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Hydrocarbons in Thermal Areas, Northwestern Wyoming

GEOLOGICAL SURVEY PROFESSIONAL PAPER 644-B

Prepared in cooperation with the National Park Service, the Geological Survey of Wyoming, and the Department of Geology of the University of Wyoming



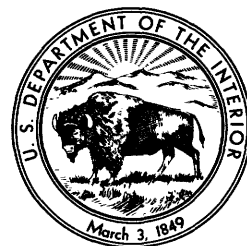
Hydrocarbons in Thermal Areas, Northwestern Wyoming

By J. D. LOVE, U.S. GEOLOGICAL SURVEY, and JOHN M. GOOD, NATIONAL PARK SERVICE

SHORTER CONTRIBUTIONS TO GENERAL GEOLOGY

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UNITED STATES DEPARTMENT OF THE INTERIOR

WALTER J. HICKEL, *Secretary*

GEOLOGICAL SURVEY

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HYDROCARBONS IN THERMAL AREAS, NORTHWESTERN WYOMING

By J. D. LOVE, U.S. Geological Survey, and JOHN M. GOOD, National Park Service

ABSTRACT

Five natural occurrences of hydrocarbons in thermal areas lie in an arcuate southeastward- to eastward-trending area 70 miles long in northwestern Wyoming. They are, from northwest to east: Tower Bridge, Calcite Springs, Rainbow Springs, Sweet-water Mineral Springs, and Cedar Mountain. The westernmost three are in Yellowstone National Park. All are associated with abundant sulfur and thermal springs and vents (active in four localities, recently extinct in one). Four are surrounded and underlain by volcanic rocks, which range in age from Eocene to Pleistocene. The fifth emerges from Paleozoic strata.

The source of the hydrocarbons could be Paleozoic or Mesozoic sedimentary rocks that underlie the surficial volcanics, but at Rainbow Springs the oil might have been distilled from Pleistocene nonmarine algae at shallow depth. Sulfur isotope analyses do not indicate conclusively whether the sulfur is of igneous or bacteriogenic origin.

In at least two of the localities, hot water and steam that derive their heat from an igneous source below the sedimentary sequent are believed to relate directly to the extraction of the hydrocarbons from the strata, to their subsequent transport upward along conduits, and their extrusion on the surface.

INTRODUCTION

The purpose of this report is to call attention to five natural occurrences of liquid hydrocarbons in thermal areas. Two (loc. 1 and 3, fig. 1) offer promise of yielding significant data on the geochemical processes that are responsible for the origin of oil in an unusual environment. This knowledge should, in turn, lead to a better understanding of the characteristics of the oil that results from these processes and of the mechanics of its emplacement. Two of the localities of hydrocarbons in thermal areas have already been obliterated by man (loc. 2 and 5, fig. 1), and a third (loc. 4) has been considerably altered. It is hoped that this preliminary discussion will stimulate the search for new localities and

encourage more sophisticated studies of those that remain before they, too, are damaged or destroyed and the opportunity for recording and interpreting this type of data is lost.

Hydrocarbons in thermal areas of northwestern Wyoming have been known or suspected ever since the verbal reports of John Colter, who observed "the great tar spring" at Cedar Mountain (loc. 5, fig. 1) in 1807 (Chittenden, 1895, p. 23; 1901, p. 3781). Casual references to springs that contained oil, tar, bitumen, or asphalt in other parts of northwestern Wyoming were made by several explorers and writers. For example, Denig (1961, p. 141), in a manuscript written about 1854 and published over a hundred years later, stated, "Some of the springs near the head of the Yellowstone are bituminous, sending forth a substance like tar, which is inflammable." Father DeSmet (letter of Jan. 20, 1852, quoted by Chittenden, 1895, p. 388) likewise commented on the abundant "bituminous, sulphurous and boiling springs" between the sources of the Madison and Yellowstone Rivers in what is now northwestern Wyoming.

Despite the general knowledge among early trappers and explorers that oil seeps were present in thermal areas of this region, we have found no reference to these phenomena in any of the scientific studies by the Hayden (1883) or the Hague (1904) groups or by any of the other pioneer geologists such as Comstock (1875) and Eldridge (1894) who worked in the region. As far as we have been able to determine, Allen and Day (1935) were the first scientists to make mention, and that only brief, of bituminous material at localities 1 and 3. Hewett (1913, 1914) gave a short account of the oil at locality 4. Our data were obtained on brief reconnaissance trips between 1963 and 1968.

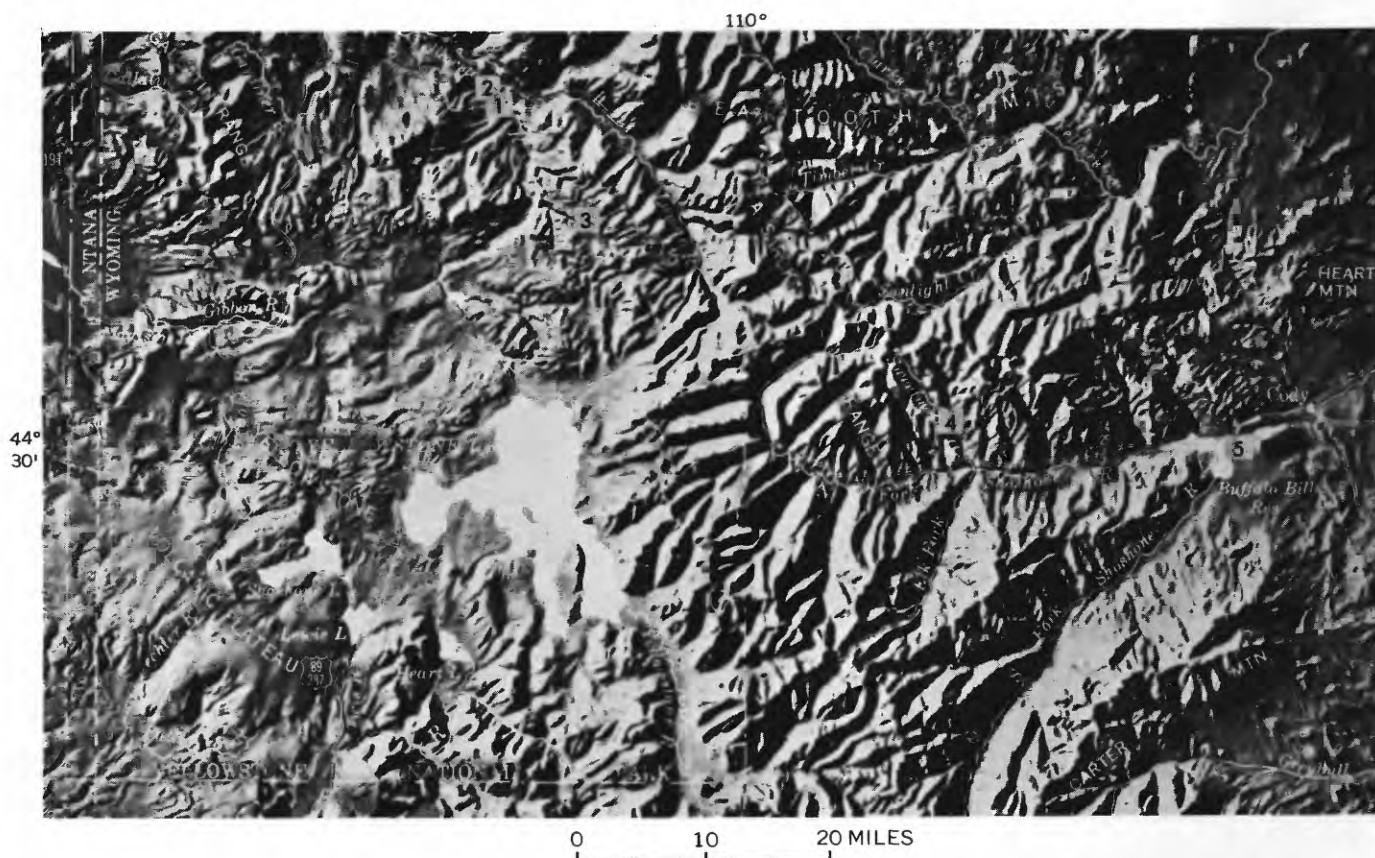


FIGURE 1.—Relief map of northwestern Wyoming showing described localities of hydrocarbon occurrences in thermal areas. Indicated are (1) Calcite Springs, (2) Tower Bridge, (3) Rainbow Springs, (4) Sweetwater Mineral Springs, and (5) Cedar Mountain.

We are grateful to many people for help on various aspects of this study. The following U.S. Geological Survey paleontologists studied the fossils: E. B. Leopold identified pollen, K. E. Lohman and G. W. Andrews identified diatoms from the Rainbow Springs locality, and J. A. Wolfe identified leaves from the early basic breccia. We are especially grateful to M. F. Skinner, of the American Museum of Natural History, for comparing a bison skull from one of our localities with his reference collection. J. W. Smith, U.S. Bureau of Mines, and G. J. Schrayner, Gulf Research and Development Co., provided not only interest and encouragement but many analyses during a period of several years. W. E. Haines and A. B. Hubbard, U.S. Bureau of Mines, were most helpful in supplying both counsel and analyses. J. G. Palacas, U.S. Geological Survey, studied a sample of oil-impregnated silt from the Sweetwater Mineral Springs locality. K. L. Pering, Ames Research Center, National Aeronautics and Space Administration, collected oil samples and made

laboratory comparisons of the samples with biogenic and possible abiogenic oils from other parts of the world. Irving Friedman, U.S. Geological Survey, provided two carbon isotope analyses. M. L. Jensen, University of Utah, sampled sulfur in the Calcite Springs area and made a series of sulfur isotope analyses from both his samples and ours.

This study was conducted with the cooperation of R. S. Houston, Chairman, Department of Geology, University of Wyoming, and D. L. Blackstone, Jr., State Geologist of Wyoming.

CHARACTERISTICS AND GEOLOGIC SETTING OF THE LOCALITIES

The five described localities lie in an arcuate south-eastward- to eastward-trending area 70 miles long (fig. 1). They are, from northwest to east, Tower Bridge (loc. 2), Calcite Springs (loc. 1), Rainbow Springs (loc. 3), Sweetwater Mineral Springs (loc. 4), and Cedar Mountain (loc. 5). Characteristics common to

most of these localities, in addition to the occurrence of hydrocarbons, are the abundance of sulfur and its close association with the hydrocarbons, the presence of thermal springs and vents (active in four localities, recently extinct at loc. 4), and the presence of volcanic rocks that surround and underlie localities 1-4. The water in many springs at localities 1 and 3 is boiling, but it is cooler at 2, cold at 4, and reportedly 90°F at 5.

Localities 1, 2, and 4 are in the early basic breccia of Hague (1904). At locality 2 is a dark-colored facies of volcanic-rich strata equivalent to the lower part of the Cathedral Cliffs Formation (H. J. Prostka, oral commun., 1969). Locality 3 is in Pleistocene lacustrine tuff adjacent to and probably underlain by rhyolite. Below the rhyolite, presumably, is early basic breccia. Locality 5 is probably in Pennsylvanian or Permian sandstone and carbonate rocks. Geologic details are given in the description of each locality. The regional structural pattern and distribution of prevolcanic rocks in areas adjacent to localities 1-4 suggest that Paleozoic and Mesozoic sedimentary rocks underlie the volcanics; the type of thermal features at localities 1 and 3 suggests that at still greater depth there are bodies of hot magma or only partly cooled igneous rocks. The actual depths of these sedimentary rocks and igneous material have not been determined; they could be hundreds to thousands of feet below the surface. The attitude of the sedimentary rocks is not known, and geophysical data are not definitive as yet. No drilling has been done in the vicinity of the localities.

SOURCES OF OIL AND SULFUR

The characteristics of the oil at each locality are given in the detailed discussions. Only at localities 1 and 3 was sufficient oil obtained for even a preliminary interpretation as to source. The gas chromatograms of the alkane portion of these two oils (fig. 11) are so different that they may well have been derived from unrelated sources. The source of oil at locality 1 is unknown. The oil at locality 3 appears to have no highly unusual characteristics and may have been derived from underlying organic-rich Cretaceous rocks and carried upward along conduits by thermal water and steam. On the other hand, aided by the available heat, it might have been distilled from Pleistocene nonmarine algae at shallow depth. This possibility is discussed later.

The sulfur from locality 1 was analyzed in some detail, but the resulting data were not sufficiently definitive to assign it an igneous or bacteriogenic origin. At all localities, the sulfur was hydrothermally concentrated.

RELATION OF THERMAL PHENOMENA TO EMPLACEMENT OF OIL

Hot water and steam are closely associated with the conduits along which oil traveled at localities 1 and 3 and almost certainly are responsible for the surface and near-surface emplacement of the oil. At the other localities, because of floods or tampering by man, conclusive evidence of the process of transport and emplacement has been obliterated, but it is believed that the process was somewhat similar to that at localities 1 and 3. When more surface and subsurface information on thermal features elsewhere in and near Yellowstone National Park (Campbell, 1969) is obtained, an interpretation can probably be made concerning the depth at which the thermal activity originated, how far the oil was transported, and what chemical changes occurred in it en route from the source area to the surface.

INDIVIDUAL LOCALITIES

CALCITE SPRINGS (LOC. 1)

The Calcite Springs emerge near the bottom of Yellowstone Canyon, about 1 mile down the Yellowstone River from the Tower Fall area (fig. 2). The geology of the springs area has been described by Howard (1937). Allen and Day (1935, p. 495-500) discussed the springs and gave the first description of tarry bitumen at that locality.

Oil emerges from the early basic breccia, as well as from Quaternary deposits. The lower 200 feet of the Yellowstone Canyon at this locality is cut in the early basic breccia, a sequence of drab dark-green to brown mafic tuff, conglomerate, and possibly basalt flows (fig. 3). These rocks have been extensively altered by thermal action to produce the yellow to white canyon walls. The age of the early basic breccia is considered to be Eocene on the basis of a small flora collected from the breccia at the base of Tower Fall and identified by J. A. Wolfe (written commun., 1962) as *Celastrus inaequalis* Knowlton, *Ficus densifolia* Knowlton, and *Magnolia spectabilis* Knowlton.

The upper 130 feet of rocks on the east wall was called "Canyon basalts and associated gravels" by Howard (1937). This sequence consists of lenticular basalt flows separated by dark-brown conglomerate made up chiefly of basalt and rhyolite pebbles, cobbles, and boulders. There are, however, many light-colored highly rounded quartzite pebbles and cobbles, similar to those in the Pinyon Conglomerate farther south, that were extensively fractured after deposition. The conglomeratic units thin rapidly from east to west near Calcite Springs; Bumpus Butte (figs. 2, 3) is composed of ba-

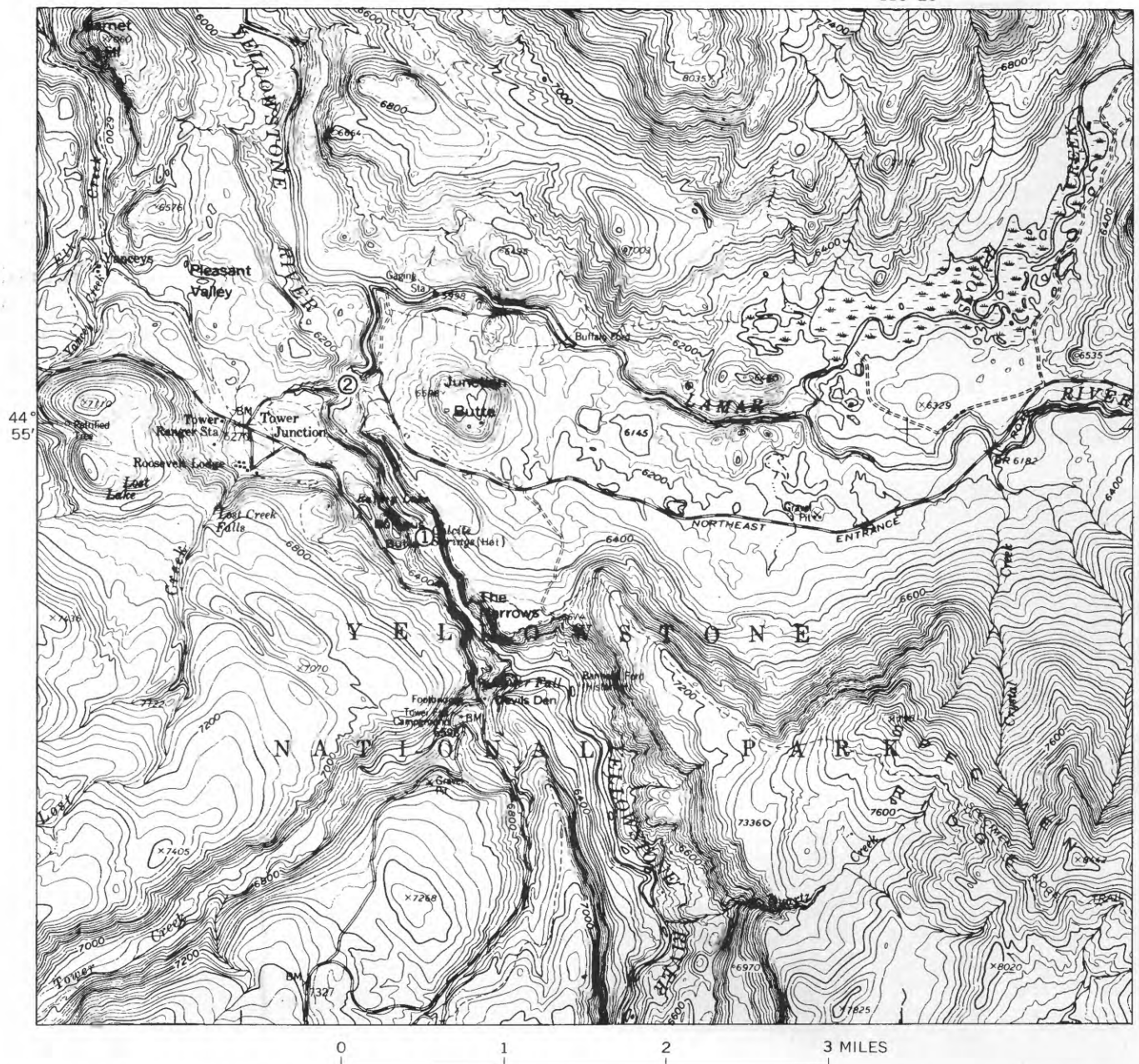


FIGURE 2.—Location of Calcite Springs (loc. 1) and Tower Bridge (loc. 2). Base from U.S. Geological Survey Tower Junction quadrangle, 1959.

salt with a thin conglomerate at the base. The relation of this conglomerate to the Tower Creek Conglomerate (Hague, 1904) near Tower Fall, 1 mile southeast, has not been established. The Tower Creek was considered to be of Pliocene age on the basis of a horse tooth identified by O. C. Marsh (in Hague, 1904). No other fossils have been found in it. An unsuccessful attempt was made by Love in 1937 to locate the horse tooth at the U.S. National Museum and in the Marsh collection at

Yale University in order to check its identification.

A flat terrace on the west side of the Yellowstone River at Calcite Springs (fig. 3, lower right corner) is composed of alluvial boulders cemented with white siliceous hot-spring deposits and sulfur and impregnated with oil.

The hot springs have been adequately described by Allen and Day (1935); their data are not repeated here. Chemical analyses of the water and identification of

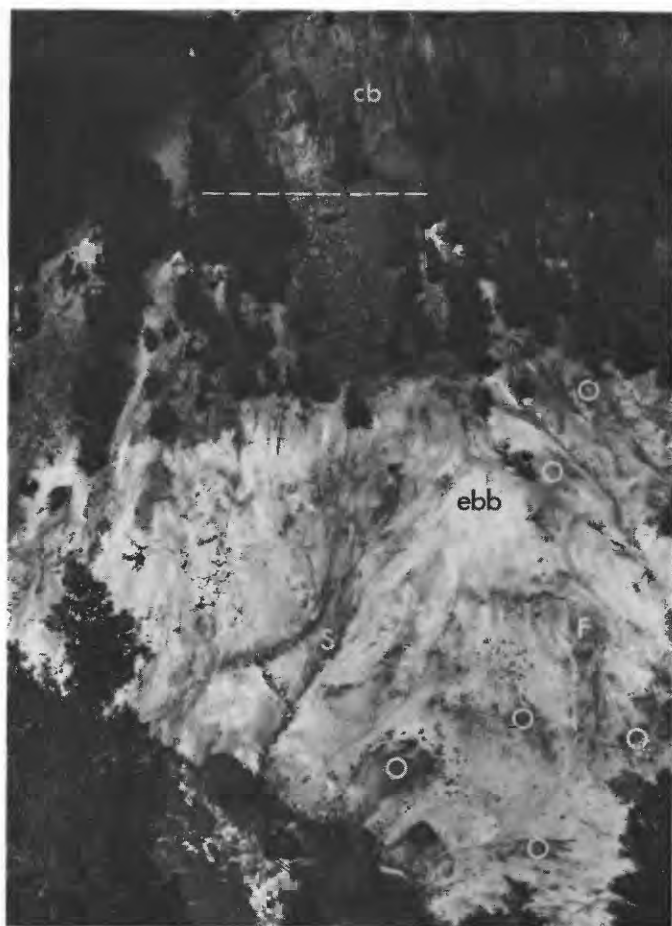


FIGURE 3.—View west across the Yellowstone River toward Calcite Springs locality. Indicated are highly altered early basic breccia (ebb); Canyon basalt (cb) of Howard (1937), capping Bumpus Butte at top center; boiling spring (S); oil seeps (O); and lithified tarry residue from an old oil flow (F) shown in figure 4. Height of scarp is about 500 feet.

some of the associated minerals are likewise given by Allen and Day. Regarding the origin of the water, they stated (p. 498):

The thermal waters are best explained as of mixed origin; the high sulphate and free sulphuric acid probably washed down the slope in a superficial circulation, the chloride, bicarbonate and carbonate brought up from greater depths. In those spring waters of this group that show an acid reaction, the infiltration of superficial drainage is in excess, while in the alkaline springs the carbonate and bicarbonate of the deeper water are more than equivalent to the acid of the shallow supply.

The north-south areal extent of oil seeps at this locality has not been determined. The seeps occur for at least one-fourth mile along the west side of the river and emerge at many elevations between water level and a horizon 250 feet up the west side of the canyon (fig. 3). No streams of oil flow at present, but they have at several times in the moderately recent past. This con-

clusion is based on the occurrence of at least 10 lithified flows, one of which is shown in figure 4; the oil emerged as a fluid, cascaded down the steep slopes, incorporated rock debris, then hardened, and finally broke up into blocks and cakes of bituminous residue. These flows are of different ages. Some are old and gray, whereas others are black and fresh appearing and must have been extruded in the last few years. The rapidity of breakup and obliteration of these flows was demonstrated by comparing photographs of the flow shown in figure 4 (taken July 16, 1964) with a similar view taken 3 years later. During this interval of time, much of the hard crust had broken up and had been scattered by water and snowslides.

The orifices from which the oil emerges are along fractures in soil and rock. Temperatures of vapors 1 foot inside the orifices range from warm to hot. Several of the hottest (fig. 5) that were measured were 93°C, but the average was 80°–85°C. The oil is highly fluid, has a strong but pleasant petroleum odor, and is light brown. It is accompanied by sulfurous gas and steam in the hottest vents and by small amounts of water in the cooler ones. The conduits and fractures are invariably lined with layers of beautiful euhedral yellow sulfur crystals, some as much as 2 inches long. Many crystals contain globules of oil and are generally oil stained. Some fractures, such as the one shown in figure 5, widened gradually during a considerable period of time; and as they widened successive layers of sulfur crystals with interstitial hydrocarbons were deposited.

After the oil reaches the surface in the active vents, it mixes with soil, rock, and dead vegetation to form spongy, bulbous, flexible masses. These deposits, resulting from the slow extrusion of oil, are different from the lithified flows, which were apparently emplaced much more rapidly.

The Calcite Springs, so named because of the nearby masses of milky-white calcite crystals, are directly adjacent to the oil seeps near river level. Barite crystals are associated with the calcite. In addition, there are deposits as much as 50 feet thick (fig. 6) of finely crystalline calcite interlayered with spongy, fibrous mats of gypsum. A geochemical and mineralogical study of these deposits would contribute much to an understanding of the nature of the underlying rocks, including those from and through which the oil, sulfur, and thermal water came. Elemental sulfur is invariably associated with the oil but it is not known if this sulfur and that in the gypsum and barite had a common origin.

Allen and Day's comments (1935, p. 496) regarding the oil seeps are very perceptive:

Breaking into fumaroles with the pick, one finds well-crystallized masses of it [sulfur], mixed with bitumen of tarry



FIGURE 4.—View west at part of Calcite Springs locality where oil that emerged from the early basic breccia at point A flowed downslope and then was lithified into a tarry crust. Dashed line indicates margin of flow. For general location see figure 3. Ledge of crystalline sulfur is at S. Temperature of active oil and sulfur vents is 80°–85°C. Oil sample PC65-3 is from seep at point A, and PC65-4 is from lithified flow.

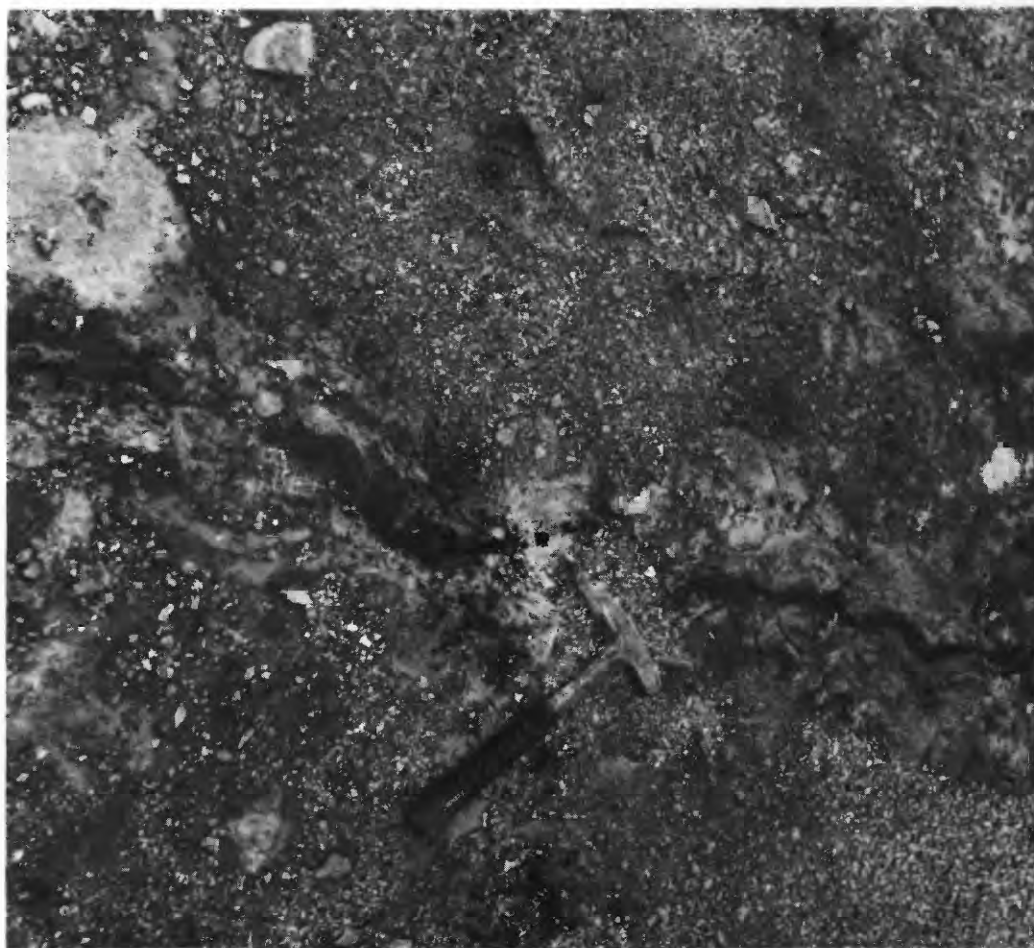


FIGURE 5.—One of the hottest (93°C at point of hammer) sulfur and oil vents at Calcite Springs. Layered deposits on both sides of dark fissure are oil-saturated crystalline sulfur, and fissure is filled with brown fluid oil.

appearance and odor. On the bench above the river's edge, sinuous trails, resembling the marks of burrowing moles, follow the lines of cracks where the same products have been deposited. No evidence regarding the origin of this tarry substance in the fumaroles is at hand. A unique occurrence in the Yellowstone Park, it seems to be best explained as a distillate from organic matter in buried sediments.

No analyses of the oil were made by Allen and Day. Therefore, as a part of the present study, samples of oil-saturated silt and sand were collected from vents between the river level and the highest occurrences of such material, 250 feet above the river (fig. 3). A representative sample (sample PC65-3) of oil from one of the hottest vents about 100 feet above the river contained (A. B. Hubbard, U.S. Bur. Mines, written commun., 1965) 15.5 percent benzene-soluble oil and 64.1 percent free sulfur (because the oil and free sulfur are both benzene soluble and difficult to separate, the figures may not be exactly correct). The sample also contained 20.1 percent benzene-insoluble matter. Total carbon analy-

sis of this benzene-insoluble residue showed that it contained 13.62 percent organic carbon (J. W. Smith, written commun., 1965). Concerning this insoluble residue Smith commented:

Presence of this amount of organic carbon not soluble in benzene is a very surprising feature of your samples. While many petroleum carry heavy asphalts, the asphalts are almost entirely benzene-soluble. The insoluble organic carbon in the Yellowstone samples may well be a parent material for the oil, carried along in the oil by the hot water.

It is interesting to compare the composition of the oil with that of the lithified flow shown in figure 4. The lithified material (sample PC65-4) contained only a trace of benzene-soluble oil (detected by ultraviolet fluorescence and infrared spectroscopy), 59.6 percent free sulfur, and 40.4 percent benzene-insoluble residue (A. B. Hubbard, written commun., 1965). This residue contained 1.42 percent organic carbon (weight percent; J. W. Smith, written commun., 1965).



FIGURE 6.—View northeast across the Yellowstone River at Calcite Springs. Indicated are tilted light-colored interbedded calcite and gypsum (C), early basic breccia (ebb), and partly solidified dark-colored oil flow (O) in center and left foreground that comes up through the breccia. Shovel (S) at bottom indicates scale.

M. L. Jensen, University of Utah, made sulfur isotope studies of water and sulfur from the Calcite Springs area, with results as follows (written commun., 1967):

Sample	δS^{34} per mil		
water.....	-1.9		
Sulfur.....	-1.9	+4.7	+7.8
	+3	+7	+4.7
	+1.1	+3.0	+5.4

With reference to these data, Jensen commented:

This spread in values is a little greater than I would like to see for undoubted magmatic hydrothermal sulfur. On the other hand, it is not quite as broad as I would like to see to be diagnostic of a bacteriogenic origin. Even considering that the δS^{34} values are near zero per mil does not enhance the magmatic hydrothermal origin of the sulfur, as a bacteriogenic origin would involve the reduction of SO_4^{2-} to H_2S , and exothermic oxidation of H_2S to S^0 with the SO_4^{2-} being typically enriched in S^{34} with a δS^{34} value of +20 with ± 10 per mil. Such reduction could readily provide the δS^{34} values obtained, suggesting biogenic sulfur enriched to a variable content in S^{32} in comparison to the S^{32} content of the SO_4^{2-} that was reduced. A magmatic hydrothermal origin

would more closely average zero per mil and should exhibit a more narrow spread in δS^{34} values than those obtained. In conclusion, therefore, with a strong assist from the geologic occurrence, I favor the bacteriogenic origin of the sulfur.

K. L. Pering, research chemist for the National Aeronautics and Space Administration, sampled oil seeps throughout the 250 feet of vertical section in which they occur. She commented on the nature of the oil as follows (written commun., 1968):

A gas chromatogram of the alkanes in the bitumen from Calcite Springs [fig. 11B, this report] is characterized by a largely unresolved hump, which suggests the presence of an unresolvable mixture of alkane isomers. Individual peaks on the hump may be normal alkanes. Because of the abundance of free sulfur in the oil sample, the amount of alkanes was difficult to estimate but a rough guess is that less than 1 percent is present.

A comparison of the gas chromatogram of this oil with that of oil from Rainbow Springs (loc. 3, fig. 11A) is given in the discussion of the latter locality. It is worth noting that of the two oil samples on which gas chromatograms were run, the Calcite Springs oil prob-

ably contains less than 1 percent alkanes, whereas the Rainbow Springs oil contains about 99 percent.

No data are available as to the composition, age, depth, and attitude of the underlying rocks that might be supplying the oil and sulfur but, as mentioned in the first part of this report, some guesses probably can be made when regional tectonic, stratigraphic, and structural studies currently in progress in Yellowstone National Park are completed (Campbell, 1969). The reason for the sporadic flows of oil down the canyon slope is not known. The flows may be related to earthquake activity that caused rapid extrusion of oil that had accumulated underground. The unique occurrence of crystalline calcite and barite and the volume and source of the associated sulfur and gypsum warrant further investigation.

TOWER BRIDGE (LOC. 2)

The Tower Bridge oil seeps (fig. 1, loc. 2; fig. 2) are adjacent to the westernmost pylon of the new Tower Bridge across the Yellowstone River, about half a mile northeast of Tower Junction, Yellowstone National Park. No oil was known in this area prior to 1962. During January 1962, a construction company dug a pit about 30 feet deep and 20 feet square in which to put the base of the westernmost pylon of the bridge. The pit was entirely in a dark-colored facies of volcanic-rich strata equivalent to the lower part of the Cathedral Cliffs Formation (H. J. Prostka, oral commun., 1969). This sequence had previously been mapped as the early basic breccia by Hague (1904). It consists of dark-green to dark-brown coarse-grained mafic tuff, conglomerate, and basaltic breccia with a few partings of plastic gray claystone. The claystone was checked for pollen but proved to be barren. The rock has been deeply altered by hydrothermal action so that most outcrops appear white, yellow, and light green. Near the bottom of this pit, light-brown translucent oil seeped out and dribbled down the walls. At first it was thought that this was oil from construction machinery used in digging the pit, but excavation back along the conduits showed that the oil actually came from bedrock. The matrix of the rock is soft and porous because of the extensive alteration.

A few small samples of the oil-stained claystone and tuff were collected before the pylon was built and the excavation filled. Unfortunately, however, no oil sample was obtained, and no photographs were taken of the actual seeps. The rock samples were too small for adequate oil analysis, so during the following summer a bulk sample of petroliferous rock fragments that had been thrown out of the excavation was collected and analyzed for hydrocarbons. J. W. Smith (written com-

mun., 1963) extracted it for approximately 32 hours using a Soxhlet extractor that had a 60- by 180-mm thimble, with benzene solvent, and recovered 0.24 percent benzene-soluble hydrocarbon and 0.10 percent sulfur.

The gray claystone, taken from the original pit while it was open and checked for pollen (barren), seemed unusually heavy, so a spectrographic analysis was run. The only anomalously high amount of any heavy metal was 0.2 percent molybdenum. Because the rock was slightly petroliferous, carbon and sulfur analyses were made (I. C. Frost, written commun., 1963), with the following results: 0.29 percent total carbon and 0.02 percent mineral carbon (total carbon determined by induction furnace and mineral carbon determined gasometrically); total sulfur is 1.1 percent (determined by pyrometric-titration method).

There is no present thermal activity in or adjacent to the pylon pit, although the intense alteration of the volcanic-rich strata indicates past activity. On the east bank of the Yellowstone River, on the upstream side of the bridge, however, active thermal vents are present. These emit lethal amounts of gas, probably some type of sulfur gas. The most specific record of this gas occurrence is given in a National Park Service accident report. According to W. A. Whitmore (written commun., 1939), a test pit 26 feet deep was dug in 1939 in connection with construction of a highway bridge over the Yellowstone River at the site of the present bridge. Gas with a slightly sulfurous odor was encountered. One morning, shortly after the pit was dug, several men in it were overcome by gas in a matter of minutes, and one of them died shortly thereafter. A second pit, 10 feet from this one and dug to a depth of 47 feet, encountered only small amounts of sulfurous gas. No gas was noted in a third pit, which was on the west side of the river. No hydrocarbons were noted in any of these pits, but they could easily have been overlooked, as were those in the 1962 excavations.

The original source of the oil is not known. Precambrian granite along the southwest margin of the Bear-tooth Mountains is exposed 2,800 feet northeast of Tower Bridge and may have been thrust southward over Paleozoic and Mesozoic rocks prior to deposition of the volcanic-rich strata. Farther northwest, Brown (1961) mapped the Gardiner and Everts thrust faults along the southwest margin of the Bear-tooth Mountains. Both faults disappear southeastward beneath igneous and pyroclastic rocks, so their extent in that direction is not known. The oil might be migrating along these or other buried faults and reaching the surface at this locality because of the porosity and permeability of the highly altered volcanic-rich strata.

RAINBOW SPRINGS (LOC. 3)

Rainbow Springs were named by Everett (Ben) Arnold, an oldtime ranger in Yellowstone National Park (Lee Coleman, written commun., 1964). The name appeared for the first time on the 1959 Tower Junction 15-minute topographic quadrangle map (fig. 7). This descriptive name could have been derived from the rainbows of oil on the hot-water pools and streams or from

the unusually brightly colored algae in the thermal area. Of all the localities, this one contains the most oil, is the most fossiliferous, and is the least accessible.

The only previous mention of oil in this area was by Allen and Day (1935, p. 356-357), and it was based on notes by Allyn Hanks, a park ranger. Allen and Day stated: "A short distance down stream from the area described is another 30 by 50 yards in size, with a brown

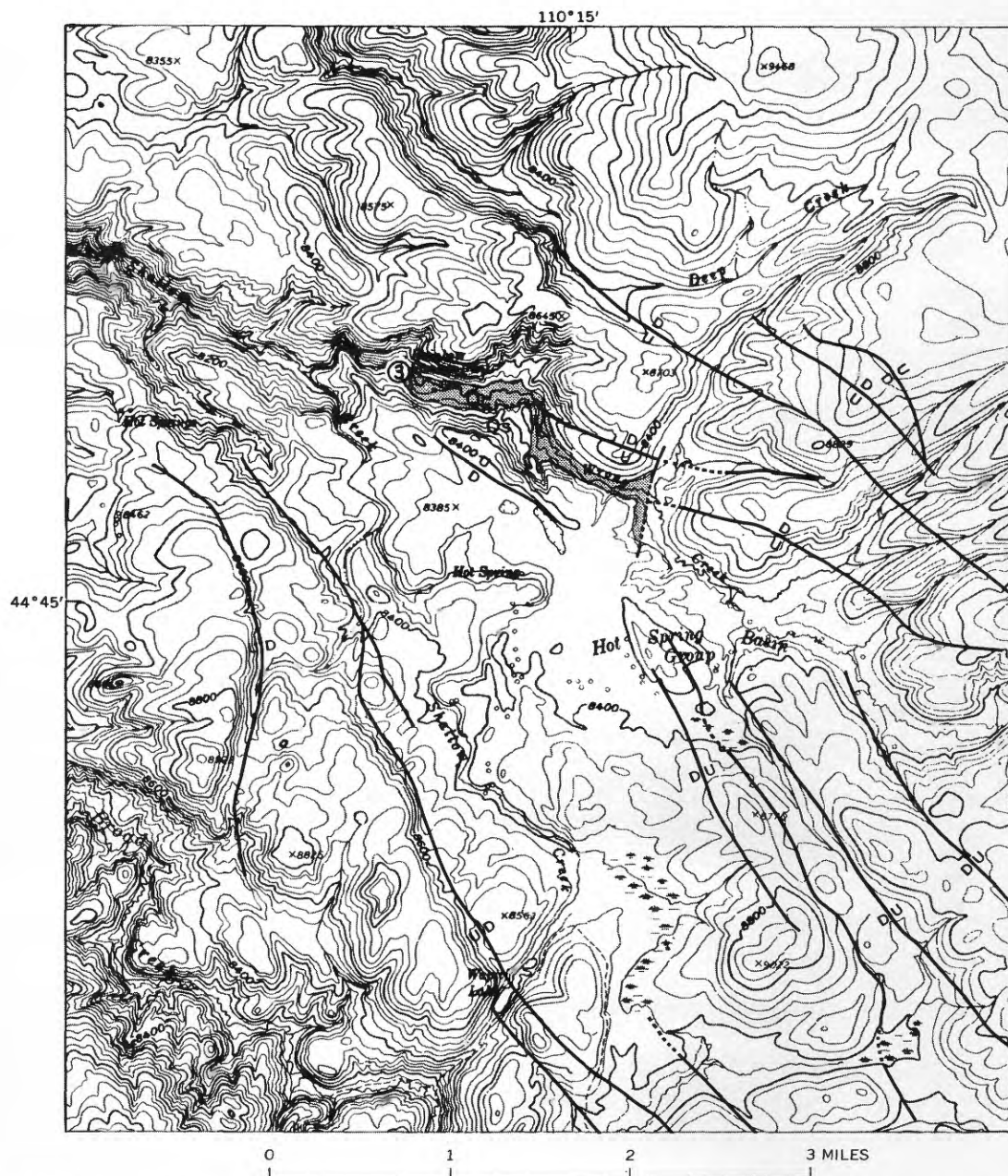


FIGURE 7.—Map of Rainbow Springs area (loc. 3). Indicated are some of the Pleistocene faults and two Pleistocene sedimentary sequences. Oil seeps emerge from the claystone sequence (Qc, stippled area), which is overlain by a sand (Qs). Position of faults is taken from mapping by Love (1961); U, upthrown block; D, downthrown block; dotted where concealed. Base from U.S. Geological Survey Canyon Village, Tower Junction, Abiathar Peak, and Pelican Cone quadrangles, 1959.

oily deposit smelling of petroleum." The locality is designated "Deep Creek Springs (Eastern Group)." In order to determine if there was actually a set of petro-liferous springs on Deep Creek or if this described locality was Rainbow Springs on Wrong Creek, which flows into Shallow Creek rather than into Deep Creek, we sent the 1959 topographic maps and aerial photographs of the area to Allyn Hanks. After examining them, he stated (written commun., 1964) that his observations that were published by Allen and Day were probably of Rainbow Springs. The confusion of drainages is understandable, because the stream pattern is unusually complex as a result of Pleistocene faulting (fig. 7), and the 1884-85 topographic map of this part of the Canyon quadrangle, which was the only map available at the time of Hanks' examination, contained extensive errors, not only in the positions and relations of the streams, but also in the direction of their flow.

Two widespread sequences of Pleistocene strata are present in the Rainbow Springs area, a blue-gray claystone and mudstone at least 75 feet thick and an overlying pebbly sandstone and sand at least 125 feet thick. These are discussed in some detail because of the bearing of stratigraphy and environment of deposition on the interpretation of the possible Pleistocene origin of the oil. The lower sequence, from which the oil seeps emerge, is exposed only in the bottom part of the valley of Wrong Creek near Rainbow Springs but is more widespread in areas to the south and southeast. The claystone and mudstone is bright to dull blue gray, soft to hard, blocky, and noncalcareous; it is locally interbedded with gray fine- to medium-grained poorly cemented volcanic sandstone containing abundant clear glass shards, black magnetite grains, and larger clear angular quartz and feldspar grains. Much of the rock is peppered with tiny black specks that have not been identified. Irregularly distributed angular grains of clear quartz and feldspar are characteristic of the claystone as well as the sandstone. The mudstone has a persistent acrid odor. Analysis of a representative sample (lab. No. D110908) showed 76 ppm (parts per million) arsenic, 0.5 ppm selenium, 0.10 percent fluorine, and 1.1 percent sulfur (determined by A. J. Bartel, G. T. Burrow, W. D. Goss, and I. C. Frost, respectively, written commun., 1963).

Spectrographic analyses show that this claystone and mudstone sequence contains less iron, calcium, manganese, strontium, and nickel than the other lacustrine Pleistocene sequences that we have studied in the area north of Yellowstone Lake.

The claystone and mudstone sequence in adjacent localities laps across Tertiary and possibly Quaternary igneous and pyroclastic rocks and is unconformably

overlain by the sandstone and sand sequence and in places by lithified conglomeratic hot-spring deposits (fig. 8) or by glacial debris.

The Pleistocene age of the claystone and mudstone sequence is based on fossil diatoms and pollen. The following diatoms were identified from a sample in the lower part of a section 6,500 feet upstream from the main part of Rainbow Springs (U.S.G.S. diatom loc. 5589; identified by K. E. Lohman and G. W. Andrews, written commun., 1966). Occurrence is indicated by R, rare, and F, frequent:

<i>Cyclotella comta</i> (Ehrenberg) Kützing	F
cf. <i>C. operculata</i> (Agardh) Kützing	F
sp	F
<i>Melosira</i> cf. <i>M. italica</i> (Ehrenberg) Kützing	F
sp	R
<i>Rhopalodia gibba</i> (Ehrenberg) O. Müller	R
<i>Stauroneis anceps</i> Ehrenberg	F
<i>Stephanodiscus astra</i> (Ehrenberg) Grunow	F
astraea var. <i>minutula</i> (Kützing) Grunow	F

Concerning this assemblage, as well as others from Pleistocene lacustrine strata in the general area, they commented, "The environment in which these diatoms lived was probably a cool to cold, fairly shallow, clear lake, very near neutral, as the rare species usually preferring slightly acid water are balanced by those usually preferring slightly alkaline water, and many are indicative of water of low mineral content."

Pollen assemblages from oil-saturated claystone from the Rainbow Springs locality consist of the following forms (identified by E. B. Leopold, written commun.,



FIGURE 8.—Ledge of Pleistocene brown oil-stained conglomerate; darker appearing unvegetated spots are active oil seeps. View is of north bank of Wrong Creek, east of bison skull site at Rainbow Springs locality. Base of ledge marks contact with blue-gray claystone sequence which yielded pollen collection D3366.

1964, 1966). Collection D3310 is from the Rainbow Springs, and collection D3366 is from an area one-fourth mile upstream from Rainbow Springs and stratigraphically a few feet higher.

	Pollen collection D3310	Pollen collection D3366
<i>Pinus</i>	42	57
<i>Artemisia</i>	35	12
<i>Picea</i>	2	12
<i>Ephedra</i> and <i>Ephedra</i> ?.....	1	1
<i>Botryococcus</i>	1	7
<i>Quercus</i> ?.....		1
<i>Juniperus</i>		1
cf. <i>Acer</i>		1
<i>Eriogonum</i>	1	
<i>Polygonum</i> cf. <i>P. bistortoides</i>	1	
<i>Sarcobatus vermiculatus</i>	1	
Gramineae.....	1	1
Compositae.....	2	2
Cyperaceae.....	1	2
Dicots, undet.....	10	1
Chenopodiaceae, undet.....	3	
Total number of grains.....	101	98

These collections represent pollen rains that are nearly identical with modern pollen accumulations present in lakes of this general area today.

The sandstone and sand sequence is about 125 feet thick. The basal bed is a hard rounded pebble conglomerate. It is overlain by sandstone that is sufficiently lithified to form a weak ledge about 15 feet thick. The remainder of the sequence is crudely stratified un cemented coarse- to fine-grained sand; much of it consists of clear shards and white pumice fragments. Black obsidian shards, clear angular quartz and feldspar grains, and some rounded granules of pink rhyolite are present. These soft strata support a dense growth of trees, and exposures are rare. The sequence extends westward along both sides of Wrong Creek at elevations beginning just above the thermal vents. No fossils were found in it.

Along the bottom of Wrong Creek within the thermal area, there are conspicuous bare to grassy outcrops of hard rusty-brown conglomerate cemented with siliceous hot-spring deposits (fig. 8). Some white to rusty-brown hot-spring deposits contain little or no conglomerate. These outcrops are exposed in weak ledges along the banks of Wrong Creek, which in Holocene time cut through them into the underlying claystone. Partly rotted and partly silicified logs are embedded at various horizons in the conglomerate and in the hot-spring deposits. If the logs are within the range of carbon-14 dating methods, analyses could provide a precise age for the conglomerate besides data on the rate of accumulation of these deposits.

In connection with an earlier study (Love, 1961), Quaternary faults were mapped in this area, and these are shown in figure 7. Because of dense timber, landslides, and poor exposures, the traces of less conspicuous faults were determined in part by low-level helicopter traverses at times when light was very oblique. Under these conditions, lines that are related to drainage and topographic anomalies and thermal features became visible in unconsolidated debris. Several faults trend into the Rainbow Springs area, but exposures are such that we were not able to determine if the thermal conduits are along faults.

The ground throughout the thermal area is warm. Many springs boil violently, although the actual volume of water that enters Wrong Creek from the north is not large. On the south side, however, one thermal complex emits about 1 cubic foot (about 7½ gallons) of hot water per second. Some springs have built siliceous cones as much as 5 feet high. Others, not quite as hot, are rimmed with white siliceous deposits and harbor algae which are red, pink, brilliant green, and inky black. Trees that have fallen into some pools are partly silicified, indicating the abundance of silica in the water and the rapidity of petrification. A few springs contain blue-black iron sulfide. Sulfur is not as abundant as at Calcite Springs, but some pools and rivulets have long white streamers of sulfur, and the sulfurous odor is moderately strong. More sulfur is present on the south side of the creek than on the north. Hissing steam vents are present, and gas bubbles up violently in some pools. Most of the gas that was tested was nonflammable, but a few seeps ignited explosively.

Oil seeps are numerous on the north side of Wrong Creek from Rainbow Springs upstream for at least three-eighths of a mile. No attempt was made to determine the maximum areal distribution of the seeps, and they may be considerably more widespread. None was observed on the south side of Wrong Creek; there, the color of the brown deposits that superficially resemble oil seeps was caused by iron staining.

Some seeps are entirely oil (figs. 8, 9), whereas others are a combination of oil and warm-to-boiling water. Rainbows of oil are conspicuous, streaming along the surface of water that moves out of the more aqueous seeps.

A few feet west of the oil seep shown in figure 8 is an oil-impregnated warm-water swamp in which both ancient and modern bison have mired and died. While exploring this swamp, we excavated an unusual oil-soaked bison skull that had long, slender, back-swept horns with a greater spread than that of modern bison in the region. This skull was sent to Morris F. Skinner, of the American Museum of Natural History, who has



FIGURE 9.—View northeast showing western part of Rainbow Springs locality. In foreground, unvegetated spot is dark-brown oil-saturated siliceous hot-spring deposit (site of oil sample SBR63-359X). Hole is mold of partly silicified tree that was conduit for the oil. In grass at upper left is swamp that yielded *Bison* skull (site of oil-saturated sand and silt sample SBR63-149X, highly fluid oil sample for Rainbow Springs gas chromatogram in fig. 11, and dark oil sample analyzed for carbon by Irving Friedman). Steam vents are at upper right.

studied in detail the fossil bison of North America (Skinner and Kaisen, 1947). He made comparative measurements of various parts of the skull and concluded that it was most like *Bison (B.) bison athabasca* (the Mountain bison). This form is still living in northern Canada but had a prehistoric range as far south as Colorado. This skull is of special interest to our study because its presence near the surface indicates that the water and oil level in this swamp has changed little since prehistoric time.

As a result of this discovery, we used an iron bar, 4 feet long and one-half inch in diameter, to probe the swamp for bones of other animals. During the process of probing, we found several places in the swamp where explosively flammable gas bubbled up after the iron bar was withdrawn. Following the emergence of this gas, a cream-colored waxy substance with

the consistency of soft butter emerged on the surface of the warm water. This was collected immediately, and after 2 days, even in 50°F temperature, it changed to a dark-reddish-brown transparent highly fluid oil. In other parts of the swamp, a light-amber-colored transparent oil (fig. 10) with a strong but pleasant petroliferous odor accumulated on the surface of pools of water; at 70°F it also was highly fluid, but at lower temperatures it congealed.

Two types of samples were studied: oil-saturated sand and silt, and fluid oil. Table 1 (G. J. Schrayner, Gulf Research and Development Co., written commun., 1965) presents data on representative samples of oil-saturated sand and silt from several parts of the Rainbow Springs locality. These samples, collected from within 6 inches of the weathered outcrop surface, were brown and had a strong petroleum odor. J. W. Smith



FIGURE 10.—Untreated transparent amber-colored oil and associated water (hot at time of collection) from Rainbow Springs swamp that yields *Bison* skull.

(written commun., 1964) analyzed benzene extracts of two of these samples with the following results:

	Sample	
	SBR63-364X (oil-impregnated sand)	SBR63-366X (oil-impregnated sand)
Extract, weight percent rock.....	4.8	8.6
Nitrogen, weight percent extract.....	.03	.03
Sulfur, weight percent extract.....	.16	.16
Carbon residue, weight percent extract.....	.2	1.2
Nitrogen to carbon residue ratio.....	.15	.025

TABLE 1.—Composition of oil, in weight percent, from seeps at Rainbow Springs locality, Yellowstone National Park, Wyo.

[Material analyzed is benzene-soluble extract from oil-saturated sands and silt. Sample SBR63-149X, midway between sites of figs. 8 and 9; sample SBR63-364X, locality shown in fig. 9; sample SBR63-366X, locality shown in fig. 8. Analyses by G. J. Schrayner]

	Sample		
	SBR63-149X	SBR63-364X	SBR63-366X
Gross composition of crude oil:			
Volatile hydrocarbons.....	8.4	16.5	22.1
Asphaltenes.....	0	0	0
Maltenes (Asphaltene-free, hexane-soluble non-volatile residue).....	91.6	83.5	77.9
Gross composition of maltenes:			
Saturated hydrocarbons.....	84.3	79.1	73.1
Aromatic hydrocarbons.....	10.8	15.3	20.3
Nonhydrocarbons (resins).....	3.9	5.6	5.8
Group composition of saturated hydrocarbons:			
Alkanes.....	75.2	58.7	56.9
Noncondensed cycloalkanes.....	17.0	27.7	28.5
Condensed cycloalkanes.....	7.7	13.5	14.5
Group composition of aromatic hydrocarbons:			
Substituted benzenes.....	39.0	38.0	32.0
Substituted naphthalenes.....	13.0	13.0	13.0
Acenaphthylenes.....	11.4	11.6	14.5
Indanes.....	6.9	7.2	7.3
Acenaphthenes.....	10.3	10.3	11.7
Pyrenes.....	4.0	3.9	4.5
Dinaphthenobenzenes.....	9.2	9.6	10.3
Phenanthrenes and (or) anthracenes.....	3.8	3.6	4.0
Chrysenes.....	2.0	2.1	2.1
Distribution of cycloalkanes:			
Monocyclic.....	68.7	67.2	66.2
Bicyclic.....	16.0	17.0	16.0
Tricyclic.....	6.6	7.5	7.7
Tetracyclic.....	4.9	5.0	5.5
Pentacyclic.....	2.0	2.0	2.9
Hexacyclic.....	2.0	0.7	1.0

Two samples of fluid oil were collected from the locality of figure 9; one was a split of that shown in figure 10, from the surface of pools of water, and the other was a darker, more highly fluid oil, described earlier, from a probe hole. Preliminary examination of these fluid oil samples showed that they were not appreciably different from the oil in the nearby sand and silt (table 1; G. J. Schrayner, oral commun., 1968).

A gas chromatogram of the alkanes extracted from the light-amber-colored oil shown in figure 10 was made by K. L. Pering and is reproduced as part of figure 11. She commented on the nature of this oil sample as follows (written commun., 1968):

Preliminary examination of a gas chromatogram of the alkanes from the Rainbow Springs oil [fig. 11A] shows that it consists almost entirely of saturated, acyclic alkanes. Normal alkanes predominate, and peaks with the retention time of the isoprenoids, pristane and phytane, are evident. These alkanes exhibit a distribution seen in many sediment alkanes. Lack of major alkane components below nC_{16} suggest a possible loss of volatile constituents.

The disparity between the gas chromatographic distribution of alkane mixtures from Calcite Springs and Rainbow Springs [figs. 11A, B] suggests either that they came from two different sources, or that one or both represent altered fractions of the same oil.

Figure 12, reproduced from figure 2 of Ponnamperna and Pering (1967), is included for the purpose of comparing the gas chromatograms of oil from Calcite Springs and Rainbow Springs (fig. 11) with those of a normal marine shale, the Posidonian (Jurassic)

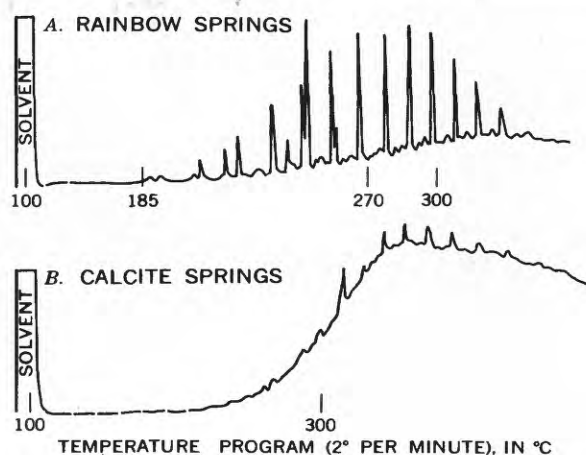


FIGURE 11.—Gas chromatograms of the alkanes in unprocessed oils. A, Rainbow Springs; B, Calcite Springs. 50-ft Micropak SE-30 column; 2°C per min; Aerograph 660; flow rate 6 ml per min. Data by courtesy of K. L. Pering, National Aeronautics and Space Administration.

of Europe, and a nonhydrothermal deposit, the Trinidad Lake asphalt. On the basis of similarities between these two sets of gas chromatograms, it would be easy to reach conclusions that might be invalidated when suites of gas chromatograms are made of many samples from various parts of the Calcite Springs and Rainbow Springs areas. Therefore, the ones presented here are meaningful only in the sense that they call attention to a line of investigation that may yield significant data.

As mentioned earlier, the contrast in alkane content of the two oil samples on which gas chromatograms were run is very striking (about 99 percent alkane in the

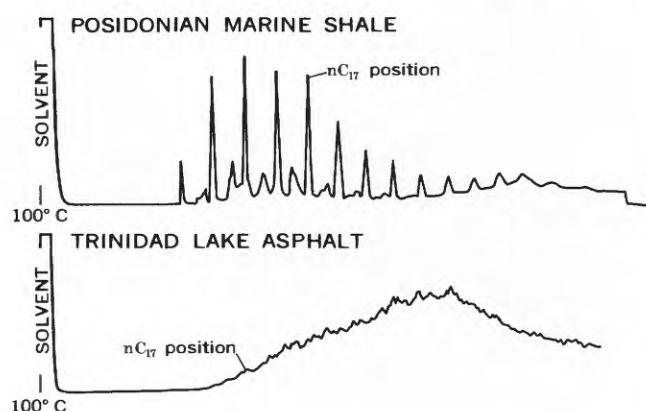


FIGURE 12.—Comparison of the gas chromatogram of the aliphatic hydrocarbons extracted from Posidonian marine shale with that of the aliphatic hydrocarbons extracted from Trinidad Lake asphalt. Temperature progression 2°C per min; 12 ft by 1/8 in., 3 percent SE-30 column; Aerograph 660. (From Ponnampetuma and Pering, 1967, fig. 2.)

Rainbow Springs oil and less than 1 percent alkane in the Calcite Springs oil). More analyses are needed to confirm this difference and, once confirmed, to determine its significance.

Carbon samples from a light-colored highly fluid oil (fig. 10) skimmed off the surface of a spring and from a dark-colored even more fluid oil from a probe hole were analyzed by Irving Friedman (written commun., 1968), with results as follows:

Oil sample	C ¹³ per mil PDB ¹	Deuterium/ Hydrogen percent SMOW ²
Light.....	-28.9	-18.6
Dark.....	-26.4	-19.5

¹ The carbon analyses are given in terms of the PDB standard. PDB is a Cretaceous belemnite, *Belemnitella americana*, from the Peedee Formation of South Carolina (Craig, 1957, p. 135). A value of -28.9 per mil indicates that the sample contains 2.89 percent less C¹³ than does the standard belemnite.

² The deuterium results are given relative to Standard Mean Ocean Water (SMOW), a standard water whose isotopic composition is close to that of mean ocean water. A value of -18.6 percent SMOW indicates that the sample has 18.6 percent less deuterium than does SMOW (Craig, 1961).

The carbon data are suggestive but not definitive; they suggest that the oil at Rainbow Springs probably is of marine origin, but there is, nevertheless, a small possibility that it is of fresh-water origin.

Examination of the dark-colored highly fluid oil sample by infrared spectroscopy and nuclear magnetic resonance shows it to have a very high paraffin content with only 1.5 ± 0.5 percent aromatics. The ratio of CH₃ to CH₂ is 0.7. Content of even the simplest cycloalkanes is low. The oil was already extensively refined before it reached the near-surface probe hole, for it contains a minimum of unsaturates, nitrogen, sulfur, and oxygen (J. W. Smith, written commun., 1965).

Oil in Pleistocene and Holocene sediments is known in a few places in the Rocky Mountain region, but is commonly believed to have migrated into these young strata from older, buried petroliferous rocks. New studies of modern sediments (Swanson and others, 1968) and algal communities (Parker and Leo, 1965; Leo and Parker, 1966), however, indicate that under certain conditions, such as shallow-water and near-shore environments favorable to abundant growth of plants of various types, significant local accumulations of bitumen can and do occur.

The oil-secreting alga, *Botryococcus*, was identified, though it is not abundant, in the claystone and mudstone sequence at several localities in the Rainbow Springs area. (See pollen list, p. B12.) Greater concentrations of plant material may be present at depth. The diatoms do not indicate an unusually saline environment of deposition for these strata, but it is not known if such an environment is necessary for accumulation of organic material that could yield oil in the amount and of the type observed at Rainbow Springs. As far as is known now, it is possible for oil to have

been distilled, with the help of thermal conditions, from dead algae and other plant debris at shallow depths, perhaps less than 100–200 feet, in the Rainbow Springs area. A more detailed investigation of this possibility should be made.

An alternate interpretation of origin is just as likely. The PDB and SMOW data suggest a marine origin, and the sulfur and nitrogen contents and ratio of nitrogen to Ramsbottom carbon residue indicate post-Jurassic age. If these data are indicative, the hydrocarbons are probably Cretaceous and therefore must have come up from buried Cretaceous rocks at some unknown depth.

SWEETWATER MINERAL SPRINGS (LOC. 4)

The Sweetwater Mineral Springs (fig. 1, loc. 4; fig. 13) are located on Sweetwater Creek, about 3.5 miles north of the North Fork of the Shoshone River and 18 miles east of Yellowstone National Park.

The general geology of the region was described by Hague (1899). Later, Hewett (1914) studied sulfur deposits adjacent to the springs and mentioned the occurrence of oil as an item of special interest (1913). There are no subsequent publications describing the area.

The rock exposed at the surface is the early basic breccia of Eocene age. It is a brown mafic volcanic conglomerate and agglomerate several thousand feet thick and nearly horizontal in position. One of the conspicuous features of this sequence at this locality is the presence of angular masses, as much as 20 feet in diameter, of light-colored dolomite and limestone of Paleozoic age.

The mineral springs emerge an estimated 500 feet above the base of the volcanic rocks, a few hundred feet upstream (north) from the hydrocarbon seeps, between the upper and lower sulfur deposits described by Hewett (1914). The water in these springs differs from that

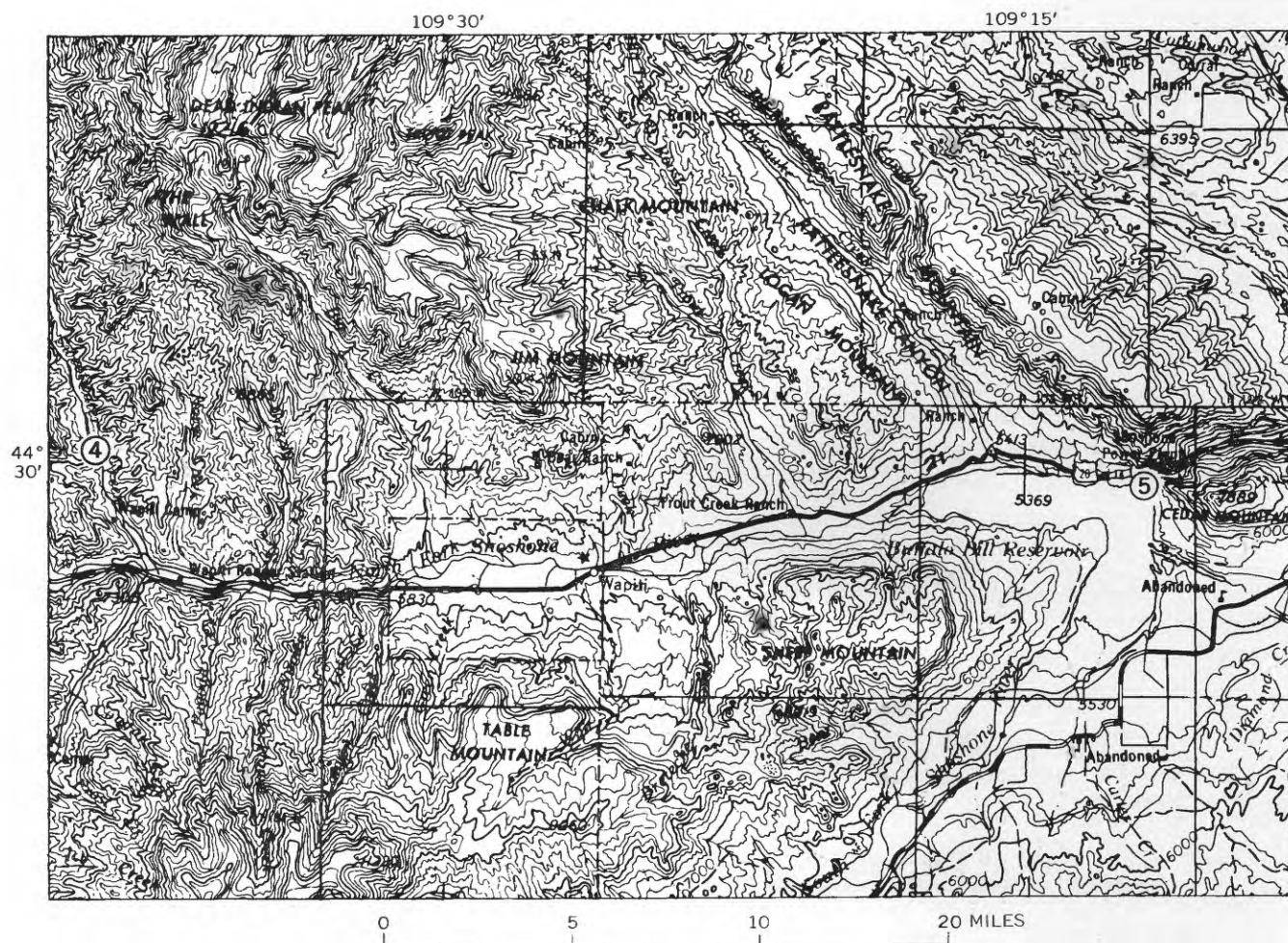


FIGURE 13.—Locations of Sweetwater Mineral Springs (loc. 4) and Cedar Mountain (loc. 5). Base from U.S. Geological Survey Cody, 1: 250,000, 1955–62.

at the localities previously discussed, because it is cold. The presence at and near the present stream level, however, of bedded sulfur, siliceous sinter, travertine, and gas vents suggests that this is a thermal area that has recently cooled. Some latent heat apparently remains in the rocks, for in winter the snow melts quickly from some spots near the sulfur deposits but accumulates elsewhere (Mel Stonehouse, owner, in 1968, of the Sweetwater Minerals Springs Resort, oral commun., 1968).

The water is so highly charged with iron that the channelways are lined with a bright limonite yellow iron precipitate. The surface of water in quiet pools and seeps has a thick iridescent coating of iron which, unlike oil, breaks up into chunks when a twig is dragged through it. At one time, because of its reported curative attributes, the water was bottled and sold. In recent years, the springs have become so choked with alluvial debris that they flow only a few tens of gallons per day. Analysis of the water by the U.S. Geological Survey (O. J. Feist, Jr., analyst, 1968) is as follows:

Chemical components

Cations:	Milligrams per liter	Milli- equivalents per liter
SiO ₂	27	.....
Fe.....	.31	.....
Ca.....	45	2.25
Mg.....	12	.99
Sr.....	.48	.01
Na.....	16	.70
K.....	1.1	.03
Li.....	<.01	.00
Total.....	.....	3.98
Anions:		
HCO ₃	97	1.59
CO ₃	0	.00
SO ₄	131	2.73
Cl.....	1.3	.04
F.....	.3	.02
NO ₃.....	.5	.01
PO ₄.....	.00	.....
Total.....	.....	4.39

Physical characteristics and computed values

Dissolved solids:	
Residues on evaporation	
at 180° C.....	milligrams per liter.. 340
Calculated.....	milligrams per liter.. 283
Hardness as CaCO ₃ :	
Total.....	milligrams per liter.. 163
Noncarbonate.....	milligrams per liter.. 83
Specific conductance.....	micromhos at 25° C.. 449
pH.....	6.2

Hewett did not mention the mineral springs. Regarding the spring deposits, he stated (1914): "Siliceous sinter and travertine, such as in many places accompany sulphur deposited by hot springs, are conspicuously absent."

The sulfur deposits described by Hewett (1914) are on the east side of Sweetwater Creek and extend from water level to more than 400 feet up the slope (fig. 14).

He apparently did not see the bedded sulfur and travertine, referred to later, on the west side of the creek. His description of the oil and sulfur is as follows (1913, p. 51):

The [oil] spring is unique in that it lies within 100 yards of several small sulfur deposits, situated on the east side of Sweetwater Creek. The sulfur deposits * * * embrace two classes of material: (1) sulfur which lies along the walls of open fractures in the lavas, and from which gases containing CO₂, CH₄ and H₂S are issuing, and (2) sulfur filling the interstices of gravels and surface debris along stream channels. The second class of material probably covers fracture zones. The oil spring is opposite an area 100 feet square into which prospect pits have been sunk showing sulfur cementing angular rock debris to a depth of 9 feet. Other smaller deposits of sulfur lie 700 feet farther up the creek.

Oil was first recognized issuing from the sands adjoining the creek.

In the hole which was dug along the bank, water and oil slowly accumulated and several quarts of clear light oil were thus collected during the summer of 1911. During the writer's visit a pit was dug near the location of the old one which had been destroyed by freshets. The sand at this point is dark brown and has an asphaltic odor, but otherwise is such as would form bars along rapid mountain streams. In the short time at the writer's disposal only enough oil was collected to give assurance of its identification, but not enough for analysis.

Tho the superficial rocks of this region are igneous flows and breccias, these rocks overlie a great thickness of sedimentary rocks ranging in age from Cambrian to Eocene, the Mesozoic section alone being approximately 14,000 feet thick 25 miles east.

Another occurrence of sulfur not mentioned by Hewett is on the west side of Sweetwater Creek beneath a flat alluvial valley fill covered with trees 100 feet west of the camera point for figure 14. The sulfur is yellow, finely crystalline, vuggy, and bedded; associated with it is a breccia of white laminated fine-grained siliceous sinter similar to that deposited by thermal water at localities 1 and 3. Overlying this is about 3 feet of peculiar alluvium consisting of soft brown sand and silt that is not bouldery as is alluvial debris in the adjacent stream channel. Carbonized twigs are abundant, the darkest brown parts have a strong petroliferous and sulfur odor, and some layers look like a lapilli tuff. It may be that the deposit is residual debris left after a fire that burned the forest cover and ignited the oil and sulfur. Subsequently, enough oil reimpregnated the silt to give it the petroliferous odor.

Laboratory studies by J. G. Palacas (written commun., 1969) of a single sample of this brown silt indicate that the retained saturated hydrocarbons, restricted to those molecules containing 19 carbon atoms and over, which make up only about 1 percent of the total benzene-extractable organic matter, appear to be derived from indigenous organic substances, such as algal organisms, rather than from petroleum sources. Petroleum hydro-

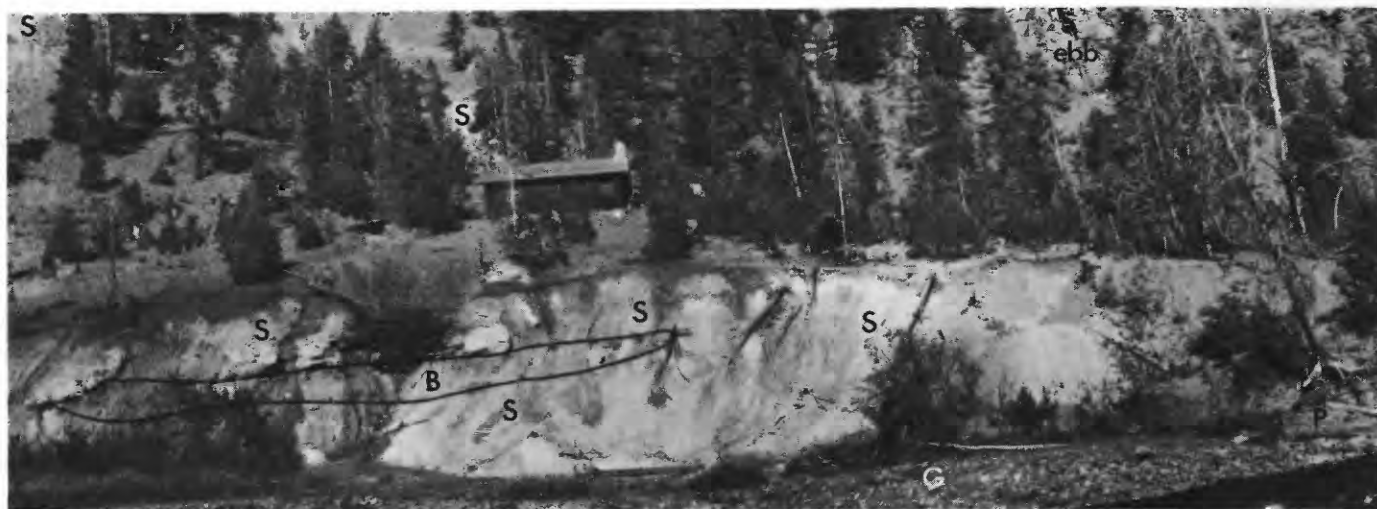


FIGURE 14.—View east across Sweetwater Creek at Sweetwater Mineral Springs locality. Indicated are early basic breccia (ebb); exposed yellow sulfurous deposits (S); black sulfurous deposit (B); brown petroliferous iron-cemented gravel and sand (P); and stream gravel in which pits were dug that yielded oil (G).

carbons, especially saturated hydrocarbons with carbon numbers less than 18, may still be present, as is indicated by the petroleumlike odor of the alluvium, but were not detected by the analytical procedures used. These procedures included pulverization, extraction with benzene at room temperature, removal of elemental sulfur by use of a copper-amalgam chromatographic column, and fractionation of sulfur-free bitumen by silica-gel-column chromatography into saturated hydrocarbons, aromatic hydrocarbons, and asphaltic compounds. The saturated hydrocarbon fraction was studied further by gas-liquid chromatography. In addition, ultimate analysis was made of an aliquot of the bitumen extract. The negative results of these procedures on the alluvial sample, despite its petroliferous odor, suggest that future studies should concentrate on fluid oil from pits such as those described by Hewett. A puzzling feature of the alluvial sample is its surprisingly low sulfur content, which was 0.79 percent though the sample was taken less than 3 feet above bedded sulfur deposits.

When locality 4 was visited, both in 1963 and in 1968, a series of torrential floods had recently plastered much of the banks and stream bottom with mud so that the oil occurrences at water level could not be studied or sampled adequately. Bulk samples of fetid gravel, sand, and fine-grained alluvium were taken, but they did not yield sufficient oil for analysis. The oil is extremely volatile (C. A. Burk, written commun., 1963), and even the residue is not tarry or gummy as is that at Calcite Springs and Rainbow Springs. Sporadic traces of oil were observed within an area more than 100 yards in diameter on the west side of the creek. In 1967, petroliferous alluvium was found on the east side in a ditch

for a waterline between the cabin and the sulfur bank shown in figure 14 (Mel Stonehouse, oral commun., 1968). A strong petroleum odor was detected in ferruginous cemented alluvial gravel at several places along both sides of the flood channel (fig. 14).

Two samples, one from a sulfur pit west of the creek (SBR63-362X) and the other from a ferruginous cemented gravel at the west edge of the creek (SBR63-363X), 100 feet north of the pit, were submitted to the U.S. Bureau of Mines for analysis. They were extracted for approximately 32 hours by means of a Soxhlet extractor with 60- by 180-mm thimble, using chloroform solvent. Sample SBR63-362X yielded 3.21 percent extract, and SBR63-363X yielded 0.01 percent (J. W. Smith, written commun., 1963). The extract of petroliferous material from the sulfur pit was brown and had a rubbery consistency and an unusually pungent odor.

The position of the sulfur deposits in the bottom of the valley on the west side of Sweetwater Creek (which has a gradient of 150 feet per mile), only 5-10 feet above the present flood channel, indicates that this episode of sulfur deposition and thermal activity was in Holocene time. When larger samples of oil are analyzed, the source rock from which they originated may be determinable. Isotope studies of sulfur from the active and extinct vents should provide a clue concerning the source of the sulfur, the depth and nature of the heat source, and the relation of the heat source to the oil.

CEDAR MOUNTAIN (LOC. 5)

The description of the oil spring at the Cedar Mountain locality is based entirely on observations made by others more than 60 years ago; the spring was obliterated

ated in 1907 by water of the Buffalo Bill Reservoir. Nevertheless, the scattered data can be used to reconstruct a general description that is pertinent to this study when considered within the context of the other localities. This locality is included primarily because the oil spring emerged directly from Paleozoic strata, yet is in a thermal area that previously had been buried by several thousand feet of igneous, pyroclastic, and nontuffaceous sedimentary rocks. It may, therefore, provide some data as to what might be expected at depth at the other localities.

This is the locality (loc. C, fig. 15) of John Colter's "great tar spring" or "boiling tar spring" (Harris, 1952, p. 95). Several thermal areas are present along the Shoshone River near here. The one that was shown on many maps (for example, Wheat, 1957-1963) is now called De Maris Springs; it is at the east end of the Shoshone Canyon (loc. E, fig. 15), where colorful sulfur deposits have long been recognized and intermittently exploited. The thermal area at the west end of the canyon received no scientific attention, however, and as far as we have been able to determine was never studied by a geologist prior to its destruction.

Comstock (1875) came close to the oil spring but apparently did not know of its existence. One of his men (Assistant Surgeon C. L. Heizmann), however, described two small adjacent thermal areas (loc. A and B, fig. 15 of this report) as follows (Jones, 1875, p. 295-296):

Camp 32, July 26, was made on the Stinkingwater, near which we found a large spring raised two or three feet above the ground [loc. A, fig. 15], with an abundant flow of a blackish water of great specific gravity, of strong sulfurous smell (temperature 56°; of air 75°), and depositing black. The water contained soda, sulphates, and sulphides. The deposit was made up of sulphur and hyposulphite of soda. As we approached the river, by Cretaceous bluffs, an odor of sulphuretted hydrogen became distinctly perceptible in the air, observable several miles away. A number of extinct springs occur here [loc. B, according to Jones' route map, sheet 24], but the existence of numerous active ones near, besides the last mentioned, was indubitable.

Jones (1875, p. 17) added a few more details:

We passed the remains of a large depositing sulfur spring [loc. A, fig. 15]. The water oozed from a cylindrical mound of soft mud, a little hardened on its rim and held together by the roots of a rank growth of water-grasses. It lies close to the Ish-a-woo-a River, on the south side near where our trail crosses, and probably at one time contributed largely to the odorific title of the main river. A few miles lower down, below the canon, a mass of sulphur springs occur [loc. E, fig. 15] which still give cause for the river's name. On the North Fork we found the extinct remains of a mass of depositing springs [loc. B, fig. 15]; the whole hill-side was covered with the large sedimentary mounds of soft black and brown earths, having a good deal of transparent gypsum in crystals and small pieces scattered through them.

Eldridge (1894) made a remarkably detailed geologic map of the Bighorn Basin region and described the sulfur spring at locality E (fig. 15) but did not mention those up the river to the west. Chittenden (1895, p. 23), however, was aware of the oil spring, for he stated:

* * * after [Colter] had passed through Pryor's Gap, he took a south-westerly direction as far as Clark's Fork, which stream he ascended for some distance, and then crossed over to the Stinkingwater. Here he discovered a large boiling spring, strongly impregnated with tar and sulphur, the odor of which, perceptible for a great distance around, has given the stream its "unhappy name."

Later, in an official report to the War Department, Chittenden (1901, p. 3781) amplified his earlier remarks:

This stream has heretofore been known as the Stinkingwater River. It was so named in 1807 by its discoverer, John Colter, who came upon it where there is a large tar spring near the junction of the two forks and gave it the name on account of the impression received at this particular point.

Fisher (1906) was the last geologist to map the area covered by the Buffalo Bill Reservoir before it was filled in 1907. He showed a small area of hot-spring deposits overlapping Paleozoic rocks at the west end of the Shoshone Canyon downstream from the forks of the Shoshone River (loc. D, fig. 15). He did not describe them, although he did discuss those at the east end of the canyon (loc. E, fig. 15) in moderate detail. He made no mention of the oil spring. The geology of the entire area shown in figure 15 was mapped in detail in recent years by Pierce and his associates (Pierce, 1966, 1970; Pierce and Nelson, 1968, 1969). On the basis of their mapping, it seems probable to us that the oil spring emerged from the Tensleep Sandstone (Pennsylvanian) or from Permian rocks. Pierce investigated the reservoir area during an especially low water stage in 1941 and noted travertine and sulfur on both sides of the valley west of the canyon and sulfurous gas bubbling up through the reservoir water on the south side (W. G. Pierce, written commun., 1968).

By far the most detailed description of the oil spring at locality C was by J. K. Rollinson, a rancher and writer who published several books (for example, 1948) on the human history of the region. As a preface to Rollinson's observations, Harris (1952, p. 95) stated:

The legend of Colter's Hell calls for boiling springs, sulphur lying on the ground, flames shooting from the earth, and the great tar spring. Much fun has been poked at the story of the tar springs, since none are known to the present-day residents of the Shoshone valley. Nevertheless, the maps of Drouillard and Clark, by showing the trail winding around Cedar Mountain prove that Colter, if not Drouillard, actually saw at least one of the tar springs. The "boiling tar spring" was not the product of Colter's imagination but was located on the South Fork of the Stinking Water just above the junction with the

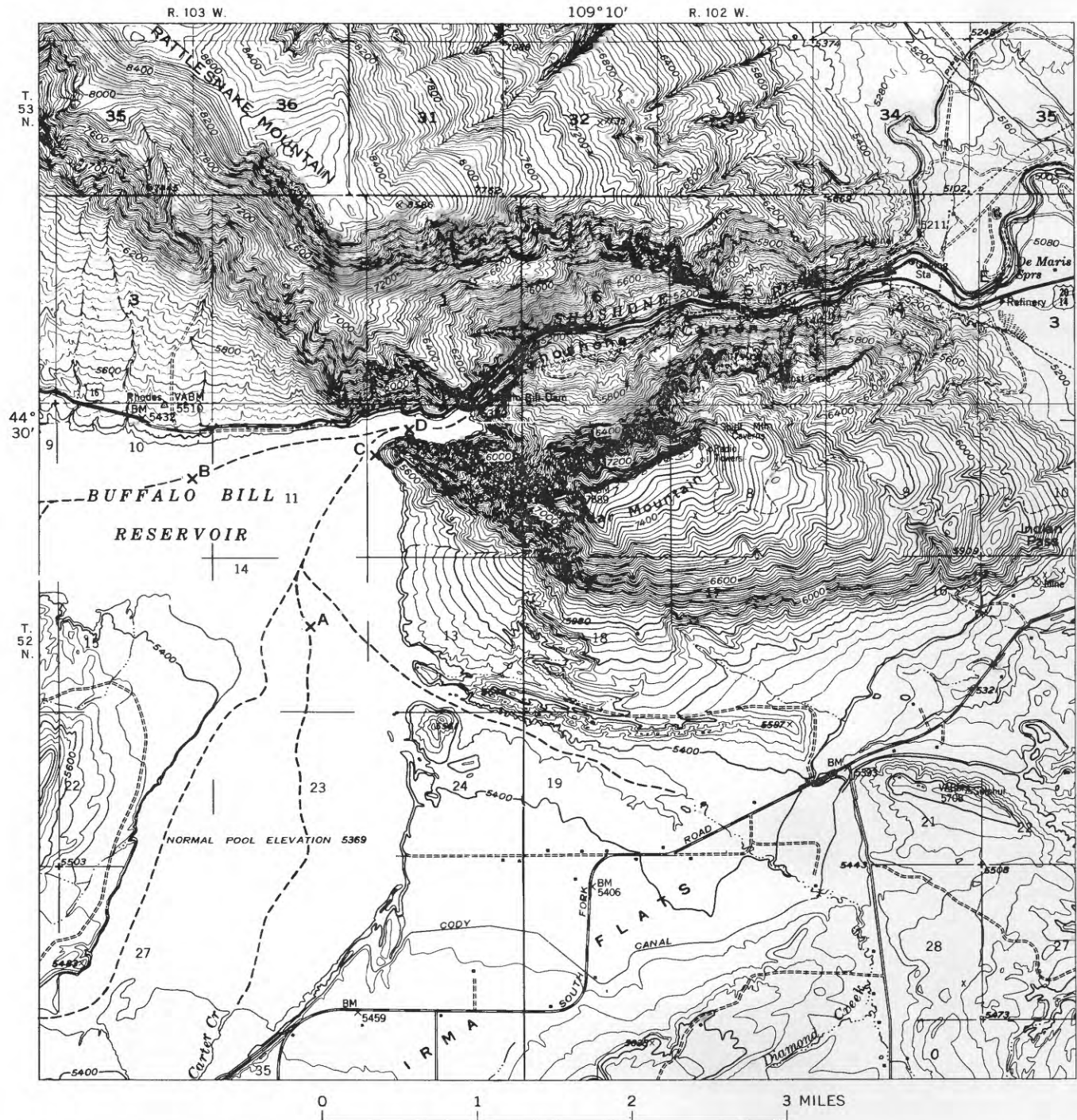


FIGURE 15.—Cedar Mountain oil seep (loc. C) and adjacent thermal localities near forks of the Shoshone River, reconstructed from data by Comstock (1875), Fisher (1906), and J. K. Rollinson (in Harris, 1952, p. 170). Indicated are: A, sulfur spring described by Comstock; B, extinct sulfur and iron spring described by Comstock; C, Colter's "great tar spring" described by Rollinson; D, hot-spring deposit mapped by Fisher; and E, De Maris sulfur springs at mouth of Shoshone Canyon. Heavy dashed lines indicate original stream courses prior to flooding by reservoir water. Base from U.S. Geological Survey Cody quadrangle, 1949, and Devils Tooth quadrangle, 1957.

North Fork and at the bottom of Cedar Mountain. The entire area has been at the bottom of Shoshone, or Buffalo Bill, Lake for more than forty years. The late J. K. Rollinson, who punched cattle on the upper Stinking Water before the irrigation dam was constructed in 1906, is authority for this statement. Mr. Rollinson described the boiling tar spring, which he saw several times, as being situated with several other hot-water springs that were surrounded by a number of small semi-geyser spouters.

Rollinson's statement, quoted by Harris (1952, p. 170), is as follows:

In the years prior to the government Shoshone Reclamation Project * * * there was a spring of water highly impregnated with sulphur and magnesium located on the extreme north end of the ranch then known as the Buffalo Meadows, which lay at the junction of the Forks of the Stinking Water River. There were also a half-a-dozen little "puffer" or semi geyser spouts * * * these small sulpho-sodium geysers which steamed up all the time and bubbled up mud and minerals. Then exactly at the very foot of Cedar Mountain close to these incipient geysers there was a forty foot cut bank or cave-in, and from the bottom of this came a considerable flow of asphaltum, which travelled by gravity about eighty feet before it disappeared for a few feet (about 30 feet) where it again appeared in one of the hot Sulpho-Magnesia Springs. While the temperature was (in my time) never hot enough to boil, still the gasses came up and gave the spring the bubbling appearance * * *. I suppose the temperature was about 90 degrees and with the foam and gas from the subterranean passage, it gave the complete effect of a boiling tar spring. This spring and all others on the side of Cedar Mountain were inundated by the impounding of the flood waters.

The various descriptions of the oil as "tar" or "asphaltum" by nontechnical observers suggest that it is much more like the viscous high-sulfur oils characteristic of Paleozoic rocks in the Bighorn Basin than like the typically lighter colored more fluid Cretaceous oils (Stone, 1967; Wenger and Lanum, 1954; open-file crude-oil analyses, Rocky Mountain regional office, Laramie Petroleum Research Center, U.S. Bureau of Mines). This is compatible with the interpretation that the "tar spring" emerged from Pennsylvanian or Permian rocks.

Fisher (1906) postulated that the origin of the hot water (he says about 98°F) in the sulfur springs which emerge chiefly from Permian rocks at locality E could be accounted for on the basis of thermal gradient. Woodruff (1908), however, disagreed. On the basis of his study of the sulfur deposits, he concluded (p. 454):

As the source of the water is not known, the cause of the heat remains undiscovered. There is no evidence of solfataric origin and the indications are that only a small amount of the heat is derived from chemical reactions, because but little of the material produced by chemical changes below is brought to the surface. It is known that intensive activity must necessarily take place to maintain the water at a temperature above 98°F., the temperature found in these springs. It is supposed, therefore, that the heat is derived from slowly cooling magmatic bodies, probably intrusions, and increased slightly by heat from chemical reactions.

Pierce (written commun., 1968), as well as Fisher, considered a thermal gradient as a sufficient explanation for the hot water. His interpretation used evidence of high temperatures in wells 5 miles to the southeast. Water heated by thermal gradient in the deep part of the Dry Creek syncline (Pierce and others, 1947; Zapp, 1956), 15 miles southeast of Cedar Mountain, could have flowed northwestward up the trough of the syncline, then divided, continued around both sides of Cedar Mountain, and emerged in the hot springs at localities A, B, C, and E (fig. 15). The temperature at De Maris Springs (loc. E) ranges from 75° to 100°F. No detailed figures are available on magnitude of flow, but one spring that formerly provided water for a swimming pool emitted 50-100 gallons per minute.

It is apparent that an interpretation of the geologic history of the Cedar Mountain area must include an explanation of the oil spring closely associated with the hot-water springs, sulfur, open conduits, and caverns. The hot-spring conduits would have to be so open that the observed volume of water could reach the surface rapidly enough to retain the heat acquired at depth, regardless of the nature of the heat source. Active solution of the Madison Limestone (Mississippian) has gone on for a long time, as is indicated by the location and elevation of an extensive network of caves, such as Spirit Mountain caverns and Frost Cave (Jones, 1875, p. 17; fig. 15, this rept.) on Cedar Mountain, more than 1,000 feet above the oil spring to the west and De Maris springs to the east.

It is probable that cavern solution began before the pyroclastic rocks were stripped from the area. At least locally, the caves developed first, and sulfur was then precipitated in them. For example, great bulbous masses of crystalline sulfur, forming stalactites and stalagmites, were encountered in some of the caves cut by the Bureau of Reclamation tunnel on the south side of the Shoshone Canyon, 200 feet or more above the present river level. Descriptions of this sulfur have not been published, but samples of the sulfur collected by Love in 1935 at the time the tunnel was being driven are in the University of Wyoming mineral collections.

It seems unlikely that these caves would have been formed by cold-water solution on an anticline that had hot springs emerging from both sides and that the sulfur found in the tunnel that cut these caves would be unrelated to the adjacent thermal phenomena.

In summary, the source of oil at locality C was probably Paleozoic rocks at a relatively shallow depth. The close association of the oil and sulfur with hot water suggests that all three were boosted to the surface together. The absence of oil from locality E might be accounted for by the emergence of these springs from

Paleozoic rocks that had previously been flushed of any oil that was originally present. On the other hand, oil may be present but could have been overlooked.

All these various shreds of evidence indicate or suggest a long and complex episode of solution and thermal activity, at least some of which is involved in the emergence of the oil. Sulfur isotope studies of the various occurrences of sulfur in the Cedar Mountain area may determine whether the deposits are of magmatic-hydrothermal or bacteriogenic origin. More detailed studies of the composition, temperature distribution, and flow of the thermal springs and of the adjacent wells should provide additional pertinent information.

CONCLUSIONS

Localities 1, 3, and 4 should be studied in detail before they are destroyed or damaged further and vital evidence is lost. As the foregoing discussion indicates, data are not sufficient as yet at any locality to justify unequivocal conclusions about the origin or the geochemical processes involved in emplacement of the oil. Nevertheless, the data are so encouraging that they provide impetus for detailed studies which may lead to a reasonable explanation for these occurrences. It is pertinent to consider whether the problems of origin and emplacement of oil in thermal areas are worth investigating. We think they are. The literature on origin and emplacement of hydrocarbons in general is voluminous, and research on these subjects is continually expanding. However, oil in thermal areas is rare and in most places has not been studied in detail. These occurrences may offer previously overlooked clues as to the role of heat in natural processes of oil extraction from source rocks, the subsequent migration and emplacement of the oil, and the changes that occurred in it along the route.

The five described occurrences of oil in thermal areas are the only ones of any type that are known to us in this part of Wyoming. This suggests that hot water is an integral part of the process that liberates the oil from the source sediments adjacent to the hot-water conduits. The primary source of heat at localities 1 and 3 is believed to be igneous rocks or possibly magma at depth.

Publication of descriptions of the known localities will, hopefully, result in the discovery of additional ones that will broaden our knowledge of what types of phenomena are related to oil in thermal areas, what characteristics can be predicted for these occurrences, and how the data can be utilized elsewhere.

Locality 1 (Calcite Springs) shows evidence that there were periods of spasmodic outflow of oil, separated by periods of quiescence. Observations of these

petroliferous vents over a considerable period of time may show whether these intervals of outflow are related to earthquakes. If such a relation is established, the remnants of semilithified and partly buried old oil flows here and perhaps in other areas may give clues to the age, magnitude, and frequency of prehistoric earthquakes. It is possible that the youngest flow at Calcite Springs, now rapidly breaking up, may have been formed at the time of the severe earthquake of 1959 in and near Yellowstone National Park.

The source of the abundant sulfur at localities 1 and 4 has not been explained. When studies of other sulfur occurrences in Yellowstone National Park and areas to the east are assembled, the significance of those associated with oil may become more apparent.

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