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STRATIGRAPHY AND NAHCOLITE RESOURCES OF THE SALINE FACIES OF THE GREEN RIVER FORMATION, RIO BLANCO COUNTY, COLORADO

By John R. Dyni

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CONVERTING MEASUREMENTS TO METRIC EQUIVALENTS

To convert	*to this*	*multiply by*
feet	metres	0.3048
inches	centimetres	25.4
square miles	square kilometres	2.6
acres	hectares	0.4047
gallons	litres	3.785

STRATIGRAPHY AND NAHCOLITE RESOURCES OF THE SALINE FACIES OF THE GREEN RIVER FORMATION, RIO BLANCO COUNTY, COLORADO

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ABSTRACT

Based on a study of 10 drill cores, a sequence of oil shale and associated nahcolite, nearly 2,000 feet thick, in the lacustrine Green River Formation (Eocene) in the Piceance Creek basin, Rio Blanco County, Colo., was divided in ascending order into zones 1 to 13, B-groove, Mahogany zone (with lower, middle, and upper parts), and A-groove at the top. The odd-numbered zones and the Mahogany zone are mappable subsurface units of relatively thick oil shale and are distinguished from the even-numbered zones and A- and B-grooves which are thinner units of oil shale of lower grade.

Large amounts of nahcolite found in zones 5 to 12 occur in (1) coarse-grained crystalline aggregates scattered through oil shale, (2) laterally continuous units of fine-grained crystals disseminated in oil shale, (3) brown microcrystalline beds, and (4) white coarse-grained beds that grade laterally into halitic rocks toward basin center. The original upper limit of the nahcolite and halitic rocks is not yet completely known, but the present top is marked by a dissolution surface. Above this surface the rocks, extending from zones 11 or 12 upward into the Mahogany zone, form a water-saturated "leached zone," a geohydrologic unit in which large amounts of water-soluble minerals probably mostly nahcolite and halite, were removed by ground-water dissolution. Rocks in the leached zone, mostly oil shale, are commonly broken and fractured and contain crystal cavities and solution breccias. Several solution breccias can be traced laterally into unleached beds of nahcolite and halite. Although evidence of salines is found in rocks above A-groove, the original saline facies that includes most of the bedded deposits extends from zone 5 upward into A-groove.

Potentially minable beds of white nahcolite as much as 12 feet thick are found at depths of 1,560 or more feet below the surface. Some thicker beds of high-grade nahcolite are believed to be too close to the dissolution surface for safe room-and-pillar mining. Probably the most economical method of mining nahcolite would be as a coproduct of a shale-oil industry. Removal of nahcolite prior to retorting increases significantly the grade of oil shale by as much as 1.6 times. Several zones are more than 300 feet thick and average 30 or more weight percent nahcolite. Resources of nahcolite per square mile range as high as 489 million short tons. The total nahcolite resource in the basin is conservatively estimated at 32 billion short tons, which makes it the second largest deposit of sodium carbonate known in the world.

INTRODUCTION

Hite and Dyni (1967), and Trudell, Beard, and Smith (1970) have shown that the saline facies of the Green River Formation in the Piceance Creek basin, northwest Colorado, contains halite and several types of nonbedded and bedded nahcolite and that some units of nahcolite have considerable lateral extent in the subsurface. No detailed stratigraphic study of the saline facies, however, has been made.

In this investigation cores from 10 drill holes that penetrate the saline facies were examined and analyzed. The main objectives were to differentiate among the several types of nahcolite, to identify and correlate mappable subsurface units of nahcolite and halite, and to divide the deposits of sodium minerals and oil shale into a series of mappable stratigraphic zones. Several hundred feet of oil shale that underlies the saline facies was also included in this study because these rocks are a part of the total resource. In addition, shale-oil and nahcolite resource data for the 10 drill cores are presented.

The 10 core holes selected for study lie within an area of about 40 square miles in the northern part of the Piceance Creek basin in T. 1 N., R. 98 W., T. 1 S., Rs. 97 and 98 W., and T. 2 S., R. 98 W., Rio Blanco County, Colo. The core hole locations are shown on the index map on figure 1 and are described under the headings for the core holes shown on figures 1 and 2. Core holes C1, C2, C5, C153, C154, C155, and C156 were drilled by several companies and individuals under Federal sodium prospecting permits between 1964 and 1966. Core hole C34 was drilled by the U.S. Bureau of Mines and the U.S. Atomic Energy Commission in 1965 and 1966 to evaluate the oil-shale deposits in the northern part of the basin. Core holes C177 and C179 were drilled by Shell Oil Co. in 1968 to evaluate the oil-shale deposits on Federal lands being considered for lease under the Department of Interior's first oil-shale lease program.

Most cores were sawed lengthwise and one-quarter of the core was crushed and ground to the size required by the method of analysis. Each sample represents about a 2-foot length of core except those from core holes C1 and C156 which represent a somewhat larger average sample interval, and those from core hole C34 which represent between 1 and 2 feet of core. The 2-foot sample intervals for core holes C5, C177, and C179 were chosen arbitrarily whereas the sample intervals for the other seven core holes were determined mostly by changes in lithology.

Most samples were analyzed for nahcolite and shale-oil content. Quantitative nahcolite analyses were made in the U.S. Geological Survey laboratories using the thermal method of Dyni and others (1971). Shale-oil analyses were made by the modified Fischer assay technique of Stanfield and Frost (1949). Eight of the 10 drill cores were analyzed for shale-oil by the Laramie Energy Research Center, U.S. Bureau of Mines, and two cores (C177 and C179) were analyzed for shale-oil by the Colorado School of Mines Research Foundation, Golden Colo.

Histograms of the shale-oil and nahcolite analyses, drawn mechanically by a computer-controlled plotter, are shown for each core hole on figures 1 and 2. The cores were examined visually and written descriptions of several cores were prepared. The use of the shale-oil histogram in conjunction with a photolog of the core was found to be the most useful combination for studying the detailed stratigraphy of the saline facies. The method of preparing a photolog is briefly described.

Most cores were sawed lengthwise in half and were boxed in 2-foot lengths with 10 feet of core per box. Two boxes of core with labels showing depths were photographed with black-and-white film, and glossy prints enlarged to 1:30 scale were made. These prints were trimmed and attached along their sides, accordion fashion, with cloth tape. Several such photologs could be examined simultaneously to identify and correlate key beds and to study lithofacies relationships between core holes.

A detailed lithologic description of core from drill hole C34 and generalized lithologic columnar sections and shale-oil histograms for core from drill holes C154 and C155 were published by Trudell, Beard, and Smith (1970). Shale-oil analyses for the unleached part of the saline facies in core holes C154 and C155, shown as histograms on figure 1, are new analyses made by the Bureau of Mines in 1971-72 on samples provided by the Geological Survey. These analyses, as well as sample depths, and lithologies of cores from the two drill holes differ in some details from the data given by Trudell, Beard, and Smith (1970, fig. 4). The nahcolite analyses for cores from the 10 drill holes were placed on open-file by the Geological Survey (Dyni, Beck, and Mountjoy, 1971; and Dyni, 1974). Shale-oil analyses for core holes C177 and C179 were released to open-file by the U.S. Geological Survey in 1971.

The nahcolite analyses were made by Timothy K. Martin, P. Charles Beck, John W. Blair, Jr., John L. Porterfield, and J. R. Dyni. Computer data readouts and mechanically plotted histograms of the shale-oil and nahcolite analyses were provided by the U.S. Geological Survey. Janet K. Pitman aided in preparing the computer data.

STRATIGRAPHY

The lacustrine Green River Formation of Eocene age extends throughout most of the Piceance Creek basin between the Colorado and White Rivers in northwest Colorado. The thickest and richest deposits of oil shale and the greatest concentration of associated sodium minerals in the formation are found in the northern part of the basin in Rio Blanco County. The drill cores studied in this investigation penetrate the central part of these deposits.

In the study area, the Green River Formation is divided, in ascending order, into the basal sandstone member (Hail, 1972), and the Garden Gulch, Parachute Creek, and Evacuation Creek Members. The name Evacuation Creek Member, as it has been used in the basin, has been replaced by the Uinta Formation by Cashion and Donnell (1974) and subdivided by Duncan, Hail, O'Sullivan, and Pipiringos (1974). The sequence of rocks studied in this report extends upward from the base of the Garden Gulch Member to the top of the A-groove, a zone of lean oil shale and solution breccia, in the upper part of the Parachute Creek Member. This sequence of rocks is about 1,975 feet thick in core hole C34, the only well of those studied to penetrate the entire sequence. The top of A-groove lies between 830 and 1,370 feet below the surface in the core holes studied. Within the study area the oil-shale deposits in the Parachute Creek Member contain a saline facies that extends from near the base of the member to the top of A-groove, and possibly higher in section. The lower part of this facies consists locally of large amounts of nahcolite and halite in oil shale and the upper part consists of oil shale containing many saline cavities and solution breccias that mark units of probable nahcolite and halite that have been removed by ground-water dissolution.

Using histograms of shale-oil analyses of cores and cuttings from many wells, J. R. Donnell (written commun., 1974) divided the oil-shale deposits of the Green River Formation into a series of alternating lean and rich units of oil shale that can be mapped in the subsurface throughout most of the Piceance Creek basin. Several of these zones were described by Donnell and Blair (1970) and illustrated by Cashion and Donnell (1972). The latter authors showed that the zones are identifiable on sonic and density well logs as well as on shale-oil histograms, and that many key beds of oil shale and volcanic tuff are traceable into the Uinta Basin, Utah; some of these units were traced as much as 100 miles west of the Piceance Creek basin. Toward the saline depocenter in the northern part of the Piceance Creek basin, Donnell and Blair (1970, p. 77) found that the greater abundance of nahcolite and halite alters the shale-oil values to the extent that several zones containing these minerals cannot be recognized solely on shale-oil histograms. However, many units of nahcolite and halite which were identified and correlated between core holes in this study make it possible to extend Donnell's oil-shale zones through the saline facies. Correlation of the numbered zones established in this study with those used previously by Donnell and coworkers is shown on figure 1.

The sequence of rocks from the base of the Garden Gulch Member to the base of B-groove (a zone of lean oil shale and solution breccia in the upper part of the Parachute Creek Member) was divided into zones 1 to 13 from the base upward. Although the oil shale of the Garden Gulch Member differs mineralogically and in physical character from that of the Parachute Creek Member, the oil shales of both members are vertically gradational with each other; these oil shales form essentially one continuous mineral deposit and are treated stratigraphically as such in this report. The B-groove, the Mahogany zone (which is divided into a lower, middle, and upper part), and the A-groove at the top complete the sequence of rocks studied. Within the 13 zones many mappable units of nahcolite, halite, and solution breccia were recognized and are identified on figures 1 and 2. Correlation of the numbered zones established in this study with those used previously by Donnell and coworkers is shown on figure 1.

In this report the grade of oil shale, when not given in gallons per ton, is described as follows:

Grade	Gallons of shale-oil per ton
Low	<20
Moderate	>20 <40
High	>40 <60
Very high	>60

Lithology of the saline facies

Lower unleached part

The lower 610 to 1,130 feet of the Parachute Creek Member consists of low- to high-grade oil shale that contains variable amounts of nonbedded crystalline aggregates of nahcolite and beds of nahcolite and halite. The thickest evaporite section in the Piceance Creek basin is probably in core hole C155 which is located at or near the saline depocenter of the basin. In this core hole, 852 feet of nahcolitic and halitic rocks were penetrated, but the total thickness of the evaporite section is estimated, on the basis of nearby core holes, to be about 1,130 feet.

Nahcolite occurs in the lower unleached part of the saline facies as (1) nonbedded crystalline aggregates scattered through oil shale, (2) mappable units of nahcolite crystals disseminated in oil shale, (3) brown microcrystalline beds, and (4) white coarse-grained beds. Excluding halite beds, oil shale containing nahcolite aggregates comprises about 77 to 86 percent of the saline facies in the study area. Units of disseminated nahcolite in oil shale make up 6 to 17 percent of the facies, and nahcolite beds constitute about 1 to 9 percent.

Nahcolite aggregates.--Nahcolite aggregates are typically coarse grained, irregular to round in outline, and range rather widely in size (fig. 3). Many aggregates are about 1 to 3 inches across, but some are as large as 3 feet. Nahcolite crystals within aggregates are bladed, 1/4 to 1 inch or more long, and are commonly separated from each other by paper-thin septa of oil shale. In some aggregates the nahcolite crystals are arranged in a radiating rosettelike pattern, whereas in others the crystals show crude clustering, or are more or less randomly oriented. Most of the nahcolite is colored light brown by organic impurities. Irregular white patches of microcrystalline quartz are found in some aggregates. Many aggregates are rimmed with pyrite or marcasite that alters to a soft expanded black material on exposure to air. A secondary coating of sodium sulfite formed on sawed core surfaces of some nahcolite aggregates. The sodium sulfite may have formed by reaction with the pyrite rims or possibly the source of sodium sulfite is from liquid inclusions within the nahcolite aggregate. Bedding laminae commonly bend around the aggregates indicating the aggregates grew when the enclosing sediments were still soft and plastic as shown on figure 3.

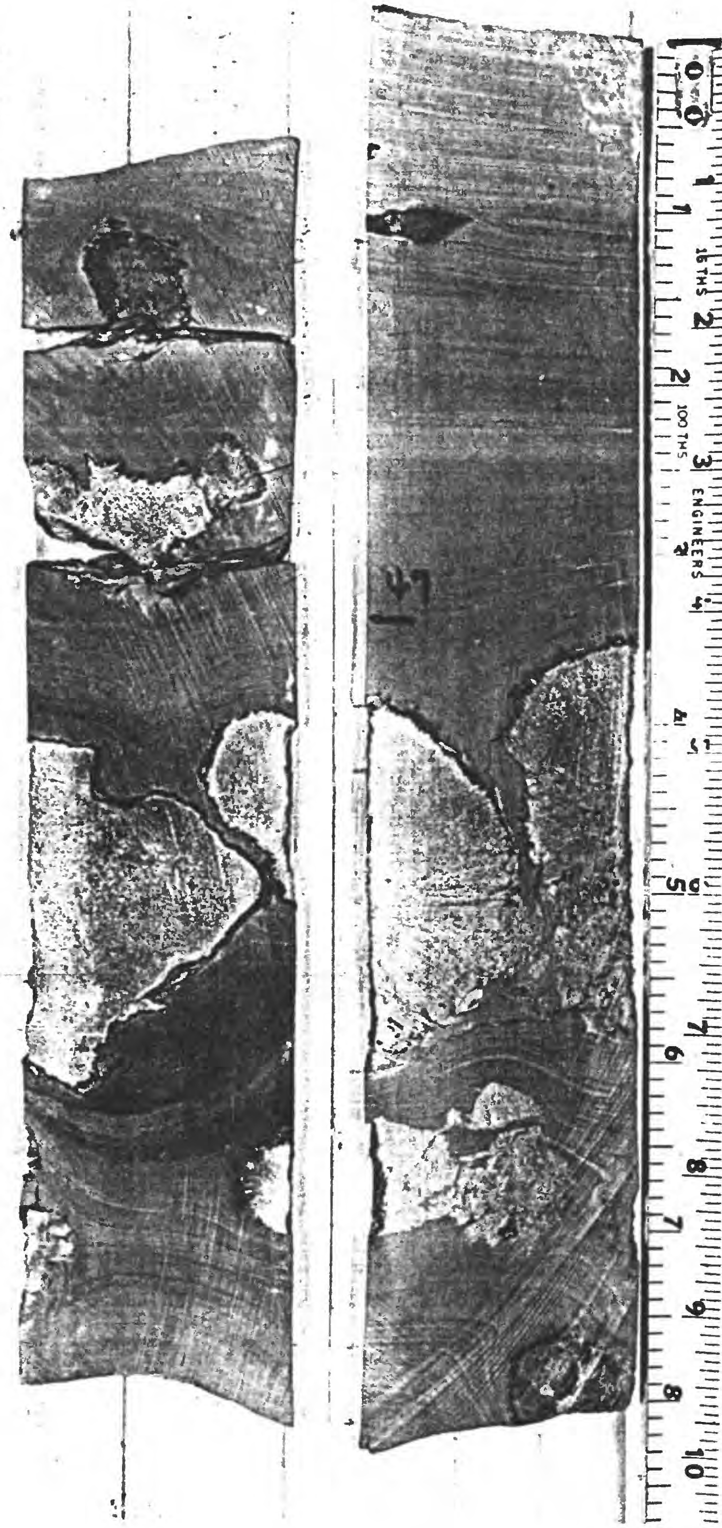

Figure 3.--Nahcolite aggregates in oil shale between the depths of 2,146.7 and 2,147.2 feet in the lower part of zone 10 in core hole C2. The coarse-grained internal structure of the aggregates is obscured by white coatings of probable sodium sulfite. The dark rims around most of the aggregates are pyrite or marcasite.

Disseminated nahcolite in oil shale.--Some nahcolite occurs as discrete fine- to medium-grained crystals mixed with oil shale (fig. 4). Textures vary widely depending upon the size and distribution of the nahcolite crystals in the oil shale. A given unit may grade vertically from close-packed crystals to rather widely spaced crystals and may include intermediate layers of oil shale free of nahcolite. Some units are composed of alternating oil-shale laminae and nahcolite-rich laminae. The contacts of units of disseminated nahcolite may be sharp or gradational. Most of the nahcolite is fine to medium grained, but some crystals are 1/4 inch or more long. Blebs of fine-grained to microcrystalline nahcolite and small nahcolite aggregates are present in some units. Despite the variations in textures and gradational contacts, many units of disseminated nahcolite have remarkable lateral continuity.

Bedded nahcolite.--Two types of bedded nahcolite are found in the saline facies: (1) beds of white fine- to coarse-grained nahcolite, and (2) beds of brown microcrystalline nahcolite. The first type consists of beds 4 to 24 feet thick of porous white nahcolite that contains oil shale and marlstone in scattered laminae to layers 1 to 2 feet thick. The nahcolite forms clear, equant to elongate crystals commonly 1 to 6 mm across. The nahcolite is relatively free of organic matter. Halite is present in some beds. Many beds typically contain scattered irregular and interconnected cavities 2 to 7 mm in size that may have been filled with the last interstitial brines within the bed. Available evidence indicates that all the beds of white nahcolite grade laterally into halite toward the saline depocenter of the basin.

The brown variety of nahcolite is chiefly fine grained to microcrystalline, compact, and nonporous (fig. 5). The nahcolite, commonly interstratified with laminae and thin layers of oil shale, occurs mostly in beds 1/2 inch to 12 feet thick. Textures range from nearly featureless to faintly laminated. Some thin beds are contorted and show internal flowage structure. These features probably formed before lithification when the nahcolite and enclosing sediments were still soft and subject to local slumping. Most of the nahcolite is colored light to medium brown by small amounts of organic impurities. Pyrite in microcrystalline blebs about 0.25 mm across are scattered through some beds. Nahcolite in thin brown layers also occurs in halite and is described in the section on halite. Many beds of brown nahcolite are continuous across the study area. Some beds seem to grade into halite toward the saline depocenter of the basin.

Halite.--Halite interstratified with nahcolite, oil shale, and marlstone occurs in units 2 to 64 feet thick in the upper one-half of the unleached part of the saline facies. The halitic rocks are commonly composed of alternating thin layers of halite and nahcolite that form rhythmically deposited couplets (fig. 6). These couplets are composed of a layer of halite overlain by a layer of nahcolite and range from paper-thin to 15 cm thick. In a typical couplet the halite is commonly clear to light smoky gray and medium to coarse grained; the nahcolite is tan to light brown and fine grained to microcrystalline. Within a couplet the contact between the halite and nahcolite layers is gradational but contacts between couplets are

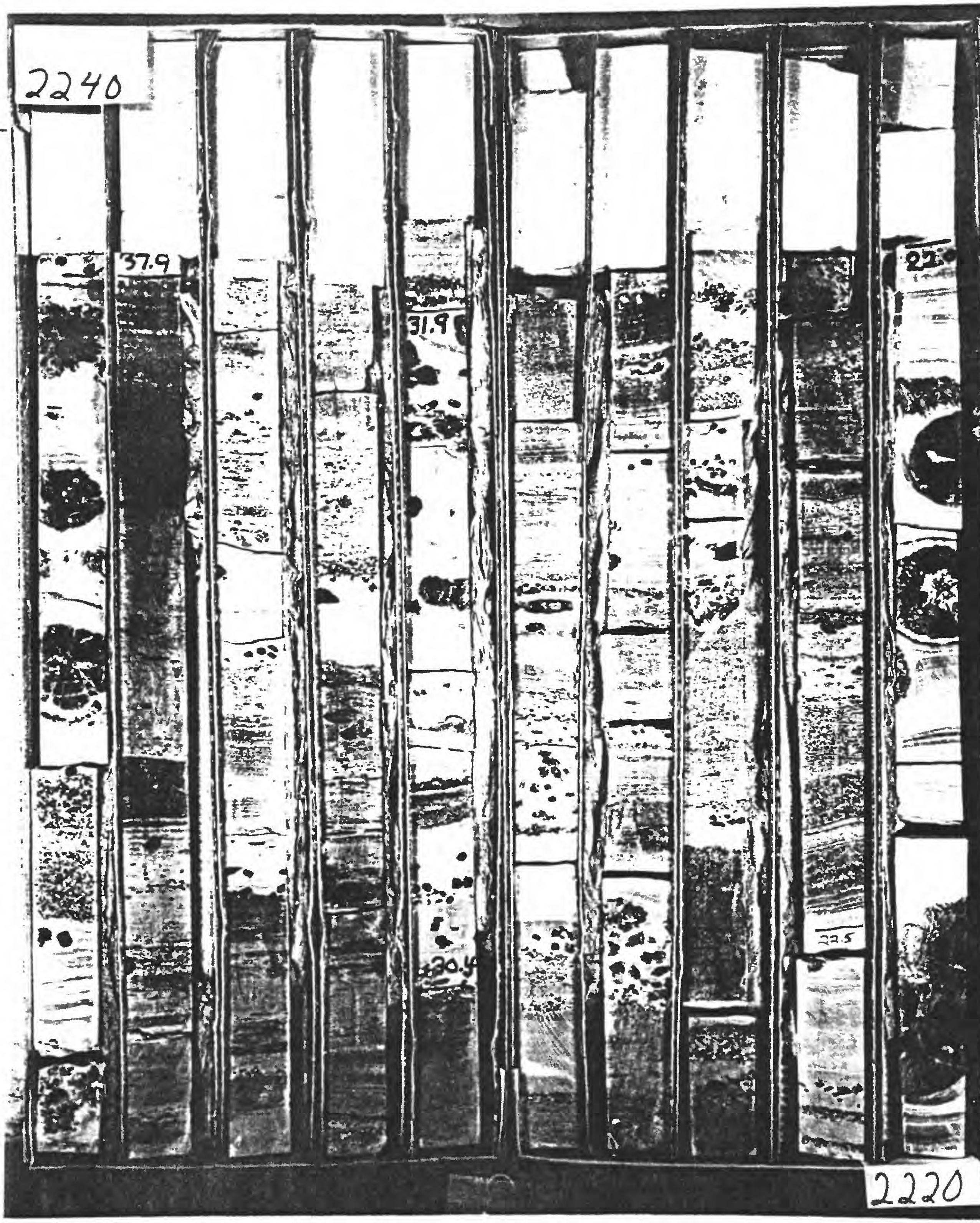

Figure 4.--Unit of disseminated nahcolite, 15.4 feet thick, in the middle of zone 7 between the depths of 2,222.5 and 2,237.9 feet in core hole C177. Fine-grained nahcolite occurs in darker laminated bands which are interbedded with light-colored oil shale that contains scattered small coarse-grained aggregates of nahcolite. Note the well-developed rosettelike aggregates of nahcolite at the top and bottom of the core.

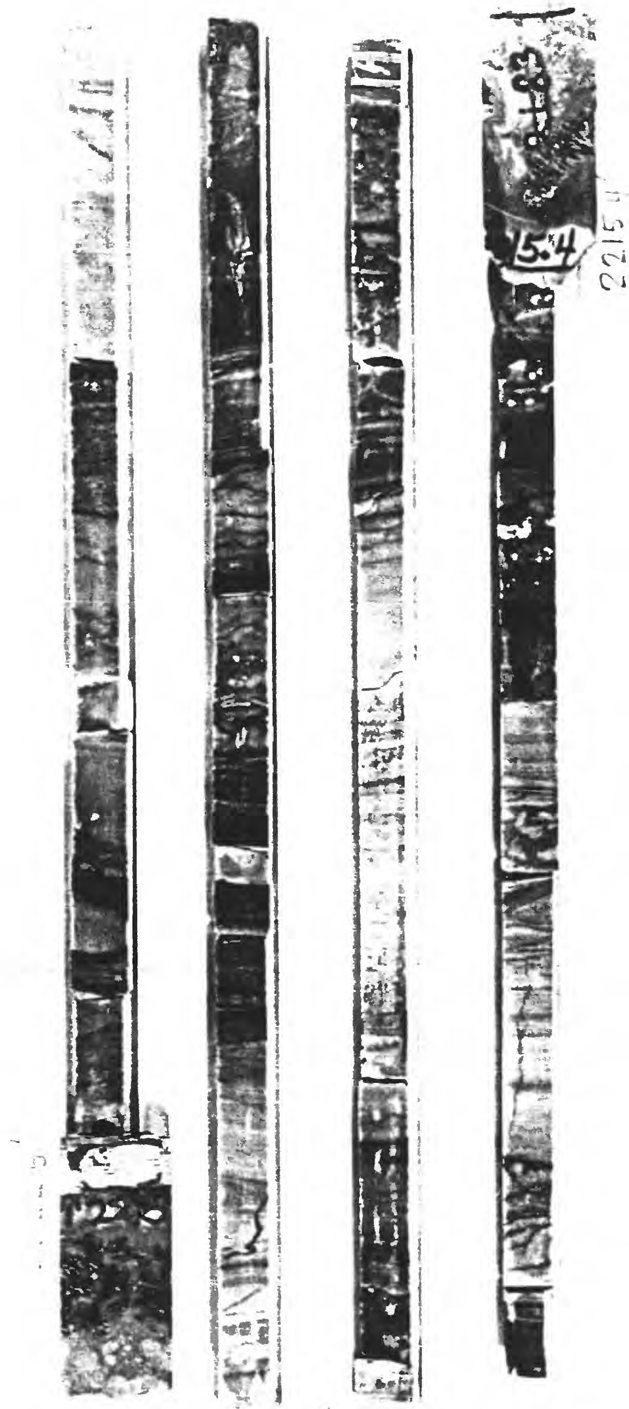

Figure 5.--Brown microcrystalline nahcolite (nahcolite bed 10-D) in the middle of zone 10 between the depths of 2,215.4 and 2,222.5 feet in core hole C155. Thin laminae and layers of dark oil shale are scattered through the lighter colored nahcolite.

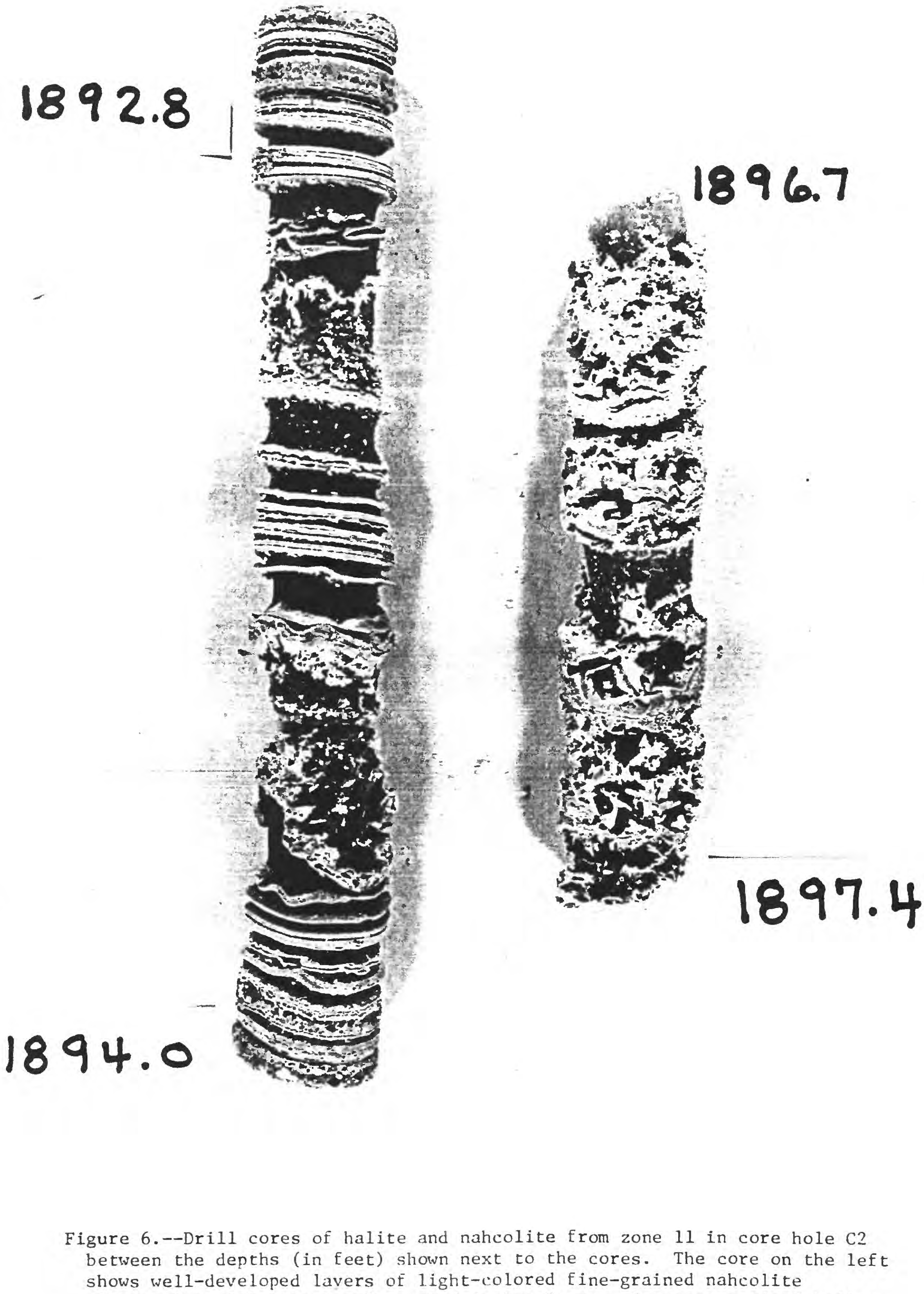

Figure 6.--Drill cores of halite and nahcolite from zone 11 in core hole C2 between the depths (in feet) shown next to the cores. The core on the left shows well-developed layers of light-colored fine-grained nahcolite alternating with more deeply etched darker layers of coarse-grained halite. Individual layers of nahcolite and halite can be traced in the subsurface for several miles. The core on the right is mixed halite and nahcolite showing some crude layering.

usually sharp. In some beds the nahcolite and halite form irregular patchy mixtures (fig. 6). Nahcolitic oil shale and marlstone in laminae to layers 2 feet thick are scattered through the halitic beds. Additional details on the petrology and bromine content of the halitic rocks are given by Dyni, Hite, and Raup (1970).

Oil shale.--The nahcolitic oil shales in the unleached part of the saline facies are typically tough with relatively few bedding-plane partings; in terms of splitting properties, they range commonly from slabby to massive. These rocks commonly display four main types of sedimentary bedding structures: nonlaminated, laminated, streaked, and blebby. Some blebby oil shale seems to be associated with higher kerogen content (fig. 7). Although these oil shales have a relatively high crystalline water content, chiefly in nahcolite and dawsonite, the amount of pore water (and porosity) is nil. Oil-shale colors range from brown to black with dark yellowish brown predominating. The mineral content of the fine-grained matrix of the oil shale consists chiefly of quartz, dolomite, Na- and K-feldspars, and dawsonite in variable amounts, and small but persistent amounts of pyrite or other sulfide minerals. Small amounts of illite, calcite, magnesite, ferroan dolomite, and several kinds of rare sodium minerals are found in oil shale in some parts of the unleached saline facies (Dyni, Hite, and Raup, 1970, p. 171; Hite and Dyni, 1967, p. 32; and Trudell, Beard, and Smith, 1970, table B-1, p. 71-165). Some data suggest these authigenic minerals occur in laterally continuous units and may be important in interpreting the geochemical history of the oil shale and sodium mineral deposits.

Upper leached part

The top of the nahcolite and halite deposits is clearly defined by a dissolution surface which forms a sharp contact between the lower unleached part of the saline facies and an overlying sequence of water-leached rocks. The dissolution surface is irregular and cuts across as much as 455 feet of strata as determined from core holes C155 and C5. The configuration of the dissolution surface is probably controlled primarily by intrabasinal structural folds with local deepening of the surface along faults.

A geohydrologic unit of highly porous and permeable rocks in the upper part of the Parachute Creek Member that extends from the dissolution surface in zones 11 and 12, upward through zone 13 and B-groove, and into the lower part of the middle unit of the Mahogany zone is described in earlier reports as the "leached zone" (Hite and Dyni, 1967; Dyni, Hite, and Raup, 1970). This zone once contained extensive deposits of probable nahcolite and halite that have been dissolved and removed by ground water. The leached zone is about 350 to 580 feet thick in the core holes studied and is composed of much broken and rubbly oil shale and solution breccia and contains units of disseminated fine-grained crystal cavities, and larger solution cavities similar to the molds filled by coarse-crystalline aggregates of nahcolite below the dissolution surface. Because of dissolution of water-soluble minerals and subsequent collapse and fracturing, the leached zone is highly porous and permeable and is probably water-saturated in the central part of

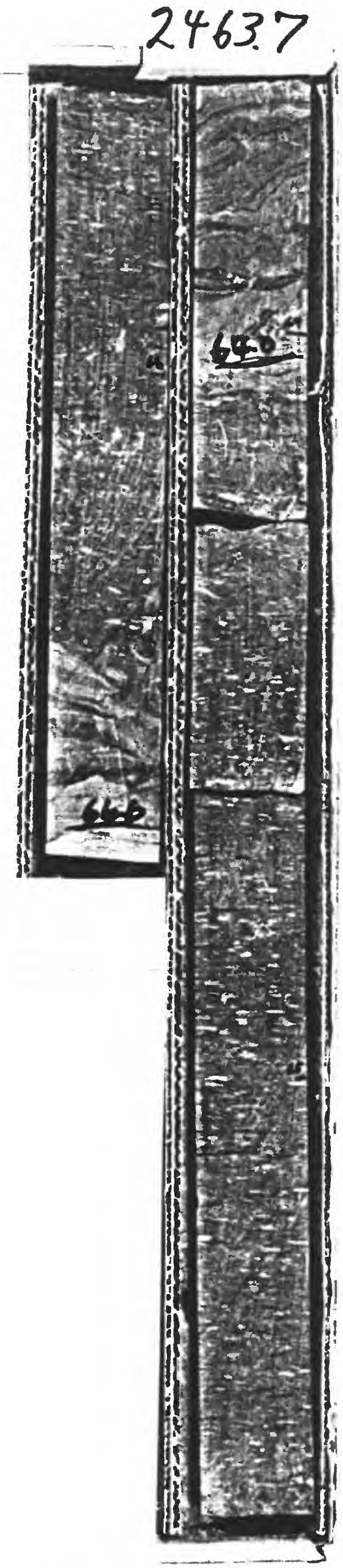

Figure 7.--The "Sixty" oil-shale bed near the base of zone 9 between the depths of 2,464.0 and 2,466.6 feet in core hole C155. In this core hole the bed averages 64.0 gallons of shale-oil per ton. Note the light-colored elongate blebs of dolomite scattered through the rock.

the basin. Coffin, Welder, and Glanzman (1971), who described the leached zone as the principal bedrock aquifer of the basin, found transmissivities in the zone ranging as high as 20,000 gallons of water per day per foot. Water quality ranges from fresh on the basin margins to highly saline sodium carbonate-chloride water toward basin center. Probably some dissolution of nahcolite and halite is taking place at the dissolution surface. Coffin, Welder, and Glanzman (1971) reported the total water in storage in the leached zone to be 2.5 million acre-feet, but Samuel W. West, U.S. Geological Survey (oral commun., 1973), believes the amount is about 25 million acre-feet.

The upper stratigraphic limit of salines in the Parachute Creek Member is not yet clearly defined. Trudell, Beard, and Smith (1970, figs. 4, 5, and 6) found undifferentiated "vugs and collapse breccia" to nearly the top of the member. Additional study of the leached zone and younger rocks in the Green River Formation is needed to determine the original vertical and lateral extent of the saline facies.

Description of zones

Zones 1 to 4

Zones 1 to 4, which make up the Garden Gulch Member, consist of slabby to subfissile, dark-yellowish-brown, low- to moderate-grade oil shale; some dark-yellowish-brown, subfissile to papery shale; some olive-gray, blocky, silty claystone; and small amounts of dolomite and siltstone. Most of the rocks are faintly to prominently laminated and contain sparse fish and vertebrate (turtle?) bone fragments and sparse to locally abundant ostracodes. Small amounts of fine-grained pyrite persist throughout the member. X-ray diffraction analyses of samples from core holes C5 (J. R. Dyni, unpub. data) and C34 (Trudell, Beard, and Smith, 1970, table B-1, p. 165-205) show the mineral content of the member to be chiefly illite, quartz, feldspar, dolomite, and calcite. Dawsonite was found in the upper 50 to 60 feet of the member. The typical slabby to fissile character of these rocks and occasional slickensided and waxy bedding-plane surfaces are due to an abundance of clay minerals and contrast sharply with the overlying massive dolomitic oil shales of the Parachute Creek Member. In core hole C34 the Garden Gulch is 413 feet thick.

In core hole C34, zone 1 is about 145 feet thick and its base is placed at the top of a white fine-grained sandstone, 29 feet thick. The shale-oil content of zone 1 ranges from about 7 to 20 gallons per ton with higher values in the upper 60 feet of the unit. The top of zone 1 coincides with the orange marker, a laterally persistent electric-log datum (Dyni, 1969, p. 58-61). Zone 2 ranges from 24 to 32 feet thick in three core holes and has consistently low shale-oil values, mostly 5 to 10 gallons per ton. Zone 3 is 120 feet thick in core hole C5 and nearly doubles in thickness northward across the study area to core hole C34 where it is 210 feet thick. Zone 3 has the highest shale-oil values for the Garden Gulch Member; it averages between 20 to 30 gallons per ton with some beds reaching 40 to 60 gallons of shale-oil per ton. Zone 4 at the top of the member is 20 to 30 feet thick and averages about 5 to 15 gallons of shale-oil per ton, except in core hole C179 where the upper one-half of the zone consists of oil shale that averages as much as 25 to 30 gallons per ton. The top of zone 4 coincides with the blue marker of some workers (Trudell, Beard, and Smith, 1970).

Zones 5 to 13

Zone 5.--Zone 5, the lowermost unit of the Parachute Creek Member in the study area, is about 60 to 90 feet thick and consists of slabby to massive, moderate- to high-grade oil shale and some low-grade oil shale. The unit thins and its shale-oil content decreases northward toward core hole C34. In the lower 20 to 25 feet there are two laterally persistent 5- to 10-foot-thick units of high-grade oil shale. The upper of the two units is distinctively blebby textured, and averages about 60 gallons of shale-oil per ton. Zone 5 contains the stratigraphically lowest occurrence of nahcolite in the Piceance Creek basin. Some 4- to 8-inch aggregates and coarse-grained crystals of nahcolite are scattered through the upper 30 feet of the zone in core holes C5, C179, and C177.

Zone 6.--Zone 6 is 20 to 30 feet thick. Near the base is a laterally continuous unit of disseminated nahcolite 2 to 8 feet thick that contains 62 to 76 percent nahcolite by weight. This unit was identified in an earlier report by Hite and Dyni (1967, p. 26, and fig. 2) as nahcolite unit 1. A few feet of oil shale at the base of the zone contains some scattered 1-inch aggregates of nahcolite. The remaining part of the zone is mostly prominently laminated, slabby, nahcolite-barren, low-grade oil shale.

Zone 7.--Zone 7 is about 150 to 160 feet thick near the saline depocenter and thins northward to 110 feet in core hole C34. The zone is chiefly massive, low- to moderate-grade, and some high-grade oil shale that contains large amounts of disseminated nahcolite and nahcolite aggregates.

Five units of disseminated nahcolite are recognized in zone 7; these units thin or pinch out toward core hole C34. The lowest unit, about 15 feet above the base, is 0 to 5 feet thick and contains between 60 and 70 weight percent nahcolite. The second unit, about 45 feet above the base of zone 7, is about 2 to 8 1/2 feet thick and is the richest of the five units in nahcolite, averaging between 64 and 77 percent in the core holes near the basin center. These two units, consisting chiefly of fine-grained nahcolite in close-packed crystals mixed with oil shale with a few stringers and layers of oil shale 3 to 4 inches thick, were identified as nahcolite units 2 and 3 in a report by Hite and Dyni (1967, p. 26, and fig. 2). The third unit of disseminated nahcolite, near the middle of the zone, is, in most of the core holes, 15 to 22 feet thick and contains 47 to 57 percent nahcolite by weight (fig. 4). About two-thirds to three-fourths of the unit consists of thin 1/4- to 8-inch laminated bands of fine- to medium-grained disseminated nahcolite. Scattered layers of oil shale containing coarse-crystalline 1/8- to 1-inch aggregates of nahcolite make up the remaining one-third or so of the unit. About 5 feet higher is a similar unit of disseminated nahcolite 4 to 5 feet thick that averages between 42 and 57 weight percent nahcolite. At the top of zone 7 is a rather poorly defined nahcolite-rich unit 18 to 23 feet thick that averages between 31 and 47 percent nahcolite by weight. In this unit nahcolite occurs in disseminated form in many thin bands about 1/4 to 2 inches thick, in scattered 1/4- to 2-inch aggregates, and locally in fine- to medium-grained beds as much as 9 inches thick. Much of the oil shale between the 5 units of disseminated nahcolite in zone 7, is nonlaminated or blebby-textured and contains few to many 1- to 2-inch coarse-crystalline aggregates and rosettes of nahcolite with a few reaching 5 to 10 inches across.

Zone 8.--Zone 8 is 22 to 42 feet thick and consists mostly of low- to moderate-grade oil shale. A few scattered 1- to 3-inch aggregates of nahcolite and some irregular stringers of fine-grained pyrite are present in the lower part of the zone. The oil shale is mostly dark brownish gray, well laminated, and slabby to blocky. A marker bed of altered tuff(?), 1 to 4 inches thick, occurs at 11 to 14 feet below the top of the zone in five of the core holes. A thin-section study showed the tuff(?) to consist of very fine grained dolomite and dawsonite, scattered grains of quartz and K-feldspar, and some blebs of pyrite. The tuff(?) has been informally identified by some workers as the "Square-S marker."

Zone 9.--Zone 9, one of the richest zones of oil shale in the basin, consists of moderate- to high-grade oil shale, some thin beds of very high-grade oil shale, and small to moderate amounts of nahcolite, mostly as aggregates. The zone thickens from 124 feet in core hole C34 to about 150 to 160 feet toward the saline depocenter. The oil shale is slabby to mostly blocky and displays blebby, streaked, and nonlaminated to laminated bedding structures. Near the base of the zone there is a bed of very high-grade oil shale, about 2 to 4 feet thick, that averages 60 gallons or more of shale-oil per ton. This bed, a useful subsurface marker, informally designated here as the "Sixty" oil-shale bed, is easily recognized on shale-oil histograms and in core by its distinctive blebby structure (fig. 7). Immediately overlying the Sixty bed in most core holes is several feet of well-laminated oil shale that contains many thin white laminae of dawsonite in tabular crystals commonly 0.5 to 2 mm long. The top of zone 9 is marked by a change from high to low values on the shale-oil histograms, but the break is not obvious in the cores. The shale-oil resources of zone 9 (R-4 zone of Donnell) were evaluated by Donnell and Blair (1970).

Two units of disseminated nahcolite are in the middle third of zone 9. Both units contain substantial amounts of nahcolite in aggregates. In most core holes the lower unit is 7 to 9 feet thick and averages between 42 and 55 percent nahcolite by weight; the unit thins to 2.5 feet in core hole C34 and is absent in core hole C5. The lower few feet and the upper 1 to 2 feet of the unit consists of 1- to 5-inch-thick bands of disseminated nahcolite interlayered with nahcolite-free oil shale and the middle 3 to 5 feet is nonlaminated oil shale that contains scattered 1- to 4-inch aggregates of nahcolite. The upper unit of disseminated nahcolite is 6 to 11 feet thick in most core holes and thins to 2.5 feet in core hole C34. The nahcolite content ranges from 40.4 to 62.7 percent by weight. Like the unit of disseminated nahcolite below, this unit consists of about 2 feet of interlayered bands of disseminated nahcolite and oil shale at the base, 2 to 5 feet of nonlaminated oil shale containing scattered 1- to 3-inch aggregates of nahcolite in the middle, and 1 to 5 feet of interlayered bands of disseminated nahcolite and oil shale at the top. The remaining parts of zone 9 contain 2- to 18-inch nahcolite aggregates, of which some are rimmed with pyrite and have secondary bluish-white coatings of sodium sulfite on sawed core surfaces.

Zone 10.--Zone 10 is 142 to 163 feet thick and consists of low- to moderate-grade oil shale and large amounts of nahcolite in aggregates, disseminated and scattered crystals, and beds. The oil shale is slabby to blocky, and has nonlaminated to laminated and streaked bedding structures; blebby oil shale is not common.

In the lower 55 to 70 feet of the zone nahcolite occurs in 1- to 4-inch aggregates with a few aggregates reaching 9 or 10 inches across. Scattered fine- to medium-grained crystals of nahcolite are abundant in the upper one-third of the sequence. Many of the nahcolite aggregates are rimmed with pyrite (fig. 3). As many as five 0.5- to 2-foot-thick beds of brown microcrystalline nahcolite are scattered through this sequence; the lowest one which lies 5 to 20 feet above the base is a good stratigraphic marker and is shown on figures 1 and 2.

Overlying the sequence of rocks described above is a unit of disseminated nahcolite 4 to 9 feet thick that averages between 38 and 63 percent nahcolite. The lower part of the unit consists of 1- to 5-inch-thick bands of alternating oil shale and disseminated nahcolite; the upper part is mostly medium-grained disseminated nahcolite. About 10 to 20 feet above, near the middle of zone 10, is a prominent bed of brown microcrystalline nahcolite, 6 to 11 feet thick, named informally the 10-D nahcolite bed. This bed contains scattered laminae and thin layers of oil shale and averages between 40 and 75 weight-percent nahcolite (fig. 5). About 5 to 10 feet below the 10-D bed, another bed of brown microcrystalline nahcolite 2 to 5 feet thick is present locally in a few core holes. About 20 feet above the 10-D bed is a unit of disseminated nahcolite, 4.5 to 11 feet thick, that averages between 20 and 73 percent nahcolite and contains some nahcolite-barren oil shale in the middle. Another thin marker bed of brown microcrystalline nahcolite, 10 feet below the top of zone 10, is shown on figures 1 and 2. In addition to the disseminated units and beds of nahcolite, much nahcolite occurs in other parts of zone 10 as scattered crystals and some 1- to 9-inch aggregates of nahcolite.

Zone 11.--In the area where it is unleached zone 11 contains large amounts of nahcolite, mostly in aggregates and some in beds and in units of disseminated nahcolite. Thin to thick beds of halite and subordinate nahcolite are present especially in the lower part of the zone. On the average, the oil shale in zone 11 is of moderate grade but ranges from low to very high grade. The nahcolitic oil shale is mostly slabby to massive but some units of light-colored well-laminated oil shale are flaggy.

Parts of the zone have been leached of salines as shown by the stratigraphic position of the dissolution surface on figures 1 and 2. The zone is unleached or nearly so in all core holes except C1, C2, and C5. In the remaining core holes zone 11 thickens from 283 feet in core hole C34 to a maximum of 368 feet in core hole C153. Most of zone 11 is leached of salines in core hole C5 and its thickness here is reduced to 241 feet. Assuming the original thickness of the zone in core hole C5 was about the same as in core hole C179 where the zone is mostly preserved and is 361 feet thick, about 120 feet of water-soluble salines were removed in core hole C5. The amount of salines dissolved may be less, however, because of stratigraphic thinning of the saline facies from core hole C179 toward core hole C5. Removal of salines causes an apparent enriching of the oil shale as seen by comparison of the shale-oil histograms of zone 11 in core holes C5 and C179; the significance of this fact is discussed later in this report.

At the base of zone 11 is a unit of disseminated nahcolite about 4 to 12 feet thick that averages 40 to 77 weight-percent nahcolite. This unit consists of many laminated bands of fine-grained disseminated nahcolite a few millimeters to 2 feet thick in nonlaminated oil shale. Above is a sequence of halitic rocks and nahcolitic oil shale 45 to 115 feet thick. The halitic rocks consist of couplets of alternating laminae to thin layers of halite and nahcolite or irregular patchy mixtures of halite and nahcolite (fig. 6) and scattered thin beds of nahcolitic oil shale. Near the saline depocenter several of these beds of halite and nahcolite reach 40 feet in thickness and thin away from basin center and grade laterally into beds of light-brown to predominantly white medium- to coarse-grained vuggy nahcolite. This facies relationship is well illustrated between core holes C156 and C1 (fig. 1). The oil shale between the halitic units is moderate to very rich grade and contains much nahcolite in bands of disseminated crystals, 1- to 2-inch coarse-grained aggregates, and fine-grained brown pods.

Overlying the above sequence of halitic rocks is a unit of disseminated nahcolite 10 to 16 feet thick. In the upper part of the unit there is a 1- to 2-foot-thick marker bed of brown microcrystalline nahcolite that is locally underlain by 1 foot of halite. The nahcolite content of the entire unit ranges from 37 to 66 weight percent.

The upper 220 to 240 feet of zone 11 consists of slabby to blocky oil shale of mostly moderate grade and variable, but generally large, amounts of nahcolite in 2- to 8-inch aggregates with some aggregates reaching 2 feet across. A few 1- to 10-inch thick bands of fine- to medium-grained nahcolite are also present. Several thin beds of halite and nahcolite similar to the halitic rock below and several beds of brown microcrystalline nahcolite are shown in this sequence on figures 1 and 2. Several of the beds of halite and nahcolite grade laterally from basin center into white nahcolite as below.

Zone 12.--Zone 12 has been leached extensively of its water-soluble minerals by ground water and it is unlikely that a complete unleached sequence of rocks in the zone is preserved anywhere in the basin. Zone 12 ranges from a minimum thickness of 110 feet in core holes C5 and C179 where the zone is completely leached of salines to an estimated 250 feet in core hole C155 in which the upper 90 feet of the zone is leached. Abundant evidence of the former presence of bedded and disseminated salines in the upper leached part of zone 12 suggests that the original thickness of the zone was considerably greater than 250 feet.

The unleached part of zone 12 in core holes C154 and C155 contains two 60- to 70-foot-thick units of bedded halite and nahcolite and some nahcolitic oil shale. The evaporites occur in beds consisting of patchy mixtures of medium- to coarse-grained halite and light-brown fine-grained to microcrystalline nahcolite. Some beds contain coarse-grained bladed to fibrous aggregates of wegscheiderite ($Na_2CO_3.3NaHCO_3$). Well-developed laminae of halite and nahcolite are present locally. Laminae to beds of oil shale as much as 2 inches thick are scattered through the units. The lower unit of halite and nahcolite, which contains a 4-foot-thick unit of disseminated nahcolite near its base, thins and grades laterally away from basin center into bedded white nahcolite in core holes C34 and C177. In the latter core hole the bed of white nahcolite is 32.7 feet thick and averages nearly 80 weight-percent nahcolite. Although the thickness and grade of this bed look economically attractive, its areal extent may be small because of dissolution by ground water, and where it is present, the bed may be too close to the dissolution surface to be mined safely.

The two thick units of halite and nahcolite are separated by 20 feet of oil shale and nahcolite. The lower 9 to 12 feet of this 20-foot-thick sequence is a unit of disseminated nahcolite that averages about 51 percent nahcolite by weight. The upper part is mostly nahcolitic oil shale that contains an unusual assemblage of authigenic minerals including scattered thin platelets of searlesite ($NaBSi_2O_6.H_2O$) as much as 10 mm long, 1-2 mm octahedra of northupite ($Na_2CO_3.MgCO_3.NaCl$), and 1-2 mm stubby prismatic crystals of shortite ($Na_2CO_3.CaCO_3$).

Beds of high-grade white nahcolite 6 and 11 feet thick overlie the upper unit of halite and nahcolite in core holes C155 and C154. It is not certain if the two beds are the same.

The two thick units of halite and nahcolite were correlated laterally with units of solution breccia in several core holes as shown on figures 1 and 2. Although the leached parts of zone 12 were not studied in detail, they contain many solution breccias and zones of crystal cavities. One such solution breccia forms a unit, about 9 feet thick, 45 feet below the top of zone 12 and is present probably in all 10 core holes (figs. 1 and 2). This and other solution breccias consist of units of firm to soft crumbly fragments of white to light-brown marlstone or low-grade oil shale that can be recognized and correlated on the shale-oil histograms. Undoubtedly, the upper leached part of zone 12 once contained extensive, and probably thick, beds of salines, most likely nahcolite and probably halite. Most of the oil shale in the zone is of low to moderate grade.

Zone 13.--In the study area zone 13 consists of low- to high-grade oil shale, solution breccia of marlstone or low-grade oil shale, and locally some siltstone. The general geology and shale-oil resources of zone 13 (R-6 zone of Donnell and Blair) were described by Donnell and Blair (1970). In most core holes the entire zone averages between 22 and 26 gallons of shale-oil per ton. The zone becomes leaner in core hole C34 where it averages 19 gallons per ton. The zone thickens northward through the study area from about 165 feet in core hole C5 to nearly 260 feet in core hole C34. This thickening is probably due to an influx of fine-grained clastic sediments from a northerly source, not because of dilution of nahcolite as suggested by Donnell and Blair (1970, p. 82).

At the base of zone 13 is a unit of oil shale 20 to 25 feet thick that consists of two rich beds of oil shale separated by a bed of moderate-grade oil shale containing some solution breccia and saline cavities. The high-grade beds of oil shale form a distinctive doublet on the shale-oil histograms of most of the core holes.

Solution breccias, zones of crystal cavities, and nahcolite(?) aggregate cavities a few inches across are scattered through zone 13, but they seem to be less abundant than in the leached part of zone 12 below. Most of the core recovered from zone 13 is flaggy to slabby; much of it is fractured and in broken fragments commonly less than 4 to 5 inches across. Some beds of higher grade oil shale seem to resist fracturing and form coherent beds. Most of the fracturing in zone 13 was probably caused by dissolution of salines by ground water and subsequent collapse of enclosing rocks.

In the upper part of zone 13 there is a unit of lenticular blocky siltstone that reaches a maximum thickness of about 30 feet in core hole C156. The siltstone is pale grayish brown, massive, and contains many scattered angular contorted fragments of laminated oil shale as much as 2 inches across and scattered dark-brown kerogenaceous streaks. The siltstone is dolomitic and may be tuffaceous. Its bedding suggests very rapid deposition with local slumping or subaqueous flowage before consolidation.

B-groove

The B-groove is composed of about 15 to 30 feet of light-brown to buff saline-cavity-bearing marlstone and low-grade oil shale, and marlstone solution breccia. Recovery of drill core was generally poor, but most of the core recovered is soft and earthy or is in angular and platy fragments commonly less than a few inches across. Sedimentary structures indicate that B-groove originally contained one or more beds of evaporites, most likely nahcolite and possibly halite, and scattered aggregates of nahcolite and units of disseminated nahcolite.

Mahogany zone

The Mahogany zone is the stratigraphically highest zone of rich oil shale in the Parachute Creek Member in the Piceance Creek basin. The shale-oil resources of the zone are summarized by Donnell and Blair (1970). On the basis of its shale-oil content, the Mahogany zone is readily divisible into three units, the lower and upper units being relatively leaner than the middle unit. All three units thicken and decrease in shale-oil values northward through the study area, probably because of increased content of fine-grained clastics.

In the study area the lower unit is 63 to 84 feet thick and averages 18 to 23 gallons of shale-oil per ton in eight of the core holes studied. The oil shale is generally slabby to blocky and is considerably fractured. Solution breccias composed of crumbly fragments of low-grade oil shale and saline crystal and crystal aggregate cavities are abundant.

The middle unit of rich oil shale is 72 to 108 feet thick and averages 26 to 37 gallons of shale-oil per ton. The lower 30 feet of the unit is commonly fractured and contains scattered cavities leached of saline minerals, probably nahcolite. Although there are some scattered saline cavities and solution breccia in the upper part of the Parachute Creek Member above the Mahogany zone, the lower 30 feet of the middle unit of the Mahogany zone marks the approximate top of the "leached zone" of the Parachute Creek Member in the study area. A thin bed of high-grade or very high grade oil shale about 5 to 15 feet below the top of the middle unit is the Mahogany oil-shale bed.

The upper unit of the Mahogany zone is 35 to 57 feet thick and averages 16 to 25 gallons of shale-oil per ton. The oil shale is commonly evenly and prominently laminated, slabby to blocky, locally fractured, and contains only a few solution cavities. In several core holes a thin bed of altered tuff about 0.5 foot thick may be the Mahogany marker; similar beds of tuff are present in this unit and in the lower two units, but their stratigraphic correlation was not attempted.

A-groove

A-groove, recognized by its low shale-oil content on the shale-oil histograms, is 14 to 18 feet thick in five core holes. The unit consists of evenly and prominently laminated, platy to flaggy, buff to dark-yellowish-brown marlstone that contains some disseminated crystal cavities, solution breccia composed of soft earthy marlstone and small angular marlstone fragments, and low-grade oil shale. In five core holes the shale-oil content averages 6 to 7 gallons per ton. As below, the breccias mark former beds of salines, probably nahcolite and possibly halite.

Time and stratigraphy

An ideal time-stratigraphic unit is one whose upper and lower contacts are isochronous surfaces. The zones established for the oil-shale deposits and associated minerals in this study are, for the most part, time-stratigraphic and economic rock-stratigraphic units. Many of the contacts for the oil-shale zones and beds of sodium minerals are isochronous, or nearly isochronous, surfaces. Evidence for this is the lateral continuity of individual beds of oil shale and sodium minerals and the precise physical correlation of microstratigraphic structures within these zones and beds. Tuff beds, which are ideal synchronous units, are present in the oil-shale and saline facies, but they were not studied.

Many thin beds of rich oil shale can be identified and correlated between core holes on shale-oil histograms, and in some cases by their distinctive lithologies. The pair of rich oil-shale beds at the base of zone 5, the Sixty oil-shale bed in zone 9, the pair of rich oil-shale beds at the base of zone 13, and the Mahogany bed are several such examples that are easily recognized on figures 1 and 2. These beds probably reflect paleoclimatic conditions that favored maximum production of algal and other aquatic matter that were the probable precursors of the kerogen in the oil shale. It might be expected that under such conditions, and depending on the paleophysiography of the lake and hydrographic basins, the beds of oil shale would be of rather uniform thickness and have wide areal extent. Cashion and Donnell (1972), as well as this study, have shown this to be the case.

A variety of microstratigraphic structures that can be physically correlated between core holes provides further evidence of the lateral contemporaneity of the zones and beds. Curry (1964) showed the precise correlation of bedding laminations in oil shale, commonly believed to be varves, in drill holes 8 1/2 miles apart in the Uinta Basin. Nahcolite-halite couplets, as shown in figure 7, were likened to oil-shale varves, and were precisely correlated between drill holes several miles apart in the Piceance Creek basin by Dyni, Hite, and Raup (1970). Similar correlation of oil-shale laminations in a unit of disseminated nahcolite is shown in figure 8.

NAHCOLITE RESOURCES

The thickness and average nahcolite content of selected beds of nahcolite and units of disseminated nahcolite are shown on figures 1 and 2. The beds of coarse-grained white nahcolite seem to offer the best possibility for mining. Unfortunately, several of the thickest beds, such as those at the top of the unleached saline section in core holes C34, C154, and C177, may be too close to the dissolution surface and the overlying water-bearing leached zone for safe mining by conventional room-and-pillar methods. Perhaps the best potentionally minable beds of white nahcolite are the three beds found about 160 feet below the dissolution surface between the depths of 1,567 and 1,623 feet in core hole C1. Additional drilling is needed to delineate their areal

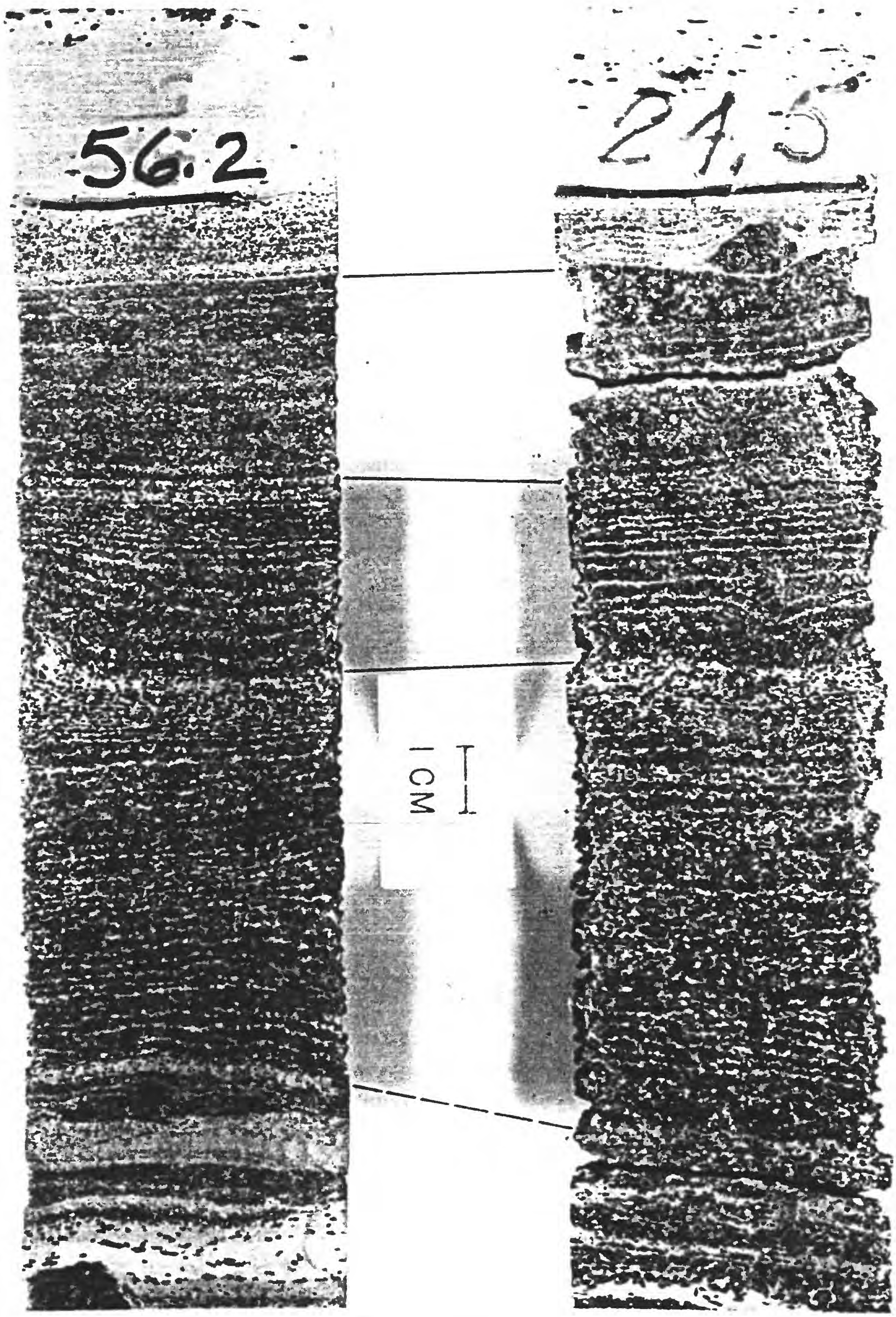

Figure 8.--Alternating laminae, possibly varves, of light-colored oil shale and dark fine-grained nahcolite in the upper 16 cm of the unit of disseminated nahcolite in the middle of zone 7 in core holes C154 (on left) and C1 (on right). The same laminae, and groups of laminae can be identified in the two cores which are from drill holes about 2 miles apart. The entire unit of disseminated nahcolite is shown on figure 4.

extent, thickness, grade, and lateral relationship to halite into which they grade toward basin center. The bed of microcrystalline brown nahcolite in the middle of zone 10 has wide lateral extent, but its depth, moderate grade, and thinness reduce its economic value.

Many units of disseminated nahcolite are scattered through the saline facies. Some units reach 20 or more feet in thickness and contain as much as 50 to nearly 75 weight percent nahcolite. However, depth of burial and the recovery of nahcolite, most of which is fine-grained and intimately mixed with oil shale, may be deterrents to mining these units.

By far, the major portion of nahcolite in the basin is in coarse-grained aggregates scattered through oil shale. In terms of efficient mineral conservation practices and economics, perhaps the best method of recovering nahcolite would be to mine it as a coproduct with oil shale. Compared with oil shale, nahcolite is soft and easy to crush. This suggests that much of the coarse-grained nahcolite aggregates could be separated by appropriate screening and elutriation methods, as well as by dissolution, depending upon the product sought. Removing nahcolite prior to retorting would increase the grade of oil shale in selected parts of some zones by a factor of as much as 1.5-1.6. The average enrichment in the grade of oil shale for the entire nahcolite-bearing sequence is 1.2 to 1.4 times, or 6.3 to 9.5 gallons per ton (table 1).

Table 2 lists the average nahcolite content of zones 5 to 12 and of the total thickness of the nahcolite-bearing sequence in each of the 10 core holes. Zones 7, 10, and 11 are the best in terms of thickness and average grade. The total nahcolite-bearing sequence averages 17 to 28 weight-percent nahcolite in the 10 core holes. The nahcolite resource, calculated in short tons per square mile, ranges from 174 million tons for core hole C5 to a maximum of 489 million tons for core hole C177.

Based on information from the 10 core holes and data from other wells, a resource of nahcolite-bearing oil shale at least 100 feet thick underlies an area of about 257 square miles (fig. 9) and contains a conservatively estimated amount of 32 billon short tons of nahcolite (Smith and others, 1973, p. 206). This is the second largest known deposit of sodium carbonate in the world, surpassed only by the Wyoming trona deposit.

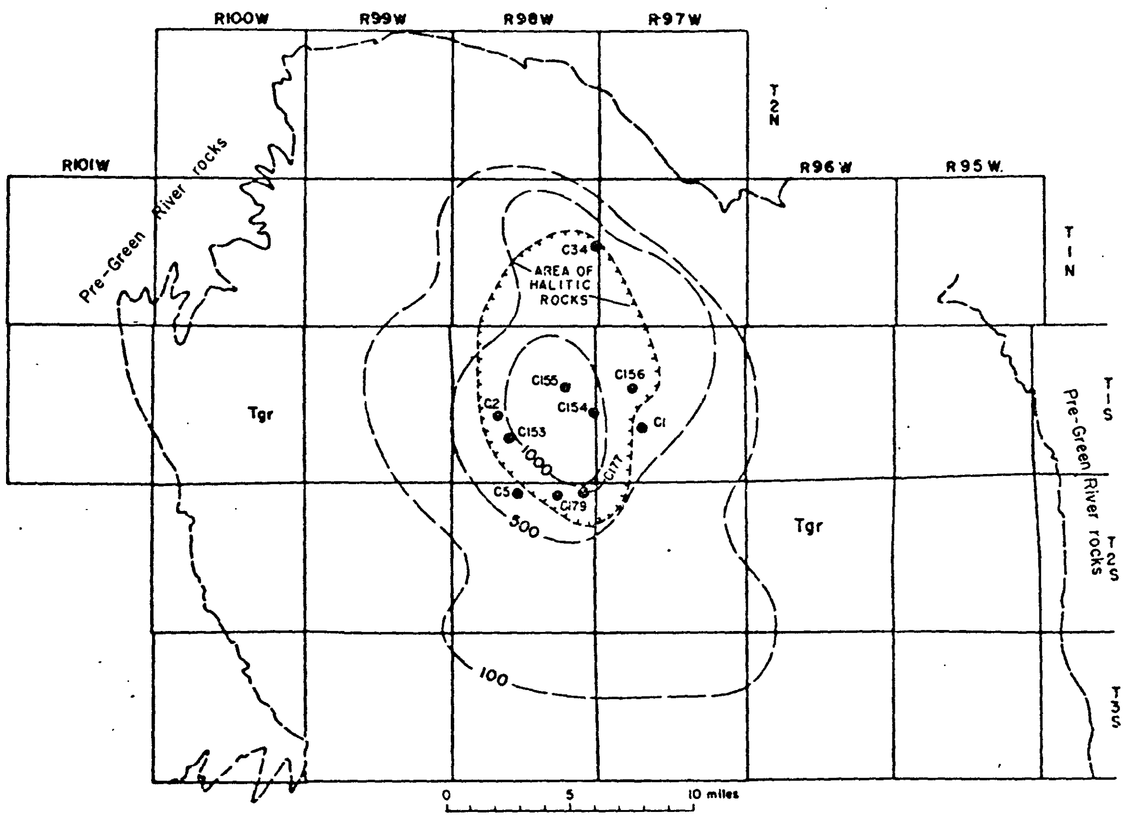

Figure 9.--Isopach map (in ft) of nahcolite-bearing oil shale in the Green River Formation, northern part of the Piceance Creek basin. Tgr, Green River Formation. Numbered dots are core holes studied in this report.

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Table 1.--Average grade of oil shale in the nahcolite-bearing interval in 10 core holes

Core hole	Nahcolite-bearing interval Depth (ft)	Nahcolite-bearing interval Thickness (ft)	Average shale-oil content of whole rock (gallons/ton)	Average shale-oil content of rock without nahcolite (gallons/ton)	Increase in oil shale content (gallons/ton)
C1-------	1404.9-2084.0	679.1	25.2	34.2	+9.0
C2-------	1702.0-2413.2	711.2	29.1	38.6	+9.5
C5-------	1841 -2401	560	32.0	38.8	+6.8
C34------	1737.0-2512.5	775.5	21.7	26.1	+4.4
C153-----	1565.6-2181.0	615.4	26.4	35.5	+9.1
C154-----	1885.0-2796.8	911.8	22.7	29.6	+6.9
C155-----	1636.3-2488.1	851.8	20.5	26.8	+6.3
C156-----	1852.5-2554.3	701.8	23.1	29.7	+6.6
C177-----	1453.2-2363.8	910.6	22.4	31.2	+8.8
C179-----	1538 -2434.5	896.5	24.8	33.3	+8.5

Table 2.--Nahcolite resources in 10 core holes

Zone	Core hole C1 Thickness (ft)	Core hole C1 Grade (Weight percent)	Core hole C2 Thickness (ft)	Core hole C2 Grade (Weight percent)	Core hole C5 Thickness (ft)	Core hole C5 Grade (Weight percent)	Core hole C34 Thickness (ft)	Core hole C34 Grade (Weight percent)	Core hole C153 Thickness (ft)	Core hole C153 Grade (Weight percent)
12----	----	----	----	----	----	----	1/ 30.8	54.8	----	----
11----	1/ 240.1	32.6	2/ 312.8	24.7	1/ 14	40.3	282.8	17.0	1/ 368.4	25.9
10----	149.9	25.0	155.7	32.6	142.0	22.0	162.3	17.8	155.0	28.4
9----	152.1	15.0	160.5	16.7	156.0	7.6	124.1	4.6	3/ 92	20.4
8----	21.7	2.9	28.3	9.3	31	3.0	42.0	1.7	----	----
7----	3/ 115.3	34.8	3/ 53.9	31.2	157	25.6	109.8	21.5	----	----
6----	----	----	----	----	28	21.3	4/ 23.7	10.3	----	----
5----	----	----	----	----	4/ 32	9.1	----	----	----	----
Total-	679.1	26.4	711.2	24.5	560	17.6	775.5	16.9	615.4	25.7
Millions of short tons of nahcolite per square mile--------	333		315		174		249		291	

Zone	Core hole C154 Thickness (ft)	Core hole C154 Grade (Weight percent)	Core hole C155 Thickness (ft)	Core hole C155 Grade (Weight percent)	Core hole C156 Thickness (ft)	Core hole C156 Grade (Weight percent)	Core hole C177 Thickness (ft)	Core hole C177 Grade (Weight percent)	Core hole C179 Thickness (ft)	Core hole C179 Grade (Weight percent)
12----	1/ 112.4	21.5	1/ 159.7	10.9	----	----	1/ 41.8	74.0	----	----
11----	363.8	22.5	358.3	29.1	1/ 337.8	24.8	342.7	29.2	1/ 338.4	29.5
10----	160.9	28.8	161.7	31.2	162.8	28.0	144.3	31.9	151.6	32.7
9----	154.9	15.2	152.0	17.8	148.9	11.7	158.7	16.4	162.5	11.3
8----	23.1	3.7	3/ 20.1	5.0	25.2	0	23.8	5.2	24.8	3.6
7----	3/ 96.7	37.8	----	----	3/ 27.1	34.1	149.9	29.4	158.3	31.1
6----	----	----	----	----	----	----	19.6	27.4	29.0	24.6
5----	----	----	----	----	----	----	4/ 29.8	18.3	4/ 31.9	14.2
Total-	911.8	23.4	851.8	23.5	701.8	22.2	910.6	28.4	896.5	25.6
Millions of short tons of nahcolite per square mile-------	403		385		293		489		426	

1/ Interval between dissolution surface and base of zone.

2/ Interval between top of core and base of zone.

3/ Interval between top of zone and bottom of core hole.

4/ Interval between top of zone and base of nahcolite-bearing rocks.