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A Thermal Resistance Method for Computing Surface Heat Flow and Subsurface Temperatures with Application to the Uinta Basin of Northeastern Utah

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ABSTRACT

The thermal resistance method has been modified to test the utility of oil and gas well bottom-hole temperature data in determining heat flow and subsurface temperature patterns. Thermal resistance, defined as the quotient of a depth parameter "Δz" and thermal conductivity "k", governs subsurface temperatures as follows:

$$T_B = T_o + q_o \sum_{z=o}^{B} \left(\frac{\Delta z}{k}\right)_i$$

where T_B is the temperature at depth z = B, T_o is the surface temperature, q_o is surface heat flow and the thermal resistance ($\Delta z/k$) is summed for all lithological units between the surface and depth B. In practice, bottom-hole temperatures are combined with a measured or estimated thermal conductivity profile to determine the surface heat flow q_o, which in turn is used for all consequent subsurface temperature computations.

The method has been tested in the Tertiary Uinta Basin of northeastern Utah, a region of intermediate geologic complexity (structurally simple yet lithologically complex) where numerous oil and gas well data are available. Thermal conductivity values, determined for 852 samples from five representative wells varying in depth from 670 to 5180 meters, were used to assign average conductivities to geologic formations and to investigate the effect of facies changes on intra-formation conductivities. In situ conductivities were corrected for porosity and temperature effects. Formation thicknesses needed for the thermal resistance summation were obtained by utilizing approximately 2000 wells in the WEXPRO Petroleum Information file, the computations being expedited by describing all formation contacts as fourth order polynomial surfaces. Bottom-hole temperatures were used from 97 selected wells where multiple well logs permitted correcting temperatures for drilling effects.

The average geothermal gradient and heat flow for the test area of the Uinta Basin are $25^{o}C\ km^{-1}$ and $59\ mW\ m^{-2}$ respectively. Maps of surface heat flow and temperatures at a depth of 1000 m are presented. An error analysis included in the thermal resistance method suggests that uncertainty in heat flow and subsurface temperature values are of the order of 15%. Errors arising from interpolating temperature gradients without regard for thermal conductivity structure will be larger.

Introduction

Bottom-hole temperatures obtained from routine geophysical logs of oil and gas wells comprise an under-utilized data set in geothermal and heat flow studies. There are good reason for this situation. Neither the bottom-hole temperature, and consequently the thermal gradient, nor the thermal conductivity profile, both required for heat flow determinations and sensible interpretation of temperature data, can be obtained with confidence from routine geophysical logs of the wells taken soon after the completion of drilling. Even if accurate temperature measurements are made, which generally has not been necessary in oil and gas well logging, temperatures in and around wells are perturbed by the drilling process, principally by the circulation of mud at a temperature which differs from in-situ conditions. There is seldom sufficient information to make accurate corrections for this perturbation. Assigning thermal conductivity values for any particular drillhole is even more problematic. Thermal conductivities are not routinely measured and general predictive relationships between conductivity and parameters determined in routine geophysical logs are not always reliable (Goss, 1974). Thus, spatial variations in thermal gradients deduced from bottom-hole temperatures may simply be spurious, caused by errors in the temperature data, or, in the case of the overall gradients being fortuitously correct, the ambiguity in interpreting gradient patterns in terms of thermal processes as opposed to thermal conductivity variations will not be resolved.

In spite of these difficulties, it is possible, especially upon application of temperature corrections and additional conductivity measurements, to extract useful information from bottom-hole temperature data on a case by case basis. This has been done by Evans and Tammemagi (1974) for the Somalian Horn and Sudan, by Evans and Coleman (1975) for the North Sea oil fields, by Carvalho and Vacquier (1977) for the Reconcavo Basin of Brazil, by Carvalho et al. for Centra Summatra, and by Hodge, et al.

(1980) for upper New York State. Unfortunately, in the most comprehensive study of bottom-hole temperatures in the conterminous USA, Klemme et al. (1976) have ignored thermal conductivity effects and so their thermal gradient maps are of limited use.

In this paper we further develop the thermal resistance method (Bullard, 1939) for determining and evaluating heat flow variations within a single basin, and for producing subsurface temperatures maps within the basin. Although our method does not totally alleviate problems arising from non-equilibrium temperature logs and incomplete description of thermal conductivity patterns, we attempt to utilize fully the data available within a basin by allowing the possibility of lateral variations in heat flow. Individual oil and gas fields are not homogenized to a single gradient and single conductivity function as has been done by Carvalho and Vacquier (1977). Finally, the method is amenable to a formal error analysis. The Tertiary Uinta Basin of northeastern Utah has been chosen to illustrate our thermal resistance method because of its intermediate geologic complexity structurally simple yet lithologically complex, and the abundance of oil and gas well data.

Thermal Resistance Method

Thermal resistance is defined as the quotient of a thickness "Δz" and a characteristic thermal conductivity "k". In the case of negligible heat production and fluid movement, subsurface temperatures in the earth are governed by the thermal resistance of a vertical lithologic section in the following way (Bullard, 1939; and Figure 1)

$$T_B = T_o + q_o \sum_{z=o}^{B} \left(\frac{\Delta z}{k}\right)_i \qquad (1)$$

where T_B is the temperature at depth z = B, T_o is the surface temperature at z = 0, q_o is surface heat flow, and the thermal resistance ($\Delta z/k$) is summed for all lithological units between the surface and depth B. This equation, or the integral form of it, is commonly used in heat flow data reduction, heat flow q_0 being calculated as the slope of the plot of consecutive values of T_B versus the summed thermal resistance to the measurement depth. The method in such use is termed the Bullard method and is especially suited when the borehole intersects discrete lithologic units.

The thermal resistance method as we will use it for the analysis of heat flow and subsurface temperatures in a sedimentary basin comprises several steps. First, a set of bottom-hole temperatures (T_B) are compiled and corrected, if possible, for drilling disturbances. The wells from which temperatures are taken should represent a wide geographic distribution throughout the basin. This is not always possible, however, since the preponderance of wells are drilled in discrete oil or gas fields. Second, thermal conductivity values must be measured for all representative lithologies in the basin. This may be done on drill chip or core samples from several wells or on representative samples from outcrop or both. Laboratory results for conductivities will have to be modified for temperature and porosity effects in order to simulate in situ conditions. At this stage both temperature-depth profiles and thermal conductivity-depth profiles are allowed to vary with lateral position in the basin. The third step involves summing the thermal resistance at each well from the surface to the depth of the bottom-hole temperature observation, and solving for the site heat flow using equation (1).

Whereas the thermal resistance sum is ideally performed individually for each well using conductivities and thicknesses for all lithologic units intersected, for large numbers of wells this individual well treatment is cumbersome. An automatic processing procedure can be substituted if the structure of the bain is sufficientlly simple and well known so that lithologic contacts and conductivity variations can be described conveniently by functions. In the case of the Uinta Basin we will show that formation contact depths can be adequately described in terms of low order polynomial surfaces, and so we are able to automate the procedure. In this case the modified form of equation (1) used to calculate individual site heat flow values is

$$q_o^{\cdot\cdot} (x, y) = [T_B (x, y) - T_o (x, y, h)] / \sum_{z=o}^{B} (\Delta z (x, y)/k (x, y, z)_i \qquad (2)$$

For each well the latitude and longitude (equivalently x and y), well collar elevation h, corrected bottom-hole temperature T_B and corresponding depth z = B are stored in a data file. Surface temperature as a function of position and elevation T_o (x, y, h), lithologic unit thickness Δz (x, y) as a function of position and thermal conductivity k (x, y, z) as a function of position and depth are all generated from empirical functions. Once surface heat flow values have been determined from (2) for all wells sampled, and the heat flow field has been suitably smoothed, subsurface temperature maps can easily be created by a forward application of (1) or (2).

An alternative approach to analyzing oil and gas well bottom-hole temperature data is the simple gradient method (Klemme et al.; Chaturvedi and Lory, 1980; Jones et al., 1982). Thermal gradients are calculated either as a two point gradient utilizing a single bottom-hole temperature and an estimate of the mean annual ground temperature, or by using regression techniques on multiple bottom-hole temperatures at different depths. This technique for treating bottom-hole temperature data is shown schematically in Figure 1. The single advantage of the simple gradient method is its convenience, especially as bottom-hole temperature information is now commonly stored in data files. However, scatter in these uncorrected temperatures for a common depth in any given field is typically 10 to 20°C (Carvalho and Vacquier, 1977, Figures 3-8) and thus leads to rather large uncertainties in the computed gradient. Also without thermal conductivity information the explanation of the scatter is unclear. Our thermal resistance method, in contrast, requires the measurement or estimation of thermal conductivity values, but in return provides an estimate of actual temperature errors and of lateral heat flow variations.

We now present our analysis of heat flow and subsurface temperature variations within the Uinta Basin. The geologic setting of the basin and the basic data available from oil and gas wells files will be described first. The analyses of temperature and conductivity data and corrections which may be applied to them are discussed separately. Finally, the heat flow and subsurface temperature maps produced by the thermal resistance method are presented.

Geologic Setting of Uinta Basin

The Uinta Basin is an intra-plate structural and topographic sedimentary basin within the northern Colorado Plateau (Figure 2). It is bounded on the south by the Book Cliffs, on the west by the southern Wasatch Mountains, on the north by the Uinta Mountains and on the east by the Douglas Creek Arch. The Basin is roughly elliptical in shape, stretching 210 km along its major east-west axis and 160 km in a north-south direction. The basin occupies an area of approximately 20,000 km^2.

The pre-Tertiary stratigraphic history of the Uinta Basin is one of great regularity and stability (Preston, 1957; Untermann and Untermann, 1964; Walton, 1957). Rock formations in the area range in age from Precambrian through Tertiary and represent periods of both marine and continental origin. Noticeable unconformities are rare, even absence of the Ordovician, Silurian and Permian periods does not reveal a profound erosional unconformity. Breaks are mostly faunal and lithologic rather than stratigraphic. Total thickness of sediments range from about 13.7 km in the eastern part of the Basin to about 19.2 km in the west. Approximately the upper one third of these sediments are Tertiary and are of special interest to this study.

The Tertiary System of the Uinta Basin (Figure 3) (Abbott, 1957; Picard, 1957a, 1957b; Preston, 1957; Murany, 1964; Roberts, 1964; Untermann and Untermann, 1964) began with the withdrawal of the Cretaceous sea due to uplift to the west and north, causing marine shales to grade laterally and interbed with continental sandstone, shales, and coal seams of floodplain and lagoonal character. The final phase of the Cretaceous and the early Tertiary are both represented by a continental facies of clastic sediments, thus obscuring the Cretaceous-Tertiary boundary.

The coalescing of small freshwater lakes in the western part of the Basin brought an end to the widespread fluviatile sedimentation (Wasatch and equivalent - Current Creek, North Horn, Colton) of the early Tertiary . Two major periods of lacustrine sedimentation then followed, depositing the Flagstaff limestone, and the Green River formation. Of these, the Green River, deposited by lake Uinta, is more extensive. The complex interfingering of marginal, fluvial and deltaic beds with those of lacustrine origin indicate that lake Uinta, which was probably stable for long periods and is estimated to have existed for 8 to 10 million years, underwent many fluctuations as it slowly transgressed across the broad fluviatile flood plain. In its later stages, the lake increased in salinity and gave way to an interfingering of fluviatile and lacustrine sediments during Uinta, Eocene time, as it withdrew to the west-central part of the Basin.

Deposition of the fluviatile Duchesne River Formation (Eocene?-Oligocene) followed as downwarping ceased and the Basin filled with fluviatile sediments as streams again because the major agents of deposition.

Along the northern edge of the Basin, against the southern flank of the Uinta Range, formations progressively overlap the upturned and eroded edges of the pre-Tertiary formations. Here maximum warping has produced the Uinta Basin syncline where dip varies from 10° to 35° on the north limb but flattens to 2° to 4° on the south limb (Figure 3).

The structure of the basin is relatively simple. Thus formation contacts form simple concave upward surfaces which can be described by two dimensional low order polynomial surfaces with no more than a hundred meters or so misfit to identified contacts across the basin. The interfingering of deltaic, fluviatile and lacustrine deposits coming from several source areas, on the other hand, has given rise to complex lateral facies changes within formation with consequent complications for deriving thermal conductivity profiles.

Data

The basic data set consisted of information from approximately 2000 wells in the area defined by latitudes 39.77°N to 40.50°N and longitudes 109.00°W to 110.75°W, made available from the WEXPRO Petroleum Information file. Data for each well included: a general description of the well, location (township, range, section, quarter section, distance from north-south and east-west section lines, county, petroleum field, latitude and longitude), operator, well name, surface elevation, ground level, total depth, spud and completion data, shows-oil or gas, producing formation, formation at total depth, sequence number (wells are numbered consecutively from one to the last well in the output, in this case 1969), API number, and a list of depths to formation and member tops.

The quality and completeness of data in the master file was variable. For instance, we required knowledge of formation thicknesses for our thermal resistance calculation, but from the entire data set only 1200 wells had the top of the Green River formation entered, 1000 the top of the Wasatch formation, and 70 the top of the Uinta formation. On the other hand, surface elevations were included for all wells. Bottom-hole temperatures were available for most of the wells, but the correction for drilling disturbances require multiple bottom-hole temperature measurements at successive times in order to extrapolate to an equilibrium temperature. This requirement eliminated the vast majority of the wells and limited the data set of wells with correctable temperatures to approximately 5% of all wells in the Basin. Few wells drilled prior to 1960 met this requirement. From the more recent wells with multiple measurements we further estimated those wells which had identical temperatures recorded for several log runs, believing that a temperature was measured on one log run only and simply recorded on later logs. By carefully searching well logs from the 2000 wells in the Uinta Basin, we identified 97 wells for which we could calculate a credible corrected bottom-hole temperature.

Five wells were sampled for thermal conductivity measurements. These wells were chosen from wells available at the core library of the Utah Geological and Mineral Survey on the basis of having continuous samples from near the surface to below the Wasatch Formation. The shallow Cottonwood Springs well was chosen to obtain more samples in the Duchesne River formation. The wells were also chosen to be as close as possible to areas with concentrations of bottom-hole temperature data while also sampling different areas of the Basin. Hindsight suggests that we undersampled this basin in a lateral sense.

Temperatures

Detailed temperature data were taken from well logs at the Utah Oil, Gas and Mining Division. Due to several factors, primarily fluid circulation before logging, bottom-hole temperatures from well logs are lower than the static formation temperatures. A method commonly used to correct these temperatures is the Horner technique as described by Dowdle (1975). This technique involves plotting the bottom-hole temperature in a given well versus time according to the equation:

$$T(t) = T_\infty + A \log \left(\frac{t_c + t_e}{t_e}\right) \qquad (3)$$

where t_c is the circulation time, t_e is the time elapsed since circulation, and T(t) is the time dependent bottom-hole temperature. By plotting $\log \left(\frac{t_c + t_e}{t_e}\right)$ against T one can determine T_∞, the true formation temperature, as the ordinate intercept (Figure 4). When the circulation time corresponding to a bottom-hole temperature measurement was not known, a standard circulation time of 4 hours was used (Ted Glenn, Earth Sci. Lab., Univ. of Utah, pers. comm.).

Of approximately 2000 wells in the Uinta Basin, 97 were found in which the bottom-hole temperature was recorded accurately more than once thus allowing for a determination of the constant A and application of the Horner techqnique. The determination of A and T_∞ was done by linear regression rather than graphically.

The majority of the wells are located in the Altamont-Bluebell to Cedar Rim fields of Duchesne Co. Most of the others are in the Natural Buttes field of Uinta County. The bottom-hole temperatures in these wells are at depths ranging from 1500 m in Natural Buttes to 5500 m in Altamont-Bluebell. These depths correspond to the lower Green River and Upper Wasatch formations. The locations of the 97 wells are shown in Figure 11. The corrected temperatures from these wells are plotted versus depth in Figure 5. The wide scatter indicates that the geothermal gradient is not uniform throughout the basin. The mean geothermal gradient for the Basin from these data is $25^{o}C\ km^{-1}$.

Since the vast majority of the wells in the Basin do not have sufficient data for correction by the Horner technique, a method for correcting these temperatures has been derived empirically from the corrected temperatures and times since circulation. As shown in Figure 5 the relation is $T_\infty = T\ (1.1104 - .0259\ \ln(t_e)$ with an uncertainty of about 3%. The magnitude of this correction agrees with corrections suggested by others. Schoeppe and Gillaranz (1966) suggest that maximum logged temperatures of deep wells are within 5% of true static formation temperatures. Carvalho (1977) stated that for elapsed times greater than 10-12 hours the bottom-hole temperatures are accurate to within 8% of the true static formation temperatures. Note that from Figure 5 the mean correction for the Uinta Basin wells was 5%.

Thermal Conductivity

All thermal conductivity values were determined using the modified divided bar designed by Blackwell (Roy et al., 1968) and similar in operation to that described by Sass et al. (1971a). The bar was calibrated with standards of fused silica and crystalline quartz using temperature dependent conductivity given by Ratcliffe (1959) and a procedure given by Chapman (1976) which accounts for lateral heat losses and sample contact resistance. Reproducibility of thermal conductivity determination is typically better than 2%, inter-laboratory agreement between measurements on identical samples has been shown to be better than 5% (Chapman, 1976). For drill cuttings we used the cell technique of Sass et al. (1971b).

Five wells in the Uinta basin were sampled for thermal conductivity measurements. The wells are identified as Rock Creek, Fisher, Cottonwood Springs, Red Wash and South Ouray; details including location, depth and lithology are given in Table 1. We sampled the wells initially at 30 m intervals so that we would have between 10 and 20 samples per formation per well. This sample interval was decreased to 15 m when erratic behavior in the conductivity profile was observed. Subsequent analysis indicates that this constituted an unnecessary oversampling in a vertical sense; it would have been preferable to sample a greater number of wells with fewer samples per formation.

Thermal conductivity results for the five wells are shown in Figures 6(a) through 6(e). In each figure we have plotted the individual results for all samples measured, together with a histogram representing each formation. The numbers of samples, conductivity and standard deviation are compiled in Table 2.

The variety in the thermal conductivity results, both in the formation means between wells, and in the distribution of values in a single well, reflects primarily the complex depositional environment for the Tertiary Uinta Basin formations. For the South Ouray well conductivities of all formation are quite well constrained, as indicated by tight distributions and standard deviations between 0.3 and 0.5 $Wm^{-1} K^{-1}$. In other wells certain formation conductivities are poorly constrained, as for example the Duchesne River Fm. in the Fisher well or the Green River Fm. in the Red Wash well where standard deviations are 1.5 to 1.7 $Wm^{-1} K^{-1}$. In both these latter cases the distribution is bimodal resulting from a mixed sand-clay lithology where the sandy components are characterized by conductivities of 5 - 7 $Wm^{-1} K^{-1}$ as opposed to clay rich sediments having conductivities of 1.5 - 3 $Wm^{-1} K^{-1}$.

The thermal conductivities given in this paper are consistent with values reported in previous studies. Reiter et al. (1979) report a mean conductivity for the Evacuation Creek and upper Parachute Creek members of the Green River formation in the Red Wash field to be 2.32 (s.d. 0.25) $Wm^{-1} K^{-1}$. For the same interval in the Red Wash well used in this study, the mean for the measurements is 2.50 (s.d. 0.95) $Wm^{-1} K^{-1}$. A second comparison can be made in the south Ouray field. The mean value for the Uinta formation of 2.14 (s.d. 0.45) $Wm^{-1} K^{-1}$ determined in well W-EX-1 by Sass et al. (1971a) closely agrees with our value of 2.12 (s.d. 0.41) $Wm^{-1} K^{-1}$ (see Table 2).

A less welcome feature of the thermal conductivity results is the different conductivities from well to well in any given formation. For example the Green River Formation has a conductivity of 3.7 $Wm^{-1} K^{-1}$ in the Red Wash well but 3.1 for Rock Creek and Fisher and only 2.2 at South Ouray. While such a pattern is consistent with depositional environments, in particular the high Red Wash value coincides with an extensive tongue of high percentage sand sediments, it complicates the processing of thermal data as on an entire basin scale. Our initial approach was to characterize each formation by a constant thermal conductivity as has been possible in the Mesozoic sedimentary rocks of the Central Colorado Plateau (Bodell and Chapman, 1982). Mean values following this approach are given in Table 2, and subsequent calculations of heat flow and surface temperatures use these values. However a preferable approach which we will explore in the future involves relaxing the constant conductivity requirement and allowing thermal conductivity within each formation to vary with position.

The thermal conductivity value determined for chips using the cell technique corresponds to the conductivity k_s of the solid grain component only and at the temperature at which measurements are made. Several corrections must be applied to adjust for in situ thermal conductivity.

For rocks with a natural porosity ϕ_o, the water saturated rock conductivity k_r, appropriate for in situ conditions, will be given by

$$k_r = k_w^{\phi_o} k_s^{(1-\phi_o)} \tag{4}$$

where k_w is the conductivity of water. Chapman et al. (1981) illustrated the importance of this effect on the thermal conductivity k_r. For example, for a conductivity range of 1.5 to 3.5 $Wm^{-1} K^{-1}$, a 10% porosity adjusts the measured chip conductivity by 9-16%. It was not possible to measure porosities for individual samples and porosities from well logs are reliable only as a general indicators. Therefore we have chosen a generalized porosity-depth function to characterize the basin. Figure 7 shows a variety of porosity-depth functions varying from linearly decreasing curves suitable for pure sands and exponentially decreasing curves more appropriate for shaley lithologies. The distribution chosen for the Uinta basin is

$$\phi_o = 0.16 \exp(-z/4.1) \tag{5}$$

where z is depth in kilometers. This relation yields a porosity of 16% at the surface and a little less than 4% at 6 km depth.

The conductivity of water k_w is also needed for the porosity correction, assuming the pores are filled with water. Water has a conductivity of 0.56 $Wm^{-1} K^{-1}$ at 0^oC but it increases to 0.68 $Wm^{-1} K^{-1}$ at 100°C. We have approximated temperature-conductivity data for water given by Kappelmeyer and Haenel (1973) by the following functions:

$$k_w = 0.56 + 0.003\ T^{0.827} \qquad 0 \leq T \leq 63°C \qquad (6)$$

$$k_w = 0.481 + 0.942 \ln T \qquad T > 63°C \qquad (7)$$

These equations were then used to adjust k_w for in situ conditions in the basin.

As more data are gathered on the temperature coefficients of thermal conductivity for a variety of sedimentary rocks, it would be appropriate to give each characteristic lithology a temperature dependent conductivity through the parameter k_r also. For this study we have assumed that k_r is independent of temperature. No attempt was made to make anisotropy corrections due to the complexity of the problem and the relatively small effect it is believed the corrections would have in this situation.

Surface Heat Flow

This section describes procedures which may be used in processing large data sets of bottom-hole temperatures to obtain heat flow patterns and subsurface temperature maps. If, for each well, a corrected bottom-hole temperature were available, and if the detailed lithology were known and could be converted into a thermal conductivity profile, then the computation of heat flow would be relatively simple. In reality the data set is incomplete, and alternative approximation measures must be adopted.

For the Uinta Basin there are approximately 2000 wells between latitudes 39.75 N and 40.50 N and between longitudes 109.00 W and 110.75 W. Of these, only 97 have multiple bottom-hole temperatures recorded so that equilibrium corrections can be made. However, not even all of these 97 well records contain complete lithological information necessary for the thermal resistance method. Fortunately, in the Uinta Basin the structure of the basin is sufficiently regular to permit estimation of formation contacts.

We approximate the position of formation contacts by fourth order polynomial surfaces. The surfaces were generated utilizing all wells with pertinent information: the top of the Uinta formation was available in 70 well records and the Green River and Wasatch formations in about 1000 records each. The choice of fourth order polynomials to represent the formations was made on the basis of a plot of rms residual (difference between recorded formation position and calculated position using the polynomial surface) versus polynomial order. Figure 8 illustrates that formation contacts are adequately expressed as fourth order surfaces and that little benefit is gained by adding higher orders.

One filtering process required for the Uinta Basin concerned raw data where formation tops identified on well logs departed from the polynomial surfaces by several hundred meters. In such a case the data points were eliminated and the surface coefficient were recalculated. This process led to a reduction of 5% in the Wasatch formation records, 10% in the Green River formation records, and 10% in the Uinta formation records. The discrepancy lies partly in the difficulty of identifying formation boundaries but also in systematic differences between the stratigraphic conventions adopted by different companies. The average rms errors for each formation after filtering the data are: Uinta formation top 81 m, Green River formation top 70 m, and Wasatch formation top 70 m.

From these polynomial surfaces depths to formations were obtained for wells in which any formation tops were missing, and formation thickness were calculated for use in the thermal resistance calculation. A subroutine was developed to compute porosity corrected thermal conductivity for each formation at any location. This subroutine computes the average conductivity of water k_w as a function of temperature and hence depth, the average porosity and the porosity corrected thermal conductivity for each formation according to the relations described earlier. Because the formations are at different depths in different parts of the basin, the porosity corrections causes the thermal conductivity of each formation to vary laterally, primarily in a north-south direction, but also to a lesser extent in the east-west direction, corresponding to the depth of the formations. Once the conductivities were calculated, all the information was available for the computation of surface heat flow from the thermal resistance equation.

Surface heat flow in the Uinta Basin is shown in Figure 9. After rejecting three anomalous values using the Chauvenet rejection criteria (p. 23, Beers 1962) the mean heat flow for the 94 wells is 58 mW m^{-2} with a standard deviation of 8 mW m^{-2}. Heat flow varies from 40 mW m^{-2} to 70 mW m^{-2} across the Altamont-Bluebell fields in Duchesne Co. The Natural Buttes area in Uinta Co. has a mean heat flow of about 60 mW m^{-2} with no particular trend.

The heat flow values determined by using oil well data in this study agree reasonably well with the two values determined previously in the Uinta Basin by more conventional heat flow techniques. As shown in Figure 9 the value of 63 mW m^{-2} determined by Sass et al. (1971) at South Ouray over a depth range 61 to 907 m is surrounded by our values of 61, 57, 62, 59 and 58 mW m^{-2}. And while the value of 65 mW m^{-2} given by Reiter et al. (1979) for Red Wash departs from our 43 mW m^{-2} to the north it is not very different from the two nearest values to the west of 56 and 63 mW m^{-2}. The lower value from our method in Red Wash probably results from our assumption of constant conductivity within formations, whereas in fact formations undergo rapid facies changes in this region as discussed previously.

Once the surface heat flow pattern has been determined, then subsurface temperatures at any depth can be determined by a direct application of equation 1 with the sum being performed to the depth required. An example of temperatures at 1 km depth is shown in Figure 10. The temperature pattern will generally be similar to the heat flow pattern, except where lateral lithological varition cause thermal conductivity constrasts. Mean subsurface temperatures in the Uinta Basin are 21.2 ± 2.6°C at 500 m, 32.8 ± 5.0°C at 1000 m depth, 57.6 ± 9.2°C at 2000 m depth and 85.1 ± 12.6°C at 3000 m.

Error Analysis

Throughout the calculation, error propagation was computed using the general formula (Bevington 1969):

$$\sigma_x^2 = \sigma_u^2 \left(\frac{\partial x}{\partial u}\right)^2 + \sigma_v^2 \left(\frac{\partial x}{\partial v}\right)^2 + 2\sigma_{uv}^2 \left(\frac{\partial x}{\partial u}\right) \left(\frac{\partial x}{\partial v}\right) \qquad (8)$$

where x = f(u, v). Since all the errors encountered in formation depths, thermal conductivities, and temperatures were uncorrelated, the covariance terms, $\sigma^2 uv$, are all zero. This leads to the following specific formulas which were used in an error subroutine:

for $x = au \pm bv$ $\qquad \sigma_x = (a^2\sigma_u^2 + b^2\sigma_v^2)^{1/2}$

for $x = \pm auv$, $x = \pm au/v$ $\qquad \sigma_x = x(\frac{\sigma_u^2}{u^2}) + \frac{\sigma_v^2}{v^2})^{1/2}$

for $x = au^{\pm b}$ $\qquad \sigma_x = xb \frac{\sigma u}{u}$

In computations, the average rms errors of the polynomial surfaces were used as the errors of the formation depths whether the depths used were picked tops or polynomial computed tops. Accuracy of picked formation tops in the PI file is not less than about 50 m (pers. comm. J. Hummel, C. Tripp). These errors in formation depths result in an average error of 5.6% in surface heat flow. An error of 2°C in surface temperature results in an error of about 1% in surface heat flow. The standard deviation in formation thermal conductivity which range from 8% to 40% result in a 14% error in surface heat flow. The cumulation of these errors results in a total error of 15% in surface heat flow values. Because the errors are uncorrelated, the larger error in thermal conductivity dominates the error propogation. If the error in surface heat flow solely due to conductivity could be reduced from 14% to 10% the cumulative error in surface heat flow would drop to 11%. Reducing the error due to conductivity to 5% would reduce the cumulation error to 8%.

The uncertainty in subsurface temperatures are larger, approaching 21%, because the calculations of the temperatures involve the surface heat flow with its error of 15% as well as the thermal conductivity with its large errors. The subsurface temperatures are also affected more by error in mean annual surface temperature. A 2°C error at the surface propagates directly as a 2°C error anywhere in the subsurface. Because of this, the average percent error at 500 m reaches a maximum of 22% depth. Uncertainty increases with depth due to accumulation of errors in depth are balanced as the 2°C error at the surface becomes a smaller factor in the error due to increased in situ temperatures.

Discussion

The thermal resistance method described in this report and applied to the Uinta Basin is generally applicable to data sets of oil and gas well thermal data in sedimentary basins. The method makes few assumptions of uniformity concerning thermal gradients, thermal conductivity or homogeneity within the basin. Instead, bottom-hole temperature data are treated individually, together with a best estimate of the vertical thermal conductivity profile at the well site, to produce a local heat flow value. Maps of surface heat flow and subsurface temperatures at arbitrary depths are products of the method.

For the Uinta Basin, we restricted our investigation to 97 wells where bottom-hole temperatures could be corrected for drilling effects. Surface heat flow values, determined by this thermal resistance method agree reasonably well with values determined by conventional heat flow methods in the two cases where comparisons could be made. Heat flow in the basin varies from 40 to 70 mW m^{-2} with a pronounced gradient of increasing heat flow away from the Uinta Mountains. This gradient could possibly be an artifact caused by our uniform thermal conductivity assumption within each formation, but also could be influenced by either refraction of heat flow into the conductive quartzites of the Uinta Mountains or a regional groundwater flow from the Uinta Mountains towards the Duchesne River drainage in the basin. Subsurface temperature maps show similar spatial variations to the surface heat flow map.

Difference between temperatures computed by the simple gradient method and those computed by the thermal resistance method, on the average, are small for the Uinta Basin. This is due to the almost identical porosity corrected thermal conductivities of the Green River and Uinta formations. The Duchesne River and Wasatch formations have significantly different conductivities, but the Duchesne River formation is absent in two thirds of the study area and is thin compared to the depths of the bottom-hole temperatures where it is present. The difference between the simple gradient temperatures and the thermal resistant temperatures does increase with depth. At 3000 m, average temperatures are different by 8%.

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FIGURE CAPTIONS

Figure 1. Schematic representation of two methods for processing bottom-hole temperature data from oil and gas wells. Symbols: T_o surface temperature, T_B bottom-hole temperature, q_o surface heat flow, z depth, k thermal conductivity.

Figure 2. Location map for the Uinta Basin of northeast Utah. Shaded area indicates Tertiary outcrop. Rectangle is study area, for reference in Figures 9 and 10.

Figure 3. North-south cross section through the Uinta Basin. Section follows profile DD' of Figure 2.

Figure 4. Top. An example of a bottom-hole temperature correction. Multiple log readings 9, 16, and 32 hours after circulation ceased are used to extrapolate to the equilibrium temperature T_∞. Bottom. Magnitude of bottom-hole correction, expressed as a percentage of the observed value in ^oC as a function of elapsed time after circulation, for 97 wells with multiple BHT values recorded.

Figure 5. Corrected bottom-hole temperatures versus depth for 97 wells distributed over the Uinta Basin. Wells are coded with respect to the producing fields.

Figure 6. Thermal conductivity results for five wells in the Uinta Basin: (a) Rock Creek, (b) Fisher, (c) Cottonwood Springs, (d) Red Wash and (e) South Ouray. Well locations are shown in Figure 9 and tabulated in Table 1.

Figure 7. Porosity-depth functions for some typical lithologies. UB indicates generalized porosity relationship adopted for the Uinta Basin.

Figure 8. Root mean square (rms) residuals between position of formation top recorded on well log and position computed from the polynomial surface approximation.

Figure 9. Surface heat flow for 97 wells (solid dots) in the Uinta Basin computed from the thermal resistance method. Open circles with crosses indicate wells used for thermal conductivity sampling. Triangles give sites of conventional heat flow determination with corresponding heat flow values in square brackets.

Figure 10. Subsurface temperatures at a depth of 1000 m in the Uinta Basin.

Table 2. Thermal conductivity results for the Uinta Basin.

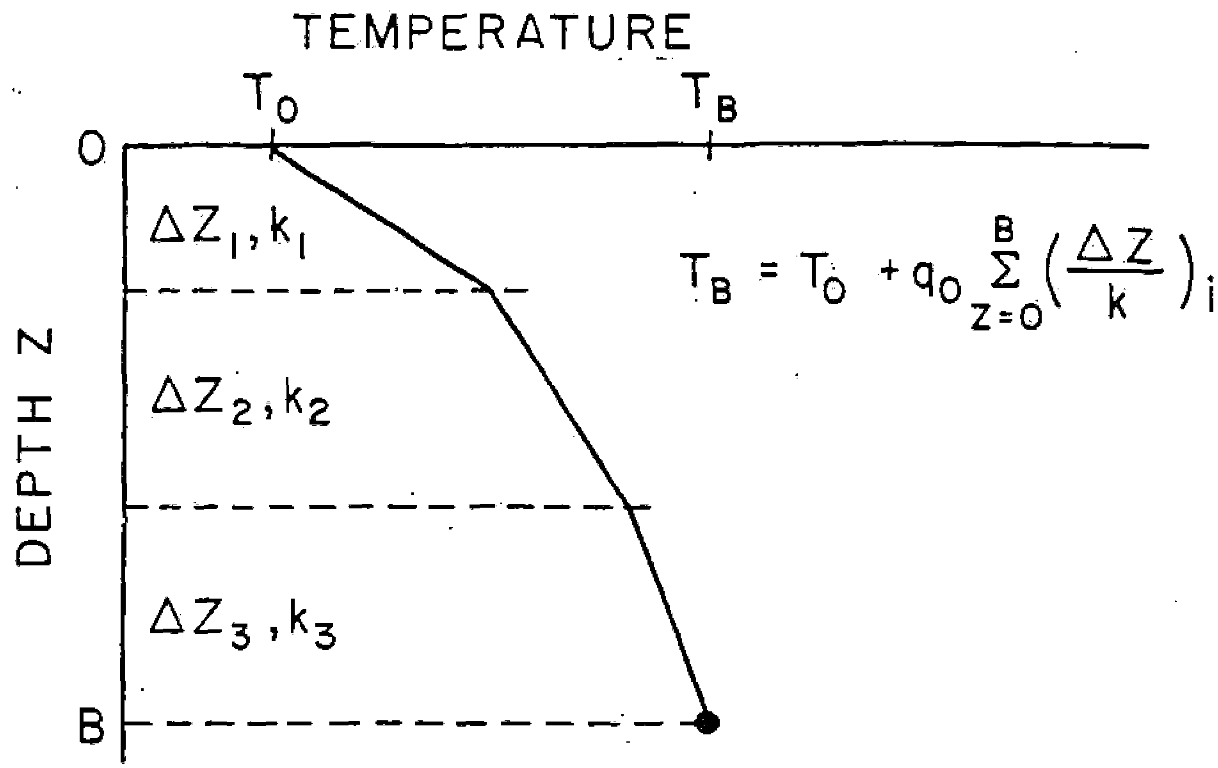
Well	Duchesne R.			Uinta			Green R.			Wasatch			Mesa verde		
	N	k	s.d.	N	k	σ	N	k	σ	N	k	σ	N	k	σ
Rock Creek				41	4.37	0.94	135	3.13	0.80						
Fisher	28	4.80	1.65	77	2.78	0.59	106	3.15	0.86	75	2.57	0.30			
Cottonwood Spr.	23	4.81	0.35	17	4.37	0.78									
Red Wash				15	2.44	0.41	58	3.70	1.55	37	2.89	0.40	32	2.80	0.79
S. Ouray				49	2.12	0.41	53	2.22	0.48	59	2.29	0.38	47	2.79	0.31
(Mean)	51	4.80		199	3.22		352	3.05		171	2.58		79	2.80	

(The column headings are grouped under "Formation".)

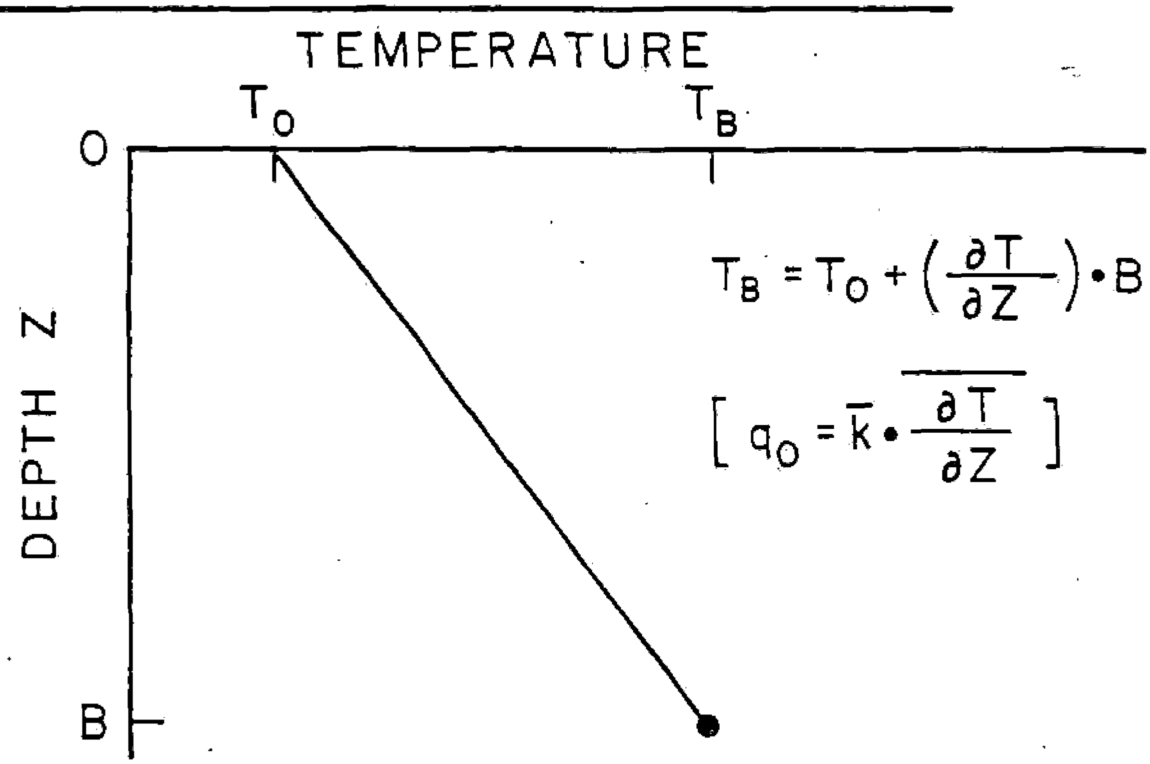
Notes: N is number of samples, k is thermal conductivity in $Wm^{-1} K^{-1}$, σ is standard deviation in $Wm^{-1} K^{-1}$.

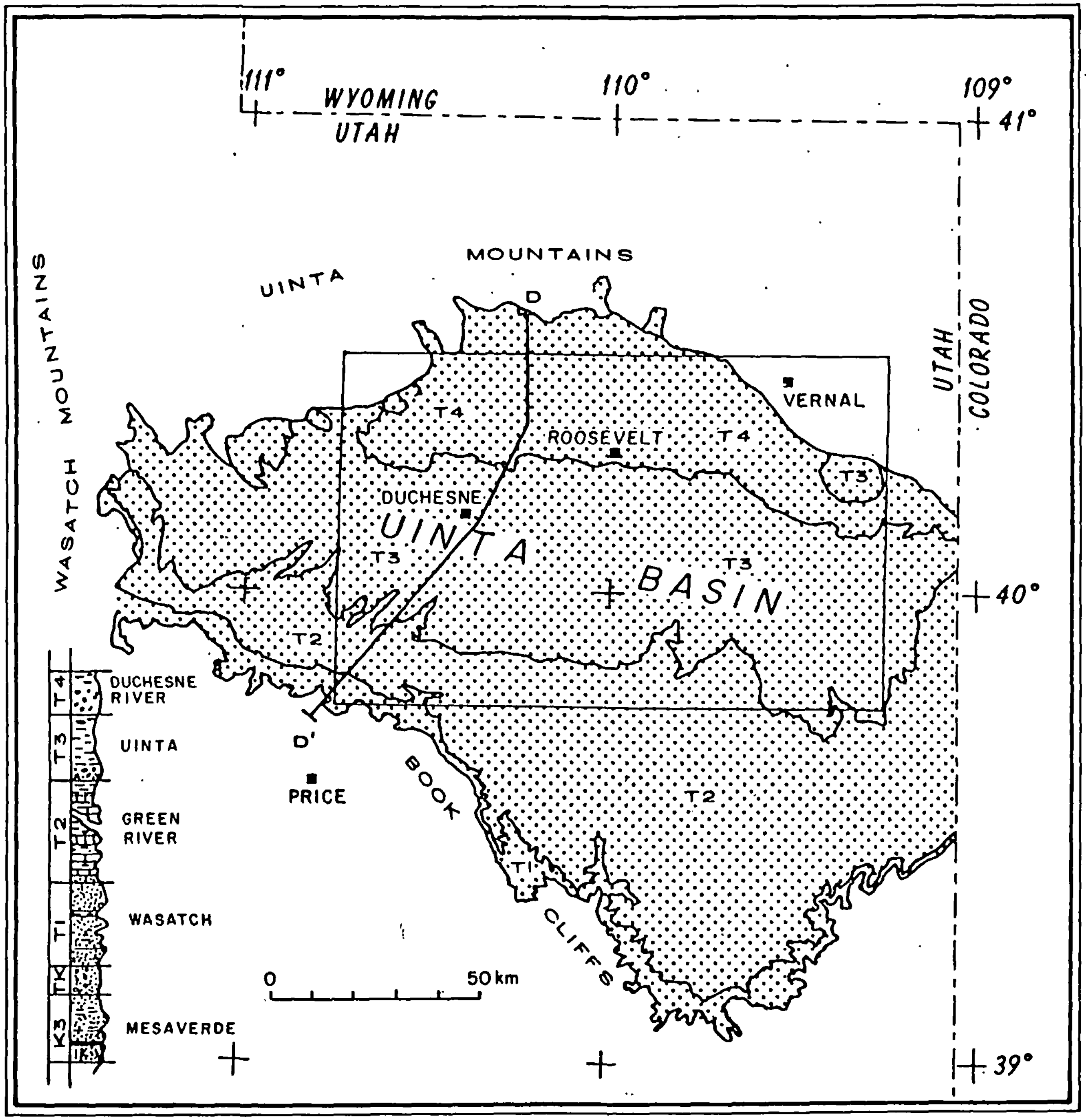
Compiled June 28/82 from histograms and data sheet (M. Bauer) giving N.

THERMAL RESISTANCE METHOD

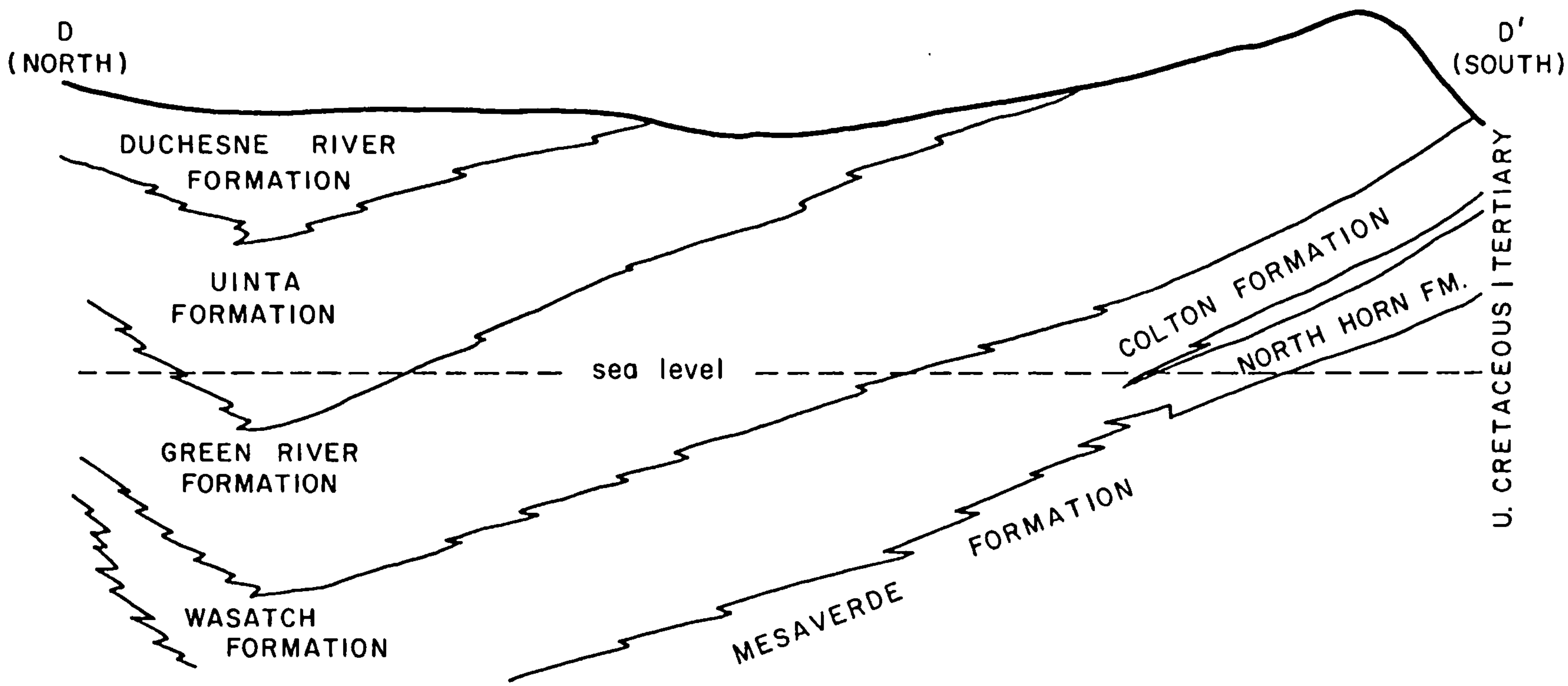


SIMPLE GRADIENT METHOD



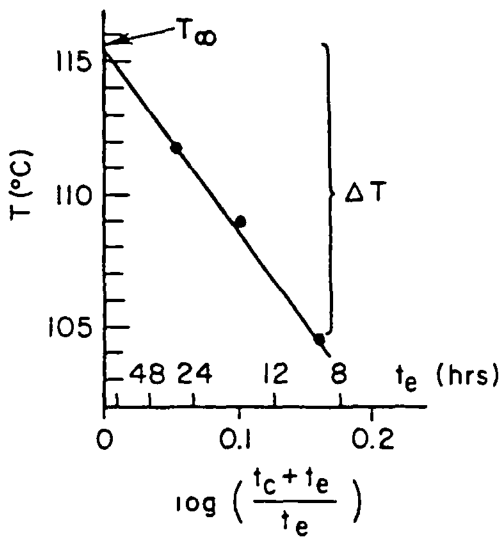


111°
110°
109°
WYOMING
UTAH
41°
40°
39°
MOUNTAINS
UINTA
WASATCH MOUNTAINS
UTAH
COLORADO
D
VERNAL
T4
ROOSEVELT
T4
T3
DUCHESNE
UINTA
BASIN
T3
T3
T2
T2
T1
D'
PRICE
BOOK
CLIFFS
0
50 km
T4
DUCHESNE RIVER
T3
UINTA
T2
GREEN RIVER
T1
WASATCH
TK
K3
MESAVERDE



D
(NORTH)
D'
(SOUTH)
DUCHESNE RIVER FORMATION
UINTA FORMATION
sea level
GREEN RIVER FORMATION
WASATCH FORMATION
COLTON FORMATION
NORTH HORN FM.
MESAVERDE FORMATION
U. CRETACEOUS | TERTIARY

BOTTOM HOLE TEMPERATURE CORRECTIONS



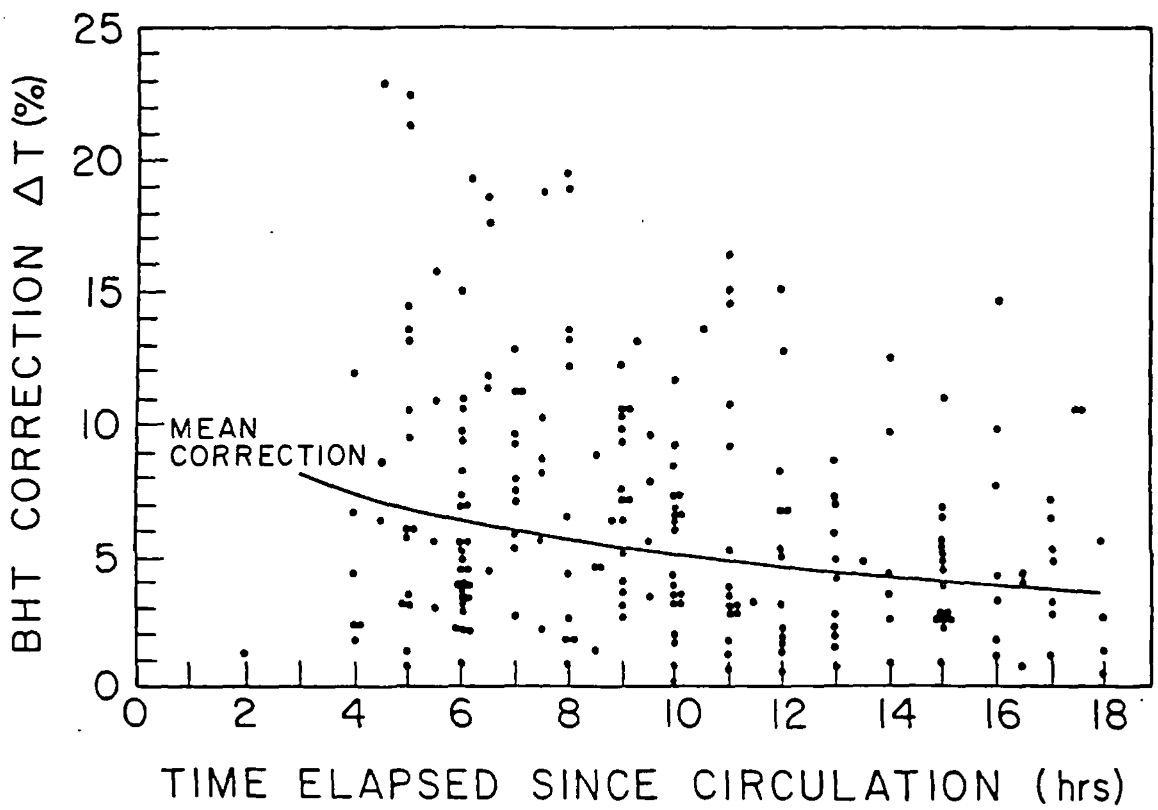
MODEL

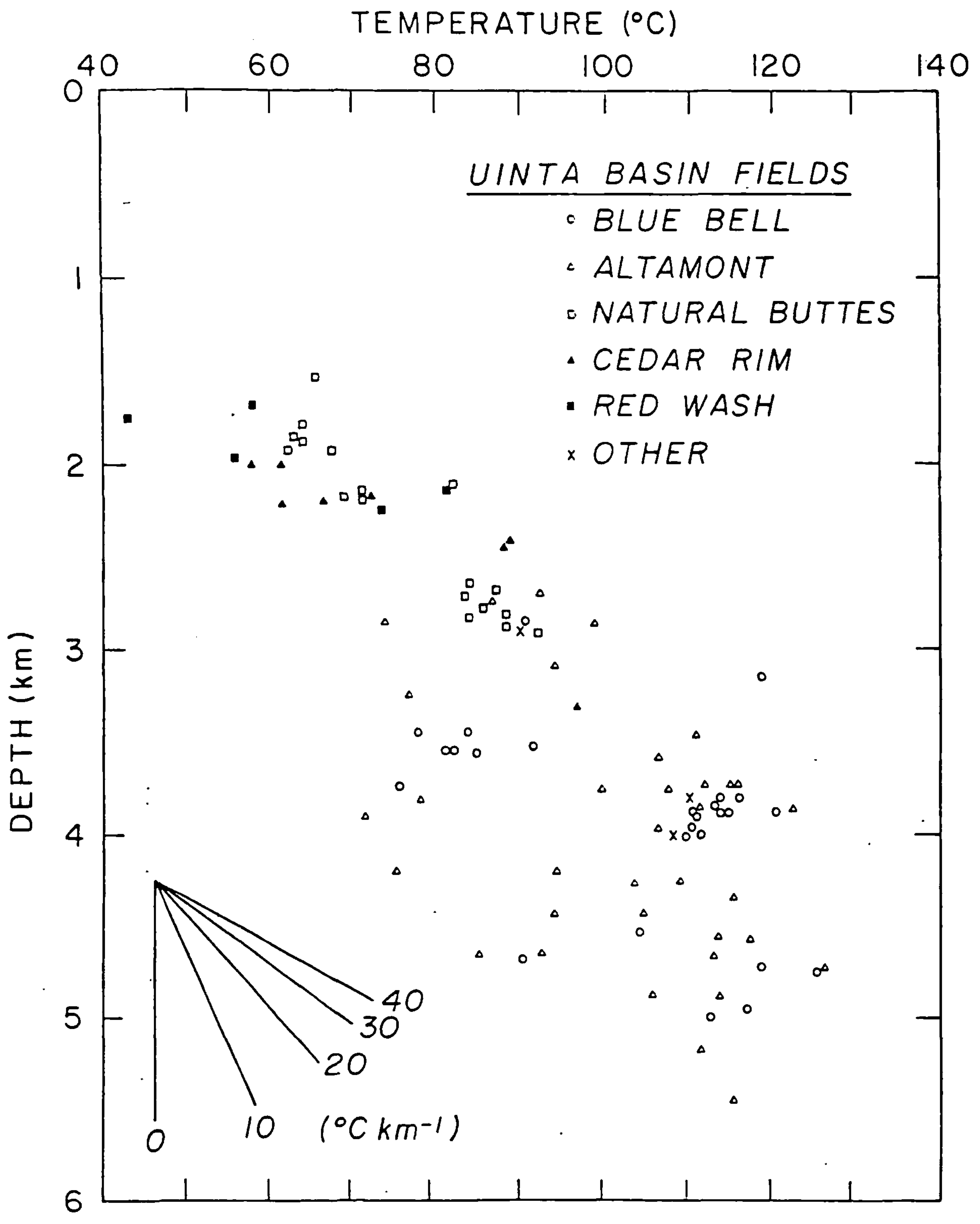
$$T(t) = T_\infty + A \log\left(\frac{t_c + t_e}{t_e}\right)$$

where t_c circulation time

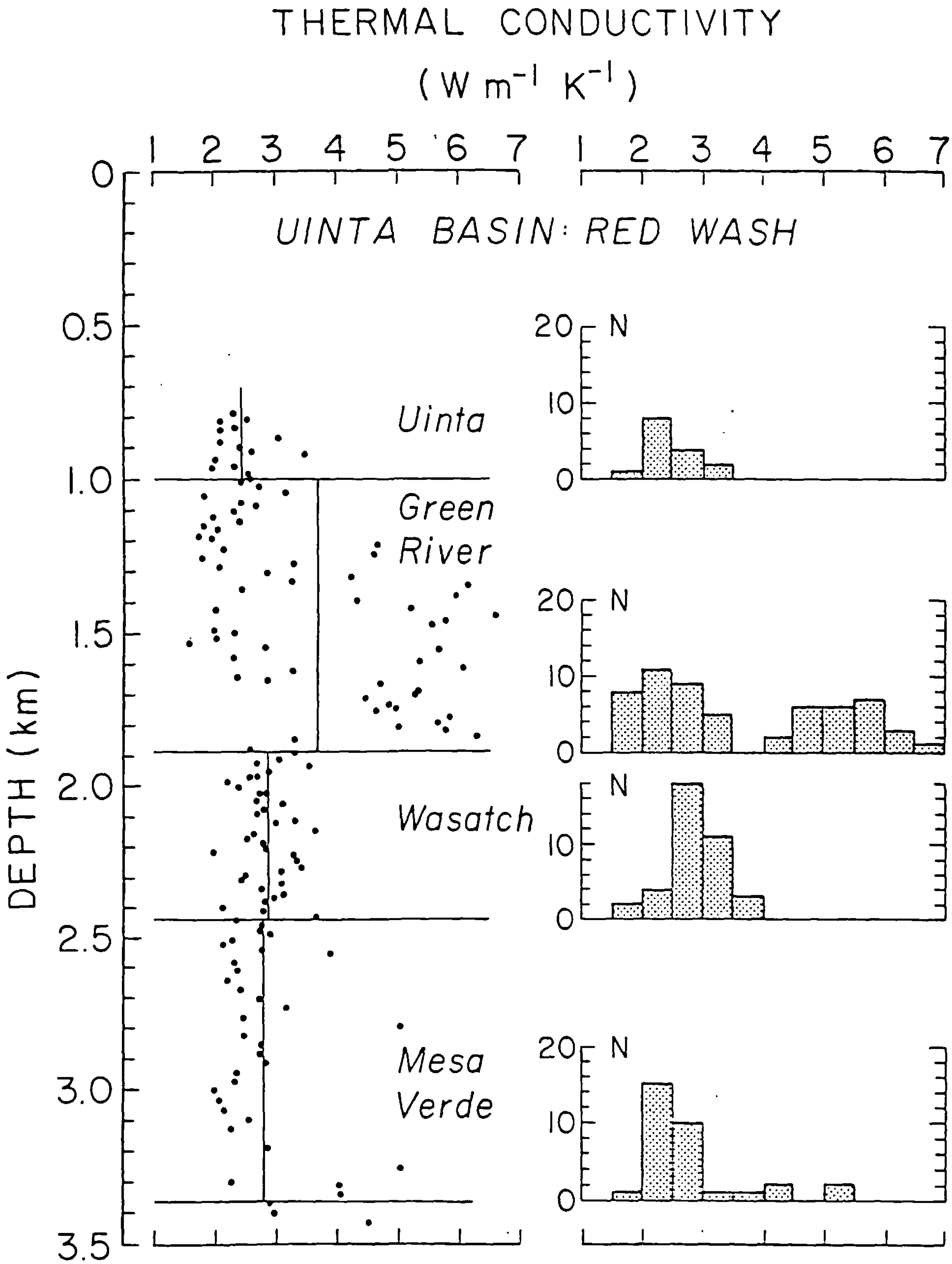
t_e elapsed time

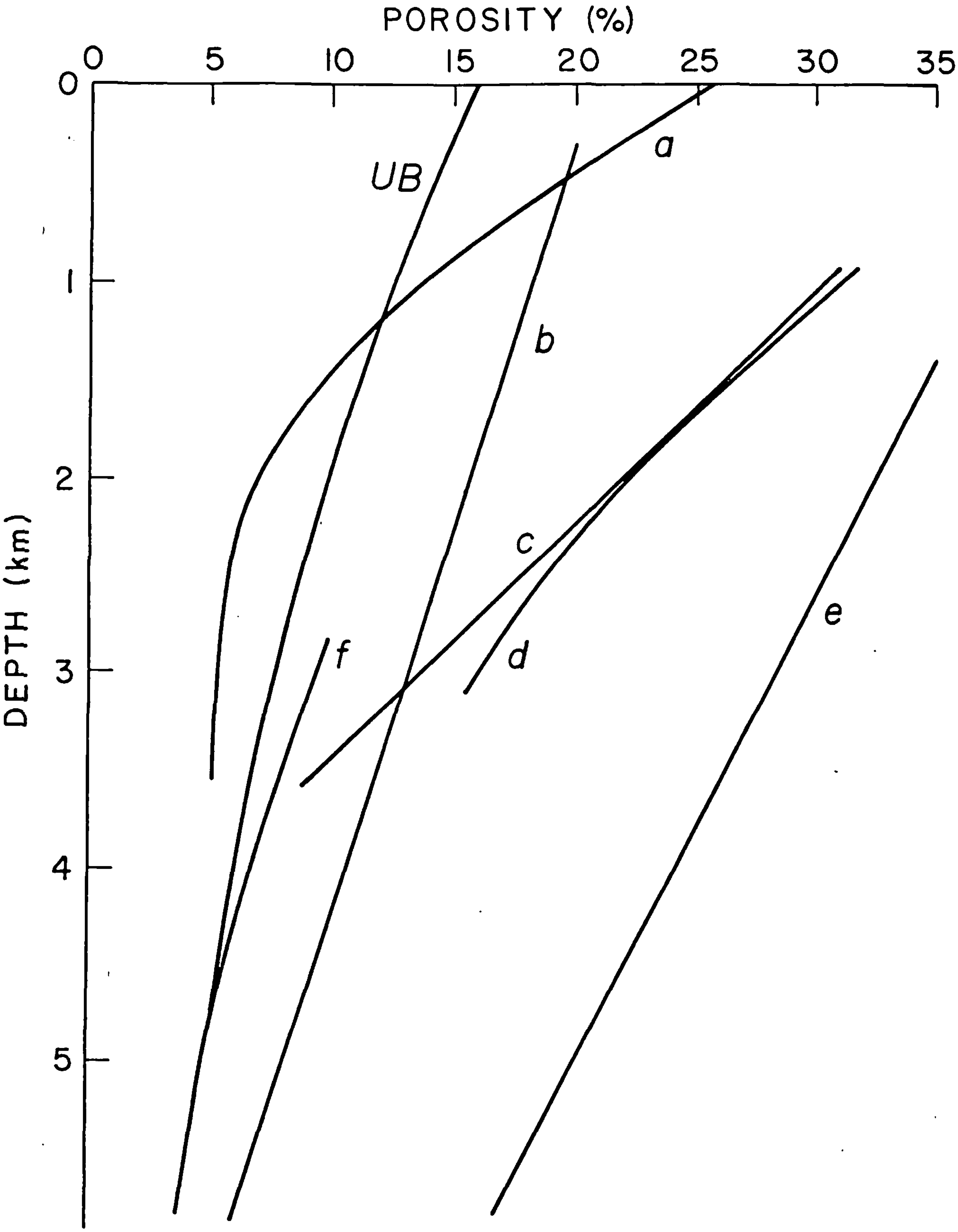
T_∞ equilibrium T

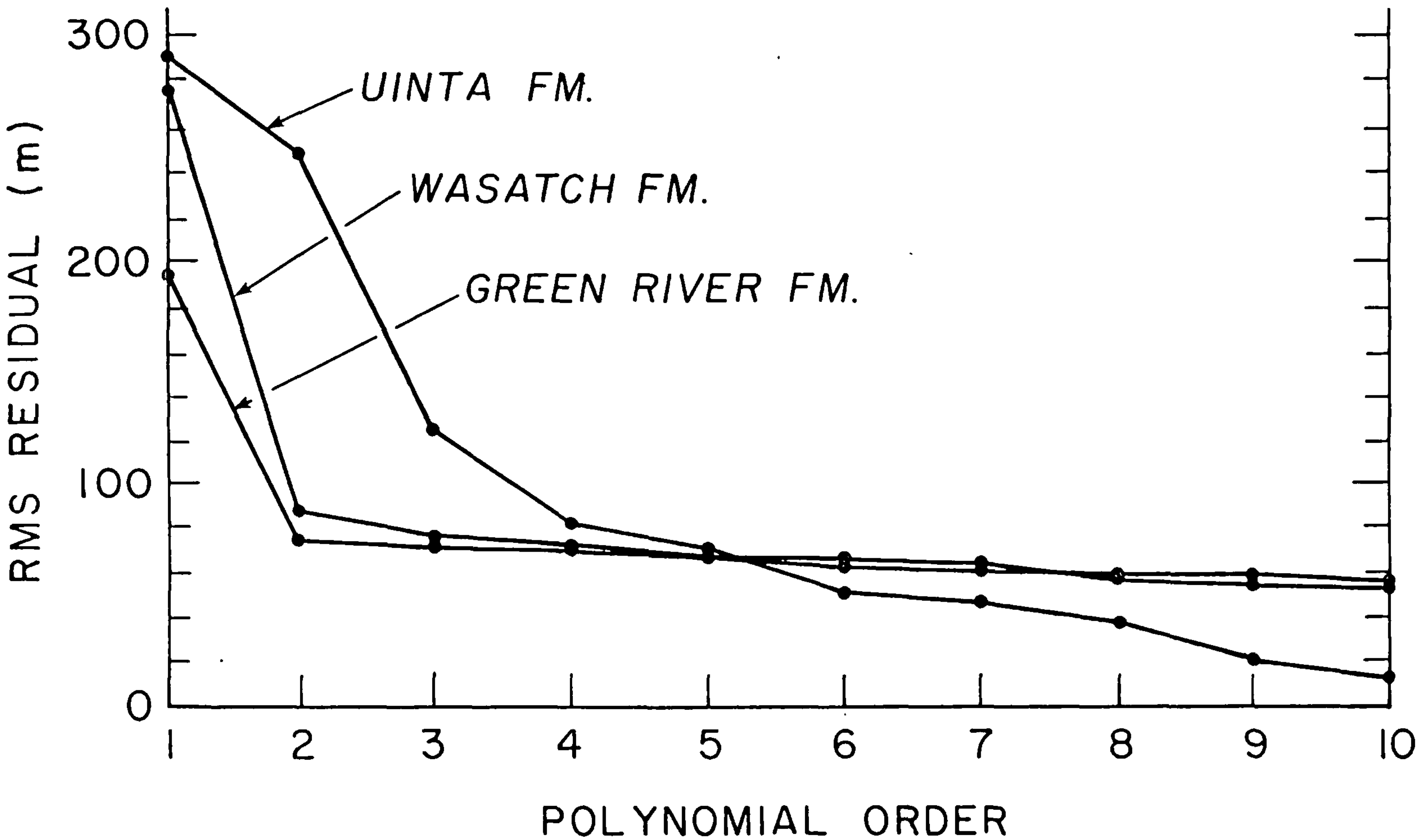




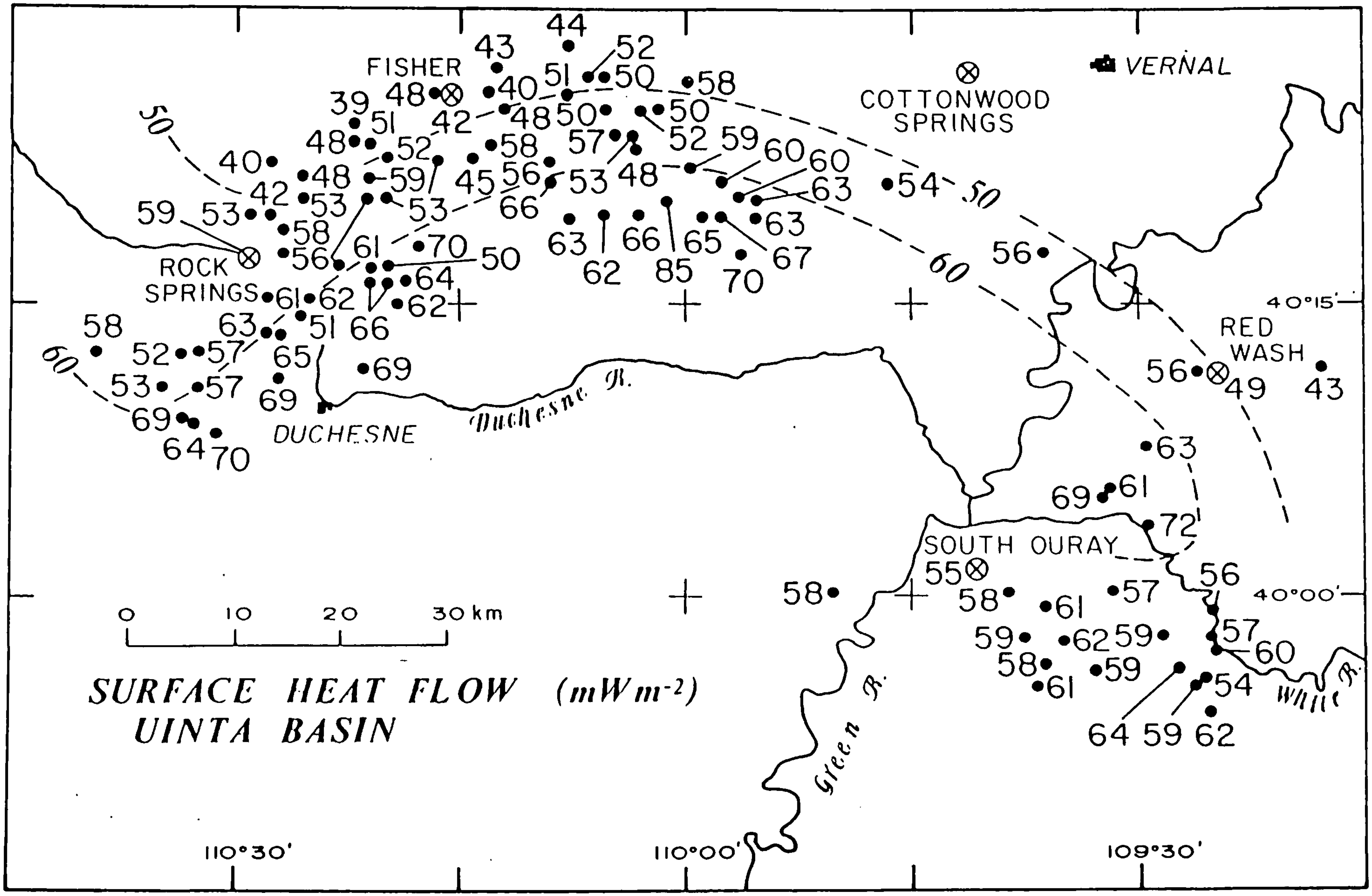
TEMPERATURE (°C)
40
60
80
100
120
140
0
1
2
3
4
5
6
DEPTH (km)
UINTA BASIN FIELDS
BLUE BELL
ALTAMONT
NATURAL BUTTES
CEDAR RIM
RED WASH
OTHER
40
30
20
10
0
(°C km-1)


THERMAL CONDUCTIVITY
(W m⁻¹ K⁻¹)
1 2 3 4 5 6 7
1 2 3 4 5 6 7
UINTA BASIN: RED WASH
DEPTH (km)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Uinta
Green River
Wasatch
Mesa Verde
N
20
10
0

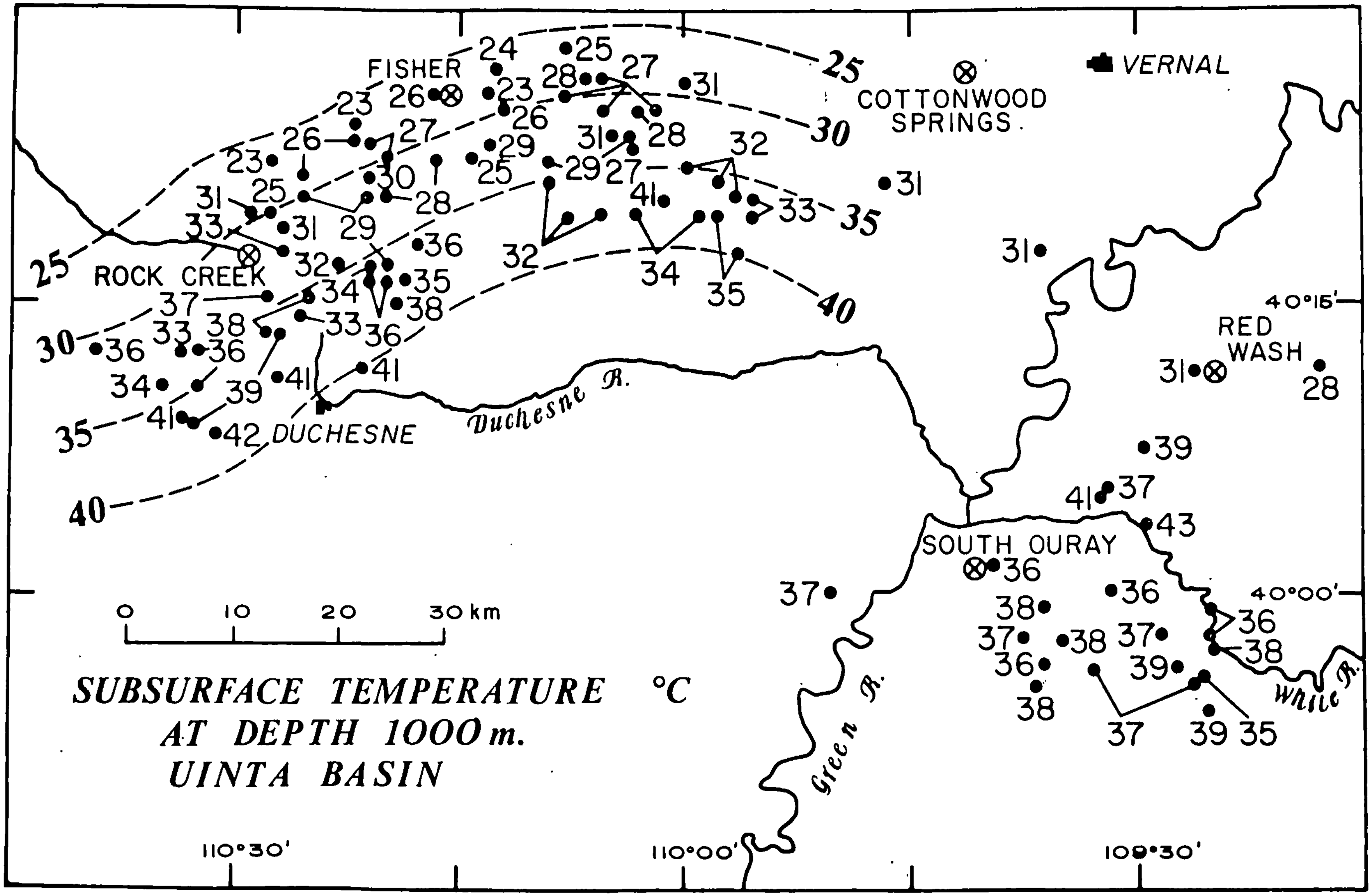

POROSITY (%)
0
5
10
15
20
25
30
35
DEPTH (km)
0
1
2
3
4
5
UB
a
b
c
d
e
f



UINTA FM.
WASATCH FM.
GREEN RIVER FM.
300
200
100
0
RMS RESIDUAL (m)
1
2
3
4
5
6
7
8
9
10
POLYNOMIAL ORDER



SURFACE HEAT FLOW (mWm-2)
UINTA BASIN



FISHER
VERNAL
COTTONWOOD SPRINGS
ROCK CREEK
DUCHESNE
Duchesne R.
RED WASH
SOUTH OURAY
Green R.
White R.
40°15'
40°00'
110°30'
110°00'
109°30'
0 10 20 30 km
SUBSURFACE TEMPERATURE °C
AT DEPTH 1000 m.
UINTA BASIN