Chapter 3

Methodology for Calculating Oil Shale and Nahcolite Resources for the Piceance Basin

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

Chapter 3 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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Methodology for Calculating Oil Shale and Nahcolite Resources for the Piceance Basin

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Abstract

A detailed description of the methodology employed to perform a geology-based assessment of in-place oil shale and nahcolite resources in the Piceance Basin of northwestern Colorado is presented here. Considerable advancements in computer and database technology since the previous oil shale assessment in 1989 provided the U.S. Geological Survey (USGS) assessment team with new tools to convert legacy data, store and manipulate new data, perform calculations, and quantify, report, and display the assessment results. Relational database and geographic information systems (GIS) software were used seamlessly to streamline the storage and manipulation of the data. A deterministic spatial interpolation method, the Radial Basis Function (RBF), was used to generate isopach and isoresource models in the GIS software, which provided a spatial statistics function to summarize the prediction models and determine the in-place oil shale and nahcolite resource totals.

Introduction

This report presents the results of a comprehensive, geology-based assessment of the in-place oil and nahcolite resources in 17 oil shale zones of the Eocene Green River Formation in the Piceance Basin of northwestern Colorado (fig. 1; Donnell and Blair, 1970; Cashion and Donnell, 1972; Donnell, 2008). The focus is on the methodology used to: (1) convert legacy and new data; (2) analyze the data through application of updated computer techniques; and (3) ultimately quantify the resultant data using spreadsheet, database, and geographic information systems (GIS) software.

After converting, combining, and loading individual legacy Fischer assay (American Society for Testing and Materials, 1980) data files into relational database software (Dyni, 1998), custom scripts and queries were written to filter records and perform various calculations using a database form. The legacy data also contained location information for each oil shale core hole that was converted to spatial data and then linked to its associated Fischer assay data.

After performing calculations in the database, the data were migrated to a GIS and a cell-based modeling technique was employed to calculate total barrels of oil yield per oil shale zone. Through this process original and new data were updated to a contemporary database format and new spatial data models were created for use in GIS software. Detailed technical descriptions of the methodology and the tools employed in the assessment from a software-centric perspective are presented in the two case studies following this report.

Oil Shale Assessment

Data Preparation, Capture, and Conversion

In order to calculate in-place oil shale resources using relational database and GIS software, it was necessary to collect data points with accompanying oil-yield data, create digital outcrop boundary lines to constrain resource calculations, and correlate the 17 oil shale zones within the Piceance Basin.

Spatial Data

The legacy Fischer assay files contained header information detailing the locations of core holes, but not all of the files contained latitude and longitude coordinates. To maintain consistency, the majority of the core hole locations were digitized in GIS software based on footage measurements north, south, east, and west of Public Land Survey System (PLSS) section corners or by using the best available location information present in the header, such as the section centerpoint.

In addition to placing the core holes in real-world coordinates and plotting their locations on maps, 17 oil shale zones (Donnell and Blair, 1970; Cashion and Donnell, 1972; Donnell, 2008) were correlated between holes in the subsurface using oil-yield histograms generated from the Fischer assay data files (fig. 2). The previous USGS assessment (Pitman and Johnson, 1978; Pitman, 1979; Pitman and others, 1989) subdivided the oil shale interval into a series of oil-rich and oil-lean zones that could be traced across most of the basin

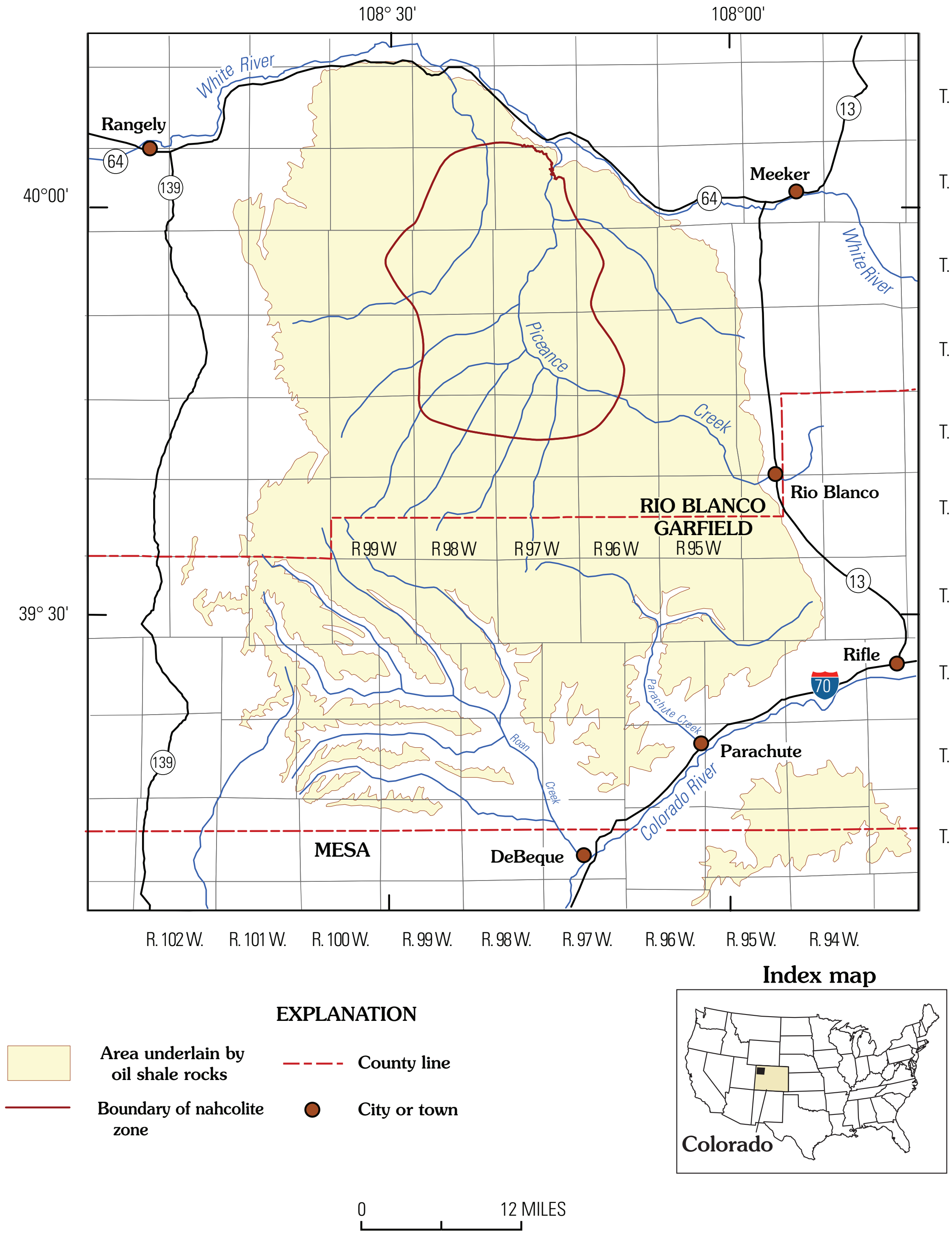

Figure 1. Map of Piceance Basin, northwestern Colorado, showing inferred boundaries of the nahcolite-bearing zone (Brownfield and others, chapter 2 this CD-ROM), and generalized outcrop of oil shale-bearing rocks in Parachute Creek Member of the Green River Formation shown in yellow.

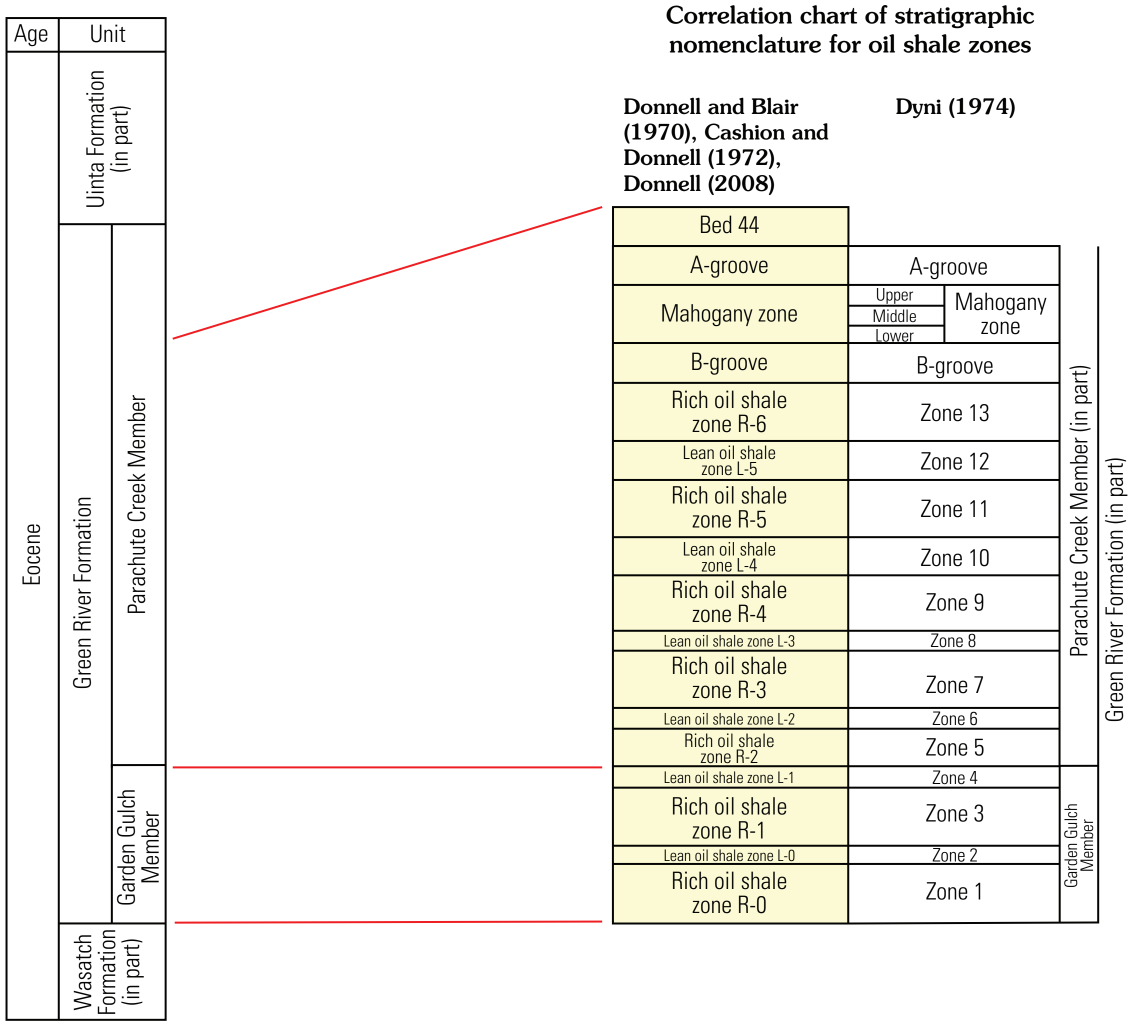

Figure 2. Stratigraphic column and correlation chart of stratigraphic nomenclature for oil shale zones in the Eocene Green River Formation, Piceance Basin, Colorado. The assessments of in-place oil and nahcolite resources use the nomenclature of Donnell and Blair (1970), Cashion and Donnell (1972), and Donnel (2008) shown in yellow.

(Cashion and Donnell, 1972), and each zone was assessed separately. For the present study, the same set of rich and lean zones was used as much as possible in order to make the two assessments comparable. Only a computer printout of part of the files listing the tops for these zones in the drill holes that were used in the previous assessment was recovered, and this information was incorporated into the new digital file. In addition, a considerable amount of core hole information was collected subsequent to the previous assessment, as tops had to be picked for these additional holes. A series of stratigraphic cross sections was constructed to aid in this effort, and these are published separately (Self and others, chapter 5, this CD-ROM). Although different workers in the past used slightly different picks for the tops of some of the rich and lean zones, an attempt was made to use the same zonal contacts that were used in the previous USGS assessment to also make the two assessments as comparable as possible. In some isolated cases, it was necessary to correct minor errors in the tops file used in the previous assessment. The tops and bases of the 17 identified zones were entered in a spreadsheet and then imported into the database where the tops and bases were linked with their associated Fischer assay records to create subsets of data on which calculations were performed.

Two updated boundary files (fig. 3) were created for the oil shale deposits of the Piceance Basin by digitizing the top of the Mahogany zone and the base of the Parachute Creek Member of the Green River Formation from two published 1:100,000-scale geologic maps (Hail and Smith, 1994, 1997). These lines served as bounding polygons for in-place resource calculations. Due to the steepness of the vertical cliffs formed

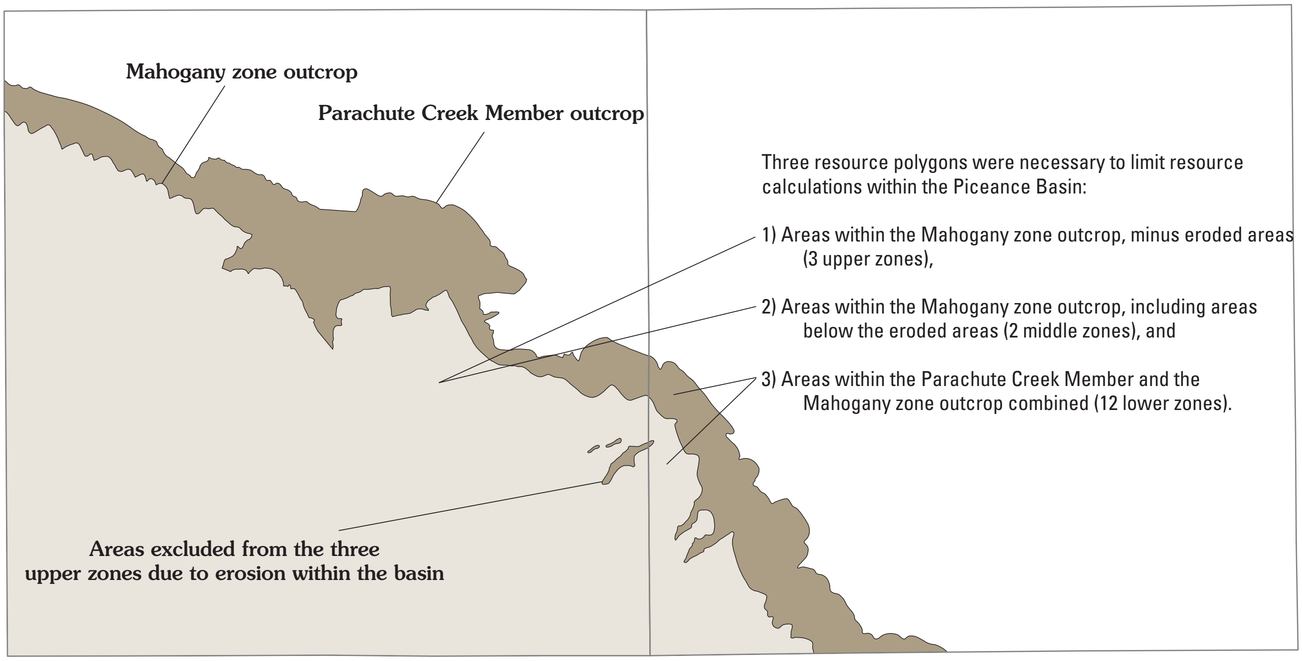

Figure 3. Map of northeastern part of the Piceance Basin, Colorado, showing the three resource polygons used to limit in-place oil shale resource calculations: base of the Parachute Creek Member of the Green River Formation, top of the Mahogany zone, and small outcrop areas excluded from resource calculations due to erosion.

by these strata throughout the Piceance Basin, three resource polygons were defined for the 17 zones rather than 17 pseudo-outcrops. The Mahogany zone outcrop was used to delineate a resource polygon file for the three uppermost zones in the basin—Mahogany zone, A-groove, and Bed 44 (figs. 2, 3); this polygon file excluded some areas within the basin where the upper three zones were eroded. The Mahogany zone outcrop line was also used to delineate a resource polygon file for the B-groove and R-6 zones, but these zones are below the Mahogany zone and were not eroded. A third resource polygon file was created for all oil shale zones below the R-6 zone (fig. 3) by expanding the Mahogany zone polygon with the areal extent of the Parachute Creek Member in the northern half of the Piceance Basin.

The three resource-polygon files were intersected spatially with a Public Land Survey System (PLSS) land grid for the Piceance Basin to allow resource calculation on a per township basis. Resource calculations were then directly comparable to legacy reports that estimated in-place oil shale resources by township.

Tabular Fischer Assay Data

Source ASCII text data were obtained from published Fischer assays (Dyni, 1998) and from previously unpublished Fischer assay data stored by USGS. These files were stored as individual ASCII-formatted text files (fig. 4) for each borehole that contained the header-location information and the column-delimited Fischer assay records. Each borehole was assigned a unique four-digit number preceded by “C” for Colorado by USGS. In order to expedite the querying of the Fischer assay data, a file-conversion software package was used to convert and combine all of the Fischer assay records into one relational database table allowing detailed queries on one large table (some 300,000 records) instead of hundreds of different files.

Some of the original Fischer assay records were incomplete, especially those associated with rotary drill holes, and those records were not used in this assessment—that is, those boreholes containing an “R” in their USGS identifier (USGSID). Almost all drill holes contain missing intervals that represent samples that were not recovered during the drilling process. Missing records in the original data files were labeled as “0.0B” or “0.00B” in all columns except for the top and base of the interval fields (Dyni, 1998). During the initial data import and conversion process (table 1), it was necessary to remove the “B” in order for those values to be imported as a numeric field, which was then considered a missing interval in the assays table. This step allowed us to perform calculations on any given field as those values were converted from characters to numeric values. Four other fields were also added to the master Fischer assay table: (1) the “USGSID” field, the unique borehole identifier, was added to each record in the Import Wizard conversion process by using the original text filename; (2) the “INTVL” field, an abbreviation for thickness of the sampled interval, was calculated in Access

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Wolf Ridge Minerals Corp., Dunn 20-1 T 01S,R098W,Sec 20
1172 FEL 1197 FNL 6362 GL

Column 1	2	3	4	5	6	7	8	9	10	11
724683	1702.0	1703.0	11.5	2.2	78.1	8.2	30.8	5.3	0.894	2.0
724684	1703.0	1704.0	7.8	2.0	83.0	7.2	21.1	4.8	0.890	1.0
724685	1704.0	1705.2	7.2	2.9	78.9	11.0	19.5	7.0	0.885	2.0
	1705.2	1707.0	0.0B	0.0B	0.0B	0.0B	0.0B	0.0B	0.000B	0.0B
724686	1707.0	1709.0	7.3	5.8	69.3	17.6	19.7	13.9	0.890	2.0
724687	1709.0	1710.8	18.7	2.0	69.5	9.8	50.4	4.8	0.889	2.0
724688	1710.8	1712.6	4.4	6.9	68.2	20.5	11.7	16.5	0.901	1.0
724689	1712.6	1714.0	10.5	2.3	77.9	9.3	28.3	5.5	0.892	1.0
724690	1714.0	1716.0	5.9	5.6	71.5	17.0	15.7	13.4	0.901	1.0
	1716.0	1717.8	0.0B	0.0B	0.0B	0.0B	0.0B	0.0B	0.000B	0.0B
724691	1717.8	1719.0	11.0	4.2	72.3	12.5	29.6	10.1	0.894	2.0
724692	1719.0	1720.0	9.7	4.2	71.1	15.0	26.0	10.1	0.896	1.0
724693	1720.0	1721.2	6.7	3.0	78.5	11.8	17.9	7.2	0.898	1.0
	1721.2	1723.8	0.0B	0.0B	0.0B	0.0B	0.0B	0.0B	0.000B	0.0B
724694	1723.8	1725.0	6.4	3.2	75.5	14.9	17.0	7.7	0.901	1.0
724695	1725.0	1726.0	4.7	5.0	75.2	15.1	12.6	12.0	0.902	1.0
724696	1726.0	1727.0	8.2	3.4	77.9	10.5	22.0	8.1	0.891	1.0
724697	1727.0	1728.0	2.8	5.7	73.7	17.8	7.4	13.7	0.908	1.0
724698	1728.0	1728.9	1.6	6.9	67.2	24.3	4.1	16.6	0.000B	1.0
724699	1728.9	1731.0	12.2	2.6	73.9	11.3	32.2	6.4	0.904	1.0
724700	1731.0	1733.0	11.2	3.0	74.3	11.5	29.8	7.3	0.900	1.0
724701	1733.0	1734.5	11.3	3.0	75.3	10.4	30.1	7.3	0.899	1.0
724702	1734.5	1736.0	9.6	4.0	73.5	12.9	25.6	9.6	0.900	1.0
724703	1736.0	1738.0	14.2	2.0	76.9	6.9	37.9	4.9	0.895	1.0
724704	1738.0	1740.0	9.6	4.3	70.6	15.5	25.5	10.3	0.901	1.0
724705	1740.0	1742.0	9.5	4.0	74.0	12.5	25.2	9.6	0.903	1.0

Figure 4. Image clip of a portion of the original Fischer assay data (Dyni, 1998) for the Wolf Ridge Minerals Corporation, Dunn 20–1 borehole showing header data (first two rows). Header data includes operator name, borehole name, location, and elevation. Columns (see table 1 for explanation of abbreviations): 1, LABNO; 2, TOPFT; 3, BOTFT; 4, SHLOILPCT; 5, WATERPCT; 6, SHLRSDPCT; 7, GASPLSPCT; 8, OILGPT; 9, WATERGPT; 10, SPCFCAV; 11, COKETEND. [FEL, feet east of section line; FNL, feet north of section line; GL, ground level in feet; 0.0B or 0.00B, not analyzed].

by using an update query (base of the sampled interval minus the top of the sampled interval); (3) the "INTXOIL" field (thickness of interval times shale oil in gallons per short ton of rock) was also calculated by using an update query, which was necessary to perform weighted-average calculations; and (4) the "ROCKTYPE" field was added to denote beds of halite ("NH") and (or) nahcolite, and sandstone ("NO"). Although such beds were commonly assayed, the assay results typically produced zero oil and thus are listed as containing zero oil in the assay tables. However, these legitimate zero-oil-yield values needed to be distinguished from the missing intervals that are also listed as zero oil yield in the assay tables in order to correctly calculate an average gallon per ton for the zone in which they were contained. In order to distinguish the two, a minimum oil-yield value of 0.1 GPT was assigned to these nahcolite and sandstone beds.

Overview of Assessment Methodology

The column-delimited ASCII text Fischer assay records were converted using Import Wizard 9 (Beside Software, 2006) and then stored in a Microsoft Access (Microsoft Corporation, 2006) table (fig. 5). Additionally, the oil shale zone "tops" file with correlation data was converted from a Microsoft Excel 2007 spreadsheet and then stored in the Access database (CO_Tops_080115). A one-to-many relation was established between formation tops and the Fischer assay data (CO_Assays_INTV), providing access to many assay records for each core hole. By establishing this link, Structured Query Language (SQL) queries and Visual Basic formulas were developed to calculate resource estimates for each core hole by oil shale zone. After calculating resource estimates for each core hole, derivative maps were then

Table 1. Column names and definitions of the Microsoft Access table after converting the original Fischer assay data and adding additional columns needed for calculations.

Column name	Column definition
OBJECTID	Software-calculated identifier
LABNO	Six-digit USBM Laramie laboratory number
TOPFT	Depth, in ft, measured from the surface datum to the top of the sampled interval
BOTFT	Depth, in ft, measured from the surface datum to the base of the sampled interval
SHLOILPCT	Amount of shale oil, in weight percent
WATERPCT	Amount of water, in weight percent
SHLRSDPCT	Amount of shale residue, in weight percent
GASPLSPCT	Amount of "gas plus loss," in weight percent
OILGPT	Shale oil, in U.S. gallons per short ton of rock
WATERGPT	Water, in U.S. gallons per short ton of rock
SPCFGRAV	Specific gravity of the shale oil
COKETEND	Tendency for spent shale to coke
USGSID	Unique ID assigned by staff geologist
INTVL	Thickness of interval, in ft (BOTFT-TOPFT)
INTXOIL	Column used for weighted-average gallons per ton calculation (INTVL * OILGPT)
ROCKTYPE	Column added to filter out halite intervals ("NH") and to denote intervals that were edited to distinguish between missing records and records found in core descriptions to be either nahcolite or sandstone ("NO").

constructed, including: (1) oil shale-zone thicknesses, (2) average oil yield in gallons per ton (GPT), (3) oil yield in barrels per acre (BPA), (4) barrels of oil yield per township, and (5) percentage of missing intervals determined from the core sample.

The header information from the legacy borehole files was used to digitize the spatial location for each hole using GIS software. The point location as well as its unique identifier (USGSID) were stored in a point feature class in a personal geodatabase. Each borehole was assigned a unique USGSID that was used in correlation-data and resource-estimate tabular relationships. Geostatistical modeling software was then used to model the resource data for each zone using a RBF method. After comparing and testing several modeling techniques, it was determined the RBF-Multiquadric function produced the most geologically reasonable models.

Once satisfied with a particular model, raster datasets were generated for further analysis, including the ability to generate summary statistics based on the BPA models. Zonal statistics functions were used to quantify resources using the established resource polygons intersected with townships as limiting zones to count each raster cell's estimated BPA value. As the analysis cell size was one acre, no mathematical conversions were necessary as the software simply counted each cell's BPA value contained within each individual polygon of each resource reporting file (the outcrop-polygon file intersected with the township file). Various summary calculations and presentation-quality tables were then generated using the resource estimates for total barrels of oil yield per township.

In-Place Resource Calculations

Gallons Per Ton

Resource calculations were performed for each core hole in each zone in a Microsoft Access form (fig. 6). An Access form "is a database object that you can use to enter, edit, or display data from a table or a query" (Microsoft Corporation, 2006), and to view many records from several linked tables in an easier and less cluttered manner. Additionally, by creating a custom form with Visual Basic, SQL, and several macros, we were able to apply filters and perform calculations on many subsets of the master Fischer assay table. Although the results are calculated within the form interactively, we stored the results permanently in a separate database table that we were then able to directly link to GIS software. By using this method, we could continually revise the database (fig. 7) and concurrently generate numerous iterations of spatial models on corrected figures using ArcGIS's GeoStatistical Analyst (ESRI, 2006) extension. Diagrams describing the table relationships in the database are in the Appendix following this report.

To calculate average oil yield per zone (in GPT) for each core hole, missing records were first removed from each zone so they would not affect the weighted-average calculation. This was accomplished by writing queries that filtered out those records where the INTXOIL (thickness of interval times oil yield in GPT) field had a value of 0. As stated previously,

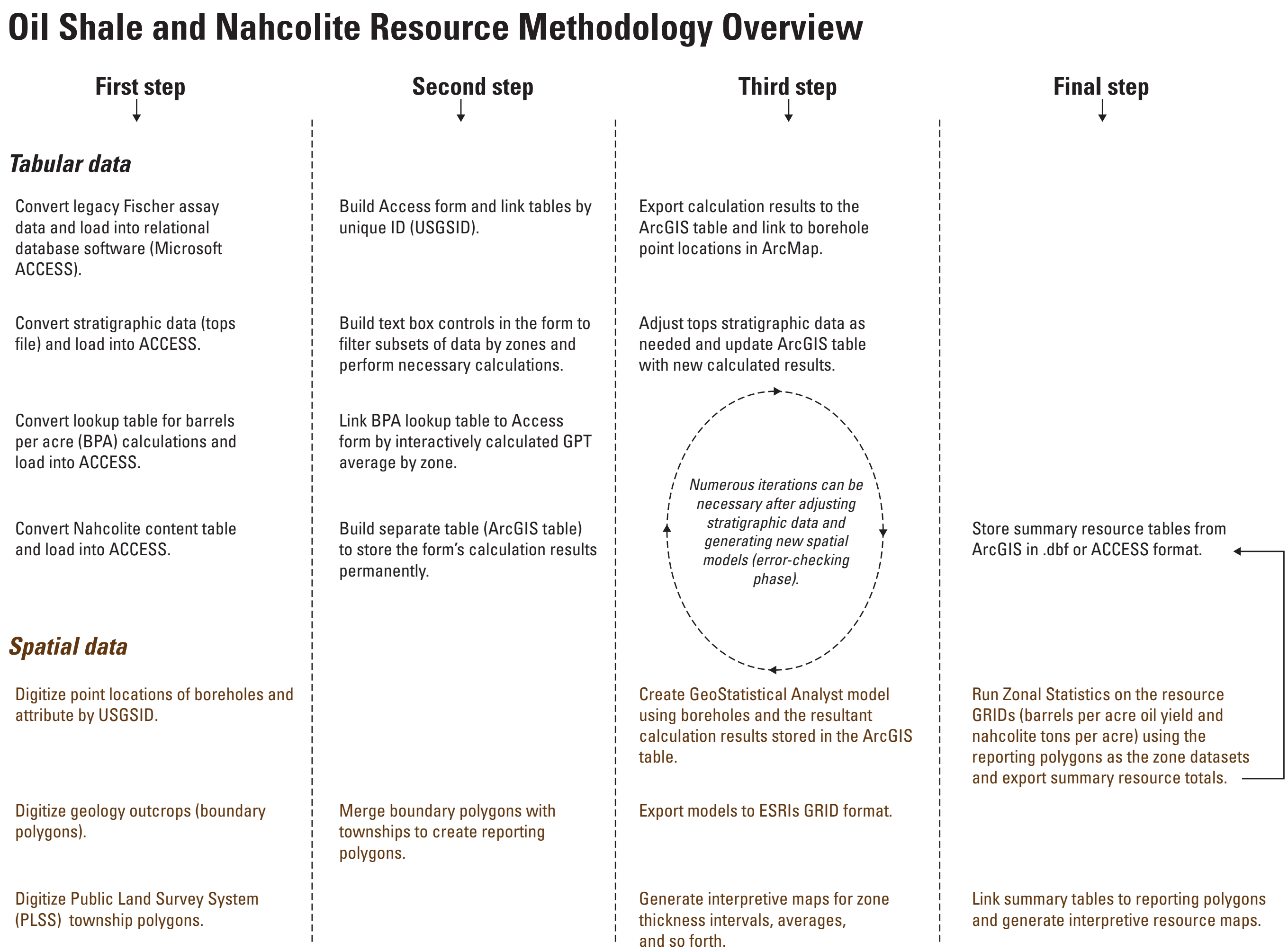

Figure 5. Overview chart showing the four steps and processes performed on the spatial and tabular data for the Piceance Basin oil shale and nahcolite assessments.

missing records were identified and removed from the computation if either the OILGPT or INTXOIL fields contained 0 values. It should be noted that the weighted-average calculation used only valid values for GPT for a particular zone (no zero values), but used the entire thickness of all the sampled intervals within that zone in the formula. The formula used to calculate the weighted average of GPT for each zone was: Sum of (thickness of interval in feet * gallons per ton)/thickness of interval in feet.

Barrels Per Acre

The determination of oil-in-place resource numbers in BPA were generated from the derived GPT weighted-average values calculated in the database form. Stanfield and others (1954) reported data on volume-weight oil-yield relations from nearly 20,500 U.S. Bureau of Mines (USBM) oil-yield analyses (table 2). Smith (1956) reported that oil-yield values were related to the specific gravity of the oil shale. Table 2 contains original values for oil yield in GPT, as well as specific gravity, and were only reported to the nearest 1 GPT. Values for weight of oil shale, volume of oil shale, and oil yield per unit volume were updated using currently accepted conversion factors (table 3). A third-order trendline with a R^2 value of 0.9998 was generated to compare oil yield with specific gravity (fig. 8). As the original table contained only integer values for GPT, new records were inserted to fill in values to one decimal place (for example, 0.1 GPT). A linear-trend series-fill function was then used to calculate specific gravity values for each 0.1 value for the GPT column. A third-order trendline was then regenerated comparing the new oil-yield versus specific-gravity data yielding a R^2 value of 0.9997. Values for weight of oil shale, volume of oil shale, and oil yield per unit volume were then calculated using the new values for oil yield and specific gravity. A final lookup table was then created containing records for oil yield (GPT), specific gravity, and oil yield per unit volume from 1.0 to

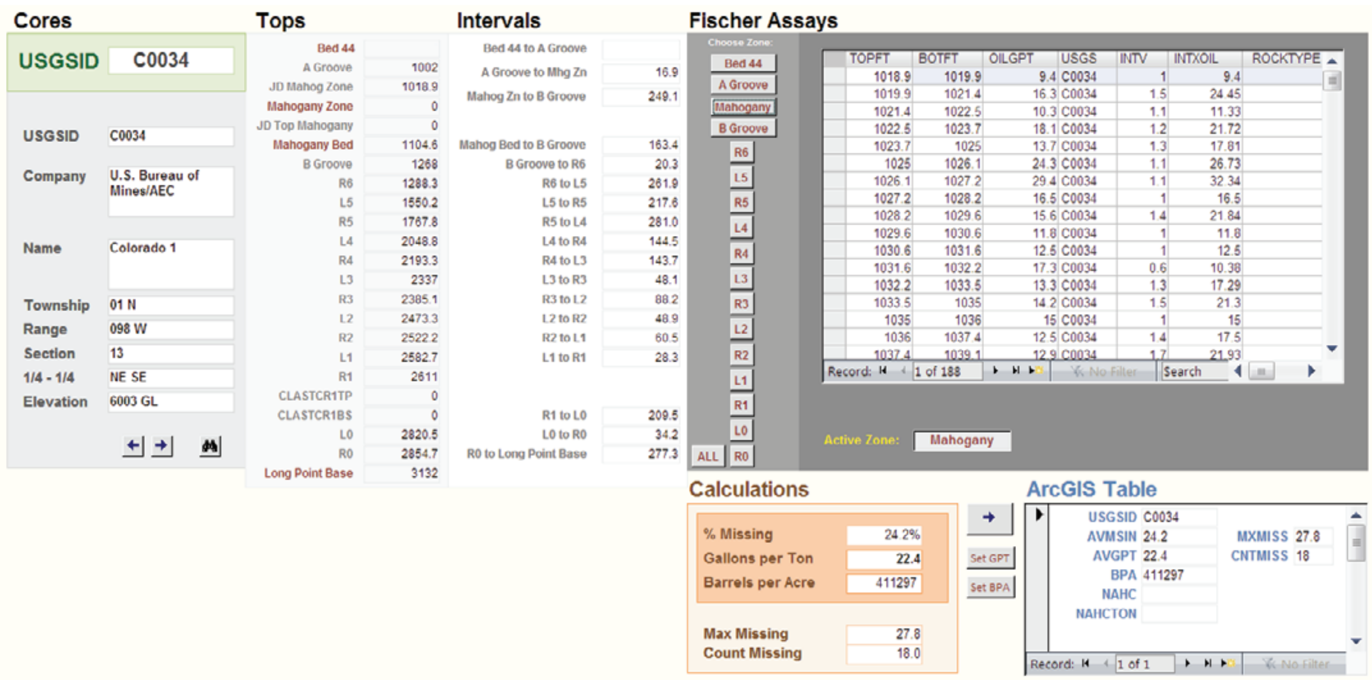

Figure 6. Image clip of Microsoft Access 2007 form used to perform oil shale resource calculations containing: (1) tops table under the headings Cores, Tops, and Intervals; (2) Fischer assays table; (3) calculations section containing controls that performed assessment calculations; and (4) ArcGIS table used to store calculation values permanently.

80.0 GPT, at 0.1 GPT intervals that were then related to the database form by using the values for oil yield in GPT.

To calculate barrels per acre (BPA) for each core hole, the previously calculated weighted-average value for GPT was related to the lookup table (table 3) in order to retrieve the associated value for oil yield per unit volume (gallons per cubic foot); this value was needed to perform the BPA calculation: Interval thickness in feet (without halite beds) * 43,560 (ft^2/acre) * oil yield per unit volume (gal/ft^3)/42 (gals/barrel of oil).

In short, the calculated value for GPT was used as another unique identifier to link to the lookup table (table 3) in order to use the associated value for oil yield per unit volume in that record to be input into the BPA formula. For example, if the Microsoft Access form (as in fig. 6) listed GPT to be 10.0 for a specific core hole and zone, this would correspond to a value of 0.790 gal/ft^3 in table 3, which would then be the input into the BPA formula as the oil yield per unit volume multiplier. The interval thickness value in the formula was calculated by summing all of the intervals within a zone and then subtracting any beds denoted as halite in the ROCKTYPE column–“NH.”

Missing Intervals

In addition to resource calculations, statistics describing missing intervals in percent, maximum thickness of missing intervals, and the number of missing intervals for each core sample were generated for each borehole and zone (fig. 9). In general, the larger the proportion of a given core that constitutes missing interval, the greater the imprecision of the resource calculation. The number and thickness of missing intervals is especially important, because a few thick, missing intervals could potentially have a greater impact on the precision of a resource calculation than a large number of thin intervals. Once a specific borehole was filtered by zone in the database form, a series of custom-scripting functions would count and perform calculations on the missing records in the Fischer assay table. These values are then permanently stored in the table used for GIS functions and a series of derivative maps can be produced by linking the missing-interval statistics to the borehole locations in the GIS. The missing-intervals derivative maps are a valuable aid in assessing the uncertainty of the resource estimates.

Geospatial Modeling, Analysis, and Presentation

Oil Shale Zone Thickness Isopachs

Oil shale zone thickness values were calculated using the zonal contacts as identified in boreholes. This was accomplished by subtracting a pick for any given zone if there was also a pick in the spreadsheet for the immediately underlying zone. Formulas were created to automate this function, but

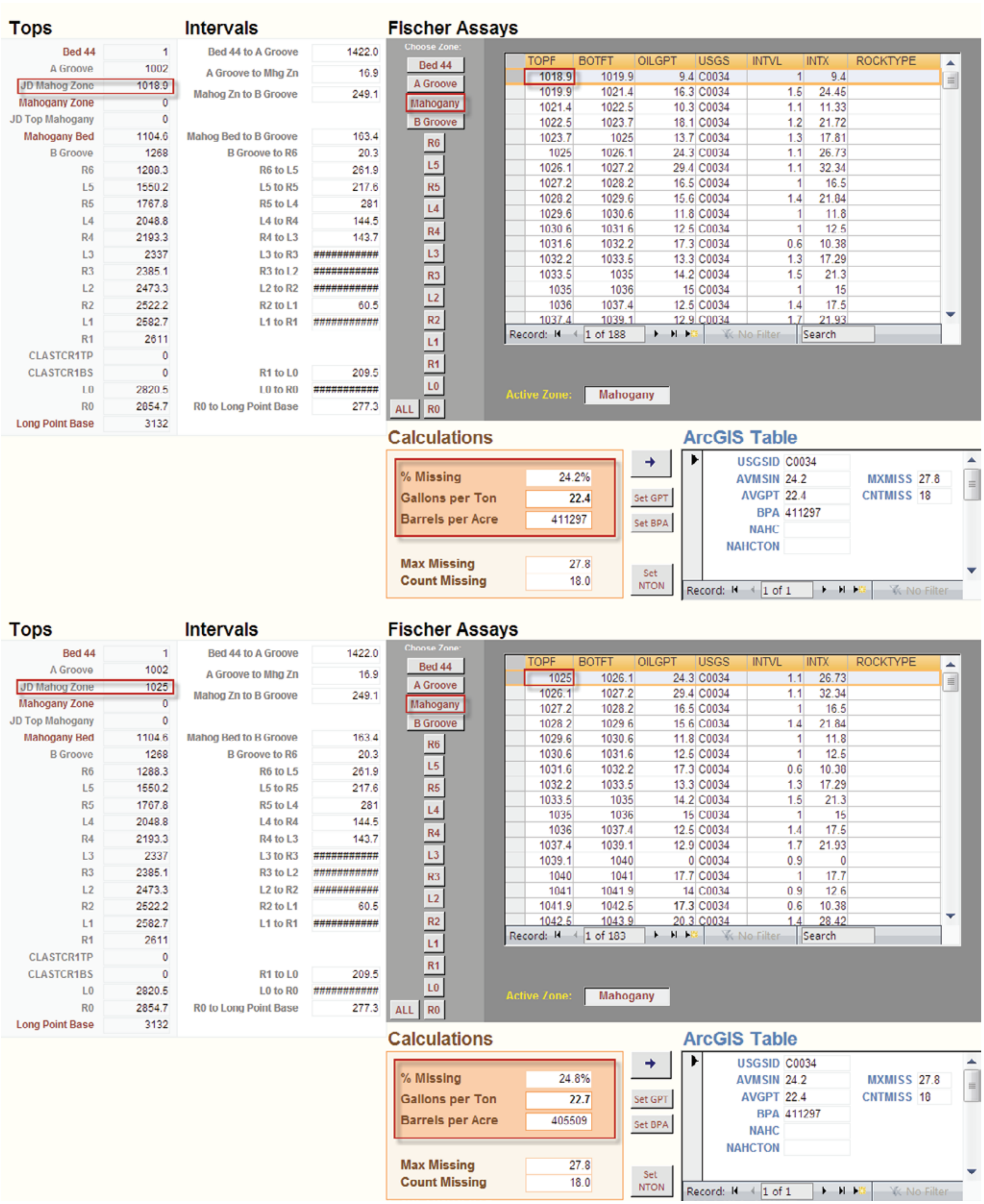

Figure 7. Image clip showing how changing an interpretation of a tops pick in the tops table and re-filtering the Fischer assays table immediately affects the Microsoft Access 2007 form's resource calculations, but not the ArcGIS table's records. Example shown is for the Mahogany oil shale zone in core hole C0034 (see fig. 13 for location data).

Table 2. Original volume-weight oil-yield relationships based upon Green River oil shale from U.S. Bureau of Mines oil shale mine, Rifle, Colo. from Stanfield and others (1954). [GPT, gallons per ton; lbs/ft^3, pounds per cubic foot; ft^3/ton, cubic feet per ton; gal/ft^3, gallons per cubic foot]

Oil yield by assay (GPT)	Specific gravity of oil shale	Weight of oil shale (lbs/ft^3)	Volume of oil shale (ft^3/ton)	Oil yield, per unit volume (gal/ft^3)
1	2.740	170.98	11.70	0.085
2	2.715	169.42	11.80	0.169
3	2.690	167.86	11.91	0.252
4	2.655	166.30	12.03	0.333
5	2.640	164.74	12.14	0.412
6	2.618	163.36	12.24	0.490
7	2.596	161.98	12.35	0.567
8	2.574	160.61	12.45	0.642
9	2.552	159.24	12.56	0.716
10	2.530	157.87	12.67	0.789
11	2.508	156.49	12.78	0.860
12	2.486	155.12	12.89	0.930
13	2.464	153.75	13.01	0.999
14	2.442	152.38	13.13	1.067
15	2.420	151.01	13.24	1.133
16	2.400	149.76	13.35	1.198
17	2.380	148.51	13.47	1.262
18	2.360	147.26	13.58	1.325
19	2.340	146.02	13.70	1.387
20	2.320	144.77	13.80	1.448
21	2.302	143.64	13.92	1.508
22	2.284	142.52	14.03	1.567
23	2.266	141.40	14.14	1.625
24	2.248	140.78	14.26	1.683
25	2.230	139.15	14.37	1.740
26	2.216	138.28	14.46	1.797
27	2.202	137.40	14.56	1.854
28	2.188	136.53	14.65	1.910
29	2.174	135.66	14.74	1.966
30	2.160	134.78	14.83	2.022
31	2.147	133.97	14.92	2.077
32	2.134	133.16	15.02	2.131
33	2.121	132.35	15.11	2.184
34	2.108	131.54	15.20	2.236
35	2.093	130.73	15.30	2.288
36	2.082	129.92	15.44	2.339
37	2.069	129.11	15.49	2.389
38	2.056	128.29	15.59	2.438
39	2.043	127.48	15.69	2.486
40	2.030	126.67	15.79	2.534
41	2.018	125.92	15.88	2.581
42	2.006	125.17	15.98	2.628

Table 3. Recalculated volume-weight oil-yield relationships based upon Green River oil shale from U.S. Bureau of Mines oil shale mine, Rifle, Colo. from Stanfield and others (1954). [GPT, gallons per ton; lbs/ft^3, pounds per cubic foot; ft^3/ton, cubic feet per ton; gal/ft^3, gallons per cubic foot]

Oil yield by assay (GPT)	Specific gravity of oil shale	Weight of oil shale (lbs/ft^3)	Volume of oil shale (ft^3/ton)	Oil yield, per unit volume (gal/ft^3)
1	2.740	171.06	11.69	0.086
2	2.715	169.50	11.80	0.169
3	2.690	167.94	11.91	0.252
4	2.655	165.75	12.07	0.332
5	2.640	164.82	12.13	0.412
6	2.618	163.44	12.24	0.490
7	2.596	162.07	12.34	0.567
8	2.574	160.69	12.45	0.643
9	2.552	159.32	12.55	0.717
10	2.530	157.95	12.66	0.790
11	2.508	156.57	12.77	0.861
12	2.486	155.20	12.89	0.931
13	2.464	153.83	13.00	1.000
14	2.442	152.45	13.12	1.067
15	2.420	151.08	13.24	1.133
16	2.400	149.83	13.35	1.199
17	2.380	148.58	13.46	1.263
18	2.360	147.33	13.57	1.326
19	2.340	146.09	13.69	1.388
20	2.320	144.84	13.81	1.448
21	2.302	143.71	13.92	1.509
22	2.284	142.59	14.03	1.568
23	2.266	141.47	14.14	1.627
24	2.248	140.34	14.25	1.684
25	2.230	139.22	14.37	1.740
26	2.216	138.34	14.46	1.798
27	2.202	137.47	14.55	1.856
28	2.188	136.60	14.64	1.912
29	2.174	135.72	14.74	1.968
30	2.160	134.85	14.83	2.023
31	2.147	134.04	14.92	2.078
32	2.134	133.23	15.01	2.132
33	2.121	132.41	15.10	2.185
34	2.108	131.60	15.20	2.237
35	2.093	130.67	15.31	2.287
36	2.082	129.98	15.39	2.340
37	2.069	129.17	15.48	2.390
38	2.056	128.36	15.58	2.439
39	2.043	127.54	15.68	2.487
40	2.030	126.73	15.78	2.535
41	2.018	125.98	15.88	2.583
42	2.006	125.23	15.97	2.630

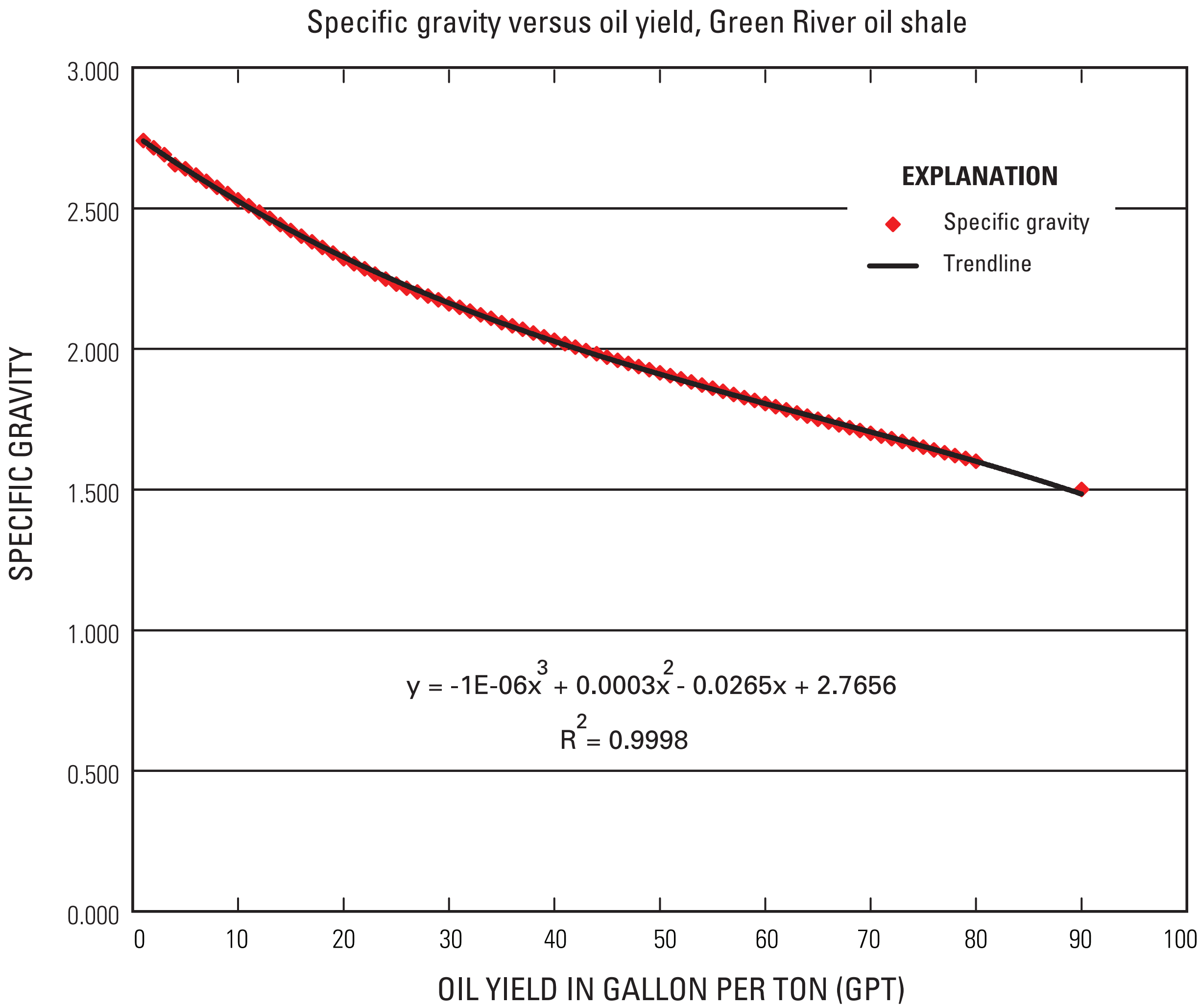

Figure 8. Graph of a third-order trendline showing relation between oil yield for Green River oil shales and specific gravity.

actual values were used in converting the spreadsheet to a database table. When a zone top pick was revised in the database form, the thickness of the zone interval was recalculated. Using this method, values for all resource calculations were continuously and immediately updated, as the new tops and interval values affected all formulas contained in the form and were recalculated on-the-fly (fig. 7).

Once a set of tops for a given zone was finalized, the thickness values for each zone were used to generate spatial-data models using a RBF-Multiquadric modeling method. By generating and analyzing a spatial model for each zone, errors were located in the tops file and changes were made to the correlations as needed. Upon completion of the database, a final model was converted to a fixed raster dataset and a series of oil shale zone thickness isopach maps were generated.

Generating Oil-Yield Models

In a previous oil shale assessment, Pitman and others (1989) used geostatistical interpolation by kriging to generate resource maps and numbers. They reported that kriging gave good results in areas with large numbers of control points, but that the calculations gave unreliable resource numbers with large error limits in areas with fewer control points; consequently, they resorted to hand-contouring and hand-calculating resources in these areas. In the present assessment, three modeling methods were evaluated for

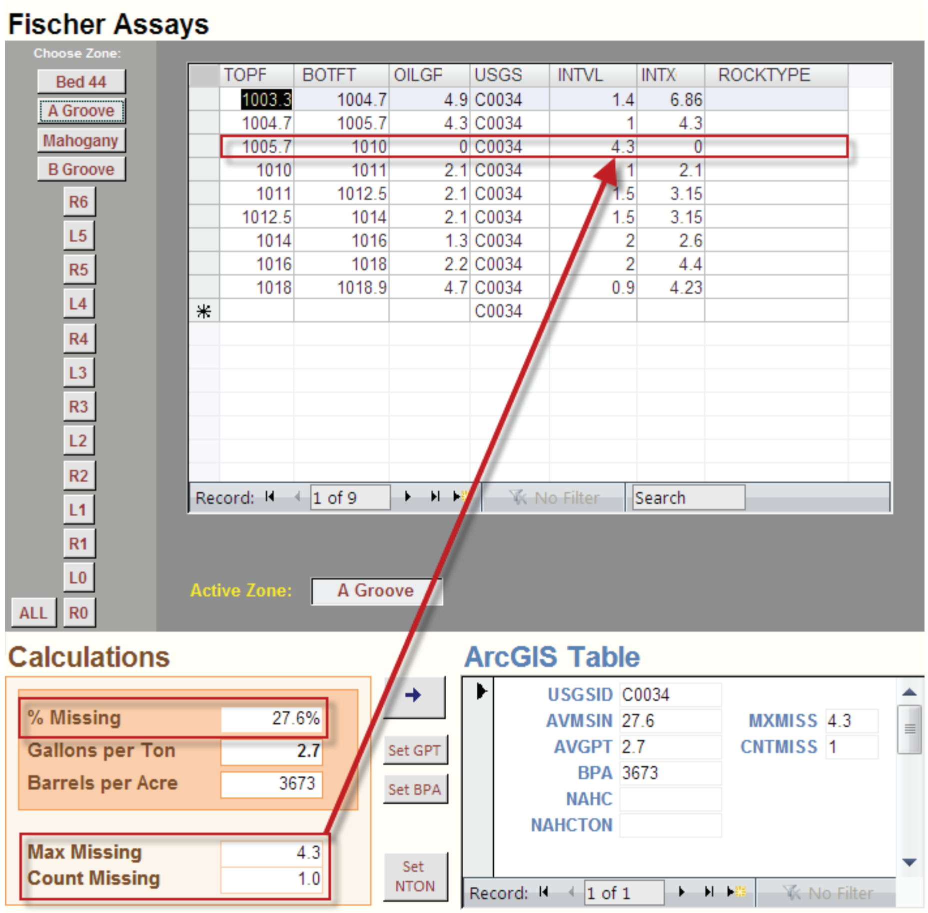

Figure 9. Image clip of Microsoft Access 2007 form showing how missing intervals were reported for each core sample. Example shown is for the A-groove oil shale zone in core hole C0034 (see fig. 13 for location data).

spatial interpolation and extrapolation purposes: (1) the RBF method, (2) the Inverse Distance Weighted (IDW) method in ArcGIS (ESRI, 2006), and (3) the minimum-tension gridding technique in EarthVision (Dynamic Graphics, Inc., 2004). The three methods gave remarkably similar results, and RBF was ultimately chosen. One of the determining factors was that the RBF method did not limit us to coarse-cell spacing, so we were able to model and report resources using a one-acre cell size. Although not as robust as kriging or other geostatistical spatial modeling methods, it has been demonstrated that the RBF method can give comparable results (Rusu and Rusu, 2006). RBF is an exact interpolator; it will honor all data points and not introduce any error at those locations (ESRI, 2006). Although 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. Extrapolation of values beyond the dataset boundaries was appropriate in this geology-based assessment, as each zone's oil yield varies in a predictable manner throughout the basin.

After the database revisions were completed, the resultant calculated values for gallons per ton (GPT) and barrels per acre (BPA) were migrated to a separate database table and linked to the core hole locations file. RBF models were then generated using the resultant core hole data containing oil yield values (fig. 10). The values for GPT and BPA were modeled using the RBF-Multiquadric method. The final resource models were created using a sampling method containing eight moving window sectors with eight neighbors in each sector. After numerous tests, these parameters yielded the most geologically reasonable oil shale resource models due to the number of core holes and the extent of the dataset. After all of the models were finalized, they were exported to a fixed raster format with a one-acre cell size (208.7 ft (63.615

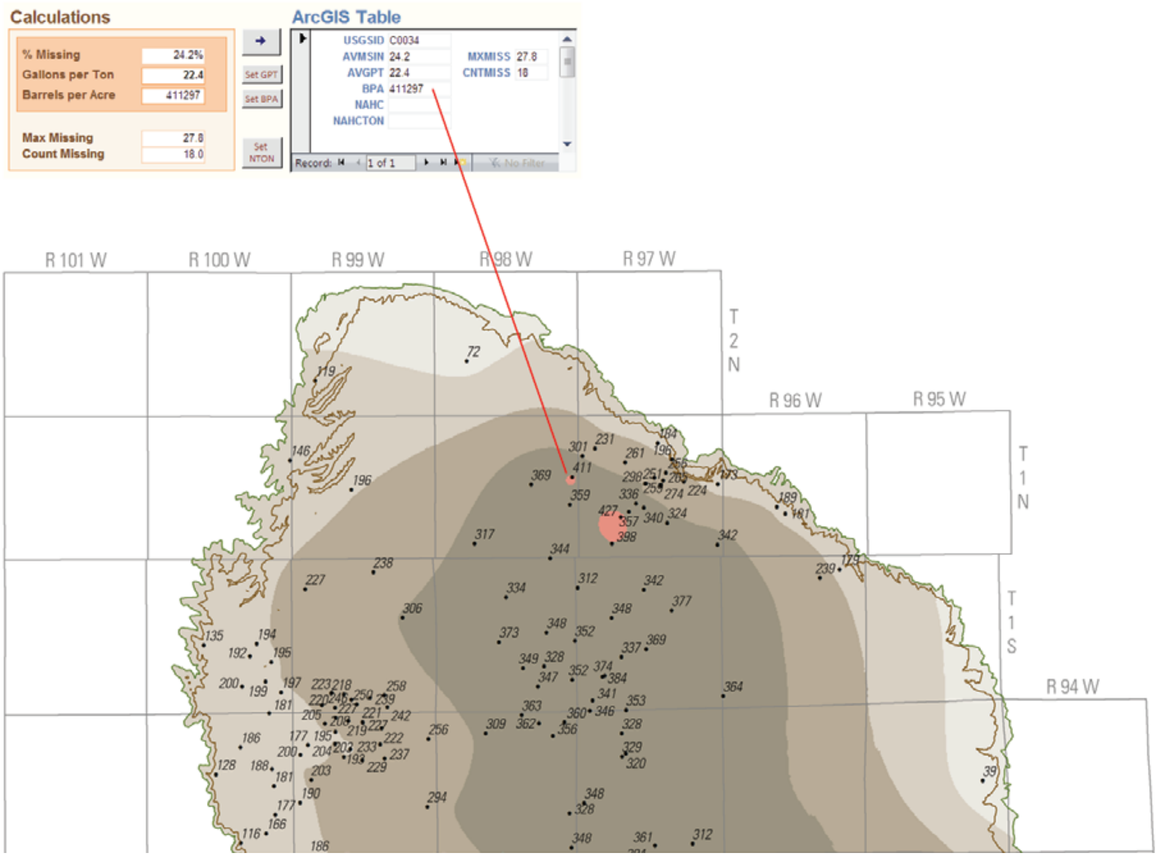

Figure 10. Image clip showing how data are migrated from the Microsoft Access 2007 database form and then modeled in the GIS software. Values labeled in model are in thousands of barrels. Example shown is for the Mahogany oil shale zone in core hole C0034 (see fig. 13 for location data).

m) per side) along with a mean error, root mean-squared error (RMS), and cross-validation table for each BPA model. A more detailed description of the error tables is presented in Case Study 1 at the end of this report. A series of derivative maps were then created using ArcGIS (ESRI, 2006).

Summarizing Resource Models

A zonal-statistics function was used on the finalized BPA model to calculate resources per township; this step being critical inasmuch as the software was able to count each cell's BPA value within a specified zone (fig. 11). In this case, the surface zones that the software required to summarize the raster cells (not to be confused with the subsurface oil shale zones) were townships or portions thereof that were cropped by the outcrop lines. As the analysis cell size was one acre and BPA were modeled, a straightforward summary of total barrels of oil yield per township was performed as the software simply counted all of the values for BPA for each cell, or acre, contained within each resource township. The summary statistics were then linked to each township and another series of derivative maps detailing the total barrels of oil yield per township were generated. Although a polygon file delineating township boundaries within the resource zones was used, in the future a user could easily run statistics using a different zone boundary, such as sections, in order to obtain a summary of barrels of oil yield per section.

Interpretive Maps

Once the spatial analysis and quantification of resources were completed, a series of interpretive maps were generated for each of the 17 oil shale zones, including isopachs of oil shale zones, average oil yield in GPT, oil yield in BPA, oil yield in barrels per township, and the percentage of missing intervals in each core sample (fig. 12).

Nahcolite Assessment

Data Preparation, Capture, and Conversion

Calculation of in-place nahcolite resources in the north-central part of the Piceance Basin applied the same

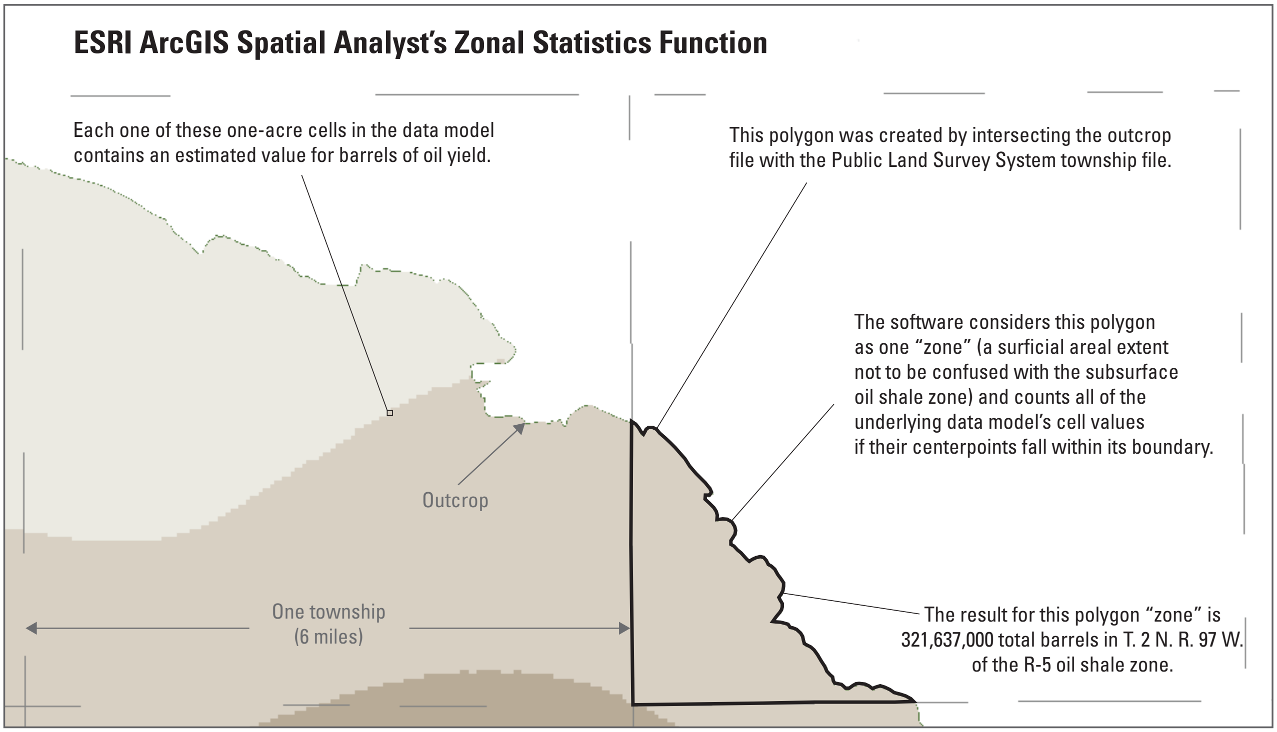

Figure 11. Map of northeastern part of the Piceance Basin, Colorado, showing how the GIS software summarized total barrels of oil yield by township.

methodology as was used in the assessment of in-place oil in oil shale zones with a few variations: (1) an additional table containing nahcolite-content data was linked to the main database form, (2) spatial data delineating the areal extent of the nahcolite-bearing zone in the Parachute Creek Member of the Green River Formation was created and combined with the outcrop data, and (3) a formula in the database form was regenerated to calculate in-place nahcolite resources (Beard and others, 1974).

Spatial Data

The same core hole point-locations file as the oil shale assessment was used for all nahcolite mapping and spatial modeling tasks. In order to constrain resource calculations, a new nahcolite-bearing polygon file was digitized using nahcolite-bearing and non-nahcolite-bearing (zero points) core holes and was intersected with the Mahogany zone outcrop file. The resultant file was then intersected with the PLSS grid to create the surface zones required for zonal-statistics functions used to calculate tonnage per township.

Tabular Nahcolite Data

Multiple tables containing nahcolite weight-percent data derived from the original USBM analyses performed at the Laramie, Wyo. Oil Shale Laboratory (since shutdown) and USGS nahcolite analyses were combined into one spreadsheet using a public domain macro (VBAX, 2008). The resultant table was then linked to the database form by the unique core hole identifier (USGSID).

Estimates of nahcolite content in oil shale samples from the lower part of the Parachute Creek Member of the Green River Formation were compiled in a database containing 58 core holes by oil shale zone (fig. 2; table 4). This database was compiled from USBM and USGS sample data that were analyzed at the Laramie, Wyo. facility and contains data on sample interval, Al_2O_3, Na, and nahcolite values in weight percent, specific gravity of the sample, and oil yields. Table 4 defines the column names in the nahcolite-data spreadsheet.

In-Place Tonnage Resource Calculations

The following data are required from the nahcolite table and the Fischer assay table to estimate nahcolite resources: (1) weight-percent nahcolite for each sample or zone, (2) oil yield in 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

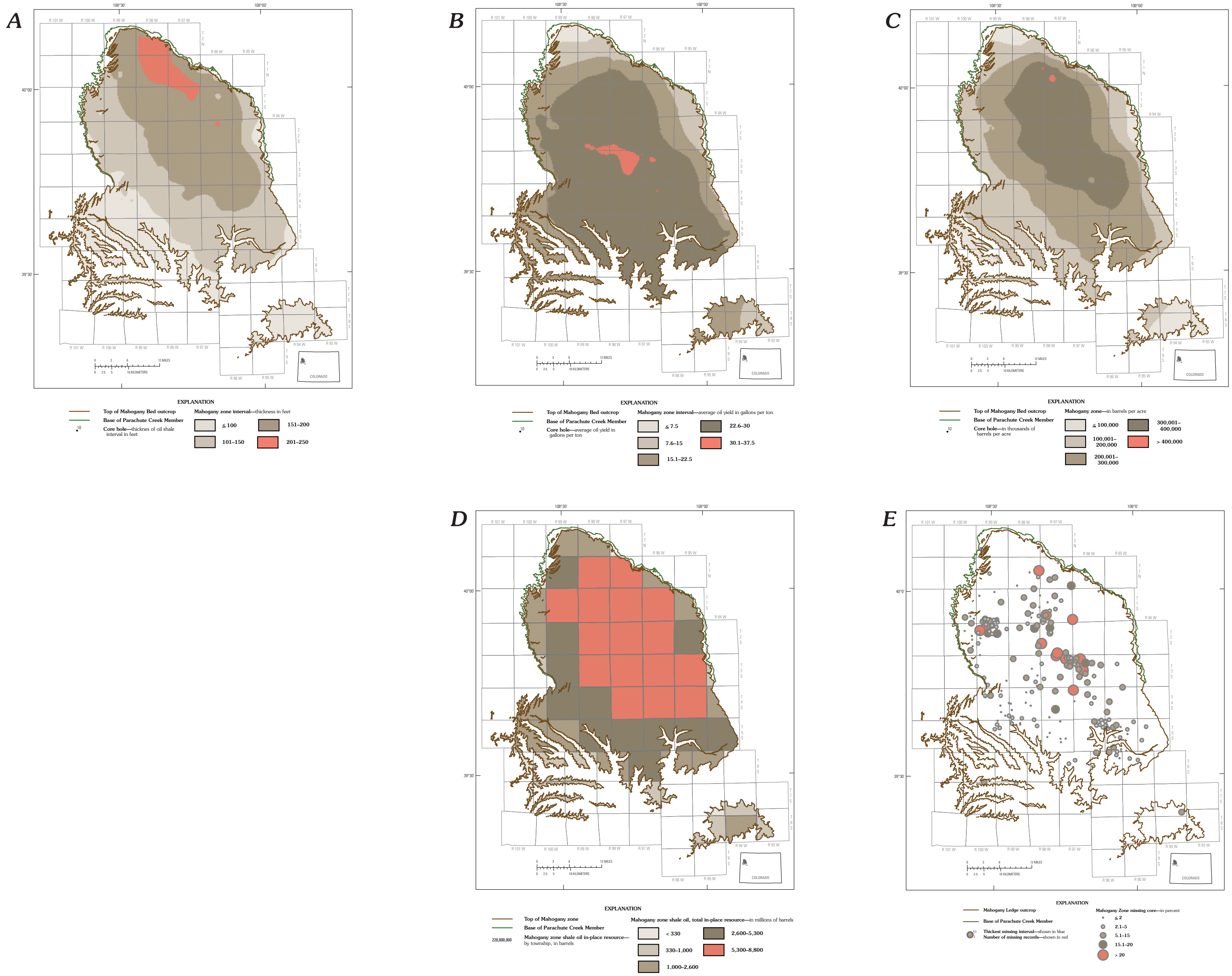

Figure 12. Examples of interpretive maps generated from resource models: *A*, oil shale zone isopachs; *B*, average oil yield in gallons per ton; *C*, oil yield in barrels per acre; *D*, oil yield in barrels per township; *E*, percentage of missing intervals from each core sample. See Johnson and others, chapter 1, this CD-ROM, for original figures.

Table 4. 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	Al2O3 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

(Smith, 1956). The procedure, modified from Beard and others (1974), 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:

$$\text{Weight fraction nahcolite} = \frac{\text{Weight \% nahcolite}}{100}$$

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

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):

Specific gravity of oil shale fraction =

$$\frac{205.998 - \sqrt{(205.998)^2 - 4 \times 31.563 \times (326.624 - \text{Oil yield, weight fraction, GPT})}}{2 \times 31.563}$$

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

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

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

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

6. Calculate the weight of 1 ft^3 of sample from the sample specific gravity (step 5) using 62.3 lb/ft^3 as the weight of water at room temperature in air (Stanfield and others, 1960):

$$\text{Nahcolite sample weight, lb/ft}^3 = \text{Sample specific gravity} \quad 62.3$$

7. Calculate the weight in pounds of 1 ft^2 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:

$$\text{Weight, interval or zone, lb/ft}^2 = \text{Sample weight, lb/ft}^3 \quad \text{Sample or zone thickness, ft}$$

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 ft^2 of the interval or zone calculated in step 7:

$$\text{Weight, nahcolite in well or zone, lb/ft}^2 = \text{Nahcolite weight fraction} \quad \text{Weight, interval or zone}$$

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

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

The methodology for calculating in-place nahcolite resources (Beard and others, 1974), shown above, was regenerated in the Microsoft Access form using several controls and Visual Basic scripting (figs. 13, 14). The formulas and their associated control boxes in the database form were able to filter data from the nahcolite and Fischer assay tables in order to perform calculations. An average nahcolite weight percent was first calculated for each oil shale zone (Cashion and Donnell, 1972). Another critical value needed for the resource methodology was an average per zone for GPT oil yield extracted from the Fischer assay table. It is important to note that the form controls performed calculations using only those records that were common to both the nahcolite table and Fischer assay table. That is, the average GPT value was calculated from the Fischer assay table using only that part of a particular zone containing nahcolite. For this reason, a separate database was created that contained only those Fischer assay records that correlated with the nahcolite intervals. This allowed calculations of the average GPT to be dependent on the assays common to the nahcolite intervals, yielding values for each zone in each hole in terms of tons of nahcolite per square mile. This process was repeated for the average nahcolite value over the total thickness of the nahcolite-bearing interval, resulting in values in tons of nahcolite per square mile for the entire nahcolite-bearing interval within each borehole. These values were migrated from the Access form to a separate ESRI shapefile (Nahc_Master_pts.shp) to keep the oil shale and nahcolite final values in separate tables.

Geospatial Modeling, Analysis, and Presentation

Generating Tonnage Models

The resultant nahcolite shapefile contains the point locations of nahcolite core holes as well as their final calculated-resource values. As the assessment-analysis cell size was one acre, all values for tons per square mile were converted to tons per acre. Nahcolite-resource models were then created using ArcGIS's GeoStatistical Analyst extension. The RBF in GeoStatistical Analyst was used to interpolate (and extrapolate) surfaces using the same Multiquadric method as the oil shale assessment. The final resource models were created using a sampling method containing 10 moving window sectors with 15 neighbors in each sector. After numerous tests, these parameters were observed to yield the most geologically reasonable nahcolite-resource models due to the number of core holes and the extent of the dataset.

Summarizing Resource Models

Once the models were created and converted to ArcGIS's GRID format, the Spatial Analyst extension's Zonal Statistics function was applied to determine total tonnages of nahcolite as well as tonnages per township. We also summarized

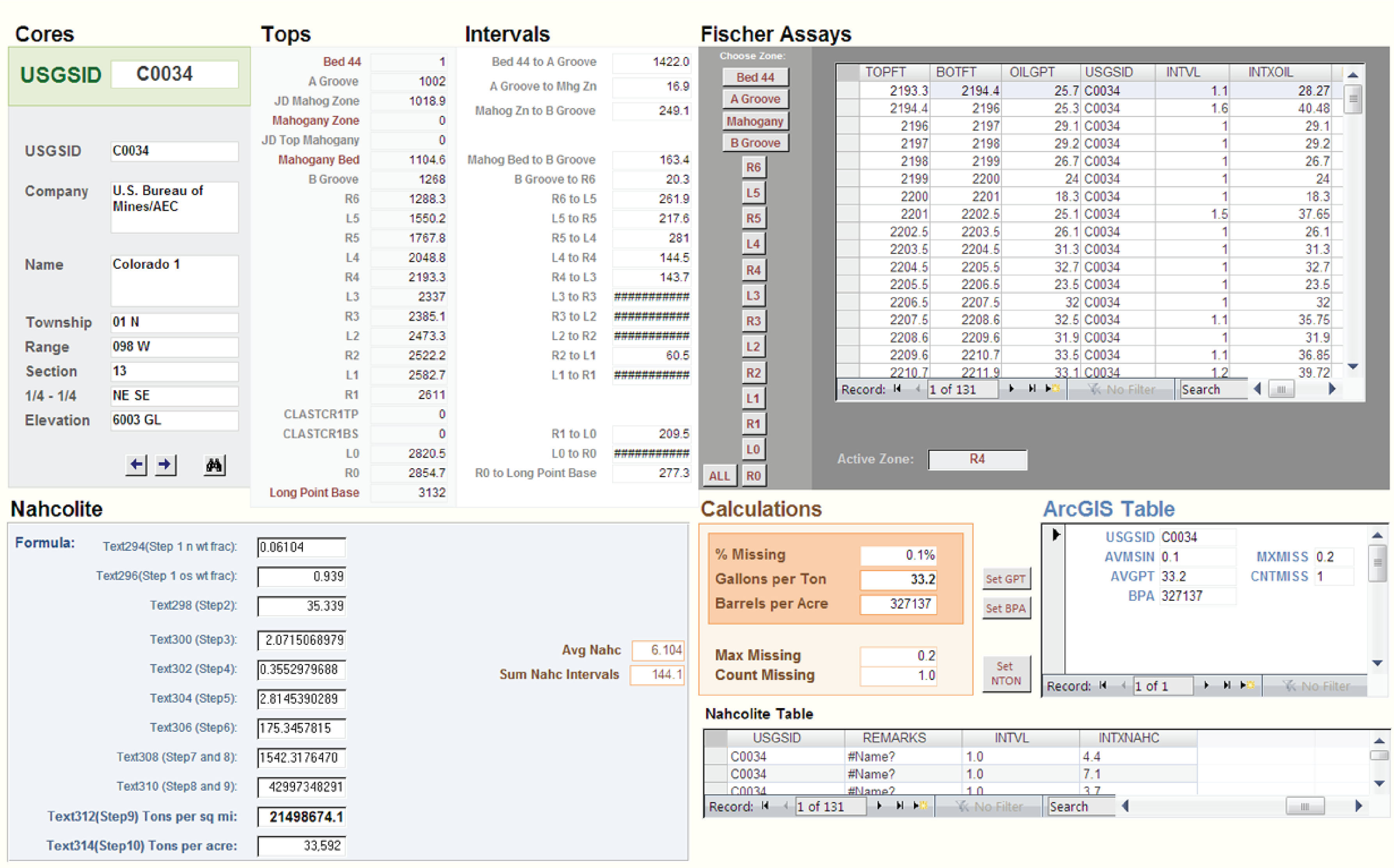

Figure 13. Image clip of Microsoft Access 2007 form used to perform nahcolite-resource calculations containing: (1) tops table under the headings Cores, Tops, and Intervals, (2) Fischer assays table, (3) Calculations section containing controls that performed the assessment calculations, (4) nahcolite resources step-by-step formula and calculations reproduced under the Nahcolite heading, and (5) ArcGIS table used to store the calculation values permanently.

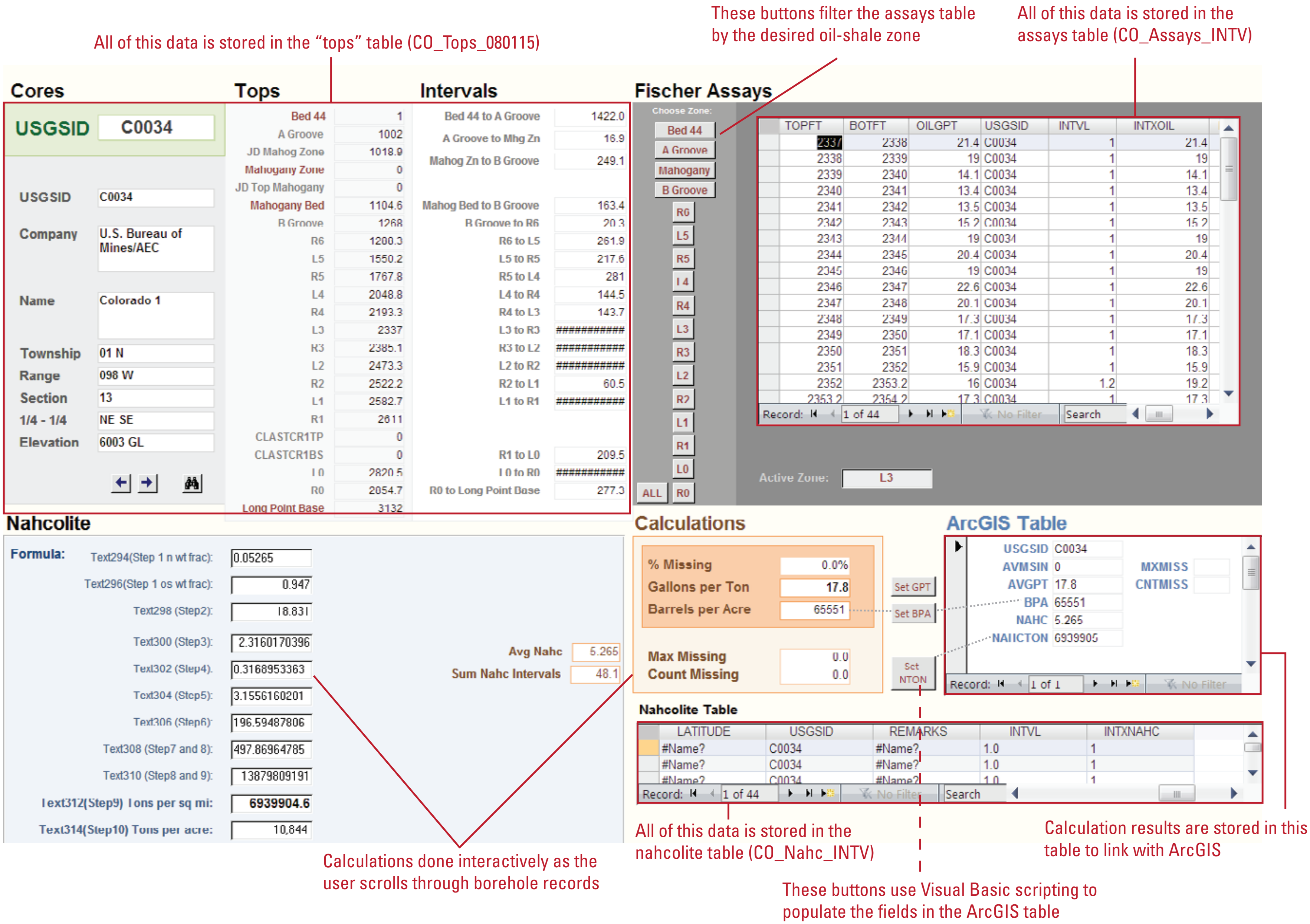

Figure 14. Image clip of Microsoft Access 2007 form detailing how the user interacts with the form’s buttons and controls. Red text and linework details the visual representation of the database’s tables within the form as well as buttons and controls added to utilize Visual Basic scripting and macros.

nahcolite resources by oil shale zone and total in-place nahcolite within the inferred extent of the nahcolite-bearing interval.

In addition to modeling resources, we generated a nahcolite total-thickness interval model that contained thicknesses for each nahcolite-bearing interval for each core hole being assessed. For this, we also used ArcGIS's GeoStatistical Analyst (GA) extension to model the interval thickness values using a RBF-Multiquadric modeling method.

Interpretive Maps

Upon completion of the spatial analysis and quantification of nahcolite resources, a series of interpretive maps were generated for eight of the 17 oil shale zones for publication, including total nahcolite-bearing interval isopachs, average weight-percent nahcolite for the entire nahcolite-bearing interval, total in-place nahcolite resource in tons per acre, total in-place nahcolite resource by township, tons per acre by zone, and tons per township by zone.

Conclusions

For the 17 oil shale zones in the Piceance Basin, an updated and reproducible method was created to calculate in-place oil and nahcolite resources using modern relational database and GIS software. The process involved the conversion of legacy data and generation of new data. The results are presented in digital formats that can be used by other investigators to develop their own interpretations and generate their own data models using other spatial-modeling techniques.

Acknowledgments

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Case Study 1—Oil Shale Assessment

Converting and Loading Legacy Fischer Assay Data

We loaded legacy Fischer assay data files (Dyni, 1998) into a Microsoft Access (Access) database table (fig. 15) using Import Wizard ver. 9 (Beside Software, 2006). It was necessary, initially, to create an Import Wizard model file (A_FISCHER_DEPTHS.iwm; fig. 16) that defined the column names according to the delimiters in the original ASCII text files (Dyni, 1998). After the model was created, we imported more than 700 Fischer assay files into one Access table. We then defined the fields according to the character spacing in the original ASCII files. Once the table was created and populated in Access, columns were added for the thickness of each sampled interval (INTVL), the thickness of the interval times the oil yield in gallons per ton (INTXOIL), and a field to denote halite and records added by staff geologists (ROCKTYPE). We populated the INTVL and INTXOIL fields by using update queries in Access.

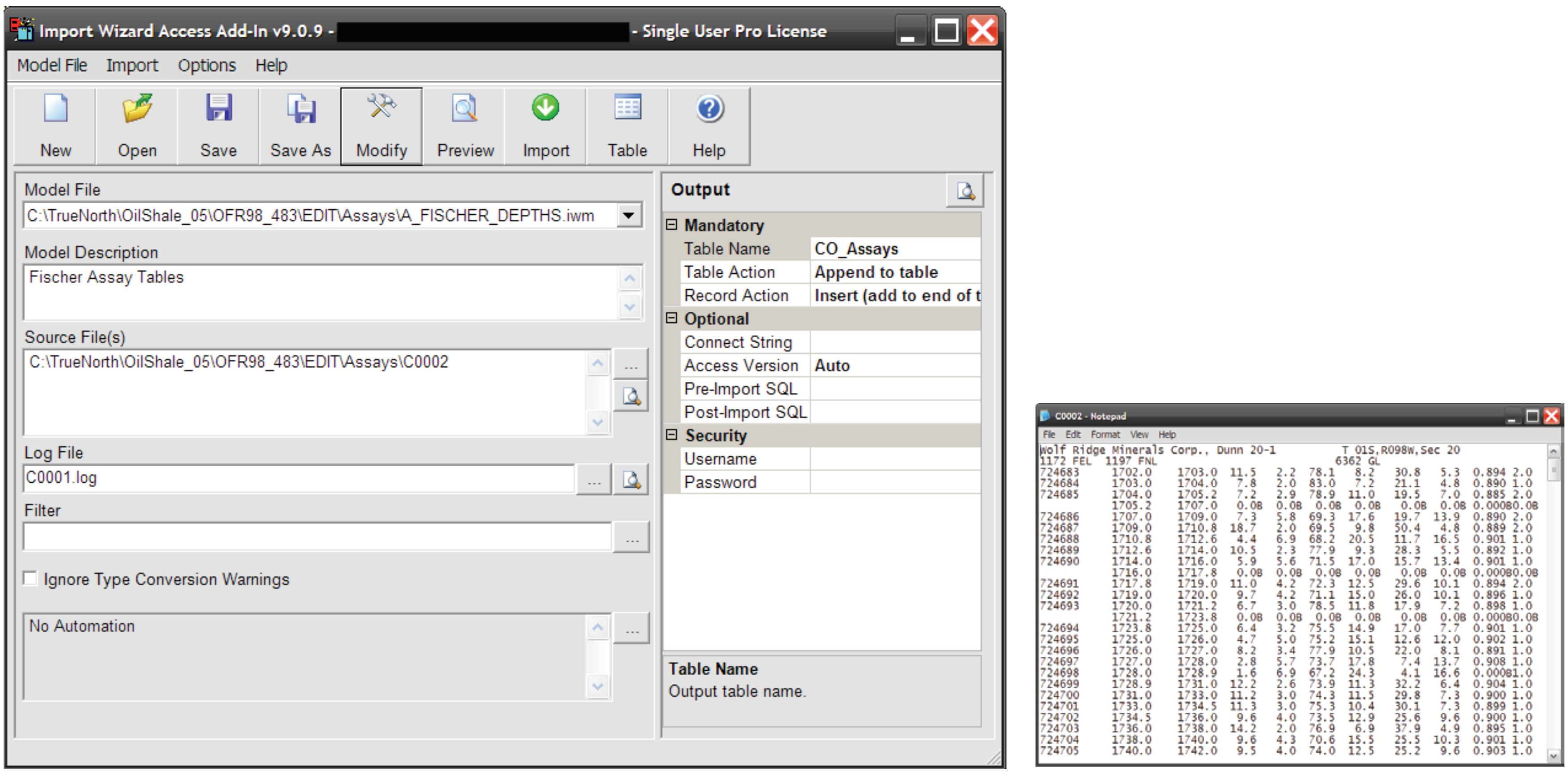

Figure 15. Image clip of Beside Software Import Wizard dialog window to import legacy Fischer assay data (Dyni, 1998). A portion of the original Fischer assay data for the Wolf Ridge Minerals Corp. Dunn 20-1 borehole is shown to the right (see fig. 4, table 1).

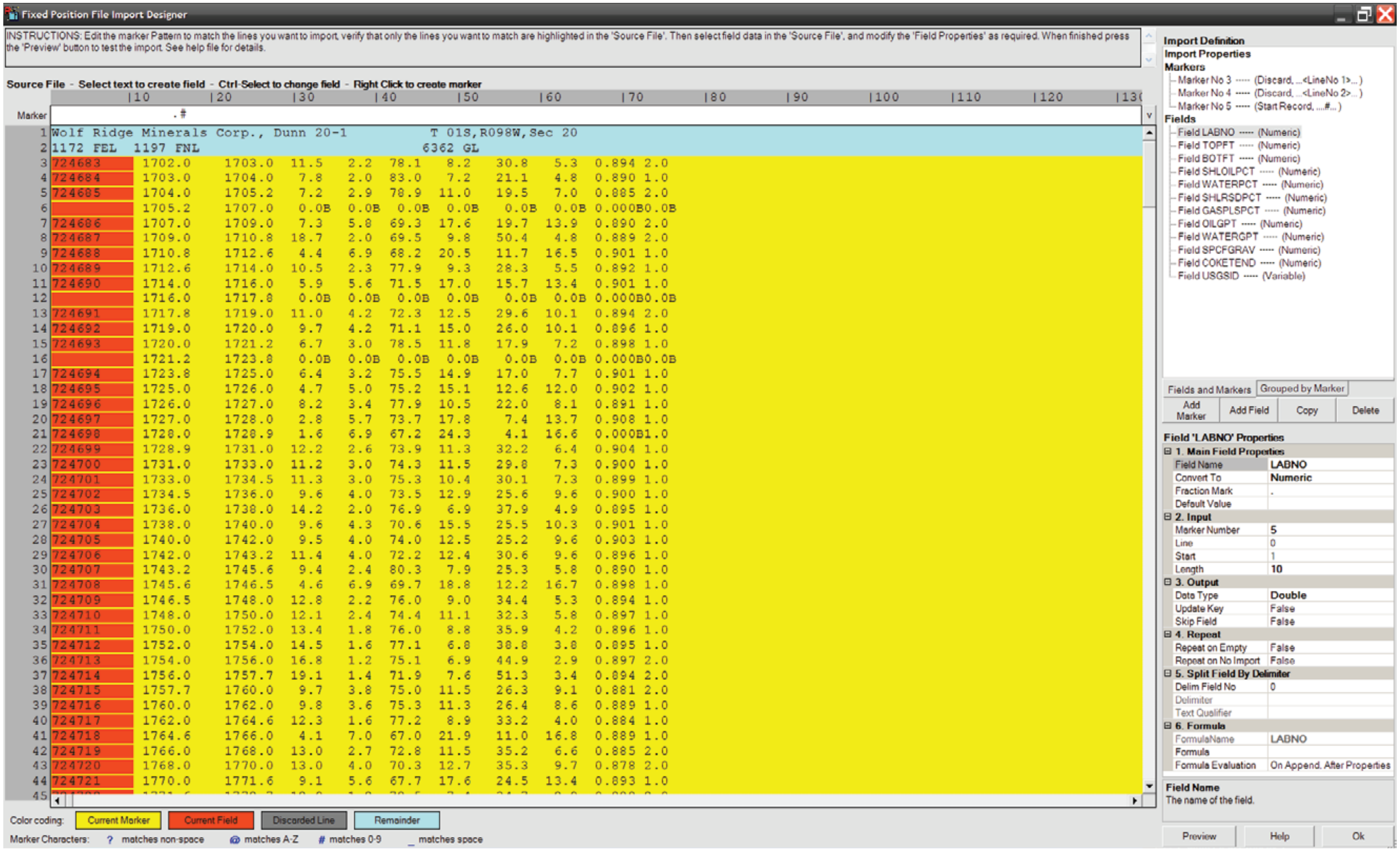

Figure 16. Image clip of Import Wizard model file (A_FISCHER_DEPTHS.iwm) setup dialog window. The blue area denotes the header information that was ignored during the import process. The red area denotes the selected field (LABNO, laboratory number) and the width of the column. The yellow area denotes the rest of the fields to be imported.

Converting and Loading Stratigraphic “Tops” Data

The stratigraphic “tops” table (fig. 17) contains depths (in ft) to each oil shale zone, from which the thickness of each oil shale zone was determined. Formulas were created in Microsoft Excel to calculate the interval thicknesses and the results were converted to cell values in order to transfer all the necessary data to Access. The Excel spreadsheet was then imported to an Access table (CO Tops_080115).

USGSID	JDAGROOV	JDMAHOGZN	OMAHOGZN	JDTPMAHOG	OMAHOG	JDBGROOV	JDR6	JDL5
C0001	831.0	845.4	0.0	0.0	886.7	1026.0	1083.0	1244.0
C0002	0.0	0.0	0.0	0.0	0.0		0.0	0.0
C0003	0.0	0.0	0.0	0.0	1179.0	1313.0	1346.0	1585.0
C0004	0.0	1212.0	0.0	0.0	1275.0	1440.0	1460.0	1698.0
C0005	0.0	0.0	0.0	0.0	1209.9	1341.4	1353.0	1516.7
C0006A	0.0	925.0	0.0	0.0	975.0	1111.0	1133.0	1344.0
C0006B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C0007	0.0	1114.0	0.0	0.0	1158.0	1289.0	1308.0	1483.0
C0008	0.0	1418.0	0.0	0.0	1462.0	1590.0	1621.0	1812.0
C0009	618.0	629.0	0.0	0.0	684.0	803.0	823.0	982.0
C0010	636.0	653.0	0.0	0.0	697.0	821.0	837.0	1001.0
C0011	1012.0	1025.0	0.0	0.0	1073.0	1196.0	1211.0	1394.0
C0012	1102.0	1113.0	0.0	0.0	1158.0	1265.0	1280.0	1444.0

Figure 17. Structure of the stratigraphic tops table (CO_Tops_080115) as viewed in Microsoft Access 2007 showing the depth, in ft, to the top of the A-groove through L-5 oil shale zones for core holes C0001 through C0012. Tops of oil shale zones are listed stratigraphically from left to right: AGROOV, A- Groove; MAHOGZN, Mahogany Zone; TPMAHOG, Mahogany Bed; MAHOG, Mahogany Bed; BGROOV, B- Groove; R6 (rich-zone 6); L5 (lean-zone 5). Tops picked by JD, John Donnell (USGS) or Janet Pitman (USGS); O, authors of this report.

Converting and Loading the Barrels Per Acre (BPA) Lookup Table

The Lookup Table containing the updated values for gallons per cubic foot necessary for the BPA calculations was converted from a Microsoft Excel 2007 spreadsheet to an Access table (BPA Lookup Table). After the gallons per ton weighted average is calculated for a particular zone interactively in the Access form, the "GALFT3NEW" value associated with that gallons per ton average is required as a multiplier in the formula. For example, if a zone's weighted average for gallons per ton oil yield is 1.4, the multiplier is 0.119 for the calculation. We used a linear trend based on Excel 2007's fill series function to fill in values for every 0.1 gallon per ton in Excel before importing the spreadsheet to Access (fig. 18).

ID	GALPERTON	GALFT3NEW
793	0.0	0.000
794	0.1	0.009
795	0.2	0.017
796	0.3	0.026
797	0.4	0.034
798	0.5	0.043
799	0.6	0.052
800	0.7	0.060
801	0.8	0.069
802	0.9	0.077
93	1.0	0.086
94	1.1	0.094
95	1.2	0.102
96	1.3	0.111
97	1.4	0.119
98	1.5	0.128
99	1.6	0.136
100	1.7	0.144
101	1.8	0.153
102	1.9	0.161
103	2.0	0.169

Figure 18. Structure of the barrels per acre lookup table (BPA Lookup Table) used for the form calculations as viewed in Microsoft Access 2007, showing how values for gallons per cubic foot oil yield were filled in for every 0.1 gallon using a linear trend fill series function.

Digitizing Borehole Locations

Locations of boreholes (fig. 19) were digitized in ESRIs ArcMap based on footage measurements from section corners recorded in the original Fischer assay ASCII text file's header information. A custom tool was developed that combined the distance and sketch tools in ArcMap to digitize points. Each point was attributed with its unique borehole identifier, USGSID, which allowed the linking of spatial and tabular data.

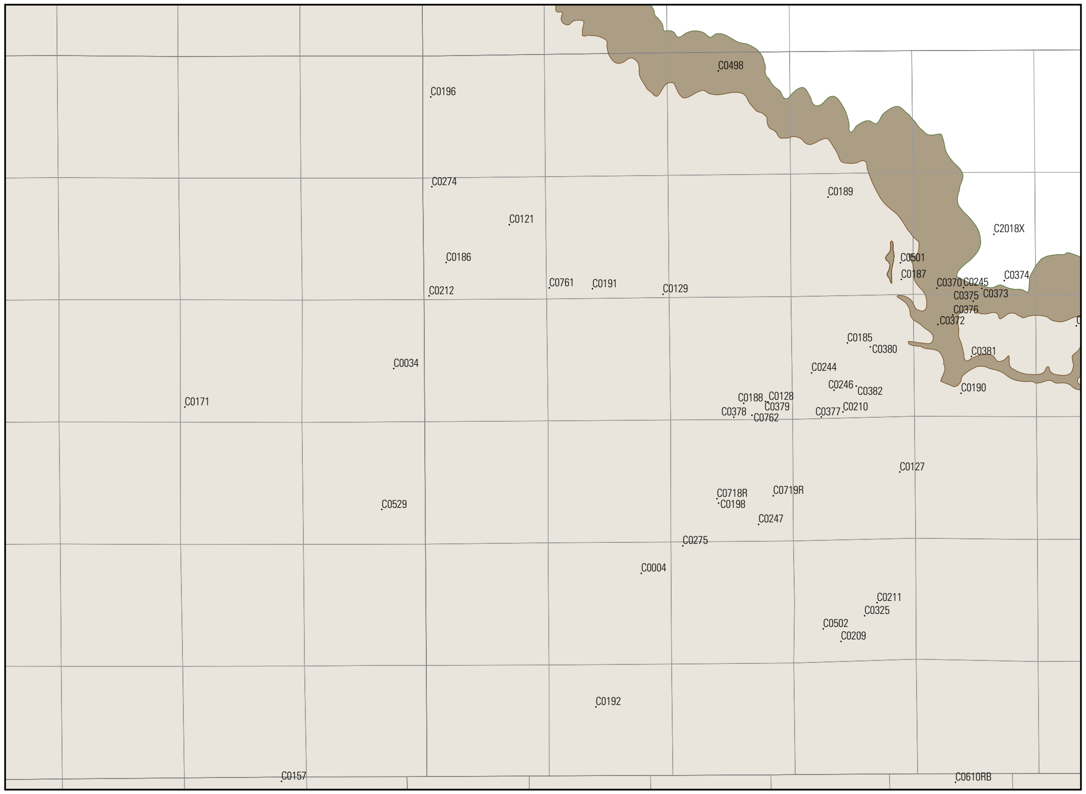

Figure 19. Map of the northeastern part of the Piceance Basin showing borehole locations after digitizing in ArcMap.

Building the Access Form

We built a custom Access Form (CO Form) (fig. 20) that allowed the linking of tables by a unique identifier (USGSID) used in all tables except for the BPA Lookup Table. The form was based on the stratigraphic tops table (CO_Tops_080115) and the linked tables are considered subforms.

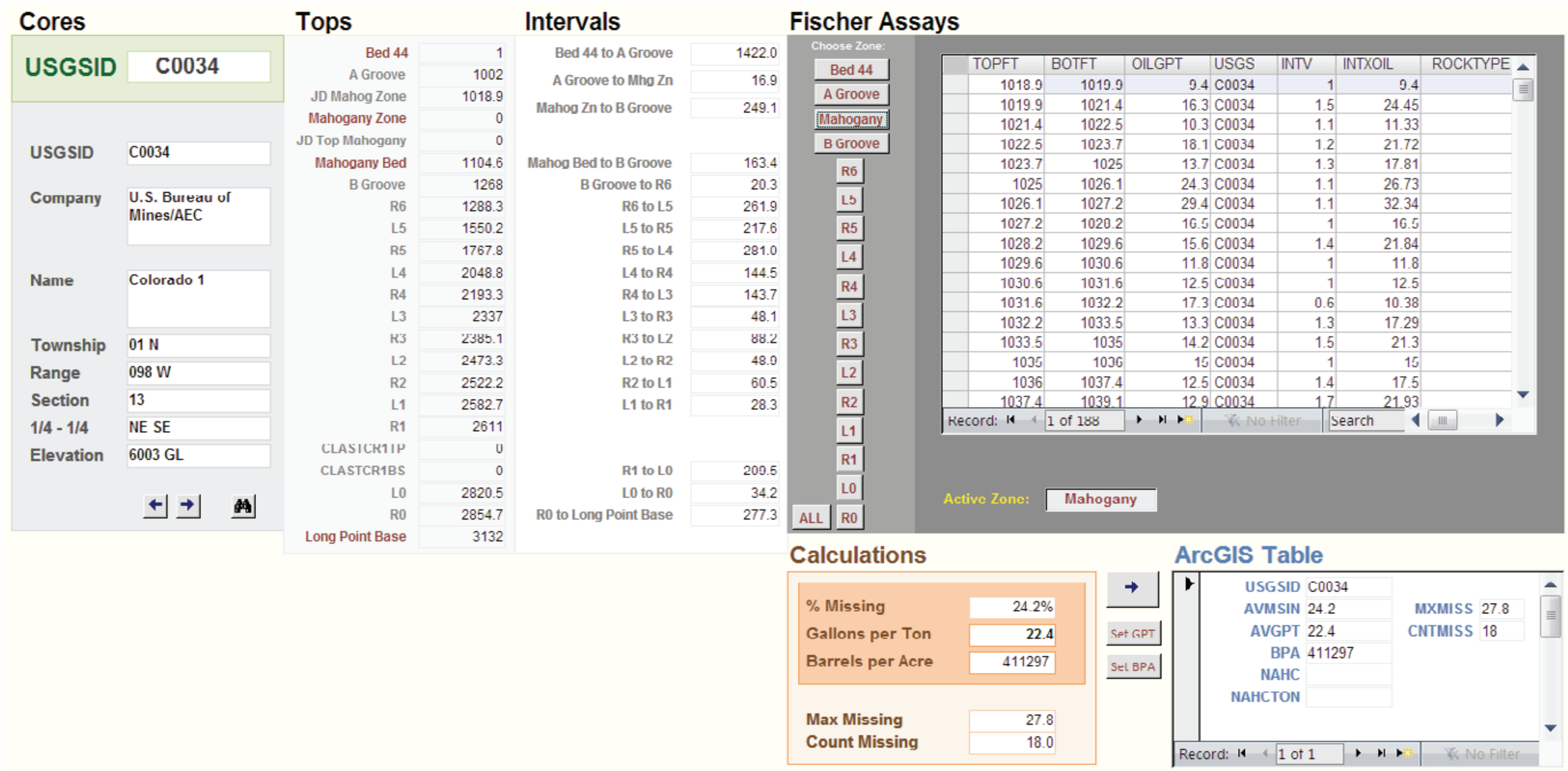

Figure 20. Image clip of the main Access form showing how subforms were linked by the unique identifier, USGSID, and performed all resource calculations.

Intersecting Polygon Files to Create Reporting Polygons

Initially, outcrop lines were digitized in ArcMap for the top of the Mahogany ledge and the base of the Parachute Creek Member of the Green River Formation, based on 1:100,000-scale geologic maps. These polygons served as bounding resource polygons for resource assessments by oil shale zone. We downloaded township lines in ESRI shapefile format from the Bureau of Land Management's (BLM) geocommunicator website (http://www.geocommunicator.gov). We intersected the township polygons with the outcrop boundary resource polygons in ArcGIS's ArcToolbox to create "reporting" polygons (fig. 21). The reporting polygons gave us the areal extent used to quantify barrels per acre oil yield for only that part of each township that is underlain by a particular oil shale zone.

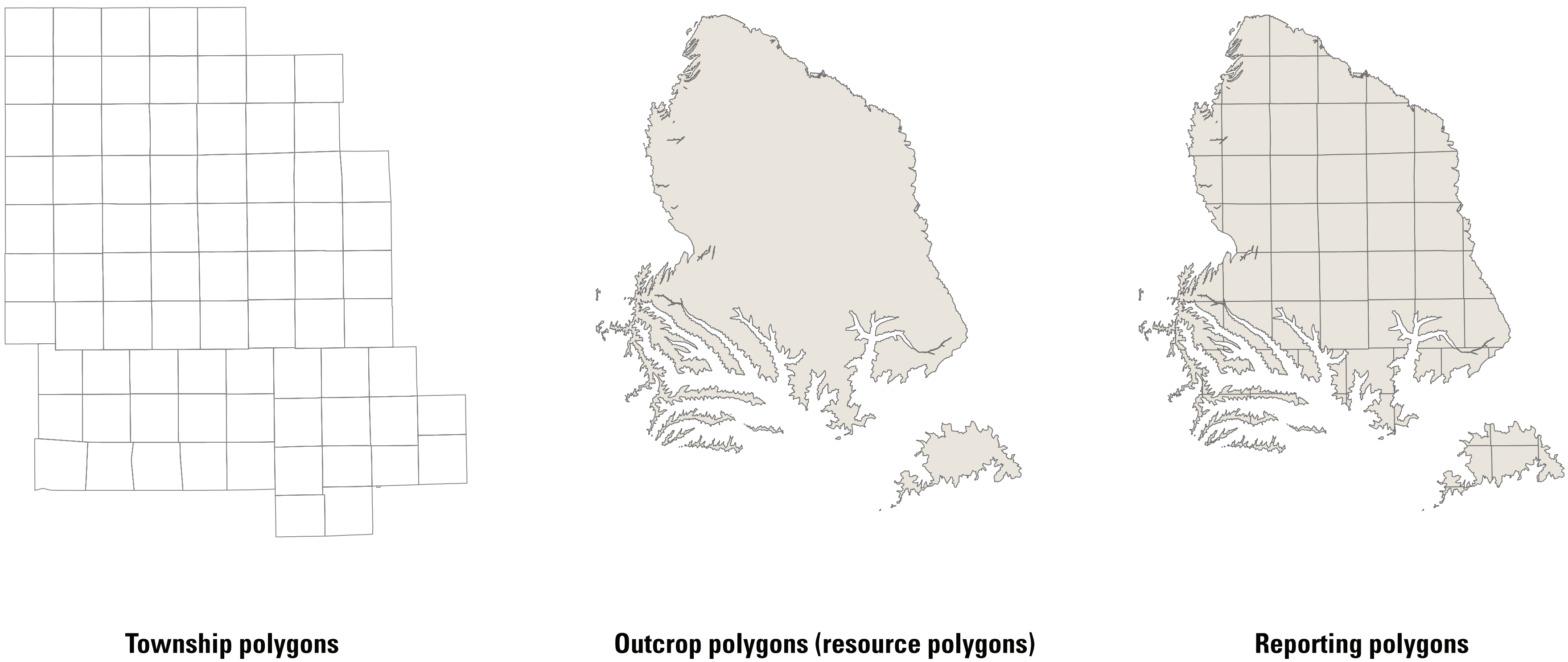

Figure 21. Diagram showing how ESRI ArcToolbox's Intersect command was used to create the assessment's reporting polygons for the Piceance Basin in northwestern Colorado.

SQL Query to Filter Assays By Zone

Following linkage of the Fischer assays table (CO_Assays_INTV) with the tops table (CO_Tops_080115) by USGSID in the form, we wrote Structured Query Language (SQL) queries to filter out subsets of assay records for each oil shale zone. For example, the query (QuerR4toL3) to select only those assay records that were between the R-4 zone top and the L-3 zone top picks in the tops table, and to display those records in the assays subform, utilized a BETWEEN statement:

```
SELECT CO_Assays_INTV.TOPFT, CO_Assays_INTV.BOTFT, CO_Assays_INTV.OILGPT, CO_Assays_INTV.USGSID, CO_Assays_INTV.INTVL,
CO_Assays_INTV.INTXOIL, CO_Assays_INTV.ROCKTYPE

FROM CO_Assays_INTV

    WHERE (((CO_Assays_INTV.TOPFT) Between [Forms]![CO Form]![JDR4] And [Forms]![CO Form]![JDL3])

    AND ((CO_Assays_INTV.BOTFT) Between [Forms]![CO Form]![JDR4] And [Forms]![CO Form]![JDL3])

    AND (([Forms]![CO Form]![JDR4])>0) AND (([Forms]![CO Form]![JDL3])>0))

ORDER BY CO_Assays_INTV.TOPFT;
```

In effect, the R-4 zone query would return assay records from the top of the R-4 zone to the top of the L-3 zone, but only if: (1) the value for the top of an assay record (TOPFT) was equal to or greater than the R-4 tops pick (JDR4), (2) the base of an assay record (BOTFT) was equal to or less than the top of the L-3 zone pick (JDL3), and (3) all assay records in between as long as those records contained the same USGSID as the currently selected core hole in the form.

Calculating Gallons Per Ton Weighted Average

Formula: Sum of (thickness of interval * gallons per ton)/thickness of interval

Within the assessed zones, any OILGPT value equal to 0 or thus, any INTXOIL (thickness of interval times OILGPT) value equal to 0 was not factored into weighted-average calculations; those records were considered missing or erroneous. In the Fischer assays subform (fig. 22), we built a text box control to calculate the weighted average for each oil shale zone. We accomplished this by creating a text-box control in the subform's footer and placed the following statement in that control:

=Sum(IIf([INTXOIL]>0,[INTXOIL],0))/Sum(IIf([INTXOIL]>0,[INTVL],0))

After filtering the assays subform using the SQL zone query, Access would: (1) sum all of the INTXOIL values and the INTVL values, (2) perform the division on those sums, and (3) return the result in the box as long as each record met the criteria of INTXOIL being greater than 0, that is, not missing or erroneous.

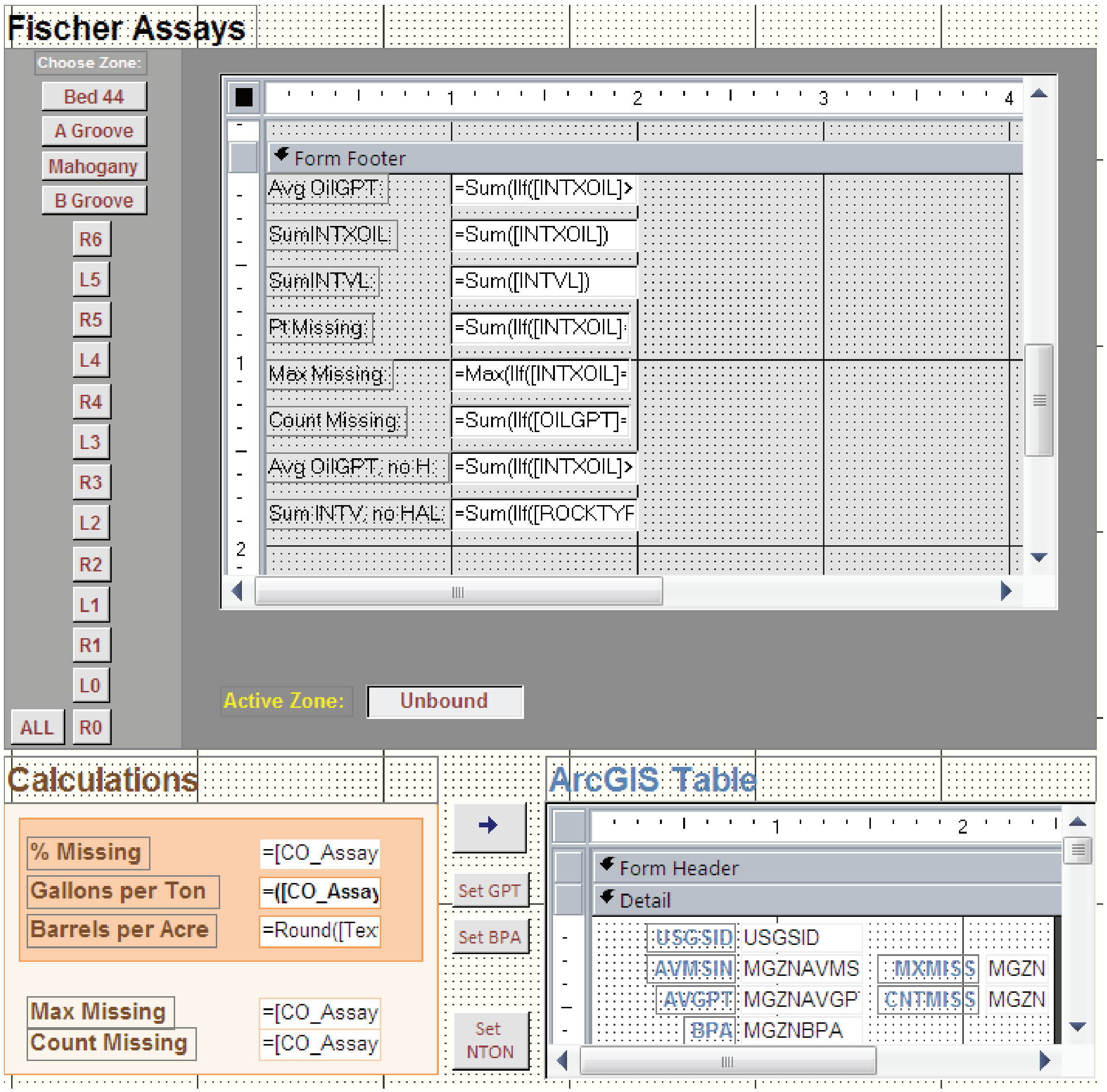

Figure 22. The oil shale assessment's Microsoft Access 2007 form as viewed in Design mode. Some text box control calculations are "hidden" in the Fischer assays subform footer.

Calculating Barrels Per Acre Oil Yield

Formula: Interval thickness * 43,560 (sq. ft/acre) * oil yield per unit volume / 42 (gals/barrel of oil)

Following determination of a weighted-average value for gallons per ton oil yield, it was necessary to calculate the total thickness of the oil shale zone, minus any halite beds. We added text box controls to the subform that contained the following statements:

To sum all intervals for the subset of assays:

=Sum([INTVL])

To sum all halite intervals for the subset of assays:

=Sum(IIf([ROCKTYPE]="NH",[INTVL],0))

To subtract halite intervals from the total and round to one decimal place:

=Round(([Text218]-[Text333]),1) where Text218 is the sum of all intervals and Text333 is the sum of halite intervals.

Next, we retrieved our multiplier for oil yield per unit volume from the Lookup Table based on the GPT calculation in the form, which was accomplished by adding a text box control containing the following statement:

=DLookUp("[GALFT3NEW]","[BPA Lookup Table]","[GALPERTON]=" & Forms![CO Form]!Text151)

where Text151 is the text-box control that calculated the weighted-average value for gallons per ton oil yield. In effect, this statement "looks up" the GALFT3NEW value in the BPA Lookup Table that is associated with the calculated GPT average. For example, for the R-4 zone in core hole C0034, a GPT average of 33.2 was returned. The associated value in the BPA Lookup table for 33.2 is 2.195. Using the statements above, the form also returned a value of 143.7 for the total thickness of the R-4 zone. Using the formula to calculate barrels per acre oil yield, the following statement was entered into another text box control in the form:

=Round([Text335]*43560*[Text239]/42,0) where Text335 is the sum of all intervals minus halite and Text239 is the value returned from the Lookup Table, with the result rounded to 0 decimal places. In this case, for the R-4 zone in borehole C0034, the form calculated 327,137 barrels per acre oil yield (143.7 * 43560 * 2.195 / 42).

Calculating the Percentage of Missing Intervals From Each Core Sample

Text-box controls were added to the form footer of the assays subform to report the percentage of missing intervals from each core sample, the maximum thickness of missing intervals, and the number of intervals missing from each core sample. The following statements were added to three separate controls.

To calculate the percentage missing:

```
=Sum(IIf([INTXOIL]=0,[INTVL],0))/Sum([INTVL])
```

To calculate the maximum thickness of missing intervals:

```
=Max(IIf([INTXOIL]=0,[INTVL],0))
```

To count the number of records missing:

```
=Sum(IIf([OILGPT]=0,1,0))
```

Storing Calculated Values in a Separate Table

To expedite attributing in Access and to help avoid data entry errors, buttons and macros (fig. 23) were added to the main form to transfer temporary, calculated values from the text-box controls to a separate table that could then be linked to in ArcGIS. We stored the results permanently in another table in the database (OilShale_Holes_pts).

Four buttons were created to transfer values for gallons per ton, barrels per acre, maximum interval missing, and the number of records missing.The buttons in the main form triggered a macro to run using a SetValue action. The SetValue action would populate the appropriate field in the ArcGIS table with the value that was calculated interactively in the form.

For example, the macro to store the value for the maximum interval missing from a core sample for a particular zone in the permanent table required two statements:

Item: [Forms]![CO form]![OilShale_Holes_pts subform].[Form]![Text21]

Expression: [Forms]![CO form]![Text341]

The Item statement contains the field we wanted to set. Text21 refers to the fieldname for MXMISS in the ArcGIS Table subform. The Expression statement simply refers to the value calculated in the main form—in this case, the Text341 text-box control that contained the statement to calculate the maximum thickness of missing intervals.

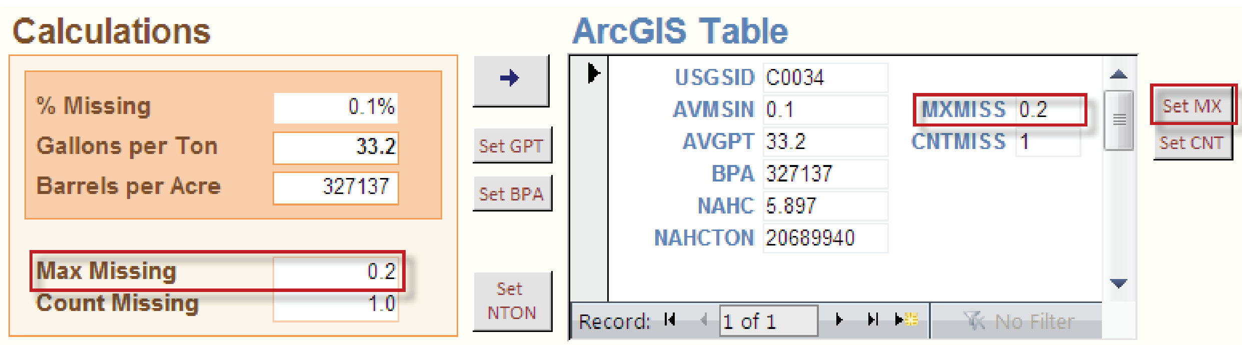

Figure 23. Image clip of a portion of the Microsoft Access 2007 form showing how calculation results performed interactively in the form were stored in a table permanently using buttons and macros. Example shown for the R-4 oil shale zone in borehole C0034.

Filtering Subforms From the Main Form

A method to filter the assay records by a particular oil shale zone was established by using SQL BETWEEN statements. Eighteen buttons were added to the main form to filter assays by each oil shale zone as well as an "All" button that would display all assay records for a particular borehole (that is, unfiltered). However, a method was also needed to restrict the display of fields in the ArcGIS Table subform by the zone being filtered. Each of the 17 oil shale zones contained a separate field for gallons per ton (AVGPT), barrels per acre (BPA), percentage of missing intervals (AVMSIN), maximum interval missing (MXMISS), and the number of records missing (CNTMISS). For example, the R-4 zone contained the fields R4AVGPT, R4BPA, R4AVMSIN, R4MXMISS, and R4CNTMISS. We were able to change the fields being displayed in the ArcGIS Table subform by applying ControlSource statements to each zone button in addition to the SQL BETWEEN query. Not only would the button filter the assay records by a particular zone, it would also change the fields to be attributed in the OilShale_Holes_pts subform. This was accomplished by using the following code:

```
Private Sub Command260_Click()

Me.CO_Assays_subform.Form.RecordSource = "QuerR4toL3"

OilShale_Holes_pts_subform.Form.[MXMISS].ControlSource = "R4MXMISS"

End Sub
```

Linking Spatial and Tabular Data

Upon completing the calculations in Access and populating all of the fields in the ArcGIS table for each oil shale zone, the data were linked to borehole locations in ArcGIS. Although several different interpretive maps could thereby be generated, this case study focuses on the barrels per acre oil-yield mapping and resource-summary task.

Our borehole locations file was stored in a point feature class (OilShale_Holes_pts) contained in an ESRI ArcGIS personal geodatabase (COPLATOS.mdb). The calculation values were stored in a table (OilShale_Holes_pts) in a separate Access database (COPLATOS.mdb). In ArcMap ver. 9.2, the attribute table was joined to the point feature class and, through several definition queries, 17 separate point layers were created corresponding to each oil shale zone. It is important to note that no rotary holes were included in any of the assessments—that is, those boreholes containing an “R” in their USGSID identifier.

Creating GeoStatistical Analyst Models and GRIDs

Once layers were defined for each oil shale zone in ArcMap, we generated models using ESRI ArcGIS's GeoStatistical Analyst (GA) extension (fig. 24). The Radial Basis Function-Multiquadric method was used to model BPA values. The searching neighborhood parameters used were the standard eight sectors containing eight neighbors in each sector. Although not as robust as kriging or other geostatistical methods in assessing error, the RBF-Multiquadric method does return a mean and Root Mean Squared (RMS) error for each model generated. We assessed these errors and judged them to be acceptable using the chosen parameters. We also exported the cross validation tables containing predictions and errors at each data point for each BPA model. 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 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.

A GA model will only interpolate and extrapolate values within the rectangular extent of the input point layer. We extrapolated values to outcrop lines by changing the extent of the model to the rectangular extent of a separate polygon file. For example, for the R-4 BPA model we changed the extent of the GA model to the rectangular extent of a Mahogany zone outcrop file we had buffered at a distance of two kilometers. We used the extent of this file for all models to ensure adequate coverage for extrapolation purposes.

After all revisions were made, sometimes after numerous iterations between the Access form and GeoStatistical Analyst, the final GA model was exported to an ESRI GRID format at a one-acre cell size (208.7 ft (63.615 m) per side) using one point for each block (acre) interpolation. One drawback to extrapolating beyond our dataset boundary was that a model sometimes contained negative values. To sum all of the values in our one-acre cells, all negative values were removed from the GRIDs by using a CON statement. In ESRI ArcGIS's Spatial Analyst extension the Raster Calculator was used to remove the negative values with this statement:

CON(([GRIDNAME] < 0), 0, [GRIDNAME]) where GRIDNAME is the name of the GRID, such as R4BPA_g

For all cells in the final BPA GRID, the CON statement set the negative values to 0. If the values were greater than or equal to 0, the values remained unchanged.

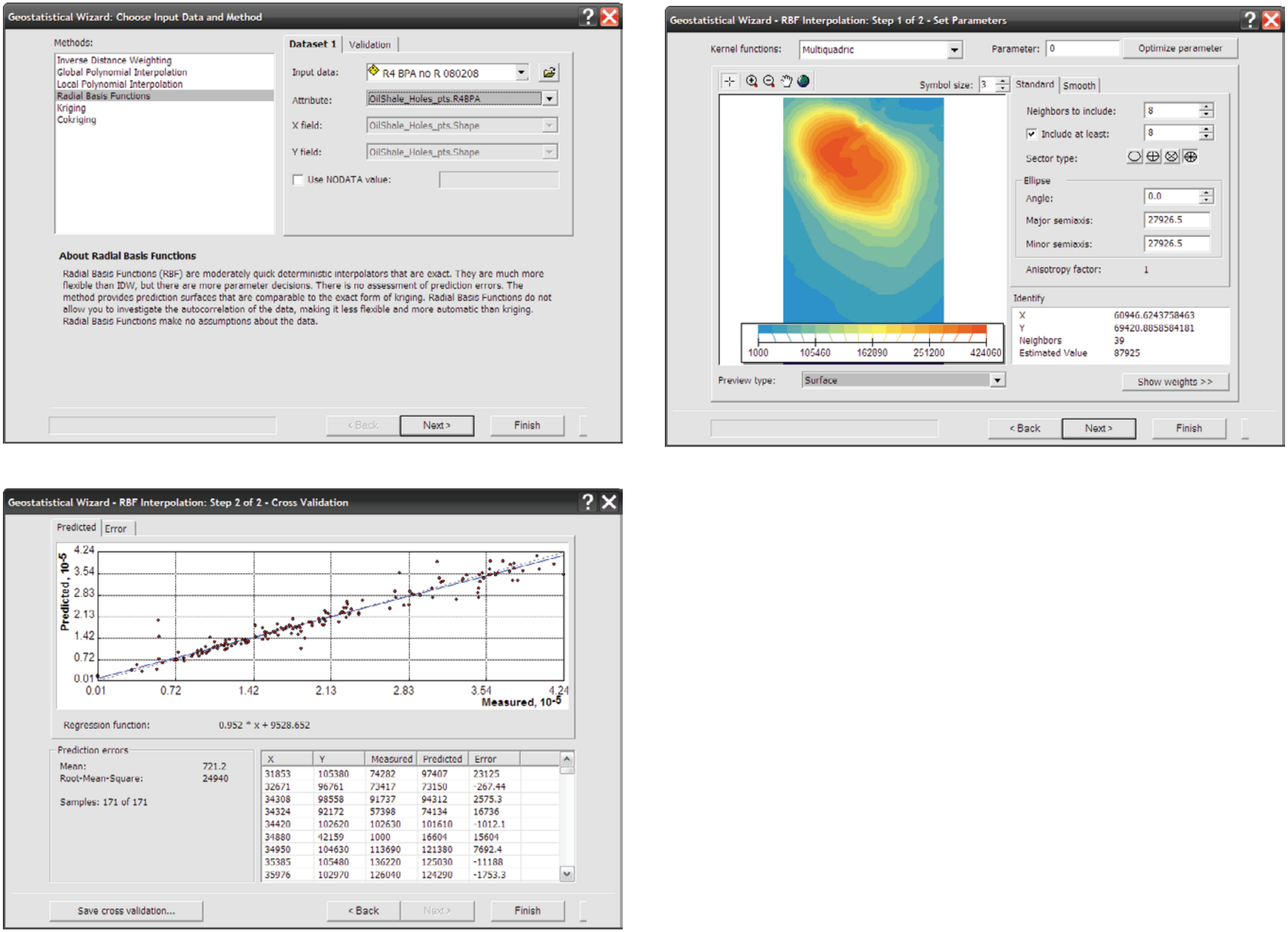

Figure 24. Image clips of the dialog windows used for creating the barrels per acre (BPA) GeoStatistical Analyst model in ArcGIS.

Running Zonal Statistics to Calculate Total Barrels of Oil Yield Per Township

The final BPA GRID model was used as the value raster for counting cell values using ESRIs Spatial Analyst extension. The Zonal Statistics function (fig. 25) was used to count all of the estimated values contained within each one-acre cell of our model, as long as their centerpoints fell within a specified zone dataset. In this case, for the R-4 zone, the zone dataset (low_12_zones_rept_pol) was a polygon feature class stored in a geodatabase created by intersecting the resource polygon for all zones below the R-6 zone with the township polygons. The Zonal Statistics function used the TWNRNG attribute as the zone field from the polygon feature class to count the GRID's BPA values (figs. 11, 25). That is, for all polygons in the zone dataset file with the same value in the TWNRNG field, the Zonal Statistics function counted all of the underlying cells in the BPA GRID and provided the sum total for each TWNRNG, or township. It is important to note that our Spatial Analyst analysis cell size was the same as our BPA GRID cell size: 208.7 ft (63.615 m) per side.

The resultant statistics were then exported to a .dbf table named by zone, such as r4_sum_twsp.dbf for the R-4 zone. We linked this table to the reporting polygons feature class by the TWNRNG field, thus were able to provide an interpretive map that quantified the total barrels of oil yield from oil shale in each oil shale zone for each township in the Piceance Basin.

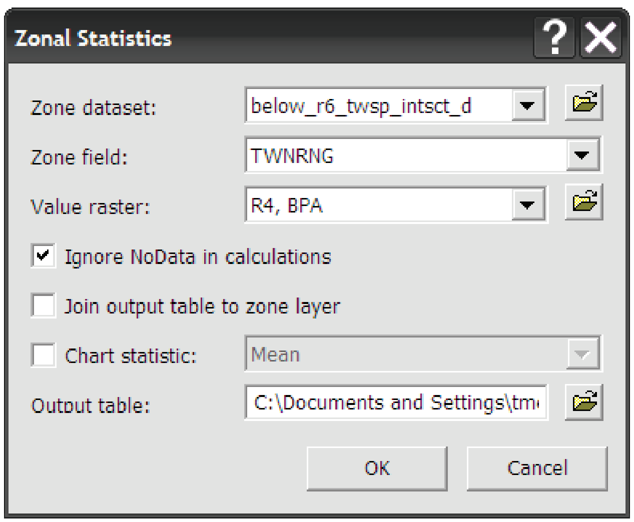

Figure 25. Image clip of the dialog window used to generate zonal statistics using ESRIs Spatial Analyst.

Case Study 2—Nahcolite Assessment

Converting and Loading Nahcolite-Content Data

We converted the nahcolite content spreadsheet from Excel 2007 to an Access table (CO_Nahc_INTV). The original spreadsheet had a separate worksheet (fig. 26) for each borehole, so we combined them using a macro (VBAX, 2008) that combined all of the separate worksheets into one before importing the combined spreadsheet to Access. The macro can be found here: http://www.vbaexpress.com/kb/getarticle.php?kb_id=151.

	A	B	C	D	E	F	G	H	I	J	K
1	OBSNO	LABNO	TOPFT	BOTFT	SAMPDEN	AL203_PCT	NA_PCT	NAPLOT	NAHCO3_PCT	NAHPLOT	OILWONAH
2	1		1702.00	1703.00	0.00	0.00	4.98	4.98	18.20	18.20	37.65
3	2		1703.00	1704.00	0.00	0.00	4.63	4.63	16.90	16.90	25.39
4	3		1704.00	1705.20	0.00	0.00	8.10	8.10	29.60	29.60	27.70
5	4		1705.20	1707.00	0.00	0.00	0.00B	0.00	0.00B	0.00	8.00
6	5		1707.00	1709.00	0.00	0.00	16.01	16.01	58.50	58.50	47.47
7	6		1709.00	1710.80	0.00	0.00	7.66	7.66	28.00	28.00	70.00
8	7		1710.80	1712.60	0.00	0.00	17.76	17.76	64.90	64.90	33.33
9	8		1712.60	1714.00	0.00	0.00	5.15	5.15	18.80	18.80	34.85
10	9		1714.00	1716.00	0.00	0.00	15.63	15.63	57.10	57.10	36.60
11	10		1716.00	1717.80	0.00	0.00	0.00B	0.00	0.00B	0.00	0.00B
12	11		1717.80	1719.00	0.00	0.00	10.34	10.34	37.80	37.80	47.59
13	12		1719.00	1720.00	0.00	0.00	10.86	10.86	39.70	39.70	43.12

COOO1 / C0002 / C0004 / C0005 / C0008 / C0034 / C0035 / CO116 / CO117 / CO121 / CO127 / CO128

Figure 26. Image clip showing the original nahcolite-content data residing in separate worksheets in Microsoft Excel 2007.

Creating Nahcolite-Resource Polygons

A new polygon (fig. 27) was digitized in ArcGIS to delineate nahcolite-bearing areas using the areal extent of nahcolite-bearing and non-nahcolite-bearing (zero points) boreholes and then intersected with the Mahogany ledge outcrop in the northeastern part of the basin. The same procedure was followed, as in the oil shale assessment—that is, intersecting the resource polygon with townships to create nahcolite-reporting polygons in order to determine total nahcolite tonnages by township.

Figure 27. Map showing the difference in areal extent between the nahcolite-bearing zone (shaded) and the oil shale resource polygon outline in the Piceance Basin, northwestern Colorado.

Calculating Average Weight-Percent Nahcolite

Upon linking the nahcolite content table (CO_Nahc_INTV) to our Access form by the unique ID (USGSID) and creating the nahcolite table subform, a weighted average for weight-percent nahcolite was calculated for each zone containing nahcolite beds. Two new columns were added to the CO_Nahc_INTV table, INTVL and INTXNAHC, and each column populated via update queries. The INVTL column was updated by subtracting the TOPFT column from the BOTFT column, and the INTXNAHC column was updated by multiplying the NAHPLOT column by the INTVL column. Because queries to filter the assays table by oil shale zone were already established, the same queries were applied to the nahcolite table to filter the nahcolite records by each zone. Text-box controls were then added to the nahcolite-table subform in Access to calculate, by zone, the sum of nahcolite intervals and the weighted average for weight-percent nahcolite.

To calculate the sum of nahcolite intervals:

```
=Sum(IIf([INTXNAHC]>0,[INTVL],0))
```

To calculate the weighted average for weight percent nahcolite:

```
=Sum(IIf([INTXNAHC]>0,[INTXNAHC],0))/Sum(IIf([INTXNAHC]>0,[INTVL],0))
```

Reproducing the Nahcolite Formula in Access

After linking all the necessary tables and creating the subforms in the main Access form, we reproduced the formula modified from Beard and others (1974; described in detail in the chapter text) as a series of text-box controls in the form (fig. 28). One important multiplier in the formula was oil yield in gallon per ton (GPT) determined by the Fischer assays subform. As it was necessary to calculate only the weighted average GPT for the nahcolite-bearing interval of each oil shale zone, we deleted all assay records from the assays table (CO_Assays_INTV) above and below the nahcolite-bearing intervals as recorded in the nahcolite table (CO_Nahc_INTV). In order to maintain the overall functionality of the main Access form, a new Access database (COPLAT_NAHC.mdb) was created. The main difference between the oil shale database (COPLATOS.mdb) and the nahcolite database (COPLAT_NAHC.mdb) is the absence of assay records above or below nahcolite intervals in boreholes containing nahcolite beds.

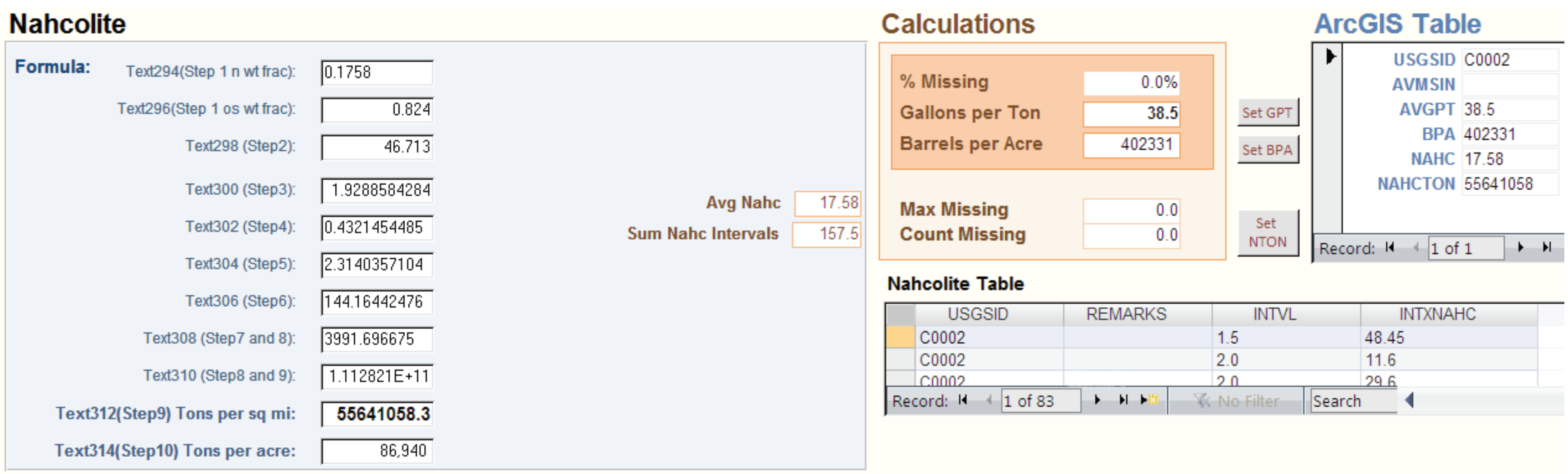

Figure 28. Image clip of the Microsoft Access 2007 form showing the reproduction of the nahcolite formula modified from Beard and others (1974) as viewed in the Access form for borehole C0002 in the R-4 oil shale zone.

Linking Spatial and Tabular Data

As the number of boreholes containing nahcolite beds was much smaller (58 total) than our oil shale point feature class, the point feature class was converted to an ESRI shapefile (Piceance_Nahcolite_Holes.shp) and all calculations from the Access form were stored permanently in the shapefile's attribute table. In ArcMap ver. 9.2, we created definition queries and generated layers based on the nahcolite-point shapefile for eight zones (L-5, R-5, L-4, R-4, L-3, R-3, L-2, and R-2) as well as a layer to display data for all nahcolite zones combined (fig. 29). The .dbf file stored the values for each zone's average weight-percent nahcolite, tons per square mile by zone, tons per acre by zone, total tons per square mile, total tons per acre, and the total nahcolite-bearing interval thickness for each borehole as determined by staff geologists.

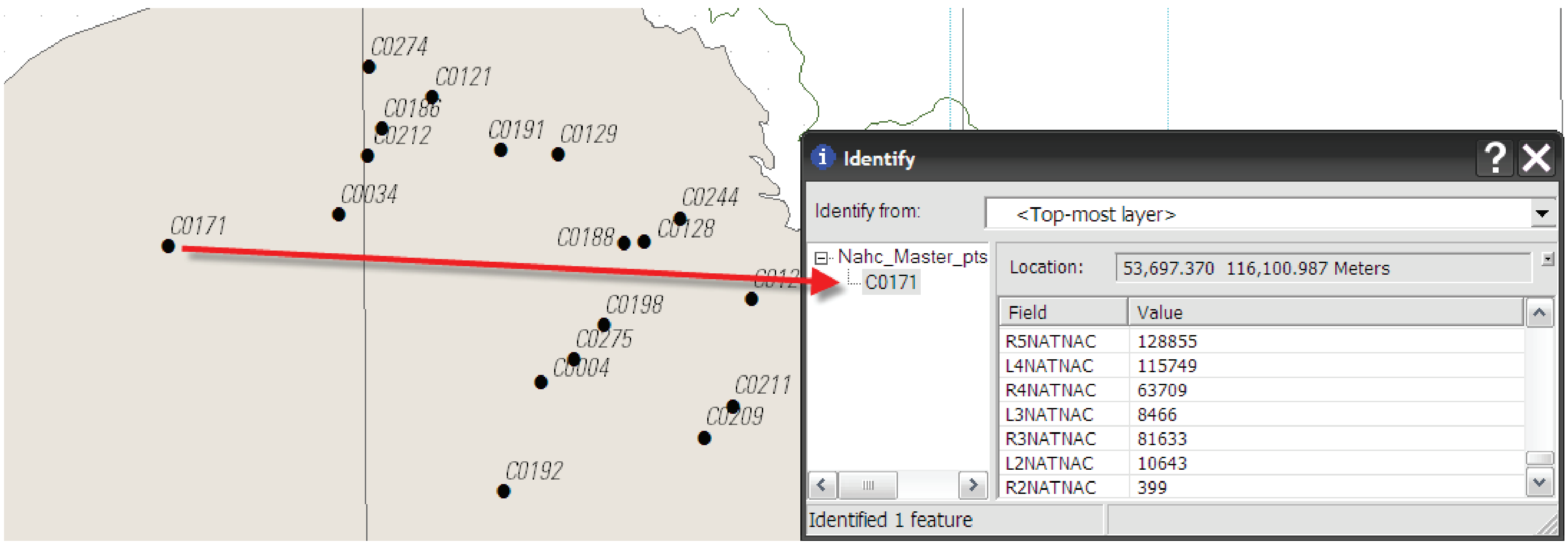

Figure 29. Image clip from ArcMap showing how borehole locations are linked to the calculation results stored in the attribute table. The table lists total nahcolite tonnages for zones R-5 through R-2 for borehole C0171.

Creating GeoStatistical Analyst Models and GRIDs

After layers for each of the eight zones, as well as a layer which combined all zones in ArcMap to model nahcolite were defined, models were generated using ESRI ArcGIS's GeoStatistical Analyst (GA) extension. The Radial Basis Function-Multiquadric method was used to model tons per acre values. The searching neighborhood parameters used were a standard 10 sectors containing 15 neighbors in each sector.

To maintain consistency with our oil shale methodology, we extrapolated nahcolite values to the nahcolite-bearing area by changing the extent of the model to the rectangular extent of a separate polygon file. For example, for the R-4 nahcolite-tonnage model, the extent of the GA model was changed to the rectangular extent of the nahcolite-resource polygon file buffered at a distance of 1 km. We used the extent of this file for all models to ensure adequate coverage for extrapolation purposes.

After all data corrections were made, commonly involving numerous iterations between the Access form and GeoStatistical Analyst, the final GA model was exported to an ESRI GRID format at a one-acre cell size (208.7 ft (63.615 m) per side). As in the oil shale modeling, one drawback to extrapolating beyond a dataset boundary was that a model, in some cases, contained negative values. As we wanted to sum all of the values in our one-acre cells, all negative values were removed from the GRIDs by using a CON statement. In ESRI ArcGIS's Spatial Analyst extension, we again used the Raster Calculator to remove the negative values with this statement:

CON(([GRIDNAME] < 0), 0, [GRIDNAME]) where GRIDNAME is the name of the GRID, such as r4_n

For all cells in the final nahcolite-tonnage GRID, the CON statement set the negative values to 0. If the values were greater than or equal to 0, the values remained unchanged.

Running Zonal Statistics to Calculate Total Tons of Nahcolite Per Township

The final nahcolite-tonnage GRID model was used as the value raster for counting cell values using ArcGIS's Spatial Analyst. The Zonal Statistics function was used to count all of the estimated values contained within each one-acre cell of our model, as long as the centerpoints fell within a specified zone dataset. In this case, for the R-4 zone, the zone dataset was a polygon feature class stored in our geodatabase that was created by intersecting the nahcolite-resource polygon for all nahcolite zones with the township polygons. The Zonal Statistics function used the TWNRNG attribute as the zone field to count the GRID's tonnage values. That is, for all polygons in the zone dataset file having the same value in the TWNRNG field, the Zonal Statistics function counted all of the underlying cells in the nahcolite-tonnage GRID and provided the sum total for each TWNRNG, or township. It is important to note that our Spatial Analyst analysis cell size was the same as our nahcolite-tonnage GRID cell size: 208.7 ft (63.615 m) per side.

The resultant statistics were then exported to a .dbf table, which was linked to the reporting polygons feature class by the TWNRNG field, thus providing an interpretive map that quantified the total tons of nahcolite in each of the eight zones.

The same methodology was employed to create the nahcolite series of interpretive maps, including total nahcolite-bearing interval isopachs, average weight-percent nahcolite for entire nahcolite-bearing interval, total in-place nahcolite resource in tons per acre, total in-place nahcolite resource by township, tons per acre by zone, and tons per township by zone.

Appendix

Digital Files, Entity-Relationship Diagrams, and Data Dictionaries

Digital file – COPLATOS.mdb (Microsoft Access database)

Digital file – COPLAT_NAHC.mdb (Microsoft Access database)

Entity relationship diagrams (figs. A1, A2)

Data dictionaries (tables A1–A6)

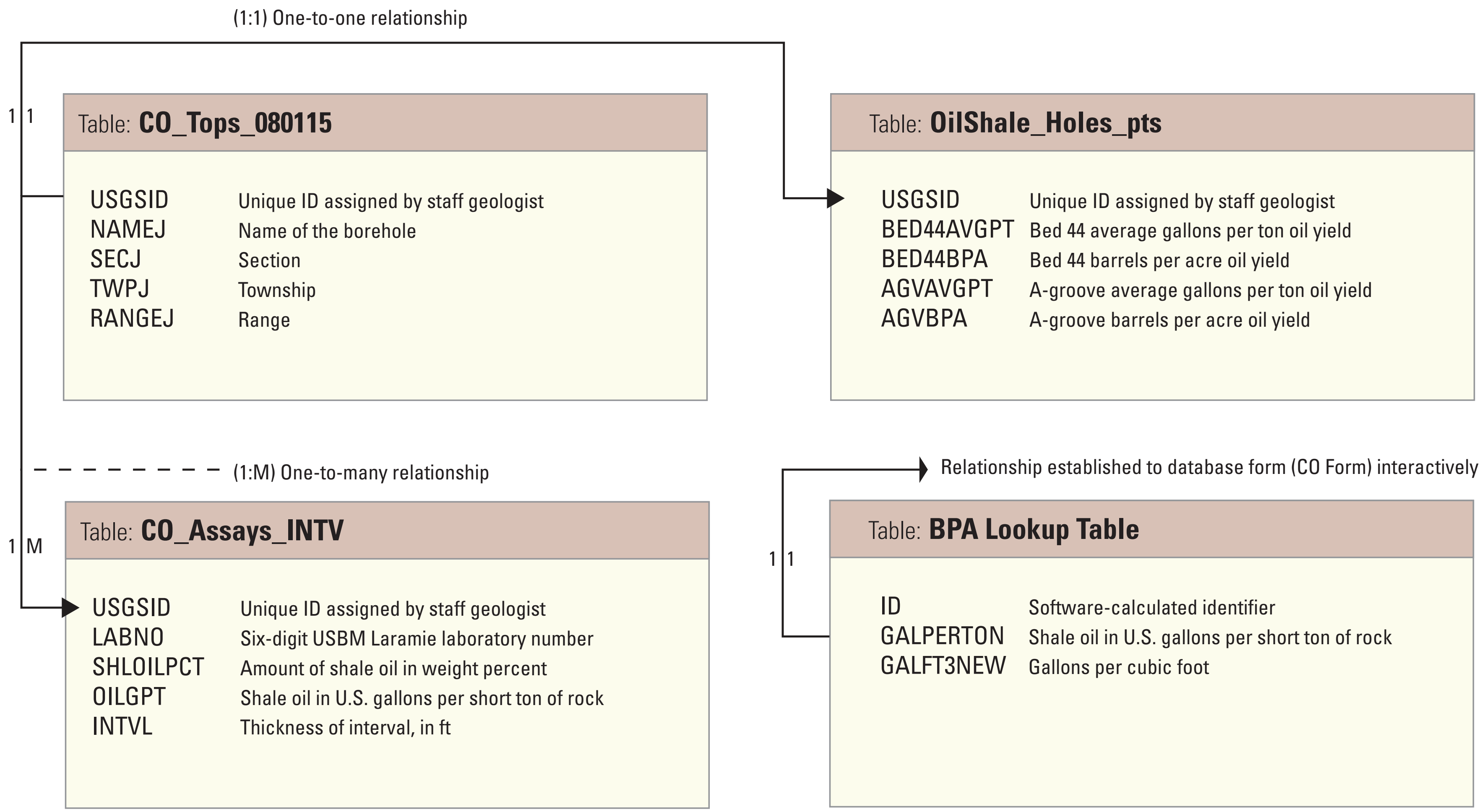

Figure A1. Entity relationship diagram (ERD) of the tables in the Microsoft Access 2007 database (COPLATOS.mdb) showing how the tables are linked in the calculations form (CO Form). The figure contains a partial listing of column names for illustrative purposes only.

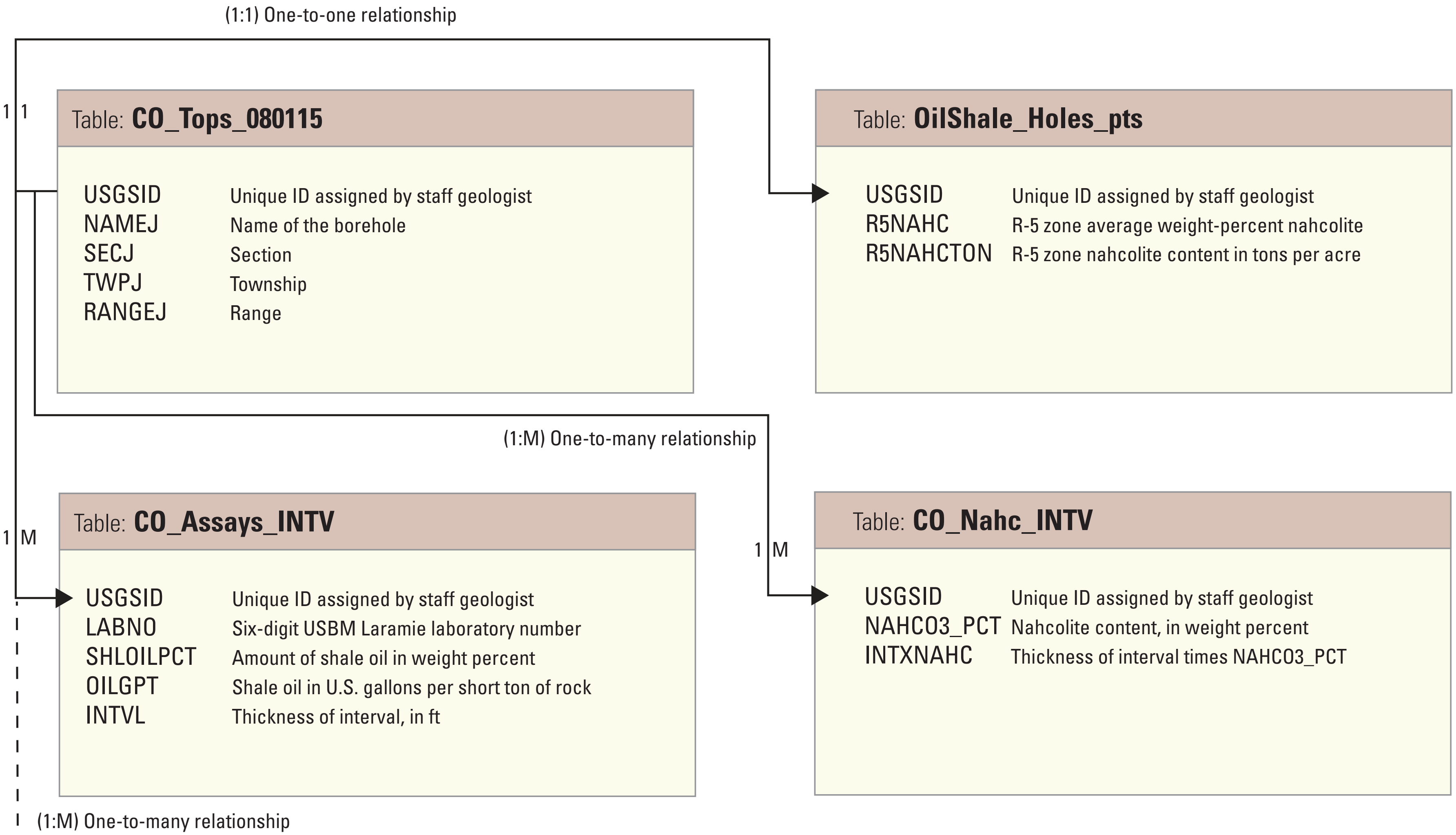

Figure A2. Entity relationship diagram (ERD) of the tables in the Microsoft Access 2007 database (COPLAT_NAHC.mdb) showing how the tables are linked in the calculations form (CO Form). The figure contains a partial listing of column names for illustrative purposes only.

Table A1. The column names and definitions of the Microsoft Access table CO_Tops_080115.

(Note: all column names ending in "J" originated from J. Dyni's original tops file)

Column name	Column definition
ID	Software-calculated identifier
USGSIDJ	Unique ID assigned by staff geologist
CMPNYPROJJ	Name of the company or agency that drilled the borehole
NAMEJ	Name of the borehole assigned by the company or agency that drilled it
EASTWESTJ	Distance, in ft, measured east or west from section line
NORSOUJ	Distance, in ft, measured north or south from section line
QQJ	Quarter-quarter section
RANGEJ	Range
SECJ	Section
TWPJ	Township
LATDDJ	Latitude, in decimal degrees, North American Datum 1927, original record
LONGDDJ	Longitude, in decimal degrees, North American Datum 1927, original record
LOCSRCJ	Source of the borehole location, usually from the Fischer assay file, geophysical log, lithologic log, or survey
COUNTYJ	Name of county in Colorado
ELEVFTJ	A borehole-reference elevation, such as ground surface, rotary bushing, or rotary table, from which down-hole depths were measured.
COREDINTVJ	Depths, in ft, of the sequence that was cored in the borehole
ELEVSRCJ	Source of elevation, usually from the Fischer assay file, geophysical log, lithologic log, topographic or survey
TOTDEPTFTJ	Total depth of the borehole, in ft
QUADJ	Name of 7.5-minute USGS topographic map, borehole may or may not be shown on map
ARCHIVEDJ	Core archived, yes or no
YRDRILLEDJ	Year that the borehole was drilled
LOCCOREJ	Physical location of the core from core hole, for example, USGS Core Research Center
SHOWNMAPJ	Indicates whether the actual borehole location is shown on the topographic map
LITHFTJ	Top and bottom borehole depths, in ft, of sequence of core or rotary cuttings for which a lithologic log was prepared.
PHOTOFTJ	Top and bottom borehole depths, in ft, of photographic record of drill core
ELECFTJ	Top and bottom depths, in ft, of electric log of borehole
GAMMAFTJ	Top and bottom depths, in ft, of gamma-ray log of borehole
DENSFTJ	Top and bottom depths, in ft, of density log of borehole
SONICFTJ	Top and bottom depths, in ft, of sonic log of borehole
NEUTRONFTJ	Top and bottom depths, in ft, of neutron log of borehole
CALIPERFTJ	Top and bottom depths, in ft, of caliper log of borehole
RQDFTJ	Top and bottom borehole depths, in ft, of rock-quality data log
TEMPFTJ	Top and bottom depths, in ft, of temperature log of borehole
OTHERLOGSJ	Top and bottom depths, in ft, of other geophysical logs
FISCHASSYJ	Top and bottom depths, in ft, of sequence analyzed by Fischer assays
LABJ	Name of laboratory where Fischer assays were performed
ALUMINAFTJ	Top and bottom depths, in ft, of sequence analyzed for alumina
NUMBASSYSJ	Number of Fischer assays that were made
USBMNUMBRJ	A number assigned to the report of Fischer assays made by the former U.S. Bureau of Mines
LOCATNOTEJ	Additional information, commonly used where there is a problem with the location

Table A1. The column names and definitions of the Microsoft Access table CO_Tops_080115. —Continued

(Note: all column names ending in "J" originated from J. Dyni's original tops file)

Column name	Column definition
NAHCOLTFTJ	Top and bottom depths, in ft, of sequence analyzed for nahcolite
XRDFTJ	Top and bottom depths, in ft, of X-ray diffraction analyses made on samples from the borehole
ELEVNOTEJ	Additional information, commonly used where there is a problem with the elevation
MISCNOTEJ	Miscellaneous information, such as publications related to the borehole, and other data
REVISDATEJ	Date of last revision for original borehole data
NAME	Name of the borehole assigned by the company or agency that drilled it
TRSEC	Township, range, and section
EASTWEST	Distance, in ft, measured east or west from section line
NORSOU	Distance, in ft, measured north or south from section line
LATDD	Latitude, in decimal degrees, North American Datum 1927, software-calculated, this report (2009)
LONGDD	Longitude, in decimal degrees, North American Datum 1927, software-calculated, this report (2009)
ELEVFT	A borehole reference elevation, such as ground surface, rotary bushing, or rotary table, from which down hole depths were measured.
CHDH	Core hole or drill hole
ELEVDATUM	Elevation, in ft, for various reference surfaces including Kelly bushing, ground level, topographic map, and rotary table.
USGSID	Unique ID assigned by staff geologist
JD76	Depth to top of Bed 76, in ft
JD74	Depth to top of Bed 74, in ft
JD72	Depth to top of Bed 72, in ft
JDTPPORCTF	Depth to top of Porcupine Creek tuff, in ft
JDBSPORCTF	Depth to base of Porcupine Creek tuff, in ft
JD70	Depth to top of Bed 70, in ft
JD68	Depth to top of Bed 68, in ft
JD67	Depth to top of Bed 67, in ft
JD66	Depth to top of Bed 67, in ft
JD64	Depth to top of Bed 64, in ft
JD62	Depth to top of Bed 62, in ft
JD60	Depth to top of Bed 60, in ft
JD58	Depth to top of Bed 58, in ft
JD56	Depth to top of Bed 56, in ft
JD54	Depth to top of Bed 54, in ft
JD52	Depth to top of Bed 52, in ft
JD50	Depth to top of Bed 50, in ft
JD48	Depth to top of Bed 48, in ft
JD46	Depth to top of Bed 46, in ft
JD44BIG3	Depth to top of Bed 44 of Big 3 oil shale beds, in ft
JD42BIG3	Depth to top of Bed 42 of Big 3 oil shale beds, in ft
JD40BIG3	Depth to top of Bed 40 of Big 3 oil shale beds, in ft
JD39	Depth to top of Bed 39, in ft
JD38STLWTR	Depth to top of Stillwater Zone, in ft
JD37	Depth to top of Bed 37, in ft

Table A1. The column names and definitions of the Microsoft Access table CO_Tops_080115. —Continued

(Note: all column names ending in "J" originated from J. Dyni's original tops file)

Column name	Column definition
JD36A	Depth to top of Bed 36A, in ft
JD36	Depth to top of Bed 36, in ft
JD34	Depth to top of Bed 34, in ft
JD32FRSENR	Depth to top of Bed 32 of the Four Senators, in ft
JD30	Depth to top of Bed 30 of the Four Senators, in ft
JD28FRSENR	Depth to top of Bed 28 of the Four Senators, in ft
JD26	Depth to top of Bed 26 of the Four Senators, in ft
JD25	Depth to top of Bed 25, in ft
JD24	Depth to top of Bed 24, in ft
JD22	Depth to top of Bed 22, in ft
JD21	Depth to top of Bed 21, in ft
JD20	Depth to top of Bed 20, in ft
JD18	Depth to top of Bed 18, in ft
JD16	Depth to top of Bed 16, in ft
JD14	Depth to top of Bed 14, in ft
OTPUPWAVY	Depth to top of Upper Wavy, in ft
OBSUPWAVY	Depth to base of Upper Wavy, in ft
JD12	Depth to top of Bed 12, in ft
JD10	Depth to top of Bed 10, in ft
JD08	Depth to top of Bed 8, in ft
JD06	Depth to top of Bed 6, in ft
JD04	Depth to top of Bed 4, in ft
JD02	Depth to top of Bed 2, in ft
JDAGROOV	Depth to top of A-groove, in ft
JDMAHOGZN	Depth to top of Mahogany Zone, in ft
OMAHOGZN	Depth to top of Mahogany Zone, in ft (space holder, not used in this assessment)
JDTPMAHOG	Depth to top of Mahogany Bed (Donnell, USGS), in ft (space holder, not used in this assessment)
OMAHOG	Depth to top of Mahogany Bed (Johnson, USGS), in ft
JDBGROOV	Depth to top of B-groove, in ft
JDR6	Depth to top of R-6 Zone, in ft
JDL5	Depth to top of L-5 Zone, in ft
JDR5	Depth to top of R-5 Zone, in ft
JDL4	Depth to top of L-4 Zone, in ft
JDR4	Depth to top of R-4 Zone, in ft
JDL3	Depth to top of L-3 Zone, in ft
JDR3	Depth to top of R-3 Zone, in ft
JDL2	Depth to top of L-2 Zone, in ft
R2	Depth to top of R-2 Zone, in ft
L1	Depth to top of L-1 Zone, in ft
R1	Depth to top of R-1 Zone, in ft
CLASTCR1TP	Depth to top of clastic wedge in R-1 Zone, in ft
CLASTCR1BS	Depth to base of clastic wedge in R-1 Zone, in ft
L0	Depth to top of L-0 Zone, in ft

Table A1. The column names and definitions of the Microsoft Access table CO_Tops_080115. —Continued

(Note: all column names ending in "J" originated from J. Dyni's original tops file)

Column name	Column definition
R0	Depth to top of R-0 Zone, in ft
LPBS	Depth to base of Long Point, in ft
BMARKRTP	Depth to top of B Marker, in ft
BMARKRBS	Depth to base of B Marker, in ft (space holder, not used in this assessment)
CMARKRTP	Depth to top of C Marker, in ft
CMARKRBS	Depth to base of C Marker, in ft (space holder, not used in this assessment)
DMARKRTP	Depth to top of D Marker, in ft
DMARKRBS	Depth to base of D Marker, in ft (space holder, not used in this assessment)
FMARKR	Depth to top of F Marker, in ft
IMARKR	Depth to top of I Marker, in ft
TOPILES	Depth to top of Iles, in ft
TOPKMV	Depth to top of Kmv, in ft
TOPRLNS	Depth to top of Rollins, in ft
TOPCSGT	Depth to top of Castlegate, in ft
MHG2BGRV	Thickness of interval from the Mahogany bed to B-groove, in ft
MHGZN2BGRV	Thickness of interval from the Mahogany Zone to B-groove, in ft
BGRV2R6	Thickness of interval from B-groove to the R-6 Zone, in ft
R62L5	Thickness of interval from R-6 to the L-5 Zone, in ft
L52R5	Thickness of interval from L-5 to the R-5 Zone, in ft
R52L4	Thickness of interval from R-5 to the L-4 Zone, in ft
L42R4	Thickness of interval from L-4 to the R-4 Zone, in ft
R42L3	Thickness of interval from R-4 to the L-3 Zone, in ft
L32R3	Thickness of interval from L-3 to the R-3 Zone, in ft
R32L2	Thickness of interval from R-3 to the L-2 Zone, in ft
L22R2	Thickness of interval from L-2 to the R-2 Zone, in ft
R22L1	Thickness of interval from R-2 to the L-1 Zone, in ft
L12R1	Thickness of interval from L-1 to the R-1 Zone, in ft
R12L0	Thickness of interval from R-1 to the L-0 Zone, in ft
L02R0	Thickness of interval from L-0 to the R-0 Zone, in ft
R02LPBS	Thickness of interval from R-0 to the Long Point base, in ft
AGRV2MHGZN	Thickness of interval from A-groove to the Mahogany Zone, in ft
B442AGRV	Thickness of interval from Bed 44 to A-groove, in ft
MGBS2R5	Thickness of interval from the Mahogany Zone base to the R-5 Zone, in ft
R52LPBS	Thickness of interval from R-5 to the Long Point base, in ft
JD762JD44	Thickness of interval from bed 76 to bed 44, in ft

Table A2. The column names and definitions of the Microsoft Access table CO_Assays_INTV.

Column name	Column definition
OBJECTID	Software-calculated identifier
LABNO	Six-digit USBM Laramie laboratory number
TOPFT	Depth, in ft, measured from the surface datum to the top of the sampled interval
BOTFT	Depth, in ft, measured from the surface datum to the base of the sampled interval
SHLOILPCT	Amount of shale oil, in weight percent
WATERPCT	Amount of water, in weight percent
SHLRSDPCT	Amount of shale residue, in weight percent
GASPLSPCT	Amount of "gas plus loss," in weight percent
OILGPT	Shale oil, in U.S. gallons per short ton of rock
WATERGPT	Water, in U.S. gallons per short ton of rock
SPCFGRAV	Specific gravity of the shale oil
COKETEND	Tendency for spent shale to coke
USGSID	Unique ID assigned by staff geologist
INTVL	Thickness of interval, in ft (BOTFT-TOPFT)
INTXOIL	Column used for weighted-average gallons per ton calculation (INTVL * OILGPT)
ROCKTYPE	Column added to filter out halite intervals ("NH") and to denote intervals that were edited to distinguish between missing records and records found in core descriptions to be either nahcolite or sandstone ("NO").

Table A3. The column names and definitions of the Microsoft Access table BPA Lookup Table.

Column name	Column definition
ID	Software-calculated identifier
GALPERTON	Shale oil, in U.S. gallons per short ton of rock
GALFT3NEW	Oil yield, per unit volume, gallons per cubic foot

Table A4. The column names and definitions of the Microsoft Access table OilShale_Holes_pts.

Column name	Column definition
OBJECTID	Software-calculated identifier
USGSID	Unique ID assigned by staff geologist
LATDD	Latitude, in decimal degrees, North American Datum 1927, software-calculated, this report (2009)
LONGDD	Longitude, in decimal degrees, North American Datum 1927, software-calculated, this report (2009)
BED44AVGPT	Bed 44 average gallons per ton oil yield
BED44AVMSIN	Bed 44 percent missing intervals from core, represented as a floating point value
BED44BPA	Bed 44 barrels per acre oil yield
AGVAVGPT	A-groove average gallons per ton oil yield
AGVAVMSIN	A-groove percent missing intervals from core, represented as a floating point value
AGVBPA	A-groove barrels per acre oil yield
MGZNAVGPT	Mahogany Zone average gallons per ton oil yield
MGZNAVMSIN	Mahogany Zone percent missing intervals from core, represented as a floating point value
MGZNBPA	Mahogany Zone barrels per acre oil yield
BGVAVGPT	B-groove average gallons per ton oil yield
BGVAVMSIN	B-groove percent missing intervals from core, represented as a floating point value
BGVBPA	B-groove barrels per acre oil yield
R6AVGPT	R-6 average gallons per ton oil yield
R6AVMSIN	R-6 percent missing intervals from core, represented as a floating point value
R6BPA	R-6 barrels per acre oil yield
L5AVGPT	L-5 average gallons per ton oil yield
L5AVMSIN	L-5 percent missing intervals from core, represented as a floating point value
L5BPA	L-5 barrels per acre oil yield
R5AVGPT	R-5 average gallons per ton oil yield
R5AVMSIN	R-5 percent missing intervals from core, represented as a floating point value
R5BPA	R-5 barrels per acre oil yield
L4AVGPT	L-4 average gallons per ton oil yield
L4AVMSIN	L-4 percent missing intervals from core, represented as a floating point value
L4BPA	L-4 barrels per acre oil yield
R4AVGPT	R-4 average gallons per ton oil yield
R4AVMSIN	R-4 percent missing intervals from core, represented as a floating point value
R4BPA	R-4 barrels per acre oil yield
L3AVGPT	L-3 average gallons per ton oil yield
L3AVMSIN	L-3 percent missing intervals from core, represented as a floating point value
L3BPA	L-3 barrels per acre oil yield
R3AVGPT	R-3 average gallons per ton oil yield
R3AVMSIN	R-3 percent missing intervals from core, represented as a floating point value
R3BPA	R-3 barrels per acre oil yield
L2AVGPT	L-2 average gallons per ton oil yield
L2AVMSIN	L-2 percent missing intervals from core, represented as a floating point value
L2BPA	L-2 barrels per acre oil yield
R2AVGPT	R-2 average gallons per ton oil yield
R2AVMSIN	R-2 percent missing intervals from core, represented as a floating point value
R2BPA	R-2 barrels per acre oil yield
L1AVGPT	L-1 average gallons per ton oil yield

Table A4. The column names and definitions of the Microsoft Access table OilShale_Holes_pts.—Continued

Column name	Column definition
L1AVMSIN	L-1 percent missing intervals from core, represented as a floating point value
L1BPA	L-1 barrels per acre oil yield
R1AVGPT	R-1 average gallons per ton oil yield
R1AVMSIN	R-1 percent missing intervals from core, represented as a floating point value
R1BPA	R-1 barrels per acre oil yield
L0AVGPT	L-0 average gallons per ton oil yield
L0AVMSIN	L-0 percent missing intervals from core, represented as a floating point value
L0BPA	L-0 barrels per acre oil yield
R0AVGPT	R-0 average gallons per ton oil yield
R0AVMSIN	R-0 percent missing intervals from core, represented as a floating point value
R0BPA	R-0 barrels per acre oil yield
BD44MXMISS	Bed 44 maximum thickness of records missing from core
BD44CNTMISS	Bed 44 number of records missing from core
AGVMXMISS	A-groove maximum thickness of records missing from core
AGVCNTMISS	A-groove number of records missing from core
MGZNMXMISS	Mahogany zone maximum thickness of records missing from core
MGZNCNTMISS	Mahogany zone number of records missing from core
BGVMXMISS	B-groove maximum thickness of records missing from core
BGVCNTMISS	B-groove number of records missing from core
R6MXMISS	R-6 maximum thickness of records missing from core
R6CNTMISS	R-6 number of records missing from core
L5MXMISS	L-5 maximum thickness of records missing from core
L5CNTMISS	L-5 number of records missing from core
R5MXMISS	R-5 maximum thickness of records missing from core
R5CNTMISS	R-5 number of records missing from core
L4MXMISS	L-4 maximum thickness of records missing from core
L4CNTMISS	L-4 number of records missing from core
R4MXMISS	R-4 maximum thickness of records missing from core
R4CNTMISS	R-4 number of records missing from core
L3MXMISS	L-3 maximum thickness of records missing from core
L3CNTMISS	L-3 number of records missing from core
R3MXMISS	R-3 maximum thickness of records missing from core
R3CNTMISS	R-3 number of records missing from core
L2MXMISS	L-2 maximum thickness of records missing from core
L2CNTMISS	L-2 number of records missing from core
R2MXMISS	R-2 maximum thickness of records missing from core
R2CNTMISS	R-2 number of records missing from core
L1MXMISS	L-1 maximum thickness of records missing from core
L1CNTMISS	L-1 number of records missing from core
R1MXMISS	R-1 maximum thickness of records missing from core
R1CNTMISS	R-1 number of records missing from core

Table A4. The column names and definitions of the Microsoft Access table OilShale_Holes_pts.—Continued

Column name	Column definition
L0MXMISS	L-0 maximum thickness of records missing from core
L0CNTMISS	L-0 number of records missing from core
R0MXMISS	R-0 maximum thickness of records missing from core
R0CNTMISS	R-0 number of records missing from core

Table A5. The column names and definitions of the Microsoft Access table CO_Nahc_INTV.

Column name	Column definition
OBJECTID	Software-calculated identifier
OBSNO	Sample number
SAMPLEID	U.S. Bureau of Mines, Laramie, Wyo. laboratory number
TOPFT	Depth, in ft, measured from surface datum to top of sampled interval
BOTFT	Depth, in ft, 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 without 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
INTVL	Thickness of interval, in ft (BOTFT-TOPFT)
INTXNAHC	Column used for weighted-average nahcolite content within nahcolite-bearing interval only (INTVL * NAHPLOT)

Table A6. The column names and definitions of the Microsoft Access table Nahcolite_Holes_pts.

Column name	Column definition
ID	Software-calculated identifier
USGSID	Unique ID assigned by staff geologist
NAZNTHK	Total thickness, in ft, of nahcolite-bearing interval
ALLNAHC	Average weight-percent nahcolite of all zones
ALLNAHCTON	Tons per square mile of nahcolite for the entire nahcolite-bearing interval
ALLNAHTNAC	Tons per acre of nahcolite for the entire nahcolite-bearing interval
L5NAHC	Average weight-percent nahcolite, L-5 oil shale zone
L5NAHCTON	Tons per square mile of nahcolite, L-5 oil shale zone
R5NAHC	Average weight-percent nahcolite, R-5 oil shale zone
R5NAHCTON	Tons per square mile of nahcolite, R-5 oil shale zone
L4NAHC	Average weight-percent nahcolite, L-4 oil shale zone
L4NAHCTON	Tons per square mile of nahcolite, L-4 oil shale zone
R4NAHC	Average weight-percent nahcolite, R-4 oil shale zone
R4NAHCTON	Tons per square mile of nahcolite, R-4 oil shale zone
L3NAHC	Average weight-percent nahcolite, L-3 oil shale zone
L3NAHCTON	Tons per square mile of nahcolite, L-3 oil shale zone
R3NAHC	Average weight-percent nahcolite, R-3 oil shale zone
R3NAHCTON	Tons per square mile of nahcolite, R-3 oil shale zone
L2NAHC	Average weight-percent nahcolite, L-2 oil shale zone
L2NAHCTON	Tons per square mile of nahcolite, L-2 oil shale zone
R2NAHC	Average weight-percent nahcolite, R-2 oil shale zone
R2NAHCTON	Tons per square mile of nahcolite, R-2 oil shale zone
L5NATNAC	Tons per acre of nahcolite, L-5 oil shale zone
R5NATNAC	Tons per acre of nahcolite, R-5 oil shale zone
L4NATNAC	Tons per acre of nahcolite, L-4 oil shale zone
R4NATNAC	Tons per acre of nahcolite, R-4 oil shale zone
L3NATNAC	Tons per acre of nahcolite, L-3 oil shale zone
R3NATNAC	Tons per acre of nahcolite, R-3 oil shale zone
L2NATNAC	Tons per acre of nahcolite, L-2 oil shale zone
R2NATNAC	Tons per acre of nahcolite, R-2 oil shale zone

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