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Shallow Geothermal Anomalies Overlying Deeper Oil and Gas Deposits in Rocky Mountain Region[1]

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ABSTRACT

Eight of nine Rocky Mountain area oil and gas fields surveyed by shallow geothermic methods show hot spots or positive shallow temperature anomalies at depths ranging from 500 ft (150 m) to as shallow as 10 ft (3 m). The magnitudes of these anomalies generally range from 1 to 3F° (0.5 to 1.5C°), but in one case reached 16F° (8.9 C°) at 500 ft (150 m). Similar shallow thermal anomalies associated with oil or gas fields are reported in Russian and other literature.

The methodology of drilling shallow holes and recording accurate temperatures therein is fairly simple, inexpensive, and rapid.

The primary cause of the observed temperature anomalies at and above oil and gas fields is unknown, but the writers believe that lateral and upward fluid movements through subsurface rocks are an important contributing factor. Because four of the fields that show both shallow and deep positive temperature anomalies are stratigraphically controlled and are not on or near crests of structural features, the commonly held belief that positive temperature anomalies over oil and gas fields simply reflect structural highs is not supported by our data.

The addition of shallow geothermal surveys to the suite of conventional exploratory methods should improve exploratory efforts to find new oil and gas fields.

INTRODUCTION

Meyer and McGee (1985) presented evidence supporting the association of positive geothermal anomalies at producing levels with certain oil and gas fields in the Rocky Mountain region. The background work yielding that evidence was done in the early 1970s. Their work was followed by shallow surveys made specifically to determine if anomalies seen at producing levels continue upward to shallow depths with enough amplitude to be detected reliably.

The shallow surveys indicated that such programs can detect shallow anomalies overlying deeper anomalies and thereby can increase the probability of finding oil and gas fields. Data from nine Rocky Mountain oil and gas field areas, eight of which support this conclusion, are discussed. One or more temperature profiles are presented for each field surveyed, and, in a few cases, other geothermal data such as isothermal surface maps are included. Geothermal gradient maps, calculated from the surface to producing depths, also are provided for several fields so that comparisons can be made between the deep and shallow zones. In addition, similar positive anomalies associated with three fields described in the literature are cited.

Because available temperature data for shallow depths over and around most of the surveyed oil and gas fields are too meager to allow definition and removal of any regional temperature gradients, our temperature anomalies are defined in terms of the data collected. We use the following operational definition for positive temperature anomalies or hot spots. When a temperature profile contains a segment of one or more temperature values measurably higher than the temperature values on either side of them (or it in the case of a single value) we define the part of the profile with the higher temperature as a positive temperature anomaly or hot spot. If enough temperature data are available to make a map instead of, or in addition to, profiles, then a true temperature anomaly or hot spot, like a structural anomaly, must exhibit a high area with closure apparent in all directions. We do not claim that each temperature anomaly will exactly coincide with outlines of a productive field in terms of size, shape, or magnitude. It is the pattern which is important; that is, a temperature high must somewhere coincide geographically with the productive area of the oil or gas field.

On the basis of the studies documented in this paper, the writers agree with Dumanskiy's (Dumanskiy et al, 1971) conclusion that, "The application of the geothermometric method in the search for oil and gas deposits could reduce the expensive share of drilling deep search boreholes, and augment the effectiveness of search and exploration work, to further promote the quick opening of oil and gas fields."

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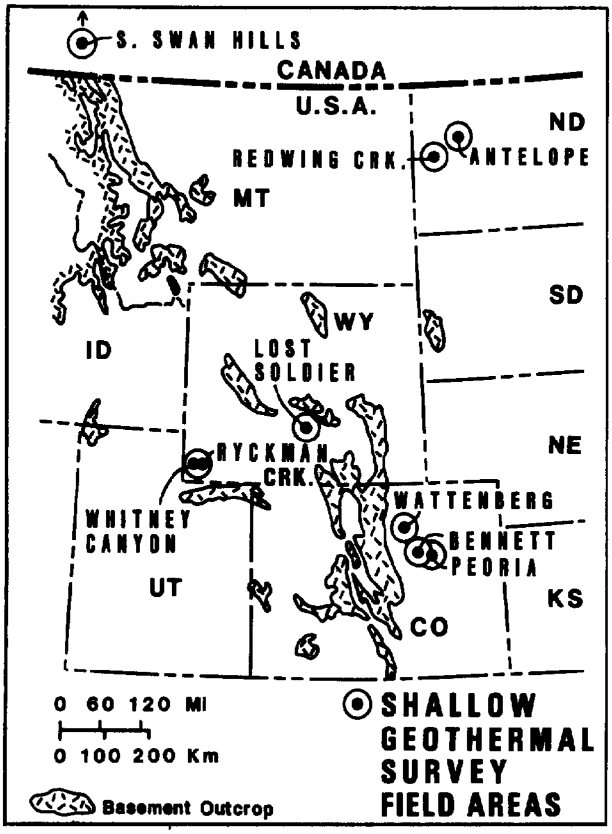


Figure 1—Locations of nine oil and gas fields over which shallow geothermal surveys were conducted.

ROCKY MOUNTAIN FIELD STUDIES

Wattenberg Field (Colorado)

The Wattenberg field (Colorado), discovered in 1970, is a giant gas and oil field stratigraphically trapped in the Lower Cretaceous Muddy formation across the structural bottom of the Denver basin (Figures 1, 2). Details of its hydrocarbon reserves and deep geothermal pattern, which is a positive anomaly, were reported by Meyer and McGee (1985). At the end of 1972, the year we surveyed this field, the Wattenberg and Spindle fields (the latter overlies the southwestern part of the Wattenberg field and produces oil from a shallower Cretaceous zone) together had produced 0.577 million bbl of oil and 5.589 bcf of gas.

In late 1972, seven shallow holes approximately 500 ft (150 m) deep were drilled for measuring temperatures at the locations shown on Figures 2 and 3B. Each shallow test hole was a twin to a deep producer or dry hole from which deep temperature data are available (Figure 3A).

Although the shallow tests were twins to deep holes, care was taken at Wattenberg and all other fields surveyed to locate the shallow tests at least 150 ft (45 m) away from any producing or service well to avoid mapping temperatures affected by production.

As might be expected, considerable damping of the deep anomaly occurs near the surface, as shown on cross section AA′ in Figure 3A (the 60°F temperature line is from our shallow temperature survey). However, the actual extent of damping is distorted by the vertical depth scale used in Figure 3A and by the fact that a 400-ft (120-m) difference in ground elevation is found between holes 1 and 7 (hole 7 is the lowest). The data presented in figure 3B remove these effects by using the ground as a reference surface and plotting temperature profiles at three depth levels, using the vertical axis for a temperature scale. Figure 3B shows plots of the temperatures measured at depths of 100, 300, and 500 ft (30, 90, and 150 m) below the ground surface in each shallow hole. A positive geothermal anomaly of 1.5 to 3F° (0.8 to 1.7C°) is clearly revealed at these depths. These results encouraged us to attempt further shallow surveys, because the agreement of shallow and deep geothermal data is surprisingly good.

Bennett Field (Colorado)

This small field, with ultimate oil recovery estimated at less than 1 million bbl, is approximately 25 mi (40 km) east of Denver, and is a stratigraphic trap in the Lower Cretaceous Muddy "D" sandstone (Figures 1, 4). From its discovery in 1970 through the end of 1973, the Bennett field had produced only 0.209 million bbl of oil and 1.189 bcf of gas. With fairly good producing-level temperature control, Bennett is revealed as a temperature-gradient hot spot anomaly coincident with the productive area (Figure 5). Eleven geothermic test holes were drilled to a depth of 500 ft (150 m) in 1973. The map of isotherms at 500 ft (150 m) below ground surface (Figure 6) and the southwest-to-northeast profile (Figure 7) show shallow confirmation of the deeper producing-level anomaly, which is about 7,600 ft (2,320 m) deep. The shallow anomaly is only about 0.5 F° (0.3C°) at 500 ft (150 m).

Figure 6 also shows that the second and third highest temperatures are outside the limits of the productive field, both southwest of the Bennett field proper. Other shallow-temperature studies done in this area by Meyer and McGee (unpublished data) show a regional temperature gradient increase from northeast to southwest across the entire map area included in Figure 6. The high temperature values recorded in the holes southwest of the Bennett field (Figure 6) very likely reflect this regional temperature gradient.

The term "temperature gradient," as used in this paper, is synonymous with "geothermal gradient," or the rate of increase of temperature in the Earth with depth, expressed in degrees per unit depth, or as F° per 1,000 ft in this paper. (Some other authors may use units of depth per degree, commonly called "reciprocal gradient.") Whenever the Earth's surface is the shallowest depth, the mean annual surface air temperature is used.

Peoria Field (Colorado)

Peoria field is a stratigraphic trap in the Lower Cretaceous Muddy "J" sandstone located about 15 mi (24 km) east-southeast of the Bennett field (Figure 1). A map of

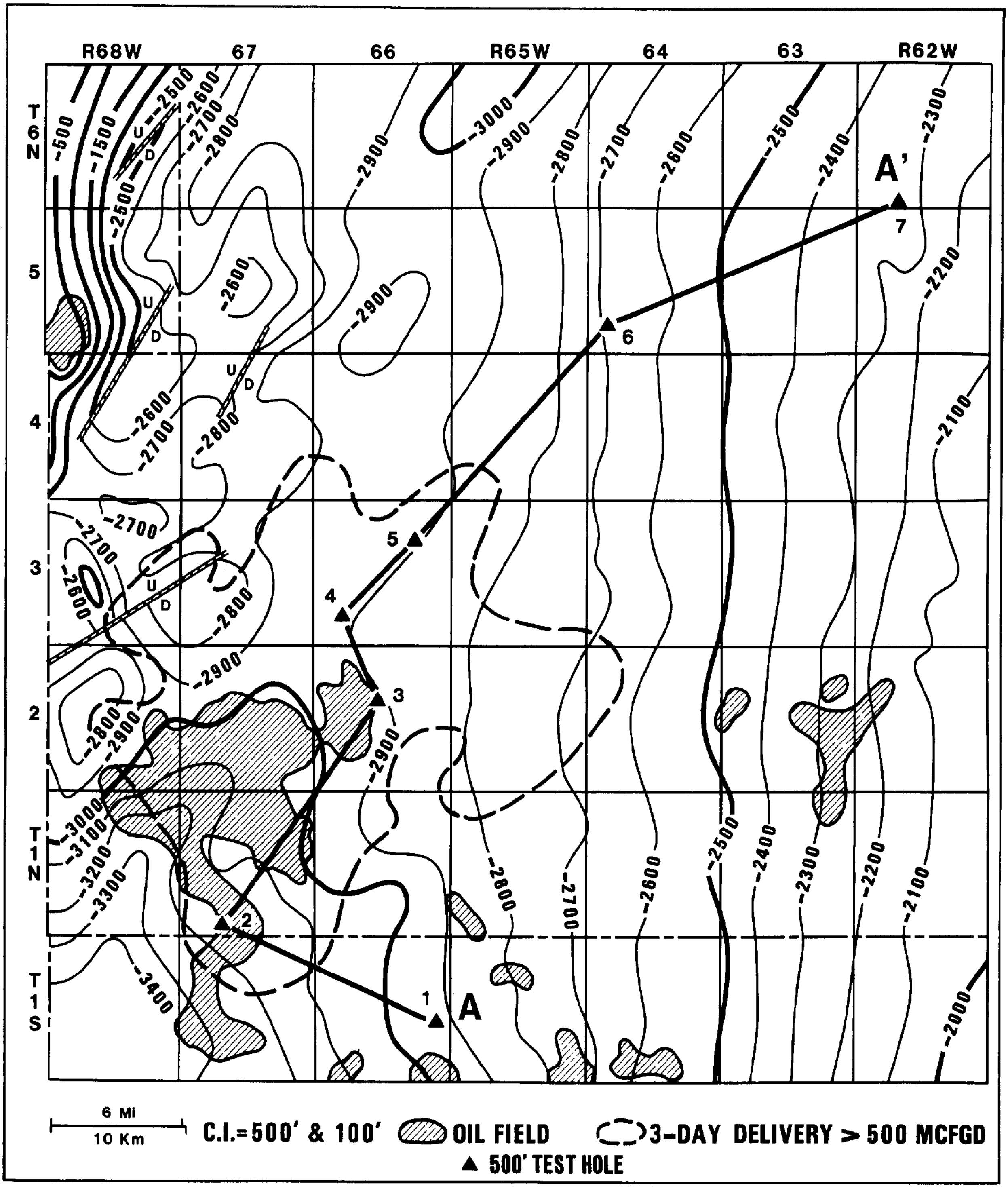
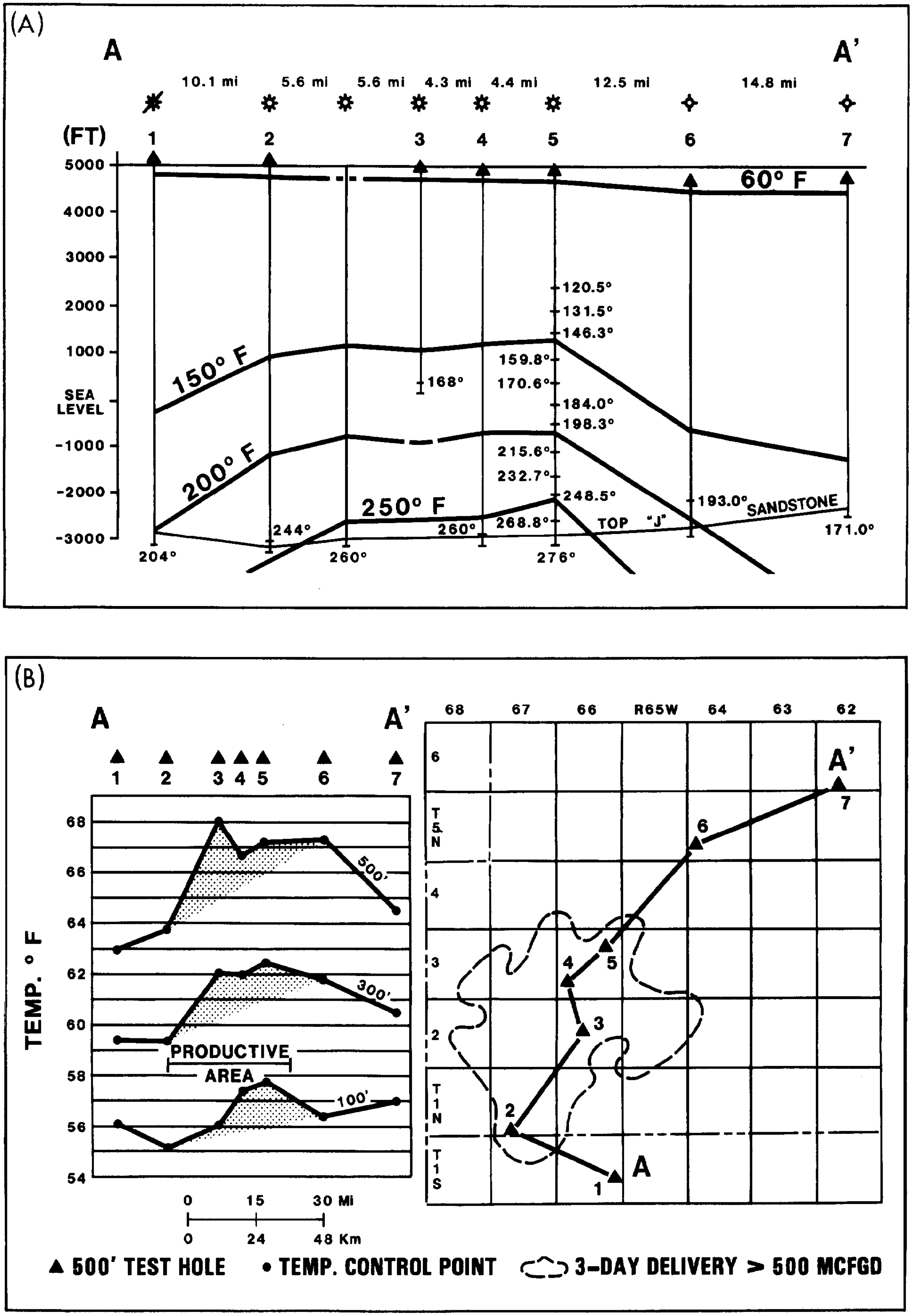


Figure 2—Lower Cretaceous "J" sandstone (producing zone) structure in Wattenberg field area, Colorado. Most prolific part of field is inside 3-day delivery > 500 MCFGD boundary line. Line of section AA ' shows locations of seven shallow test holes in Figures 3A and 3B twinned to deeper wells.

Figure 3—(A) Southwest-to-northeast cross section across Wattenberg field, Colorado, along line AA ' (Figure 2). Section shows top of Lower Cretaceous "J" sandstone (lowermost line) and 150 °F (66 °C), 200 °F (93 °C), and 250 °F (121 °C) temperature surfaces (dark lines). 60 °F (16 °C) line at top is from our shallow temperature survey. 5,000 ft (1,525 m) elevation line is included to illustrate 400 ft (122 m) drop in surface elevation between test holes 1 and 7. Noncommercial well 1 was abandoned in 1981 after producing a total of 177.1 mmcf of gas and 3,581 bbl of condensate. (B) Southwest-to-northeast temperature profile across Wattenberg field along line AA ' (Figure 2). Profile shows temperature recorded at 100-, 300-, and 500-ft (30-, 90-, and 150-m) depths in seven test holes.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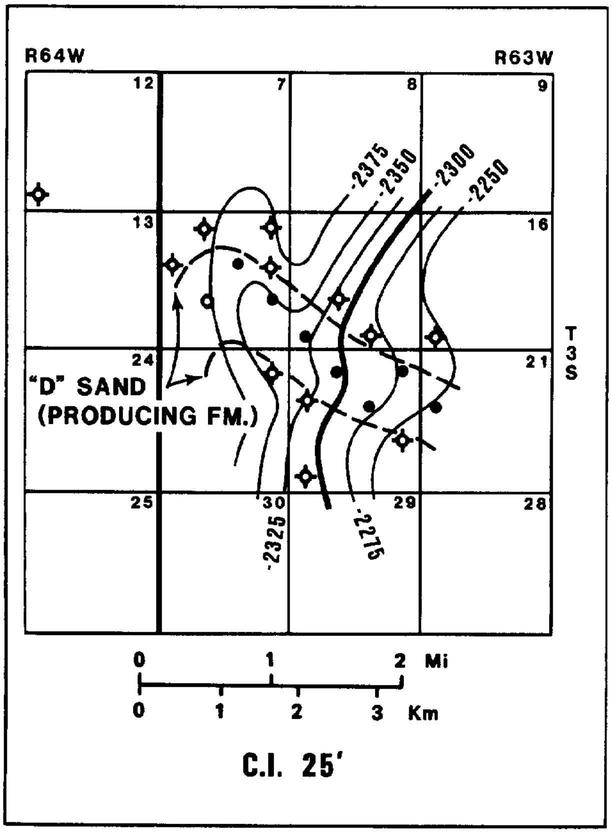


Figure 4—Structure contour map of Lower Cretaceous "D" sandstone (producing zone), Bennett field area, Adams County, Colorado. Dashed lines delineate main producing "D" sandstone trend.

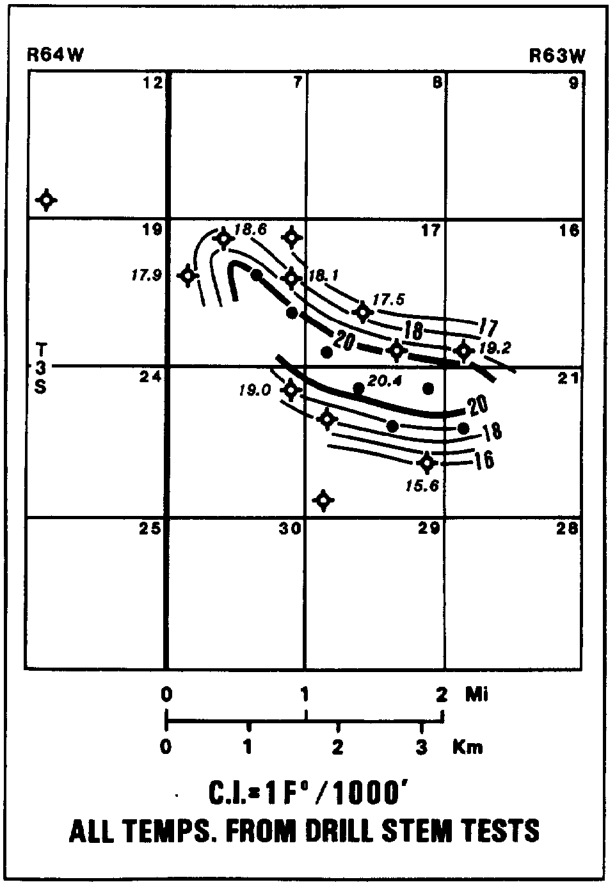


Figure 5—Temperature-gradient map from ground surface to producing level in Bennett field area, Adams County, Colorado. All producing-level temperatures used in gradient calculations are taken from measurements made during drill-stem tests. Mean annual surface air temperature is used as surface temperature in calculating all temperature gradients.

the structure and net-pay isopach in this field is shown in Meyer and McGee (1985, their Figure 16).

Producing-level temperature data are fair to good and show a well-defined geothermal gradient anomaly coincident with the productive area (Figure 8). Twelve usable shallow geothermal test holes were drilled in 1973. Two shallow (100, 300, and 500 ft or 30, 90, and 150 m) temperature profiles (Figures 9, 10) confirm the coincidence of the shallow geothermal anomaly of about 1F° (0.5C°) with the productive area.

From its discovery in 1970 through the survey year 1973, Peoria produced 7.359 million bbl of oil and 10.305 mmcf of gas.

South Swan Hills Field (Alberta, Canada)

This Canadian field was surveyed by the shallow geothermal method in 1976 (see location on Figure 1). The field was selected because of its large size, stratigraphically controlled trapping mechanism (a Devonian carbonate reef), and the fact that a reliable surface-to-producing level, positive geothermal gradient anomaly was noted there (Figures 11A, B). Gradients range from about 18F°/1,000 ft (33C°/km) outside the field to more than 23F°/1,000 ft (42C°/km) in the productive area. About 123 million bbl of oil had been recovered at the time the survey was run.

Only 19 shallow holes were completed in 28 attempts because of drilling difficulties. Despite the less-than-desired control, the shallow data reveal geothermal conditions compatible with both the deep geothermal anomaly and the productive area. The shallow geothermal map (Figure 11C) presented here confirms the anomaly. This map could have been used not only to discover the field, but also to predict the part of the field containing the thickest reef and best production (the western sector).

A west-to-east cross section (Figure 12) clearly shows a 2° to 3F° (1° to 2C°) anomaly over the field at depths of 175, 325, and 475 ft (50, 100, and 145 m). Because of Alberta provincial restrictions, our South Swan Hills field test holes could not be drilled deeper than about 480 ft (146 m). Furthermore, seasonal temperature variations exceeded depths of 100 ft (30 m) in some holes. Therefore, the temperature data were measured and are presented at slightly different depth levels for the South Swan Hills field (Figures 11C, 12) than for all the other fields studied.

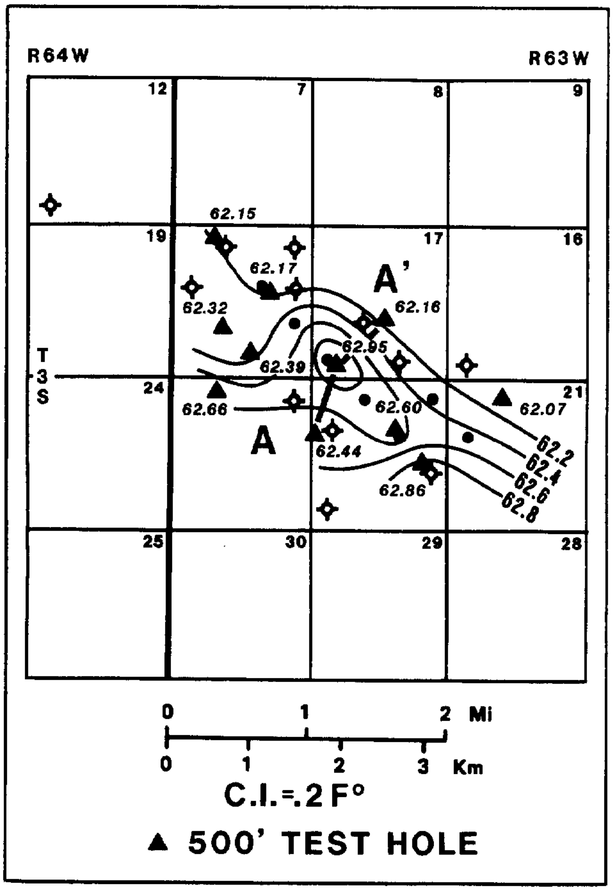


Figure 6—Isotherm map at 500-ft (150-m) depth level in Bennett field area, Adams County, Colorado.

Antelope Field (North Dakota)

Sixteen 500-ft (150-m) geothermal survey holes were drilled in two profiles across Antelope field in 1977. Antelope is a low-relief anticlinal feature (Figure 13) on the southeastern edge of the large prolific Nesson anticline of North Dakota. Cumulative production from its discovery in 1953 through 1977 was about 31.5 million bbl of oil, 3.8 million bbl of natural gas liquid, and 54 bcf gas from the Mississippian, Devonian, and Silurian at depths ranging from about 9,000 to 11,000 ft (2,740 to 3,350 m). Deep geothermal data are sparse but show a possible anomaly (Figure 14).

Results of the 16-hole shallow program are plotted on Figures 15 and 16, as west-to-east and southwest-to-northeast profiles, respectively. Temperatures at 100, 300, and 500 ft (30, 90, and 150 m), reveal a positive geothermal anomaly overlying the productive area. The magnitude is about 0.75 to 1F° (0.4 to 0.6C°) at 300 ft (90 m) and the data are considered to be reliable.

Redwing Creek Field (North Dakota)

Two lines of 500-ft (150-m) holes (totaling 19 holes) were drilled and their temperatures measured in 1977. Redwing Creek field was selected because of its small area and unusual geologic origin. Production is from fractured carbonates of the Mississippian Madison formation. Pays range up to about 1,700 ft (520 m) net and 3,000 ft (915 m) gross in the most productive part of the field. Productive depths are about 6,800 to 9,700 ft (2,075 to 2,960 m). Reported recoveries from the time of field discovery in 1972 through 1977 are 449,000 bbl of natural-gas liquid, nearly 4 million bbl of oil, and 3.35 bcf of gas.

The trap here is an anticline, believed to be an astrobleme (Sawatzky, 1975), with roughly 3,000 ft (915 m) of closure (Figure 17). Fair temperature control at producing-level depicts a positive geothermal anomaly (Figure 18).

Data from the shallow program are displayed on Figures 19 and 20, which are northwest-southeast and west-east profiles, respectively, showing temperatures at 100, 300, and 500 ft (30, 90, and 150 m). A clear-cut positive geothermal anomaly is not apparent here, except possibly in the vicinity of stations 4-7 on the west-east profile (Figure 20). The reason for the absence of a more definite, discrete anomaly is not known, but some explanations are (1) the complex structure, with possible stratigraphic complications, (2) the possibility of additional oil traps in the area, (3) the limited shallow-hole control obtained, (4) possible unknown hydrological factors, and (5) the location of the productive area in a slight topographic depression (Figures 19, 20).

Ryckman Creek and Whitney Canyon Fields (Wyoming)

Ryckman Creek and Whitney Canyon fields are located in southwestern Wyoming in the prolific thrust belt (Figures 1, 21). At the time of the shallow-temperature survey in 1977, Ryckman Creek was in its final development stages and the Whitney Canyon discovery well was in the process of completion. If the ultimate magnitude of the two fields had been realized at that time, additional shallow holes probably would have been drilled.

Ryckman Creek produces oil and gas from Triassic Thaynes and Ankara plus Jurassic Nugget rocks at depths ranging from 7,500 to about 11,500 ft (2,290 to 3,500 m). From its discovery in 1976 through 1977, Ryckman Creek produced 452,000 bbl of oil and 123 mmcf of gas. Whitney Canyon produces gas and/or condensate from the Triassic Thaynes at about 8,100 ft (2,470 m) and from the Pennsylvanian Weber, Mississippian Madison, and Ordovician Bighorn formations at depths down to 15,000 ft (4,570 m). Whitney Canyon did not produce until 1980, three years after the shallow-temperature survey.

Figure 22 shows the one 18-hole shallow-temperature survey line drilled and recorded. Although only one profile was obtained, the presence of positive anomalies of about 2F° (1C°) at both field locations is clear. This is in agreement with conclusions of Zielinski et al (1985) following their shallow-hole (100 ft or 30 m) geothermal survey covering the same two fields in 1980.

This was the first and only area in the shallow-hole program characterized by very rugged surface topography. As shown on Figure 22, the local anomalies are not

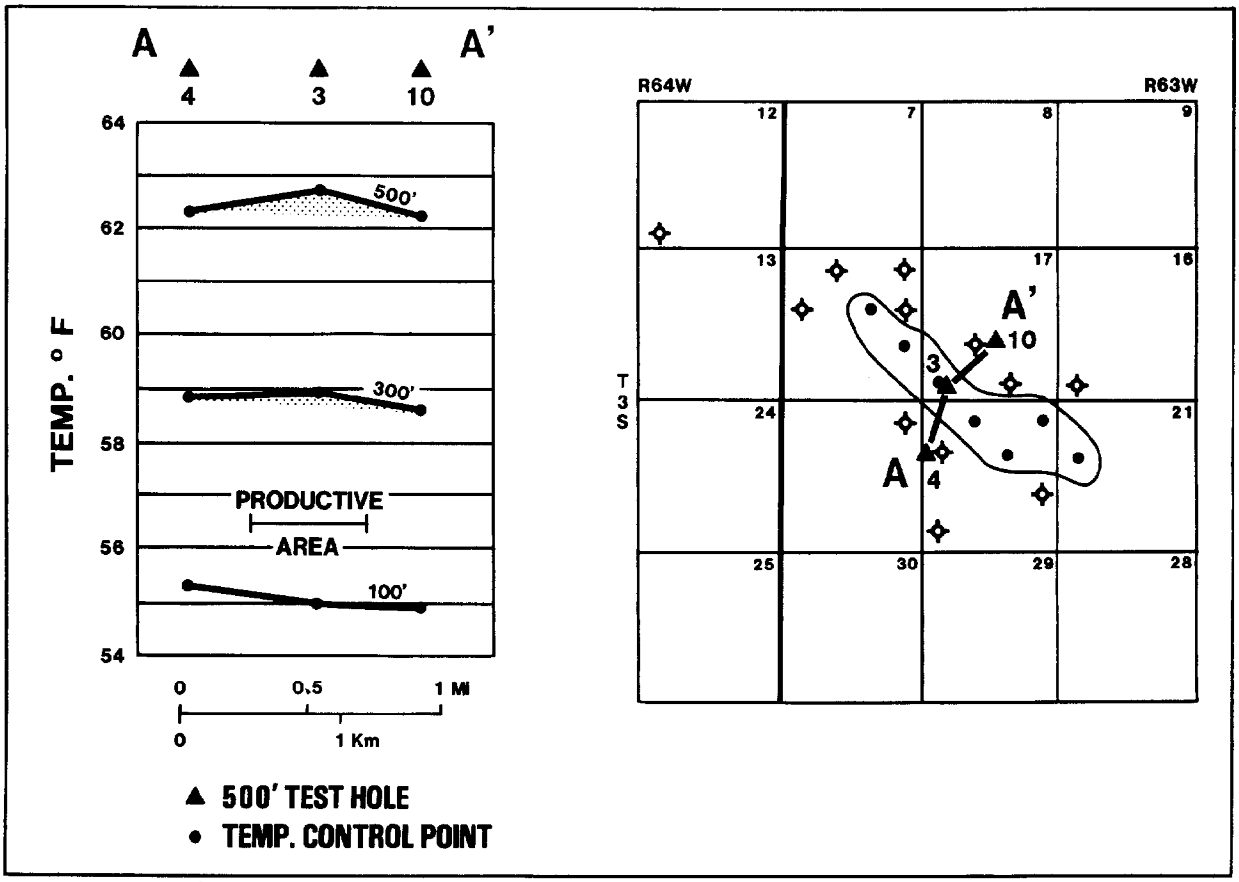


Figure 7—Southwest-to-northeast temperature profile based on three shallow test holes across Bennett field, Adams County, Colorado.

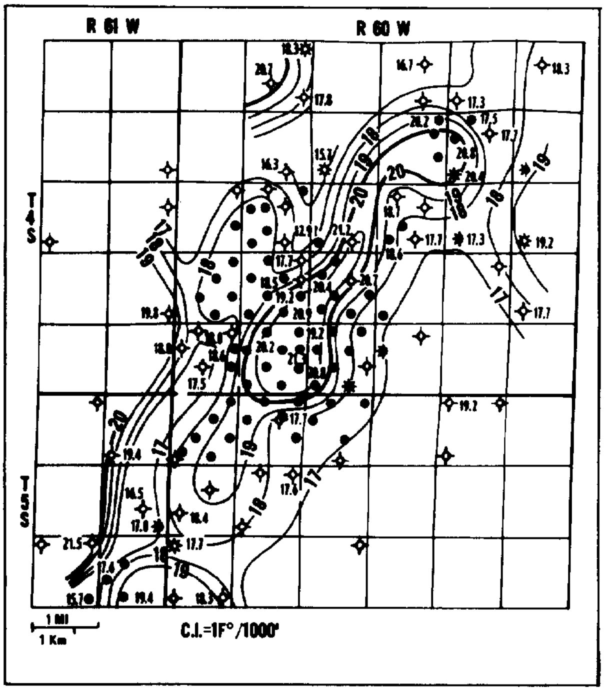


Figure 8—Temperature-gradient map from ground surface to producing level in Peoria field area, Arapahoe County, Colorado. All producing-level temperatures used in gradient calculations taken from measurements made during drill-stem tests.

significant responses to topography; however, there does appear to be a regional negative correlation between topography and temperature at all depths included in the study.

Lost Soldier Field (Wyoming)

Lost Soldier is a giant field located on an anticline that has about 3,500 ft (1,070 m) of closure at the surface (Figures 1, 23). Production ranges in depth from 200 to 6,000 ft (60 to 1,830 m) and is found in Upper and Lower Cretaceous, Jurassic, Pennsylvanian, Mississippian, and Cambrian rocks. Combined pay thicknesses amount to more than 3,000 ft (915 m). The field was discovered in 1916 and, through 1978, had produced about 3.8 million bbl of natural gas liquid, 176.5 million bbl of oil, and 67.6 bcf of gas.

One shallow-hole profile was drilled, consisting of seven locations on 0.5-mi (0.8-km) spacing. At each location, a 500-ft (150-m) hole and a 10-ft (3-m) twin hole were drilled. This work was done in bitterly cold snowy weather in early 1978. Temperature measurements, however, were made periodically until warm weather in late July. After the temperature reached equilibrium in about 2 or 3 weeks, it remained stable in all seven of the 500-ft (150-m) holes for the entire 6-month period.

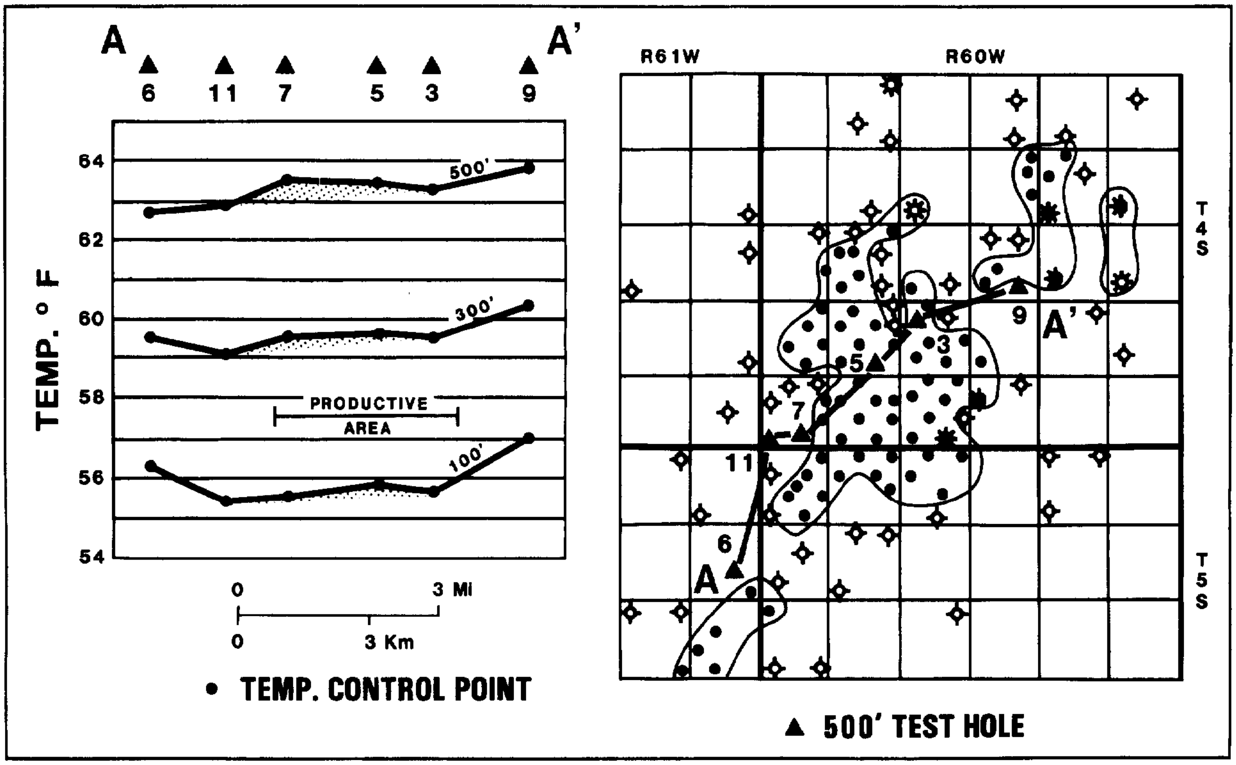


Figure 9—Southwest-to-northeast temperature profile based on six shallow test holes across Peoria field, Arapahoe County, Colorado.

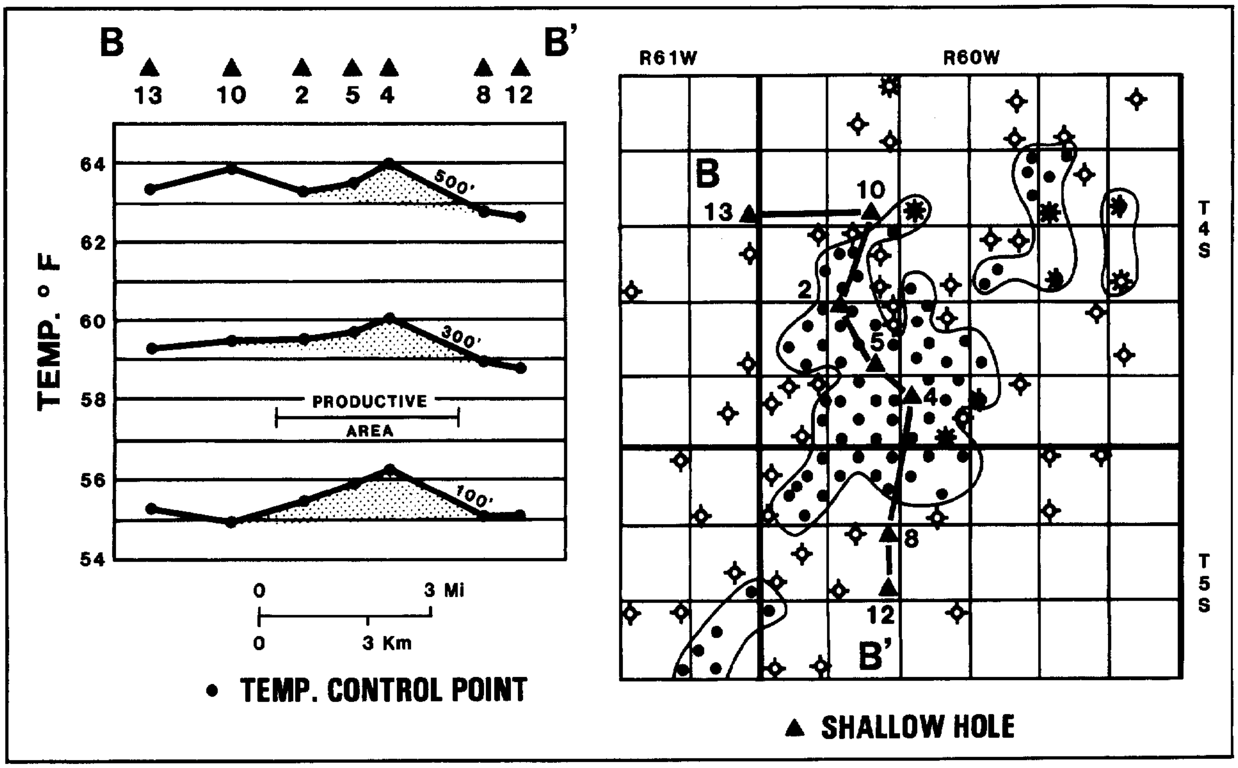


Figure 10—North-to-south temperature profile based on seven shallow test holes across Peoria field, Arapahoe County, Colorado.

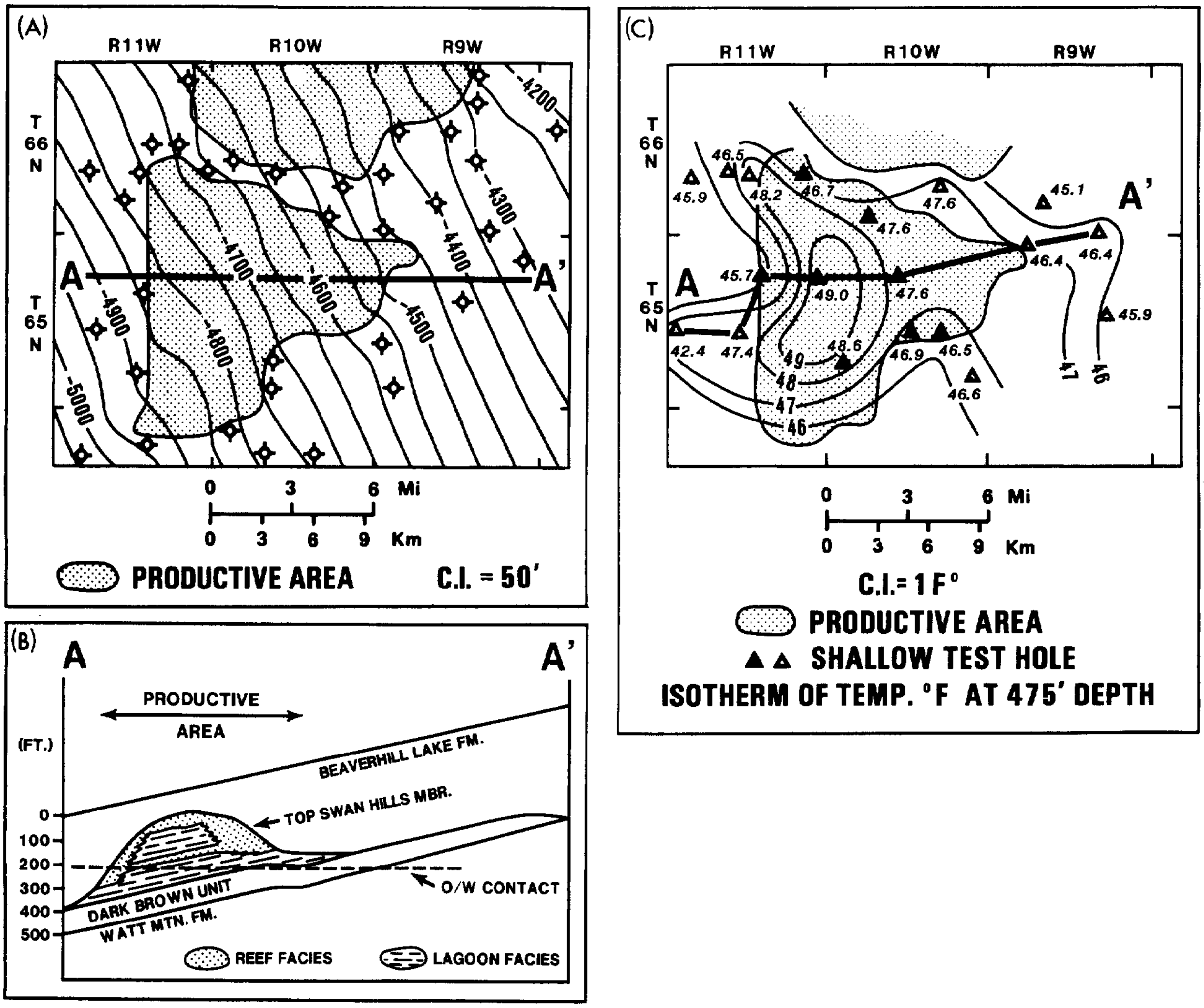


Figure 11—(A) Contour map of structure on Devonian Beaverhill Lake Formation in South Swan Hills field area, Alberta, Canada. Production is primarily from reefal facies of Swan Hills Member, top of which ranges from about 100 to 600 ft (30 to 180 m) below top of Beaverhill Lake Formation. Diagrammatic cross section along line AA′ shown in Figure 11B. (B) Diagrammatic west-to-east section along line AA′ of Figure 11A, showing relationships of reefal to lagoonal facies in productive Swan Hills Member, South Swan Hills field, Alberta, Canada. (C) Isotherm map at 475-ft (145-m) depth level, South Swan Hills field area, Alberta, Canada.

The anomaly found here (Figure 24) is spectacular. At 100 ft (30 m) the anomaly is 5F° (2.8C°), at 300 ft (90 m) it is 9F° (5C°), and at 500 ft (150 m) it is more than 16F° (9C°). Even at 10 ft (3 m), the anomaly is at least 2F° (1.1C°). Geothermal gradients from 100 to 500 ft (30 to 150 m) range from less than 20F°/1,000 ft (36.5C°/km) outside the field to more than 50F°/1,000 ft (90C°/km) in the heart of the productive area. The magnitude of the anomaly is believed to be due to the shallow depth (200 ft or 60 m) of the shallowest pays on top of the anticline and to the large (more than 3,000 feet or 915 m) combined pay thickness.

FIELD STUDIES REPORTED IN LITERATURE

Wide Gorge Field (Soviet Union)

Dumanskiy et al (1971) recognized the importance of shallow geothermal mapping in exploring for stratigraphically trapped oil. Figure 25 shows the results of their work at the Wide Gorge field in the southwestern part of the Soviet Union. The cross section on the right side of the figure shows the nature of the trap. Production is from a sandstone lens at depths of about 1,970-3,610 ft (600-1,100 m). The updip limit is controlled by the pinch-out of the pay zone and the downdip limit by the oil-water contact. Structure is monoclinal. The cross section also shows an isothermal surface at a depth of only 328 ft (100 m), well above the pay zone. That surface rises approximately 1.8F° (1C°) over the productive area. That amount of temperature increase at such a shallow level is significant and is easily mapped.

The left side of Figure 25 depicts the same geological conditions in map form—the monoclinal structure, the sandstone pinch-out, the oil-water contact, and contours of 328-ft (100-m) isothermal surface. The anomaly is clearly expressed, indicating that shallow geothermal mapping could have found this field.

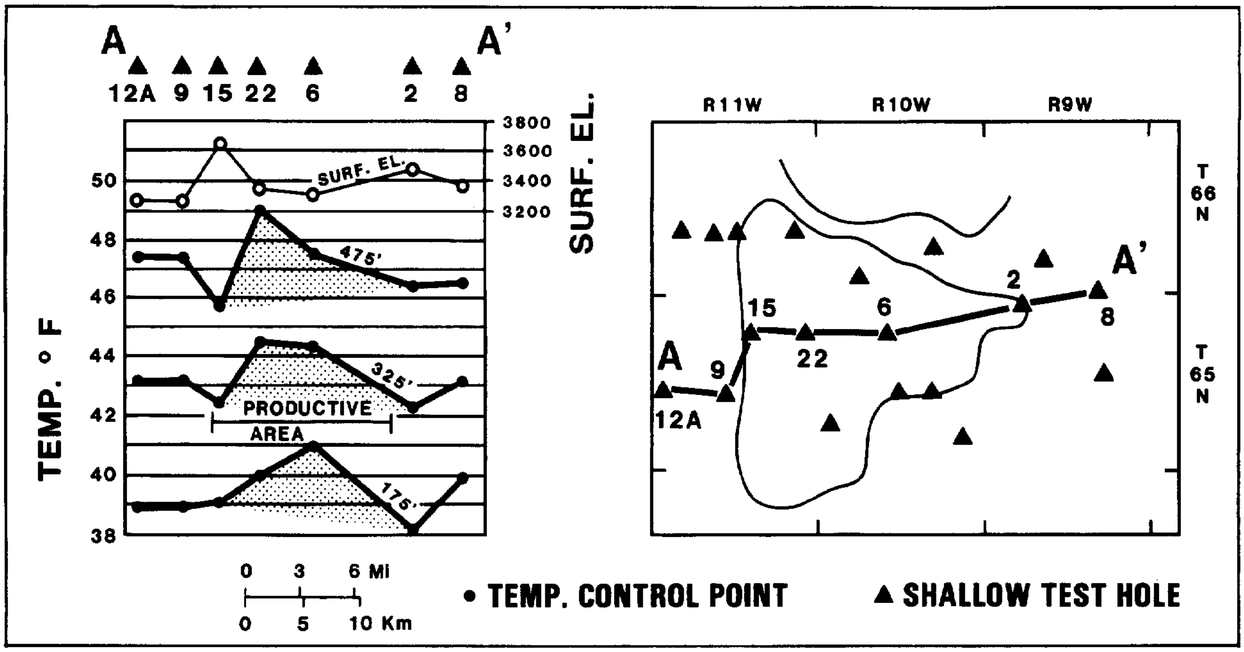


Figure 12—West-to-east temperature profile based on seven shallow test holes across South Swan Hills field, Alberta, Canada.

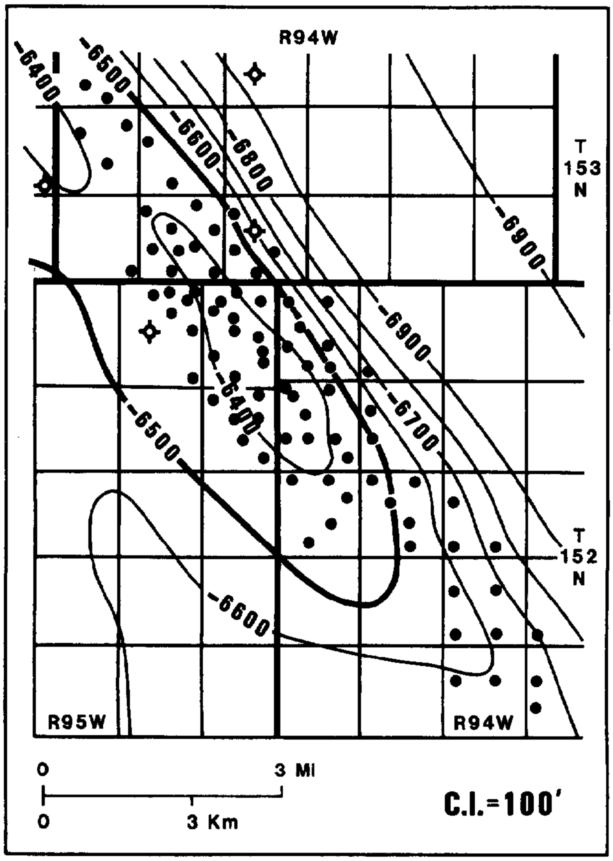


Figure 13—Structure contour map of Mississippian Madison-Charles radioactive marker, Antelope field, McKenzie County, North Dakota.

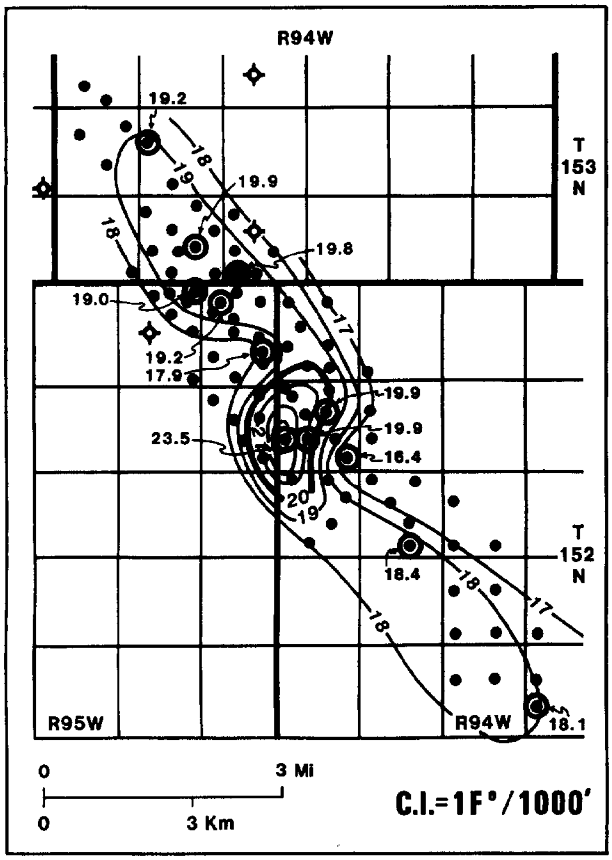


Figure 14—Temperature-gradient map from ground surface to producing level in Antelope field, McKenzie County, North Dakota. All producing-level temperatures used in gradient calculations are taken from measurements made during drill-stem tests.

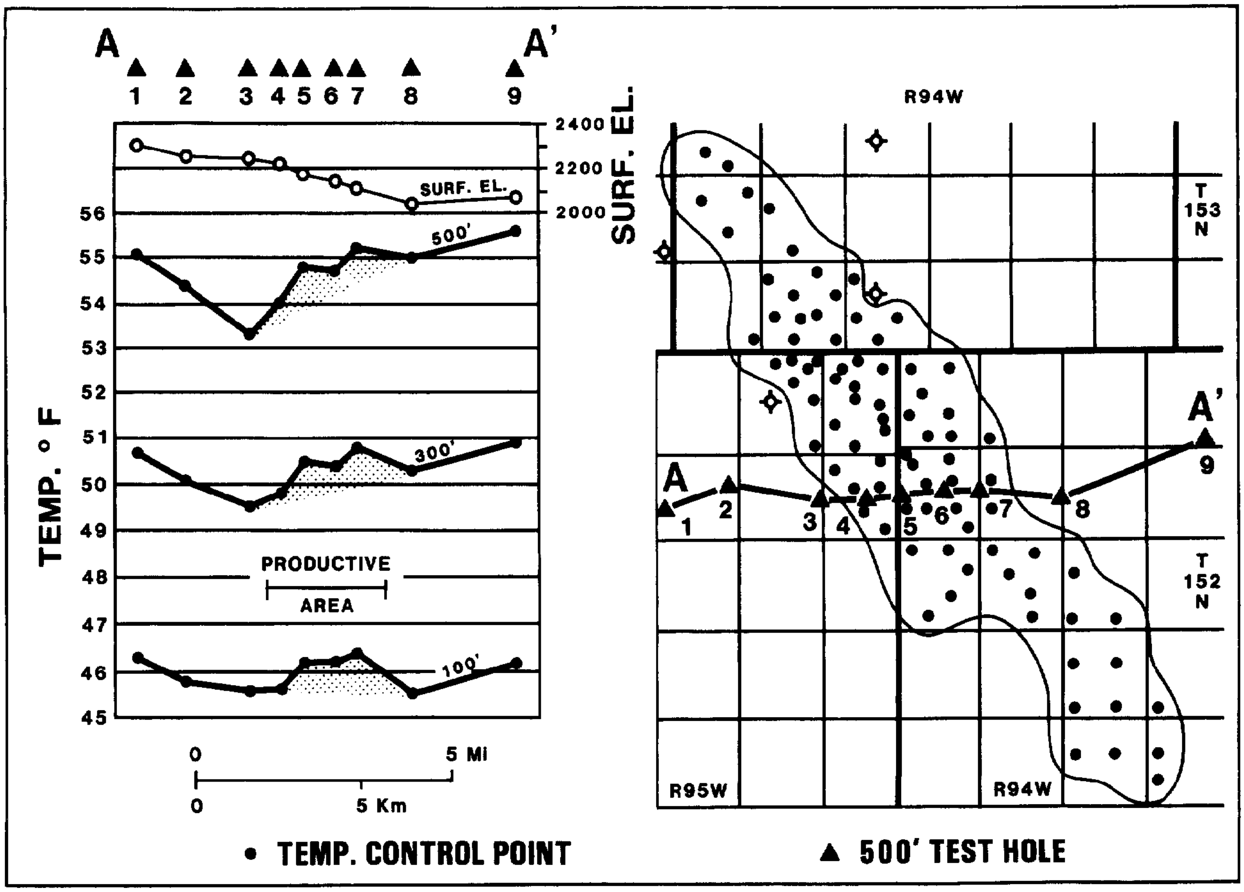


Figure 15—West-to-east temperature profile based on nine shallow test holes across Antelope field, McKenzie County, North Dakota.

Bakhar Field (Soviet Union)

This field is in the southwestern part of the Caspian Sea. Production is confined to the higher parts of an anticlinal fold (Figures 26, 27) (from Artemenko and Malovitskiy, 1977). Isotherms from only 4 ft (1.2 m) below the water bottom show a well-developed positive anomaly of about 1.3F° (0.7C°) overlying the productive area.

Figure 27 shows three profiles of isotherms at 4 ft (1.2 m) below water bottom in the field area. Profiles I-I′ and II-II′, across the "petroliferous sector" show excellent positive features. Profile XIV-XIV′, which appears to be near the southern limit of the productive area, reveals only a minimal positive feature.

Voyvozhsky Field (Soviet Union)

Lakhtionov et al (1975) identified a positive geothermal anomaly over the Voyvozhsky field based on temperatures measured at a depth of only 10 ft (3 m) in June and again in October 1972. Although the actual temperatures varied from June to October, the net effects are the same—an increase of about 3.6F° (2C°) above the field compared to temperatures around and outside the field.

METHOD OF MAKING SHALLOW MEASUREMENTS

One of the primary concerns in using shallow holes for geothermic mapping is how deep the holes should be. The following lines from Winchell (1889, p. 129) describe the problem: "...diurnal fluctuations of temperature diminish downward in amount, and at the depth of about 32 inches disappear altogether. But there are seasonal fluctuations and these can be traced to a depth of about fifty feet." We have determined that seasonal temperature variations can occur somewhat deeper than 50 ft (15 m) and that about 75 ft (23 m) is a more reliable depth for season-to-season consistency, at least in the Rocky Mountain region of the United States. These depths probably depend somewhat on the rates of meteoric water discharge and recharge, and also on the depth of the water table. For example, at the South Swan Hills field in Alberta, Canada, the seasonal variations may sometimes occur as deep as 125 ft (38 m).

Figure 28 is a schematic diagram of the method used by the writers in the early stages of the shallow geothermal investigations. First, the hole was drilled to a depth of several hundred feet using a small truck-mounted drilling rig. Drilling mud was used to protect the shallow water sands. When total depth was reached, the drill pipe was removed from the hole.

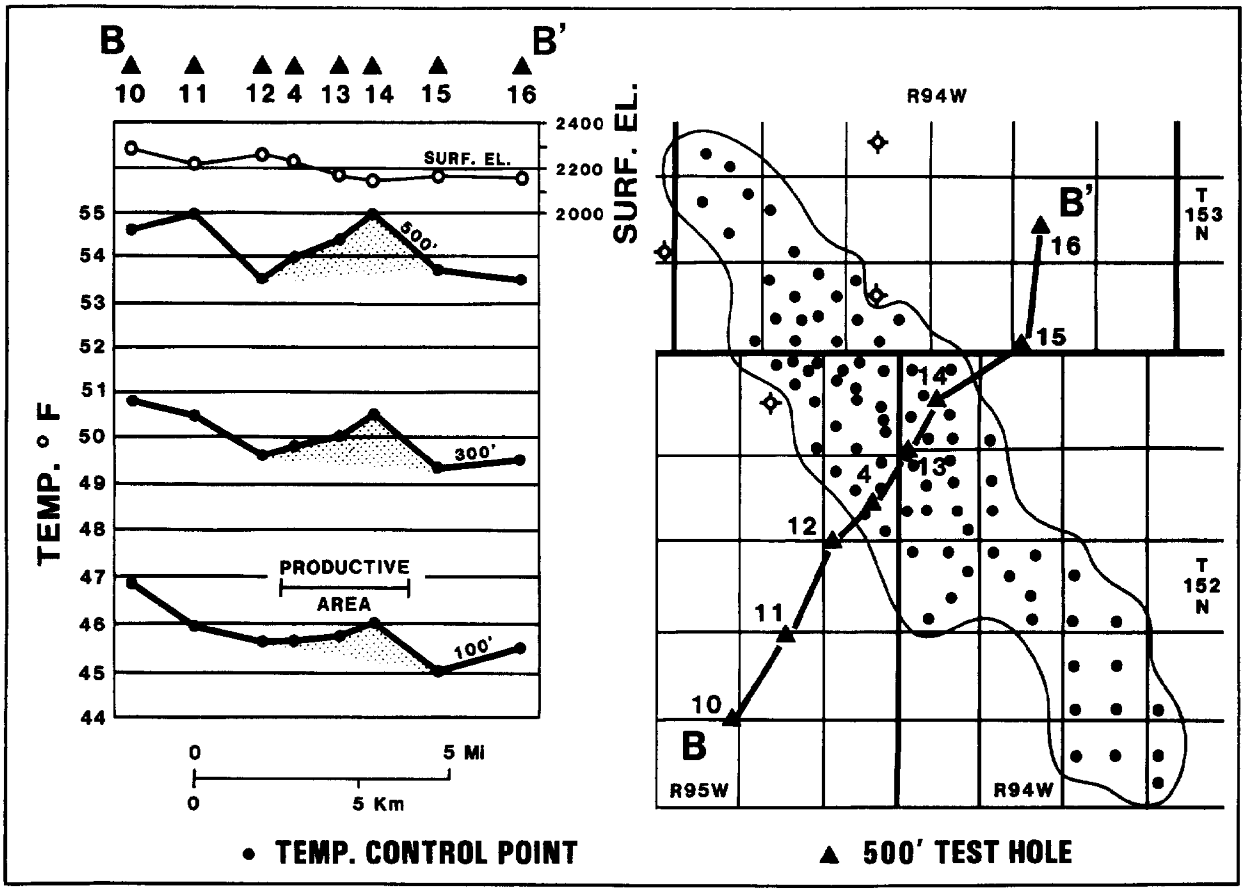


Figure 16—Southwest-to-northeast temperature profile based on eight shallow test holes across Antelope field, McKenzie County, North Dakota.

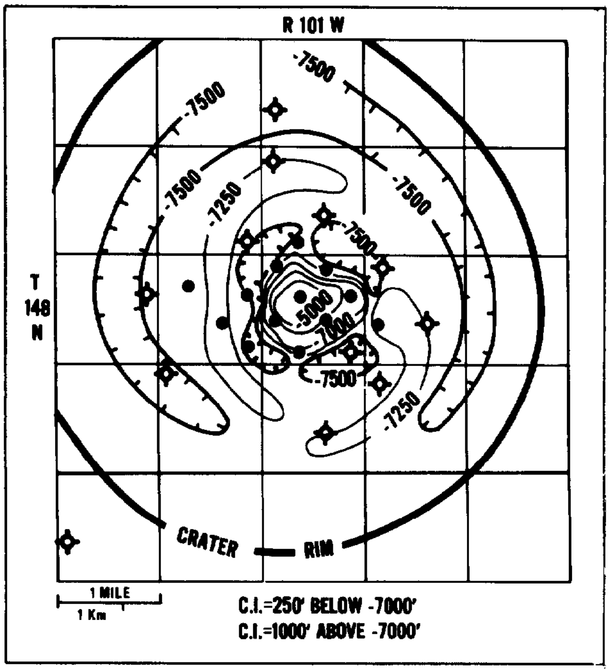


Figure 17—Structure contour map of Mississippian Mission Canyon formation in Redwing Creek field area, McKenzie County, North Dakota.

Then an expendable cable with thermistors implanted at regular intervals (typically 50 ft or 15.2 m) was installed in the hole. Thermistors are semiconductors whose electrical resistance varies sharply in a known manner for a relatively small change in temperature. Thermistors used in this work were of the "bead" type, and were accurate to about ±0.1F° (±0.05C°) over the temperature range surveyed. Multicircuited cables were used so that each thermistor had the same circuit length. The cable was hung from a surface wellhead, and mechanical logs—usually recording spontaneous potential, resistivity, and gamma-ray curves—were run, either before or after the cable installation. The hole then was backfilled with cuttings generated during drilling.

Individual resistance readings were made over a period of several days to several weeks at each thermistor level using a multimeter (or Wheatstone bridge) recording device at the surface. Resistance readings then were converted to temperature equivalents.

Later in the field operations, expendable plastic casing filled with water was used, thereby permitting routine recovery of the thermistor cables. Thus, the cost of the operation was substantially reduced.

Because of the experimental nature of the program and to ensure accuracy, readings were taken over a period of months in most cases, although thermal equilibrium was

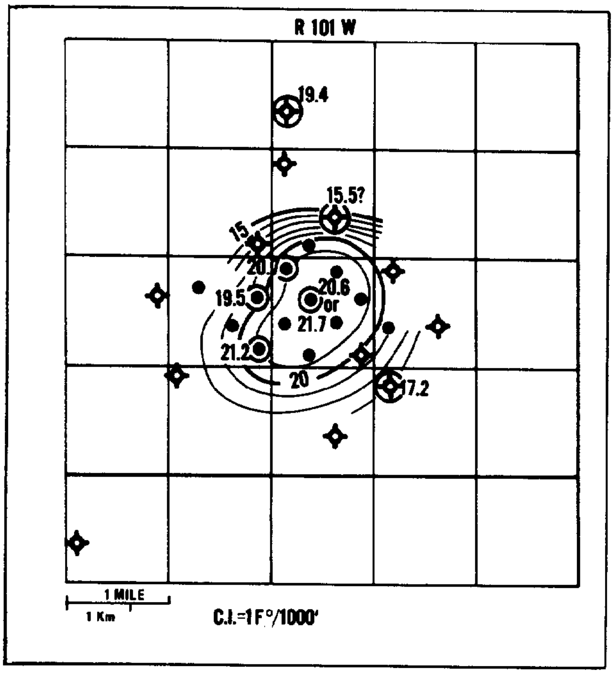


Figure 18—Temperature-gradient map from ground surface to producing level in Redwing Creek field, McKenzie County, North Dakota. All producing-level temperatures used in gradient calculations are taken from measurements made during drill-stem tests. Two values specified for well in center of field (20.6 or 21.7) are gradients determined from two different drill-stem tests run in this well at or near producing level.

reached in only a day or two if the holes were drilled in a matter of a few hours. This rate agrees with the conclusion of Bullard (1947, p. 129): "For the whole hole to get within 1 percent of equilibrium it will, therefore, be necessary to leave it for 10 or 20 times the time taken to drill. Equilibrium near the bottom, where the disturbance has not lasted so long, will naturally be attained more rapidly." At the bottom of the hole, "equilibrium will be attained in 10 or 20 times the time elapsing between reaching that point and the final stopping of the circulation of fluid."

Figure 29 shows the temperature comparisons between two holes near the Peoria field, which were drilled just a few hours apart and are located only 36 ft (11 m) from each other. Although these twin holes were not located in the Peoria field proper, they were only a few miles away. The temperatures recorded in these two holes and shown on Figure 29 were determined using two different cables and demonstrate both the stability of the local temperature field and the resolution of the measurement technique of about ±0.2F° (±0.1C°).

STABILITY OF TEMPERATURE FIELD

The observed stability of the temperature field over time is surprising considering the apparent potential for variations at such shallow depths due to ground-water movement or periodic processes such as seasonal or

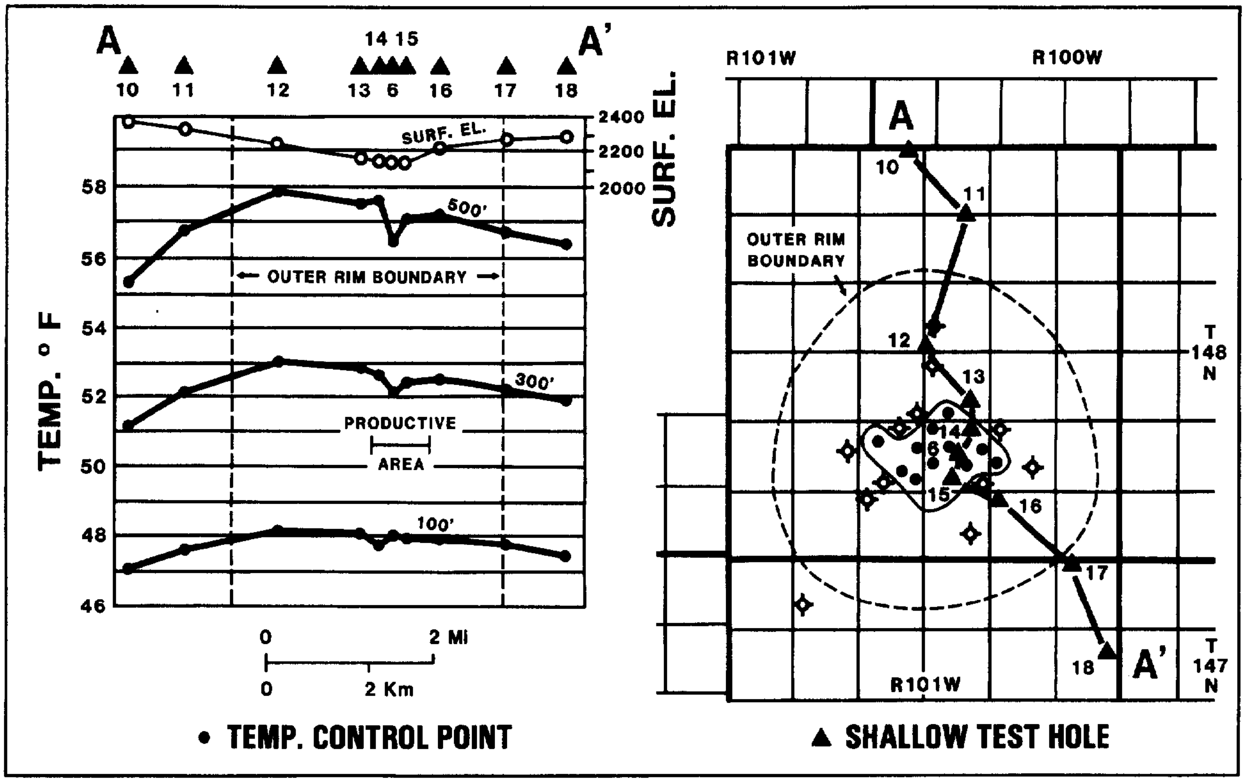


Figure 19—North-to-south temperature profile based on ten shallow test holes across Redwing Creek field, McKenzie County, North Dakota.

longer term climatic changes. Most holes were monitored for periods of 1 month to 1 year. Once the temperature in a hole stabilized, rarely were changes of more than ±0.2F° (±0.1C°) observed at any depth below 100 ft (30 m) in any of the fields surveyed.

Further evidence of this stability is shown in Table 1, which records the temperature differences observed between surveys taken on four twinned shallow holes in Peoria field drilled 2.5 years apart. The twin test holes were located between 10 to 50 ft (3 to 15 m) away from the original holes. The temperature differences also include any errors due to different cables being used in each hole, because during this study period (1973-1975) cables were not recovered when holes were abandoned.

Subsequent investigations involving many holes in another area near the Peoria field also showed that the temperature field in that area remained very stable for more than 5 years.

PROBABLE CAUSES OF GEOTHERMAL ANOMALIES OVER OIL AND GAS FIELDS

The primary purpose of this paper is to present accurate empirical evidence for the frequent association of shallow geothermal anomalies with oil and gas fields, and not to debate all possible causes of these anomalies. However, as geologists, we naturally concern ourselves with the question: "Why?"

This subject has been discussed at length by other writers (e.g., Gretener, 1981) and, therefore, will be merely

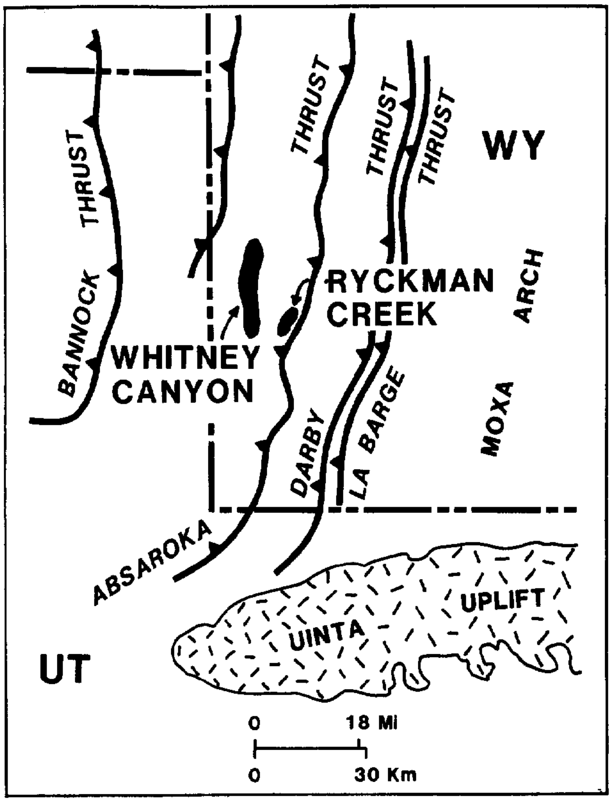


Figure 21—Location of Ryckman Creek and Whitney Canyon fields, Uinta County, Wyoming, in relation to major thrust faults.

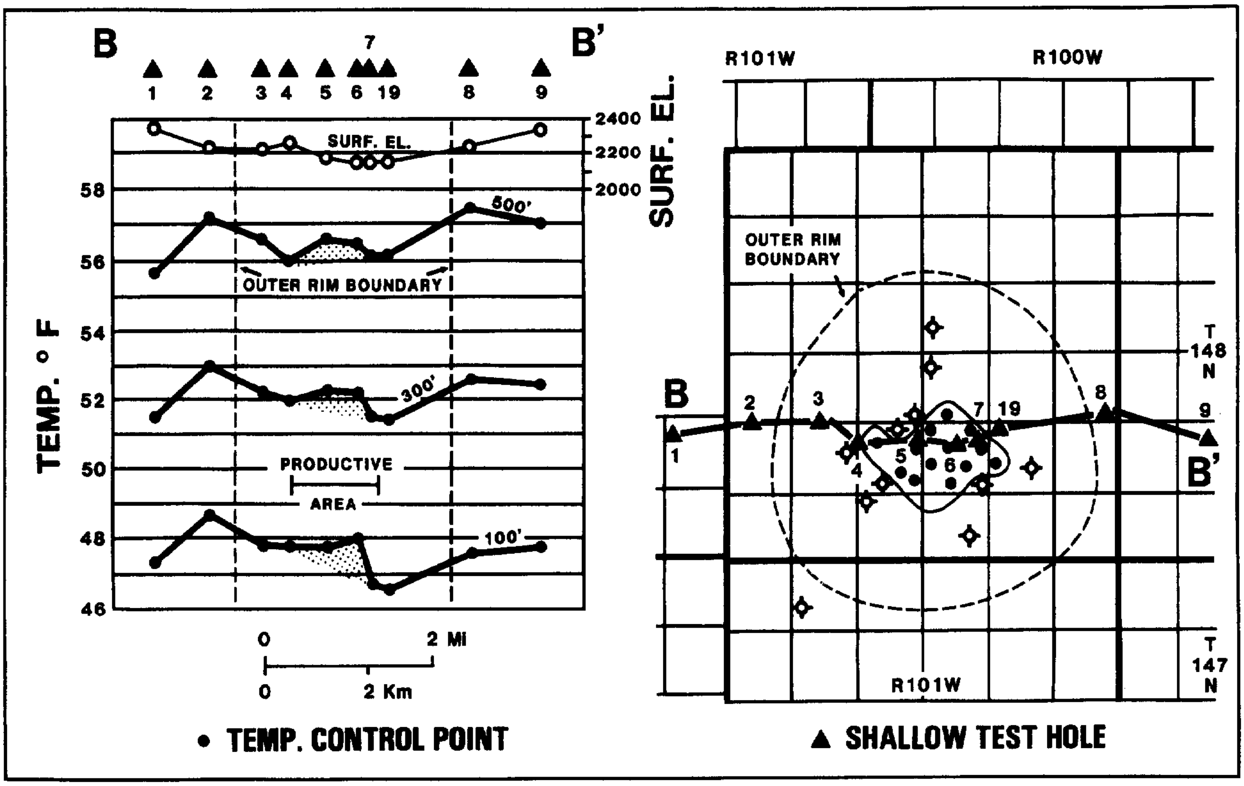


Figure 20—West-to-east temperature profile based on ten shallow test holes across Redwing Creek field, McKenzie County, North Dakota.

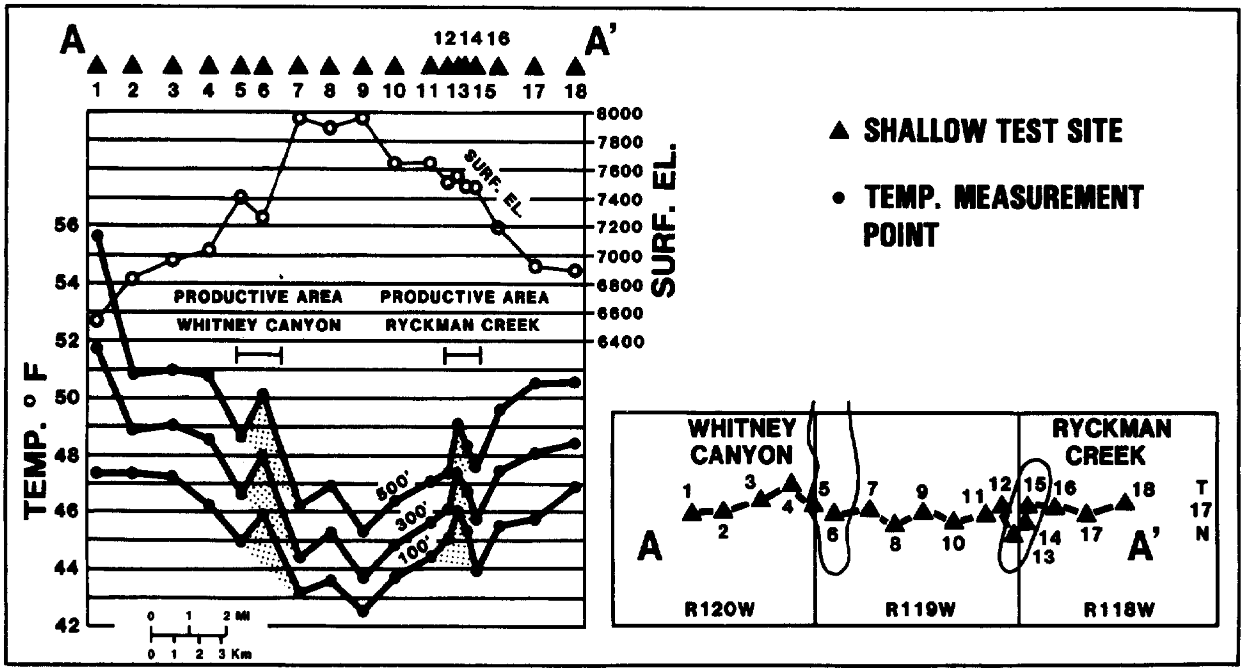


Figure 22—West-to-east temperature profile based on 18 shallow test holes across Whitney Canyon and Ryckman Creek fields, Uinta County, Wyoming.

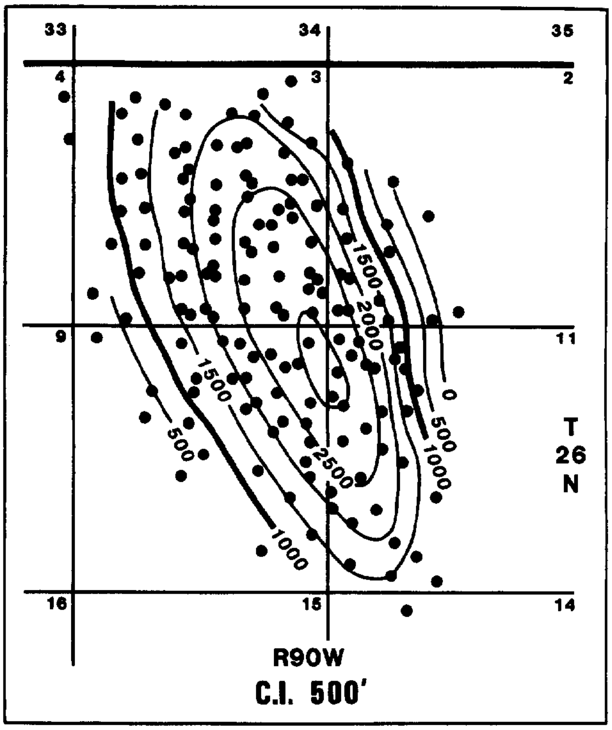


Figure 23—Structure contour map of Pennsylvanian Tensleep formation, Lost Soldier field area, Sweetwater County, Wyoming.

summarized here. At least seven general categories of processes or conditions can produce irregularities or anomalies in the Earth's temperature field: (1) near- and above-surface effects, such as topography, season, and climate, (2) meteoric waters generally moving downward or laterally in near-surface porous zones and fractures, (3) connate and juvenile fluids generally moving upward or laterally in subsurface porous zones and fractures, (4) sources of heat within the temperature field produced by physical, chemical, and biologic processes, (5) lateral differences in rock thermal conductivity due to structural deformation or changes in lithology, (6) recent intrusive or volcanic activity, and (7) nonuniform heat flow input at depth across the area of interest (Meyer and McGee, 1985).

A primary concern from the beginning of the shallow temperature mapping program was the possible influence of producing wells on temperatures measured at shallow depths. The writers feel that this was not a problem because (1) all shallow holes were located at least 150 ft (50 m), and usually several hundred feet, laterally from producing wells, (2) at the Redwing Creek field in North Dakota, which had been producing for more than 5 years, no definite anomaly was found, and (3) at the Peoria field four shallow holes drilled in 1975, which twinned four of the original holes drilled in 1973, showed a small net cooling effect over that period (see Table 1); during that period 2.6 million bbl of oil and 4.36 bcf of gas were produced from Peoria, and 11 million bbl of water were injected.

Moreover, five of the fields we studied had been produced less than 5 years at the time they were surveyed (Wattenberg, Bennett, Peoria, Ryckman Creek, and Whitney Canyon fields), and the total production from each was small.

Another concern was the possibility of encountering misleading temperature measurements due to abrupt topographic changes. Fortunately, most of the fields

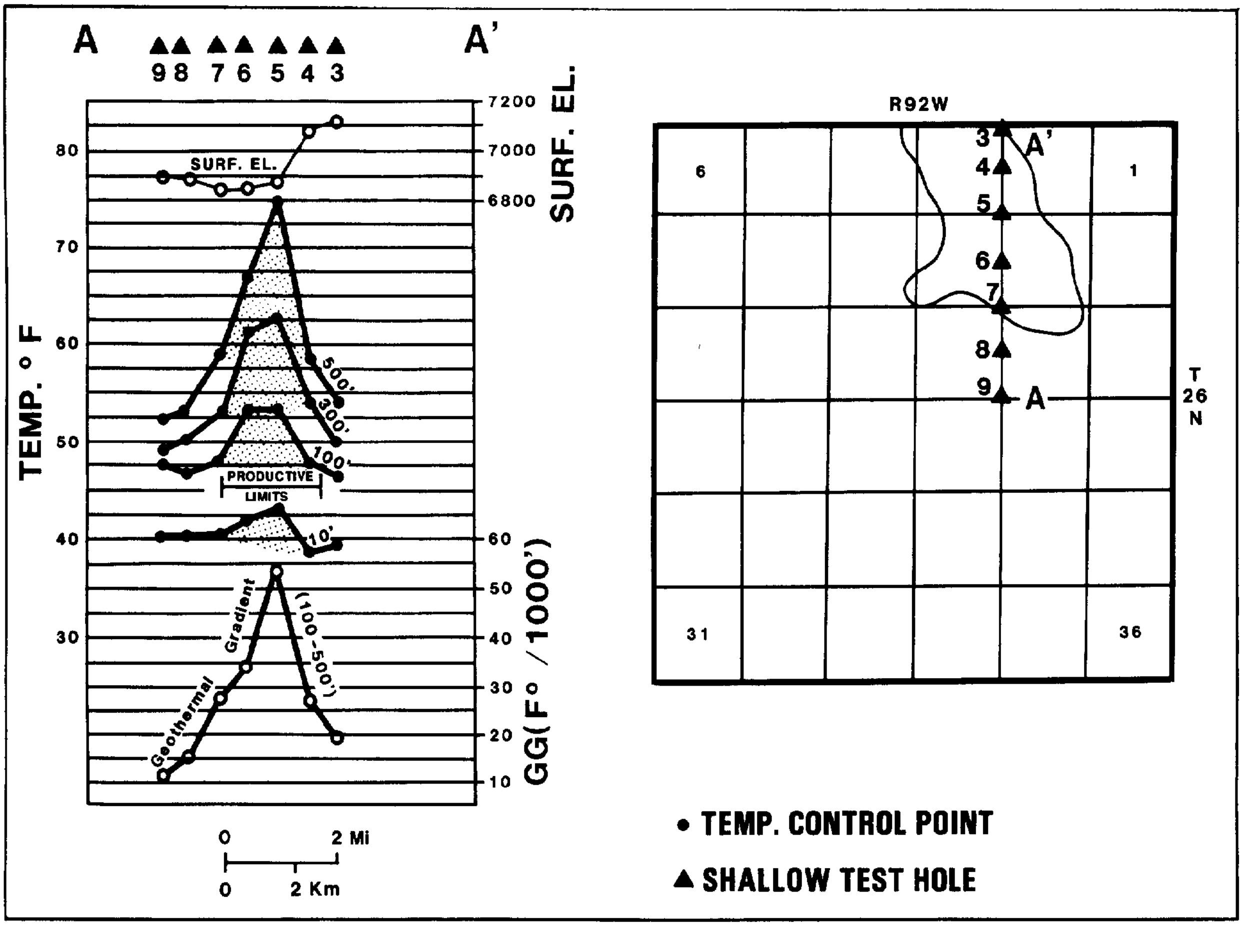


Figure 24—South-to-north temperature profile based on seven shallow test holes and seven twin ultrashallow (10-ft or 3-m) test holes across Lost Soldier field, Sweetwater County, Wyoming. 100 to 500-ft (30 to 150-m) geothermal gradient (GG) is also plotted.

mapped were in areas of low topographic relief. The main exception was the profile across the Whitney Canyon and Ryckman Creek fields (see Figure 22). In these fields, even though the topography is rather rugged, the local temperature anomalies appear to be unrelated. Another area of some topographic relief is at Lost Soldier field. As shown on Figure 24, the surface elevation of the two northernmost control points is about 200 ft (60 m) higher than other points. However, observation of the entire line indicates that topography does not cause the temperature anomaly.

It has been suggested that the relatively lower thermal conductivity of hydrocarbon-bearing reservoir rocks, which results from hydrocarbons replacing water in these rocks (water has a higher thermal conductivity than either oil or gas [Gretener, 1981, p. 6]), may somehow produce the observed anomalies. The idea is that the hydrocarbon-bearing reservoir may act like a lens and refract the constant heat flow passing vertically into and out of it, thereby distorting what otherwise would be a uniform temperature field in and around the reservoir. However, this is not a viable concept for explaining the observed anomalies, because heat-flow theory requires that, in order to compensate for a higher geothermal gradient associated with a lower average thermal conductivity in the reservoir rock, the temperature field immediately above the producing reservoir should be depressed and not elevated. Proceeding upward above the reservoir, the temperature field should become progressively less distorted until it finally returns to normal. No positive anomalies would be expected above the reservoir. Even though we have looked, we have never observed a lowering of the temperature gradient, even immediately above the producing zone, much less hundreds or thousands of feet above it. This seems perfectly reasonable to us because 10 to 100-ft (3 to 30-m) thick hydrocarbon reservoir rocks should have only very localized effects on the temperature field of the thousands of feet of rock above them, even if the thermal conductivity contrast is 2:1 or greater.

The results of one experiment we conducted suggest that hydrocarbon-bearing clastic reservoir rocks can have thermal conductivities less than one-half of their water-bearing equivalents. Two samples of water-bearing sandstone were taken from cores recovered from one of our shallow holes in the Peoria field. The thermal conductivity of these two samples was measured using the divided-bar method by Ed Decker of the University of

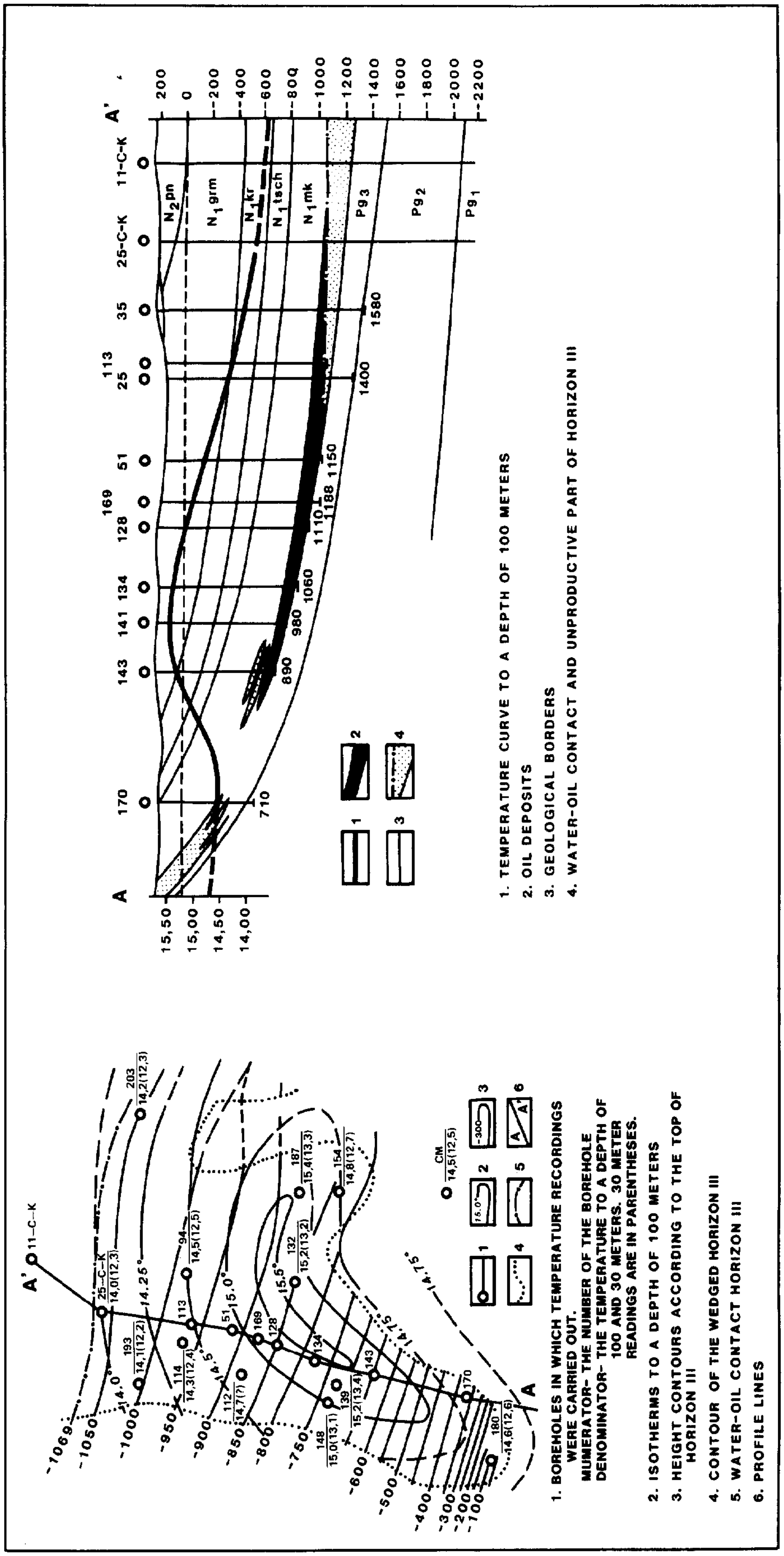


Figure 25—Geothermal map and profile from Wide Gorge field, USSR. (From Dumanskiy et al, 1971.)

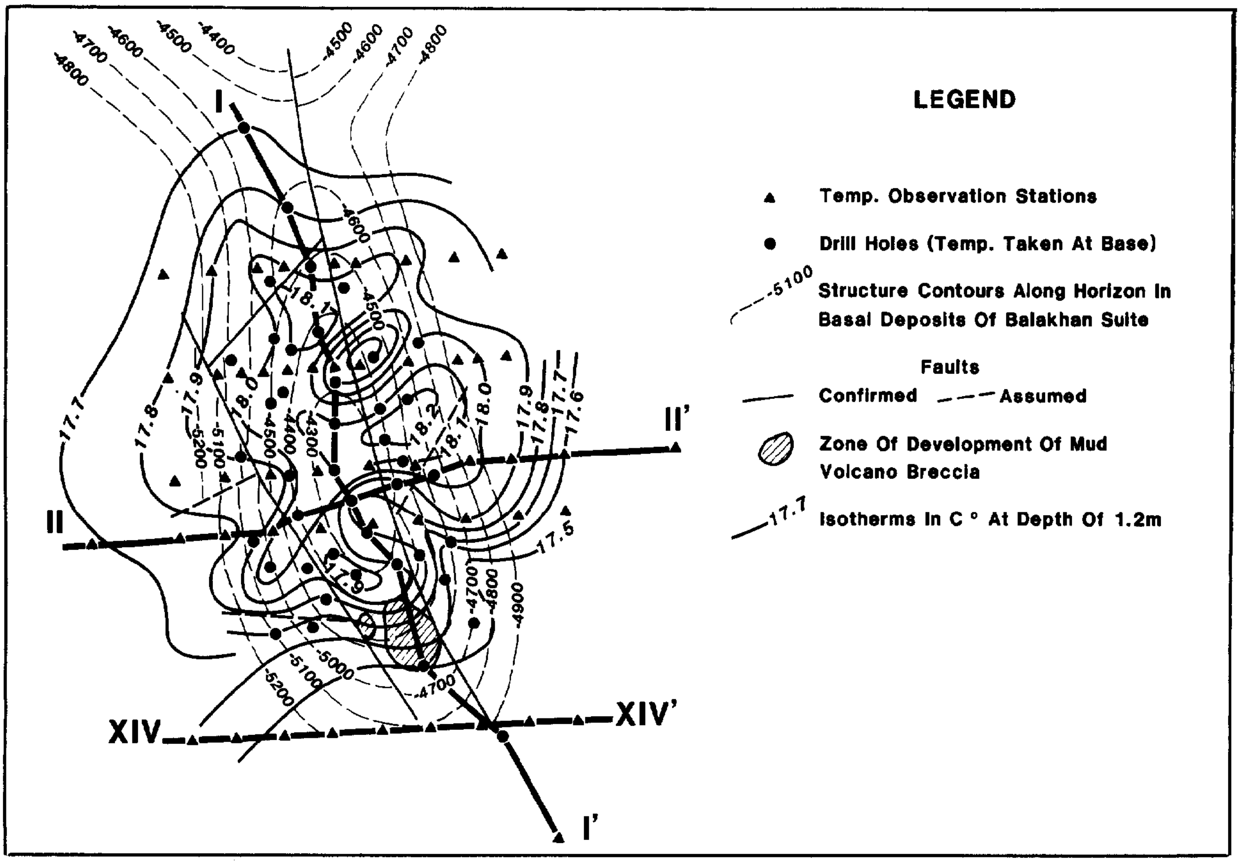


Figure 26—Structure of basal Balakhan Suite with superimposed temperature isotherms determined from ultrashallow (4-ft or 1.2-m) holes (below water bottom) across Bakhar field, in Caspian Sea south of Baku area, USSR. (From Artemenko and Malovitskiy, 1977.)

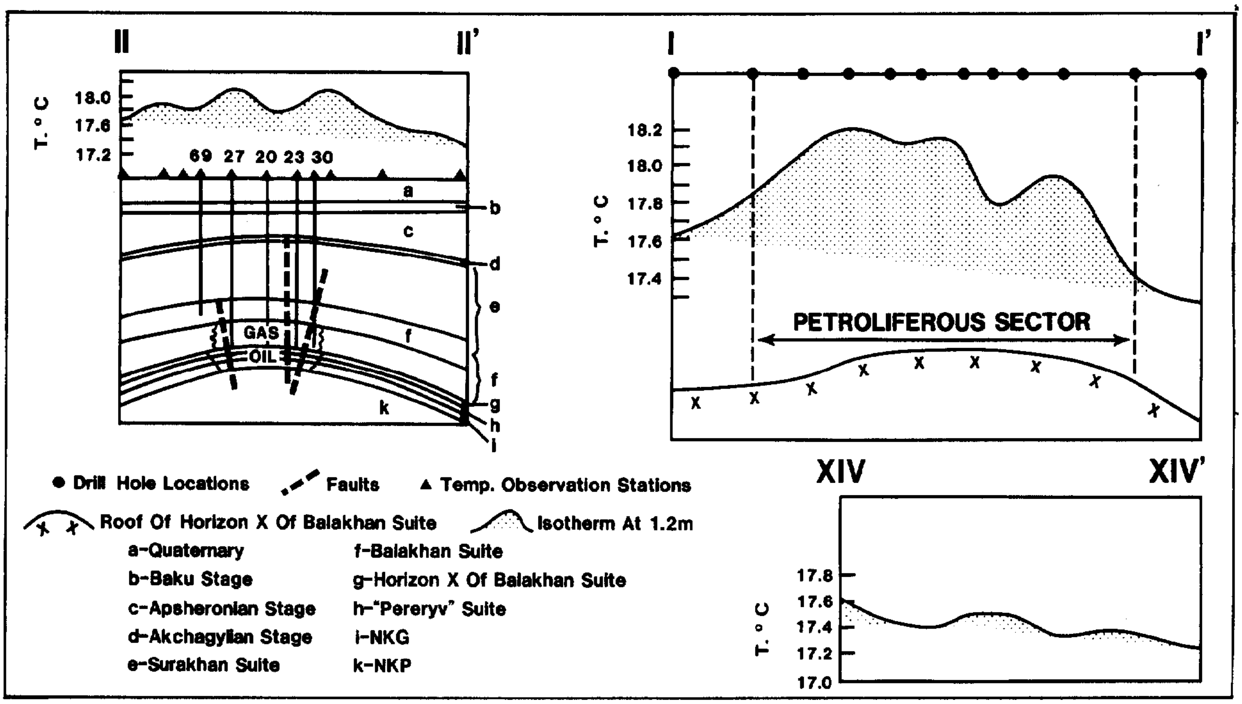
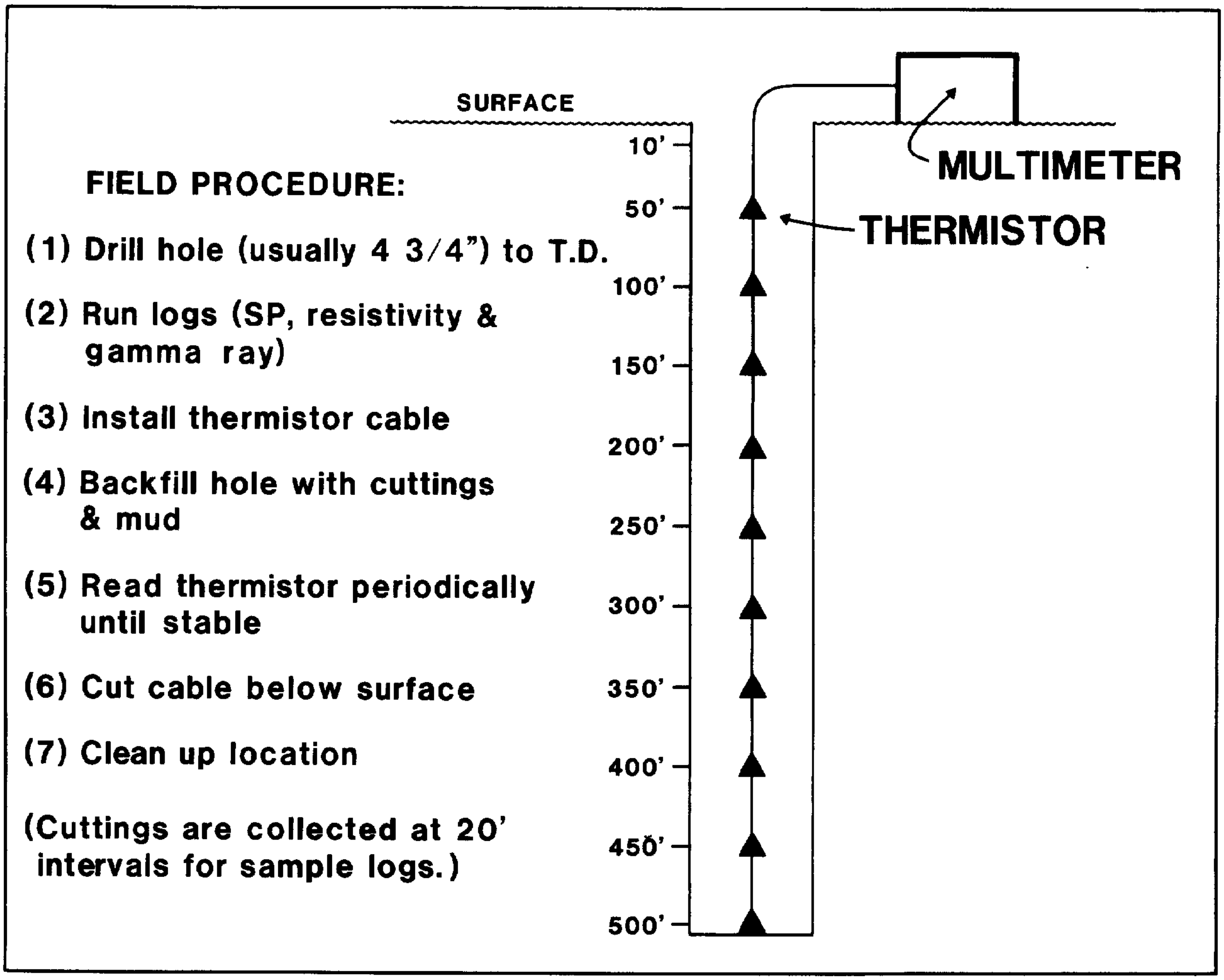


Figure 27—Geological-geothermal profile along lines I-I ', II-II ', and XIV-XIV ' of Figure 26. Bakhar field area, USSR. (From Artemenko and Malovitskiy, 1977.)



FIELD PROCEDURE:

(1) Drill hole (usually 4 3/4") to T.D.

(2) Run logs (SP, resistivity & gamma ray)

(3) Install thermistor cable

(4) Backfill hole with cuttings & mud

(5) Read thermistor periodically until stable

(6) Cut cable below surface

(7) Clean up location

(Cuttings are collected at 20' intervals for sample logs.)

Figure 28—Schematic diagram of original method used to obtain temperature measurements in shallow-hole field studies. Later field studies used expendable plastic casing, which allowed thermistor cable to be recovered when hole was abandoned.

Wyoming. One sample came from a depth of 295 ft (90 m) and had a thermal conductivity (K) of 4.10 (10^{-3} cal/cm/sec/C°); the other sample, from a depth of 303 ft (92 m) had a thermal conductivity of 4.23. Both sandstone plugs then were flushed with crude oil taken from the Cretaceous "J" sandstone producing reservoir of the Peoria field and their thermal conductivity was redetermined. The conductivity values dropped to 1.82 for the sample from 295 ft (90 m) and to 2.03 for the sample from 303 ft (92 m).

Perhaps the explanation most frequently offered for observed temperature highs over oil and gas fields is lateral variations in rock conductivity due to lateral changes in structure or lithology. For example, a granite core noted by Van Orstrand (1951) in the anticlinal fold that controls the Salt Creek field in Wyoming is cited by Gretener (1981, p. 83) in rebuttal to Meinhold's (1971) contention that the anomaly over this field is caused by deep percolating subsurface waters.

To test this concept, we selected four of our nine fields (Wattenberg, Bennett, Peoria, and Swan Hills), in large part because they are not on or near the crests of major positive structural features and are primarily stratigraphically controlled reservoirs. All these fields appear to have positive temperature anomalies over them, both at the producing level (Meyer and McGee, 1985) and at the shallow depths investigated in this study. For these particular fields, it seems unlikely the temperature anomalies can be attributed to lateral variations in conductivity due to structural configuration or lithologic changes.

Another factor that might contribute to increased thermal conductivity in rocks above a hydrocarbon deposit is the reaction between these rocks (and their contained fluids) and leaking fluids slowly percolating upward from an imperfectly sealed trap below. If such a reaction increased the thermal conductivities of the rocks penetrated, then this "altered rock chimney" above the oil or gas deposit might act like a salt dome, producing a positive temperature anomaly in and above it all the way to very shallow depths.

We have no evidence either for the existence of such a process or the postulated altered rock chimney it should produce. Unfortunately, very sensitive thermal conductivity determinations will be required to detect the small

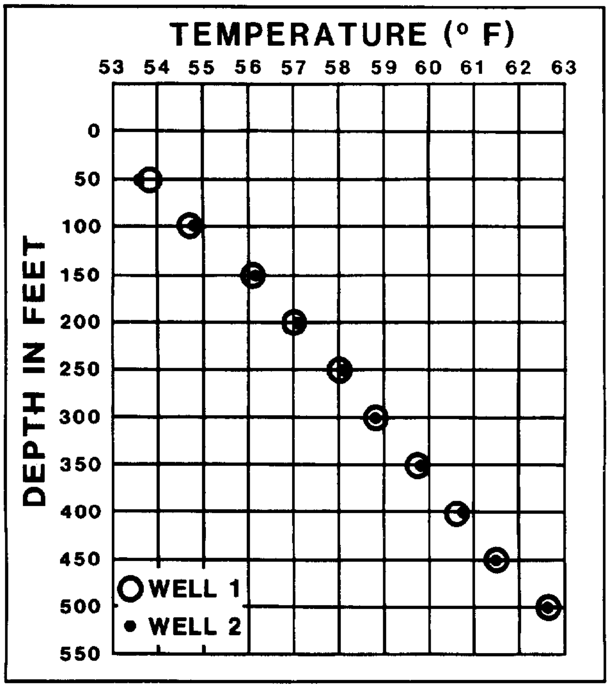


Figure 29—Comparison of stable temperatures measured in two holes drilled 36 ft (11 m) apart on same day, and located a few miles east of Peoria field, Arapahoe County, Colorado. Measurements were recorded from different expendable cables.

variations in thermal conductivities needed to produce the observed changes in the temperature field (<5%). Demonstration of the importance, or even the existence, of this process must await future investigations.

Although the primary cause for these anomalies is not known, we believe that upward and lateral fluid movement (probable cause 3), probably is the major contributor to the anomalies mapped over petroleum-producing areas. Heat is carried along with moving fluids, and when the fluids are trapped, so is the heat, creating an anomalous condition at that level. This condition is eventually transmitted to shallower depths (Figure 30). This opinion is shared by Makarenko et al (1967), Meinhold (1968), Sukharev et al (1970), Yakubov and Atakishiyev (1973), and Kappelmeyer and Haenel (1974), and is summarized by Roberts (1980, p. 8): "As the upward flow of water is focused by the configuration of the rocks, both heat and hydrocarbons tend to accumulate in upward-reaching reservoir spaces."

APPLICATION OF SHALLOW GEOTHERMAL MAPPING TO EXPLORATION

The evidence that many, if not most, oil and gas fields are accompanied by geothermal positives, which may extend toward the Earth's surface, appears convincing to the writers. Therefore, it seems that shallow geothermal mapping should take its proper place alongside other tools used in the detection, evaluation, and selection of exploratory prospects.

The estimated 1987 cost of a geothermal survey over a township (36 mi^2 or 93.2 km^2), using a 36-point or 1-mi (1.6-km) spacing, is about $15,000 for 200-ft (60-m) holes, including both equipment and field operating costs in the field areas described in this report. This amounts to about $400 to $450 per hole (control point). Naturally, 500-ft (150-m) holes would be slightly higher in cost.

SUMMARY

1. Most of the positive geothermal anomalies above many Rocky Mountain oil and gas fields, including some which are stratigraphically controlled, extend from the producing levels upward toward the Earth's surface.
2. Shallow geothermal mapping, done properly, can detect the anomalies at depths from a few hundred feet to as shallow as 10 ft (3 m).
3. Equipment and field operations required for shallow geothermal mapping are fairly simple and inexpensive, and the field work can be done in a reasonably short time.
4. Although the cause(s) for these observed geothermal anomalies are not known, the writers believe that a major contributor is upward and lateral movement of subsurface formation fluids into traps.
5. Shallow geothermal mapping, used in conjunction with other exploratory tools, should improve exploration success.

Table 1. Differences in Temperture Measurements in Four Shallow Twinned Holes, Peoria Field, Colorado*

Depth (ft)	Well 2	Well 4	Well 5	Well 6	Average
50	−0.8	+0.5	0.0	−0.8	−0.3
100	−0.3	−0.3	−0.5	−0.4	−0.4
150	−0.3	−0.5	−0.5	−0.4	−0.4
200	−0.3	−0.2	−0.4	−0.4	−0.3
250	ND	−0.1	−0.2	−0.3	−0.2
300	−0.2	−0.1	+0.4	−0.3	−0.1
350	ND	−0.2	+0.2	−0.4	−0.1
400	ND	−0.1	+0.6	−0.3	+0.1
450	ND	−0.2	ND	−0.3	−0.2
500	ND	−0.2	+0.6	−0.3	0.0

*Holes drilled 2½ years apart. Values represent temperature difference in F° between 1973 and 1975 measurements at corresponding depths. ND = no data.

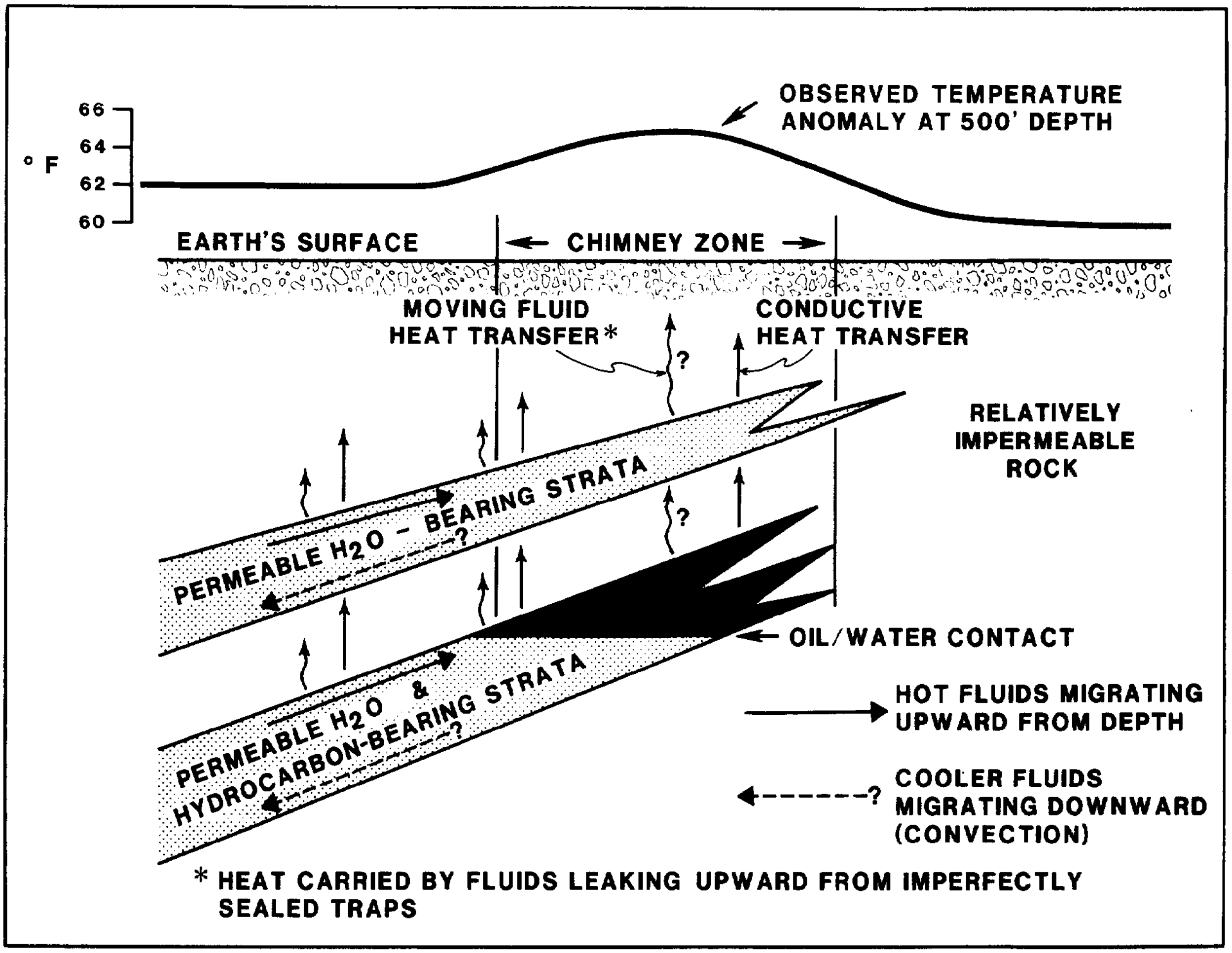


Figure 30—Schematic diagram illustrating possible processes for generating observed shallow temperature anomalies over stratigraphically controlled oil field. Hypothetical temperature anomaly is displayed at top of figure, and possible fluid movements and heat transfer to produce anomaly are shown in cross section below. Note in this model, if oil field were not there, nonhydrocarbon-bearing water strata conceivably could produce temperature anomaly by itself as long as trap is present.

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