust, the shelf has few geothermal studies, but the heat flow data can be determined by using the existing temperature data and the measured thermal conductivities of core samples from the exploration wells in the Pearl River Mouth basin of the South China Sea. 8 heat flow data calculated indicates the increasing tendency from the east to the west, and shows good consistency with the crust structures being thicker in the east and thinner in the west.

INTRODUCTION

At the end of 1988, a joint study on heat flow in the Pearl River Mouth basin on the northern part of South China Sea was established among South China Sea Institute of Oceanology, the Chinese Academy of Sciences, Nanhai East Oil Corp., CNOOC and the Japanese Geothermal Research Team. The thermal conductivities of 46 core samples and 60 cutting samples from the eight exploration wells were measured at that time. Correction was made to the temperature loggings and the conductivity data from the wells. The heat flow values of these wells were calculated (Fig. 1). Its aim is to understand the thermal structure of the northern continental shelf of the South China Sea, and to provide important parameters to hydrocarbon generation of the Pearl River Mouth basin.

THERMAL CONDUCTIVITY MEASUREMENT AND LABORATORY CONDITION

The apparatus used for measuring the thermal conductivities of core samples is a Quick Thermal Conductivity Meter (QTM, e.g. Ito *et al.*, 1975). 46 core samples were soaked in water for at least 24 hours before measurement, because the samples had been stored in dry state, and the air-filled pores were almost impossible in the *in-situ* state. A comparison experiment shows the conductivity of a core saturated by using a vacuum chamber has the difference of less than 2% from that of the core soaked in water only (Osamu and Uyeda, 1979). A thin plastic film was laid on the surface of the core sample to prevent the heating wire and the temperature sensor from contacting the water. The effect of this film is less than 1% of the thermal conductivity value when measured on a fused quartz standard sample (Osamu and Uyeda, 1979). Each core sample was measured at least three times, then a mean conductivity value was obtained.

In this study, a needle probe was also used for cutting the samples. Before the measurements, the dry weight and volume of a sample were measured, then water was added to wet the sample and squeeze air out of the sample until the water level reach the surface of the cutting sample, then the wet weight of the sample was measured. Based on the above data, porosity of the sample can be calculated in a laboratory:

$$\text{Porosity} = \text{pore volume/bulk volume} = (\text{bulk volume} - \text{rock volume})/\text{bulk volume} \quad (1)$$

The grain density data of core samples are quite uniform and ranged from 2.6 to 2.7 g/cm^3. So, 2.6 g/cm^3 was adopted as the grain density in this study. The indoor temperature of the laboratory was about 20°C during measurements.

DATA PROCESSING

Temperature loggings

During drilling, the field temperature around the well was affected by the mud circulation, the downhole temperature loggings performed by the Nanhai East Oil Corp., CNOOC, were bottom hole temperatures (BHT), and the BHT data were measured at least twice at the certain depths of different times. The true temperature T_{true} can be speculated by Horner's correction method as shown in the following equation:

$$T_{true} = T_{BHT} - \frac{Q_d}{4\pi K} \log \frac{t_1}{t + t_1}, \qquad (2)$$

where Q_d is the heat generation per unit length and per unit time during drilling, K the thermal conductivity, t_1 the duration from drilling cessation to measurement, and t the duration of mud circulation at a certain depth. If only one measured BHT existed, an empirical relationship between the BHT and the true formation temperature obtained by Kaichi (1984) was used:

$$T_{true} = 1.31(T_{BHT} - T_0) + T_0, \qquad (3)$$

where T_0 is a annual mean surface temperature. In this paper, 15°C is assumed as the annual mean surface temperature of sediment of the Pearl River Mouth basin.

Thermal conductivity correction

As to the measured samples, with the exception of a few crystallise rocks of the basement, most samples can be roughly divided into three kinds of rocks, namely, sandstone, siltstone and mudstone. Generally, the thermal conductivity of a sample is a function of temperature and its porosity, therefore, the conductivities measured in the laboratory need to be corrected before calculating the heat flow values.

Thermal conductivity vs porosity

Based on experiments, the thermal conductivities of a certain kind of rocks has the following relation with the porosity of the rocks (Kaichi, 1984):

$$K_0 = K_s^{1-\varnothing} K_f^{\varnothing}, \qquad (4)$$

where K_0 is the measured thermal conductivity, K_s and K_f the conductivities of solid phase and fluid phase respectively, $\varnothing$ the porosity of the sample.

Thus, we calculated the thermal conductivity vs porosity relationships of the three kinds of rocks

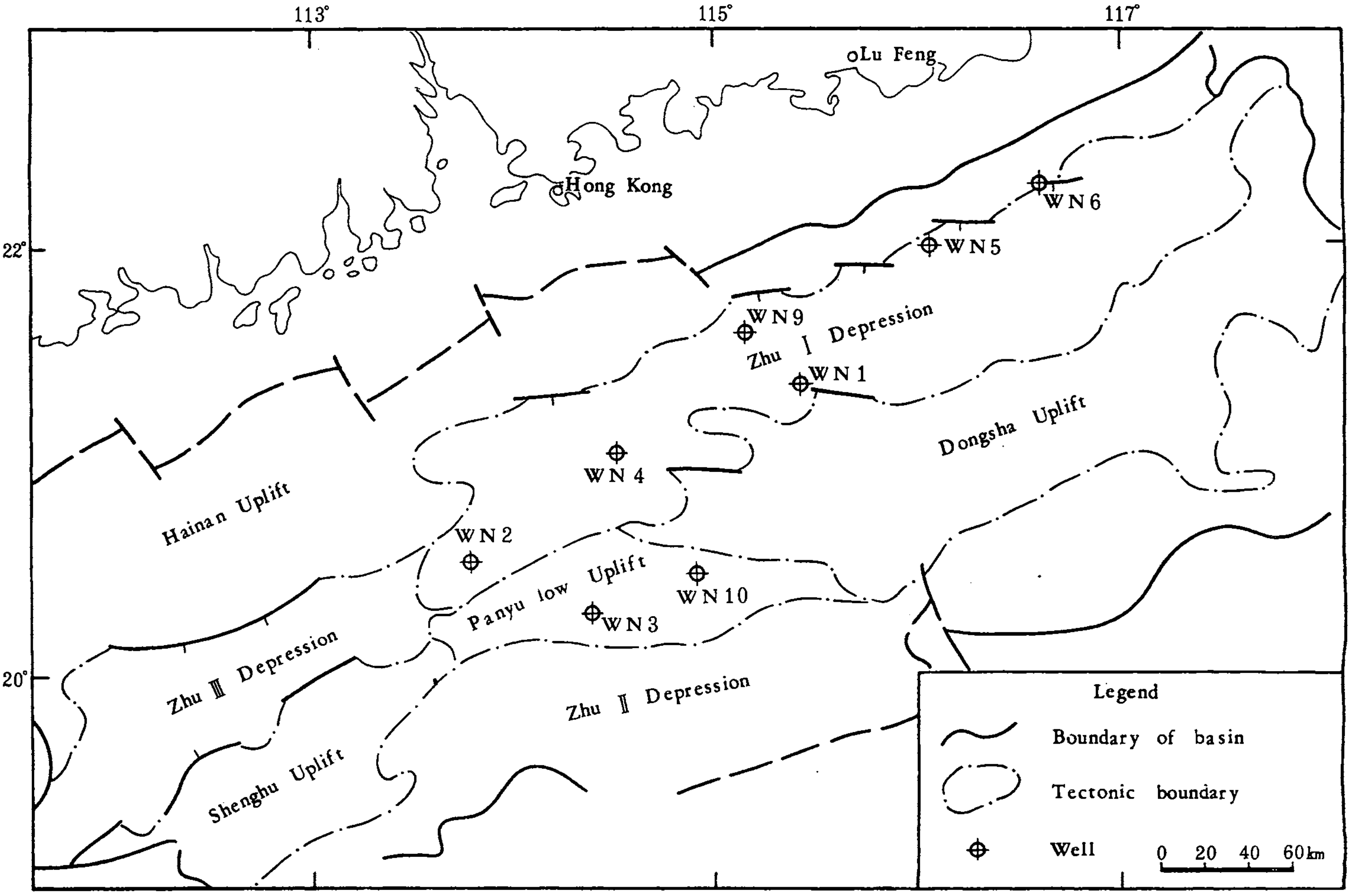


Figure 1. Tectonic divisions and well locations of Pearl River Mouth Basin.

(Fig. 2) by using the least-squares method in the Pearl River Mouth basin as follows:

$$K_1 = 4.40^{1-\phi}\ 0.63^{\phi}$$
(45 data for sandstone), (5)

$$K_2 = 3.34^{1-\phi}\ 0.63^{\phi}$$
(8 data for siltstone), (6)

$$K_3 = 2.80^{1-\phi}\ 0.63^{\phi}$$
(34 data for mudstone), (7)

where the conductivity of water saturated in samples is 0.63 W/mK. The conductivities of the cutting samples measured by a needle probe method can be corrected into the *in-situ* conductivities by using sonic and neutron density loggings and the above relationships.

Thermal conductivity vs temperature

Thermal conductivity values increase with pressure (Kieffer, *et al.*, 1976), the change in conductivity per 100 MPa is about 1% or less for harder rocks or minerals (Kaichi, 1984). This variation with pressure doesn't seem to be so large as to cause some grave error for the heat flow calculation. Thus the influence of the change of pressure can be ignored. However, the effect of temperature have to be considered, since the

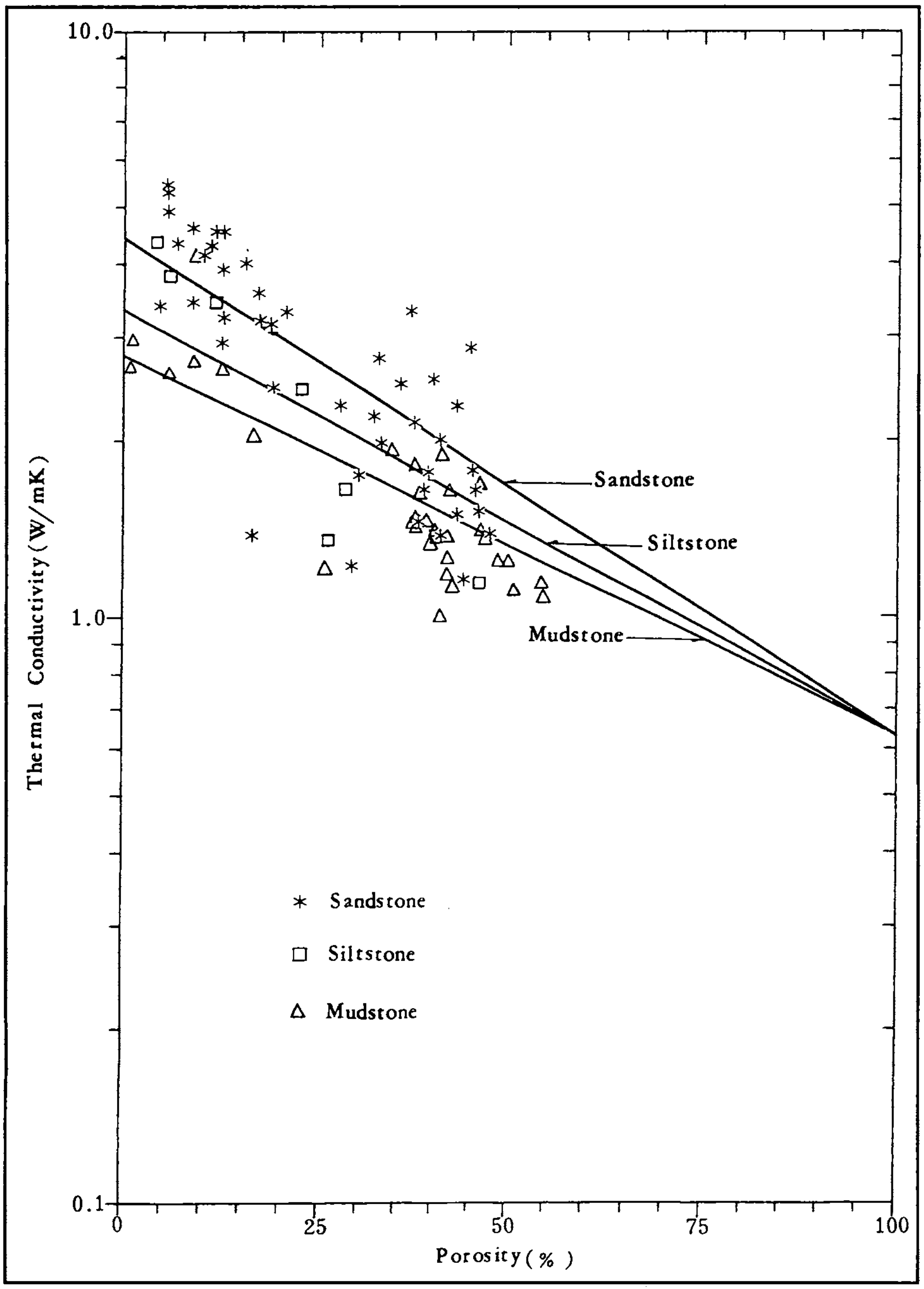


Figure 2. Measured conductivities vs. porosities of samples.

conductivity of a rock sample must be corrected according to the *in-situ* temperature. Generally the target zone for heat flow study is situated within the temperature range of 0–300°C. Most conductivities within the temperature range seem to be converge linearly to an assumed temperature point above 1,000°C. Taking all conductivities into consideration, the *in-situ* thermal conductivity K within the temperature range at an absolute temperature T can be expressed by (Kaichi, 1984):

$$K = \frac{T_0 T_m}{T_m - T_0}(K_0 - K_m)\left(\frac{1}{T} - \frac{1}{T_m}\right) + K_m, \qquad (8)$$

where K_m and T_m are the conductivity (1.85 W/mK) and the absolute temperature (1,473°K, i.e. 1,200°C) at the assumed point, respectively; K_0 is the primary conductivity of a sample at room temperature T_0 (293°K, i.e. 20°C). The above relationship can be simplified as follows:

$$K = 366(K_0 - 1.85)\left(\frac{1}{T} - 0.00068\right) + 1.85, \qquad (9)$$

Heat flow determination

The target zone for calculating heat flow should include temperature data and thermal conductivities. The temperature data of the eight wells chosen for heat flow calculation cover the whole well. The whole section for heat flow study can be divided into several geological formations as shown in Figure 3, where the conductivities of sandstone, siltstone and mudstone are determined by the corrected measurements. If there are no

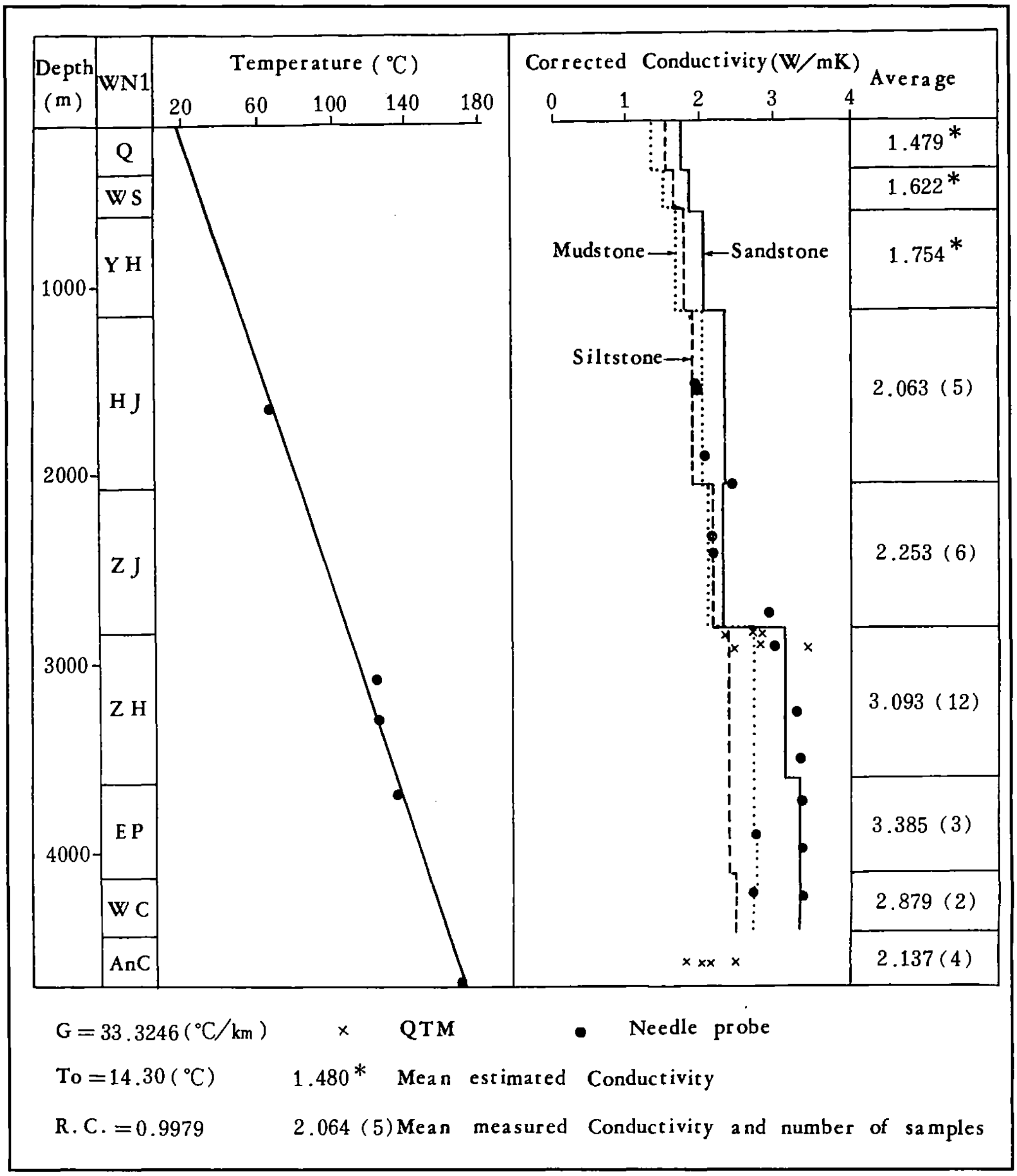
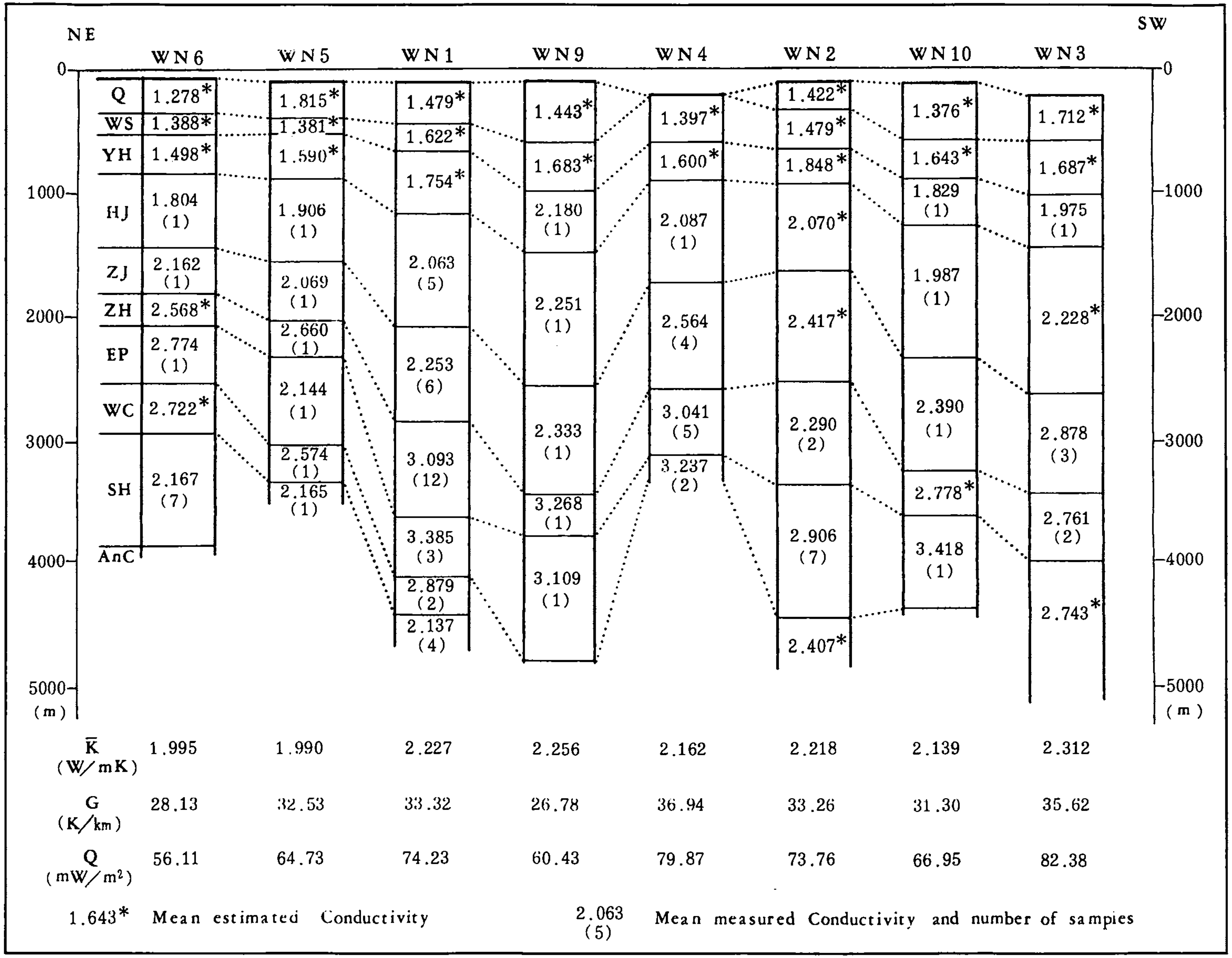


Figure 3. Temperature and thermal conductivities correction of well WN1.



	WN6	WN5	WN1	WN9	WN4	WN2	WN10	WN3
K̄ (W/mK)	1.995	1.990	2.227	2.256	2.162	2.218	2.139	2.312
G (K/km)	28.13	32.53	33.32	26.78	36.94	33.26	31.30	35.62
Q (mW/m^2)	56.11	64.73	74.23	60.43	79.87	73.76	66.95	82.38

Figure 4. Corrected thermal conductivities and heat flow values of the wells.

measured samples in a certain formation, the conductivities can only be determined by theoretical speculation.

First of all, we must take the effect of the *in-situ* porosity to the thermal conductivity into consideration. Generally, porosity decreases with depth, and has following relation:

$$\phi(z) = \phi_0 e^{-cz}, \qquad (10)$$

where ϕ_0 is the porosity at 0 m of a certain kind of rocks, c a compressive parameter of the rock.

On the other hand, we need to exclude the influence of temperature to a thermal conductivity. A temperature at a certain depth can be expressed as:

$$T = T_0 + GZ, \qquad (11)$$

where G is the temperature gradient of the well. According to relations (11), (10), (5) and (9), a function of thermal conductivity vs depth of sandstone can be obtained as follows:

$$K_1(z) = F_1(z), \qquad (12)$$

Just the same, we can get the following functions of thermal conductivity vs depth of siltstone and mudstone respectively:

$$K_2(z) = F_2(z), \qquad (13)$$

$$K_3(z) = F_3(z), \qquad (14)$$

Therefore the conductivities of the three kinds of rocks of a certain formation can be calculated from the above mathematical relations respectively. Then a mean conductivity of a certain geological formation can be obtained by the following relation:

$$K = K_1D_1 + K_2D_2 + K_3D_3, \qquad (15)$$

where D_1, D_2 and D_3 are percentages of sandstone, siltstone and mudstone in a formation, and $D_1 + D_2 + D_3 = 1$. Thus the average conductivity of each geological formation in a well can be calculated respectively. A sample calculation and temperature and conductivities correction of well WN1 is given in Figure 3. A mean conductivity of a whole well can be obtained by:

$$\overline{K} = H \sum_{i=1}^{n} \left(\frac{h_i}{K_i}\right)^{-1}, \qquad (16)$$

where H = Sh ; h is the thickness of each geological formation. Thus, the heat flow value of a well can be calculated by:

$$Q = \overline{K}G, \qquad (17)$$

Through the above relationships, the temperature gradient, thermal conductivity, and heat flow value of each well were determined as shown in Figure 4 from northeast to southwest in the Pearl River Mouth basin.

The heat flow values of wells become higher from northeast to southwest, which complies with the periods of tectonic extensions of the Pearl River Mouth basin that the northeast part extended earlier and the southwest part extended later.

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Manuscript received 3 January 1995