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GEOLOGICAL SURVEY

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EVALUATION OF CORE DATA, PHYSICAL PROPERTIES, AND OIL YIELD, USBM/AEC COLORADO CORE HOLE NO. 3 (BRONCO BR-1)

by

John R. Ege, R. D. Carroll,
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This report is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards and nomenclature.

Illustrations

Tables

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ABSTRACT

USBM/AEC Colorado Core Hole No. 3 (Bronco BR-1) is located in the SW¼SW¼SW¼ sec. 14, T. 1 N., R. 98 W., Rio Blanco County, Colorado. The collar is at a ground elevation of 6,356 feet. The hole was core drilled between depths of 964 and 3,325 feet with a total depth of 3,797 feet. The hole was drilled to investigate geologic, geophysical and hydrological conditions at a possible in situ oil-shale retorting experiment site. The drill hole passed through 1,157 feet of alluvium and the Evacuation Creek Member of the Green River Formation, 1,603 feet of the Parachute Creek Member and penetrated into the Garden Gulch Member of the Green River Formation. In-hole density log/oil yield ratio interpretation indicates that two oil-shale zones exist which yield more than 20 gallons of shale oil per ton of rock; an upper zone lying between 1,271 and 1,750 feet in depth and a lower zone lying between 1,900 and 2,964 feet. Halite (sodium chloride salt) is found between 2,140 and 2,185 feet and nahcolite (sodium bicarbonate salt) between 2,195 and 2,700 feet. Nahcolite was present at one time above 2,195 feet but has been subsequently dissolved out by ground water. The core can be divided into six structural units based upon degree of fracturing. A highly fractured interval is found between 1,646 and 1,899 feet, which coincides with the dissolution or leached nahcolite zone. Physical property tests made on core samples between 1,356 and 3,253 feet give average values of 11,988 psi for uniaxial compressive strength, 1.38×10^6 psi for static Young's modulus and 11,809 fps for compressional velocity.

GEOLOGY

By

John R. Ege

Introduction

The San Francisco Operations Office of the Atomic Energy Commission (SAN/AEC) requested that the U.S. Geological Survey investigate and interpret the geologic, geophysical and hydrological conditions at the USBM/AEC Colorado Core Hole No. 3 (Bronco BR-1) site. The drill hole is located in the SW1/4SW1/4SW1/4 sec. 14, T. 1 N., R. 98 W., Rio Blanco County, Colorado (fig. 1) at a ground elevation of 6,356 feet above sea level.

The hole, with a total depth of 3,797 feet, was core drilled between depths of 964 and 3,325 feet (G. F. Dana, U.S. Bureau of Mines, oral commun., January 1968).

Lithology of core

Approximately 2,360 feet of core was examined for lithologic and structural features (table 1, in pocket). The core consists of marlstone with varying amounts of kerogen (oil shale), siltstone, sandstone, claystone, dolomite, and tuff. Halite beds (sodium chloride salt) are found between 2,140 and 2,185 feet in depth and range between 2 inches and 2 feet in thickness. Abundant nahcolite (sodium bicarbonate salt) is present between 2,195 and 2,700 feet in depth. The nahcolite is present as fillings in vugs that are as large as 6 inches in diameter and also as beds that are as much as 2.5 feet thick. The color of the core ranges from yellowish gray to dusky brown.

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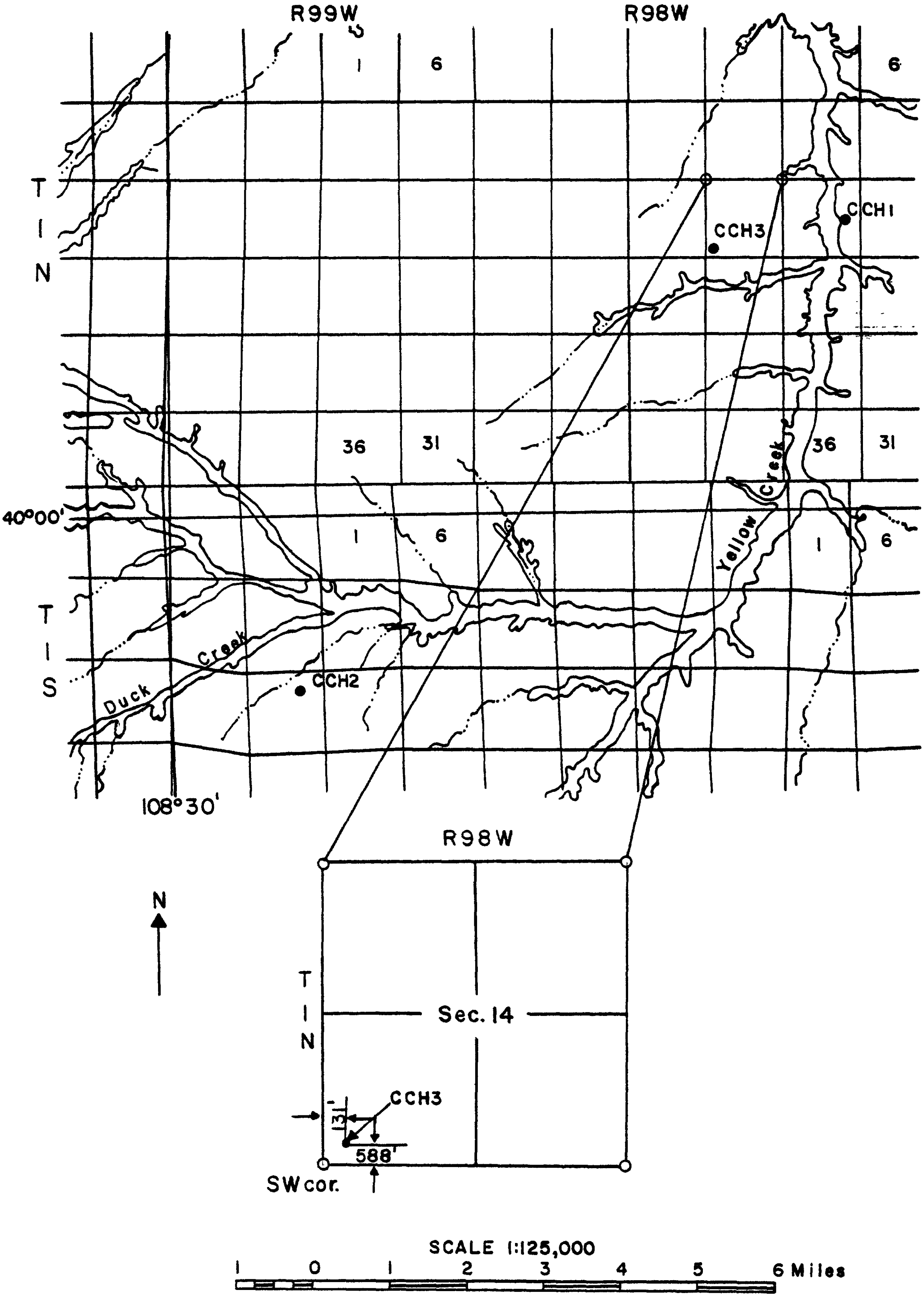

Figure 1.--Location map of USBM/AEC Colorado Core Holes 1, 2 and 3.

The continuous oil-shale section in the core starts at about 1,157 feet in depth and marks the approximate contact between the Evacuation Creek and the Parachute Creek Members of the Green River Formation (J. R. Donnell, U.S. Geol. Survey, oral commun., 1968). The core taken from the overlying Evacuation Creek Member consists mainly of siltstone, sandstone, sparse marlstone and interbedded tuff. The Parachute Creek Member consists generally of kerogenous marlstone (oil shale) with some interbedded siltstone, sandstone and tuff. The bulk of the oil-shale section is in the Parachute Creek Member. In the terminology of the U.S. Bureau of Mines, oil shale in the Piceance Creek Basin is defined as kerogenous marlstone that yields at least 3 gallons of shale oil per ton of rock (L. Trudell, USBM, oral commun., 1966). Interpretation of the in-hole density log indicates that "rich oil shale," that is, oil shale yielding more than 20 gallons per ton, is found in two zones. An upper zone lying between 1,271-1,750 feet in depth and a lower zone lying between 1,900-2,964 feet. The lower zone is the one being considered for the Bronco experiment.

Joints in the core were examined and preliminary results show that joint fillings consist of carbonate, halite, pyrite, iron oxide and minor amounts of gilsonite (asphalt). Pyrite and gilsonite are found as joint fillings in the interval between 964-1,254 feet in depth. Iron staining is found in the intervals between 1,060-1,200 and 1,475-2,000, indicating oxidation of iron minerals at these depths. Halite fillings are found between 2,000-2,250 feet and carbonate fillings between 1,300-3,200 feet in depth.

Structural and engineering properties of the core

The three criteria used to describe the structural condition of the core are: (1) joint frequency (average number of joints per foot of core), (2) lost core (in percent) and (3) broken core (in percent), or core that is fragmented into pieces less than 3 inches in length by faults, shears, vug collapse or closely spaced joints. In addition, the number of bedding plane fractures, either natural or induced by drilling stresses, were recorded. The bedding plane fractures were noted to provide an estimate of the ease of parting along bedding planes through the length of the drill hole.

An "index number," a numerical representation of the (1) joint frequency, (2) core loss and (3) broken core for 50± foot lengths of core, describes the engineering character of the core (tables 1 and 2). An increase in the numerical value of the "index number" is indicative of a corresponding increase in joint frequency, broken core, and core loss and, therefore, a decrease in the competency of the rock.

The index number is calculated by summing the joint frequency (number of joints per foot of core) with one-tenth (0.1) the amount (in percent) of broken core per foot and lost core per foot into one significant figure.

The broken core and lost core values, which vary between 0-100 percent, are reduced to one-tenth (0.1) so as to keep all figures used in calculating the index number within the range of 0-10. Experience has shown that joint frequency values also range between 0-10 joints per foot. The reason for reducing the lost core and broken core to the 0-10 range is to avoid weighting these values unrealistically at the expense of joint frequency.

Table 2.--Structural properties of units A through F and (A' through F') USBM/AEC Colorado Core Hole No. 3 (Bronco BR-1), Rio Blanco County, Colorado (see fig. 2)

Unit	Core interval (feet)	Thickness (feet)	Average joint frequency (joints/foot)	Average broken core (percent)	Average core loss (percent)	Average index number 1/	Comments
A	964 - 1,153	189	2.5	34	4	6.3	Units A through F include bedding plane fractures in the joint frequency count.
B	1,153 - 1,352	199	2.5	14	4	4.3	
C	1,352 - 1,646	294	1.6	33	16	6.5	Average index numbers for Units A through F are taken from the lower curve in figure 2.
D	1,646 - 1,899	253	3.2	43	30	10.5	
E	1,899 - 2,749	850	1.4	2	5	2.1	
F	2,749 - 3,302	553	1.8	8	5	3.1	
A'	964 - 1,153	189	0.80	34	4	4.6	Units A' through F' do not include bedding plane fractures in the joint frequency count. Comparison of the index number from the equivalent core intervals given above may indicate what influence, if any, bedding planes will have on rock competency. The further the index numbers from comparable units diverge from each other might signify an increasing role that bedding planes will have on rock fracturability.
B'	1,153 - 1,352	199	0.50	14	4	2.3	
C'	1,352 - 1,646	294	0.40	33	16	5.3	
D'	1,646 - 1,899	253	0.20	43	30	7.5	
E'	1,899 - 2,749	850	0.08	2	5	0.8	
F'	2,749 - 3,302	553	0.10	8	5	1.4	Average index numbers for units A' through F' are taken from the upper curve in figure 2.

1/ Index number = joint frequency + 0.1 X pereent of broken core + 0.1 X percent of lost core. Example: Unit A index number = 2.5 + 3.4 + 0.4 = 6.3.

An increase in number is indicative of an increase in the number of fractures in the rock and, therefore, a decrease in the competency of the rock.

In calculating the index number the values for percent of broken core and lost core (range 0-100) were reduced to 0.1 of their original values. This was done for two reasons: (1) to keep all values (joint frequency, broken core and lost core)within the range of 0-10 and (2) to avoid unrealistically weighting the broken core and lost core number values at the expense of the joint frequency number value. Joint frequency values normally range between 0-10.

The following is an example of an index-number calculation for unit A (table 2).

Thickness of interval drilled	189 feet
Amount of recovered core	182 feet
Number of joints and bedding plane fractures in 182 feet of core	461
Amount of broken core	62 feet

Recovered core (percent) = $\frac{182}{189}$ X 100 = 96

Lost core (percent) = (1.00-0.96) X 100 = 4

Joint frequency = $\frac{461}{182}$ = 2.5

Broken core (percent) = $\frac{62}{182}$ X 100 = 34

Index number = joint frequency + 0.1 X percent of broken core + 0.1 X percent of lost core

Index number = 2.5 + 0.1(4) + 0.1(34) = 2.5 + 0.4 + 3.4 = <u>6.3</u> .

Two index numbers have been calculated for each increment of logged core. One set of index numbers includes the number of bedding plane fractures as part of the joint frequency count (units A through F). A second set of index numbers (A' through F') excludes the bedding plane fractures in the joint frequency count. The two sets of index numbers, therefore, provide a numerical comparison of the number of partings observed along bedding throughout the length of core.

Figure 2 shows the two index numbers for each approximate 50-foot increment in depth, plotted as cumulative percent curves against depth. The plots indicate that the steeper the curve, the more fractured--and less competent or weaker--the rock. The lower curve includes bedding plane fractures in the joint frequency count, and the upper curve excludes bedding plane fractures. A comparison of the two curves may give an indication of the influence of bedding planes on the fracturability of the rock. By marking off changes in the slope of the curves, one can divide the interval from 964 to 3,302 feet into units, referred to as structural or engineering units. Each unit, therefore, represents a different class of structural conditions. Figure 2 shows that USBM/AEC Colorado Core Hole No. 3 has six structural units, A-F (or A'-F'), indicating six changes in engineering properties of the rock between 964-3,302 feet in depth.

Unit A (964-1,153 feet) has an average index number of 6.3, and is characterized by a moderately high percent (34 percent) of broken core (fig. 3). Comparison of Unit A with the average index number of its counterpart unit A' at 4.6, shows a 27 percent decrease in the value of the index number. This suggests that bedding plane fractures have a minor influence on the fracturability of the rock in this zone. Unit A consists mainly of siltstone, sandstone and silty marlstone and lies in the Evacuation Creek Member.

Unit B (1,153-1,352 feet) has an index number of 4.3 and has a moderate amount (14 percent) of broken core (fig. 4). It lies in the upper part of the Parachute Creek Member and consists of oil shale with thin interbeds of ash-fall tuff and sandstone. The Mahogany marker, a diagnostic

Figure 3.--Oil shale core from Unit A (1,054.1 to 1,102.8 feet)

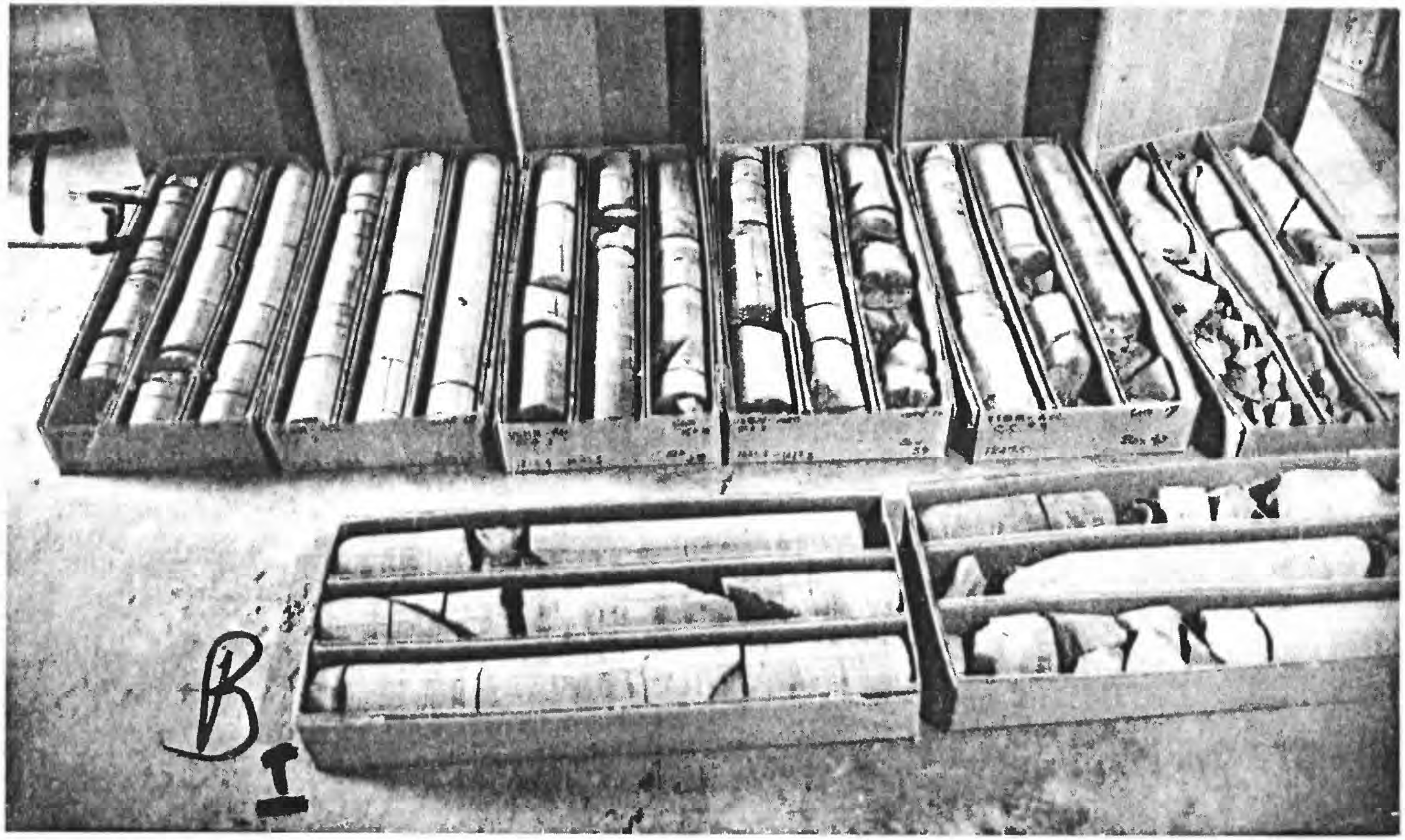

Figure 4.--Oil shale core from Unit B (1,202 to 1,254 feet)

tuff bed, is in this zone. The index number for Unit B' at 2.3, is 46 percent less than that of Unit B, indicating that bedding plane fractures will probably have some influence on fracturing of the rock.

Unit C (1,352-1,646 feet) has an index number of 6.5 and is characterized by moderate core loss (16 percent) and moderately high (33 percent) broken rock (fig. 5). Nahcolite vugs, which occur throughout this interval, collapse under drilling stress. The broken core in large part is due to these collapsed vugs. The index number for C' (5.3) is 18 percent lower than for C (6.5), and shows that bedding plane fractures do not contribute much to the fracturing of the rock.

Unit D (1,646-1,899 feet) has an index number of 10.5. It is characterized by a combined high percentage of lost core (30 percent) and broken core (43 percent) and moderately high joint frequency (3.2 joints per foot) (fig. 6). Unit D includes the zone, variously called the leached, dissolution, fractured or poor recovery zone in other drill holes which can be traced throughout this part of the Piceance Creek Basin. Abundant halite beds and nahcolite-filled vugs or beds, which in large part have been leached, are typical of this zone. [redacted] Iron staining on the core suggests that water is or has been present in Unit D. Comparison of the D (10.5) and D' (7.5) index numbers (a decrease of 29 percent) shows that bedding plane fractures do not contribute much to fracturing of the rock at these depths.

Unit E (1,899-2,749 feet) has an index number of 2.1. This interval has low values of lost core, broken core and joint frequency and is a competent and relatively unfractured rock that yields continuous core lengths as long as 5 feet (fig. 8). Unit E embraces most of the lower

Figure 5.--Oil shale core from Unit C (1,452 to 1,498 feet)

Figure 6.--Oil shale core from Unit D (1,748 to 1,802 feet)

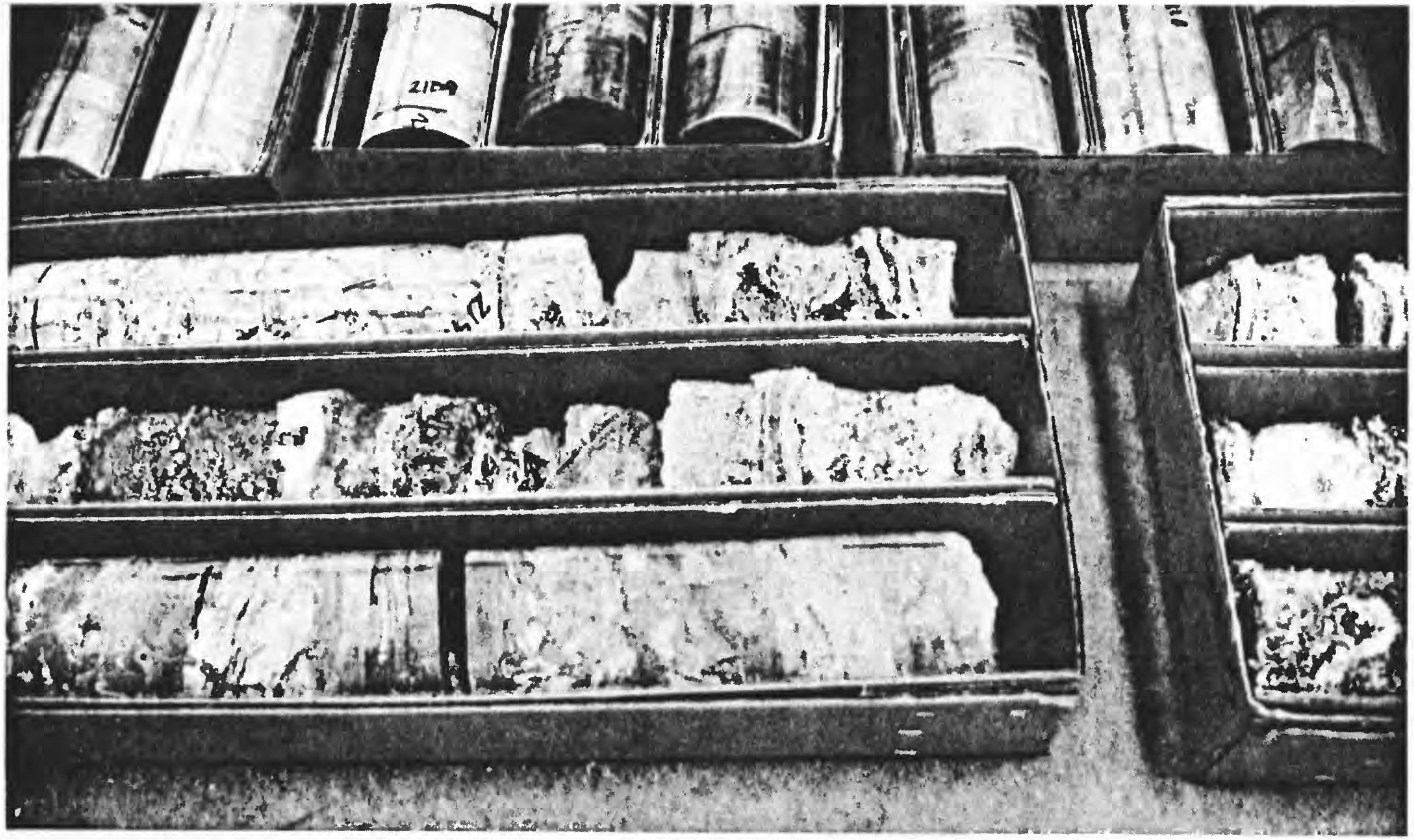

Figure 7.--Halite beds in the oil shale core (2,141 to 2,149 feet)

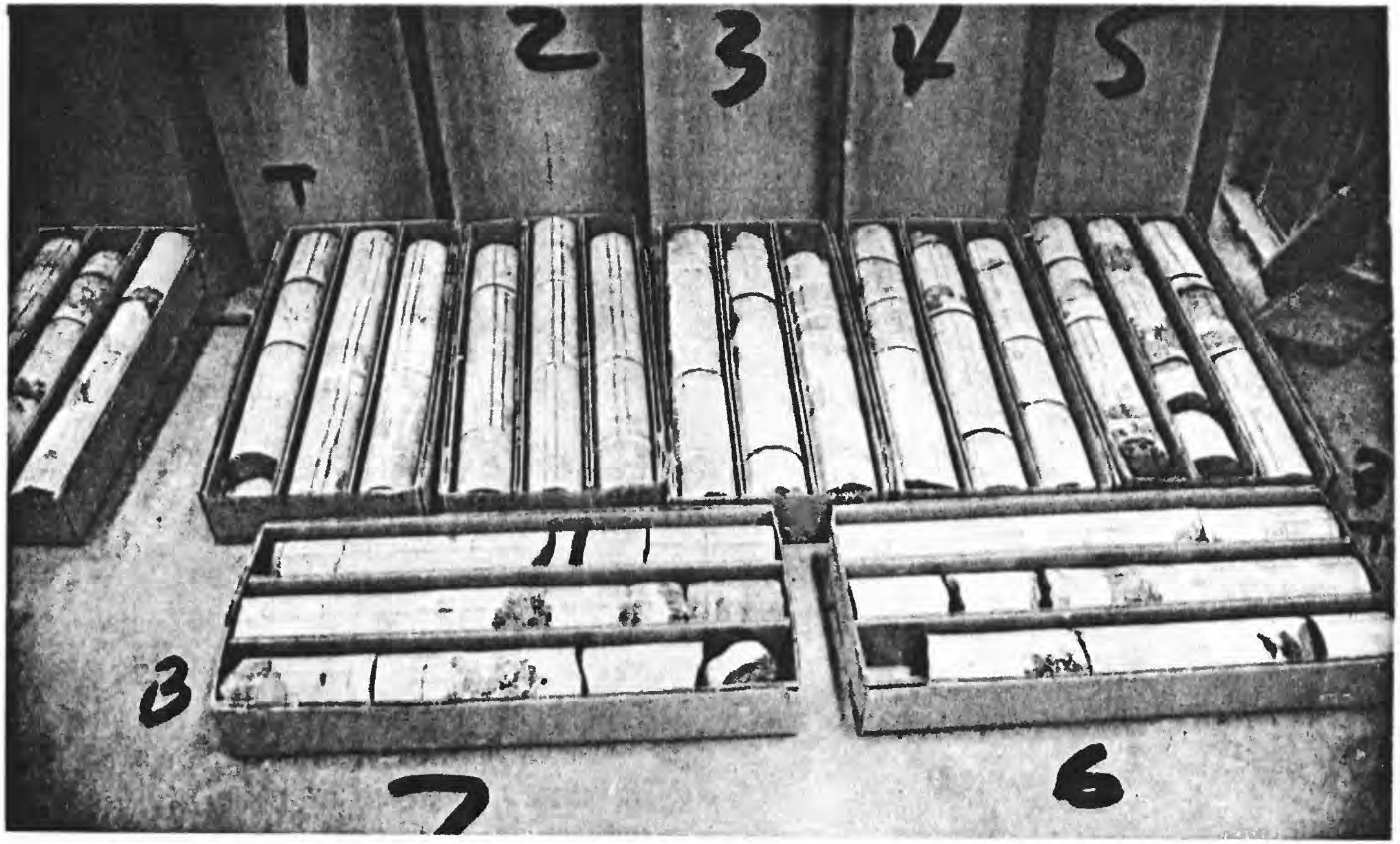

Figure 8.--Oil shale core from Unit E (2,401 to 2,450 feet) Nahcolite filled-vugs appear as dark circular inclusions

"rich oil shale" zone and includes beds of nahcolite and halite (fig. 7). A decrease of 62 percent between E' (0.8) and E (2.1) index numbers indicates that most of the fractures observed in the core were caused by separation along bedding planes.

Unit F (2,749-3,302 feet) has an index number of 3.1, has low values of lost core and broken core, and contains few natural joints. Unit F is characterized by zones of claystone that readily separate along incipient bedding planes into disks ranging between one-fourth inch and 2 inches in thickness (fig. 9). Unit F is found below the Blue marker, a horizon that appears on resistivity logs, and lies in the upper part of Garden Gulch Member. A decrease of 55 percent between the F' (1.4) and F (3.1) index numbers indicates that the majority of fractures in this zone are along bedding planes.

The general rule for fracturability is this:
Of the two average index numbers for units A-F (A'-F')--the number for A-F in all cited cases is larger than for A'-F'. The percentage decrease from A-F to A'-F' is either comparatively large (55 percent from Unit F to F') or comparatively small (18 percent from Unit C to C'). When the difference is comparatively large it can be presumed that bedding plane fractures exerted a major influence on the fracturability of the core; when the difference is small the bedding plane fractures exerted only a minor influence on the fracturability.

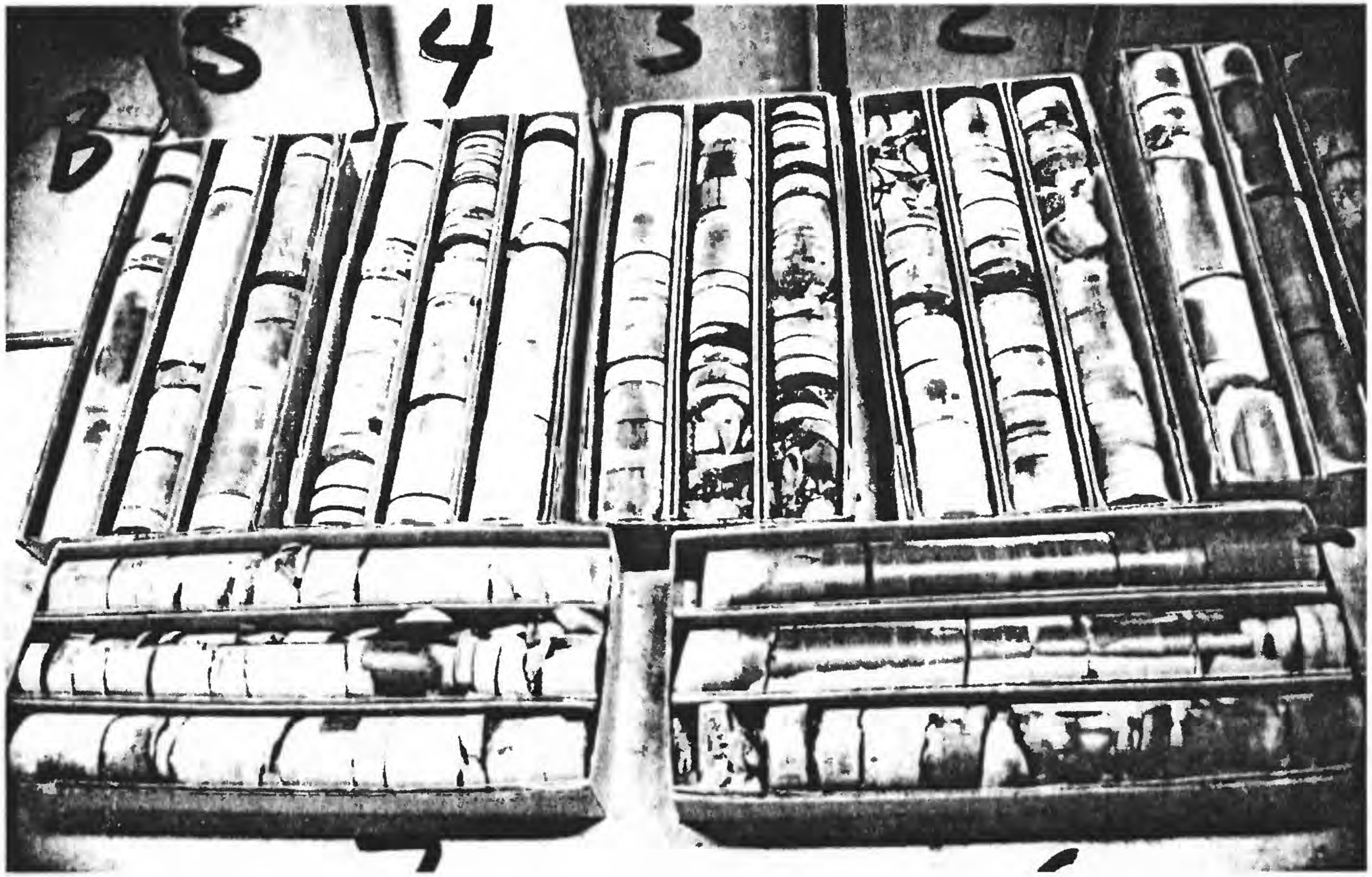

Figure 9.--Oil shale core from Unit F (3,150 to 3,199 feet)

Physical properties

Table 3 presents the results of physical property tests made on dry core samples collected between 1,356 and 3,253 feet in depth. The samples represent rock from structural units C through F and include oil shale, sandstone, claystone and dolomite.

The oil shale can be classified as a medium strength-low elastic modulus ratio rock (Deere and Miller, 1966 p. 136). A medium strength rock is defined as having a uniaxial compressive strength that ranges from 8,000 to 16,000 psi. A low modulus ratio rock is defined as having a modulus ratio of less than 200, that is, $\frac{E_r}{\sigma_a} < 200$, where E_r = tangent static Young's modulus at 50 percent ulitmate strength, and σ_a = uniaxial compressive strength.

Correlation of Colorado Core Hole No. 3 with Colorado Core Hole No. 1

Figure 10 is a cross section showing the structural and oil-yield relation between Colorado Core Hole No. 3 (Bronco BR-1) and Colorado Core Hole No. 1 sites. The six structural units, A through F, are recognized in both holes. This suggests that the structural zones are continuous between the two sites. A rich oil-shale zone (greater than 20 gallons per ton), is present in the lower half of each hole, indicating that a minimum thickness of 1,000 feet of economic oil shale exists in the region between the two holes. The difference in elevation between the tops of the rich oil shale zone is about 230 feet (4,456 feet at Hole No. 3 and 4,223 feet at Hole No. 1) and shows the trend of a subsurface basin in the area that deepens in the direction of Colorado Core Hole No. 1.

Comparison of the cores and geophysical logs from Holes No. 1 and No. 3 shows that (1) subsurface features can be classified; (2) the stratigraphy and structure are relatively uniform between the two drill holes; and (3) reasonable predictions for the area can be made in terms of oil yields and structural conditions.

Conclusions

USBM/AEC Colorado Core Hole No. 3 (Bronco BR-1) penetrated 1,157 feet of alluvium and the Evacuation Creek Member, 1,603 feet of the Parachute Creek Member and went into the Garden Gulch Member of the Green River Formation.

Based upon in-hole density log interpretation, the thickest zone of rich oil shale (greater than 20 gallons per ton rock) lies between approximately 1,900-2,964 feet in depth or 4,456-3,392 feet in elevation. An oil-shale section of about 1,000 feet in thickness that ranges between 25 and 30 gallons per ton shale oil is thus provided. The oil-yield values are preliminary and will be verified by Fischer assays that will be published by the U.S. Bureau of Mines.

Examination of about 2,361 feet of core, between 964-3,325 feet in depth, indicated that the core could be divided into six structural units, on the basis of the degree of fracturing of the rock. The zones of most concern for the *in situ* oil-shale experiment are (1) Unit D (1,646-1,899 feet in depth) which lies in a strongly fractured section containing many leached nahcolite vugs, and is for the most part incompetent rock; and (2) Unit E (1,899-2,749 feet) which lies in the lower rich oil-shale section and is a competent unfractured rock.

Physical property tests of samples taken from unit E (1,899-2,749 feet in depth), which contains the bulk of the lower "rich oil shale" section, classify the oil shale as a moderate strength-low elastic modulus ratio rock having an average uniaxial compressive strength of 10,250 psi and an average static Young's modulus of 0.68 X 10^6 psi.

Comparison of the core from Colorado Core Hole No. 3 with Colorado Core Hole No. 1, located about 9,200 feet ENE of Hole No. 3, indicates that subsurface geologic conditions are likely to be fairly constant between the two sites.

GEOPHYSICAL LOGS--ESTIMATE OF OIL YIELD

By

R. D. Carroll

The geophysical logs obtained in Colorado Core Hole No. 3 are shown on figure 11, along with pertinent horizons penetrated by the hole. Discussions of the log responses and methods of calculating oil yield have been presented in previous reports (Carroll and others, 1967; Ege and others, 1967). Estimates of oil yield based on geophysical logs and actual yields as determined by retort analyses are shown in table 4. These data are for the two previous BRONCO exploration holes and indicate that the equations of Bardsley and Algermissen (1963) afford reliable estimates of oil yield to a first approximation. Although numerous

Table 4.--Comparison of oil yields estimated from geophysical logs with Fischer analyses for USBM/AEC Colorado Core Holes No. 1 and No. 2

Interval (feet)	Thickness (feet)	Average log density (g/cc)	Average sonic log travel time (μ sec/ft)	Average oil yield (gallons/ton)[1]		
				Density log	Sonic velocity log	Fischer assay (unweighted average)
Colorado Core Hole No. 1						
986 - 1,100	114	2.35	(87)	14.8	14.3	14.5
1,100 - 1,184	84	2.19	(105)	25.2	28.5	28.7
1,184 - 1,354	170	2.32	91	16.8	17.6	[2] 17.9/13.5
1,354 - 1,554	200	2.25	101	21.3	24.9	20.7
1,554 - 1,770	216	2.37	86	13.4	13.5	10.6
1,770 - 1,876	106	2.23	(93)	22.6	18.8	21.1
1,876 - 1,996	120	2.25	96	21.3	21.1	21.2
1,996 - 2,100	104	2.24	88	22.0	15.2	17.5
2,100 - 2,210	110	2.23	92	22.6	17.6	20.6
2,210 - 2,340	130	2.12	115	29.8	37.5	33.5
2,340 - 2,456	116	2.23	96	22.6	20.9	21.4
2,456 - 2,600	144	2.27	109	20.0	32.4	23.4
Colorado Core Hole No. 2[3]						
1,130 - 1,260	130	2.30	84	18.1	12.5	14.7 Top of continuous oil shale at 1,120
1,260 - 1,580	320	2.17	102	26.5	25.8	[2] 25.6/24.0
1,580 - 1,710	130	2.24	103	22.0	26.8	20.3
1,710 - 1,870	160	1.98	123	38.9	45.4	37.2
1,870 - 2,110	240	(?)	115?	(?)	37.5?	36.3 Highly erratic log response due to combination of thin beds and hole rugosity. Gross estimate based on "smoothing".
2,110 - 2,160	50	(No valid interpretation possible due to excessively caved hole)				37.5

[1] Relationships between density and sonic velocity log values and oil yield are based on data of Bardsley and Algermissen (1963).

[2] No Fischer retort assays available for low-yield samples from "B groove" (1,240.2'-1,268.0' not assayed in No. 1, and 1,392.0'-1,410.0' not assayed in No. 2); first number is unweighted average of assays excluding the "B groove," and second number in unweighted average for entire interval assuming the "B groove" samples contain 2 gallons per ton.

[3] Depth reference in USBM/AEC Colorado Core Hole No. 2 is from the Kelly bushing, 11 feet above ground level.

investigators report the density log/oil yield relationship only, here the sonic-log-determined yield is also reported because it has not yet been determined to what precision either log can be used to calculate oil yield in the deeper oil-shale section of the Piceance Creek Basin.

The oil-yield assays based on geophysical log data for Core Hole No. 3 are listed in table 5.

In two intervals the estimates of oil yield, as determined by sonic and density logs, differ by a significant amount--the interval 2,209 to 2,280 feet and the interval 2,964 to 3,142. The former is in the overlap section where logging runs were interrupted. The latter is in a different lithologic formation, where the lithology [redacted] is described as more clayey (claystone) than is normal for the oil shale (kerogenous marlstone) of the Parachute Creek Member, table 1. This lithologic difference may result ina lower sonic velocity than is normal for oil shale in the Parachute Creek Member and consequently lead to higher estimates of oil yield. The possibility also exists that the density log relationship is also invalid in this latter interval. Confirmation will have to await the results of actual retort analyses.

The estimates of oil yield determined from geophysical logs listed in table 5 indicate that the oil shale penetrated by Core Hole No. 3 contains, in general, greater than 25 gallons of oil per ton. The richest continuous interval in the hole appears to be that lying between 1,900 and 2,964 feet. This interval probably averages around 25 gallons of oil per ton of shale or greater.

Table 5.--Average oil yield estimates determined from geophysical logs of oil shale section in USBM/AEC Colorado Core Hole No. 3 (Bronco BR-1, Rio Blanco County, Colorado

Interval (feet)	Length (feet)	Average density (g/cc)	Average sonic travel time (μ sec/ft)	Average oil yield (gallons/ton)	
				Density log	Sonic log
1,158 - 1,271	113	2.33	84.8	16.1	12.8
1,271 - 1,469	198	2.22	102.4	23.3	26.3
1,469 - 1,750	281	2.25	97.2	21.3	22.0
1,750 - 1,900	150	2.37	89.0	13.5	15.8
1,900 - 2,209	309	2.17	100.7	26.5	24.9
1/ 2,209 - 2,280	71	2.27	85.0	20.0	12.9
2,280 - 2,964	684	2.13	115.2	29.2	37.7
2/ 2,964 - 3,142	178	2.41	106.3	10.9	29.6

1/ Interval between two logging runs.

2/ Dominantly claystone as opposed to marlstone in overlying intervals.