Prepared in cooperation with Alaska Department of Natural Resources

Rock-Eval Pyrolysis and Vitrinite Reflectance Results from the Sheep Creek 1 Well, Susitna Basin, South-Central Alaska

By Richard G. Stanley, Paul G. Lillis, Mark J. Pawlewicz, and Peter J. Haeussler

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Conversion Factors and Datum

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32.

SI to Inch/Pound

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
kilometer (km)	0.6214	mile (mi)

Datum

Horizontal coordinate information is referenced to North American Datum of 1927 (NAD27).

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Abstract

We used Rock-Eval pyrolysis and vitrinite reflectance to examine the petroleum source potential of rock samples from the Sheep Creek 1 well in the Susitna basin of south-central Alaska. The results show that Miocene nonmarine coal, carbonaceous shale, and mudstone are potential sources of hydrocarbons and are thermally immature with respect to the oil window. In the samples that we studied, coals are more organic-rich and more oil-prone than carbonaceous shales and silty mudstones, which appear to be potential sources of natural gas. Lithologically similar rocks may be present in the deeper parts of the subsurface Susitna basin located west of the Sheep Creek 1 well, where they may have been buried deeply enough to generate oil and (or) gas. The Susitna basin is sparsely drilled and mostly unexplored, and no commercial production of hydrocarbons has been obtained. However, the existence of potential source rocks of oil and gas, as shown by our Rock-Eval results, suggests that undiscovered petroleum accumulations may be present in the Susitna basin.

Introduction

The Susitna basin of south-central Alaska is located north of the Castle Mountain fault and the petroliferous Cook Inlet basin (fig. 1). Seven exploratory wells drilled in the Susitna basin during 1964–2005 found no commercial amounts of oil or gas. Nevertheless, the basin is mostly unexplored, and its hydrocarbon resource potential is unknown. Available geological and geophysical data indicate that the Susitna basin includes Cenozoic nonmarine, coal-bearing, sedimentary, and volcanic strata that are more than 4 km thick, which in turn rest unconformably on strongly deformed Mesozoic marine sedimentary strata and Mesozoic igneous and metamorphic rocks (Ehm, 1983; Kirschner, 1988; Wilson and others, 2012; Stanley and others, 2013).

The U.S. Geological Survey, in cooperation with the Alaska Department of Natural Resources, is studying the geology, geophysics, and petroleum resource potential of the Susitna basin (Saltus and others, 2012; Gillis and others, 2013; Stanley and others, 2013). As part of this effort, we studied core from the Sheep Creek 1 exploratory well that was drilled along the eastern margin of the Susitna basin. Samples of coal, carbonaceous shale, and silty mudstone from the core were analyzed using Rock-Eval pyrolysis and vitrinite reflectance in order to better understand the potential petroleum source rocks in the basin.

The Sheep Creek 1 well was drilled during the winter of 2004 by Evergreen Resources Alaska Corporation as part of a coalbed methane exploration program. The well is located about 17 mi north of Willow, Alaska (fig. 1), at a ground elevation of approximately 229 ft. The well was spudded on January 14, 2004, and reached a total depth of 1,371 ft in hard basalt on February 8, 2004. The well was cored from about 325 to 1,371 ft with generally good recovery, but the well history indicates that some of the core runs had incomplete or no recovery. The core diameter is about 2.5 in. No borehole geophysical logs (for example, spontaneous potential, resistivity, dipmeter, and so on) were run in this well, but a graphic lithologic log and portable gamma ray log are available from the Alaska Oil and Gas Conservation Commission (Anchorage, Alaska). No hydrocarbon production was obtained, and the well was plugged and abandoned on March 3, 2004.

Core from the Sheep Creek 1 well was donated by Evergreen Resources to the Alaska Geologic Materials Center (GMC) in Eagle River, Alaska, where it is available for public inspection. At the GMC, the core was stored for several years in a shipping container that was not climate controlled; during this time, the core boxes deteriorated, and parts of the core were reportedly overgrown by mold. Subsequently, portions of the core from 579 to 597 ft and 964 to 1,369 ft were cleaned, repackaged, and relabeled by Don Hartman, a volunteer at the GMC, and this is the material that we examined and sampled for analyses using Rock-Eval pyrolysis and vitrinite reflectance.

Stratigraphy of the Sheep Creek 1 Well

A preliminary interpretation of the stratigraphy of the Sheep Creek 1 well is shown in figure 2 and is based on (1) a well history and graphic lithologic log provided by the Alaska Oil and Gas Conservation Commission, (2) photographs of the well core provided by the Alaska Geologic Materials Center, (3) our own observations on well-preserved core intervals from 579 to 597 ft and 964 to 1,369 ft, and (4) preliminary results of new palynological biostratigraphy and isotopic dating. In this report, all depths in the Sheep Creek well are expressed as measured (drilled) depths. Dipmeter data are not available for this well, but we note that the apparent dips of bedding in the cored intervals range from nearly horizontal to about 10 degrees from horizontal.

The interval from 0 to 305 ft primarily consists of loose sand and gravel with subordinate clayey till. This interval is undated but is presumed to be of Holocene and Pleistocene age because of the likely glacial origin of the till.

The interval from 305 to 1,212 ft consists of conglomerate, sandstone, siltstone, mudstone, carbonaceous shale, and coal that are inferred to have been deposited in fluvial channel and overbank environments and associated mires. Woody material and plant debris are abundant. The coals are brittle and mostly dark gray to black; blebs of honey-colored amber about 1–2 mm in diameter are abundant in some coal beds. Most of the coal has a dull luster, but shiny bands occur in some intervals. Palynomorphs from the lower part of this interval at 972.5–1,214 ft indicate a nonmarine origin and an age of late middle Miocene, according to unpublished data provided in 2013 by the IRF Group, Inc., under contract with the U.S. Geological Survey. The interval from 305 to 972.5 ft in the Sheep Creek 1 well is undated, but may range in age from Pleistocene or Pliocene to late middle Miocene because it is overlain by presumed Pleistocene strata and underlain by well-dated late middle Miocene strata.

The interval from 305 to 1,212 ft is lithologically similar to, and may be partly correlative with, outcrops of conglomeratic and coal-bearing strata mapped as Pliocene Sterling(?) Formation and Miocene Tyonek(?) Formation in the Talkeetna quadrangle (Reed and Nelson, 1980) and coal-bearing strata mapped as Miocene and Oligocene Tyonek Formation in the Tyonek quadrangle (Lamberson and Spackman, 1987; Wilson and others, 2012; Gillis and others, 2013). However, precise stratigraphic correlation of surface and subsurface geologic units in the Susitna basin has not been achieved because of a lack of high-quality biostratigraphic and isotopic dating.

The interval from 1,212 to 1,255 ft in the Sheep Creek 1 well consists of volcaniclastic sandstone, granule to small pebble conglomerate, and subordinate mudstone. Plant fragments and woody material are common. A single palynological sample from 1,214 ft suggests a nonmarine origin and an age of late middle Miocene for the uppermost part of the volcaniclastic interval, but the interval from 1,214 to 1,255 ft is undated. The depositional setting of the volcaniclastic rocks from 1,212 to 1,255 ft is unknown; however, fluvial and (or) alluvial fan deposition is suggested by coarse grain size, crude stratification, and textures ranging from clast supported to matrix supported.

Rocks from 1,255 to 1,369 ft in the Sheep Creek 1 well consist of basalt that varies from altered and crumbly to fresh and hard. Isotopic dating of hard, green-gray, plagioclase-phyric basalt from depths greater than 1,300 ft indicates an age of early Eocene to late Paleocene (R.G. Stanley and P.J. Haeussler, U.S. Geological Survey, and J.A. Benowitz, University of Alaska, unpub. data, 2013). Basalt in the Sheep Creek 1 well is about the same age as basalt in the Arkose Ridge Formation in the Talkeetna Mountains, volcanic rocks on the eastern flank of the Tordrillo Mountains, and volcanic strata in the Trail Ridge Unit 1 and Pure Kahiltna Unit 1 wells (fig. 1; Wilson and others, 2012; Stanley and others, 2013). The Sheep Creek 1 well was cored to a total depth of 1,371 ft, but the lowermost 2 ft of core (presumably consisting of basalt) were not recovered.

Our palynological and isotopic data indicate that there must be a Miocene-on-Paleogene unconformity in the interval at a depth greater than the deepest palynological sample at 1,214 ft (dated as late middle Miocene), and above the top of altered Eocene to Paleocene basalt at about 1,255 ft. The exact position of the unconformity surface is unknown, but the available data constrain the unconformity surface to 1,214–1,255 ft.

Methods

Samples of coal, carbonaceous mudstone, and silty mudstone from the Sheep Creek 1 well were obtained from depths of 972.5–1,215.0 ft and analyzed using Rock-Eval pyrolysis and vitrinite reflectance (table 1). Rock-Eval analyses were performed by commercial laboratories: 35 samples were processed by Weatherford Laboratories (Shenandoah, Texas), and 7 samples were processed by GeoMark Rock Source, LLC (Humble, Texas). Four samples were processed and examined for vitrinite reflectance in the laboratories of the U.S. Geological Survey, Denver, Colorado. Detailed information on the laboratory procedures of Rock-Eval pyrolysis and vitrinite reflectance, as well as guidelines for interpreting the results of these analyses, can be found in publications by Peters (1986) and Peters and Cassa (1994).

Table 1. Rock-Eval and vitrinite reflectance results from the Sheep Creek 1 well, Susitna basin, south-central Alaska.
[Table 1 is a Microsoft© Excel file and can be downloaded at *http://pubs.usgs.gov/of/2013/1307/*.]

Results and Discussion

A total of 42 samples from the Sheep Creek 1 well were analyzed using Rock-Eval pyrolysis, including 33 samples of coal, 7 of carbonaceous mudstone, and 2 of silty mudstone (table 1). The generative potential of source rocks is evaluated based on the quantity (richness), quality, and thermal maturity of the organic matter component. Quantity is measured as total organic carbon content (TOC) in weight percent, and quality is a function of the hydrogen content of organic matter measured as atomic hydrogen/carbon ratio by kerogen elemental analysis. In this study, Rock-Eval data were used as a proxy for elemental analysis to evaluate source rock quality and should be used with caution (Peters, 1986).

The thermal maturity of all samples from the Sheep Creek 1 well should be essentially the same because all samples are within a drilled interval of 243 ft (equivalent to a stratigraphic thickness of about 239 ft, assuming a bedding dip of 10 degrees and no unrecognized unconformities or faults). Values of Tmax (range 350–434˚C, average 393˚C) and vitrinite reflectance (range 0.25–0.31 percent Ro, average 0.28 percent Ro) indicate that all samples are immature with respect to the threshold for oil generation (Tmax<435˚C and vitrinite reflectance <0.6 percent Ro; Peters and Cassa, 1994, p. 96). In terms of coal rank, the coal samples are considered lignites based on the measured Ro values (Hunt, 1996, his figs. 10–38). The relationship between Tmax and vitrinite reflectance is fairly linear between 0.5 percent Ro (Tmax about 425˚C) and 1.5 percent Ro (Tmax about 475˚C), but more scatter is observed at lower thermal maturity (Teichmüller and Durand, 1983; Espitalié and others, 1985). At the measured vitrinite reflectance of these samples, the expected Tmax values are about 385–415˚C (Sykes and Snowdon, 2002, their fig. 3). Several coal samples with anomalously low Tmax values (<380˚C) are believed to contain significant amounts of a soluble component, such as bitumen or amber that yields a low-temperature pyrolysate (S2). Amber was observed in some of the hand specimens, but was not tied to specific sample numbers. Samples with Tmax values greater than 420˚C may contain reworked organic matter as indicated by the higher oxygen index and lower hydrogen index values, consistent with depositional environments with higher energy flow regimes (silty mudstones, carbonaceous shales, low TOC coals).

The production index (PI) is a measure of the relative proportion of S1 and S2 pyrolysis peaks (S1/S1+S2). When a source rock matures, S1 increases and causes S2 to decrease, and thus PI is a thermal maturity indicator. A rock that is oil-stained or has organic contaminates will have an anomalously high PI for a given maturity. However, Suggate and Boudou (1993) noted anomalously high PI values up to 0.3 in peats and lignites presumably from original biogenic compounds that are progressively lost with coalification to the sub-bituminous stage. Most of the samples have PI less than 0.1, which is appropriate for this low maturity. However, the silty mudstones, some of the carbonaceous shales, and lower-TOC coals (<35 weight percent) contain anomalously high PI values (0.1–0.17). The cause of the high PI values is unknown; possible explanations include the presence of migrated hydrocarbons, and contamination of the samples during collection or storage.

Coals typically are defined (Hunt, 1996, p. 635) as rocks having greater than 50 weight percent organic matter (including the elements C, H, N, O, P, and S), but the total organic carbon content (TOC) may be as low as 20 weight percent in low-rank coals (lignites). In the Sheep Creek 1 well core, rock samples described in hand specimens as coal generally have TOC content of 20 percent or more, with two exceptions (SC24, TOC 11.2 weight percent; SC30, TOC 14.3 weight percent). Rock samples described in hand specimens as carbonaceous shale generally have TOC content of less than 20 percent, with one exception (SC14, TOC 21.3 weight percent). In terms of quantity (richness) of organic matter, all coal samples (TOC range 11.2–59.2 weight percent, average 43.1 weight percent) and most carbonaceous shales (TOC range 1.6–21.3 weight percent, average 6.8 weight percent) are considered to have excellent richness (TOC> 4 weight percent; Peters and Cassa, 1994). Using the criteria of richness based on S2, the carbonaceous shales rated lower (poor to very good, table 1) than the rating based on TOC probably because some of the organic matter is reworked or oxidized due to the depositional environment.

Quality (hydrogen content) of organic matter determines whether kerogen is oil-prone (Type I and II) or gas-prone (Type III), and may be evaluated based on the hydrogen index (S2/TOC) and S2/S3 (Peters and Cassa, 1994). Most of the coal samples contain mixed oil- and gas-prone to oil-prone kerogen (HI range 149–447 mg hydrocarbons (HC) per gram organic carbon (TOC), average 250 mg HC/g TOC; S2/S3 range 3.3–12.9, average 7.7), whereas the carbonaceous shales contain gas-prone kerogen (HI range 68–229 mg HC/g TOC, average 155 mg HC/g TOC; S2/S3 range 1.1–4.5, average 3.0; table 1, fig. 3). However, coals have a unique characteristic in that the HI increases with increasing thermal maturity up to the threshold of oil expulsion, then decreases similar to other source rocks (Teichmüller and Durand, 1983; Espitalié and others, 1985). Sykes and Snowdon (2002) and Petersen (2006) propose that the proper evaluation of the petroleum potential of coal should take this increase into account by either using samples with the thermal maturity near the onset of oil expulsion, or by estimating the effective HI of immature coals by translating HI along the maturation pathway to the maturity of oil expulsion. Without adjustment of the HI, the true generation potential of immature coals may be underestimated by up to 90 mg HC/g TOC. Using this scheme, the coal samples in the Sheep Creek 1 well would have an effective HI averaging 340 mg HC/g TOC (250+90) and essentially raise the quality rating to mostly oil-prone kerogen.

Two samples of silty mudstone from the Sheep Creek 1 well appear to have little potential to generate gas (Types III and III/IV), because although they have good richness based on TOC values (1.8–2.0 weight percent), they are rated as poor based on S2 (1.11–1.94 mg hydrocarbons per gram of rock).

Conclusions

Rock-Eval pyrolysis and vitrinite reflectance results from samples of Miocene strata in the Sheep Creek 1 well show that most coals include mixtures of Types II and III kerogens that are excellent potential sources of oil and gas. Additionally, the sample results show that carbonaceous shales include primarily Type III gas-prone kerogen, whereas silty mudstones have mostly low TOC values and Types III and IV kerogens with limited potential to generate gas. Values of Tmax (range 350–434˚C) and vitrinite reflectance (range 0.25–0.31 percent Ro) indicate that all samples from the Sheep Creek 1 well are thermally immature with respect to the top of the oil window (Tmax about 435˚C, Ro about 0.6 percent).

The results of these analyses may be useful in evaluating the petroleum resource potential of the Susitna basin (fig. 1). If sedimentary strata in the subsurface Susitna basin include rocks that are similar to the Sheep Creek 1 well samples in the amounts and types of organic matter, and if those rocks have been buried deeply enough to generate hydrocarbons, then oil and gas may have been generated and migrated into accumulations that can be commercially developed. The depth to the top of the oil window in the Susitna basin is unknown, but probably is deeper than the deepest sample from the Sheep Creek 1 well at 1,215 ft, which has a Rock-Eval Tmax value of 422˚C. Geological and geophysical studies are underway to better understand the stratigraphy, structure, and geologic history of the Susitna basin; when completed, these studies will provide a framework for an assessment of undiscovered oil and gas resources.

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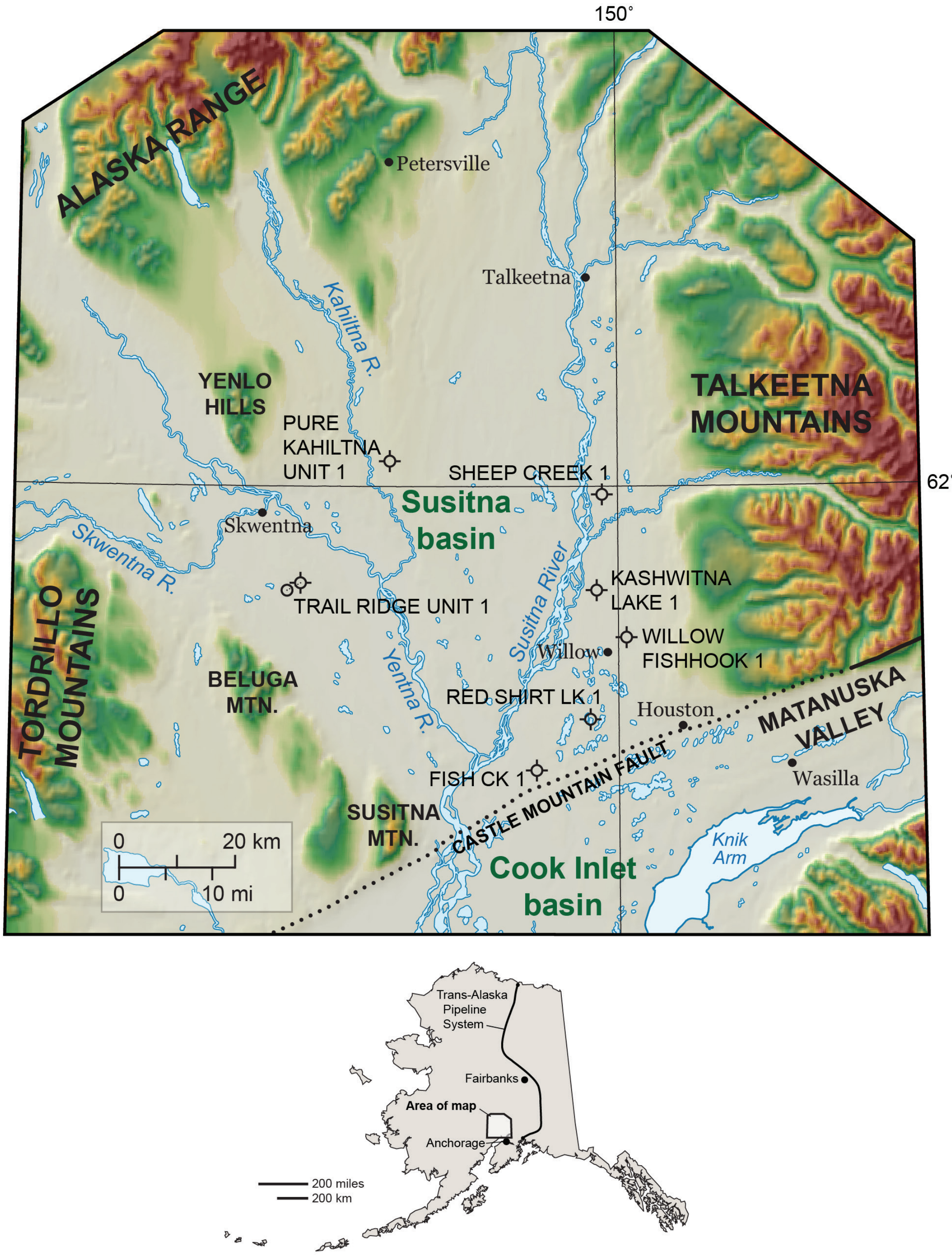

Figure 1. Location map showing Sheep Creek 1 well and other exploratory wells in the Susitna basin, south-central Alaska.

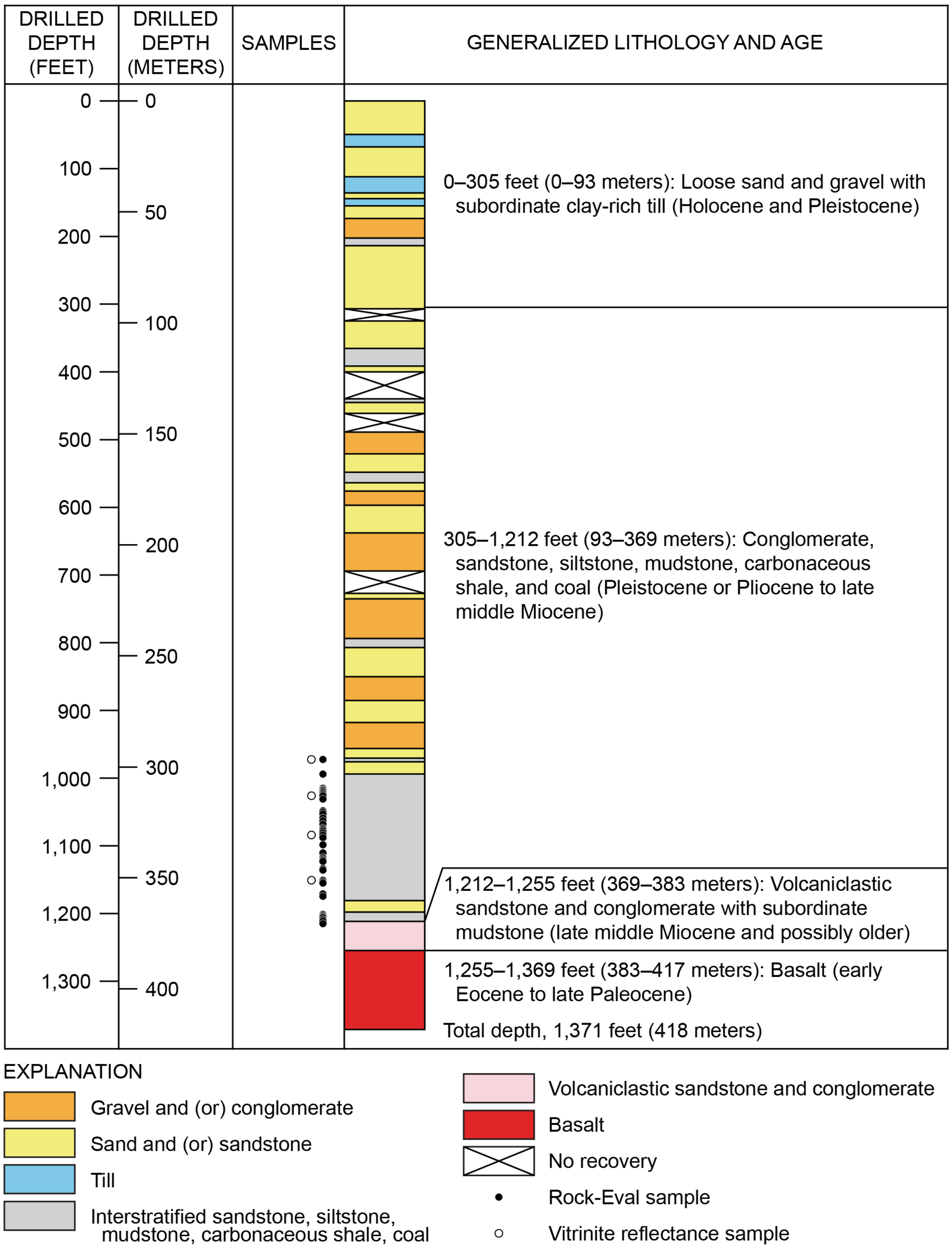

Figure 2. Preliminary stratigraphy of the Sheep Creek 1 well showing locations of Rock-Eval pyrolysis and vitrinite reflectance samples.

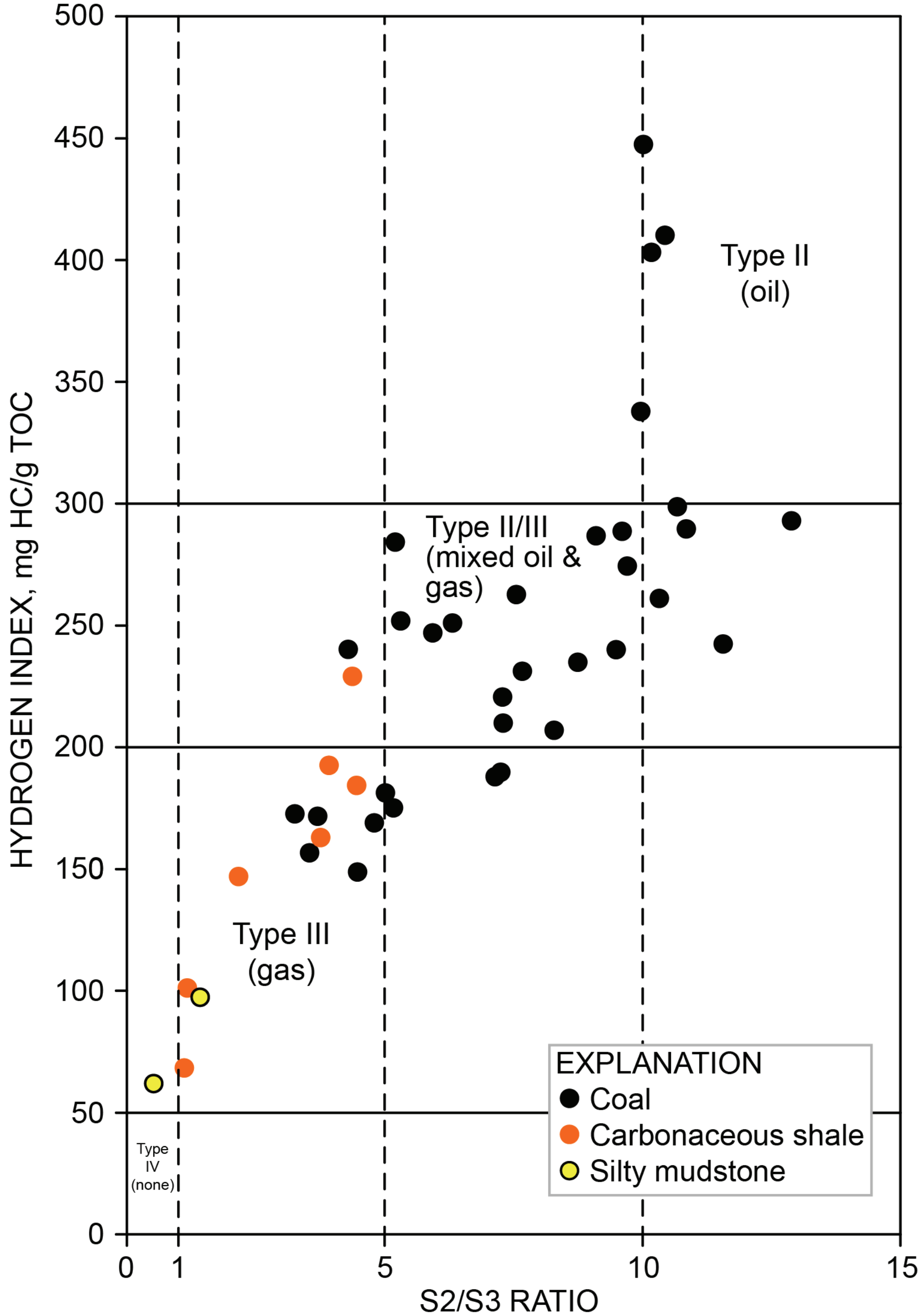

Figure 3. Plot of Hydrogen Index and S2/S3 ratio of samples from the Sheep Creek 1 well showing kerogen type (quality) and the character of expelled products as defined by Peters and Cassa (1994, table 5.2, p. 95).

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