Chapter 2

Nahcolite Resources in the Green River Formation, Piceance Basin, Colorado

By Michael E. Brownfield, Tracey J. Mercier, Ronald C. Johnson, and Jesse G. Self

Click here to return to
Volume Title Page

Chapter 2 of 7

Oil Shale and Nahcolite Resources of the Piceance Basin, Colorado

By U.S. Geological Survey Oil Shale Assessment Team

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Contents

Plates

Figures

Tables

Nahcolite Resources in the Green River Formation, Piceance Basin, Colorado

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Abstract

Nahcolite ($NaHCO_3$) is present in the oil shale deposits of the Parachute Creek Member of the Eocene Green River Formation in the Piceance Basin, northwest Colorado. Here nahcolite forms disseminated aggregates, nodules, bedded units of disseminated brown crystals, and white crystalline beds associated with dawsonite ($NaAl(OH)_2CO_3$) and halite (NaCl). Nahcolite-bearing facies includes a lower part containing the nahcolite and halite, which is estimated to be as thick as 1,130 ft, and an upper leached part several hundreds of feet thick containing minor nahcolite aggregates and nodules. Locally thick beds of halite and brown, fine-grained nahcolite are found at the depocenter of the basin and thin away from the basin center grading laterally into beds of white, coarse-grained nahcolite. The top of the nahcolitic-bearing rocks in the central part of the study area range in depth from about 1,300 to 2,000 ft below ground surface.

Dissolution of water-soluble minerals, mostly nahcolite and halite, in the upper part of the nahcolite-bearing facies has created a collapsed leached zone up to 580 ft thick, which consists of laterally continuous units of solution breccia and fractured oil shale containing solution cavities that once were filled with nahcolite. Several solution breccias can be traced across the dissolution surface that forms the base of the leached zone and into unleached beds of halite and nahcolite. The top of the leached zone is not yet defined in the basin, but it probably extends into the A-groove in the upper part of the Parachute Creek Member.

Resources of nahcolite in oil shale of the lower and middle parts of the Parachute Creek Member are evaluated as part of this oil shale assessment. In some areas nahcolite may be economically minable as a separate commodity. However, because most of the nahcolite occurs in variable-sized aggregates scattered through oil shale beds, in most areas it is subeconomic unless recovered as a co-product of oil shale extraction. Oil shale zones R-3, R-4, L-4, and R-5, from 150 to about 370 ft thick, contain the largest amount of nahcolite by weight. Total amounts of nahcolite in the Parachute Creek Member are extrapolated from estimated mineral contents of 58 core holes. Maps showing thickness, average content, and in-place resources are included in the assessment. Nahcolite resources are as much as 600 million tons per mi^2 in the nahcolite depocenter. The total in-place nahcolite resource is estimated to be about 43.3 billion short tons in the Parachute Creek Member of the Green River Formation in the north-central part of the Piceance Basin.

Introduction

Nahcolite ($NaHCO_3$) is associated with high-grade oil shale (Ertl, 1947) of the Green River Formation, Piceance Basin, northwestern Colorado (figs. 1, 2, 3), and occurs in several forms in the oil shale deposits of the lower and middle parts of the Parachute Creek Member of the Green River Formation. Nonbedded, "semibedded," and several distinctive bedded forms of the mineral, all occurring in close association with one another, attest to the complex geochemical conditions of the depositional environment in which the nahcolite was deposited.

The presence of nahcolite is a concern for the surface retorting and in-situ oil shale processes because nahcolite decomposes to natrite (Na_2CO_3) or soda ash, carbon dioxide, and water at temperatures near 100°C during the two recovery processes. In addition, nahcolite is considered a leasable mineral and thus must not be destroyed during processes used to recover oil from oil shale.

Millions of tons of nahcolite ($NaHC0_3$) occur in the Green River Formation in the Piceance Basin (fig. 1), northwest Colorado (Smith and Milton, 1966; Hite and Dyni, 1967; Trudell, and others, 1970; Young and Smith, 1970; Beard and others, 1974; Dyni, 1974a,b,c; Dyni, 1981). Although the oil shale potential has been reasonably well defined using published information (Stanfield, and others, 1954, 1957, 1960, 1967; Smith, and others, 1968; Trudell and others, 1970; Pitman and others, 1989; Dyni, 1998), little reliable analytical data for nahcolite is available (Smith and Young, 1969; Young and Smith, 1970; Dyni and others, 1971a; Smith and others, 1973). Smith and others (1972) developed a technique for estimating nahcolite from the oil-yield assay data, and Dyni and others (1971a) described a thermal method to determine the nahcolite content of oil shale samples. Beard and others (1974) and Dyni (1974b,c) combined their techniques with the geology of the mineral occurrence within the basin and

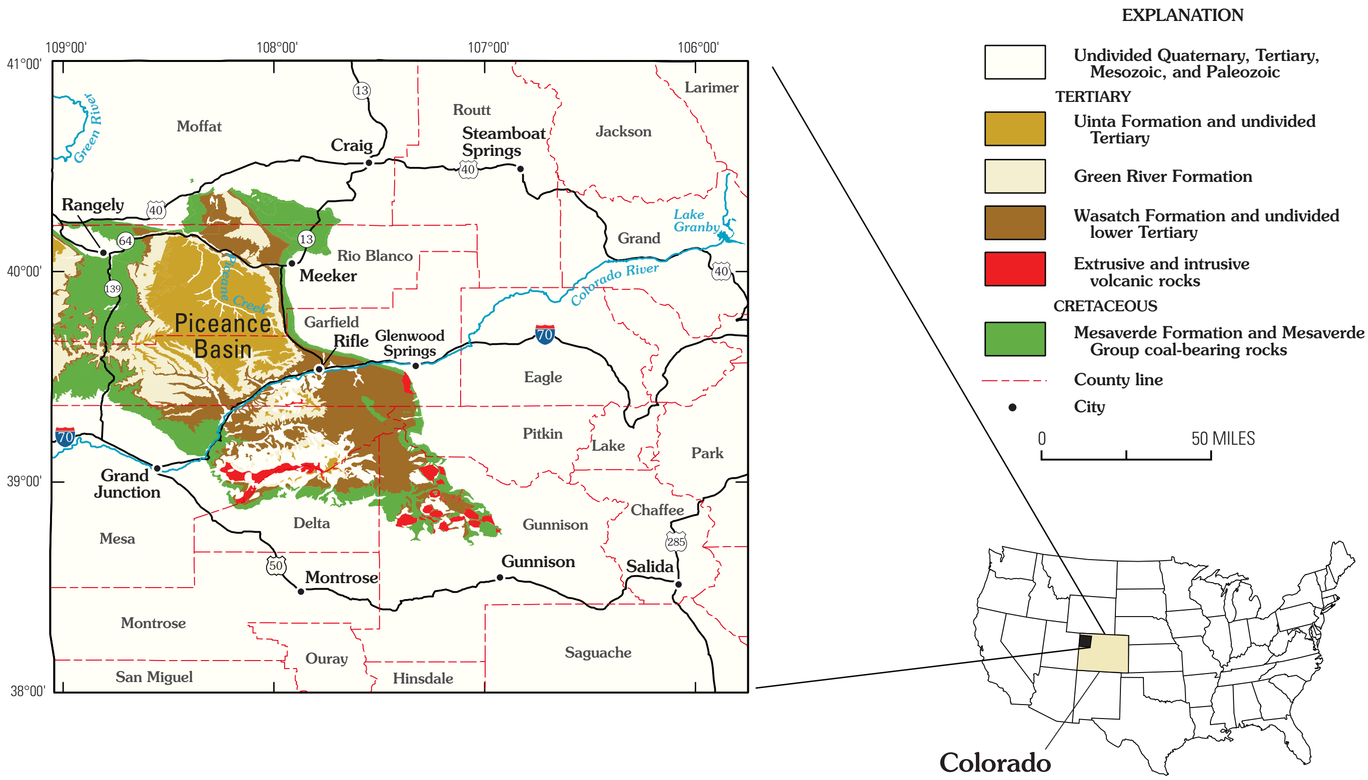

Figure 1. Geologic map of northwest Colorado showing generalized outcrops of the Mesaverde Formation and Group, and the Wasatch, Green River, and Uinta Formations in the Piceance Basin, northwestern Colorado. Modified from Brownfield, Hettinger, and Johnson (2000).

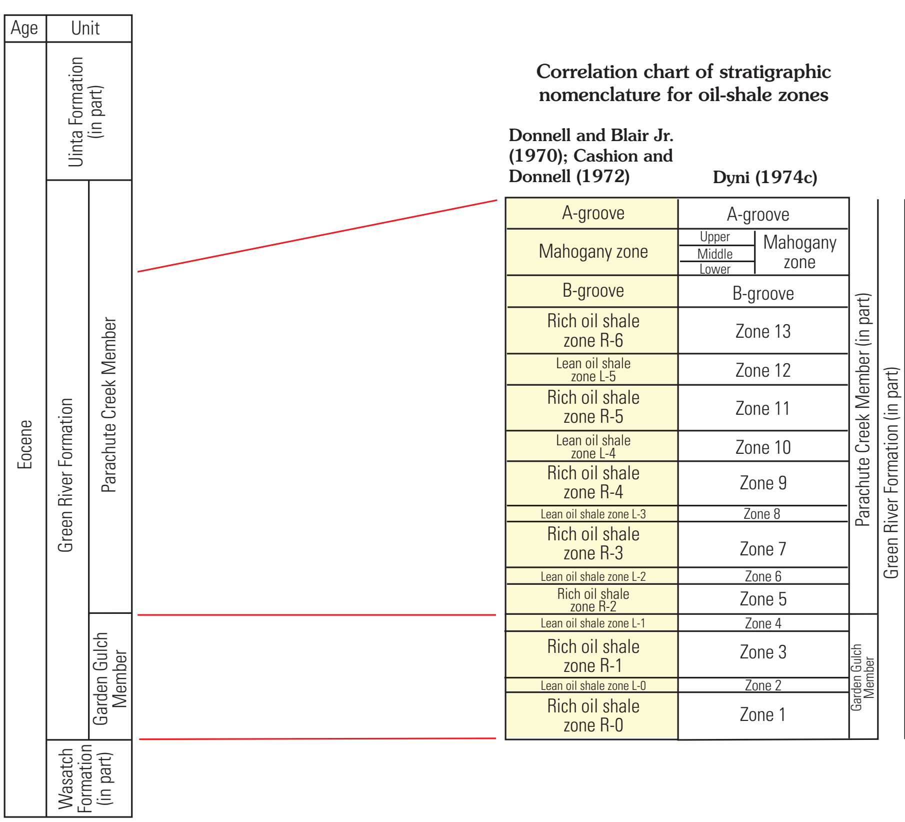

Figure 2. Stratigraphic column and correlation chart of stratigraphic nomenclature for oil shale zones for the Green River Formation, north-central Piceance Basin, Colorado. This assessment uses the nomenclature of Donnell and Blair (1970) and Cashion and Donnell (1972) highlighted in yellow.

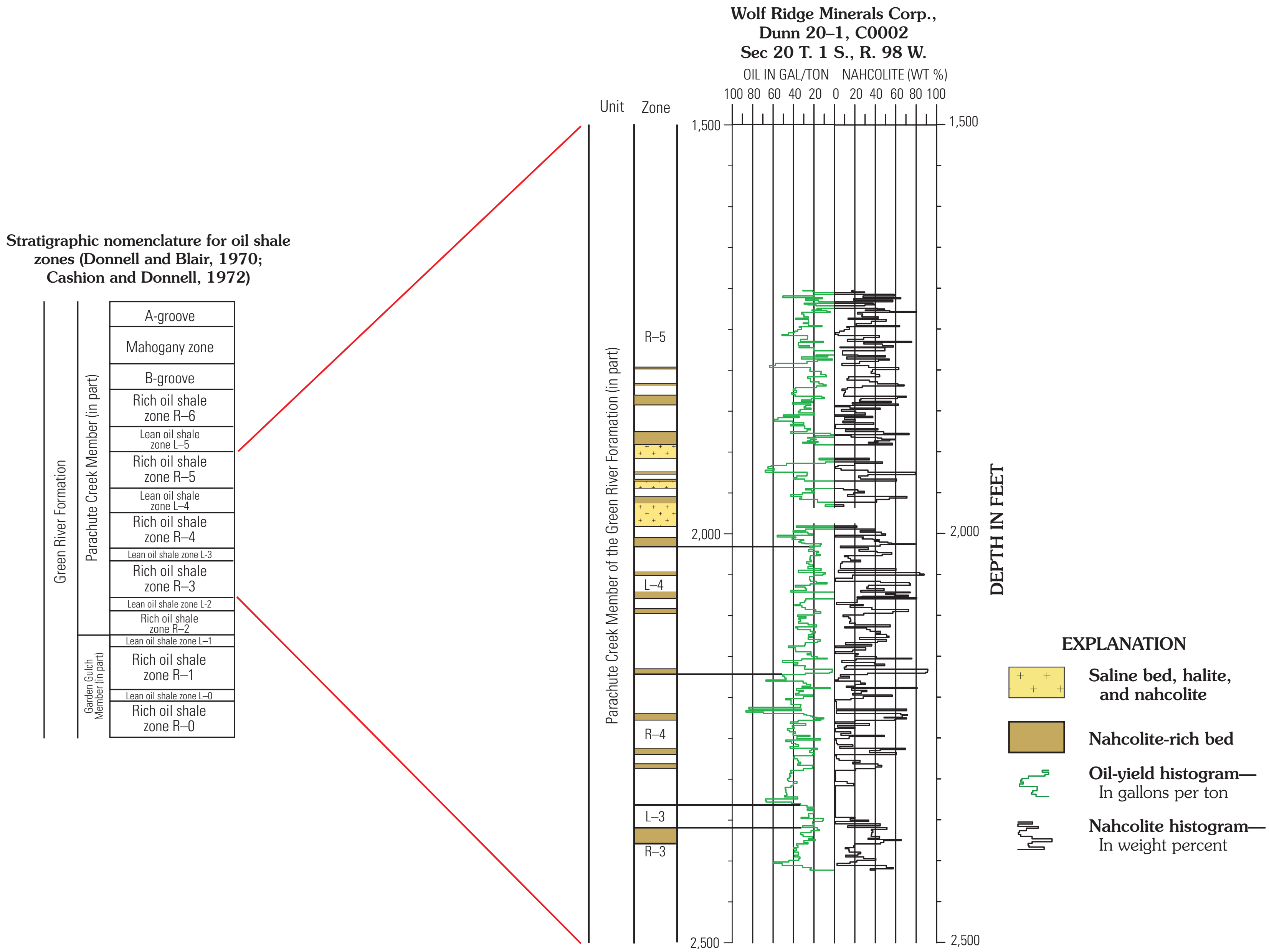

Figure 3. Plot showing oil-yield (GPT) and nahcolite (weight percent) histograms and stratigraphic nomenclature for oil shale zones (Donnell and Blair, Jr., 1970; Cashion and Donnell, 1972) for the Wolf Ridge Minerals Corp., Dunn 20-1 core hole, north-central Piceance Basin, Colorado. WT %, weight percent.

summarized the geologic occurrences and resources of nahcolite. Beard and others (1974) estimated about 29 billion tons of nahcolite using 14 boreholes with nahcolite-content data and eight holes for “0” points to determine the extent of the nahcolite-bearing zone. Dyni (1974c) estimated about 32 billion tons of nahcolite using 10 boreholes with nahcolite-content data. This nahcolite assessment will use the methodology described by Beard and others (1974).

In 2006, the United States consumed about 6,000 tons of soda ash, or about 55 percent of the total production (U.S. Department of the Interior, 2007). The estimated distribution of the 2006 consumption of soda ash by end users was glass (40 percent), chemicals (27 percent), soap and detergents (10 percent), distributors (five percent), flue gas desulfurization (two percent), pulp and paper (two percent), water treatment (one percent), and unnamed uses (four percent). New domestic supplies of these materials are extremely important to the economy of the United States.

Nahcolite, a water-soluble mineral, is a potential raw material for the manufacture of a variety of basic industrial chemicals (Nielsen, 1969, 1972), but the mineral has perhaps received more attention for its potential use in removing sulfur dioxide from industrial stack gases. In the early 1970s, Superior Oil Company developed a small quarry near the mouth of Piceance Creek (figs. 1, 4) in the Parachute Creek Member for a bulk sample to test nahcolite’s effectiveness in scrubbing stack gases. Figure 5 shows boulders containing nodules or aggregates of nahcolite surrounded by oil shale. Several companies have pursued research in the use of nahcolite as a chemical agent for controlling the emission of sulfur dioxide in stack gases of coal-burning electric power plants and smelters. Because nahcolite seems to be a potentially valuable co-product of oil shale, it becomes important to know where and in what abundance nahcolite occurs in the oil shale.

To characterize nahcolite in the Piceance Basin, the U.S. Bureau of Mines (USBM) in the late 1970s drilled a 10-ft-diameter deep shaft (fig. 6) in the northern part of the basin near Piceance Creek. The shaft was drilled to the nahcolite (saline) zone where channel samples were collected (fig. 7) for analysis.

The White River Nahcolite Minerals Company began solution mining the Boies nahcolite bed in 1990 (part of L-5A, Dyni, 1981, 1996) on a Federal lease tract located in the southeastern part of T. 1 S., R. 98 W., in the northern part of the Piceance Basin (fig. 1). The mined part of the Boies nahcolite bed is about 26 ft thick, at the depth of about 1,900 ft, and contains about 80 to 85 percent nahcolite (core holes C0154, C0177, and C0318, pl. 1, 2).

A Colorado company, AmerAlia Inc. (Natural Soda Inc.) purchased the operation and leases in 2003 and produced about 103,000 tons of sodium bicarbonate in 2007. This facility is the only operation currently producing sodium bicarbonate from nahcolite in the basin. The solution mining is currently conducted using in-situ leaching by drilling a vertical hole to the target bed and then drilling horizontally along the base of the nahcolite-bearing interval. Hot water is injected into the nahcolite-bearing zone which dissolves the nahcolite. This nahcolite-bearing brine is then pumped to the surface using a production hole located several hundreds of feet from the injection well (http://www.ameralia.com/). By reducing the temperature of the brine, sodium bicarbonate is recrystallized in the solution. Excess water is then removed by high-speed centrifuging (spin drying). The resultant damp crystal mass is further dried, screened, and packed for sale.

This paper presents data and histograms on the nahcolite content and oil yields (fig. 3) for 58 core holes (fig. 8) and databases that contain nahcolite-content and oil-yield data (nahdata.xls, Nahcolite_Data folder, this CD–ROM), and data on core hole locations, operator and well name, elevation, core location where known, intervals of lithologic log units and geophysical logs, and other data (nahdata.xls) in the Piceance Basin of northwestern Colorado. Table 1 contains data on location and total thickness of the nahcolite interval for the nahcolite-bearing core holes and is sorted by the USGS unique borehole number. Plates 1 and 2 contain detailed stratigraphic cross sections (fig. 9) through the nahcolite facies showing detailed histograms of hundreds of oil shale assays and nahcolite analyses. The oil shale deposits that include the nahcolite-bearing facies are divided into regionally correlatable stratigraphic zones of oil shale (Cashion and Donnell, 1972). Nahcolite-content (in weight percent) and oil-yield (in gallons per ton) histograms for the 58 boreholes used in this assessment are in the Oil_Nahcolite_Plot folder. Core holes used in the cross sections contain oil-yield data above and below the nahcolite-content data have the word “extended” added to the plot-file name and are included in the folder. This report also summarizes the potential resources of nahcolite by oil shale zone in the north-central part of the Piceance Basin following the methodology described by Beard and others (1974). Johnson and others (chapter 1, this CD–ROM) gives a detailed discussion of these zones along with associated estimated in-place oil shale resources.

Location and Geologic Setting

The nahcolite deposits of the Eocene Green River Formation are located in the north-central, and deeper, part of the Piceance Basin in northwest Colorado. Nahcolite-bearing oil shale, ranging from 100 ft to more than 1,100 ft thick, underlies an area in the basin of about 266 mi^2 (about 170,000 acres) in Rio Blanco County (figs. 8, 9). In the depocenter of the nahcolite and associated halite (Dyni, 1969, 1974b,c), north of the Rio Blanco County line, these rocks are about 1,130 ft thick, pinching out toward the basin margins. The top of the nahcolitic-bearing rocks in the central part of the study area range in depth from about 1,300 to 2,000 ft below ground surface. The 58 drill cores studied in this investigation are located mostly in the thicker part of the nahcolite-bearing sequence and their locations are shown on figures 8 and 9.

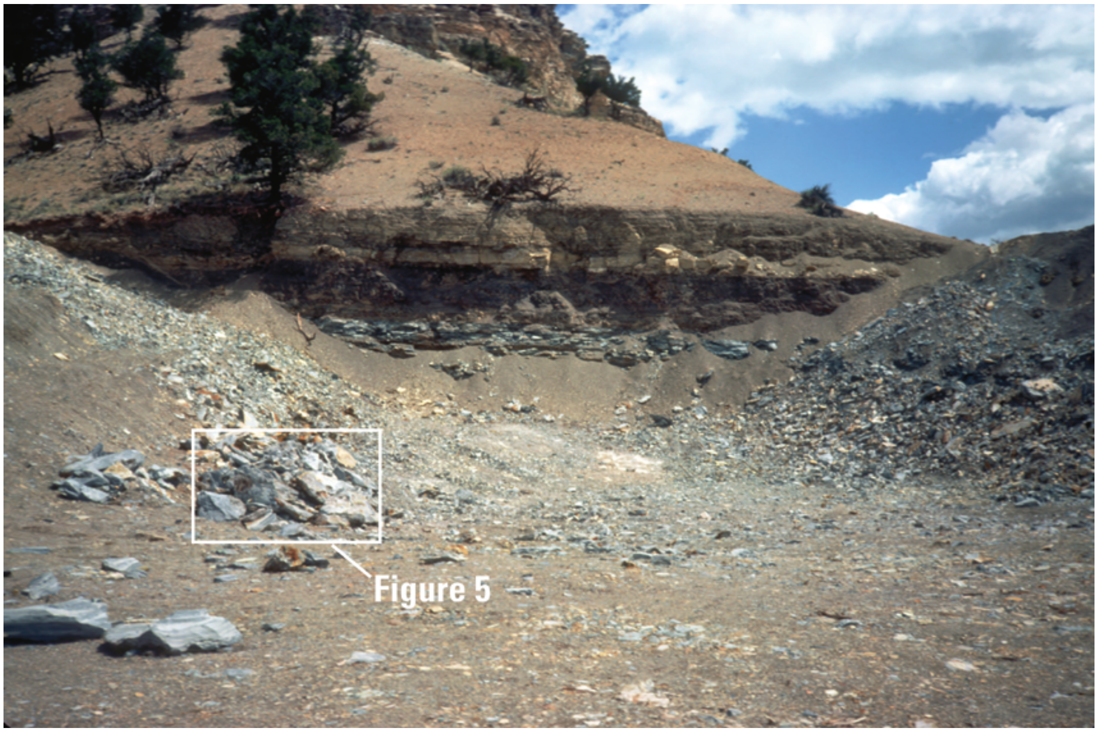

Figure 4. Superior Oil Company's nahcolite quarry located near the mouth of Piceance Creek, Piceance Basin, northwest Colorado. Quarry located in the R-5 oil shale zone (see figs. 2, 3; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation. Nahcolite from the quarry was used to test its effectiveness in scrubbing coal-fired power plant stack gases. Inset shows location of figure 5.

Figure 5. Nahcolite nodules or aggregates in the R-5 oil shale zone (see figs. 2, 3; Cashion and Donnell, 1972) in the Superior quarry in the Parachute Creek Member of the Green River Formation, near the mouth of Piceance Creek (see fig. 1), northern part of the Piceance Basin, Colorado. Bladed crystals of brown nahcolite can be seen in block on left.

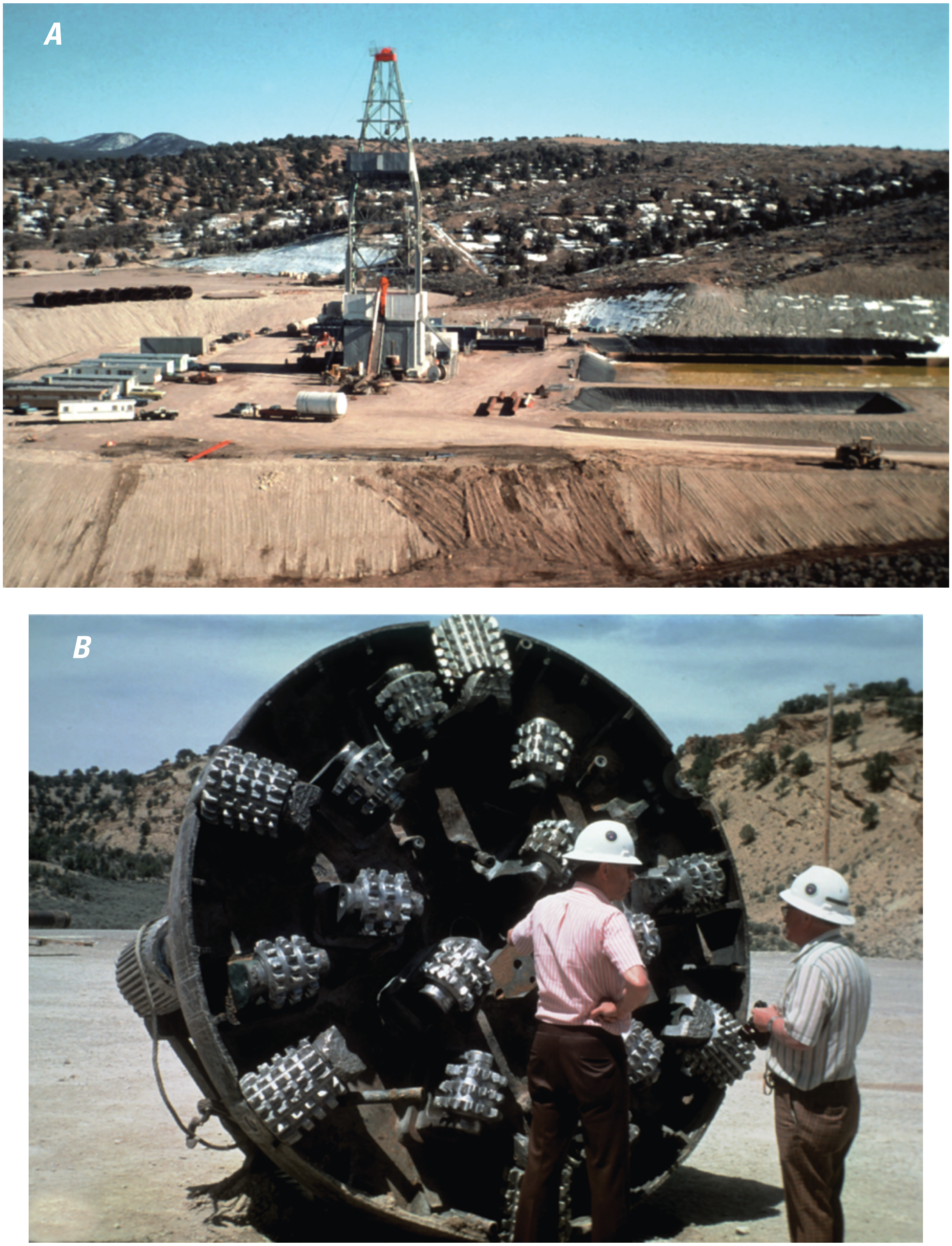

Figure 6. Site of the U.S. Bureau of Mine's deep shaft project in the Piceance Basin, northwest Colorado. *A*, Drill site showing the oil rig that drilled the 10-ft-diameter shaft to the nahcolite (saline) zone in the Parachute Creek Member of the Green River Formation; *B*, the 10-ft-diameter composite drill used in the project.

Figure 7. An excavated face in the Horse Draw Mine, third level, U.S. Bureau of Mine's deep-shaft project (1,834 ft to 1,844 ft). Channel sample analyses of face from roof to floor: nahcolite, 63 weight percent; dawsonite, 3.5 weight percent; oil yield, 12.3 gallons per ton; water, 16.3 gallons per ton; spent shale percent, 85.2; and percent gas plus loss, 3.3. Shaft drilled, with a 10-ft-diameter composite drill bit (see fig. 6). Photograph was taken in 1979 by Robert Bolhmar (U.S. Bureau of Mines).

Stratigraphy

The Piceance Basin in northwestern Colorado (fig. 1) is a broad structural basin of early Tertiary age. During middle Eocene time the basin was occupied by a lake which sometimes covered the entire area, and at other times decreased significantly in size. More than 2,500 ft of organic-rich marlstone (oil shale), sandstone, siltstone, and shale were deposited in this body of water and compose the present day Green River Formation. In the north-central part of the basin, significant amounts of nahcolite, dawsonite, and halite (NaCl) were deposited along with oil shale.

In the north-central part of the Piceance Basin, the Green River Formation is divided from oldest to youngest into a basal sandstone member (Hail, 1972), Garden Gulch, and Parachute Creek Members (fig. 2). The Green River Formation is deposited on the Wasatch Formation and is overlain by the Uinta Formation (Cashion and Donnell, 1974). The sequence of rocks within the study area extends upward from the base of the Garden Gulch Member to the top of the A-groove, a lean oil shale unit in the upper part of the Parachute Creek Member. Oil shale bearing rocks were divided from the base upward into numbered rich-oil and lean-oil zones, the B-groove, the Mahogany zone, and the A-groove (figs. 2, 3; Donnell and Blair, 1970; Cashion and Donnell, 1972). The "L" numbered zones and B- and A-grooves are thin units of relatively low-grade oil shale, whereas the "R" numbered zones and the Mahogany zone are thick units of relatively higher-grade oil shale. The correlation of the numbered zones (Dyni, 1974c) of oil shale with the same, but differently numbered, oil shale zones of Donnell (Donnell and Blair, 1970; Cashion and Donnell, 1972) is shown by the correlation chart on figure 2. It is emphasized that the zonation of the oil shale deposits used in this study is based on economic stratigraphic units. The deposits of nahcolite ($NaHCO_3$) and associated dawsonite ($NaAl(OH)_2CO_3$) and halite (NaCl) are restricted to the lower and middle parts of the Parachute Creek Member (fig. 3). The detailed nahcolite stratigraphy is shown on plates 1 and 2. Plate 1 is an east-west stratigraphic cross section (*A–A'*, fig. 9), and plate 2 is a roughly north-south cross section (*B–B'*, fig. 9). The stratigraphic datum for both cross sections is the top of the R-4 oil shale zone. The first occurrence of nahcolite is in the R-2 oil shale zone and extends through to the A-groove oil shale zone (fig. 2) in the north-central part of the Piceance Basin (figs. 8 and 9).

Geology of the Nahcolite Deposits

Significant quantities of nahcolite are restricted to the lower and middle parts of the Parachute Creek Member and were extensively studied in the late 1960s and 1970s (Smith and Young, 1969; Young and Smith, 1970; Dyni and others, 1971a,b; Smith and others, 1972; Beard and others, 1974; Dyni, 1974b,c) as part of a USBM and USGS effort. In this part of the section, nahcolite occurs both as individual nodules or aggregates and in beds. Nahcolite occurs mostly as brown fine-grained nodules and dark brown radiating nodular aggregates surrounded by oil shale and occasionally rimmed with pyrite (figs. 5, 10). Individual nodules range from less than 1 in. to several ft in diameter (fig. 11), but most nodules range from 1 to 3 in. in diameter (Beard and others, 1974; Dyni, 1974b,c). Although nodular nahcolite is not bedded, nodules do appear to be concentrated in discrete parallel-bedded zones (Dyni, 1974c, his figure 10).

Bedded nahcolite includes: (1) a white coarsely crystalline variety (fig. 11), (2) a brown micro-crystalline type, and (3) a crystal "mush." The white coarsely crystalline form

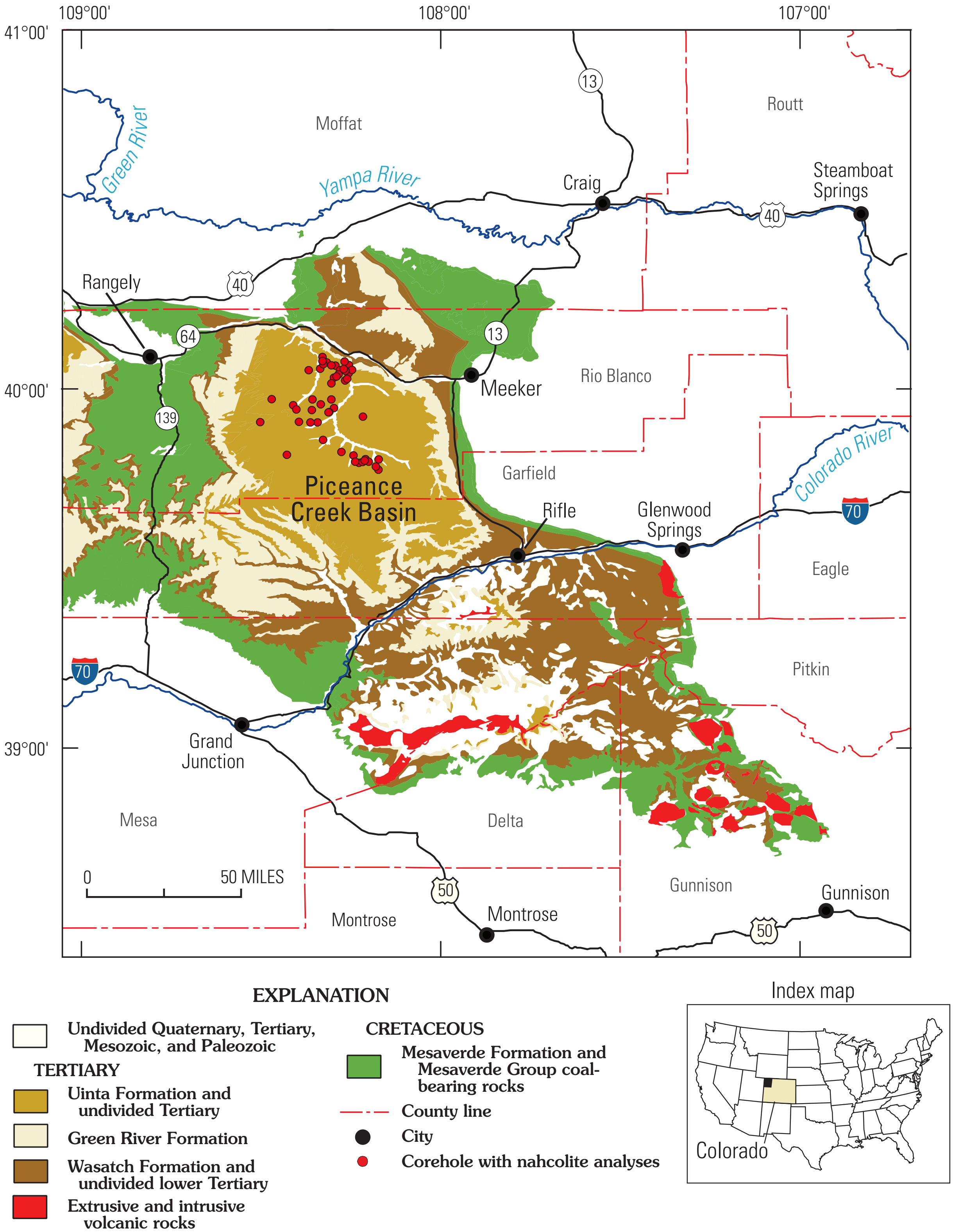

Figure 8. Geologic map of northwest Colorado showing generalized outcrops of the Mesaverde Formation and Group, and the Wasatch, Green River, and Uinta Formations within the Piceance Basin and nahcolite-bearing core holes. Modified after Brownfield, Hettinger, and Johnson (2000).

Table 1. Map number, USGS unique identification number, operator, drill hole name, location data, and total thickness of the nahcolite interval (Nahzonethk, ft) for nahcolite-bearing core holes from the Piceance Basin, northwest Colorado.

Map no.	USGS no.	Operator	Drill hole name	Year	Sec ¼	Sec	Tps	Range	Latitude	Longitude	Nah-zonethk, ft
1	C0001	Kaiser Alum. & Chem. Co.	Nielsen 20-1		SE SE	20	01 S	097 W	39.945196	-108.297279	679.1
2	C0002	Wolf Ridge Minerals Corp.	Dunn 20-1	1966	NE NE	20	01 S	098 W	39.953197	-108.409639	711.2
3	C0004	Sinclair Oil and Gas Co.	Federal 8005	1965	C NE	29	01 N	097 W	40.029541	-108.296808	683
4	C0005	Juhan- Joe T.	Juhan 4-1	1964	SW NE	4	02 S	098 W	39.907458	-108.393696	560
5	C0008	Sinclair Oil and Gas Co.	Skyline 1	1963-64	NW NE	26	01 S	098 W	39.939896	-108.358008	1027
6	C0034	U.S. Bureau of Mines/AEC	Colorado 1	1965-66	NE SE	13	01 N	098 W	40.054067	-108.334852	775.5
7	C0035	U.S. Bureau of Mines/AEC	Colorado 2	1966	NW NE	14	01 S	099 W	39.969743	-108.468959	356.6
8	C0116	Equity Oil Co.	Boies Corehole 1	1964?	SE SW	19	02 S	097 W	39.857189	-108.327264	413.9
9	C0117	Equity Oil Co.	BX-1	1964	NE SE	6	03 S	098 W	39.815737	-108.426791	205.7
10	C0121	Superior Oil Co.	Core hole 19	1973?	SW NE	7	01 N	097 W	40.071055	-108.316812	240
11	C0127	Superior Oil Co.	Core hole 20	1972?	SE NE	22	01 N	097 W	40.041339	-108.256691	30
12	C0128	Superior Oil Co.	Core hole 21	1973?	SE SE	16	01 N	097 W	40.049778	-108.277000	32
13	C0129	Superior Oil Co.	Core hole 26	1973	SE SE	8	01 N	097 W	40.062654	-108.293106	406
14	C0151	Marathon Oil	Square S No. 1	1963	NW NW	4	02 S	097 W	39.91304	-108.293920	427.3
15	C0153	Industrial Resources Inc.	Colorado Minerals 28-1	1966	NE NW	28	01 S	098 W	39.940929	-108.400695	614.5
16	C0154	Wolf Ridge Minerals Corp.	Savage 24-1	1966	NE NE	24	01 S	098 W	39.955157	-108.333725	911.8
17	C0155	Wolf Ridge Minerals Corp.	Colorado Minerals 14-1	1966	NW NE	14	01 S	098 W	39.969399	-108.356659	851.8
18	C0156	Kaiser Alum. & Chem. Co.	Nielsen 17-1	1966	NW NE	17	01 S	097 W	39.968728	-108.304686	697.1
19	C0158	Shell Oil Co.	Greeno 1-4	1962	NE NE	4	03 S	097 W	39.823832	-108.276406	358.6
20	C0171	U.S. Bureau of Mines/AEC	Colorado 3	1967	SW SW	14	01 N	098 W	40.049687	-108.367201	741
21	C0176	Tosco Corp.	TG-2-1	1968	NE SW	21	03 S	096 W	39.774583	-108.174191	0
22	C0177	Shell Oil Co.	22X-1	1968	SW NE	1	02 S	098 W	39.905936	-108.342236	908.8
23	C0179	Shell Oil Co.	23X-2	1968	NE SW	2	02 S	098 W	39.905464	-108.362240	896
24	C0185	Superior Oil Co.	Core hole 01	1967?	SE NW	15	01 N	097 W	40.056713	-108.264637	0
25	C0186	Superior Oil Co.	Core hole 02	1967	NW SW	7	01 N	097 W	40.066628	-108.326619	442
26	C0187	Superior Oil Co.	Core hole 03	1968	SE SE	10	01 N	097 W	40.064201	-108.256233	0
27	C0188	Superior Oil Co.	Core hole 04	1968	SW SE	16	01 N	097 W	40.049638	-108.280762	45
28	C0189	Superior Oil Co.	Core hole 05	1968	NE NW	10	01 N	097 W	40.074038	-108.267452	0

Table 1. Map number, USGS unique identification number, operator, drill hole name, location data, and total thickness of the nahcolite interval (Nahzonethk, ft) for nahcolite-bearing core holes from the Piceance Basin, northwest Colorado—Continued

Map no.	USGS no.	Operator	Drill hole name	Year	Sec ¼	Sec	Tps	Range	Latitude	Longitude	Nah-zonethk, ft
29	C0190	Superior Oil Co.	Core hole 06	1968	SE SW	14	01 N	097 W	40.050616	-108.247115	0
30	C0191	Superior Oil Co.	Core hole 07/07-A	1968	SE SW	8	01 N	097 W	40.063378	-108.304019	34
31	C0192	Superior Oil Co.	Core hole 09	1971	SE NW	32	01 N	097 W	40.013724	-108.303983	564.7
32	C0196	Superior Oil Co.	Core hole 10	1971	SW NW	6	01 N	097 W	40.086293	-108.328794	40
33	C0198	Superior Oil Co.	Core hole 11	1971	NE SW	21	01 N	097 W	40.037817	-108.284772	480
34	C0201	Tosco Corp.	TG-71-1	1972	NE NW	13	03 S	097 W	39.793997	-108.228447	0
35	C0207	Cameron Engineers	CE-705A	1971	SE NE	4	02 S	099 W	39.906745	-108.500650	0
36	C0209	Superior Oil Co.	Core hole 12	1971	SE SW	27	01 N	097 W	40.021269	-108.266003	394
37	C0210	Superior Oil Co.	Core hole 13	1971	SE SW	15	01 N	097 W	40.048516	-108.265406	0
38	C0211	Superior Oil Co.	Core hole 14	1972	NW SE	27	01 N	097 W	40.025835	-108.260396	368
39	C0212	Superior Oil Co.	Core hole 15	1972	SW SW	7	01 N	097 W	40.062682	108.329305	756
40	C0244	Superior Oil Co.	Core hole 22	1973?	NW SW	15	01 N	097 W	40.053192	-108.270214	36
41	C0249	Arco (C-b project)	Sorghum Gulch 01	1974	SE	2	03 S	097 W	39.814632	-108.243464	96
42	C0250	Arco (C-b project)	Sorghum Gulch 06	1974	NW SE	7	03 S	096 W	39.804134	-108.209597	0
43	C0251	Arco (C-b project)	Sorghum Gulch 08	1974	NE SW	9	03 S	096 W	39.803361	-108.173551	0
44	C0252	Arco (C-b project)	Sorghum Gulch 09	1974	SE SE	11	03 S	097 W	39.796995	-108.238358	279
45	C0253	Arco (C-b project)	Sorghum Gulch 10	1974	NE NE	13	03 S	097 W	39.79633	-108.218229	24
46	C0254	Arco (C-b project)	Sorghum Gulch 11	1974	SE SE	7	03 S	096 W	39.796703	-108.201577	0
47	C0255	Arco (C-b project)	Sorghum Gulch 17	1974	SW SW	16	03 S	096 W	39.783535	-108.181817	0
48	C0260	Atlantic Richfield Co.	AT-1A	1974	NE SW	7	03 S	096 W	39.800251	-108.212244	0
49	C0274	Superior Oil Co.	Core hole 32	1974	NW NW	7	01 N	097 W	40.075636	-108.328739	540
50	C0275	Superior Oil Co.	Core hole 30	1974	NW NW	28	01 N	097 W	40.032764	-108.290337	653
51	C0293	U.S. Geol. Survey	CR-1	1975	NW SW	31	01 S	096 W	39.921119	-108.217435	276
52	C0299	U.S. Bureau of Mines	CH 02-A	1975-76	NW SW	29	01 S	097 W	39.933973	-108.310258	1071
53	C0314	Multi Mineral Corp.	MMC-IRI-01	1980	SE SW	26	01 S	098 W	39.927613	-108.362849	987.2
54	C0318	Multi Mineral Corp.	MMC-IRI-03	1981	NW NE	27	01 S	098 W	39.938757	-108.374417	1006.9
55	C0319	Multi Mineral Corp.	MMC-IRI-05	1981	SW SE	23	01 S	098 W	39.943578	-108.355623	1059.7
56	C0321	Multi Mineral Corp.	MMC-IRI-10	1981	SE	14	01 S	098 W	39.96017	-108.355913	1109.3
57	C0322	Multi Mineral Corp.	MMC-IRI-11	1981	NW NE	25	01 S	098 W	39.931608	-108.336011	973
58	C0334	U.S. Bureau of Mines	CH 01-A	1975	NW SW	29	01 S	097 W	39.933331	-108.312157	858

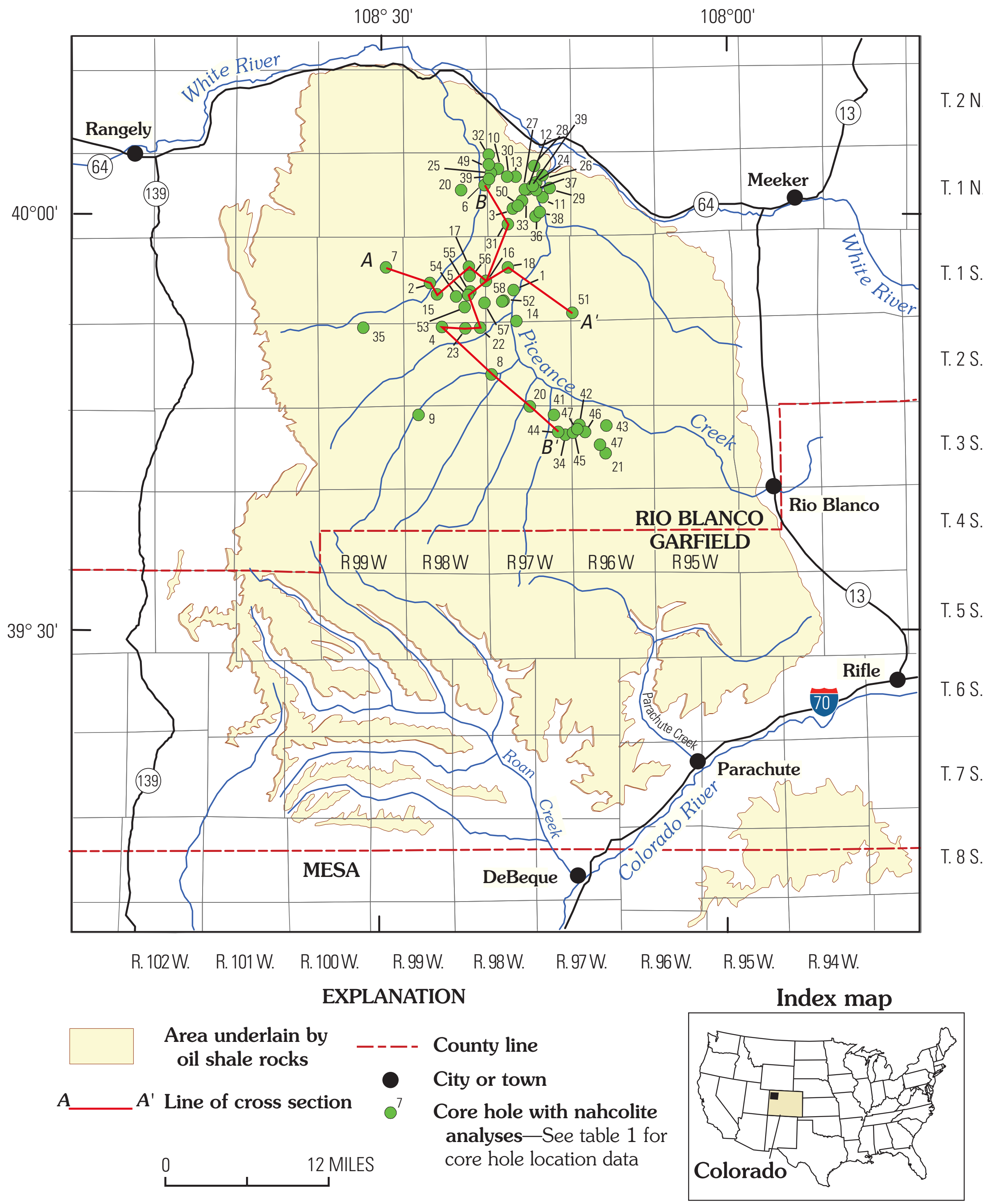

Figure 9. Map of northwest Colorado showing nahcolite-bearing core holes, cross section lines (*A-A′*, plate 1; *B-B′*, plate 2), and generalized area of the oil shale-bearing rocks in the Parachute Creek and Garden Gulch Members of the Green River Formation in the Piceance Basin, northwest Colorado.

of bedded nahcolite commonly is closely associated with halite (Beard and others, 1974; Dyni, 1974b,c). Thin beds of dark-brown microcrystalline nahcolite (fig. 12) are scattered vertically throughout the lower Parachute Creek Member in the center of the basin. Beds of microcrystalline nahcolite commonly less than 1 ft thick, have a texture and appearance similar to brown sugar. The term crystal "mush" has been used to describe a distinct type of bedded nahcolite in which individual crystals of brown nahcolite, varying from 1/8 to 1/2 in. in size, occur in an oil shale matrix (Beard and others, 1974). In some cases the crystals are scattered, whereas in others they are quite closely spaced, comprising as much as 85 percent of the rock. Generally, these crystal zones are less than 10 ft thick, but persist laterally for long distances. Bed thicknesses generally range from less than 1 ft to 10 ft but one nahcolite-bearing zone is more than 60 ft thick in the central part of the north-central Piceance Basin (core holes C0177 and C0318, pl. 1, 2). These thicker units of interbedded nahcolite and halite are present in the north-central portion of the basin (pl. 1, 2; Trudell and others, 1970; Dyni, 1974c). A portion of a thick halite bed recovered during coring (C0334) is shown in figure 13. The halite and nahcolite are preserved as alternating layers of dissolved halite and wafer-like nahcolite resulting from reaction to the drilling fluid.

The mineral composition of the nahcolite-bearing oil shales in the lower and middle parts of the Parachute Creek Member consist chiefly of Fe-bearing dolomite, dawsonite ($NaA1(OH)_2(CO_3)_3$), feldspar (K- and Na-feldspar), and quartz (Dyni, 1974c, p. 113). Generally, calcite, illite, and pyrite are present in small amounts. The mineral composition, including kerogen, for the entire nahcolite-bearing sequence of oil shale in core holes, was determined from hundreds of samples by using a variety of X-ray and chemical methods. Although nahcolite reduces the oil yields obtained by Fischer assay, nahcolite is not a component of the fine-grained matrix of oil shale and the oil shale laminae form around the nahcolite nodules and smaller crystals.

Overlying the nahcolite-bearing section is the so-called "leached zone" (pls. 1, 2). The leached interval is characterized by solution cavities, open fractures, local solution or collapsed breccia (fig. 14), and intervals of porous, earthy marlstone. Substantial amounts of nahcolite and halite originally deposited in this part of the section subsequently have been dissolved and removed by groundwater. Several collapsed-breccia zones can be traced across the dissolution surface that forms the base of the leached zone and into unleached beds of halite and nahcolite (Dyni, 1974c, 1981). The leached zone ranges in thickness from 350 to 580 ft thick and may extend upward into the lower part of the Mahogany zone (Dyni, 1974c). The position of the approximate base of the leached zone does not correspond to any geologic markers and is stratigraphically highest in the vicinity of the basin's depositional center and successively lower toward the basin margins. In some core holes, small amounts of nahcolite, mostly as nodules, may occur above the lowest evidence of leaching, but in this investigation, nahcolite in the leached zone was excluded from our resource estimations.

The nahcolite-bearing interval gradually thins and eventually disappears outward from the basin depositional center toward the margins of the basin. Most of the thinning is the result of post-depositional leaching, but a significant amount of thinning is depositional. Beneath the leached zone, stratigraphically correlatable units of nahcolite-bearing oil shale decrease both in thickness and in sodium carbonate mineral content toward the periphery of the basin (pl. 1, 2). Figure 15 shows the inferred boundary of major nahcolite deposition (this report) and the boundary of sodium carbonate minerals (saline zone), including dawsonite, from the Pitman and others (1989) assessment. The inferred boundary was determined in this study by using the nahcolite-bearing holes in the database and selected non-nahcolite-bearing holes (zero points). The size of the area of nahcolite deposition is about 170,000 acres. Much of the stratigraphic thinning is directly related to a reduction in the volume of nahcolite minerals deposited. In the areas peripheral to the main body of nahcolite, absence of nahcolite may be due either to leaching or to nondeposition.

Smith and Milton (1966) first noted that the lower Parachute Creek Member contained large quantities of dawsonite ($NaA1(OH)_2(CO_3)_3$) and had a greater lateral and vertical distribution than nahcolite (Young and Smith, 1970). This is most likely the reason that the saline zone (Pitman and others, 1989) extends further towards the basin margin than the nahcolite boundary defined in this study (fig. 15). Unlike nahcolite, dawsonite has not been dissolved by the groundwater system and the present distribution of this mineral reflects the original depositional patterns (Dyni, 1974c; 1981). Dawsonite occurs as minute crystals, 5 µm or less in size, disseminated throughout the oil shale matrix (Dyni, 1974c; 1981). Over short intervals, dawsonite may compose as much as 25 percent of the rock (Smith and Milton, 1966), but commonly it comprises less than 10 percent (Young and Smith, 1970). Over most of the basin, the base of the upper halite zone, or its stratigraphic equivalent, marks the top of abundant dawsonite**.** Above this horizon, only minor amounts of dawsonite are present. Little dawsonite is found below the base of the Parachute Creek Member (Trudell and others, 1970). The presence of dawsonite is also a concern for the surface retorting and in-situ oil shale processes, because dawsonite decomposes to natrite (Na_2CO_3) or soda ash, carbon dioxide, and water at temperatures from 200° to 370°C during the two processes. The soda ash would be recovered as part of the retorting process. Dawsonite resources were not addressed in this study because there was not enough chemistry and X-ray diffraction data related to dawsonite in the Colorado oil shale database.

The first occurrence of nahcolite is in the upper part of the R-2 oil shale zone (pl. 1, 2) and forms disseminated crystals of nahcolite in oil shale (Dyni, 1974c, 1981). Dawsonite occurs for the first time also in the lower part of the R-2 oil shale zone (Dyni, 1981), and increases in abundance upwards marking the transition from illitic-rich oil shale to carbonate-rich oil shale (Johnson, 1985, Johnson and others, chapter 1,

Figure 10. Drill core containing bands of light-brown nahcolite, small nodules of nahcolite, and nahcolite aggregates of bladed crystals in oil shale. Some nahcolite aggregates are rimmed with pyrite. Recovered core from the U.S. Bureau of Mines 01A (C0334) borehole (1,554.2 ft to 1,560.3 ft). Core is located in the U.S. Geological Survey's Core Research Center, Denver, Colo.

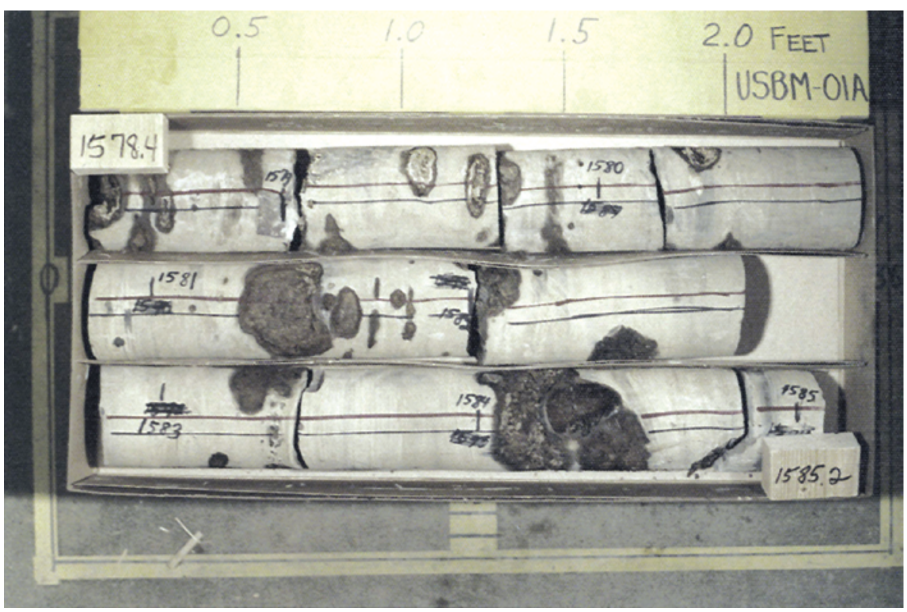

Figure 11. Drill core containing white, coarse crystals of nahcolite, small nodules of nahcolite, and dark-brown nahcolite aggregates of bladed crystals in oil shale. Some nahcolite aggregates are rimmed with pyrite. Recovered core from the U.S. Bureau of Mines 01A (C0334) borehole (1,578.4 ft to 1,585.2 ft). Core is located at the U.S. Geological Survey's Core Research Center, Denver, Colo.

Figure 12. Drill core containing alternating beds of light-brown nahcolite and oil shale. White crystalline aggregate of nahcolite located in right part of upper piece of core. Recovered core from the U.S. Bureau of Mines 01A (C0334) borehole (1,566.5 ft to 1,574 ft). Core is located at the U.S. Geological Survey's Core Research Center, Denver, Colo.

Figure 13. Drill core containing alternating beds of deeply dissolved halite and brown resistant wafer-like nahcolite. Recovered core from the U.S. Bureau of Mines 01A (C0334) borehole (1,512 ft to 1,519.4 ft). Core is located at the U.S. Geological Survey's Core Research Center, Denver, Colo.

Figure 14. Drill core containing collapsed breccia and brown nahcolite and oil shale. Recovered core from the U.S. Bureau of Mines 01A (C0334) borehole (1,219.6 ft to 1,226.5 ft). Core is located at the U.S. Geological Survey's Core Research Center, Denver, Colo.

this CD–ROM). Dyni (1981) reported that the alkaline lake waters most likely altered clays by hydrolysis and replaced them with authigenic minerals including dawsonite, feldspars, and quartz. As the lake waters became more alkaline, anaerobic bacteria reduced most of the sulfate, which in turn allowed for the production of bicarbonate and the precipitation of nahcolite. The nahcolite-bearing zone (saline zone) in the north-central part of the Piceance Basin became well established during the deposition of the R-3 oil shale zone with several thick beds of nahcolite-bearing oil shale (Dyni, 1981). The presence of these thick nahcolite-bearing oil shale beds is, in part, the reason for the increase in thickness of the R-3 zone (Johnson and others, chapter 1, this CD-ROM). The L-3 is a thin oil shale zone (maximum thickness, 68 ft, Johnson and others, chapter 1, this CD-ROM) and contains minor nahcolite-bearing oil shale. Nahcolite is essentially absent in the lower part of the R-4 oil shale zone (Dyni, 1974a,b,c, 1981) in the nahcolite depocenter and only a few nahcolite-bearing beds of oil shale occur from the central to upper parts of the R-4 zone (figs. 3, 16, 17). This would suggest that Lake Uinta was less saline at the beginning of the R-4 zone. Large amounts of nahcolite-bearing oil shale are found in the L-4 oil shale zone (Dyni, 1974a,b,c; 1981) in the depocenter (figs. 3, 16, 17; pl. 1, 2). Several thick, persistent nahcolite beds can be traced throughout the depocenter, (pls. 1, 2). The basal bed of the R-5 oil shale zone contains significant nahcolite in the nahcolite depocenter (figs. 3, 16, 17). Thick beds of halite and nahcolite are found in the lower part of R-5 oil shale zone about 20 ft above the base (Dyni, 1974a,b,c, 1981) and plates 1 and 2 show the regional extent of the thick halite and nahcolite beds within the nahcolite depocenter in the central and northern parts of the Piceance Basin. Thinner beds of halite with minor amounts of nahcolite occur in upper parts of the R-5 zone (Dyni, 1974a,b,c, 1981). Generally, nahcolite content is high in the R-5 zone.

The lower part of the L-5 oil shale zone contains two thick beds of halite with nahcolite (Dyni, 1974b) and core holes C0154 and C0155 (pl. 1, 2) show the thick halite-bearing beds in the L-5 zone. These two beds are the highest stratigraphically preserved saline beds in the Parachute Creek Member of the Green River Formation. Above these beds is a regional collapse breccia indicating that the overlying saline-rich beds have been leached out over much of their original extent (pl. 1, 2). The collapse breccia zone is named the leached zone and its base was called the dissolution surface as first defined by Dyni (1974c). We have adopted the name "base of the leached zone" for the dissolution surface (pl. 1, 2). The R-6 oil shale zone contains only partially leached nodules of nahcolite and solution cavities or vugs that were once filled with nahcolite. These vugs were described by Pipiringos and Johnson (1976) in the upper part of the R-5 zone in an outcrop near the mouth of Piceance Creek (fig. 5). There are no collapse breccia zones in the R-6 zone (Dyni, 1974c) and it is unlikely that thick saline beds similar to those found in the underlying L-5 oil shale zone ever existed in the R-6 zone.

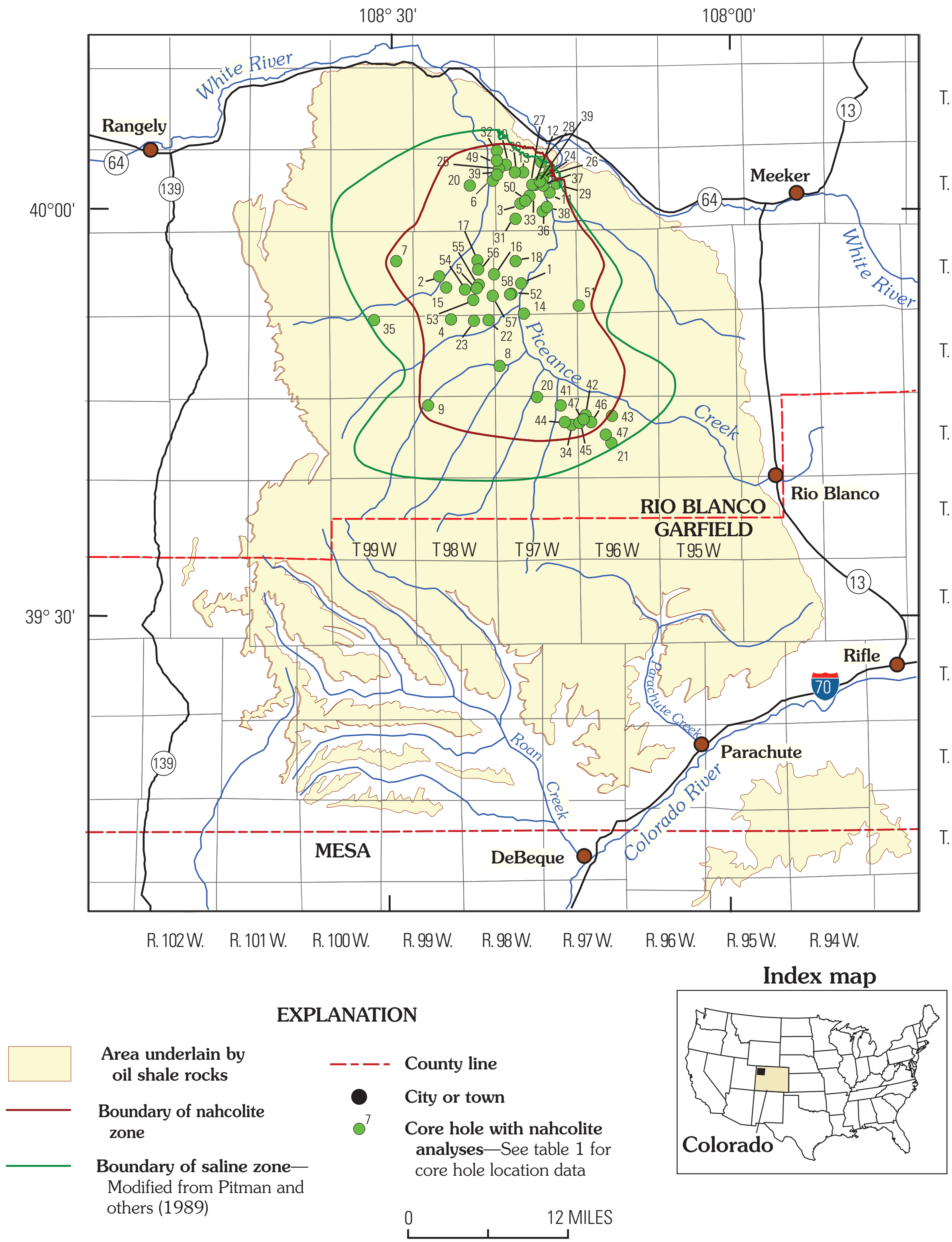

Figure 15. Map of northwest Colorado showing nahcolite-bearing core holes and the inferred boundaries of the nahcolite-bearing zone and the saline zone of Pitman and others (1989), and generalized outcrop of the oil shale bearing rocks in the Parachute Creek Member of the Green River Formation in the Piceance Basin, northwest Colorado.

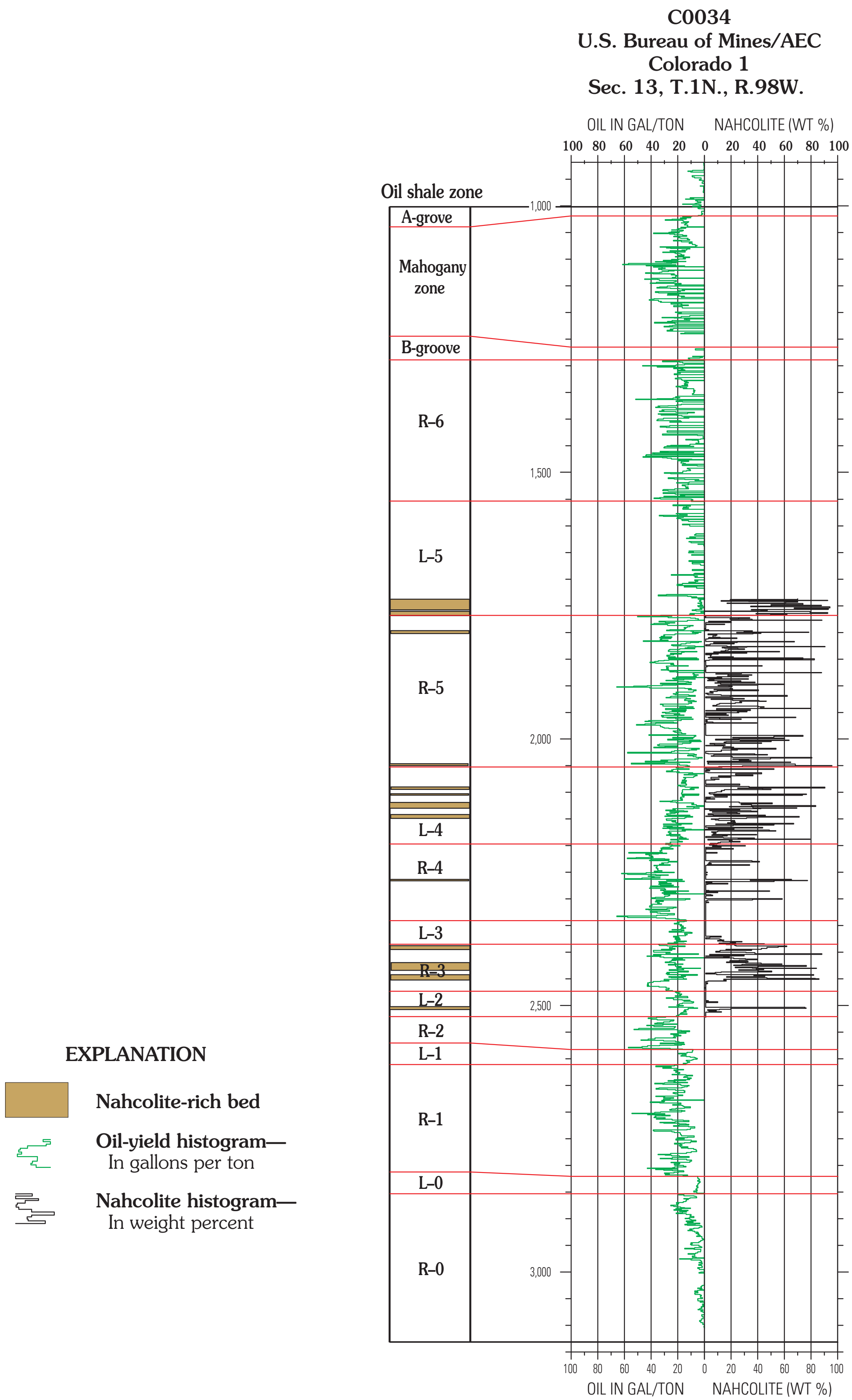

Figure 16. Chart showing oil yields, nahcolite contents, and rich and lean oil shale zones (Cashion and Donnell, 1972) for C0034 core hole, north-central Piceance Basin, Colorado. WT %, weight percent.

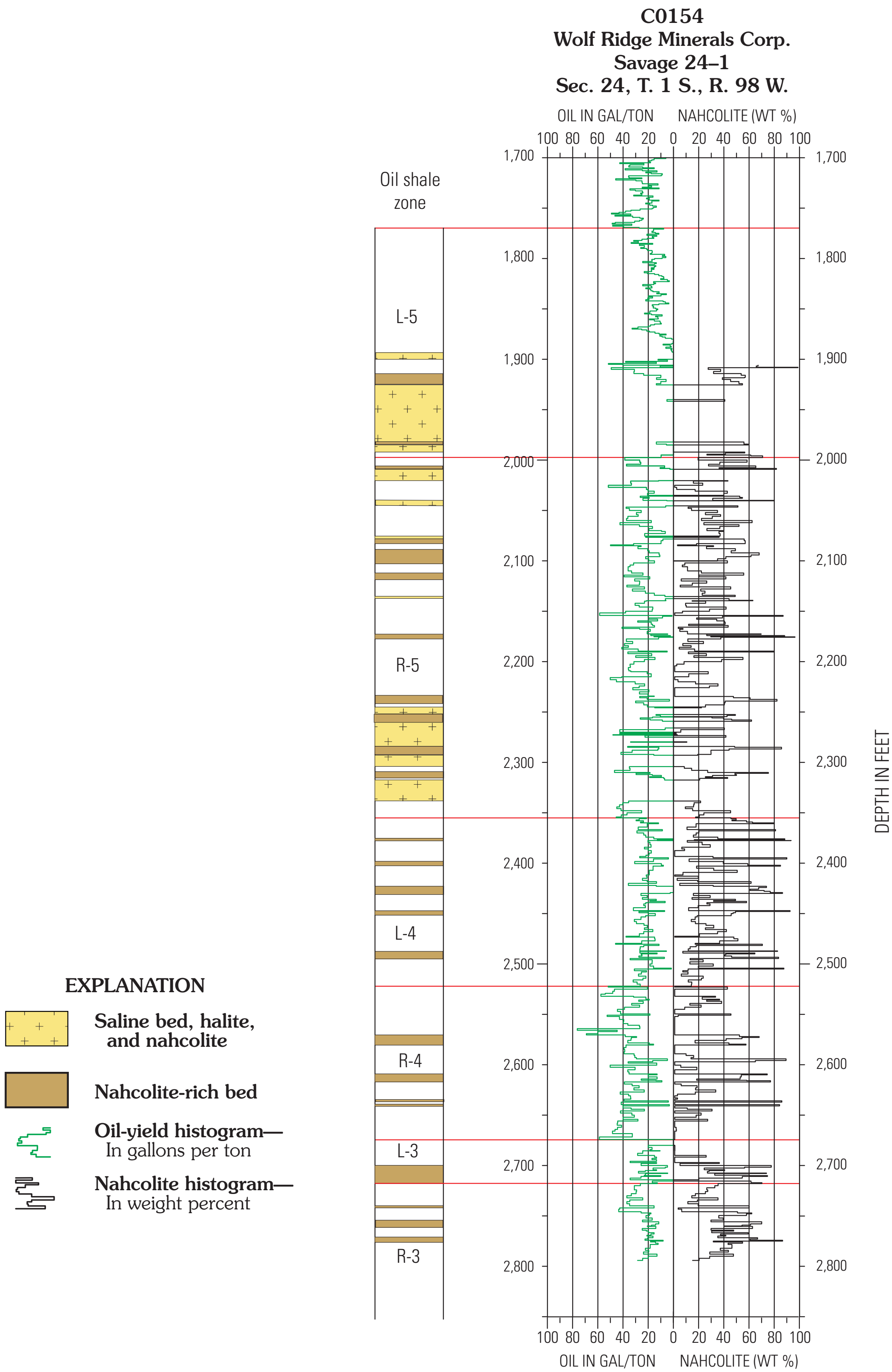

Figure 17. Chart showing oil yields, nahcolite contents, and rich and lean oil shale zones (Cashion and Donnell, 1972) for C0154 core hole, north-central Piceance Basin, Colorado. WT %, weight percent.

The stratigraphically highest evidence of nahcolite in the Parachute Creek Member is not fully understood but there is evidence of nahcolite and saline minerals, including minor solution breccias and disseminated crystals, found as high as the A-groove in 10 cores (Trudell and others, 1970). Dyni (1974b) reports that the B-groove, Mahogany zone, and A-groove contain disseminated crystals of nahcolite, possible halite, and solution cavities. We did not have access to the archived oil shale core (see the CO_Borehole_Info.xls, Nahcolite_Data folder, this CD–ROM) so we could not confirm many of these minor occurrences of nahcolite, halite, vuggy oil shale, and collapsed-solution breccia, and have relied on the observations of the earlier authors and core descriptions found in the USGS National Oil Shale Database located in Denver, Colo.

Nahcolite Resource Methodology

Calculating Nahcolite Content

Estimates of nahcolite content in oil shale samples from the lower part of the Parachute Creek Member of the Green River Formation have been compiled in a database containing 58 core holes (nahdata.xls; naholes_info.xls) by oil shale zone (fig. 8; table 1). This database was compiled from U.S. Bureau of Mines (USBM) and USGS sample data that were analyzed at the USBM Laramie, Wyo., laboratory and contains data on sample interval, alumina (Al_2O_3), Na, nahcolite values in weight percent, specific gravity of the sample, and oil yields in gallons per ton. Table 2 defines the column names in the nahcolite data spreadsheet.

Amounts of nahcolite are estimated using two methods described by Smith and Young (1969), Young and Smith (1970), and Smith and others (1972). The first method was developed by Smith and Young (1969) and involves the leaching of core samples with water to extract water-soluble nahcolite and then determining sodium (Na) content of the solution. Sodium was determined using either flame emission photometry or atomic absorption spectroscopy. Nahcolite content of each sample was determined using the following gravimetric formula (Smith and Young, 1969):

Weight % nahcolite = Weight % Na 3.654

This method assumes that all the water-soluble Na is contained in nahcolite and the sample does not contain halite (NaCl). If a significant contribution of Na from halite is suspected, X-ray diffraction can be used to detect halite in amounts less than one weight percent. If halite is detected, chloride must be determined and a value for water-released Na released by halite can be determined.

The second method to calculate weight percent of nahcolite and dawsonite separately within a sample statistically was developed by Smith and others (1972). This method uses the water and gas contents released by nahcolite during Fischer assay procedures (American Society for Testing and Materials, 1980). The Fischer assay standard method consists of heating a crushed and screened (-8 mesh (2.38-mm mesh) 100-gram sample in a small aluminum retort to 500°C at a rate of 12°C per minute and then held at that temperature for 40 minutes. The volatile vapors of shale oil, gas, and water pass through a condenser cooled with ice water (about 5°C) and collected in a graduated centrifuge tube. The oil and water are then separated by centrifuging and weighed. The quantities reported in the original sample are the weight percentages of shale oil, water, shale residue (contains carbon char), and "gas plus loss" (noncondensable gas yield) by difference. The specific gravity of the shale oil is measured and used to calculate the oil yield in gallons per ton.

The Fischer assay method does not determine the total amount of hydrocarbons in an oil shale sample. The method does not measure the amount or composition of the gases released during the heating of the sample. These gases—chiefly light hydrocarbons, hydrogen, and carbon dioxide—are reported as the "gas plus loss."

During the Fischer assay procedure, the nahcolite completely decomposes as follows at a temperature of about 125°C:

$$2NaHCO_3 = Na_2CO_3 + CO_2 + H_2O \tag{1}$$

Dawsonite decomposes with the following formula at a temperature of about 370° C:

$$2NaA1(OH)_2CO_3 = Na_2CO_3 + A1_2O_3 + 2H_2O + CO_2 \tag{2}$$

These reactions are rapid and easily reached during completion of a Fischer assay (Smith and others, 1972). During the Fischer assay procedure the water is produced by decomposition of nahcolite, dawsonite, and the inorganic and organic matrix of the oil shale is condensed and caught in an oil-water receiver (centrifuge tube), and the carbon dioxide (CO_2) produced escapes as a noncondensable gas. The FORTRAN program (Smith and others, 1972) for the estimation of nahcolite and dawsonite was developed from a data set consisting of 179 samples previously analyzed for nahcolite (Smith and Young, 1969; Young and Smith, 1970) using multiple linear regression techniques (Ezekial and Fox, 1959). Fischer assay data yields for oil, water, gas (plus loss) in weight percent, and oil specific gravity are the independent variables in the equations. Smith and others (1972) state that the estimates for nahcolite and the sum of the sodium carbonate minerals (nahcolite and dawsonite) obtained from Fischer assay data are sufficiently accurate for stratigraphic correlation, whereas individual dawsonite estimates were considered to be generalized. Resource estimates of both nahcolite and dawsonite were accurate within 10 percent.

A third method described by Dyni and others (1971b) involves the heating of nahcolite-bearing oil shale. When nahcolite-bearing oil shale is heated at 105°C for 14 hours,

Table 2. Column names and definitions found in the nahcolite data spreadsheet (nahdata.xls).

Column name	Column definition
OBSNO	Sample number
SAMPLEID	U.S. Bureau of Mines, Laramie, Wyo. laboratory number
TOPFT	Depth, in feet, measured from surface datum to top of sampled interval
BOTFT	Depth, in feet, measured from surface datum to base of sampled interval
SAMPDEN	Density of oil shale core sample
AL2O3_PCT	Al_2O_3 content, in weight percent
NA_PCT	Na content, in weight percent
NAPLOT	Na content, numeric data
NAHCO3_PCT	Nahcolite content, in weight percent
NAHPLOT	Nahcolite content, numeric data
OILWONAH	Oil yield without nahcolite, in gallons per ton
OILWOPLOT	Oil yield without nahcolite, numeric data in gallons per ton
OILWNAH	Oil yield with nahcolite, in gallons per ton
OILWPLOT	Oil yield with nahcolite, numeric data in gallons per ton
OILGPTWNAH	Oil yield with nahcolite in gallons per ton, 0.00B = not analyzed
OSZONE	Oil shale zone (Cashion and Donnell, 1972)
LONGITUDE	Longitude, in decimal degrees
LATITUDE	Latitude, in decimal degrees
USGSID	Unique drill-hole number assigned by the USGS
REMARKS	Comment field

the nahcolite decomposes to sodium carbonate (Na_2CO_3) and releases carbon dioxide and water (see equation 1 above). The weight of the oil shale sample is determined prior to heating and then reweighed after heating and the weight loss is calculated. The nahcolite content of the sample is calculated using the following formula:

$$\text{Nahcolite (weight percent)} = \frac{\text{weight loss (percent)}}{2.690 + 0.375}$$

Dyni and others (1971b) state that the statistical accuracy of the thermal method compared to the chemical method (Smith and Young, 1969) is ± 2 weight percent at the 95-percent confidence limit. Nahcolite contents were determined in 10 cores in the saline facies in the north-central Piceance Basin (Dyni and others, 1971a; Dyni and others, 1974a; Dyni, 1974b,c). The accuracy of the thermal method depends on the absence of other sodium carbonate minerals in the analyzed sample (Dyni, 1974c). The presence of halite in analyzed samples has no effect on Dyni's thermal method because halite does not decompose during the heating of the sample (105°C). The thermal method cannot be used to determine dawsonite in samples of oil shale because the higher temperatures (about 370°C) necessary to completely decompose dawsonite causes measurable thermal decomposition of kerogen at 220°C and would interfere with the weight-loss values for dawsonite.

Calculating Nahcolite Resources

The following data are required from the nahcolite database (nahdata.xls) to estimate nahcolite resources: (1) estimated weight-percent nahcolite for each sample or zone, (2) oil yield in gallon per ton (GPT) determined by Fischer assay, (3) sample or zone depth and thickness, and (4) depth to the top and bottom of the nahcolite intervals. This procedure compensates for the wide variation in oil shale specific gravity with changes in oil yield (Smith, 1956). The procedure, modified from Smith and others (1972), for determining the amount of nahcolite in each well by zone is as follows:

1. Calculate the weight fraction of nahcolite and oil shale in a sample or zone:

$$\text{Weight-fraction nahcolite} = \frac{\text{Weight-percent nahcolite}}{100}$$

$$\text{Weight-fraction oil shale} = 1 - \text{Weight-fraction nahcolite}$$

2. Calculate oil yield of the oil shale weight fraction using Fischer assay oil yield and weight-fraction oil shale (step 1);

$$\text{Oil yield, weight fraction, GPT} = \frac{\text{Oil yield, Fischer assay, GPT}}{\text{Weight-fraction oil shale}}$$

3. Calculate specific gravity of the oil shale weight fraction using quadratic equation that relates oil yield to shale specific gravity (Smith, 1956) using the oil yield, weight fraction (step 2):

$$\text{Specific gravity of oil shale fraction} = \frac{205.988-\sqrt{(205.988)^2+4\times 31.563\times(326.624-\text{Oil yield, weight fraction GPT})}}{2\times 31.563}$$

4. Calculate volume of 1 gram (gm) of sample using nahcolite specific gravity as 2.18 and the specific gravity of the oil shale fraction (step 3):

$$\text{Volume, 1 gm nahcolite sample, cc}=\frac{\text{Weight-fraction nahcolite}}{2.18}+\frac{\text{Weight-fraction oil shale}}{\text{Specific-gravity oil shale}}$$

5. Calculate specific gravity of whole sample using the volume of 1 gm of nahcolite (step 4):

$$\text{Sample specific gravity}=\frac{1}{\text{Volume of 1 gm nahcolite sample}}$$

6. Calculate the weight of 1 cu ft of sample from the sample specific gravity (step 5) using 62.3 lb/cu ft as the weight of water at room temperature in air (Stanfield and others, 1960):

$$\text{Nahcolite sample weight, lb/cu ft} = \text{Sample specific gravity} \quad 62.3$$

7. Calculate the weight in pounds of 1 sq ft of sample as thick as the sample interval or zone thickness in the well using nahcolite sample weight (step 6) and interval or zone thickness from the nahcolite database:

$$\text{Weight, interval or zone, lb/sq ft}=\text{Sample weight, lb/cu ft} \quad \text{Sample or zone thickness, ft}$$

8. Calculate the weight of nahcolite in the nahcolite-bearing interval or zone in the well using the weight fraction of nahcolite (step 1) and the weight of 1 sq ft of the interval or zone calculated in step 7:

$$\text{Weight, nahcolite in well or zone, lb/sq ft}=\text{Nahcolite weight fraction} \quad \text{weight, interval or zone}$$

9. Calculate short tons of nahcolite per mile by multiplying the weight of nahcolite in a well or zone (step 8) by a given number of sq ft (1 mile = 27,878,400 sq ft) and divide by 2,000 lbs/short ton:

$$\text{Nahcolite, short tons/sq mi} = \frac{\text{Weight of nahcolite, lb/sq ft} \quad 27{,}878{,}400 \text{ sq ft/mi}}{2{,}000 \text{ lbs/short ton}}$$

For this assessment Microsoft Excel spreadsheets were created that contained nahcolite weight-percent data derived from the original USBM analyses and USGS nahcolite analyses (nahdata.xls). These spreadsheets were combined into one spreadsheet using a public domain macro which can be obtained at the following site: http://www.vbaexpress.com/kb/getarticle.php?kb_id=151. The combined spreadsheet was then imported to a master oil shale assessment Microsoft Access database and converted to a table. Once in Access, the table was able to be linked to other tables using a master form in order to perform calculations.

The methodology for calculating in-place nahcolite resources (Beard and others, 1974), shown above, was regenerated in the Access form module using several controls and Visual Basic scripting. The methodology and its associated control boxes were able to draw filtered data from the nahcolite table and from a Fischer Assay table for the Piceance Basin. To calculate in-place nahcolite resources an average nahcolite-weight percent was first calculated from the Fischer Assay table for each oil shale zone (Cashion and Donnell, 1972). For each zone, an average gallons per ton (GPT) oil yield was also extracted from the Fischer Assay table using only that part of a particular oil shale zone which contained nahcolite. The resultant value from the formula yielded (tons of nahcolite per square mile) for each zone in each hole. The process was repeated for the average nahcolite value over the total thickness of the nahcolite-bearing interval in each drill hole, resulting in values in tons of nahcolite per square mile for the entire nahcolite-bearing interval.

The resultant values were then linked to spatial data including the regional extent of oil shale bearing rocks and Public Land Survey System (PLSS) data in ArcGIS (Environmental Systems Research Institute, Inc. (ESRI), Redlands, Calif., 2006, ver. 9.2). As the assessment-analysis cell size was one acre, all values for tons per square mile were converted to tons per acre.

In this assessment we tried three spatial interpolation and extrapolation methods for generating resource maps and resource numbers: (1) Radial Basis Function (RBF) method in ArcGIS GeoStatistical Analyst (Environmental Systems Research Institute, Inc. (ESRI), Redlands, Calif., 2006, ver. 9.2); (2) Inverse Distance Weighted (IDW) method in ArcGIS GeoStatistical Analyst (Environmental Systems Research Institute, Inc. (ESRI), Redlands, Calif., 2006, ver. 9.2); and (3) EarthVision's minimum tension gridding method (Dynamic Graphics, Alameda, Calif., 2004, ver. 7.5). The three methods gave similar results, and we ultimately settled on the RBF method. EarthVision was limited with a maximum gridding size (2,001 2,001 cells) that was smaller than the Piceance Basin study area using our one-acre cell size. Pitman and others (1989) used geostatistical interpolation by kriging to generate their resource maps. However, kriging requires an understanding of advanced statistical concepts, and false results can be obtained if kriging is not done correctly. Pitman and others (1989) found that kriging gave good results in areas with large numbers of data points, but that it calculated unreasonable resource numbers with large error limits in areas with little control. We compared our results obtained by the RBF method with those derived by kriging (Pitman and others, 1989) and found that the two methods calculated similar resource numbers. A detailed discussion of this assessment and its comparison to the Pitman and others (1989) assessment is found in the oil shale assessment chapter included with this assessment (Johnson and others, chapter 1, this CD–ROM).

The Radial Basis Function (RBF) method in GeoStatistical Analyst is an exact interpolator; it will honor all data points and not introduce any error at those locations. Where it is important for the modeling method to honor the measured values, RBF can also extrapolate values above or below the actual values outside the data-point locations. The final resource models for each nahcolite-bearing zone were created using a sampling method containing 10 moving window sectors with 15 neighbors or sample points in each sector except for the L-5 zone where the model was limited to 10 sample points. After numerous iterations, these parameters were found to yield the "best" nahcolite-resource models. It has been demonstrated that the RBF method can give comparable results to those from the kriging method (Rusu and Rusu, 2006).

Although the RBF method does not generate as complete an error estimate as kriging, it does give the difference between the predicted and measured value for each control point and an overall error for the entire map. To obtain the difference between the predicted value and the measured value, the RBF method predicts a value at a given control point from the nearest control points (in this assessment either 10 or 15) without knowing the actual value measured at that control point. That predicted value is then compared with the measured value, and the difference between the two is calculated.

Nahcolite-resource models using the nahcolite database (nahdata.xls) were created using ESRI's ArcGIS GeoStatistical Analyst extension. The RBF in GeoStatistical Analyst was used to interpolate (and extrapolate) surfaces using a multiquadric gridding method. Once the models were created, we were then able to quantify total tonnages of nahcolite by using ESRI Spatial Analyst's Zonal Statistics function. We determine tonnages per township by using the nahcolite model (208.71 ft = 63.615-m cell size) and a township grid which had been clipped with an outcrop file based on the base of the Mahogany zone of the Green River Formation for both nahcolite resources in the oil shale zones and the total in-place nahcolite within the inferred extent of the nahcolite-bearing interval. In short, as the cell size in the model is one acre, the function sum totals all of the cells contained by each polygon to be assessed in the zone data set.

A more detailed discussion of this methodology used in determining in-place nahcolite and oil shale resources is found in the methodology chapter included with this assessment (Mercier and others, chapter 3, this CD–ROM).

Nahcolite Resources

Nahcolite resources in oil shale of the lower and middle parts of the Parachute Creek Member of the Green River Formation (fig. 2) in the Piceance Basin, Colorado were evaluated and estimated using the methodology of Beard and others (1974). This report presents an in-place assessment of nahcolite resources using 58 core holes and geologic data defining the deposit in Rio Blanco County (fig. 8). The size of the area included in this assessment is about 170,000 acres. Table 1 lists the nahcolite-bearing core holes used in this assessment and are sorted by the USGS unique borehole number (C0002, where C = Colorado). An Excel spreadsheet (nahdata.xls) containing data on weight-percent nahcolite, oil yield in gallons per ton, and oil shale zones, is included in this assessment. Table 2 describes the column names for the spreadsheet.

Nahcolite resources were determined by oil shale zone (fig. 2; Donnell and Blair, 1970; Cashion and Donnell, 1972) where sufficient data was available in the nahcolite-bearing interval (fig. 15). Plates 1 and 2 show nahcolite-content and oil-yield histograms and correlations of selected halite and nahcolite-rich beds within the oil shale zones in the northern and central parts of the Piceance Basin (fig. 5). The thickness of the nahcolite-bearing interval for each oil shale zone was determined for the 58 core holes and the average nahcolite content in weight percent was determined for each zone present in each core hole. Both average nahcolite content and nahcolite-bearing interval thickness are used to determine the total in-place nahcolite resources. Following the methodology of Beard and others (1974), described previously, nahcolite contents in tons per acre were determined for the core holes. Isopleth maps and resource tables were generated for each nahcolite-bearing zone.

The first occurrence of nahcolite is in the upper part of the R-2 oil shale zone (pl. 1, 2) and consists mostly of disseminated crystals (Dyni, 1974c, 1981) marking the transition from illitic-rich oil shale to carbonate-rich oil shale (Johnson, 1985, Johnson and others, chapter 1, this CD–ROM). Fifteen core holes contained nahcolite data within the R-2 zone (fig. 18, see fig. 9 and table 1). Nahcolite contents range from about 400 to more than 13,000 tons per acre. Regionally, the nahcolite content in the zone thins towards the margins of the inferred extent of the nahcolite-bearing zone (fig. 15). Nahcolite deposition is greatest in T. 1 S., R. 98 W. where one core hole contained a nahcolite content of about 13,250 tons per acre (fig. 18, C0318, see fig. 9 and table 1) and the township contains about 205 million tons of nahcolite (fig. 19 and table 3). The total in-place nahcolite resource in the R-2 zone is about 386 million tons and covers an area of more than 91,000 acres (table 3).

The central part of the nahcolite depocenter was less developed in L-2 oil shale zone than in the R-2 zone (fig. 20), but the L-2 zone covers more of the inferred nahcolite depositional area (fig. 15). Twenty core holes contained nahcolite data within the L-2 zone (see fig. 9 and table 1) and the nahcolite deposition is greatest in townships T. 1 S., R. 97 W. and T. 1 S., R. 98 W., where more than 1.4 billion tons of nahcolite is estimated to be in the L-2 zone (fig. 21) and nahcolite contents are greater than 50,000 tons per acre. The total in-place nahcolite resource in the L-2 zone is more than 2.75 billion tons (table 4) and covers an area more than 158,000 acres in size.

The nahcolite depocenter in the north-central part of the Piceance Basin became well developed during the deposition of the R-3 oil shale zone (fig. 22, pl. 1, 2). Several thick beds of mostly nahcolite are found throughout the zone (Dyni, 1974c, 1981) and can be correlated across the depocenter (pl. 1, 2). Thirty-five core holes contained nahcolite data within the R-3 zone (see fig. 9 and table 1). Several core holes contain nahcolite contents greater than 100,000 tons per acre (fig. 22). The nahcolite deposition is centered in T. 1 S., R. 98 W. where more than 2.489 billion tons of in-place nahcolite was estimated to be within the R-3 zone (fig. 23) where nahcolite contents are greater than 125,000 tons per acre (fig. 22). The nahcolite deposition thins towards the margins of the nahcolite-bearing zone (fig. 22). The total in-place nahcolite resource in the R-3 zone is more than 10 billion tons (table 5) and covers an area of more than 166,000 acres.

Nahcolite deposition in the L-3 oil shale zone (fig. 24) is considerably less than the R-3 zone (fig. 22, pl. 1, 2) but still covers most of the nahcolite-bearing interval (fig. 15). Twenty-eight core holes contain nahcolite data within the L-3 zone (see fig. 9 and table 1). Two minor depositional centers developed: one near the southern margin of the depocenter and the other in the central part where maximum nahcolite contents are greater than 30,000 tons per acre (fig. 22). Nahcolite deposition thinned towards the margins of the nahcolite-bearing interval (fig. 24). Over an area of more than 159,000 acres, the total in-place nahcolite resource in the L-3 zone is more than 2.3 billion tons (fig. 25, table 6).

Nahcolite deposition is generally missing in the lower part of the R-4 oil shale zone and increases towards the top of the zone (pl. 1, 2). The central part of the depocenter redeveloped westward compared to the L-3 zone (fig. 24) where nahcolite contents are greater than 75,000 tons per acre (fig. 26). Thirty-one core holes contain nahcolite data within the R-4 zone (see fig. 9 and table 1). Nahcolite deposition is greatest in T. 1 S., R. 98 W. where more than 1.8 billion tons of nahcolite was estimated in the R-4 zone (fig. 27) and thins towards the margins of the inferred nahcolite-bearing zone (fig. 26). Over an area of more than 160,000 acres the total in-place nahcolite resource in the R-4 zone is more than 6.8 billion tons (table 7).

The L-4 oil shale zone contains large amounts of nahcolite within the nahcolite-bearing zone (fig. 28, pl. 1, 2) and several nahcolite beds have been correlated across the depocenter (Dyni, 1974c, 1981). Thirty-one core holes contain nahcolite data and were used in this assessment. The richest part of the nahcolite-bearing zone is located in T. 1 S., R. 97 W. and T. 1 S., R. 98 W. where nahcolite contents in four core holes are greater than 150,000 ton per acre (fig. 28) and an in-place nahcolite resource of about 2.3 and 3.2 billion tons, respectively (fig. 29). The maximum content trends are in a northeasterly and southeasterly direction from the center of the depocenter (fig. 28). The total in-place nahcolite resource by township in the R-4 zone is more than 10 billion tons (table 8) over an area of more than 127,000 acres.

Thick beds of halite with minor nahcolite characterize the lower part of the R-5 oil shale zone with thinner beds of halite and nahcolite found in the upper part of the zone (pl. 1, 2). Although the nahcolite depocenter is smaller (fig. 30), the nahcolite contents in the R-5 zone are comparatively high. The richest area of nahcolite is mostly found in T. 1 S., R. 98 W. where nahcolite contents in a large area are greater than 300,000 tons per acre (fig. 30) and an in-place nahcolite resource of about 5 billion tons (fig. 31). Thick beds of nahcolite are correlatable across the nahcolite-bearing interval (pl. 1, 2). Twenty-seven core holes contain R-5 zone nahcolite data and were used in this assessment (fig. 30). The total in-place nahcolite resource in the R-5 zone is more than 12.9 billion tons (fig. 31 and table 9) over an area of more than 119,000 acres.

The lower part of the L-5 oil shale zone contains two thick beds of halite and minor nahcolite (pl. 1, 2). These two beds are the highest preserved halite beds in the nahcolite-bearing part of the Parachute Creek Member of the Green River Formation in the Piceance Basin (Dyni, 1974c, 1981). Above these beds is the collapsed leach zone, which indicates that a saline bed was most likely present (pl. 1, 2). The nahcolite depocenter is considerably smaller in the L-5 zone due to both regional leaching and nondeposition (fig. 32) when compared to the R-5 zone (fig. 30). The nahcolite-bearing interval is characterized by two depocenters: one near the northern nahcolite-deposition boundary, and the second located near the center of the depocenter. Most of the L-5 nahcolite resource is located in T. 1 S., R. 98 W. where more than 498 million tons

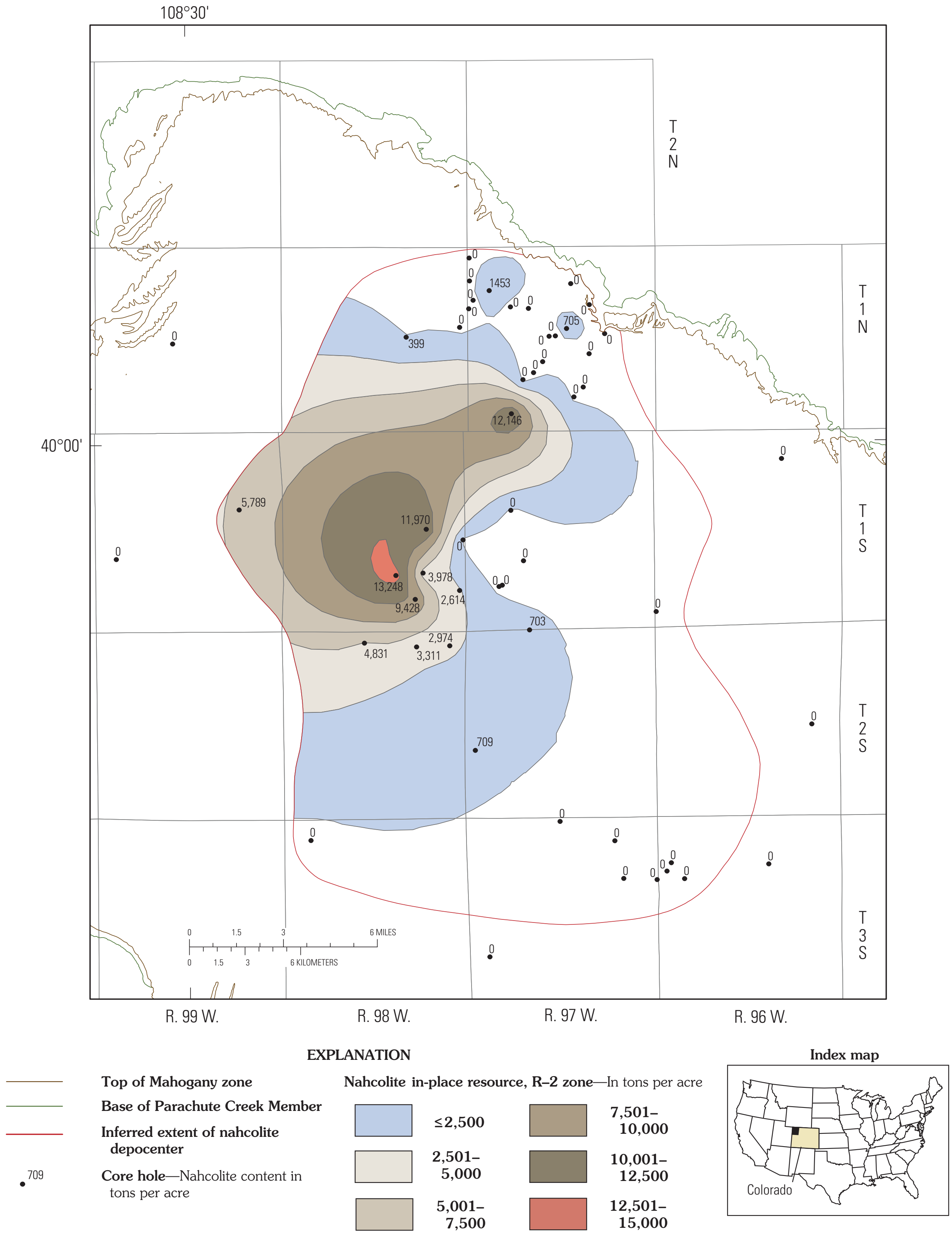

Figure 18. Isopleth map showing in-place nahcolite ($NaHCO_3$) resources in the R-2 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons per acre. Inferred extent of nahcolite depocenter outlined in red.

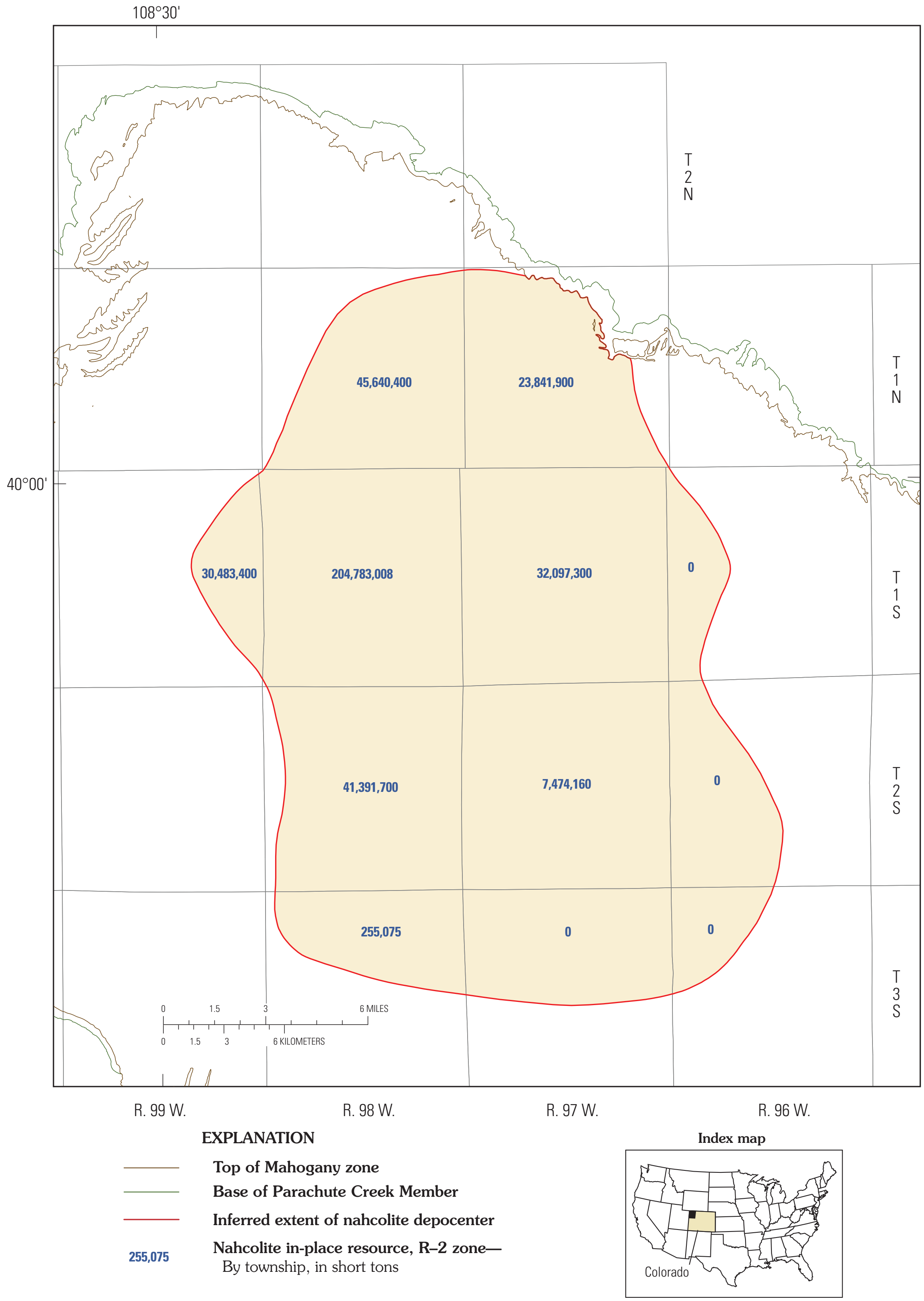

Figure 19. Map showing in-place nahcolite ($NaHCO_3$) resources in the R-2 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation by township, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons. Inferred extent of nahcolite depocenter outlined in red.

Table 3. Total in-place nahcolite resources and average tons per acre, by township, in the R-2 oil shale zone in the nahcolite-bearing interval of the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado.

[All values calculated by ESRIs ArcGIS GeoStatistical Analyst Extension with a Radial Basis Function (RBF) Multiquadratic Gridding Function; 1 acre = 4,047 m^2]

Township	Acres	Area (m^2)	Average tons per acre	Total in-place resource in tons
T1N R97W	7,560	30,594,300	1,430	23,842,000
T1N R98W	11,616	47,008,400	2,819	45,640,000
T1S R96W	0	0	0	0
T1S R97W	11,936	48,303,400	1,313	32,097,000
T1SR 98W	23,832	96,445,000	8,588	204,783,000
T1S R99W	4,881	19,752,800	6,245	30,483,000
T2S R96W	0	0	0	0
T2S R97W	9,992	40,436,300	318	7,474,000
T2S R98W	20,483	82,892,000	2,018	41,392,000
T3S R96W	0	0	0	0
T3S R97W	0	0	0	0
T3S R98W	744	3,010,870	30	255,000
Total	**91,044**	**368,443,070**		**385,966,000**

Table 4. Total in-place nahcolite resources and average tons per acre, by township, in the L-2 oil shale zone in the nahcolite-bearing interval of the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado.

[All values calculated by ESRIs ArcGIS GeoStatistical Analyst extension with a Radial Basis Function (RBF) Multiquadratic Gridding Function; 1 acre = 4,047 m^2]

Township	Acres	Area (m^2)	Average tons per acre	Total in-place resource in tons
T1N R97W	10,216	41,342,800	13,387	223,166,000
T1NR 98W	16,173	65,450,000	11,232	181,878,000
T1S R96W	4,844	19,603,000	20,560	99,594,000
T1S R97W	24,450	98,945,900	31,356	766,653,000
T1SR 98W	23,844	96,493,500	27,321	651,450,000
T1S R99W	4,881	19,752,800	14,665	71,581,000
T2S R96W	9,719	39,331,500	4,785	46,503,000
T2SR 97W	23,478	95,012,400	11,435	268,462,000
T2S R98W	20,507	82,989,100	18,694	383,348,000
T3S R96W	2,594	10,497,600	403	1,595,000
T3SR 97W	10,008	40,501,100	2,147	27,566,000
T3S R98W	8,033	32,508,500	3,757	32,356,000
Total	**158,747**	**642,428,200**		**2,754,151,000**

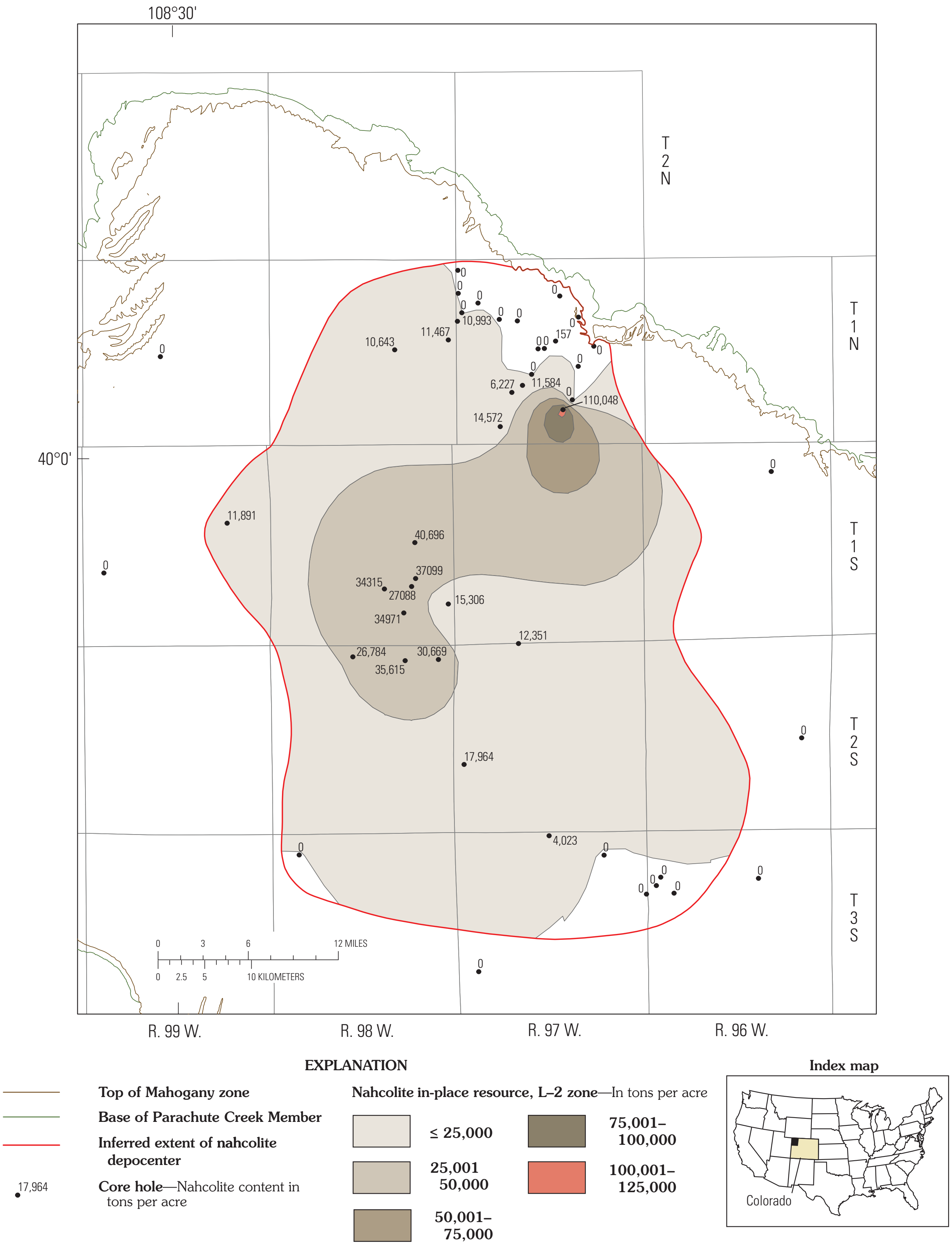

Figure 20. Isopleth map showing in-place nahcolite ($NaHCO_3$) resources in the L-2 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado. Nahcolite resource reported in short tons per acre. Inferred extent of nahcolite depocenter outlined in red.

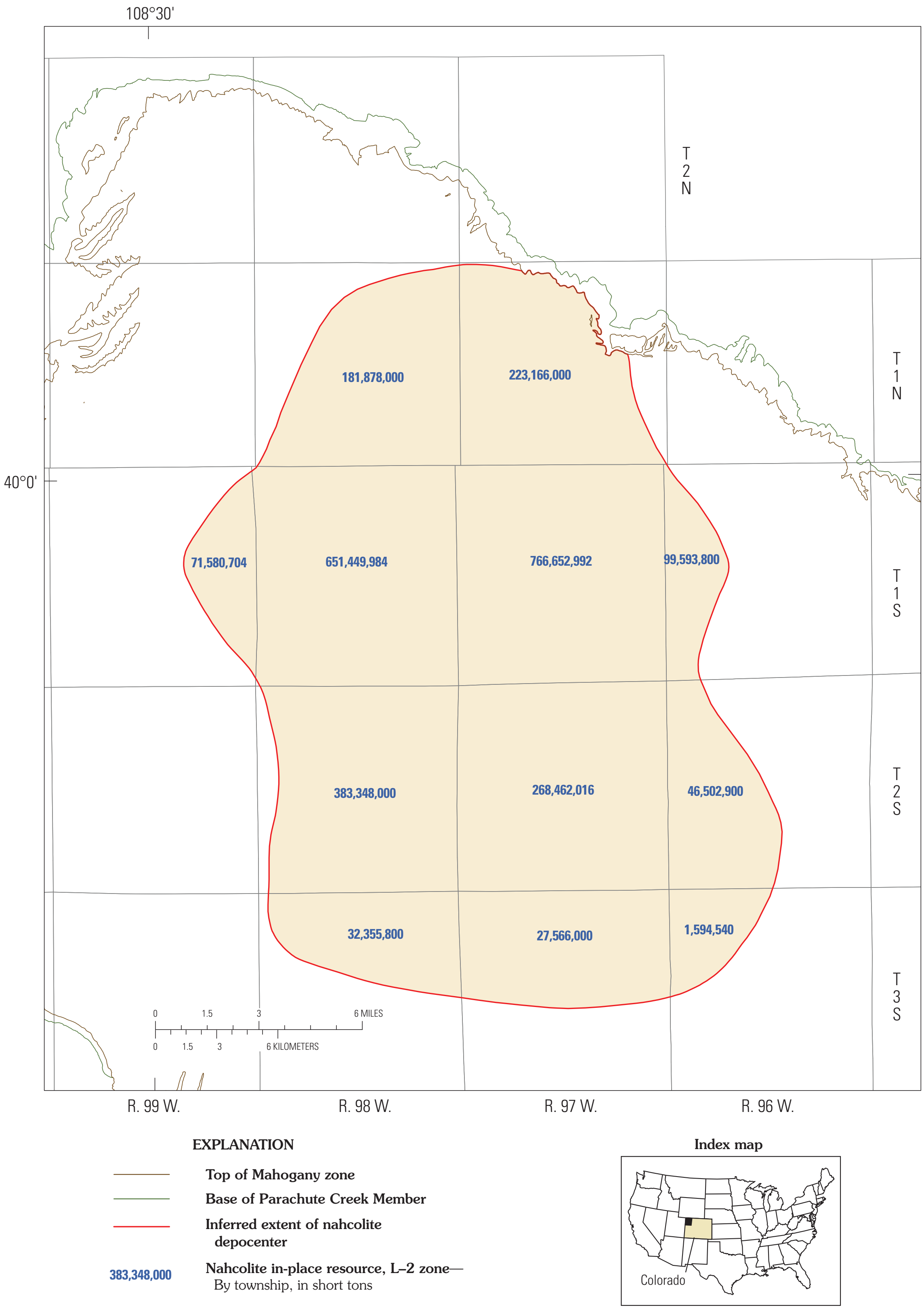

Figure 21. Map showing in-place nahcolite ($NaHCO_3$) resources in the L-2 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation by township, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons. Inferred extent of nahcolite depocenter outlined in red.

Table 5. Total in-place nahcolite resources and average tons per acre, by township, in the R-3 oil shale zone in the nahcolite-bearing interval of the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado.

[All values calculated by ESRIs ArcGIS GeoStatistical Analyst extension with a Radial Basis Function (RBF) Multiquadratic Gridding Function; 1 acre = 4,047 m^2]

Township	Acres	Area (m^2)	Average tons per acre	Total in-place resource in tons
T1N R97W	14,145	57,243,000	37,302	621,858,000
T1NR 98W	16,191	65,522,800	70,709	1,144,990,000
T1S R96W	4,844	19,603,000	41,120	199,185,000
T1S R97W	24,450	98,945,900	57,445	1,404,520,000
T1SR 98W	23,844	96,493,500	104,429	2,490,000,000
T1S R99W	4,881	19,752,800	74,715	364,683,000
T2S R96W	9,719	39,331,500	31,562	306,752,000
T2SR 97W	23,478	95,012,400	62,465	1,466,560,000
T2S R98W	20,507	82,989,100	73,792	1,513,240,000
T3S R96W	2,820	11,412,200	6,716	26,569,000
T3SR 97W	12,540	50,747,700	26,055	334,498,000
T3S R98W	8,613	34,855,700	19,693	169,617,000
Total	**166,032**	**671,909,600**		**10,042,472,000**

Table 6. Total in-place nahcolite resources and average tons per acre, by township, in the L-3 oil shale zone in the nahcolite-bearing interval of the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado.

[All values calculated by ESRIs ArcGIS GeoStatistical Analyst extension with a Radial Basis Function (RBF) Multiquadratic Gridding Function; 1 acre = 4,047 m^2]

Township	Acres	Area (m^2)	Average tons per acre	Total in-place resource in tons
T1N R97W	10,392	42,055,100	4,733	78,905,000
T1NR 98W	16,075	65,053,400	10,597	171,596,000
T1S R96W	4,844	19,603,000	5,480	26,547,000
T1S R97W	24,450	98,945,900	17,692	432,575,000
T1SR 98W	23,844	96,493,500	20,877	497,791,000
T1S R99W	4,881	19,752,800	16,784	81,920,000
T2S R96W	9,719	39,331,500	4,832	46,965,000
T2SR 97W	23,478	95,012,400	19,315	453,473,000
T2S R98W	20,507	82,989,100	14,644	300,297,000
T3S R96W	1,692	6,847,300	477	1,889,000
T3SR 97W	10,921	44,195,800	11,664	149,743,000
T3S R98W	8,613	34,855,700	9,918	85,422,000
Total	**159,416**	**645,135,500**		**2,327,123,000**

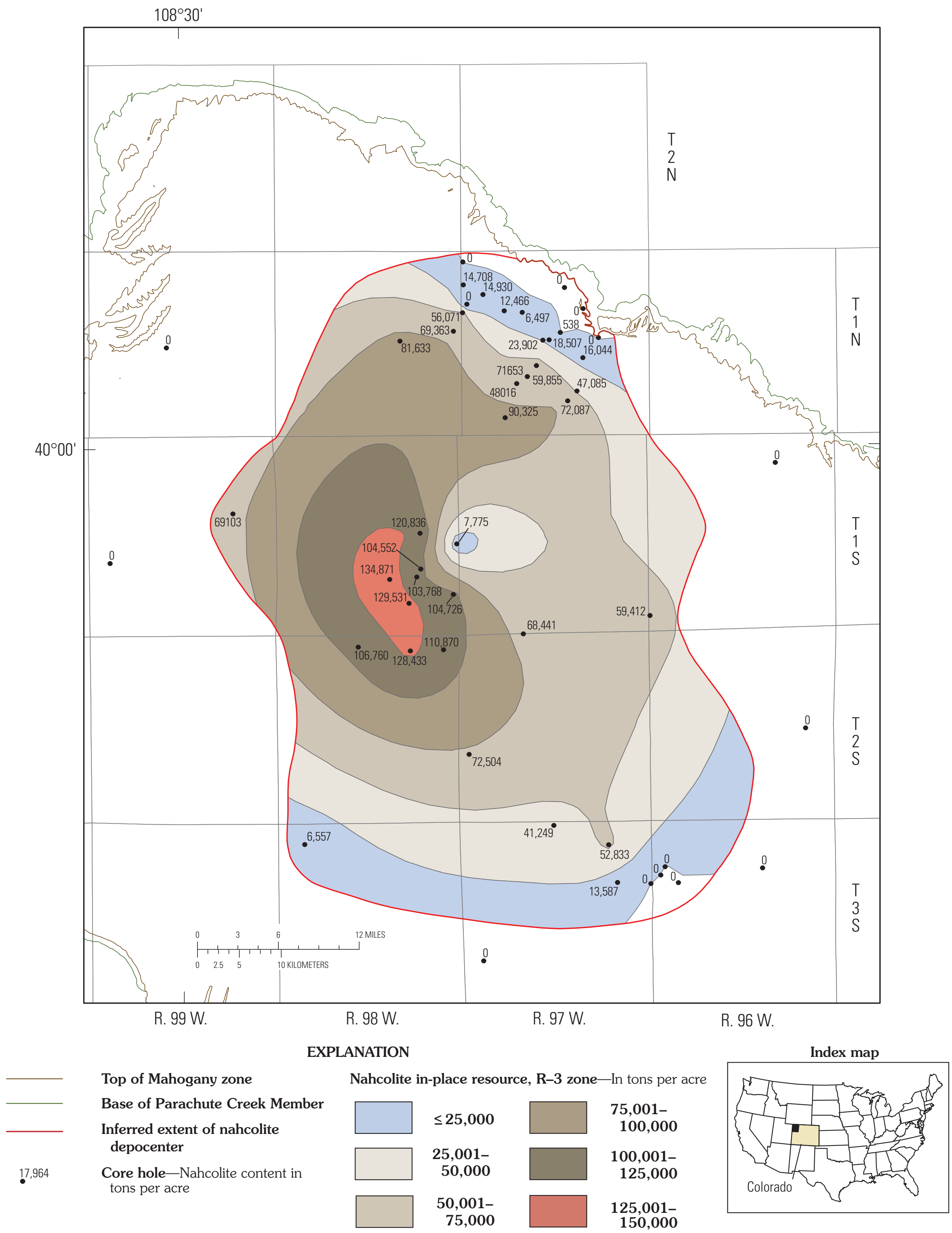

Figure 22. Isopleth map showing in-place nahcolite ($NaHCO_3$) resources of R-3 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons per acre. Inferred extent of nahcolite depocenter outlined in red.

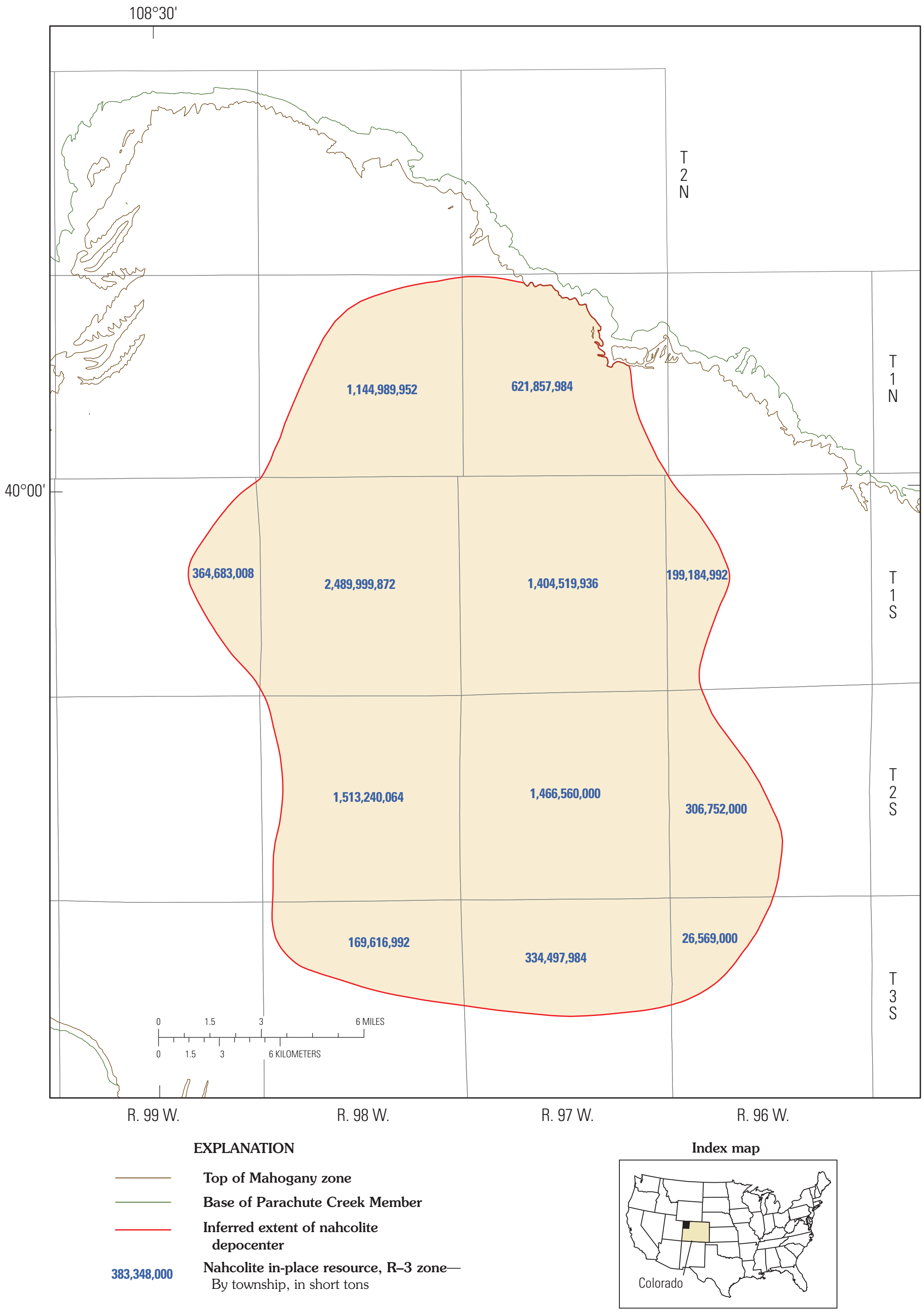

Figure 23. Map showing in-place nahcolite ($NaHCO_3$) resources in the R-3 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation by township, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons. Inferred extent of nahcolite depocenter outlined in red.

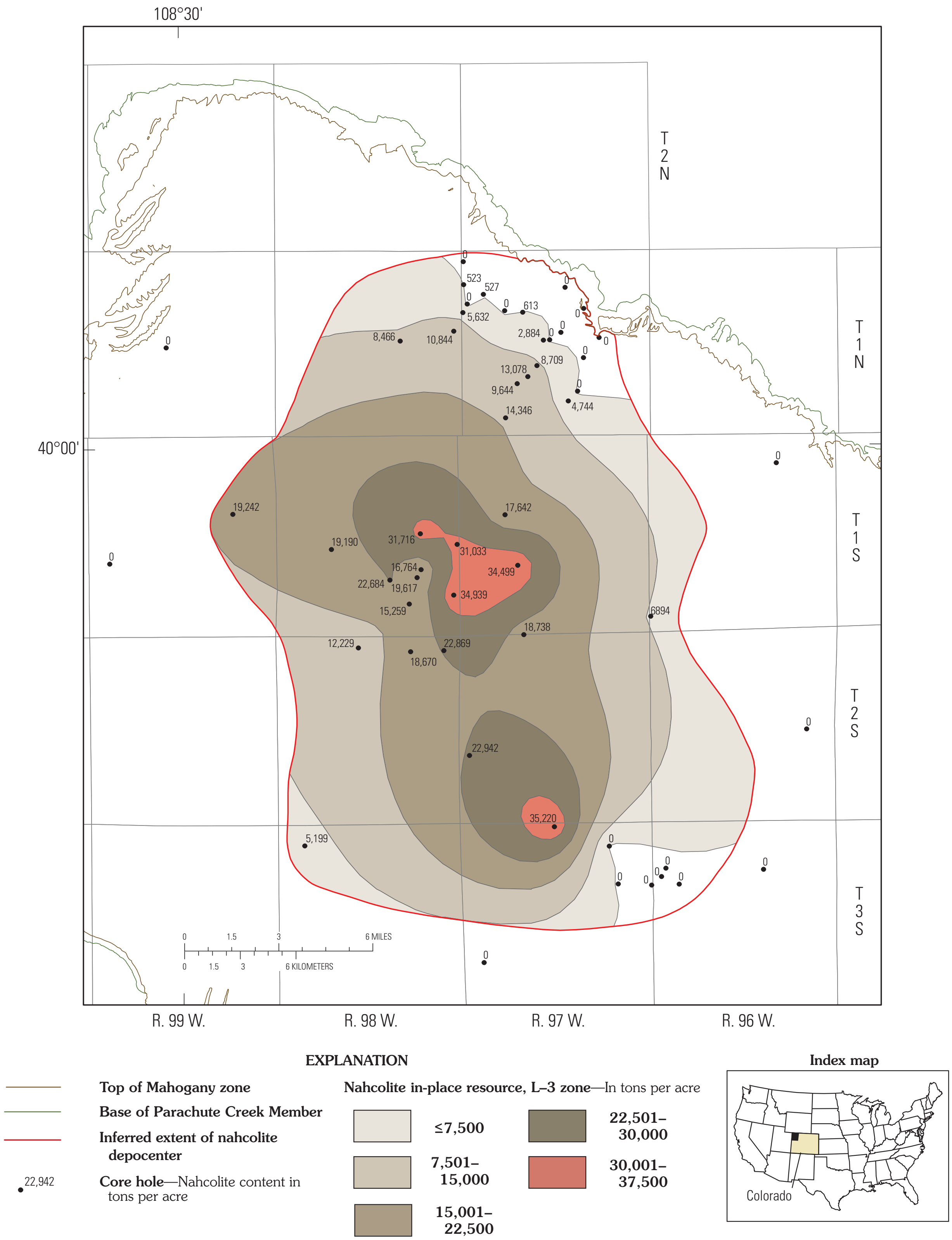

Figure 24. Isopleth map showing in-place nahcolite ($NaHCO_3$) resources of L-3 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons per acre. Inferred extent of nahcolite depocenter outlined in red.

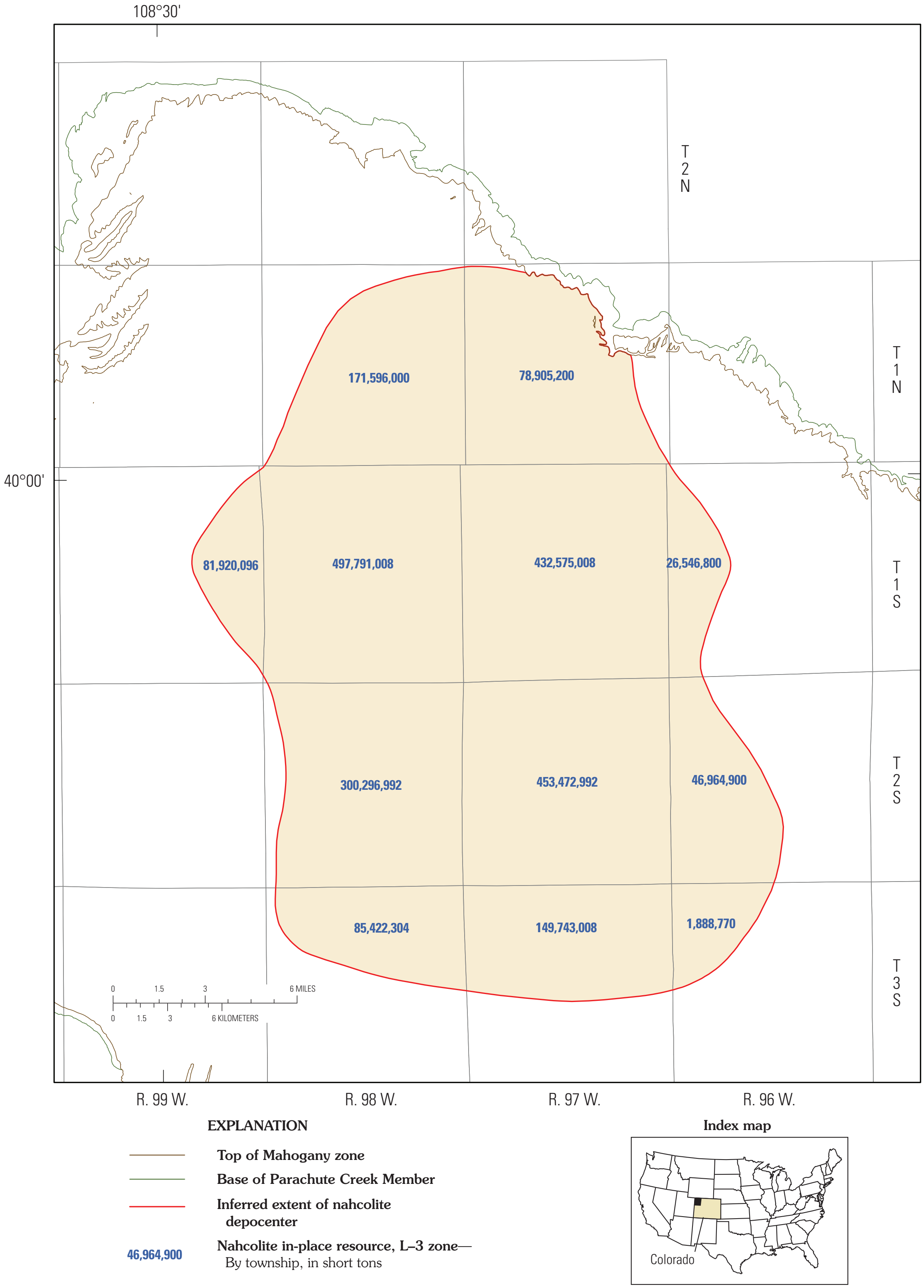

Figure 25. Map showing in-place nahcolite ($NaHCO_3$) resources in the L-3 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation by township, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons. Inferred extent of nahcolite depocenter outlined in red.

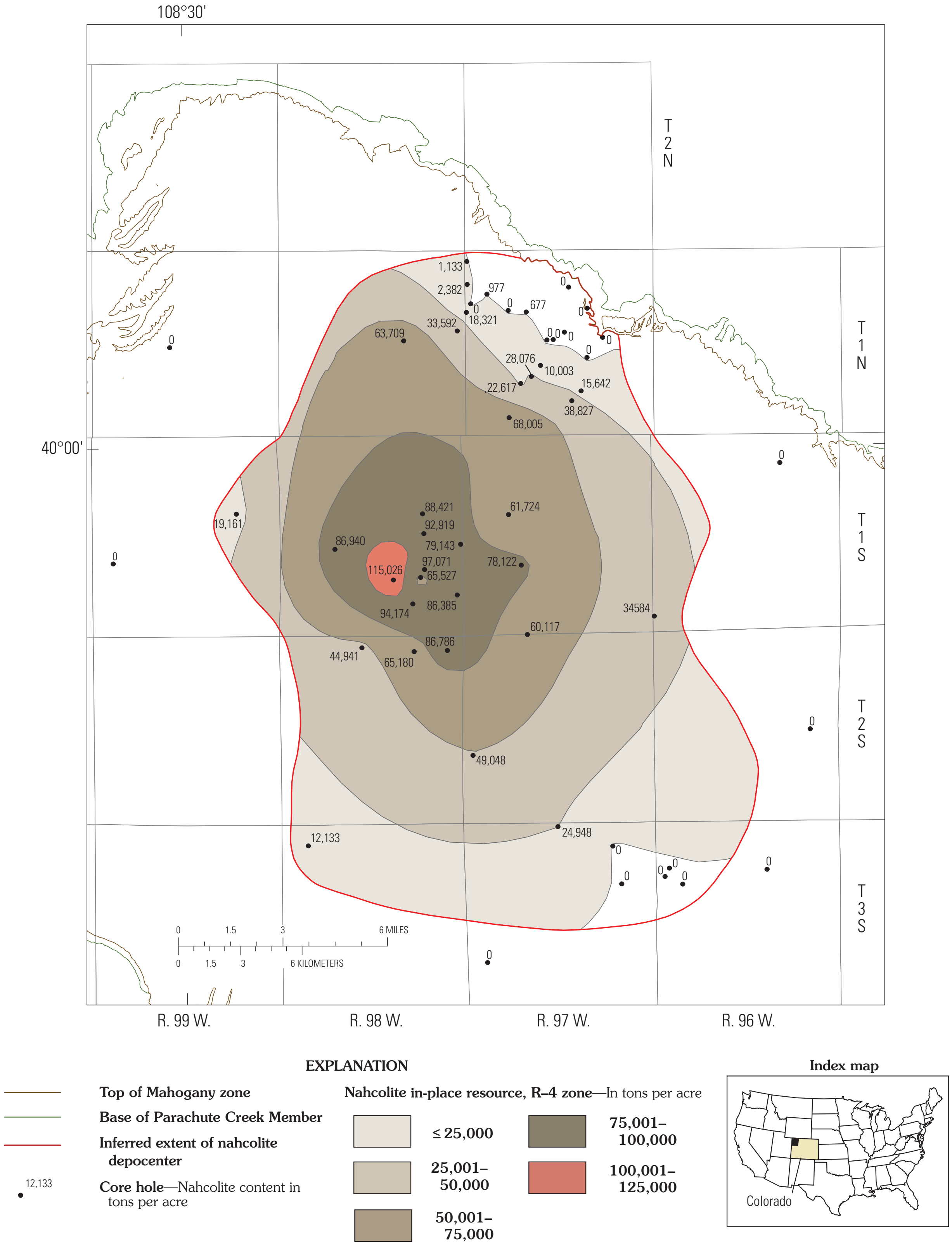

Figure 26. Isopleth map showing in-place nahcolite ($NaHCO_3$) resources of R-4 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons per acre. Inferred extent of nahcolite depocenter outlined in red.

were estimated (fig. 33). Only nine core holes contain nahcolite data in the zone. The total in-place nahcolite resource in the L-5 zone is more than 850 million tons (fig. 33 and table 10) over an area of more than 23,000 acres.

The total thickness of the nahcolite-bearing interval (saline zone) was determined for each core hole within the inferred extent of the nahcolite-bearing interval (fig. 15) and the average nahcolite content in weight percent was determined for each hole to estimate the total in-place nahcolite resource in the north-central part of the Piceance Basin. Figure 34 shows the thickness of the nahcolite-bearing interval in the Parachute Creek Member (fig. 2) in the north-central part of the Piceance Basin, and figure 35 shows the average nahcolite content in weight percent for the 58 core holes in the nahcolite-bearing depocenter. As with the in-place nahcolite resource calculations for the individual oil shale zones, the leached zone was not considered to be a part of the nahcolite interval and was excluded from the total in-place resource estimations. Average nahcolite content and the total nahcolite-bearing interval thickness are still the two variables used in determining the total in-place nahcolite resources. Figure 36 shows the isopach values of nahcolite content in tons per acre within the nahcolite depocenter and the individual core hole values in tons per acre.

The amount of in-place nahcolite is as much as 940 thousand short tons per acre (853 million metric tons; see fig. 36, core hole C0321) or about 600 million tons per mi^2 (210 million metric tons per km^2) in the nahcolite depocenter (figs. 15, 36). The nahcolite resource decreases and eventually pinches out towards the Piceance Basin margin resulting from nondeposition or leaching by groundwater. The total in-place nahcolite resource is estimated to be about 43.3 billion short tons (39.1 billion metric tons) within the north-central part of the Piceance Basin (table 11). Figure 37 shows the in-place nahcolite resource by township in tons covering an area of about 170,000 acres.

Acknowledgments

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Summary

Nahcolite ($NaHCO_3$)-bearing rocks in rich deposits of oil shale are found in the lower and middle parts of the Parachute Creek Member of the Eocene Green River Formation in the north-central part of the Piceance Basin, northwestern Colorado. Associated minerals include dawsonite ($NaAl(OH)_2CO_3$) and halite (NaCl). This nahcolite-bearing facies consists of a lower part containing the nahcolite and halite, which is estimated to be as thick as 1,130 ft, and an upper-leached part several hundreds of feet thick. Locally thick beds of halite with minor nahcolite are found in the nahcolite-bearing depocenter of the basin and thin from the basin center, grading laterally into beds of white, coarse-grained nahcolite. The top of the nahcolitic-bearing rocks in the central part of the study area ranges in depth from about 1,300 to 2,000 ft below ground surface in the central part of the assessment area and is overlain by a “leached zone” characterized by intervals of vuggy oil shale and collapsed solution breccia. The leached zone is several hundred feet thick and may extend upward to the lower part of the Mahogany zone.

The total in-place nahcolite resource is estimated to be about 43.3 billion short tons in the Parachute Creek Member of the Green River Formation, north-central part of the Piceance Basin. A few beds of nahcolite may have economic potential by themselves, but because most of the nahcolite occurs in variable-sized aggregates scattered through oil shale beds, it may be most feasibly recovered as a co-product of the oil shale industry.

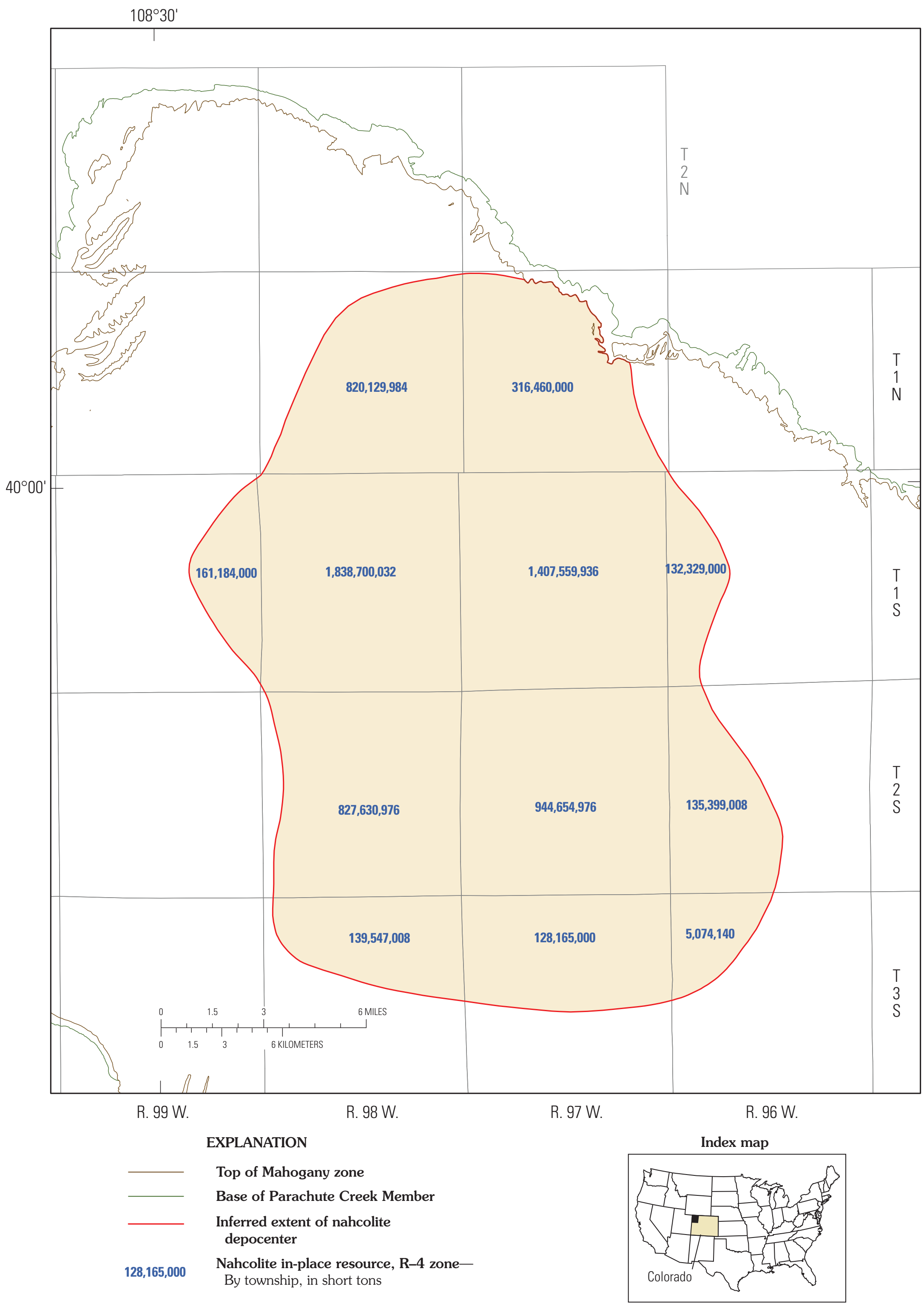

Figure 27. Map showing in-place nahcolite ($NaHCO_3$) resources in the R-4 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation by township, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons. Inferred extent of nahcolite depocenter outlined in red.

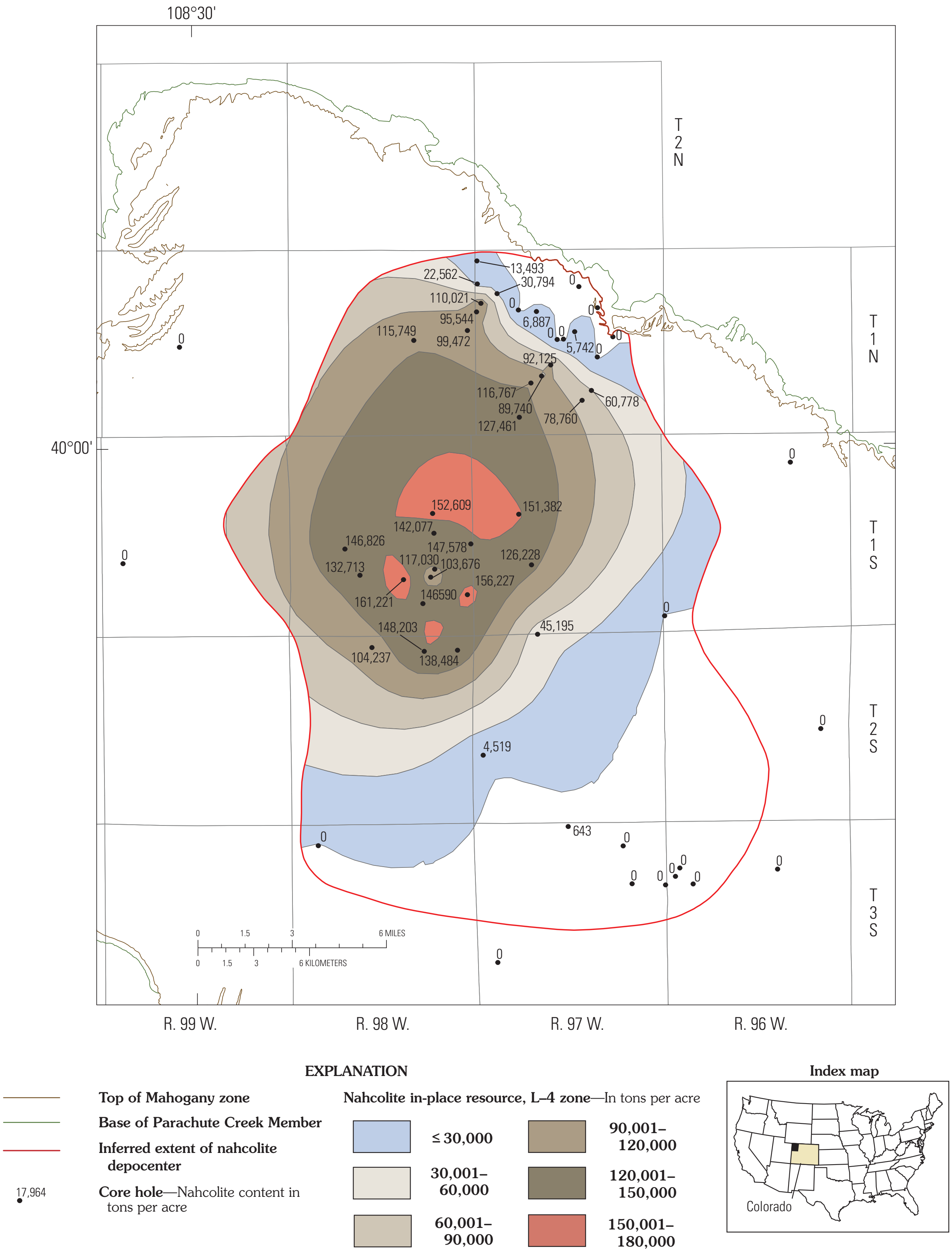

Figure 28. Isopleth map showing in-place nahcolite ($NaHCO_3$) resources of L-4 zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons per acre. Inferred extent of nahcolite depocenter outlined in red.

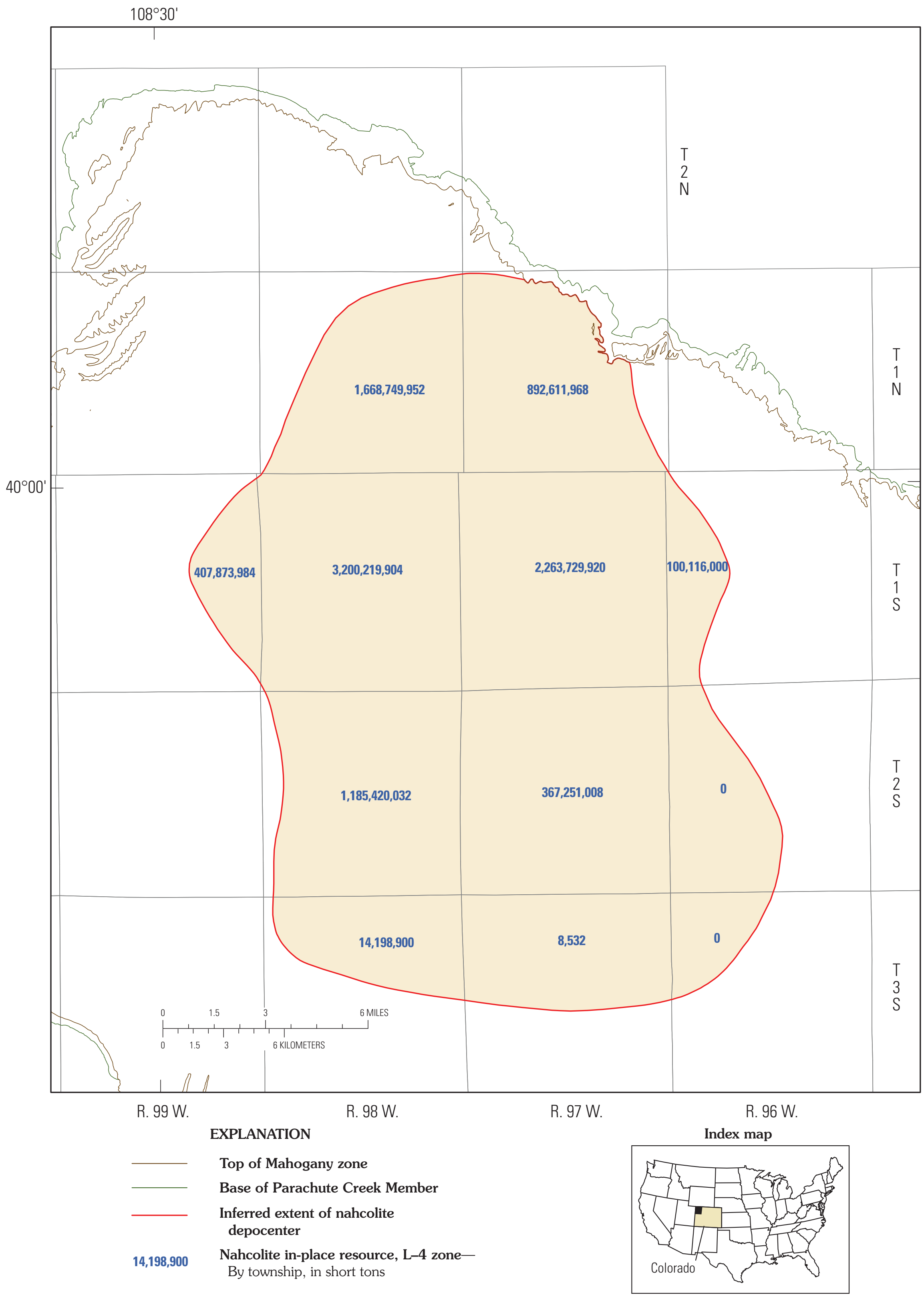

Figure 29. Map showing in-place nahcolite ($NaHCO_3$) resources in the L-4 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation by township, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons. Inferred extent of nahcolite depocenter outlined in red.

Table 7. Total in-place nahcolite resources and average tons per acre, by township, in the R-4 oil shale zone in the nahcolite-bearing interval of the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado.

[All values calculated by ESRIs ArcGIS GeoStatistical Analyst extension with a Radial Basis Function (RBF) Multiquadratic Gridding Function; 1 acre = 4,047 m^2]

Township	Acres	Area (m^2)	Average tons per acre	Total in-place resource in tons
T1N R97W	11,591	46,907,200	18,983	316,460,000
T1NR 98W	16,193	65,530,900	50,647	820,130,000
T1S R96W	4,844	19,603,000	27,318	132,329,000
T1S R97W	24,450	98,945,900	57,569	1,407,560,000
T1SR 98W	23,844	96,493,500	77,114	1,838,700,000
T1S R99W	4,881	19,752,800	33,023	161,184,000
T2S R96W	9,719	39,331,500	13,931	135,399,000
T2SR 97W	23,478	95,012,400	40,236	944,655,000
T2S R98W	20,507	82,989,100	40,359	827,631,000
T3S R96W	2,322	9,396,830	1,283	5,074,000
T3SR 97W	10,474	42,386,900	9,983	128,165,000
T3S R98W	8,613	34,855,700	16,202	139,547,000
Total	**160,916**	**651,205,730**		**6,856,834,000**

Table 8. Total in-place nahcolite resources and average tons per acre, by township, in the L-4 oil shale zone in the nahcolite-bearing interval of the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado.

[All values calculated by ESRIs ArcGIS GeoStatistical Analyst extension with a Radial Basis Function (RBF) Multiquadratic Gridding Function; 1 acre = 4,047 m^2]

Township	Acres	Area (m^2)	Average tons per acre	Total in-place resource in tons
T1N R97W	13,343	53,997,400	53,543	892,612,000
T1NR 98W	16,193	65,530,900	103,054	1,668,750,000
T1S R96W	4,465	18,069,300	20,668	100,116,000
T1S R97W	24,439	98,901,400	92,586	2,263,730,000
T1SR 98W	23,844	96,493,500	134,215	3,200,220,000
T1S R99W	4,881	19,752,800	83,564	407,874,000
T2S R96W	0	0	0	0
T2SR 97W	16,066	65,017,000	15,642	367,251,000
T2S R98W	20,507	82,989,100	57,806	1,185,420,000
T3S R96W	0	0	0	0
T3S R97W	13	52,609	1	9,000
T3S R98W	3,646	14,754,900	1,649	14,199,000
Total	**127,397**	**515,558,909**		**10,100,180,000**

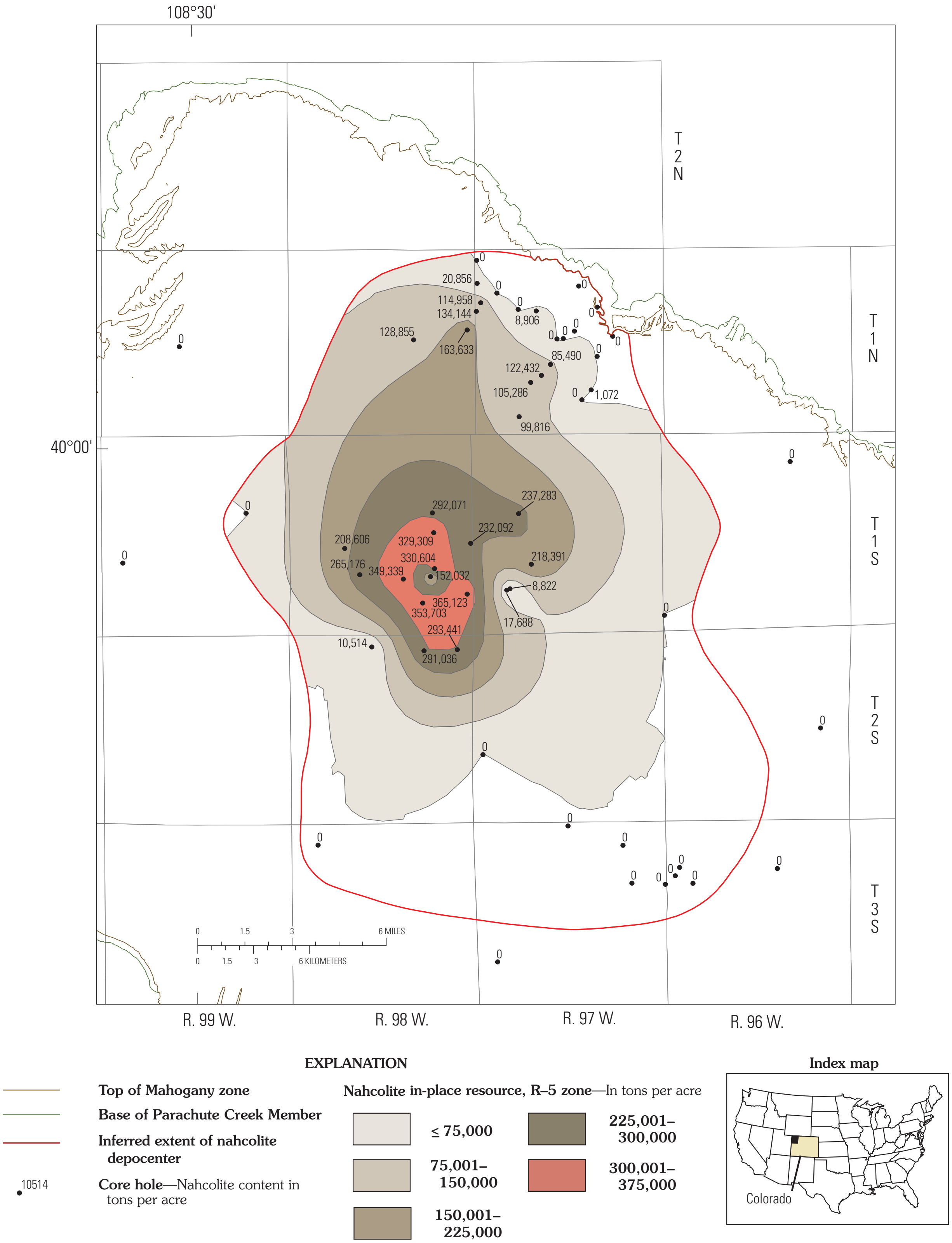

Figure 30. Isopleth map showing in-place nahcolite ($NaHCO_3$) resources of R-5 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons per acre. Inferred extent of nahcolite depocenter outlined in red.

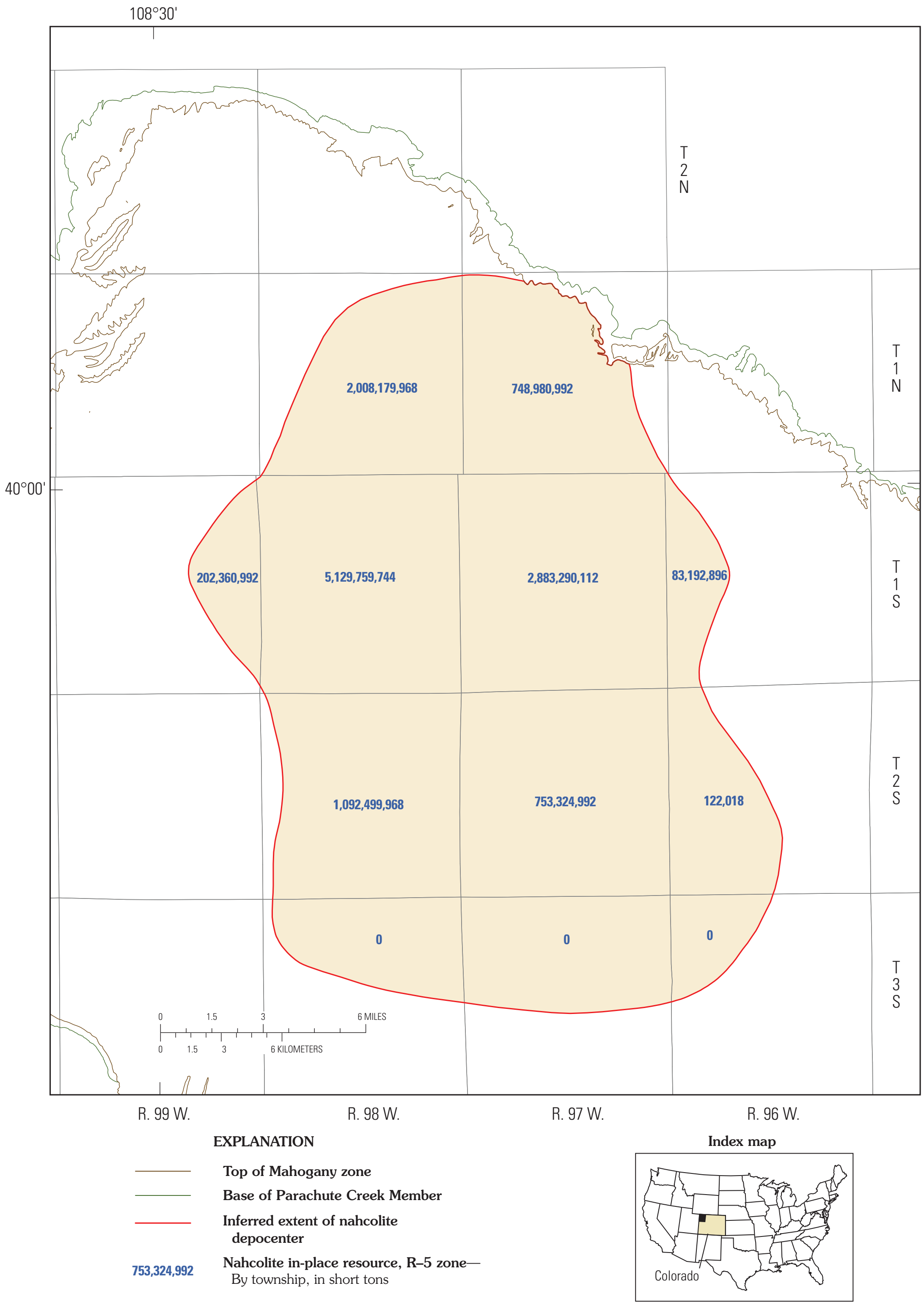

Figure 31. Map showing in-place nahcolite ($NaHCO_3$) resources in the R-5 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation by township, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons. Inferred extent of nahcolite depocenter outlined in red.

Table 9. Total in-place nahcolite resources and average tons per acre, by township, in the R-5 oil shale zone in the nahcolite-bearing interval of the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado.

[All values calculated by ESRIs ArcGIS GeoStatistical Analyst extension with a Radial Basis Function (RBF) Multiquadratic Gridding Function; 1 acre = 4,047 m^2]

Township	Acres	Area (m^2)	Average tons per acre	Total in-place resource in tons
T1N R97W	10,677	43,208,400	44,927	748,981,000
T1NR 98W	16,189	65,514,700	124,015	2,008,180,000
T1S R96W	4,438	17,960,000	17,174	83,193,000
T1S R97W	24,450	98,945,900	117,926	2,883,290,000
T1SR 98W	23,844	96,493,500	215,139	5,129,760,000
T1S R99W	4,592	18,583,200	41,459	202,361,000
T2S R96W	78	315,656	13	122,000
T2SR 97W	18,759	75,915,200	32,086	753,325,000
T2S R98W	16,759	67,821,500	53,274	1,092,500,000
T3S R96W	0	0	0	0
T3SR 97W	0	0	0	0
T3S R 98W	0	0	0	0
Total	**119,786**	**484,758,056**		**12,901,712,000**

Table 10. Total in-place nahcolite resources and average tons per acre, by township, in the L-5 oil shale zone in the nahcolite-bearing interval of the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado.

[All values calculated by ESRIs ArcGIS GeoStatistical Analyst extension with a Radial Basis Function (RBF) Multiquadratic Gridding Function; 1 acre = 4,047 m^2]

Township	Acres	Area (m^2)	Average tons per acre	Total in-place resource in tons
T1N R97W	2,020	8,174,670	2,871	47,862,000
T1NR 98W	3,355	13,577,200	4,811	77,910,000
T1S R96W	0	0	0	0
T1S R97W	2,930	11,857,300	3,588	87,728,000
T1SR 98W	9,854	39,877,800	20,886	498,013,000
T1S R99W	0	0	0	0
T2S R96W	0	0	0	0
T2SR 97W	3,035	12,282,200	3,038	71,324,000
T2S R98W	2,281	9,230,910	3,363	68,961,000
T3S R96W	0	0	0	0
T3SR 97W	0	0	0	0
T3S R 98W	0	0	0	0
Total	**23,475**	**95,000,080**		**851,799,000**

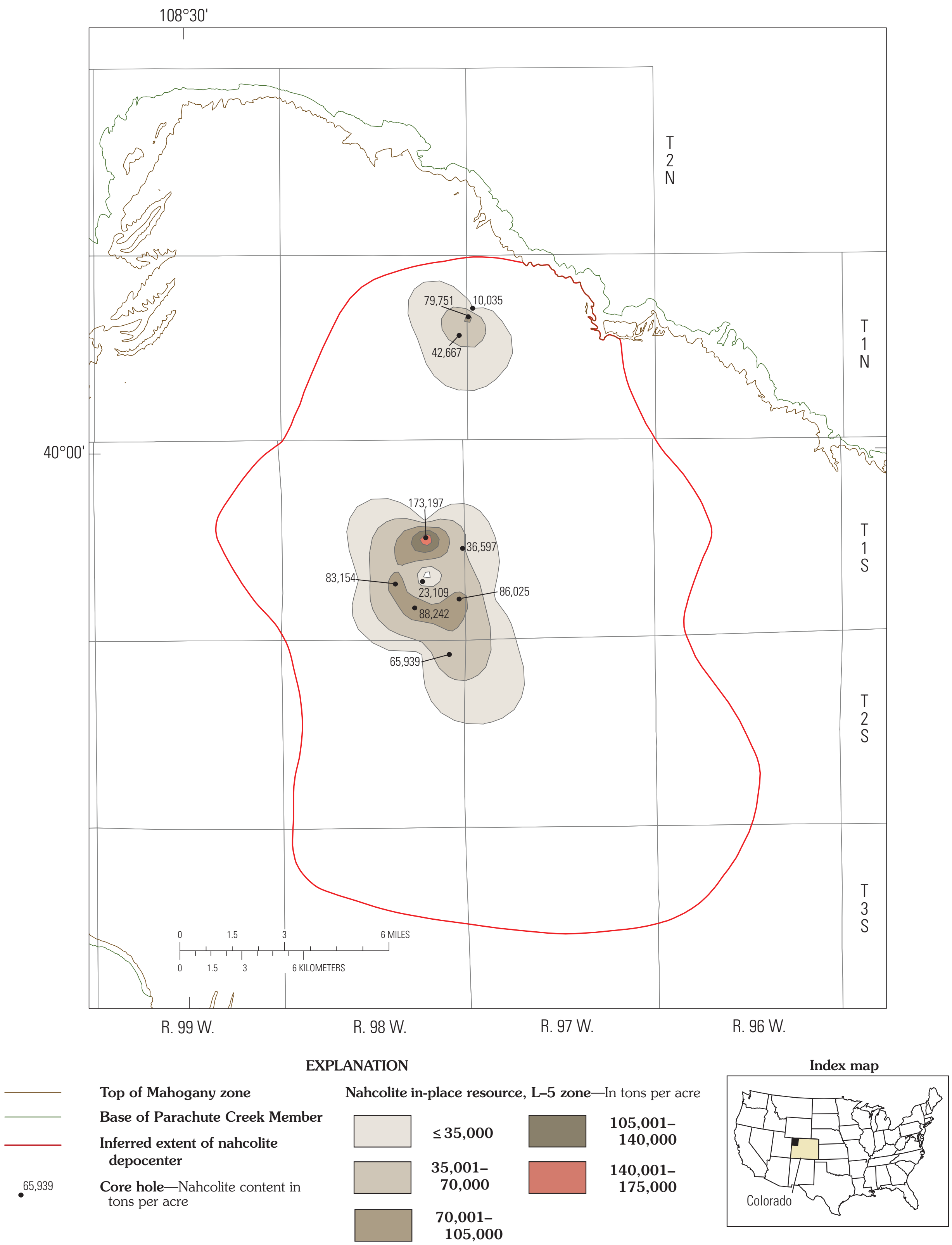

Figure 32. Isopleth map showing in-place nahcolite ($NaHCO_3$) resources of L-5 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons per acre. Inferred extent of nahcolite depocenter outlined in red.

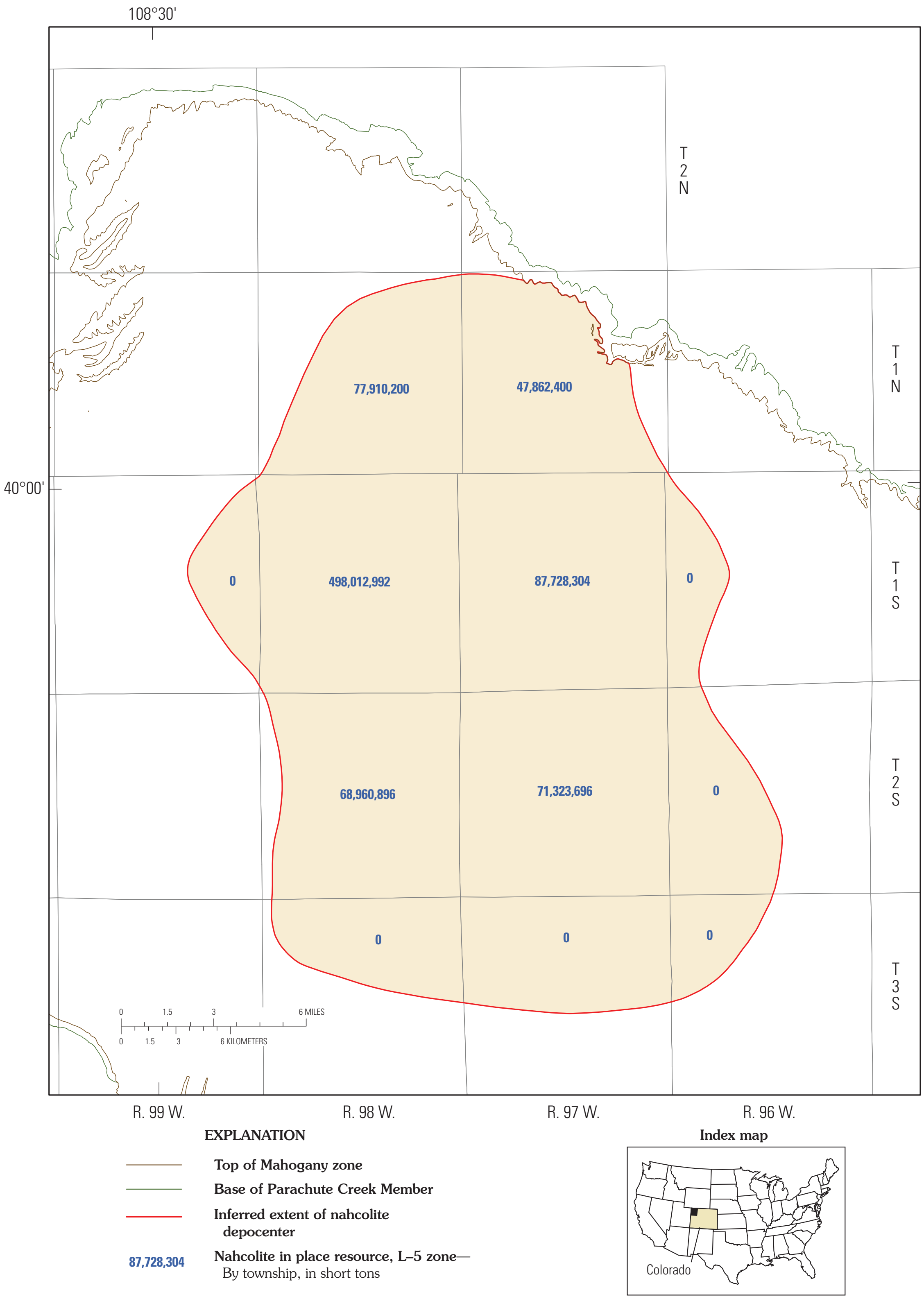

Figure 33. Map showing in-place nahcolite ($NaHCO_3$) resources in the L-5 oil shale zone (Donnell and Blair, 1970; Cashion and Donnell, 1972) in the Parachute Creek Member of the Green River Formation by township, Rio Blanco County, northwestern Colorado. Nahcolite resources reported in short tons. Inferred extent of nahcolite depocenter outlined in red.

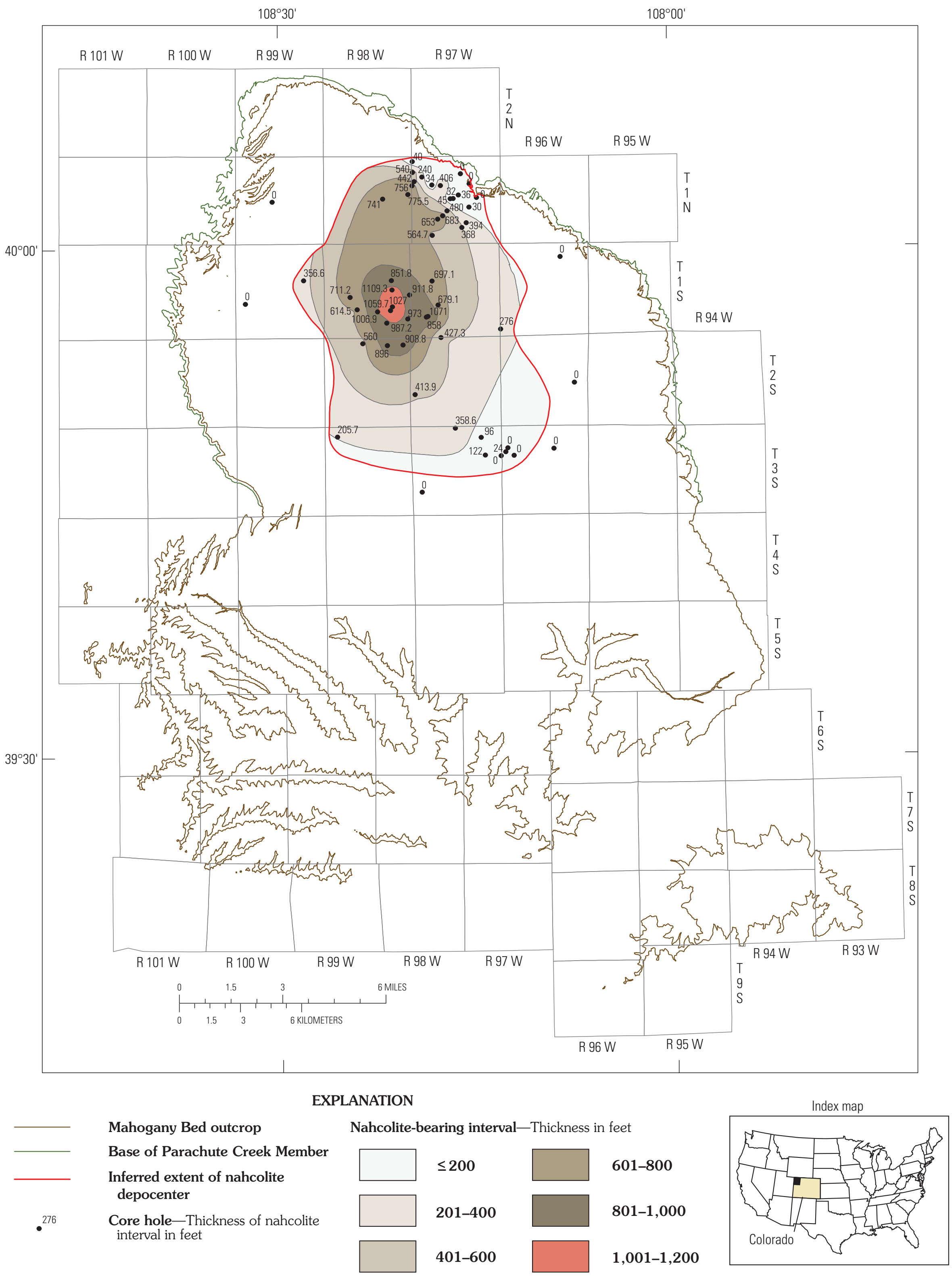

Figure 34. Map showing thickness of nahcolite-bearing interval in the lower and upper parts of the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado. Inferred extent of nahcolite depocenter outlined in red. Core holes show individual thicknesses of the nahcolite-bearing interval. See figure 7 and table 1 for core hole name and data.

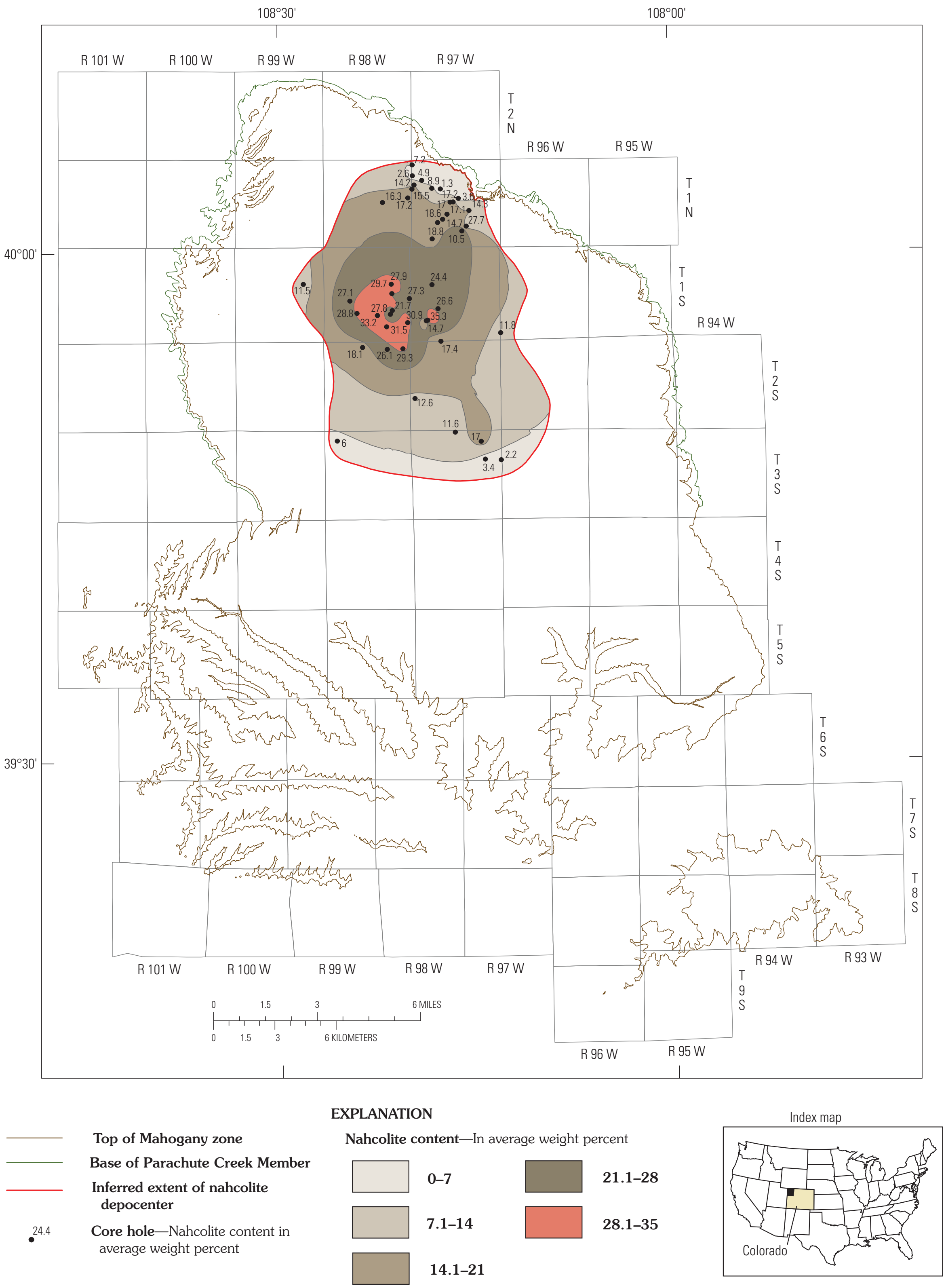

Figure 35. Isopleth map showing average nahcolite ($NaHCO_3$) content of nahcolite-bearing interval in the lower and upper parts of the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado. Inferred extent of nahcolite depocenter outlined in red. Nahcolite values reported in weight percent. Core holes show individual nahcolite contents.

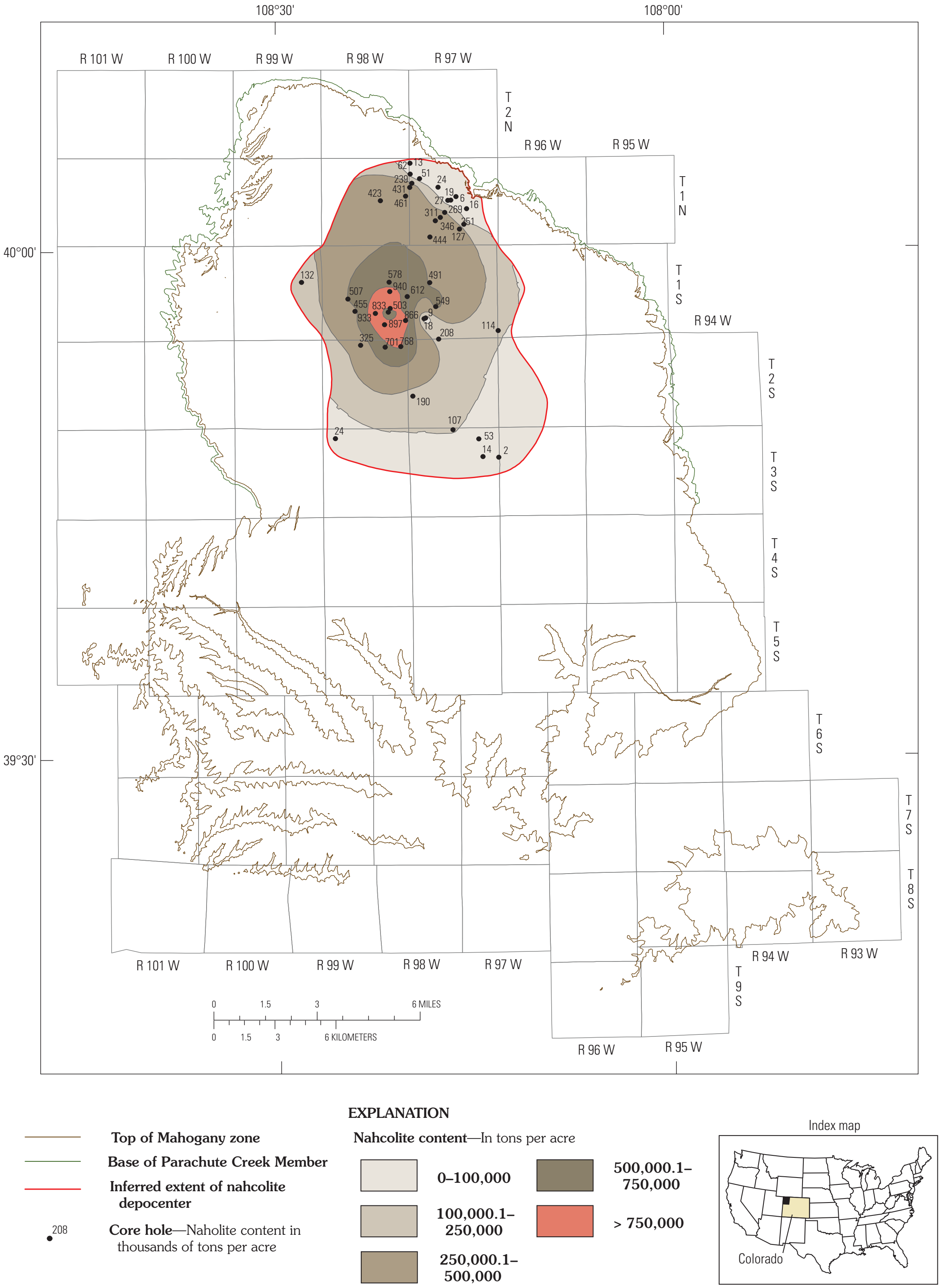

Figure 36. Isopleth map showing total in-place nahcolite ($NaHCO_3$) resources in the nahcolite-bearing interval in the lower and upper parts of the Parachute Creek and Garden Gulch Members of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado. Inferred extent of nahcolite depocenter outlined in red. Nahcolite resources reported in short tons per acre while individual core hole resources show nahcolite resource in thousands of tons per acre.

Table 11. Total in-place nahcolite resources and average tons per acre, by township, in the nahcolite-bearing interval of the Parachute Creek Member of the Green River Formation, Piceance Basin, Rio Blanco County, northwestern Colorado.

[All values calculated by ESRI's ArcGIS GeoStatistical Analyst extension with a Radial Basis Function (RBF) Multiquadratic Gridding Function; 1 acre = 4,047 m^2]

Township	Acres	Area (m^2)	Average tons per acre	Total in-place resource in tons
T1N R97W	16,671	67,465,300	186,593	3,110,690,000
T1N R98W	16,193	65,530,900	373,948	6,055,350,000
T1S R96W	4,844	19,603,000	128,893	624,360,000
T1S R97W	24,450	98,945,900	348,200	8,513,490,000
T1S R98W	23,844	96,493,500	542,541	12,936,300,000
T1S R99W	4,881	19,752,800	196,429	958,770,000
T2S R96W	9,719	39,331,500	41,166	400,090,000
T2S R97W	23,478	95,012,400	174,148	4,088,640,000
T2S R98W	20,507	82,989,100	268,289	5,501,810,000
T3S R96W	3,956	16,009,400	9,904	39,180,000
T3S R97W	12,838	51,953,700	48,726	625,540,000
T3S R98W	8,613	34,855,700	50,965	438,960,000
Total	**169,994**	**687,943,200**		**43,293,190,000**

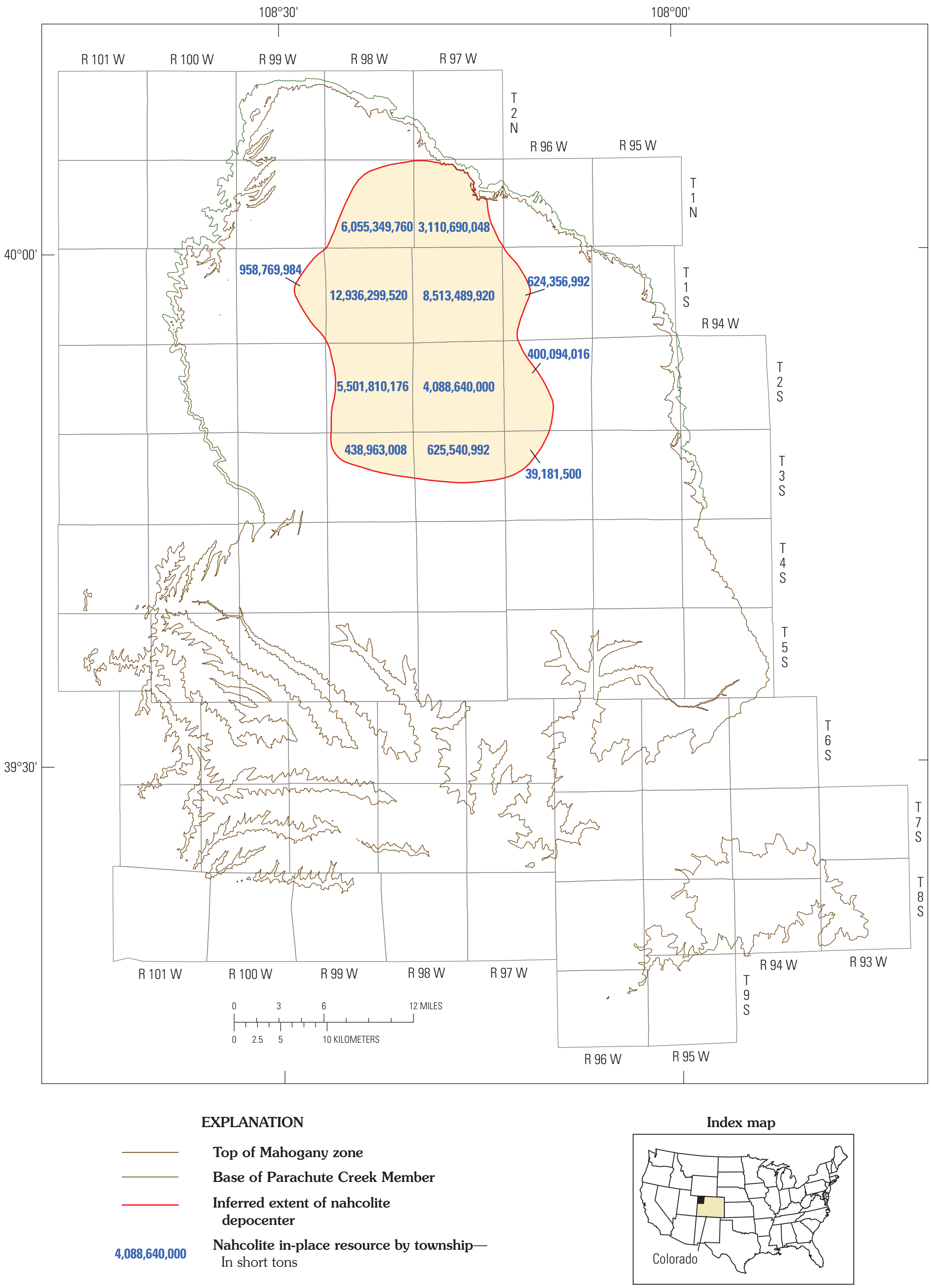

Figure 37. Map showing total in-place nahcolite ($NaHCO_3$) resources of the lower and middle parts of the Parachute Creek Member of the Green River Formation by township, Rio Blanco County, northwestern Colorado. Township resources reported in short tons. Individual core holes show nahcolite resources in short tons per acre. Inferred extent of nahcolite depocenter outlined in red.

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