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GEOLOGICAL SURVEY

A Surface Vitrinite Reflectance Anomaly Related to Bell Creek Oil Field, Montana, U.S.A.

By

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ABSTRACT

Vitrinite reflectance measurements from surface samples of mudrock and coal show anomalously high values over the Bell Creek oil field. The average vitrinite reflectance (R_m) increases to a maximum of 0.9 percent over the field against background values of about 0.3 percent. The R_m anomaly coincides with a geochemical anomaly indicated by diagenetic magnetite in surface rocks and a geobiologic anomaly indicated by ethane-consuming bacteria. These samples were taken from the Upper Cretaceous Hell Creek and Paleocene Fort Union Formations which form an essentially conformable sequence. The depositional environment is similar in both formations, and we expect little variation in the source and composition of the organic matter. The surface R_m should be approximately constant because of a uniform thermal history across the field. Temperature studies over local oil fields with similar geology suggest the expected thermal anomaly would be less than 10°C (50°F), which is too small to account for the significantly higher rank over the field. Coal clinkers are rare in the vicinity of Bell Creek and an R_m anomaly caused by burning of the thin, discontinuous coal seams is unlikely. The limited topographic relief, less than 305 m (1,000 ft), over the shallow-dipping homoclinal structure and the poor correlation between R_m and sample locality elevation ($r = -0.2$) indicate that the R_m anomaly is not due to burial, deformation and subsequent erosion.

We conjecture that activity by petroleum-metabolizing bacteria is a possible explanation of the R_m anomaly. Microseepage from oil reservoirs supports large colonies of these organisms, some of which can produce enzymes that can cleave hydrocarbon side-chains on the kerogen molecule. The loss of these side chains causes condensation of the ring structures (Stach and others, 1982) and consequently increases its reflectance.

These data indicate that vitrinite reflectance may be a useful tool to explore for stratigraphic traps in the Powder River Basin. Further, the large variation of R_m across the Bell Creek area suggests that vitrinite reflectance data from surface samples should be interpreted with caution.

INTRODUCTION

Surface samples are often used to assess the thermal maturity of petroleum basins. However, little is known about the effect of hydrocarbon microseepage during late diagenesis on the thermal maturity parameter vitrinite reflectance. Chandra (1962) found no significant difference in the vitrinite reflectance (R_m) of weathered and unweathered samples of coal from the same seam. Subsequent studies generally indicate the weathered coal at the surface has a lower reflectance than the same coal at depth (Marchioni, 1983). R_m may also be affected by the presence of petroleum hydrocarbon during diagenesis (for instance, Urban and Harding, 1979; Thompson, 1982; McFarland, 1982; Walker and others, 1983), a factor not considered by Chandra. Urban and Harding (1979) in a subsurface study of R_m over the Lenora gas field found vitrinite reflectance was lower over the field as compared to R_m off the reservoir. This paper investigates near-surface alteration of sedimentary organic matter (OM) as indicated by R_m in surface samples above the Bell Creek oil field, Montana. The sedimentary rocks cropping out over this field apparently have been affected by hydrocarbon microseepage (Dalziel and Donovan, 1983) causing lateral variations in late diagenetic history which may be recorded in the OM.

If hydrocarbon microseepage does affect vitrinite reflectance, then surface surveys of kerogen or coal maturity could be useful as a petroleum exploration tool. Various surface geochemical exploration methods for detecting hydrocarbon microseepage have been tested in the Bell Creek area: iron concentration in sage leaves and pine needles (Dalziel and Donovan, 1983); carbon-13 of carbonate cement in surface rocks (M.C. Dalziel, written communication, 1983); ethane-metabolizing bacteria activity (Miller, 1976); and aeromagnetic detection of diagenetic magnetite (Donovan and others, 1979; Dalziel and Donovan, 1983). These methods have had some success in defining the production limits of the Bell Creek field (Philp and Crisp, 1982). As discussed in the following section, the simple structure, low topographic relief, less than 300 m (1,000 ft), and the shallow stratigraphic trap make the Bell Creek oil field a particularly low-noise environment to test geochemical exploration methods. Thus, the Bell Creek oil field is a good test site for investigating weathering and hydrocarbon microseepage effects on the vitrinite reflectance of near-surface samples.

GEOLOGY OF BELL CREEK OIL FIELD

The Bell Creek oil field is a shallow oil and gas reservoir averaging 1,370 m (4,500 ft) depth in a northwest-dipping, low-angle homocline on the northeast flank of the Powder River Basin, Montana (fig. 1). The reservoir consists of Cretaceous Muddy Sandstone interpreted to be a barrier bar that interfingers updip with lagoonal mudrocks (Berg and Davies, 1968; McGregor and Biggs, 1970). There is no local structural control on the oil accumulation and the trap is formed by lateral facies change. The reservoir sand consists of fine-grained arenite that averages only 6 m (20 ft) thickness but has a porosity up to 33 percent and permeability up to 13,500 md (Berg and Davies, 1968).

Upper Cretaceous sediments cropping out in the Bell Creek area have been alternately mapped as the Hell Creek Formation, a series of gray to greenish-gray mudrock, brown carbonaceous shale, coal, and buff friable sandstone (Bryson and Bass, 1973)(fig. 2); or as the Lance Formation (Robinson and others, 1964). The Tertiary Fort Union Formation conformably overlies the Cretaceous rocks and it is similar in lithology. The Hell Creek and Fort Union Formations are thought to have been deposited in a fluvial environment.

VITRINITE REFLECTANCE SURVEY OVER THE BELL CREEK FIELD

Surface samples of mudrock and coal were taken over an area 64 km (40 mi) long and 40 km (25 mi) wide [2,600 km^2 (1,000 mi^2)] in the region surrounding Bell Creek. A major portion of Carter County east of the field was not sampled because a landowner would not allow us access. Over 1,100 sample locations were occupied in four field seasons consisting of about 35 person-weeks of work. Only about 300 of these sample localities had rock or coal exposed at a reasonable depth [0.5 to 1 m (1.5 to 3 ft)] that were amenable for vitrinite reflectance analysis. Coal samples were air dried, ground to minus 48 mesh, and mounted on glass slides for reflectance analysis (Baskin, 1979). Dispersed organic matter in mudrock and sandstone samples was concentrated before reflectance analysis (Barker, 1982). All reflectance data were measured by M. J. Pawlewicz to minimize the differences of vitrinite selection between operators.

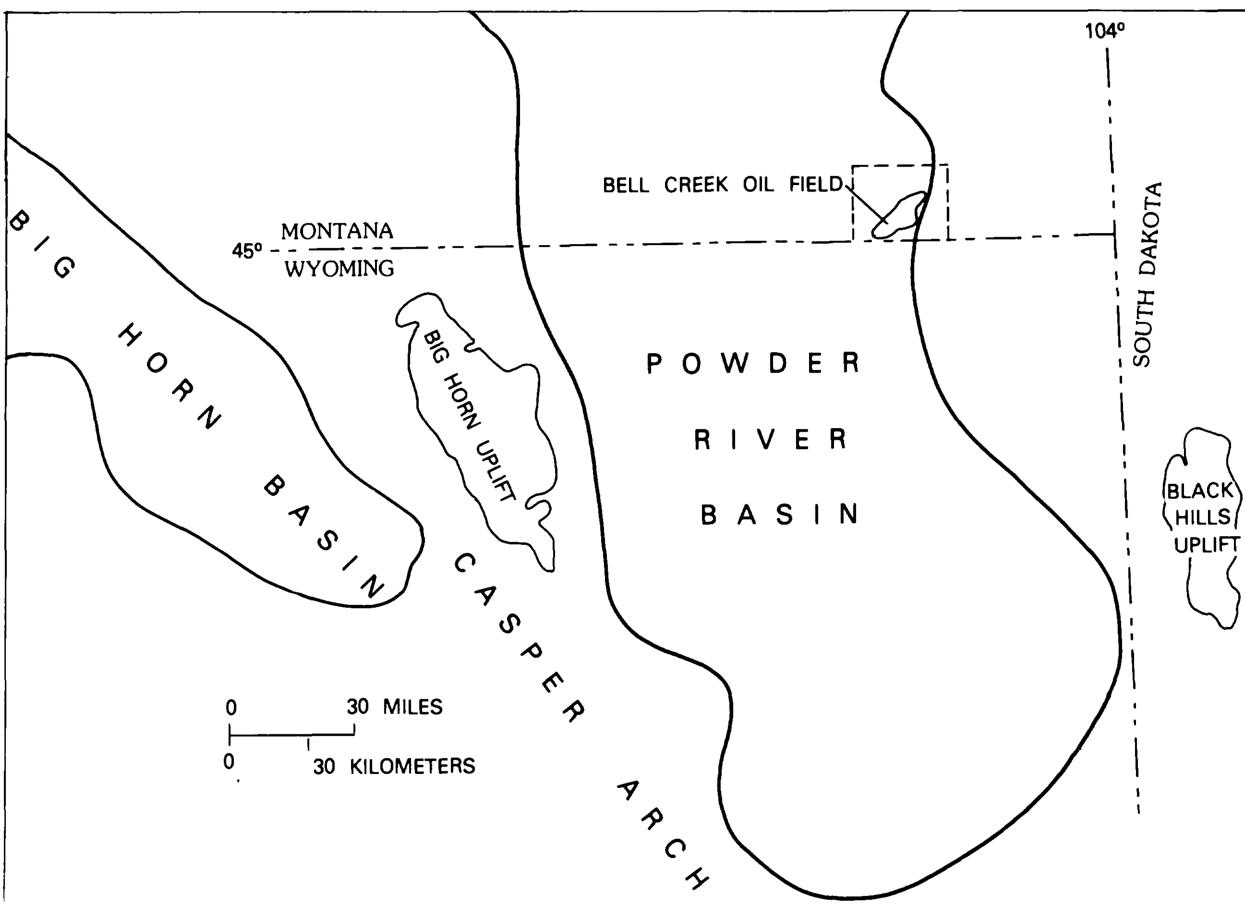


Figure 1.--Bell Creek oil field, Powder River Basin, Montana.

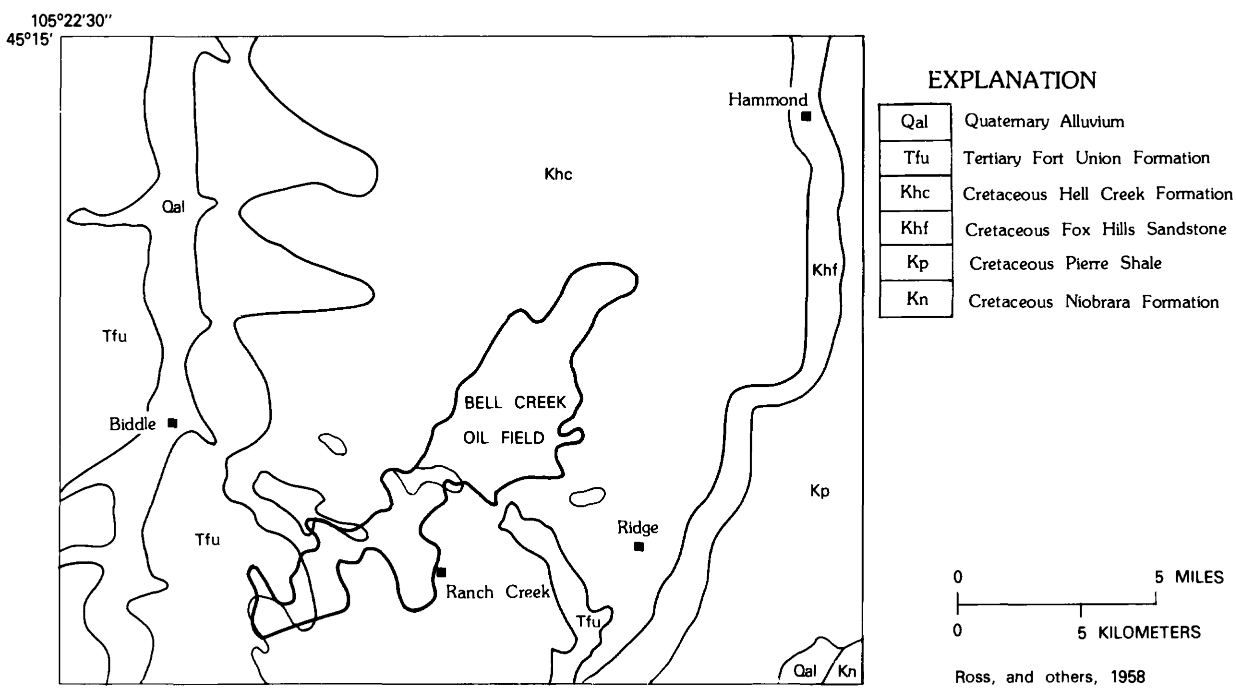


Figure 2.--Geology of the Bell Creek oil field, Montana.

The vitrinite reflectance data were contoured by computer using the Petroleum Information contouring software (fig. 3). These data show a strong vitrinite reflectance anomaly related to the production limits of the Bell Creek oil field. The anomaly peaks at about 0.9 percent over the area of oil production. This is about three times the background reflectance of about 0.3 percent. Another anomaly to the northwest of the field (fig. 3) also peaks at about three times background. This area of relatively high R_m is not as well defined as the anomaly related to the Bell Creek oil field due to sparse sampling in this area. Both anomalies have a similar trend to the northeast which parallels the strike of the regional homoclinal structure. A few spuriously high R_m values occur singly or in small groups across the study area. We do not think that R_m anomalies outlined by a few values are significant. Our computer-contouring package extends highs based on one or two R_m values to near the surrounding R_m localities making large anomalies out of spurious values that have no confirming data. Because of these facts, four R_m data localities were not used.

PHYSICAL AND CHEMICAL EFFECTS ON VITRINITE REFLECTANCE

Vitrinite reflectance responds primarily to increasing temperature during burial and can be correlated to the maximum temperature in its thermal history (Tissot and Welte, 1978). Because of these factors, R_m as function of depth is proportional to the maximum geothermal gradient attained during burial. R_m measured on coal core samples of the Muddy Sandstone from the Bell Creek reservoir and nonpetroleum-bearing areas (fig. 4) increases from the surface background reflectance of 0.3 percent to about 0.4 $\pm$0.1 percent at 1,500 m (5,000 ft) depth (fig. 5). The similar R_m in the Muddy Sandstone across the area suggests it has experienced a uniform thermal condition over its burial history. Daniel and Cole (1983) found an R_m high in subsurface samples related to an igneous intrusion into the Mississippian Heath Formation of central Montana. However, this is not a possible effect at the Bell Creek oil field because the R_m data here do not vary significantly in the subsurface and there is no evidence of an igneous intrusion in this area.

Roberts (1979) has shown a close relationship exists between increased temperature and petroleum reservoirs in areas of ascending fluid. The ascending fluid is warmer than the surrounding sediment and it causes a temperature anomaly of a few degrees Celsius in the vicinity of the fluid plume. Warm fluid plumes have been shown to increase reflectance along with quartz dissolution, potassic feldspar alteration (to sericite), and calcite cementation in the sedimentary rocks (Cassan and others, 1981). These extensive diagenetic changes have not been observed at Bell Creek (Almon and Davies, 1979). Further, the observed change of R_m from a background of 0.3 to 0.9 percent over the field would require a temperature anomaly on the order of several tens of degrees Celsius. The observed thermal anomalies over oil fields in the Rocky Mountain area (Meyer and McGee, 1982) are inadequate to explain the increased R_m over the Bell Creek oil field. Further, higher temperature and reflectance would be expected at depth if the Bell Creek reservoir was related to ascending warm fluids. The surface R_m anomaly (up to 0.9 percent) above the production field which has an R_m of 0.4 at the reservoir level indicates a reverse maturation gradient (and geothermal gradient) if temperature alone determined R_m in the Bell Creek area. The R_m anomaly at Bell Creek appears to be related to the current erosional surface and not to differences in thermal history.

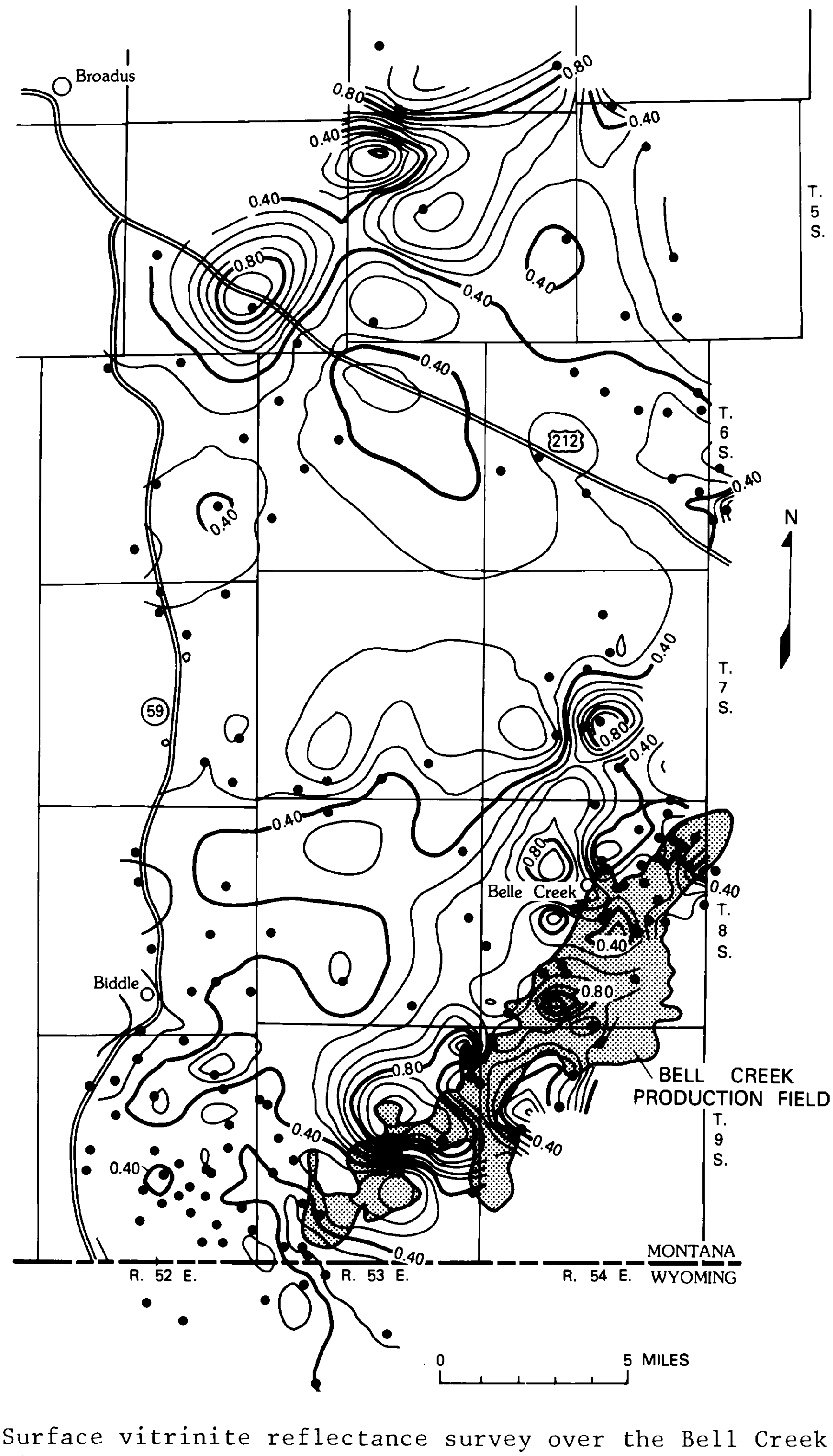


Figure 3.--Surface vitrinite reflectance survey over the Bell Creek oil field, Montana. Contour interval is 0.08 percent R_m. R_m is the average of 75 measurements (given enough vitrinite) under oil immersion. In OM-poor samples, often much less vitrinite was available, and in a few cases (about 15 samples) less than 20 R_m measurements were made. Reflectance was measured in random orientation without rotation to maximum reflectivity.

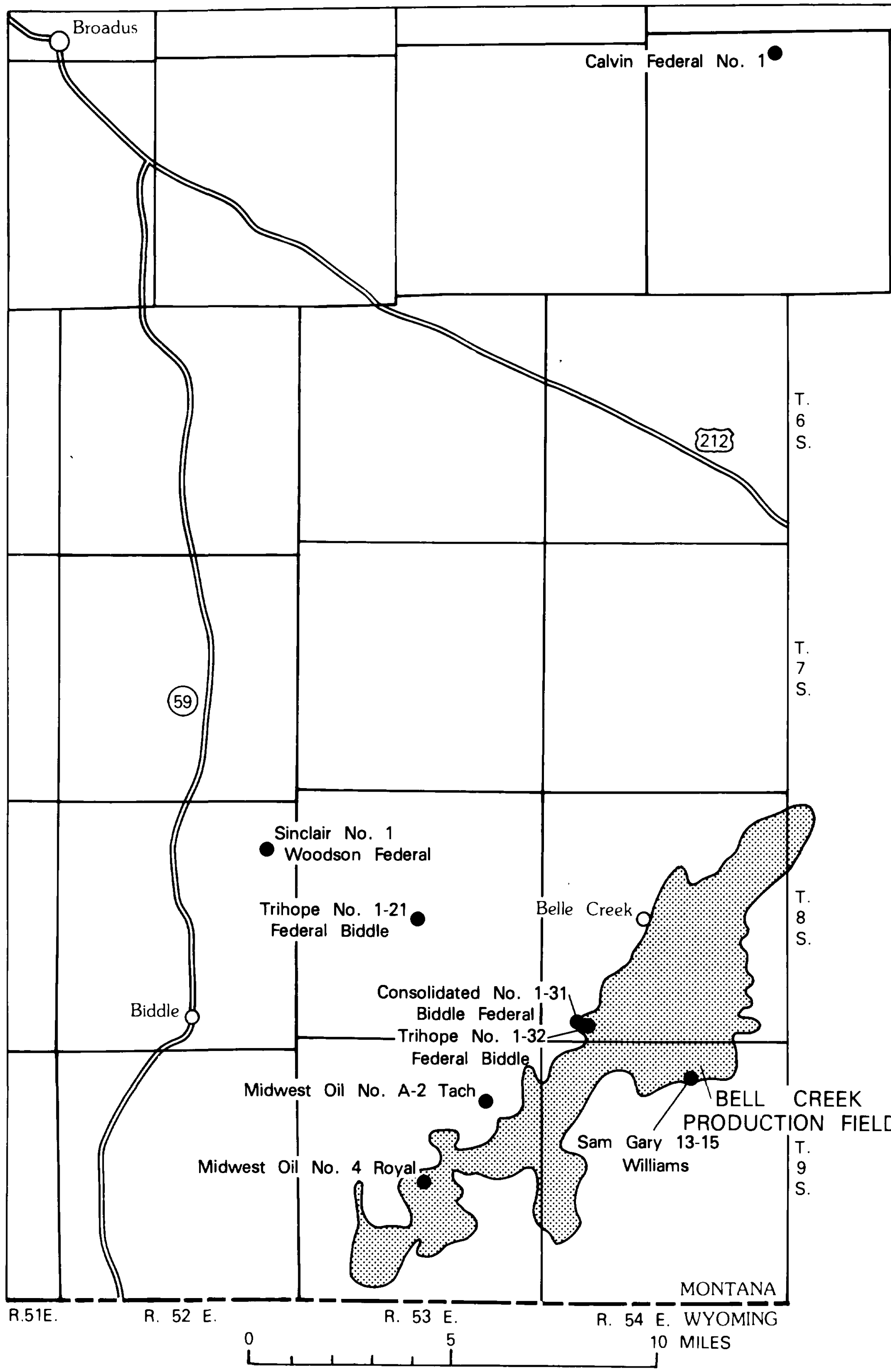


Figure 4.--Location of boreholes selected for vitrinite reflectance study in the vicinity of Bell Creek oil field, Montana. Data shown in figure 5.

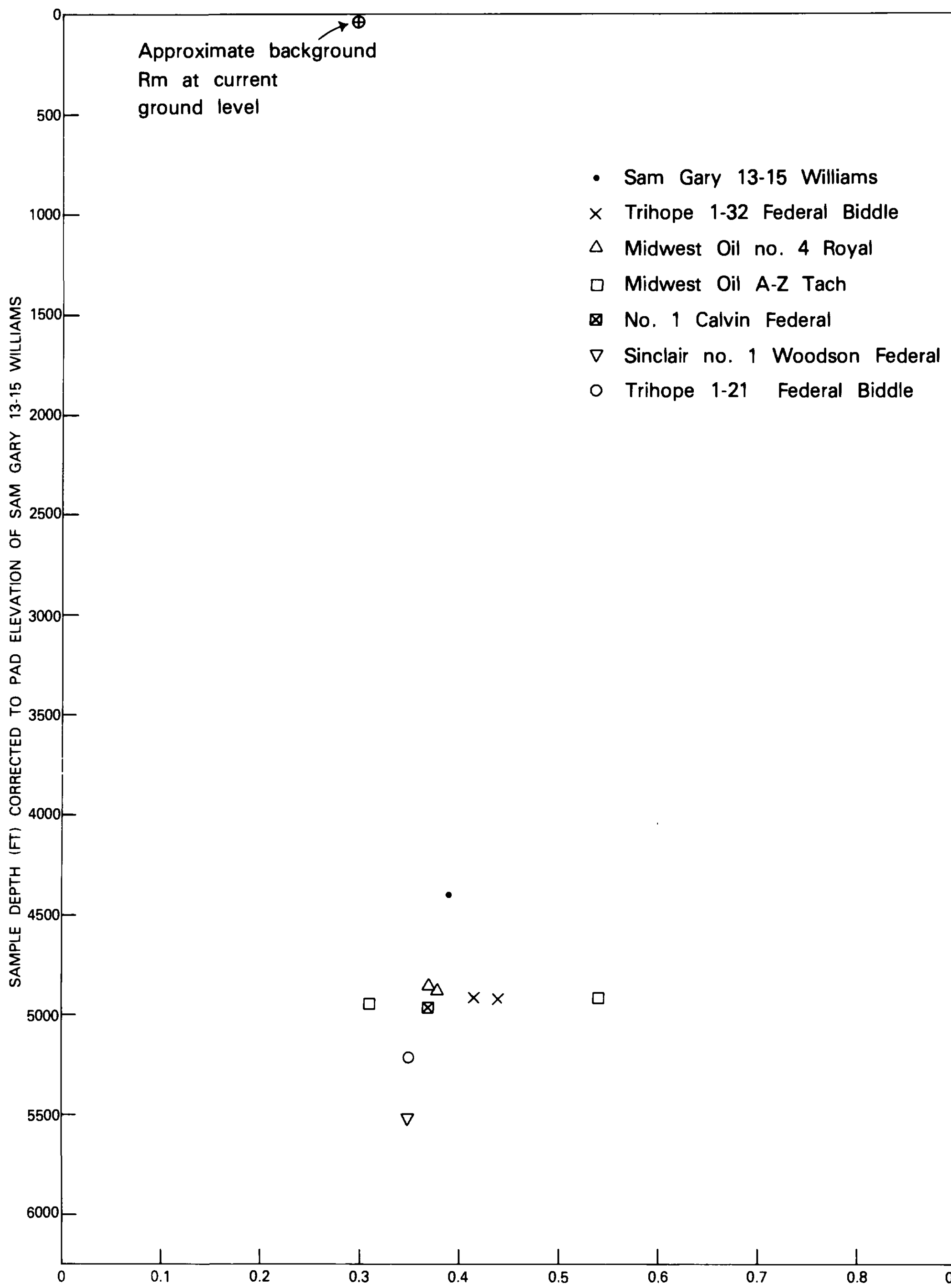


Figure 5.--Vitrinite reflectance versus depth, Bell Creek oil field, Montana. R_m data from core samples of coal lenses in the Bell Creek oil field reservoir (Cretaceous Muddy Sandstone). The sample depth in each well was corrected to the pad elevation of borehole Sam Gary 13-15 Williams. This correction allows direct comparison of R_m data between wells. No rock samples were available to us outside of the reservoir levels in these boreholes.

Deformation of a sedimentary sequence after a reflectance gradient has been established in the sediment could give surface vitrinite reflectance anomalies after erosion. Erosion of a simple homoclinal structure like that at Bell Creek would not produce the observed R_m anomaly (fig. 6). Erosion and dissection of flat or shallowly dipping beds could also produce surface vitrinite reflectance anomalies by the exposure of more mature rocks in valleys. This type of surface vitrinite reflectance anomaly would be centered over topographic lows and in general controlled by surface form and sample locality elevation. Surface R_m values do not appear to be controlled by sample locality elevation as shown by the near-random correlation (r = -0.2) between these two variables (fig. 7).

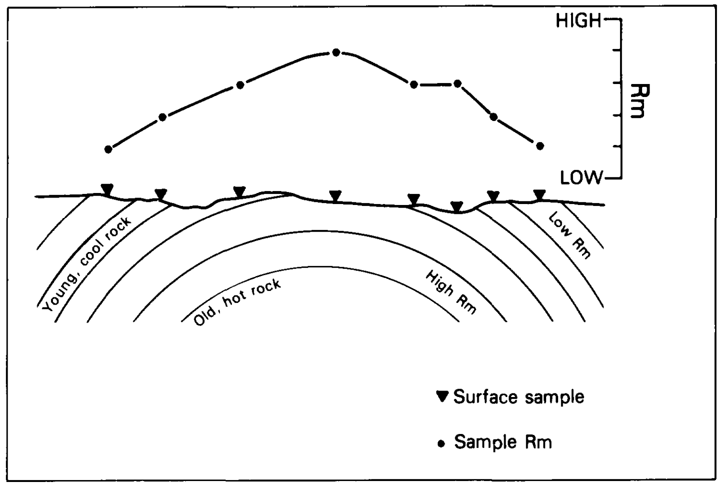
Field and laboratory studies have shown that in petroleum-rich rocks, R_m is lower than expected when compared to R_m in adjacent petroleum-poor rocks (Urban and Harding, 1979; McFarland, 1982; Thompson, 1982). This retardation effect would cause a reflectance low over a production field (Urban and Harding, 1979). The influence of a hydrocarbon-rich environment above the Bell Creek reservoir apparently increases R_m and the retardation effect suggested by these studies does not appear to influence this near-surface environment.

Hutton and Cook (1980), Newman and Newman (1982), Walker and others (1983), and others have shown that variation of maceral composition in coal and kerogen can influence its R_m. These studies indicate that certain depositional and(or) diagenetic environments can produce a hydrogen-rich OM that have lower R_m values than those expected from the thermal history of the sediment. The depositional system was apparently uniform across the Bell Creek area (Bryson and Bass, 1973; Robinson and others, 1964) and we expect little variation in the source and composition of the organic matter.

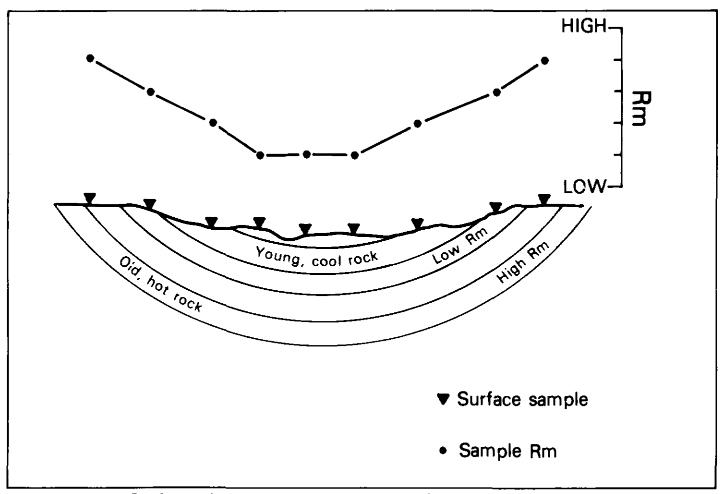
These data suggest that hydrocarbon microseepage or variation in the depositional environment can cause depressed reflectance levels after erosion and exposure at the surface. Although hydrocarbon microseepage is occurring at Bell Creek (Dalziel and Donovan, 1983), its observed effect at the surface is to increase reflectance. Other factors than those discussed must be affecting OM and its R_m in the near-surface environment at Bell Creek.

LATE DIAGENETIC EFFECTS ON VITRINITE REFLECTANCE IN THE NEAR-SURFACE ZONE

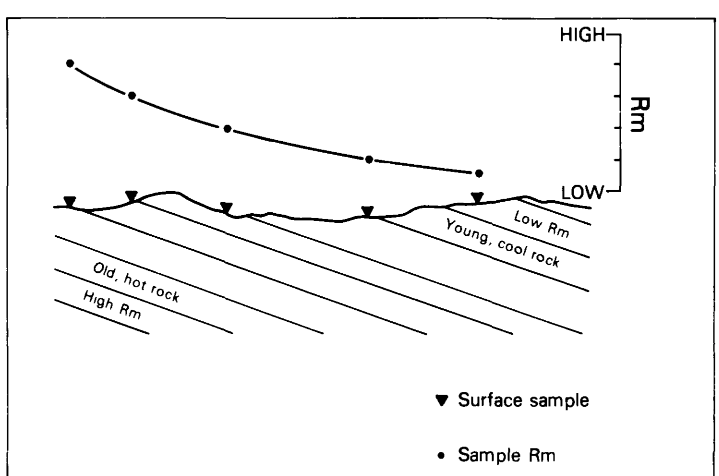
The most intense near-surface effects that increase vitrinite reflectance are heating by brush and coal fires. Brush fires heat or burn the OM increasing its reflectance and(or) forming pyrofusinite (similar to charcoal). The short duration of brush fires and the poor thermal conductivity of soil suggest heating from this source would rapidly decline with depth. Because most samples were taken at a depth of 0.5 to 1 m (1.5 to 3 ft), we feel brush fires had little influence on our R_m data. The burning of coal seams could cause more widespread heating, but clinker is scarce in this area and apparently coal fires were not common. Coal seams in the Bell Creek area are also thin discontinuous beds and their burning would not cause more than a local increase in R_m. Moreover, the effect of intense heating is detectable under the microscope during reflectance analysis. Burning or heating with oxygen present forms a characteristic sieve structure and/or bright oxidation rims [if temperature exceeds 150°C (302°F)] that may attain an R_m of 10 percent or more in some cases (Stach and others, 1982). OM alteration by intense heating or burning in the



A. Surface vitrinite reflectance anomaly caused by an anticline



B. Surface vitrinite reflectance anomaly caused by a syncline



C. Surface vitrinite reflectance caused by a homocline

Figure 6.--Hypothetical structural effects on surface surveys of vitrinite reflectance.

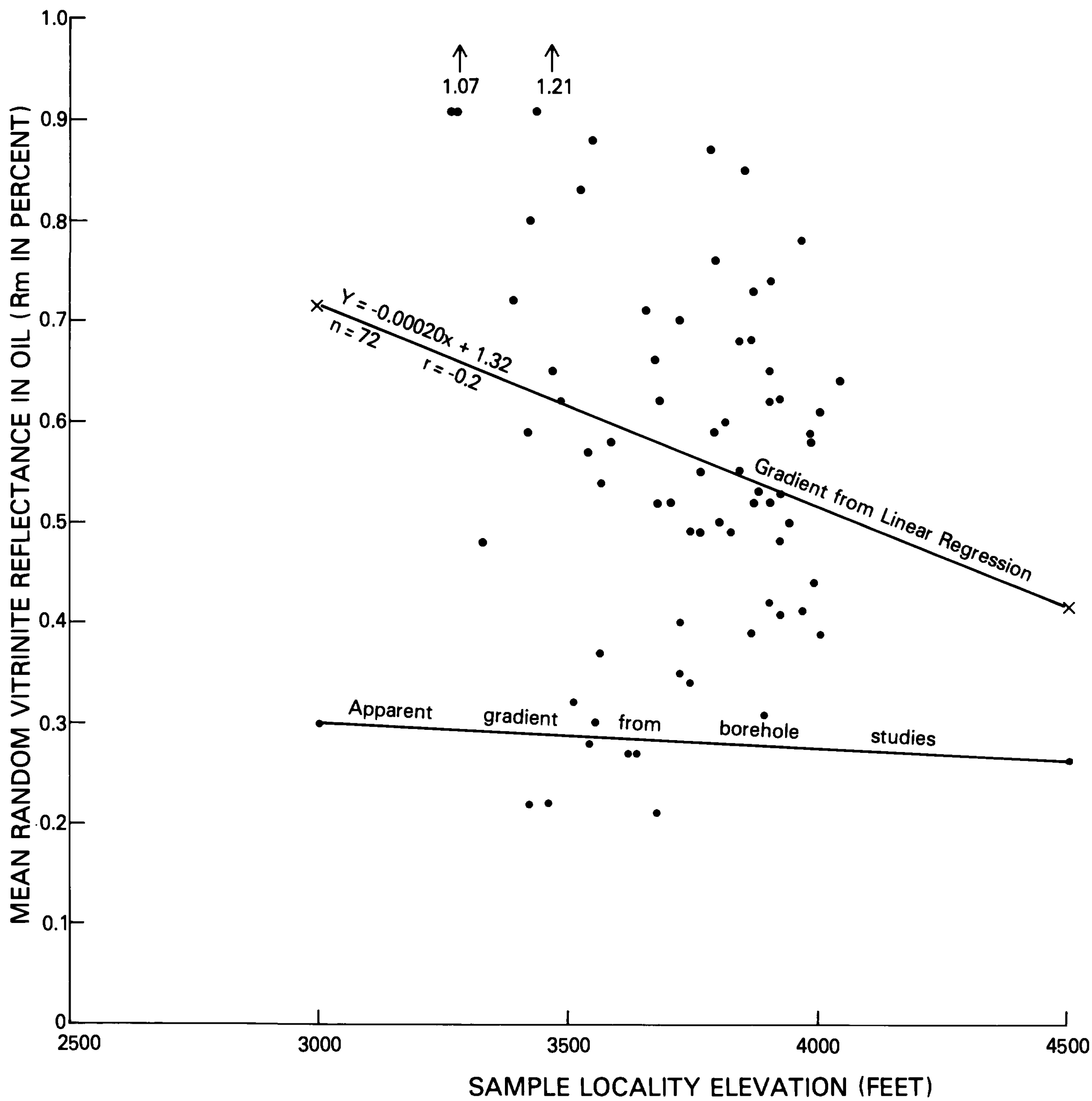


Figure 7.--Vitrinite reflectance versus sample locality elevation, Bell Creek oil field area, Montana.

near-surface zone is detectable both during sampling and analysis. We feel that these processes have not significantly influenced our R_m data because any affected OM was simply not measured.

Near-surface samples of coal seams in the Bell Creek area show both macro- and micro-scopic changes due to weathering. Weathered coal often develops extensive cleat (microfractures) and variation in polishing hardness in vitrinite (Stach and others, 1982; Marchioni, 1983). Weathering of Bell Creek coal is commonly so intense that the coal disintegrates into a fine powder during handling. Very thin coal seams may be so altered that they take on the appearance of black soils. Some coal samples rapidly expanded and disintegrated when prepared with water-base polishing compounds, possibly attributable to intense alteration in the near-surface zone. These samples were successfully polished in alcohol-base abrasives. Microscopically, the coal and kerogen also show alteration attributable to weathering by the development of cleat, the rounding of grains that would normally have distinct sharp fractures or concoidal form, and variation in polishing hardness across the vitrinite. These fractures are not due to breakage during sampling or preparation because framboidal(?) and (or) coarsely crystalline pyrite line some cleat surfaces. Although extensive and severe, this pervasive near-surface alteration and weathering generally does not affect the reflectance of vitrinite (Stach and others, 1982). Marchioni (1983) found that low-rank coal from the Rocky Mountain foothills area, Alberta, Canada, show an increase in R_m as the coal approaches the surface. The Rocky Mountain foothills coals have a similar rank to unweathered samples at Bell Creek of about 0.5 percent at 4 m (13 ft) depth that increase to about 0.6 percent at 2 m (6.6 ft) depth. This increase in R_m at the surface was not observed in higher rank coals (>1.0 percent R_m). The higher rank coals in the Rocky Mountain foothills area show a <u>decrease</u> in R_m of a few tenths of a percent at the surface. These rank changes, apparently due to weathering, are smaller than the R_m range observed at Bell Creek suggesting that other factors besides weathering influence R_m over this field. However, these data do suggest that low-rank coals increase in rank in the near-surface zone confirming our observation that weathering produces surface R_m anomalies. Further, because the high-rank coals are less influenced by weathering, surface R_m anomalies may be observed only in thermally immature areas.

These data indicate that thermal and physical weathering conditions at the near-surface are not responsible for the R_m anomaly related to the Bell Creek field. We suggest here that hydrocarbon metabolizing microbes are apparently capable of affecting R_m in the near-surface zone where hydrocarbon microseepage is occurring.

MICROBIAL ALTERATION OF ORGANIC MATTER

After sediment deposition, aerobic and anaerobic bacteria are the dominant factors controlling the composition of organic matter remaining after early diagenesis. These bacteria break down the biopolymers such as cellulose into smaller chemical units that later reform into geopolymers that constitute kerogen and coal (Tissot and Welte, 1978; Stach and others, 1982). This residual OM is resistant to further microbial attack and persists into late diagenesis.

During late diagenesis OM may reenter the near-surface zone where it once again is subject to bacterial attack. In this environment OM may be altered by microbial activity in the presence of hydrocarbon microseepage. Hydrocarbon-metabolizing bacteria are abundant in the near-surface zone

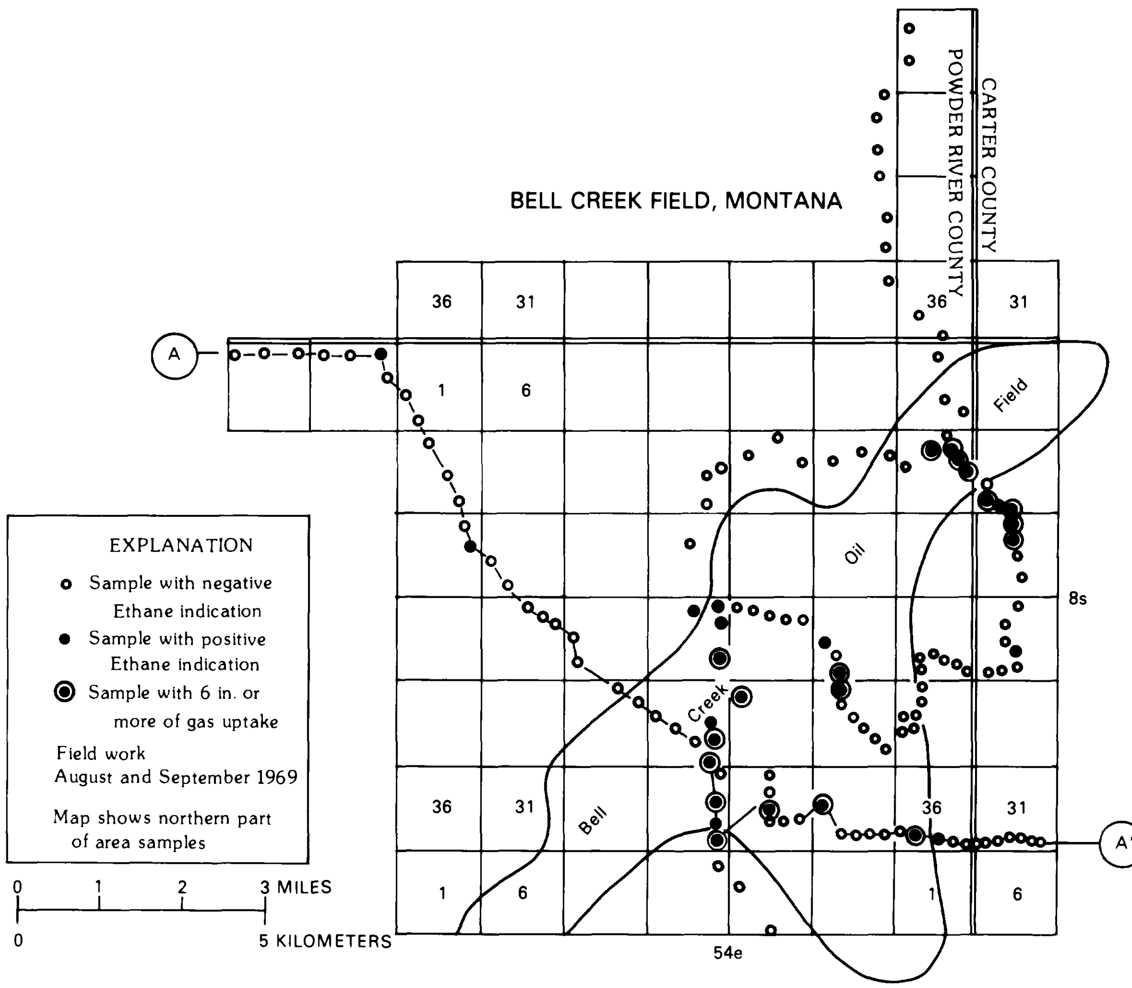


Figure 8.--Survey of microbial activity over the Bell Creek oil field, Montana. Modified from Miller (1976).

directly above petroleum reservoirs (Soli, 1957; Sealey, 1974). This relationship is expressed over the Bell Creek oil field by high levels of ethane-consuming bacteria activity that occur over the limits of the production field (fig. 8). This surface control of hydrocarbon-metabolizing microbes apparently arises from the rapid decrease in hydrocarbon microseepage away from the reservoir (Philp and Crisp, 1982).

In an environment of hydrocarbon microseepage, certain types of bacteria are apparently able to adapt towards petroleum utilization (Soli, 1957). After this initial adaptation, perhaps the bacteria can also utilize the hydrocarbons in OM. The need for additional adaptation would occur when hydrocarbon microseepage could not provide sufficient carbon and energy for the microbes, but these essential nutrients are still available (though less readily) in OM. Although laboratory experiments have shown it is difficult to rapidly degrade OM by bacterial activity (Yen, 1976), any measureable reaction would be significant over geologic time. Experiments by Findlay and others (1976) have shown that a few bacteria genera are capable of producing enzymes that can break down oil shale kerogen into smaller hydrocarbon molecules. The growth rate of Pseudomonas putida bacteria was markedly increased by the presence of humic acids from brown coal (Bazarova and others, 1980). Harrison (1980) also suggests bacteria may be able to metabolize OM in ore deposits. We postulate that microbes could also be capable of producing enzymes that would cleave straight chain and branched hydrocarbons attached to the aromatic clusters composing the vitrinite molecule. The cleaved hydrocarbon chains are then oxidized by the aerobic bacteria. The loss of these side-chains from the OM increases the aromaticity of the vitrinite, and consequently its reflectance.

CONCLUSIONS

(1) Vitrinite reflectance shows significant variability across the Bell Creek area. This variation is apparently related to differences in near-surface, late-diagenetic conditions induced by microbial alteration of OM in an environment of hydrocarbon microseepage.

(2) The large range of R_m across the Bell Creek area which has experienced a similar thermal history indicates that maturity data from surface samples should be interpreted with caution. The surface R_m values observed at Bell Creek would normally be interpreted as thermally immature (<0.6 percent R_m) off the field and at near-peak oil generation (~1.0 percent R_m) over the field--across a surface that has experienced similar maximum temperatures and burial history.

(3) Surface surveys of R_m are potentially useful in exploring for subtle hydrocarbon reservoirs. The surface R_m anomaly over the Bell Creek reservoir is closely related to the production field and could have been used to detect this petroleum-bearing stratigraphic trap.

FUTURE WORK

This paper reports on the field and organic petrography studies over the Bell Creek oil field. However, these data are insufficient to define the cause of the anomalous vitrinite reflectance over this oil field. Bacterial alteration mechanism is just a hypothesis and it needs to be substantiated.

We intend to measure the elemental composition and structural chemistry of selected coal samples across the southern half of the study area. We are now analyzing the Hell Creek Formation coal seams for carbon, hydrogen, and nitrogen content. If bacteria have altered these coals, we think they will have high contents of N-S-O compounds and show a depletion of hydrogen.

Similar effects are commonly observed in biodegraded petroleum. These same coal samples will also be soxhlet extracted to analyze the lipid fraction for depletion in n-alkanes. Bacteria apparently preferentially metabolize straight-chain hydrocarbons and a biodegraded coal should have a relatively low n-alkane content when compared to a non-degraded coal of similar rank.

ACKNOWLEDGMENTS

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