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GEOTHERMAL PROSPECTING FOR OIL: A PRELIMINARY STUDY OF ITS APPLICABILITY IN WESTERN CANADA

by

J. VISMAN

Fuels Division

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SUMMARY

Ground temperature investigations have been made in Canada since Callendar published the first paper in this field in 1894. Studies of the variations in ground temperature have been made at intervals for various purposes, mainly in connection with soil surveys, highway research and for meteorological purposes. Temperature surveys have been conducted to locate oil deposits related to salt dome and anticlinal structures in the United States and for correlation purposes during the last two decades. These measurements were always carried out near the source of variation, whereas the method described in this report is occupied mainly with near-surface temperatures affected by variations in strata buried at depths of the order of 5,000 feet. The temperature pattern near the surface is necessarily influenced by all the underlying strata. Statistical analysis of the local and regional variations and correlation with geological data are required to extract the information which may aid in increasing the chances of finding oil and gas deposits. The conclusions of this study may be condensed as follows. Analysis of available field data reveals that oil- and gas-bearing structures at depths of approximately 5,000 feet do affect the pattern of near-surface temperatures. Anticlines and ridge-faults (horsts), being of a denser structure, will generally show a positive anomaly; reef formations, a negative anomaly. Bodies of oil and gas contained in these structures will lower the thermal conductivity in proportion to the porosity of the container and depth of oil and gas and may perceptibly affect the near-surface temperature pattern. The presence of oil and especially of gas tends to offset the positive anomaly produced by anticlines, and increases the negative anomaly produced by bioherms. The efficiency of the temperature survey as a tool for prospecting depends on the availability of additional information and on the analysis of the field data. The method can be used for rapidly scanning large areas at low cost. In addition, it would appear that near-surface temperature surveys will be particularly useful in delineating the contours of newly discovered oil fields.

Knowledge of the vertical heat-flow pattern near the surface is of great importance for a correct interpretation of near-surface temperature patterns. More data relating to Canadian conditions are required to correctly interpret near-surface influences, in particular the effects of topography, moisture and vegetation.

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INTRODUCTION

This report has been prepared by a member of the staff of the Fuels Division who has specialized in the application of statistical analysis to the interpretation of experimental data in laboratory and plant research projects. In this study an example of statistical analysis is given where an experimental geophysical method has been tried to determine whether a shallow sub-surface temperature survey is indicative of variation in strata buried below depths of the order of 5,000 ft. This method has been proposed as an oil exploration technique but the oil companies require a demonstration that it has tangible possibilities as a procedure of practical significance.

The project was undertaken in November 1956 following discussions under the auspices of the Director of the Alberta Research Council between Petronics of Canada Limited, the company responsible for the geothermal prospecting, and the author.

The study indicates that the method requires considerable geological control but it also demonstrates the merits of statistical analysis in the examination of a very large number of simple temperature measurements.

Geothermal surveying has been used in mineral prospecting for several decades, and its extent is described in Jakosky's Handbook "Exploration Physics" (1950):

"Temperature measurements of the earth's crust can be used to furnish fundamental information related to the origin and history of areas under observation. In addition temperature measurements in favorable cases will yield valuable information regarding zonal distribution of ores, the configuration of intrusive bodies, the contacts between sedimentary and igneous rocks, the location of hade and throw of faults; the groundwater distribution and local and regional flow. The practical application of geothermal measurements to the solution of the various problems of economic geology is usually one of two types:

(a) near-surface temperature measurements, to study lateral variations of temperature;

(b) sub-surface measurements in drill holes to study vertical distribution of temperature along the drill hole."

The growing interest in geothermal methods is reflected in the fact that in the period between 1941 and 1948 nine patents on thermometers for thermal methods were granted in the United States alone.

Thermal prospecting for oil by means of shallow holes is a new development. Credit for its introduction is due to Dr. J. N. A. van den Bouwhuijsen, and for originating the geothermal method as a tool of prospecting, in his paper "The Geothermal Method of Geophysical Surveying" and also to Petronics of Canada Limited, a private company which was formed by Southern Alberta businessmen in 1952. In this publication, which hereafter will be referred to as the Petronics Paper, the results of three field investigations are reported and an analysis is made of the data obtained from the near-surface temperature survey. From this paper it also appears that Petronics of Canada Limited has developed a thermocouple instrument of special construction, and has also developed a method of measuring near-surface temperatures. This method can be regarded as an established technique for obtaining reliable temperature data of high accuracy (0.01°C), which are practically independent of periodic variations caused by solar heat. In the present study an appraisal is offered of the data presented by Petronics of Canada Limited and includes one survey made in Alberta. The work done is necessarily of a preliminary nature as the writer has been handicapped by lack of sufficient geological information. Despite this disadvantage, some useful conclusions can be drawn from the data available at this stage. It is felt that drawing attention to these facts may aid in the further development and practical application of geothermal surveying in prospecting for oil and natural gas.

ANALYSIS OF DATA

The problem is to ascertain whether temperature differences measured near the surface can be caused by strata buried at great depths and, if so, whether these differences can be distinguished from the other concomitant temperature effects caused by near-surface discontinuities and by lateral variations in heat conductivity and thickness of the formation.

The last point is, at this stage, particularly controversial and geothermal surveys so far have mainly been used to find temperatures of the rock immediately surrounding the thermometer station only. To draw conclusions with respect to deep seated bodies seams, at first perhaps, far-fetched, in view of the large number of factors involved. There is clearly the danger of spurious correlation (the correlating of unrelated phenomena showing superficial connection). Also there are some points with regard to near-surface effects of temperatures measured at shallow depths which are not quite clear yet and which will require further investigation.

There is some doubt about the interpretation of the data as presented by van den Bouwhuijsen, who was guided by the outlines of the isogeotherms and by averages taken in the north-south and east-west direction. On the one hand, the averages found do indicate convincingly the presence of regional discontinuities. On the other hand, certain outlines of the isogeotherms are assumed to indicate faults which are not there in reality. The limitations of the method of presentation have prevented the author of the Petronics Paper from finding the 'patchiness' of the near-surface temperature pattern which is characteristic especially for the Salt Creek Survey and the Ten Section Field (Figs. 3 and 14, Petronics Paper).

All conclusions are based on the assumption that the lower strata are the more dense, so that anticlines and ridge faults will stand out as positive anomalies in the temperature pattern. This is generally true but it appears from comparison with geological control that the actual distribution of the anomalies is more complex. The presence of gas, oil or water, which recent investigations (2) have proved to have a significant effect on the thermal conductivity of porous strata, may have had an effect on the near-surface temperatures. Yet no mention is made of this in the Petronics Paper.

Despite the above limitations, the report appears to offer substantial evidence that structural features of formations buried at depths of up to 8000 feet are perceptibly reflected in the near-surface temperature pattern.

An attempt was therefore made to analyse the data in the light of more complete geological information and using mathematical statistical methods. This was done as follows: in addition to the trends found in the Petronics Paper, the temperature data of the three oilfield surveys were analyzed, to ascertain the presence of "cold" regions in the area surveyed as distinct from the remainder of the data in that area.

The advantage of this method lies in its greater flexibility; the contours of "cold" and "warm" regions are no longer tied to the orientation north-south or east-west. The "cold" regions, or "cold areas" as they will be called here, are indicated in Tables I and II by contours consisting of broken straight lines. They are found as follows: after having calculated the overall average of the field those temperatures that were lower than average were separated from the remainder of the field by a contour. A statistical test known as the t-test (a test to disprove the assumption that the difference between two averages is caused by chance) was then applied to check whether or not the average temperature of the "cold area" was significantly lower than the average temperature of the remainder of the area. There is a certain arbitrariness in the choice of the temperatures but this is limited on the one side by the fact that, if too many temperatures are included in the "cold area", the difference between its average and the average of the remainder becomes so small that its statistical significance cannot be proved. If too few temperatures are chosen the number of observations is not large enough to prove significant. A little experimenting showed this degree of arbitrariness to be small and, in fact, to be limited to the inclusion or exclusion of only a few temperatures which did not affect the conclusions. A more detailed description of the analyses of two of the three oilfields mentioned in the Petronics Paper is given in the Appendix. Some interesting inferences can be drawn from a detailed study of these tables. As sufficient geological control is lacking, only one conclusion can be drawn here, namely that the observed differences between the average temperatures of the "cold areas" and the average temperature of their corresponding remainders cannot have been caused by chance and must therefore be the results of an overriding factor originating from subterranean conditions. In the case of Table II there is hardly any doubt about the relationship between near-surface temperature and the location of the fault, but contrary to van den Bouwhuijsen's conclusion it appears that the negative anomaly is situated over the ridge-fault instead of over the down-throw side of the fault. In the case of Table I the situation is even more complicated, as the anomalies over the elevated portions are partly positive and partly negative. The observed distribution of "cold areas" might indicate the presence of gas and oil in stratigraphic traps formed by the high side of the ridge-faults; but nothing definite can be said here for lack of detailed information.

In order to obtain more complete quantitative information on what happens to the temperature pattern in regions overlying oil bearing formations, an analysis was made of two surveys released by Petronics of Canada Limited, namely, one for the Erskine field and one for the Big Valley-Fenn field in Alberta. Instead of a two-dimensional temperature pattern only one single line of temperatures was taken for each of the above fields. For the Erskine field this appeared to be insufficient as the contours of the top of the oil-bearing formation are very irregular and mask the effect of a difference in depth of approximately 100 feet along the survey-line. A two-dimensional survey would be needed to provide the information for this particular field.

The choice of the Big Valley-Fenn field however, appears to have been a more fortunate one. Here, a barrier reef of approximately 17 mi. long by 2 mi. wide is located at a depth of approximately 1 mile. The temperature survey-line which cuts right across the middle of this barrier reef indicates a negative anomaly over the top of the reef where it rises from approximately minus 6,300 feet to approximately minus 5,300 feet, from the surface. This field produces from two formations, the Nisku (D2) zone in which 23 feet of gas and 130 feet of oil are found; and from the Leduc (D3) zone where 7 feet of gas and 26 feet of oil occur. The analysis, details of which are given in the Appendix, shows, first of all, that there is a high degree of correlation between the near-surface temperature and the depth of the Leduc formation (D3). Secondly, this correlation is better than correlation between the surface temperatures and any of the other horizons above the oil producing zones. To substantiate the correlation between the near-surface temperature and the depth of the oil-producing zones further, estimates for the heat-conductivities of the basement rocks and the oil-bearing formations were obtained from private oil companies operating in the field. An estimate of temperature differentials, based on the law of Fourier, could be made for the whole cross-section. It appeared that the thermal conductivity figures found from the temperature survey and the drill log data correspond very well with the actual "in situ" thermal conductivities of the oil-bearing formations and the overlying strata. The latter were found from an analyses of velocity-log and electro-log data, following a method introduced by Zierfuss and van der Vliet (2) and using the relationship between acoustic velocity and porosity of limestones given by E. R. Denton (4).

The results of these analyses, details of which are presented in the Appendix, lead to the following conclusions.

CONCLUSIONS

1. Temperature differences of the order of 1^{O}F. measured at near-surface levels can be caused by oil-bearing formations found at depth of approximately 5,000 feet, depending on the contours and thickness of the oil-bearing formation and on its porosity.

2. In the Big Valley-Fenn field the relationship between the observed negative anomalies in near-surface temperature and the presence of the reef can be proved quantitatively from direct observations made in a number of wells in that field.

3. Near-surface temperature surveys can be used as an additional tool in oil prospecting; firstly, as an aid in locating structures which may be potential oilfields; and secondly, for delineating the outlines of proven oilfields.

4. Positive anomalies produced by anticlinal formations of high thermal conductivity may, in part, be offset by the presence of oil and gas. On the other hand, the negative anomalies produced by reef

formations will become more pronounced by the presence of oil and gas. It would appear therefore that the thermal survey is even more suited for detecting reef formations.

5. Near-surface discontinuities and lateral variations in the conductivity of individual formations tend to locally mask the regional anomalies of the deep-seated formations. Proper experimental design, judicious application of variance analysis and sufficient geological control will aid in isolating these local anomalies from the regional anomalies.

REMARKS

Although good experimental design and analysis of data will greatly enhance the economic value of geothermal surveys, geological information is required in order to correctly interpret the near-surface temperature patterns. It is felt that, with respect to near-surface discontinuities, more work should be done to further substantiate the value of geothermal surveying as a prospecting method. Considerable information has come to hand since the Petronics Paper was written. Data from velocity-logs and electrologs are more abundant today and can be used to advantage for the correct evaluation of thermal conductivities of the basement rocks and the oil-bearing formations. Much less is known about the effects of near-surface discontinuities such as moisture content and moving water, vegetation and surface contours. Field experience with the method so far would seem to indicate that the isotherms near the surface tend to follow the surface contours. According to Kersten (6) soil moisture content in the range of 0 - 10% may change the thermal conductivity of the soil from 0.0001 to 0.0006 BTU/^{o}F. ft. sec. These are features to be noted by the field operator. Moving subterranean waters cause local depressions of the temperature but these can be detected by the instability of the temperature reading. Jakosky (7) gives a number of reasons for near-surface temperature changes, but the above ones would appear to be the major causes for local anomalies. As not all of these are sufficiently known or even understood it would appear that this report should not finish without the following recommendations.

RECOMMENDATIONS

The influence of surface topography on heat-flow lines and isothermal planes are to the writer's knowledge not sufficiently known. Tests under varying conditions are recommended for analyzimg the vertical heat-flow patterns, preferably in an area where information on the geological structure is available.

Very little is known about the thermal conductivity of the glacial drift which is of particular interest for Canadian conditions. Separate tests for evaluating the effect of glacial drift on the near-surface temperature are recommended.

The effect of the ground water on the near-surface temperature reading may require further investigation. Finally, it is felt that a special test is justified to determine the minimum depth required to exclude periodic variations for Canadian conditions.

ACKNOWLEDGMENTS

The ready cooperation of officials of the Production Department of the British American Oil Company Ltd., Calgary, and of the Production Departments of Imperial Oil Ltd. in Calgary and Edmonton, in providing essential field data for this study, is gratefully acknowledged.

The writer is indebted to Prof. E. S. Keeping, Head Department of Mathematics, University of Alberta, and to Dr. G. Garland, Department of Physics, University of Alberta, for reading the manuscript and for constructive criticism mentioned elsewhere in this report.

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APPENDIX

Unit Systems

Three different systems are in use for expressing heat flow coefficients and thermal conductivities in geothermal surveying. The conversion factors for these units are given on the following page. Two other units which are used in soil mechanics and in heat insulation measurements are also given.

In the present study the heat flow coefficient (q) is expressed in Btu. per sq.ft. second. The thermal conductivities (K) are expressed in Btu. per ft. sec. degrees Fahrenheit.

The relationship between heat flow coefficient (q), thermal conductivity (K) and the thermal gradient is, in its simplest form,

$$\text{Thermal gradient} = \frac{q}{K}, \text{ in } {}^{o}F/ft.$$

For a series of geological strata, differing in thermal conductivity (K_i) and thickness (d_i), the vertical temperature difference can be expressed in the formula of Fourier as follows:

$$T_0 - T_1 = q\left(\frac{d_1}{K_1} + \frac{d_2}{K_2} + \cdots\right) \qquad \text{- - - - - - - - - (1)}$$

Corrections Petronics Paper

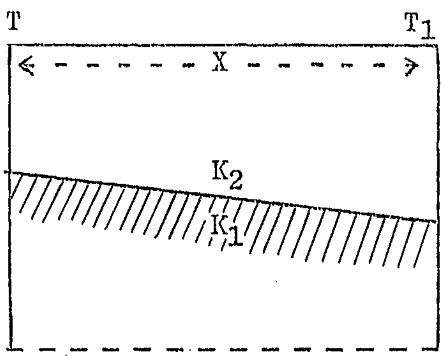
Comparison of thermal conductivity estimates presented in the Petronics Paper with those found in the literature shows that cgs-units and

CONVERSION FACTORS

Heat flow coefficient (q)			
Btu/ft.^{2}sec. to cal/cm.^{2}sec.	0.27125	cal/cm.^{2}sec. to Btu/ft.^{2}sec.	3.6866
Btu/ft.^{2}sec. to joule/m.^{2}sec.	11362.7	joule/m.^{2}sec. to Btu/ft.^{2}sec.	0.88007×10^{-4}
joule/m.^{2}sec. to cal/cm.^{2}sec.	0.23865×10^{-4}	cal/cm.^{2}sec. to joule/m.^{2}sec.	41902.4
Thermal conductivity (K)			
Btu/ft.sec.$^\circ$F. to cal/cm.sec.$^\circ$C.	14.8819	cal/cm.sec.$^\circ$C. to Btu/ft.sec.$^\circ$F.	0.067195
Btu/ft.sec.$^\circ$F. to joule/m.sec.$^\circ$C.	6234.02	joule/m.sec.$^\circ$C. to Btu/ft.sec.$^\circ$F.	1.6041×10^{-4}
joule/m.sec.$^\circ$C. to cal/cm.sec.$^\circ$C.	23.865×10^{-2}	cal/cm.sec.$^\circ$C. to joule/m.sec.$^\circ$C.	419.024
$\frac{\text{Btu.inch}}{\text{ft.}^2\text{hr.}^\circ\text{F.}}$ to $\frac{\text{cal}}{\text{cm.sec.}^\circ\text{C.}}$	3.4448×10^{-4}	$\frac{\text{cal}}{\text{cm.sec.}^\circ\text{C.}}$ to $\frac{\text{Btu.inch}}{\text{ft.}^2\text{hr.}^\circ\text{F.}}$	2902.8
$\frac{\text{Btu.ft.}}{\text{ft.}^2\text{hr.}^\circ\text{F.}}$ to $\frac{\text{cal}}{\text{cm.sec.}^\circ\text{C.}}$	4.1338×10^{-3}	$\frac{\text{cal}}{\text{cm.sec.}^\circ\text{C.}}$ to $\frac{\text{Btu.ft.}}{\text{ft.}^2\text{hr.}^\circ\text{F.}}$	241.90

practical units are used simultaneously in the Fourier formula. For instance, on page 16 of the Petronics Paper, the heat flow coefficient (q) is expressed in Btu/ft.^{2}sec. while the thermal conductivities are expressed in cal/cm.sec.^{o}C. Consequently, the temperature difference per foot of slip is not .003^{o}F/ft. as stated on page 16 but 0.050^{o}F/ft. This error does not materially affect the conclusions of the paper but changes the results of the 'problems' which are given, by way of example, on pages 16 and 19. On page 16 of the Petronics Paper (4th line from bottom of page): "--- a slip of 3 feet ---" should read: "--- a slip of 1/2 foot ---". On page 19, the last sentence: "--- the difference would amount to 0.5^{o}F. ---" should read: "--- the difference would amount to 4.6^{o}F. ---". This figure can vary widely depending on the thermal conductivities of the strata involved, as is illustrated in the following table.

<u>Temperature Difference, in ^{o}F. per mile, degree slope</u>



Formula: $T - T_1 = Xq \left(\frac{1}{K_2} - \frac{1}{K_1}\right) \tan.1^{o}$

Temperature difference $T - T_1$, in ^{o}F.					
$10^4.K_2$ / $10^4.K_1$	.5	1	2	3	4
5	7.1	3.2	1.2	0.5	0.2
4	6.9	3.0	1.0	0.3	0
3	6.6	2.6	0.7	0	-0.3
2	5.9	2.0	0	-0.7	-1.0
$1\frac{1}{2}$	5.3	1.3	-0.7	-1.3	-1.6
$\frac{1}{2}$	0	-1.0	-5.9	-6.6	-6.9

Reference is made in the Petronics Paper to geological information of the three oilfields (Salt Creek, Kern River and Ten Section field) but no geological details are given.

For the first two fields contour maps of the oil-producing formations were available and these have been sketched in on Tables I and II. For the Ten Section field no such detailed control was available to the writer at the time this report was published and the analysis which was made of this field was therefore left out. The analyses of the Bakersfield (Salt Creek) and Kern River Front surveys were carried out as explained in the Section "Analysis of Data". The following is a resume of the calculations for the guidance of those interested in the statistical treatment of the field data.

Tests of Significance

The calculations on the field data were made with the following two questions in mind.

1. Are the temperatures observed in the field significantly different from each other; and, if so,
2. Can the observed differences be quantitatively explained by the structural (faults, slopes) and textural (lithology, porosity, permeability) features of oil-bearing formations found at depths of the order of 5,000 to 10,000 feet.

The first question was answered by the analysis of the Bakersfield and Kern River Front data.

Bakersfield (Salt Creek, Cymric Area)

In this area of 1/2 mile square approximately 600 near-surface temperature observations were made following a grid of 25 by 25 lines, with a spacing of 110 ft. between stations. Three zones of lower-than-average temperatures can be distinguished, as indicated by the broken straight contours in Table I of this report. Statistical data obtained from the near-surface temperatures are condensed in the table below.

DATA OF TABLE I

	Cold Areas, Nos. I	II	III
Cold Areas[1]:			
Av. temperature, deg. F.	83.83	84.79	86.83
Number of temp. observations	45	46	64
Variance of single obs.	1.79	3.61	1.67
Remaining Areas[2]:			
Av. temperature, deg. F.	88.16	87.98	87.94
Number of observations	528	527	509
Variance of single obs.	3.61	4.06	5.09
t-test:			
Difference (d) between av. temperatures, deg. F.	4.33	3.19	1.11
s = standard dev. of differences	0.289	0.308	0.288
degrees of freedom	571	571	571
ratio t = d/s	14.98	10.36	3.85
Minimum t-ratio required to disprove the null-hypothesis at the 1% level[3]	2.81	2.81	2.81

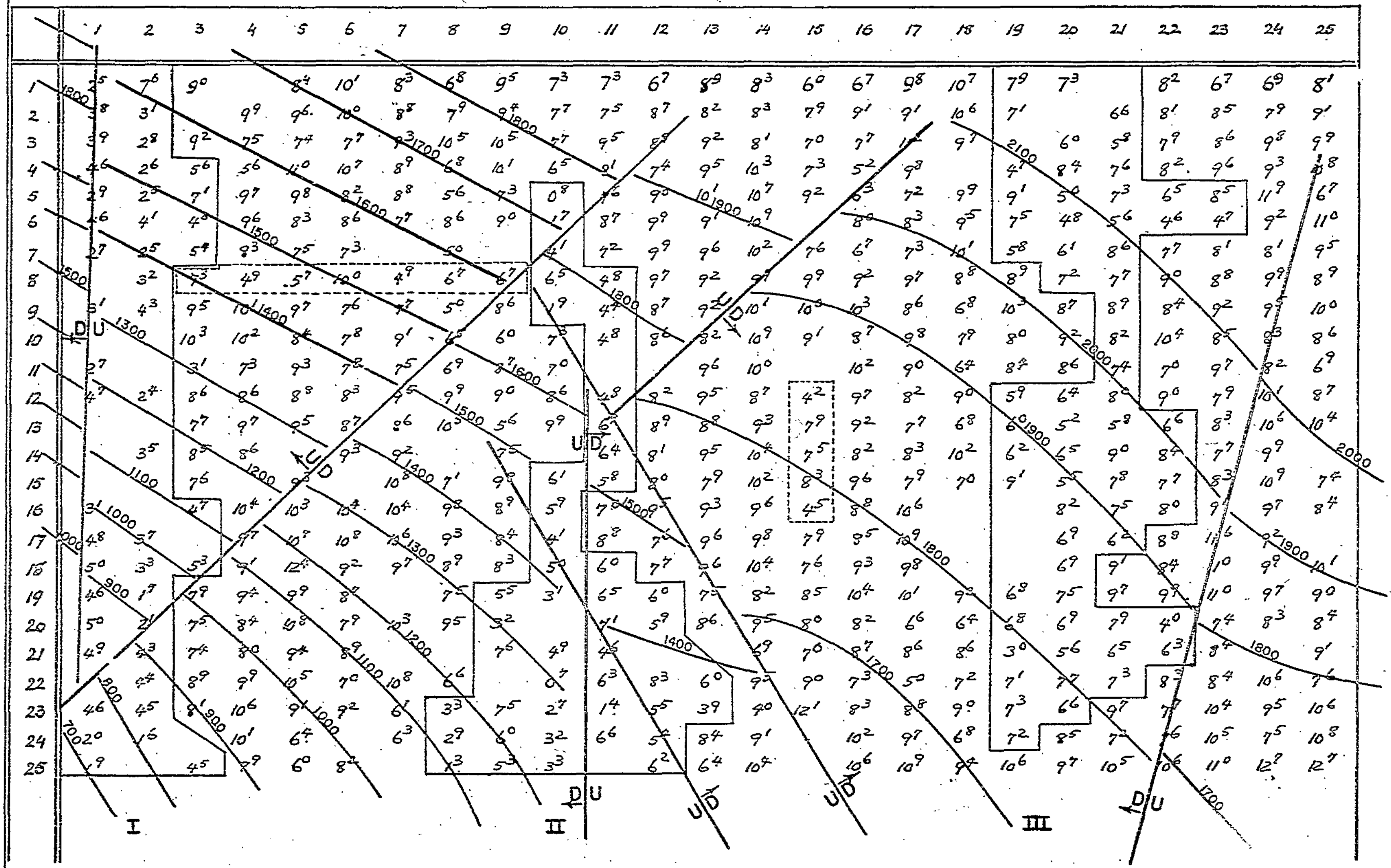
1) Two local anomalies, indicated by dotted contours (Table I) appeared to be insignificant.

2) The remaining area = total area minus the cold area under consideration.

3) Prof. E.S. Keeping (University of Alberta) has commented that, strictly speaking, the t-test applies to independent observations only. The observations used are not entirely independent and this may affect the following conclusions to a degree.

TABLE I

BAKERSFIELD (Petronics Paper – Fig. 3)



AREA I

No. of Observations:– 45

Average:– 3.83

Standard Deviation:– 1.34

AREA II

No. of Observations:– 46

Average:– 4.79

Standard Deviation:– 1.90

AREA III

No. of Observations:– 54

Average:– 6.83

Standard Deviation:– 1.29

N.B. Each figure in the table is the measured temperature – 80° F.

Spacing between temperature stations is 110 feet.

The results of this analysis are statistically highly significant, showing that the observed temperature differences of 4.33°F., 3.19°F. and 1.11°F. are not caused by chance. The contours of the top of the oil-producing formation given in Table I show a rather complicated system of ridge-faults and trough-faults sloping at considerable angles in a northeasterly direction. There seems to be a rough correspondence between the locations of the faults and those of the cold areas, but much more information would be required to substantiate any conclusion in this respect. The fact remains that the observed temperature pattern indicates local subterranean discontinuities. The following example illustrates that faults at great depths can produce anomalies in the near-surface temperature which can be easily recognised among the anomalies caused by near-surface discontinuities.

Kern River Front (Table II)

A t-test on the two areas lying on either side of the main fault shows that the observed difference of 1.30°F. is highly significant ($P < 0.1\%$). It is very likely that this anomaly is caused by the presence of the fault-block. The presence of a second, less pronounced fault (in the northwest corner) could not be proved with enough certainty, mainly because the number of observations at the down-throw side is too low. The advantages of the more flexible method used in this analysis becomes apparent when comparing Table II with Fig. 15 of the Petronics Paper, where the presence of the trough-shaped anomaly is masked, as a result of its northeast-southwest orientation.

It is further noted, firstly, that the near-surface temperatures, over the ridge-fault, are low; this indicates that the thermal conductivity of the oil-bearing formation (Chanac) must be lower than that of the overlying strata.

Table II.

KERN RIVER FRONT (Petronics Paper – Fig. 13)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1							10^9	12^0	9^1	12^3	12^6	12^2	11^4	11^8	11^9	11^1	10^9	9^0	8^4	11^0	11^1	11^7	11^3	12^8	11^6
2							10^7	9^7	12^4	11^9	11^8	10^8	7^5	6^3	15^1	7^8	9^6	9^6	8^9	8^9	11^1	10^4	10^4	13^0	13^3
3							9^4	11^6	12^7	12^2	11^3	10^2	7^4	11^0	10^6	13^1	7^0	8^0	10^3	12^4	12^8	9^7	10^3	12^7	13^2
4							10^7	12^5	12^5	10^0	9^8	12^7	11^6	10^7	11^6	12^4	11^5	10^3	11^8	9^3	12^7	10^5	12^5	11^0	12^5
5	11^2	8^1	10^3	10^6	13^3	12^0	10^7	13^1	12^7	10^7	10^0	12^0	11^4	6^3	4^1		9^3	9^6	10^6	11^8	11^1	13^2	12^9	12^4	12^2
6	13^4	10^0	9^9	8^5	9^3	10^0	10^4	10^4	10^7	11^3	10^8	10^9	11^8	12^5	14^5		8^2	10^5	9^5	11^7	12^0	10^9	12^0	13^6	11^1
7	12^3	10^5	9^5	9^5	10^9	11^3	8^8	9^2	12^5	10^8	10^8	11^1	12^1	12^3	8^4	8^6	7^2	8^4	10^5	13^6	9^3	10^3	12^7	12^8	12^4
8	12^3	9^5	11^8	10^8	12^1	11^8	10^4	11^5	11^8	11^9	11^1	11^9	11^9		12^9	12^4	9^4	10^1	7^6	11^1	10^5	11^6	11^3	13^1	13^1
9	9^8	9^1	12^7	10^8	11^4	11^1	9^9	11^4	11^7	10^9	12^2	10^4	12^1	14^6	12^3	10^2	10^2	8^8	7^9	11^1	12^1	13^7	11^4	12^8	10^5
10	9	11^1	11^1	10^8	12^6	13^4	10^7	9^1	10^2	10^6	11^5	11^9	10^3	11^2	9^6	11^7	10^9	10^1	10^2	10^8	13^1	13^0	10^9	13^1	11^3
11	10^0	9^5	9^6	12^2	11^5	11^8	10^8	6^3	9^3	8^0	13^2	10^2	9^7	7^6	10^5	10^6	8^2	9^9	10^8	9^9	10^6	9^7	12^3	12^4	12^4
12	10^3	11^4	10^4	11^2	11^8	10^5	12^2	12^3	11^3	11^3	10^1	10^5	8^7	7^3	8^7	10^8	11^6	11^1	11^1	12^6	12^1	10^2	11^6	13^3	13^5
13	9^9	8^6	10^4	9^5	11^8	9^2	9^9	11^6	10^6	10^3	10^2	9^3	9^9	5^2	6^4	11^4	11^8	10^9	11^4	12^0	10^6	11^7	13^1	12^5	11^2
14	9^9	8^9	11^2	11^9	8^8	9^7	10^1	10^9	11^4	9^5	10^1	11^7	11^0	11^4	11^4	13^1	11^8	10^9	9^3	10^0	10^0	11^9	12^1	12^1	10^9
15	9^5	10^1	11^9	12^2	12^1	10^8	11^9	11^9	11^1	10^6	11^5	10^4	11^4	10^1	12^3	11^3	11^8	10^8	10^9	10^6	11^6	11^9	11^2	12^8	12^4
16	8^7	9^9	10^9	11^4	11^3	12^1	12^5	10^9	10^5	10^7	11^1	12^2	12^9	12^5	11^8	11^5	11^2	11^8	11^6	10^4	12^2	10^8	12^4	12^3	11^6
17	8^4	8^3	12^7	11^8	11^9	11^3	11^2	11^2	10^3	10^9	12^6	12^4	11^9	12^8	12^6	11^8	13^3	11^6	11^9	8^9	12^5	12^8	12^3	12^8	11^3
18	7^8	7^6	12^8	11^0	11^1	9^8	10^7	9^4	8^5	11^3	11^4	11^2	12^3	14^7	13^5	12^8	11^5	12^3	12^0	12^1	8^9	11^1	13^4	12^3	10^4
19	8^7	9^8	12^7	10^6	10^5	9^2	9^8	11^6	11^7	11^6	12^2	12^6	11^3	11^8	12^9	12^0	13^4	10^5	11^4	10^4	10^8	12^2	13^3	12^8	13^0
20	7^7	9^8	10^0	11^4	10^4	10^6	9^5	10^7	9^5	13^0	13^3	12^0	12^3	12^8	13^0	12^8	11^4	11^4	11^9	12^1	11^9	10^5	11^5	12^5	12^7
21	7^8	8^3	9^5	12^2	11^8	7^4	7^2	10^7	10^5	12^2	13^3	11^2	11^0	14^1	12^8	10^6	11^1	10^6	11^3	13^0	12^2	10^0	10^4	12^0	11^7
22	9^4	8^5	10^2	11^4	12^1	9^7	10	10^1	11^5	12^7	13^0	12^7	13^6	13^2	12^7	12^5	12^3	12^8	12^0	12^8	12^6	11^6	8^5	11^0	12^4
23	7^4	8^6	9^6	10^4	10^0	7^8	9^7	10^4	11^0	12^4	12^4	13^4	13^7	11^8	12^7	12^0	12^6	12^6	11^6	13^1	13^4	12^8	12^0	12^4	13^0
24	6^5	8	10^9	10^5	10^4	6^7	11^6	11^1	11^4	11^9	13^0	12^6	12^3	13^0	12^9	11^2	12^9	11^9	11^5	11^9	9^7	11^9	10^3	11^1	11^1
25	5^6	8^8	7^0	10^4	8^3	9^2	8^5	8^3	9^5	12^0	11^2	10^5	11^0	11^3	12^0	9^2	10^8	9^6	11^1	7^7	9^6	9^6	11^2	11^3	11^1

Left hand Side

No. of Observations:– 334

Average:– 10.46

Standard Deviation:– 1.61

Right hand Side

No. of Observations:– 264

Average:– 11.76

Standard Deviation:– 1.14

N.B. Each figure in the table is the measured temperature – 60°F.

Secondly, the top of the Chanac slopes in a southwesterly direction at an angle of 6^{o} to 8^{o}. This is not reflected in the near-surface temperatures. There is no explanation for this, but the same can be observed in Table I. The fact remains, that the observed anomaly is significant. In the case of Kern River Front it is very likely that this anomaly is caused by a fault occurring in the Chanac formation. The conclusion which can be drawn from the Bakersfield and Kern River surveys is that, while individual observations may vary over a range of 10^{o}F., local anomalies of the order of 1^{o}F. can be detected if sufficient date are available.

The second question, posed at the beginning of this section (p.16) was whether the observed regional differences in near-surface temperature can be quantitatively explained by the presence of buried structures. The following example presents a case where sufficient data were available for a quantitative estimate of the near-surface temperatures based on thermal conductivities of underlying strata.

Big Valley-Fenn Field (Figs. 1, 2)

A series of near-surface temperature observations were taken in a straight east-west line across the reef. A vertical cross-section over this survey-line is presented in Fig. 1. Drilling log data of ten wells located nearby on a straight east-west line provided the necessary geological control needed for a quantitative check of the observed relationship between the near-surface temperature at six foot depth and the depth-from-surface, of the Leduc formation. The field data and averages used in the calculations are given in Table III.

TABLE III

FIELD DATA, BIG VALLEY-FENN

Well No.	Near-surface temp., °C. Single observations	Av. T_1		Depth, Leduc from surface = d_1
		°C.	°F.	
1				
2	7.3-7.4-7.5-7.4-7.7-7.7-7.6-7.7-7.5	7.53	45.55	5495
3	8.2-7.9-7.8-7.2-7.3-6.9-7.4-7.6-7.6-6.8-7.0	7.43	45.37	5454
4	6.8-7.2-7.2-7.2-7.6-7.2-7.3-7.4-7.2	7.23	45.01	5412
5	7.4-7.4-7.1-7.4-7.0-7.1	7.23	45.01	5382
6	7.1-6.9-7.5-7.7-7.2-6.9-7.3	7.08	44.74	5349
7	7.3-6.7-6.8-7.1-7.0-7.1	7.00	44.60	5326
8	7.0-7.2-6.9-7.0-7.2-7.4-7.6-7.6-7.2-7.1	7.22	45.00	5376
9	7.3-7.3-7.4-7.2-7.3-7.6-7.7-7.4-7.1-7.2	7.35	45.23	5444
	Average	7.34	45.06	5405
10	7.6-8.0-7.6-7.8-8.8 These data were not used as Leduc is here replaced by the Duvernay formation			

The relationship between the depth of the Leduc formation and the near-surface temperature is illustrated graphically in Fig. 2.

The observations appear to fit a straight line within narrow limits. This correlation appears to be better than any other correlation that was tried (e.g. the Banff formation, 2nd White Specks). In order to prove, quantitatively, that the observed temperature anomalies are caused by the reef, it was necessary to find estimates of the thermal conductivities of the strata and to verify their lateral stability.

Estimates of Thermal Conductivities

Data on "in situ" thermal conductivity of rock strata are

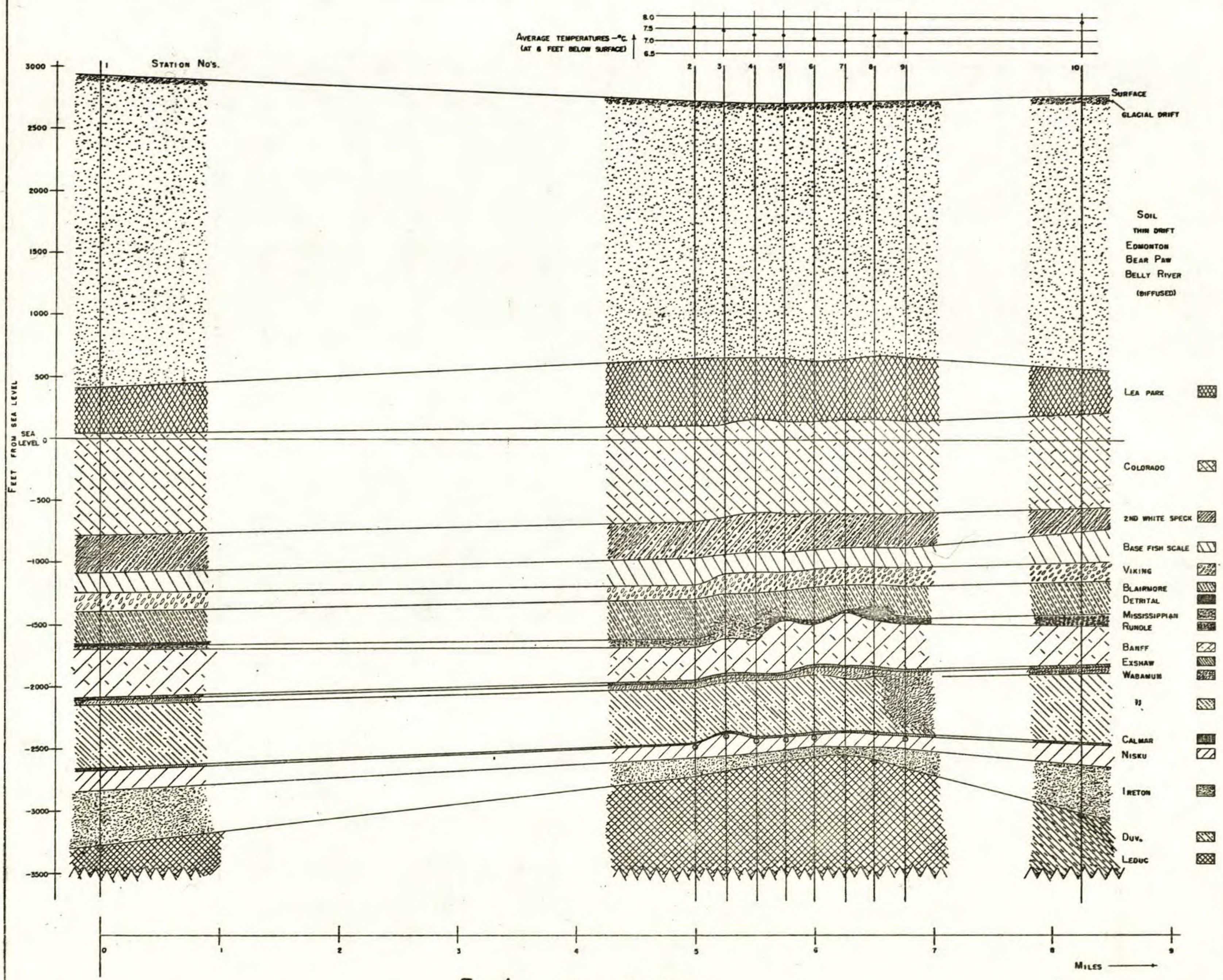


Fig. 1. Fenn to Big Valley

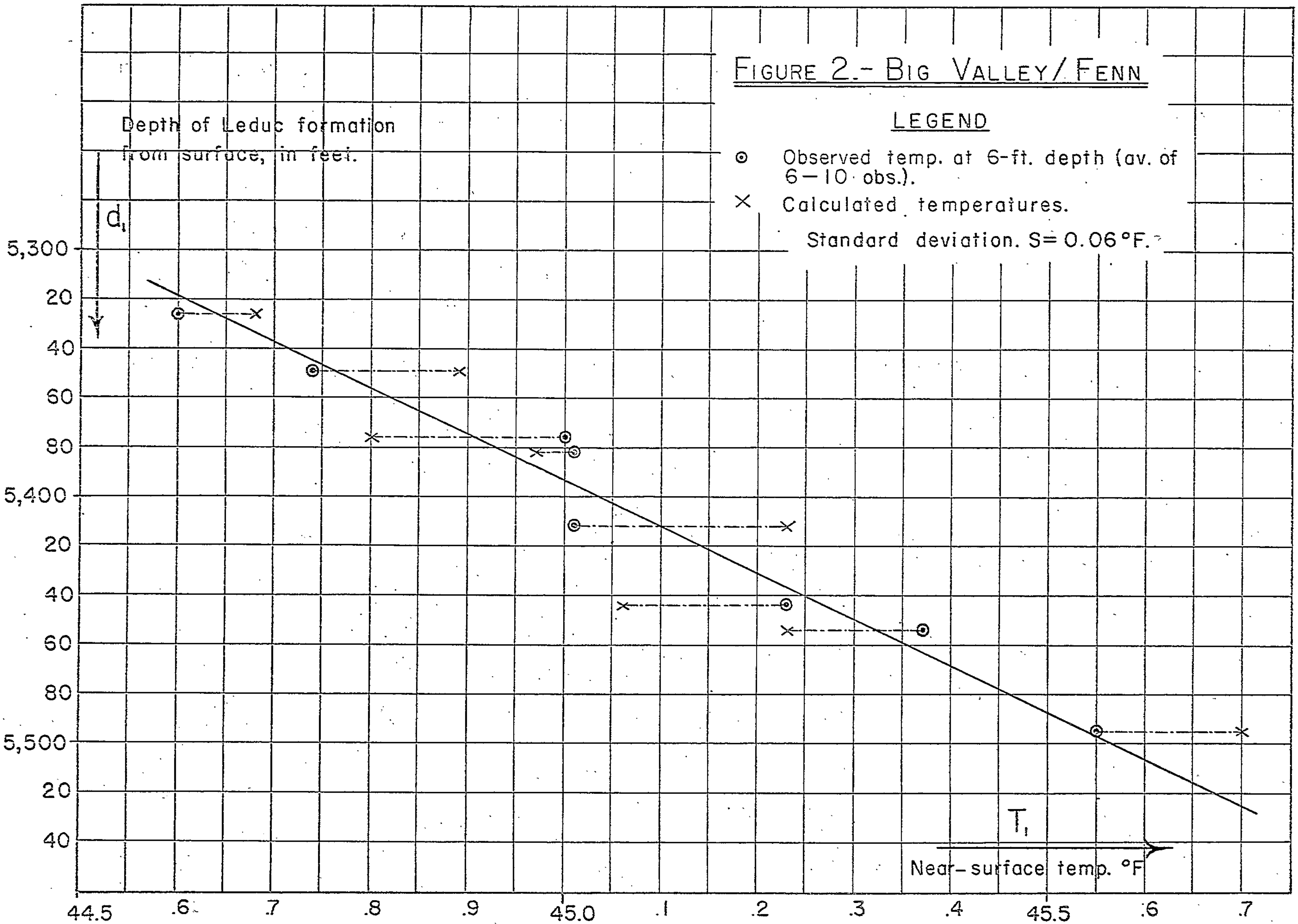


FIGURE 2.- BIG VALLEY/FENN
LEGEND
Observed temp. at 6-ft. depth (av. of 6–10 obs.).
Calculated temperatures.
Standard deviation. S= 0.06°F.
Depth of Leduc formation from surface, in feet.
d₁
5,300
20
40
60
80
5,400
20
40
60
80
5,500
20
40
T₁
Near-surface temp. °F
44.5
.6
.7
.8
.9
45.0
.1
.2
.3
.4
45.5
.6
.7

very scarce, but a comprehensive study was recently published (2), and from it approximate figures could be derived for the Big Valley-Fenn field, using local velocity-log data. This was done as follows.

The thermal conductivity of rock formations is closely related to the porosity and to the formation resistivity. Comprehensive quantitative information is given by Zierfuss and van der Vliet in the above mentioned publication (2). Porosity data are known, but average values for formations in place were not available to the writer. Use was made of the relationship which exists between the porosity and the acoustic velocity, as is shown for limestones and sandstones in Fig. 3 (Denton (4), Wyllie). Interval-velocities of individual formations, as well as resistivity data, were made available by courtesy of two major oil companies and, from these, reliable estimates of the thermal conductivities could be derived (see Table IV). It appears from these figures that, while the thermal conductivity rises generally with increasing depth, there are two notable exceptions where porous limestones occur, viz., in the Wabamun and Leduc formations (bottom Table IV), where a sharp drop in the thermal conductivity was found. Where such a formation is relatively thick, the heat flow is deflected, with a resulting negative anomaly in the near-surface temperature. It appears from Fig. 1 that the Wabamun series is relatively flat; the Leduc formation, on the other hand, shows a drop of 3° on its east flank and slightly over 1° on the west flank. In order to study the effects of the various formations, the cross-section was first regarded as consisting of two major sections, viz.:

TABLE IV

BIG VALLEY-FENN DATA (continued)

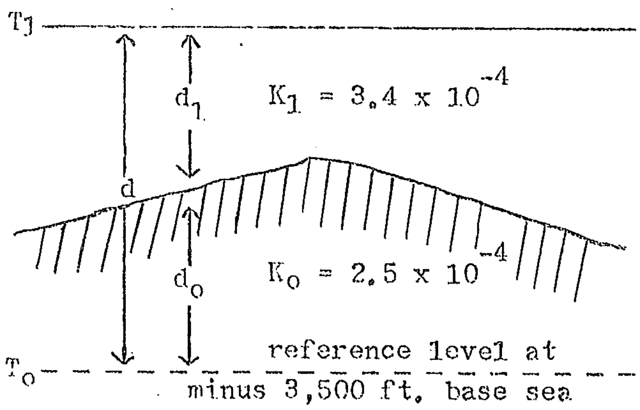
Well No. (Fig.1)	Thickness in ft.		Depth of interval, in ft.						Thermal conduct. x 10,000	Near-surface temp. ^{o}F.		
	d_o	d_1	Lea Park	Blair-more	Ex-shaw	Wabamun	Nisku (1)	Ireton (1)		Calcu-lated (2)	Ob-served = T_1	Difference calc.-obs.
1	120	6333	2535	1855	705	615	173	450	3.42	(45.58)	(3)	-
2	764	5495	2108	1942	673	525	(106)	(141)	3.44	45.70	45.55	0.15
3	794	5454	2098	1930	660	465	(176)	(125)	3.45	45.23	45.37	-0.14
4	826	5412	2083	1826	747	524	(122)	(110)	3.44	45.23	45.01	0.22
5	862	5382	2084	1901	640	563	(103)	(91)	3.41	44.97	45.01	-0.04
6	892	5349	2122	1855	632	572	(91)	(77)	3.40	44.89	44.74	0.15
7	922	5326	2099	1954	655	544	110	64	3.41	44.68	44.60	0.08
8	877	5376	2082	1874	670	551	113	86	3.42	44.80	45.00	-0.20
9	812	5444	2092	1875	695	537	(113)	(132)	3.43	45.06	45.23	-0.17
10	425	5885	2245	1730	680	648	178	404	3.41	(45.75)	(46.33)	(4)
Average	729	5547	2155	1864	676	554	14		3.42	45.07	45.09	0.115^{o}F.
Standard deviation	475		145	6	34	51	56	170	0.018	-	-	0.16^{o}F.
Thermal conduct. x 10,000	2.5 = 10^4K_o	3.4 = 10^4K_1	3.2	3.9	5.0	2.2	3.0	4.3	-	-	-	-

Notes: (1) Figures in brackets were found by linear interpolation.
(2) Calculated temperatures are based on a temperature at the reference level (minus 3,500 ft. base sea level) of 127.30^{o}F.
(3) In station (1) no temperature was observed.
(4) In station (10) the Leduc is replaced by Duvernay.

(a) the Leduc and lower strata, thickness d_o, overlying a reference level where the temperature is supposed to be constant;

(b) the strata overlying the Leduc formation, thickness d_1, (see sketch).

The thermal conductivities of the Leduc zone and of six individual groups of formations constituting the overburden (see Table IV) were found independently from porosity and velocity data provided by the oil companies. These thermal conductivities are expressed in Btu. per ft. degree F. sec. The temperatures are expressed in °F. and the heat flow coefficient $q = 4.27 \times 10^{-6}$ is expressed in Btu. per sq. ft. sec.



It appears, from Table IV, that the calculated near-surface temperatures correspond within narrow limits, with the near-surface temperatures observed in the field (see also Fig. 2). It may be concluded, therefore, that the negative anomaly over the reef could be caused by the presence of the reef and not by an accidental configuration of strata. The question that remains to be answered is, whether the favorable result for Big Valley has any general meaning. The answer lies in an analysis of the sources of near-surface temperature variations based on observations. A quantitative evaluation of these variations is presented in the following section.

Quantitative Analysis of near-surface Temperature Patterns

Three types of variations can be distinguished, which will affect the near-surface temperature. Estimates of the quantitative effect of each of these types are valuable in deciding whether or not the near-surface temperature surveys will have any practical value in the search for oil.

1. The first type of variations are the local variations in thickness of individual formations. The term 'local' will define a spacing between points of the order of one mile or less.

For the Big Valley-Fenn field, the variations in formation thickness are shown in Table IV, and from it the total thermal conductivity of the strata overlying the reference level was calculated, assuming constant thermal conductivity for each individual formation. The estimates, ranging from 3.40×10^{-4} to 3.45×10^{-4} Btu. per ft. sec. ^{o}F. therefore, reflect solely the effect of variation in formation thickness.

The standard deviation derived from this range is (Table IV): $s_1 = 0.018 \times 10^{-4}$. Using Fourier's formula, it is found that: The combined effect of local variations in thickness of individual rock formations on the near-surface temperature is of the order of 0.6^{o}F.

2. The second type of variability contributing to the near-surface temperature pattern is the local variability of thermal

conductivity in each individual rock formation. In contrast to the variation from one formation to the next, this will be termed the lateral variability of the thermal conductivity (K). Direct observations are presently not available. The only field data at hand are the interval velocities. From these, and from the known relationship between acoustic velocity and thermal conductivity, an estimate of the lateral variability of (K) was found. A resume of this calculation is given in the Addendum. The estimate is based on one series of 10 velocity-logs in the Big Valley-Fenn field and a series of 8 velocity-logs from an area in the North Pembina field.

The lateral standard deviation in (K), for a single formation, appears to be $s_K = 0.6 \times 10^{-4}$ Btu. per ft. sec. ^oF. This is a very high figure. The composite effect of all formations on the near-surface temperature however, depends on their number. For Big Valley-Fenn, where approximately 25 different formations cover the reference level, the standard deviation averages out to $s_2 = 0.12 \times 10^{-4}$ Btu./ft. sec. ^oF.

Conclusion: <u>the combined effect of lateral variations in thermal conductivity of individual formations produce local variations in the near-surface temperature of the order of 3^{o}F.</u> These variations are chiefly responsible for the 'patchiness' of the temperature pattern at the near-surface.

3. The third category of variations is of a regional character. These variations are pronounced in area rather than in temperature.

It is perhaps for this reason that these regional anomalies have not been regarded as important amongst the more violent, local variations.

Regional variations occur as a result of one overriding factor which produces a usually low, but consistent, anomaly superimposed on the local variations. It stems from a single occurrence rather than from the random interplay of a large number of common occurrences such as the ones mentioned above. The regional variation is commonly localised in one formation where a geological 'accident' happened (such as faulting and folding); or where exceptionally favorable conditions for the development of a deposit occurred during a relatively short time (as in the formative period of coral reefs).

Regional variations in thermal conductivity can generally be detected only from a relatively large number of observations (in the order of 100 or more), as illustrated in the Bakersfield and Kern River Front surveys.

In the case of Big Valley, the Leduc formation rises 159 ft. over a distance of 6,600 feet across the reef. The temperature drops 0.95°F. (between stations 2 and 7). From geological data it was possible to prove the relationship between the two. A grid survey of the type used in the other survey would bring out this anomaly over practically the whole length of this reef which measures 17 miles. The observed temperature anomaly may be relatively small. It is the regional extent of the temperature anomaly which sets it apart from the other temperature anomalies. In addition, for reef structures, the temperature anomaly becomes more pronounced in the presence of oil and, especially, gas.

Addendum

For the calculation of the lateral variability of (K), the following course was chosen.

(a) Divide velocity-logs in a number of stratigraphically identical sub-sections. Determine variances of interval velocities for each sub-section. The standard deviation appears to be 3% to 5% of the velocity, or 400 ft./sec. for an average velocity of 10,000 ft./sec.

(b) Find the experimental formula for the relationship between acoustic velocity (V) and porosity (P), from Fig. 3. Scatter is caused by lithology (L). Therefore,

$$P = a - bV + f(L) \quad \text{------------------} \quad (1)$$

Similarly, find the relationship between porosity (P) and thermal conductivity (K) from ref. (8); see Fig. 4. Considerable scatter caused by permeability (R) (convection in large pores increasing thermal conductivity), etc.

$$K = c - dP + f(R) \quad \text{------------------} \quad (2)$$

From (1) and (2), eliminate (P), find (K) and differentiate.

$$s^2_K = d^2b^2s^2_V + d^2s^2_L + s^2_R \quad \text{--------------} \quad (3)$$

Estimates for constants (d,b) and for variances are found from same graphs which leads to,

$$s_K^2 = 0.09 \times 10^{-8} + 0.05 \times 10^{-8} + 0.25 \times 10^{-8}$$

Scatter produced by permeability appears to be largest contributor to variance. This variance is possibly inflated because Fig. 4 is based on data obtained from strata in different parts of the world.

$$\boxed{s_K = 0.6 \times 10^{-4} \text{ Btu./ft. sec. } {}^{o}\text{F.}}$$

Dr. G. Garland (University of Alberta) expressed the same view by commenting that this variance was perhaps overweighed by the occurrence of extreme values in the observations used.

Edmonton, Alberta
April 27, 1957.

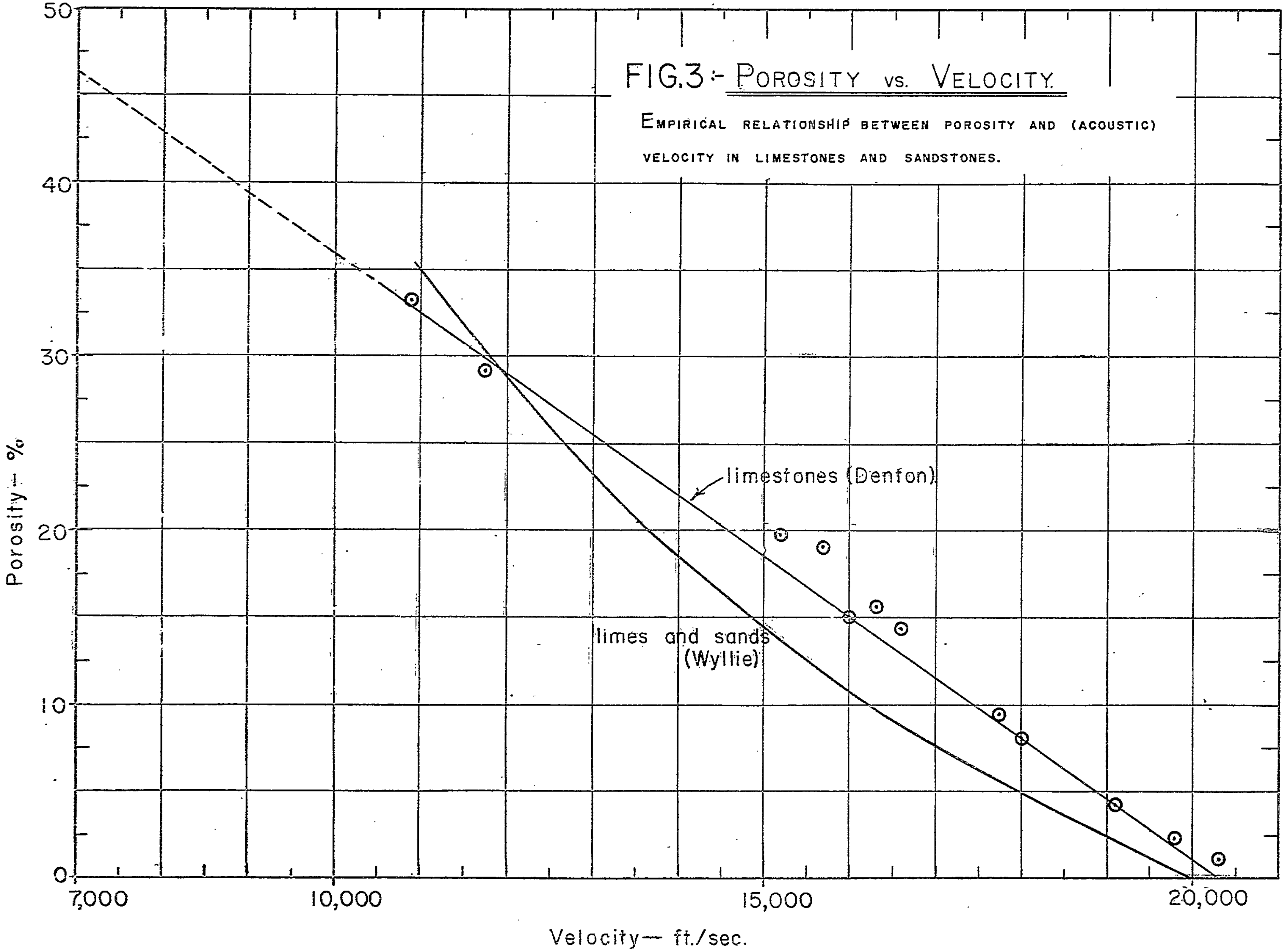
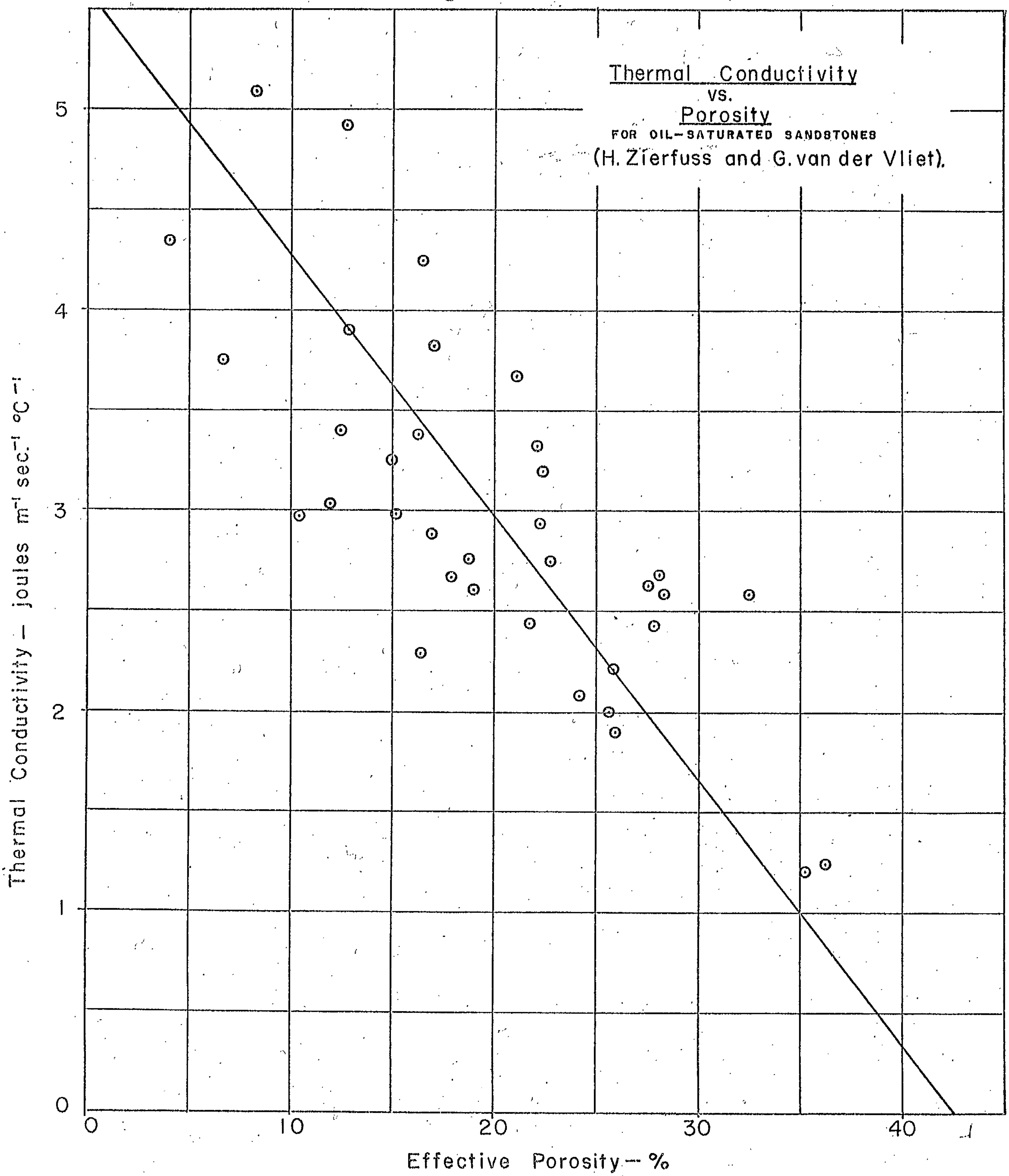


FIG.3 :- POROSITY vs. VELOCITY.

EMPIRICAL RELATIONSHIP BETWEEN POROSITY AND (ACOUSTIC) VELOCITY IN LIMESTONES AND SANDSTONES.

Figure 4.


Thermal Conductivity
vs.
Porosity
FOR OIL-SATURATED SANDSTONES
(H. Zierfuss and G. van der Vliet).
Thermal Conductivity - joules m⁻¹ sec.⁻¹ °C⁻¹
0
1
2
3
4
5
0
10
20
30
40
Effective Porosity - %