
TAR SAND TRIANGLE BITUMEN DEPOSIT, GARFIELD AND WAYNE COUNTIES, UTAH

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ABSTRACT

The bitumen in the Tar Sand Triangle deposit is reservoirized in a several-hundred-foot-thick eolian sandstone, the White Rim Sandstone (Lower Permian). Across an area of 88 square miles, the thickness of the bitumen-impregnated sandstone exceeds 100 ft. The strata are gently dipping and otherwise unstructured. Average porosity and permeability of the sandstone reservoir are in the range 15-20% and 200-500 md, respectively. The oil saturation is consistently low, averaging 30-35%. The bitumen has an API gravity less than 8° at the surface and just over 10° in core. It has a high asphaltene and sulfur content, and it is saturate-poor. Although very viscous at reservoir temperatures, the bitumen is a few orders of magnitude less viscous than the Uinta Basin heavy oils. This study estimates a total in-place bitumen resource between 4.25 to 5.15 billion barrels in a deposit less than 200 square miles in size. However, at a commercially viable resource threshold equal to and greater than 60,000 barrels per acre, the in-place bitumen resource is estimated to range between 1.30 and 2.46 billion barrels in an area of 30 to 52 square miles, respectively.

The Tar Sand Triangle deposit has several drawbacks that will make commercial bitumen recovery operations difficult and expensive, but not impossible. These include the relatively low grade of the resource and the apparent low oil saturations; the generally poor quality of the oil due to high sulfur content and high viscosity at reservoir temperatures; the difficult access by existing unimproved roads, all of which pass through the Glen Canyon National Recreation Area; potentially complicated and/or expensive process water access; the lack of petroleum service vendors and other support services in southeast Utah; and the proximity to environmentally protected and visually stunning public lands.

INTRODUCTION

The Tar Sand Triangle bitumen deposit, with a previously estimated 2.5 to 12 billion barrels of resources in-place (Meyer and Schenk, 1988; Kuuskraa and others, 1987; Campbell and Ritzma, 1979), is located on the Colorado Plateau in Garfield and Wayne Counties, southeast Utah. It lies beneath a deeply dissected plateau bounded on three sides by deep canyons: the Green River to the northeast, the Colorado River to the southeast, and the Dirty Devil River to the west (figure 1). The highest surface, supported by the Navajo Sandstone (Jurassic) and having an elevation of about 7000 ft, is preserved along a long, sinuous ridge west of the Orange Cliffs. Below this surface are several benches, principally supported by the Moenkopi Formation (Triassic) and the Cedar Mesa

Sandstone (Permian). The encircling rivers are at elevations of 3700-4000 ft.

The deposit covers an area of over 200 square miles (126,000 acres[ac]) within all or parts of eight townships (figure 2): 15E-30S, 16E-30S, 17E-30S, 16E-30½S, 14E-31S, 15E-31S, 16E-31S, and 15E-32S. About 40% of the deposit is within the Glen Canyon National Recreation Area (NRA). The remaining part of the deposit is on public lands administered by the U.S. Bureau of Land Management (BLM) and the Utah State and Institutional Trust Lands Administration (SITLA). No part of the deposit is on fee land.

Despite the remoteness of this rugged terrain, many parts of the deposit can be reached by unpaved county roads (figure 3). The principal road (#633) follows along the ridge above the Orange Cliffs from the Hans Flat ranger station on the north to the center of

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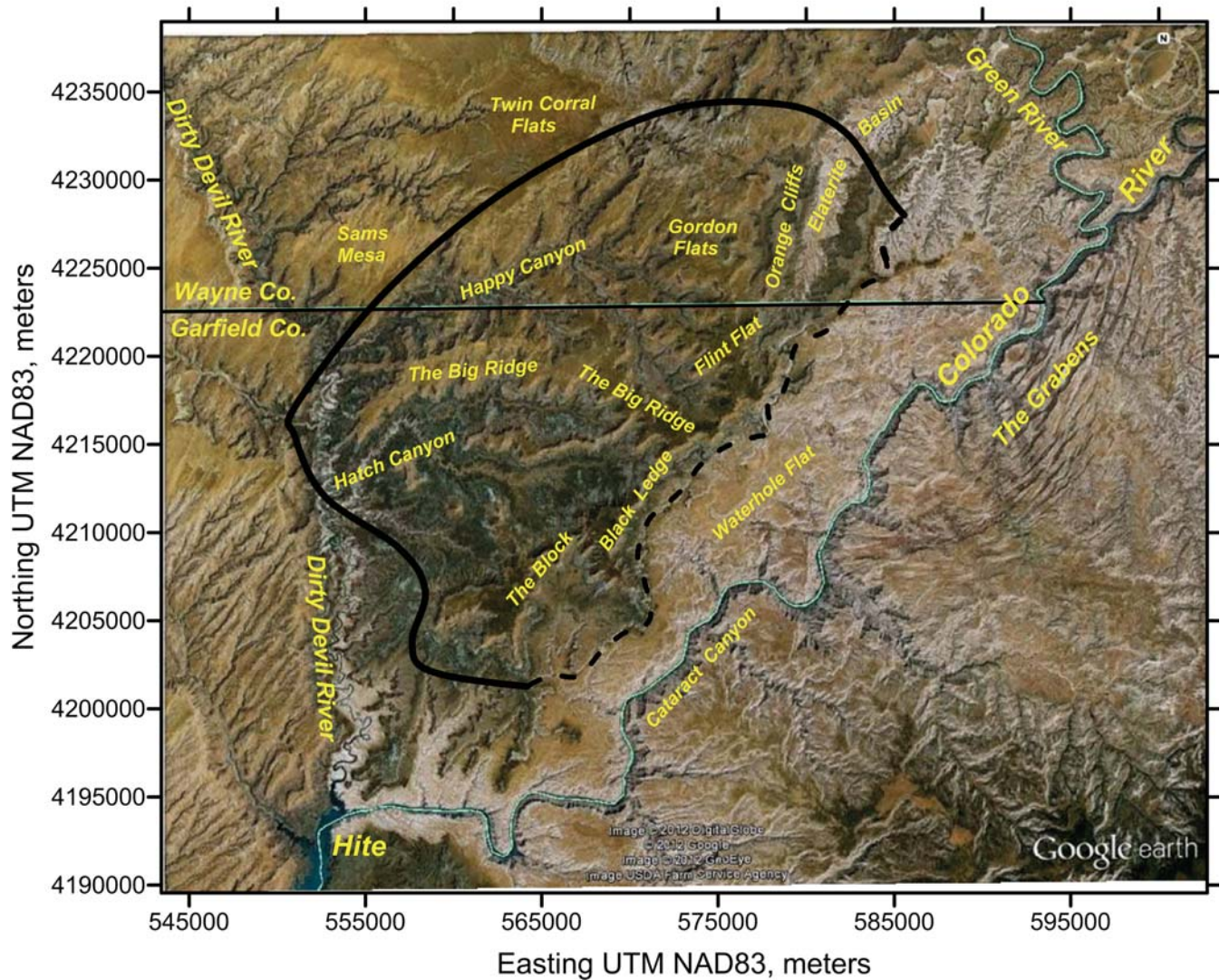


Figure 1. Location of the large Tar Sand Triangle bitumen deposit beneath a high, but dissected, plateau bounded by the Green River, the Colorado River, and the Dirty Devil River. The deposit straddles the eastern limits of Wayne and Garfield Counties. The heavy black line marks the approximate zero pinch-out of bitumen-impregnated sandstones. Where dashed, the line delineates the eroded edge of the deposit in the Colorado River canyon. The scale in meters is indicated by the UTM grid. The composite satellite image is from GoogleEarth and image data providers Digital Globe, GeoEye, and the USDA Farm Service Agency.

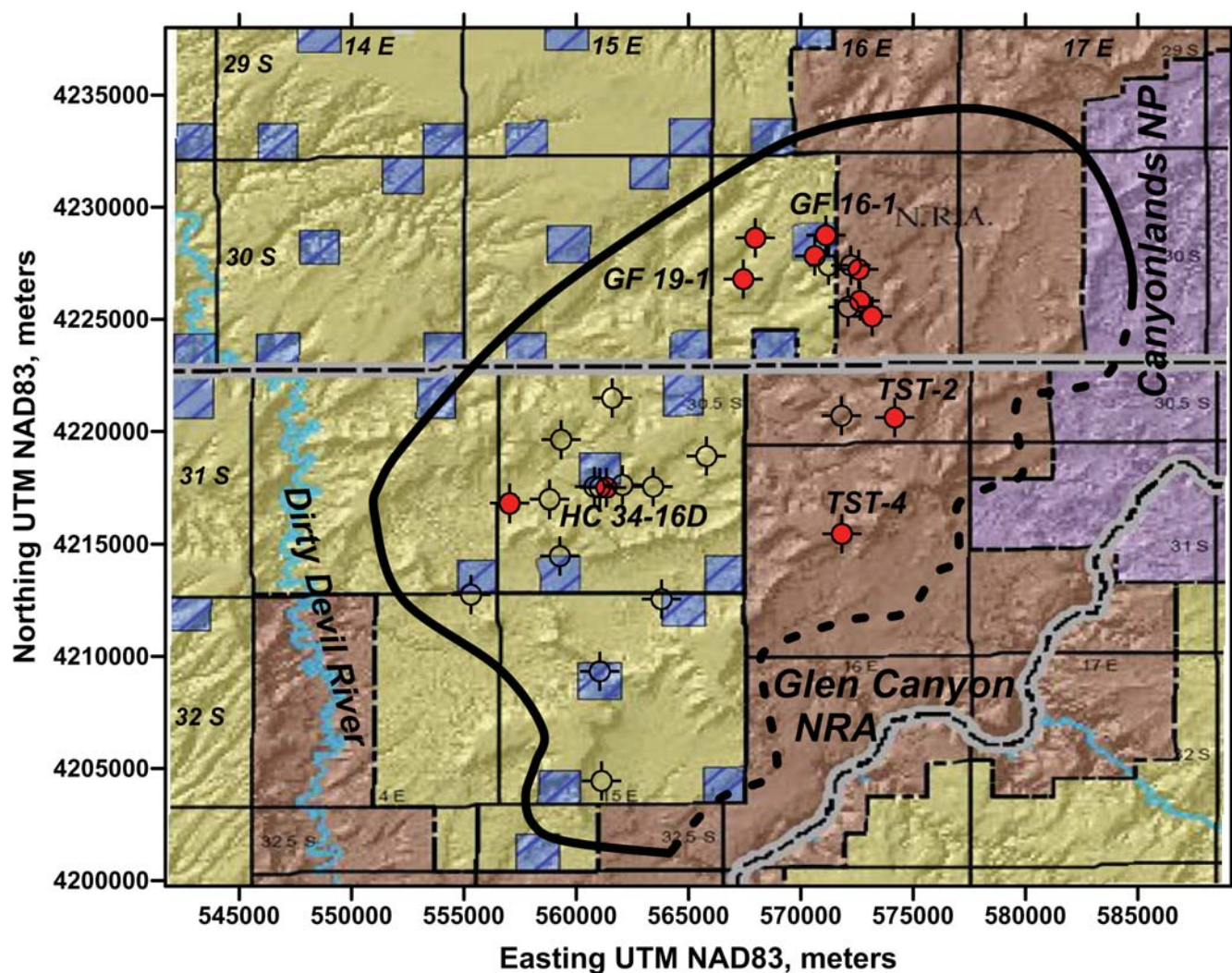


Figure 2. Location of the Tar Sand Triangle bitumen deposit displayed on a map showing township boundaries, Glen Canyon National Recreation Area (brown), and Canyonlands National Park (purple). Lands managed by the U.S. Bureau of Land Management are shown in yellow; Utah State Trust lands are shown in blue. The heavy black line marks the approximate zero pinch-out of bitumen-impregnated sandstones; where dashed the line delineates the eroded, thinning edge of the deposit. Wells penetrating the bitumen sandstone reservoir are indicated. Those marked in red have independent estimates of bitumen resource from core analysis. The scale in meters is indicated by the UTM grid.

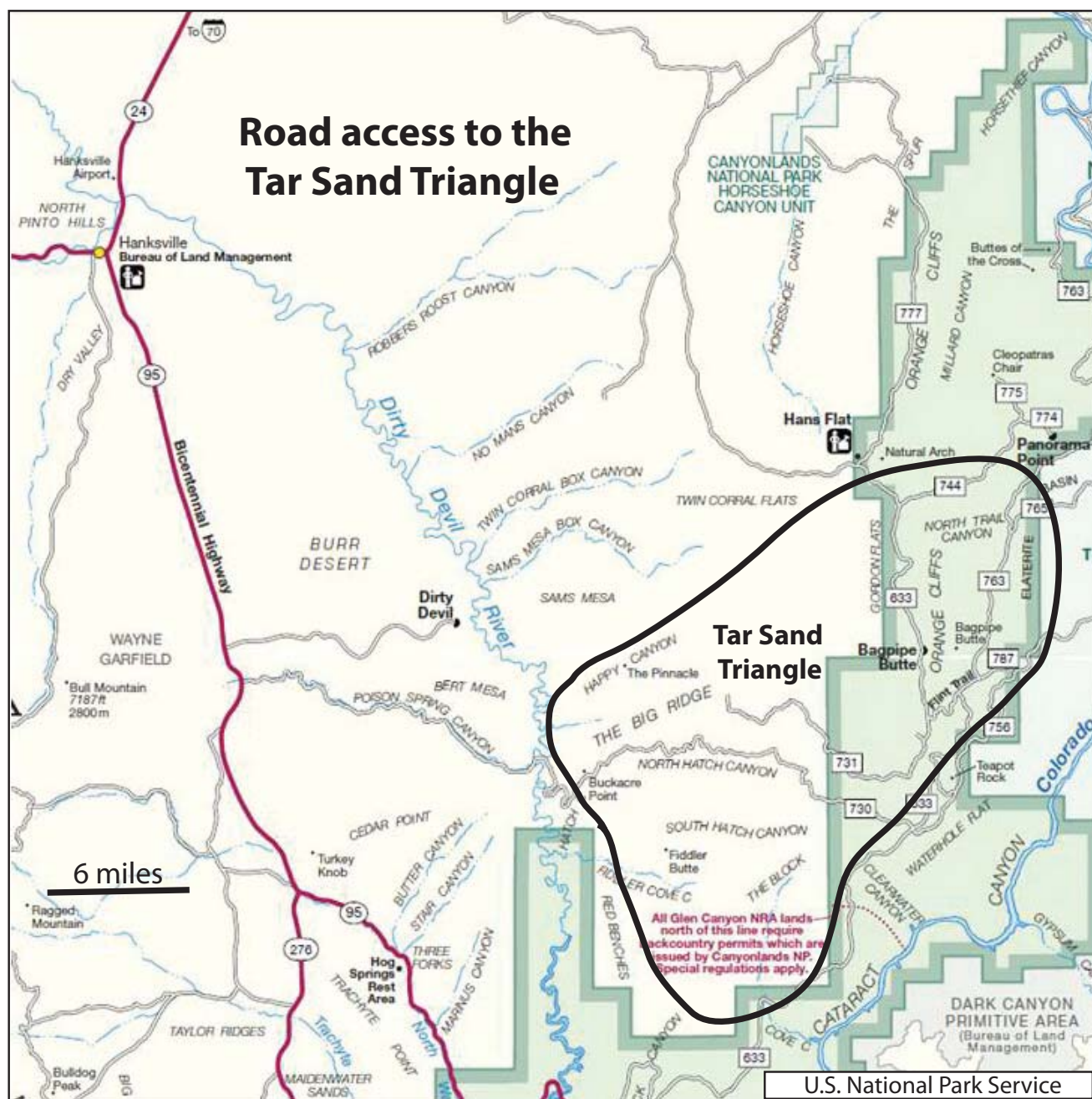


Figure 3. Roads in the vicinity of and providing access to the Tar Sands Triangle bitumen deposit. Only limited portions of the deposit can be reached by unpaved roads. Extracted from U.S. National Parks Service Glen Canyon NRA map.

The Big Ridge on the south. For the most part, this road traverses the central portion of the deposit, providing access to much of the prime operational areas in the deposit. The Hans Flat ranger station is reached by a 45-mile-long unpaved road crossing the relatively flat San Rafael Desert. The turn off for this road is on Route 24 about 20 miles north of Hanksville. From Hans Flat it is eight miles to the Gordon Flats landing strip, 11 miles to Flint Flat, 14.6 miles to entry onto The Big Ridge, 20.6 miles to The Big Ridge landing strip, and 23 miles to the end of the road (#731) at Two Pipe Springs. Road #633 continues south to connect with State Route 95 near Hite, providing an alternative access. The deposit also can be reached by a more difficult road (#730) that leads from route 95 south of Hanksville (figure 3), down Poison Spring Canyon crossing the Dirty Devil River near the western end of The Big Ridge (Buckacre Point), and continuing up North Hatch Canyon to join road 731 at Flint Flat.

Conventional oil and gas exploration was conducted in southeast Utah for much of the 20th century and many leases were awarded on public lands, most prior to the establishment of the Canyonlands National Park (NP) and Glen Canyon NRA. Until the increase in oil price in the 1970s there had been little interest in development of the Tar Sand Triangle. During the 1970s and early 1980s drilling and evaluations were performed by several operators, including Santa Fe Energy Company, Kirkwood Oil & Gas Company, Altex Oil Company, Shell Oil, and Gulf Exploration and Production Company. The deposit was also investigated by the Utah Geological Survey (Ritzma, 1969; Ritzma, 1979; Campbell and Ritzma, 1979) and by the Western Research Institute (LERC) under a U. S. Department of Energy contract (Dana and others, 1984). A small-scale in situ combustion recovery pilot project on just 1.5 ac was contemplated in the late 1970s (Berry, 1977), but it was never completed.

The 1981 Combined Hydrocarbon Leasing Act encouraged noncompetitive conversion of existing oil and gas leases to leases that also permitted tar sand exploitation. As of early 1984, 15 operators had filed applications for converting 80 leases on 91,547 ac (Dana and others, 1984), but the drop in oil price in the mid-1980s ended bitumen exploration in the deposit.

In the application to convert the leases, a group of existing lease holders led by Santa Fe Energy proposed forming a single operating unit of 66,040 ac for full-scale commercial exploitation of the tar sand by steam flood (Kerns, 1984; U. S. Department of Interior, 1984). The operation would have been in township 16E-30S, Morton Flats, and the area north of

Main Fork of Happy Canyon, in part within the Glen Canyon NRA. The project envisioned 1000 producing wells and 940 steam injectors with a projected yield of 30,000 barrels of oil per day (bopd). The 1679 ac-ft/year of water for steam generation would be brought to the site through a 15-mile pipeline from the Dirty Devil River. Part of the heavy oil produced would be used to fire the 32 MW onsite steam generator. Upgrading of the oil by coking was to have been done onsite. The project would have required major improvements to the Poison Spring Canyon-Flint Trail roads (#730, #731 and # 633), including widening and paving of some sections. Existing documents are unclear as to whether the project would have been permitted by the BLM and National Park Service.

Geologic Setting

The Tar Sand Triangle is located near the northern margin of the Colorado Plateau and lies on the southwest flank of the Paradox Basin, immediately outside of the region underlain by Pennsylvanian evaporates. This is an area of essentially flat-lying, undeformed strata of Permian to Jurassic age, which form a stepped landscape incised by steep-walled canyons (figure 1). The highest bench is supported by the Navajo Sandstone (Jurassic). Various Triassic sandstones and the Cedar Mesa Sandstone form the lower benches (figure 4). The Moenkopi Formation (Triassic) rests with an angular unconformity on the Cutler Group (Lower Permian). Bitumen is found principally in the White Rim Sandstone, the uppermost formation of the Cutler Group. However, at a few locations the upper Cedar Mesa Sandstone and the sandy basal part of the Moenkopi Formation, the Hoskinnini Member, are also bitumen-impregnated (figure 4). The Cedar Mesa Sandstone and White Rim Sandstone are similar eolian deposits, separated in the Tar Sand Triangle deposit by the Organ Rock Shale Tongue projecting southwestward out of the Paradox basin. The White Rim Sandstone is encased in less permeable strata, the Moenkopi Formation red mudstones above and the Organ Rock Shale below.

The bitumen in the White Rim Sandstone occupies a conventional stratigraphic trap (Campbell and Ritzma, 1981; Huntton and others, 1994) in which the up-dip edge is truncated by the base-Triassic unconformity (figure 5). Within this trap an inclined oil-water contact at elevations of 4200 to 4650 ft relative to mean sea level (msl) is recognized in wells. The oil-water contact establishes the western and northwestern down-dip tapered edge of the deposit. The eastern

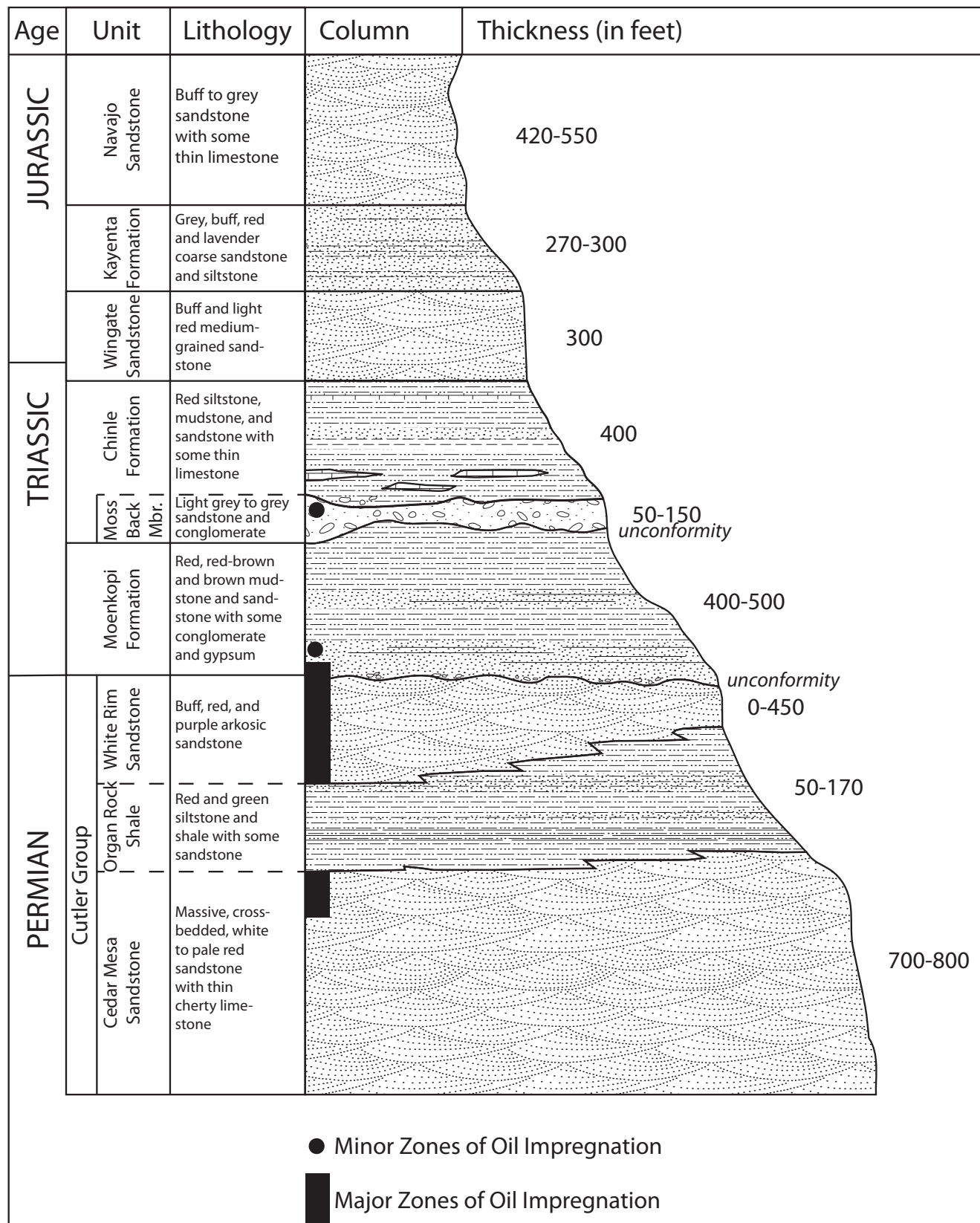


Figure 4. Stratigraphy of the Tar Sands Triangle bitumen deposit and overlying strata (from Dana and others, 1984).

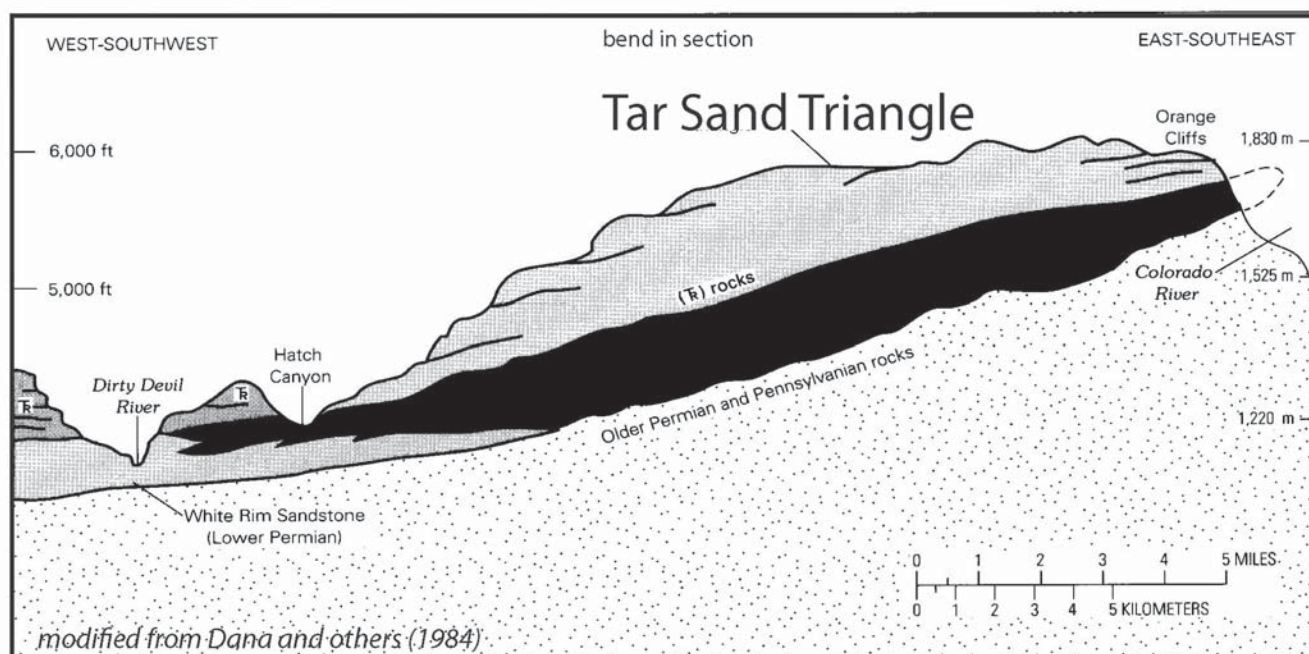


Figure 5. Generalized structural cross section of the Tar Sands Triangle bitumen deposit (modified from Dana and others, 1984).

up-dip edge is defined either by the basal Triassic unconformity cut-off or by the modern land surface in the canyon of the Colorado River. At the location of the deposit, stratification is nearly flat-lying, dipping to the northwest at just 120 ft per mile (Dana and others, 1984).

The combination of erosional beveling and stratigraphic position above the westward thinning tongue of the Organ Rock Shale has resulted in the thinning of the White Rim Sandstone towards the southeast and east. In the area of the Tar Sand Triangle deposit, the White Rim Sandstone is less than 350 ft thick. Most authors, principally Huntton and others (1994), posit that the westward thickening of the White Rim Sandstone indicates that it only could have been charged from that direction, but the source of the oil and the direction of charge are unknown.

The Tar Sand Triangle deposit is thought to be part of a much larger oil accumulation on the Colorado Plateau in the tectonic position of either the southwest rim of the Paradox Basin (Pennsylvanian) or the up dip edge of the Sevier foredeep basin (Cretaceous), or both. It may be a remnant of a 30-40 billion barrel oil (BBO) field (Hansley, 1995) in which the original oil evolved into a bitumen within the reservoir after emplacement by a combination of biodegradation, water washing, and near-surface oxidation. The degradation of the oil probably occurred as the Colorado Plateau uplifted in the late Cenozoic and the oil pool was ex-

humed. Fluid inclusion closing temperatures infer that the White Rim Sandstone had been buried to a depth of about 11,500 ft at the time of reservoir filling, most likely in the mid-Tertiary and just prior to unroofing (Huntton and others, 1999).

Character of the Reservoir

The principal reservoir in the Tar Sand Triangle deposit, containing about 99% of the bitumen resource, is the White Rim Sandstone of Lower Permian (Leonardian) age (Dana and others (1984). This reservoir is a white, subrounded to well-rounded, fine- to very fine-grained quartz arenite (Huntton and others, 1994) in thick to massive beds dominated by large-scale, high-angle cross-stratification. The White Rim Sandstone is mainly eolian in origin (Chan, 1989), but portions of the unit were modified by marine processes as the sea transgressed across the coastal dune fields (Huntton, 1985; Huntton and Chan, 1987; Chan and Kocurek, 1988; Harston and Morris, this volume). The White Rim Sandstone is truncated by an erosion surface and overlain unconformably by Lower Triassic red mudstones, locally conglomeratic (Huntton and others, 1994). Detailed lithologic logs are not available for the wells drilled in the deposit.

Twenty-eight wells provide control on the thickness of the White Rim Sandstone in the Tar Sand Triangle deposit and the thickness of the reservoir inter-

Table 1. Wells in the Tar Sand Triangle penetrating the White Rim Sandstone and providing control on the thickness of the bitumen-impregnated interval and the bitumen resource in thousand barrels per acre (MBO/ac) determined for 11 of the wells. Both the ground elevation (Elev) and elevation of the top of the White Rim Sandstone (Top WRSs) are in feet relative to mean sea level. Both the total thickness of the White Rim Sandstone reservoir (Thick ft) and the thickness of the bitumen-impregnated portion (Impr. ft) are shown. Data from the Utah Division of Oil, Gas, and Mining (DOGM) and Dana and others (1984). Gordon Flats 27-1 is the only well not reported in DOGM online files.

Well API #	Well	T	R	Sec.	loc.	Elev (ft)	Top WRSs	Thick ft	Impr. ft	MBO/ac
4305530008	Saga.-Skyline State 1	30S	16E	16	SE NE	6362	4892	240	50	29.00
4305530015	Gordon Flats 16-1	30S	16E	16	SW SE	6298	4878	230	72	29.85
4305530016	Gordon Flats 19-1	30S	16E	19	NE NE SE	6231	4701	210	98	33.94
4305530003	Skyline State 2	30S	16E	22	NE NW	6381	5037	240	89	
4305530017	Gordon Flats Fed Unit 1	30S	16E	22	NW SW NE	6542	5150	264	200	113.42
4305510924	French Sheep 1	30S	16E	27	SE NW	6465	5075	228	115	
4301710738	Robbers Roost 41-33	30.5S	16E	33	NE NE	6604	5179	185	185	
4301730163	TST-2	30.5S	16E	35	SE NW NW	6812	5400	168	165	59.42
4301730085	Technology 14-36	31S	14E	36	NE SE SW	4823	4623	235	14	
4301730091	White Rim 44-4	31S	15E	4	SE NE SE	6034	4634	na	156	
4301730089	Magnum 23-8	31S	15E	8	SE NW SE	5084	4601	371	57	
4301730092	Garfield 44-15	31S	15E	15	SW SE SE	5321	4814	303	124	
4301730087	Winfield 21-15	31S	15E	15	NE NE NW	6127	4703	na	186	
4301730086	Remington 14-15	31S	15E	15	NW SW SW	5307	4778	301	169	
4301730096	State 34-16	31S	15E	16	SW SE	5058	4733	295	175	
4301711186	Utah S-Govt 22-19	31S	15E	19	SE NW	4850	4606	333	190	103.55
4301730088	Monroe 22-20	31S	15E	20	NE SE NW	4988	4681	336	86	
4301730090	Cromwell 33-29	31S	15E	29	NW SW SE	5060	4832	259	60	
4301730144	TST-4	31S	16E	16	NE SE NE	6895	5464	130	125	53.53
4301730097	State 11-2	32S	15E	2	NW NW NW	5320	5180	180	84	
4301730095	State 31-16	32S	15E	16	NE NW NE	5535	5138	188	26	
4301711276	USA Federal A-1	32S	15E	33	C NW NE	5400	5270	160	80	
4301730107	Hatch Cyn U 34-16B	31S	15E	16	SW SE	5058	4771	na	178	
4305530046	Shell 7	30S	16E	17	SW NW	6163	4682	167	77	33.21
4305530045	Shell 1 Sentinel	30S	16E	21	NE NE NE	6333	4958	197	161	
na	Gordon Flats 27-1	30S	16E	27	NE SE	6567	5135	213	196	244.00
4305530041	Shell 9	30S	16E	27	NW NE	6540	5112	249	249	85.83
4301730109	Hatch Canyon 34-16D	31S	15E	16	SW SE	5088	4769	na	130	59.11
								Median:	232.5	124.5
								Average:	236.8	124.9
										76.80

val that is bitumen-impregnated (table 1). The average unit thickness is 236.8 ft (median = 232.5 ft), which is consistent with the regional isopach map in Dana and others (1984) showing the unit thinning southeastward toward the Colorado River. The elevation of the top of the White Rim Sandstone in the set of wells (table 1) ranges from a high of 5464 ft in section 16, T. 31 S., R. 16 E., to a low of 4601 ft in section 8, T. 31 S., R. 15 E.

Across the deposit, the average bitumen-impregnated interval constitutes only about half of total unit thickness, 124.9 ft (median = 124.5 ft). The range of thicknesses of the bitumen-impregnated interval encountered in the wells (table 1) is 14 to 249 ft. The spatial distribution of bitumen-impregnated thicknesses defines a central core of the deposit with bitumen-impregnated interval thickness in excess of 150 ft passing outward in all directions to regions of no bitumen within the White Rim reservoir. Thinning of the bitumen-impregnated zone to the southeast is related to stratigraphic thinning. However, the bitumen-impregnated zone thins to the northwest due to the low-angle intersection of the sub-horizontal bitumen-water contact with the gently northwest-dipping reservoir (figure 5).

In wells located on the high plateau, the depth to the top of the White Rim Sandstone is generally in the range of 1400 to 1500 ft. The depth is considerably less for wells located on the intermediate benches and box canyons incised into the plateau. Except along the cliff line over the Colorado River and in the deeper canyons of the Dirty Devil River drainage, the deposit is rarely exposed at the surface.

The White Rim Sandstone has had a complex diagenetic history (Schenk, 1988; Hansley, 1995) that has involved calcite cementation of primary pores, calcite and potassium feldspar dissolution forming a secondary porosity, kaolinite-illite-quartz precipitation in the secondary porosity, and minor Fe-carbonate growth. The diagenesis is related to a long history of fluid migration through the sandstone (Sanford, 1995), including reactive organic acids derived from migrating hydrocarbons (Hansley, 1995). The diagenesis predates the entry of meteoric waters under the modern arid conditions of the region (Schenk, 1988). Thus, the bitumen is reservoired primarily in secondary porosity.

Based on 121 core samples from four Santa Fe Energy wells in Wayne County (T. 30 S., R. 16 E.), Campbell and Ritzma (1981) reported the following petrophysical characteristics for the White Rim Sandstone, including oil saturation (S_o) and water saturation (S_w):

- Porosity median = 19.8%; range of 9.7-31.7%, after oil extraction,
- Permeability median = 340 md; range 0.07-2.790 md after oil extraction,
median = 268 md; range 0.03-2,580 md before oil extraction,
- So median = 32.2%; range 5.8-85.4%,
- Sw median = 4.9%; range 0.9-31.4%.

However, more detailed information on petrophysical properties of the White Rim Sandstone comes from five cores that penetrate the entire bitumen-impregnated portion of the reservoir. The core analyses are reported in Dana and others (1984) for TST-2 and TST-4 and in Utah Division of Oil, Gas, and Mining (DOGM) public files for Gordon Flats 16-1, Gordon Flats 19-1, and Hatch Canyon 34-16D. The locations of the wells are shown in figure 2 and table 1.

As might be expected of an eolian sandstone, the porosity and permeability of the White Rim Sandstone are good for a conventional oil reservoir (figure 6; table 2), with average porosity in the range 15.3 to 20.2% and permeability averaging between about 100 and 500 md. There is, however, substantial vertical variability in porosity (figures 7 through 11), which likely would be detrimental to the overall effectiveness of in situ oil recovery processes. Lithology logs are not available for these wells. However, for all cores a good correlation exists between porosity and permeability (figure 6). Note that the majority of core samples have porosity in excess of 15% and permeabilities greater than 100 md.

Fluid saturations measured in the cores and reported as percent of pore volume are summarized in table 2. Average oil saturation, S_o , is in the range 24 to 36 vol%, and the average water saturation, S_w , is somewhat lower, between 4.0 and 26 vol%. A cross-plot of the two fluid saturation values (figure 12) indicates that they sum to far less than the expected 100%. The reservoir rock is deficient in fluids. This observation leads to the conclusion that either (a) the reservoir is situated above the local water table, within the vadose zone, and air is also present in the pore space, or (b) the handling of the cores was such that fluid loss occurred before the cores were analyzed. Fluid drainage during handling is supported by the observation that samples with the highest S_w or S_o+S_w values (figure 12) also have exceptionally low permeabilities, generally less than 1.0 md. These are the tight rocks that have low S_o values because they have high capillary entry pressures to liquid hydrocarbons. The systematically higher S_w values in the TST-2 and TST-4 cores (figure 12; table 2) may indicate a more deliberate handling of the science test samples between the well head and the laboratory.

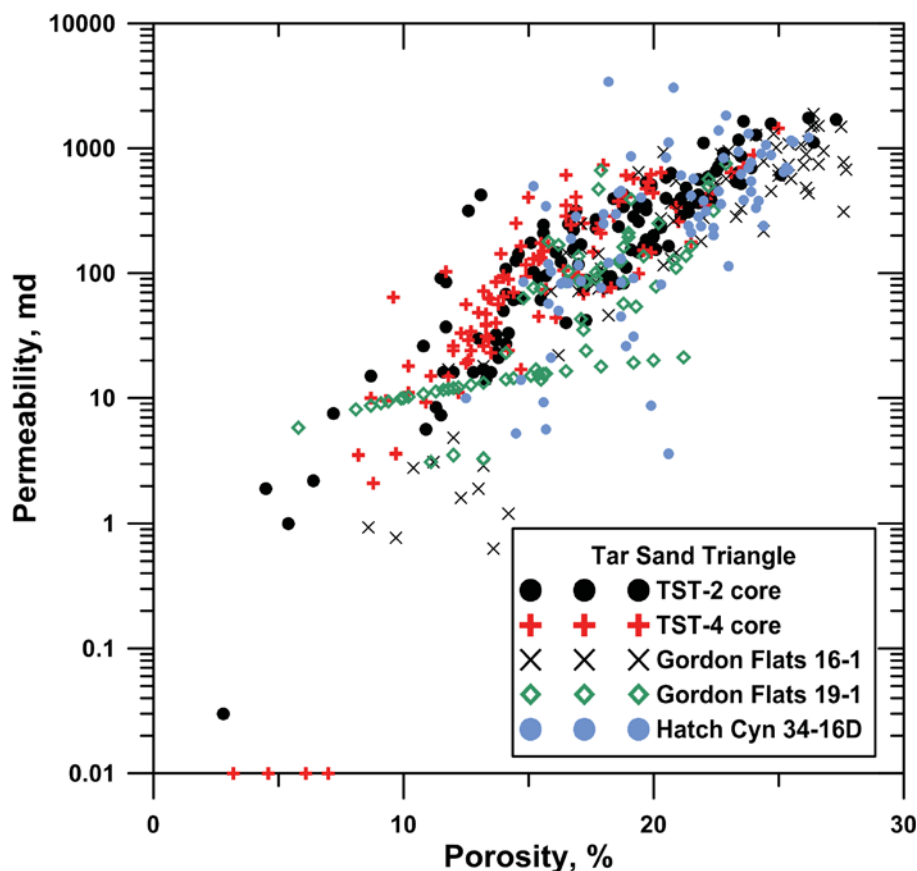


Figure 6. Porosity and permeability of bitumen-impregnated White Rim Sandstone reservoir after the bitumen is extracted from the core samples listed in table 2. Data are from Dana and others (1984) and well completion reports from the Utah Division of Oil, Gas, and Mining (DOGM).

Table 2. Average and median petrophysical properties of the White Rim Sandstone reservoir measured in continuous well cores. Data from Dana and others (1984) and well completion reports from Utah Division of Oil, Gas, and Mines (DOGM). So: oil saturation; Sw: water saturation.

	TST-2	TST-4	Gordon Flats 16-1	Gordon Flats 19-1	Hatch Cyn 34-16D
Well location	30.5S-16E-35	31S-16E-16	30S-16E-16	30S-16E-19	31S-15E-16
Interval thick, ft	165	125	72	98	130
No. of samples	151	112	102	98	82
Porosity, vol%					
Average	17.2 ± 5.5	15.3 ± 4.1	20.1 ± 4.9	16.1 ± 3.7	20.2 ± 3.4
Median	18.2	15.2	20.7	16.6	20.4
Permeability, md					
Average	293.5 ± 366.1	191.8 ± 239.5	389.9 ± 438.1	92.7 ± 139.7	465.7 ± 588.1
Median	163.0	93.0	204.5	36.0	290.0
So, vol%					
Average	27.4 ± 11.8	35.6 ± 14.7	24.0 ± 18.8	27.8 ± 14.8	30.4 ± 16.0
Median	27.8	38.7	20.1	26.0	26.0
Sw, vol%					
Average	22.0 ± 14.1	25.9 ± 8.5	5.5 ± 4.5	10.6 ± 11.1	4.0 ± 2.8
Median	17.8	24.7	4.0	6.1	3.4
Oil grade, BO/ac ft					
Average	360.1 ± 184.7	428.2 ± 197.7	414.5 ± 357.1	346.3 ± 184.1	454.7 ± 217.7
Median	355.7	440.4	367.6	338.4	411.7

Rather than proportional fluid loss, it is more likely that the water drained from the core preferentially to the highly viscous, virtually immobile bitumen. This would mean that the values of S_o reported closely reflect the actual oil saturations in the reservoir, that is 50 vol% or less (figure 12). Successful *in situ* oil recovery processes, whether thermal, chemical or electrical, normally require oil saturations greater than 60%, preferably in the 70 to 90% range (Schamel, 2009).

The richness of bitumen in the reservoir or "oil grade" is calculated from the values of porosity and oil saturation. The oil grade (in units of barrels of oil per acre foot) equals the volume in barrels of an acre foot (7758 B/ac ft) multiplied by the product of porosity times S_o , both expressed as decimal fractions. Figures 7 through 11 display the logs of oil grade. The logs show the large vertical variability of bitumen richness in the White Rim Sandstone reservoir. The oil grade is considerably more variable than porosity, reflecting the important role of oil saturation. The importance of this parameter also is displayed in figure 13, a plot of porosity against the calculated oil grade. In the five cores, the average oil grade varies from a low of 360.1 BO/ac ft (figure 7) to a high of 454.7 BO/ac ft (figure 11). The actual bitumen resource in place represented by the core is the average grade in BO/ac ft times the net thickness of the bitumen-impregnated interval in feet (table 1). In this paper, bitumen resource in place is specified as thousands of barrels per acre, MBO/ac. The resource value for each of the cores is shown on the logs (figures 7 through 11). The values range from a low of 29.85 MBO/ac in the Gordon Flats 16-1 core, where just the upper half of the White Rim Sandstone reservoir is bitumen-impregnated, to 59.42 MBO/ac in the TST-2 core, which is bitumen-impregnated through nearly the full thickness of the reservoir.

Where the actual oil or bitumen content is reported as weight percent of total rock, as it was with the TST-2 and TST-4 cores, the oil grade is a function of rock and oil densities. For the Tar Sand Triangle deposit the calculation is: BO/ac ft = $169.4 \times \text{oil wt\%}$ (Dana and others, 1984). The value of S_o is actually calculated from the weight percent of oil extracted from the rock using measured bulk rock and oil densities, and the measured porosity of the oil-free rock.

Character of Tar Sand Triangle bitumen

Most of the analyses of the Tar Sand Triangle bitumen and heavy oil were carried out on samples from surface seeps, the most degraded oil in the deposit. Thus, Wood and Ritzma (1972) report a range

of API gravity for surface samples of 9.6° to -3.6°; the average of the 12 samples is 4.3°. Chevron analyzed a single surface sample from the Tar Sand Triangle (Black Ledge; section 18, T. 32 S., R. 16 E.) with a reported grade of 487.9 BO/ac ft (Phillips, 1987). The sulfur content was a high 3.87% and the liquid chromatography SARA analysis was as follows: Saturates, 18.7%; Aromatics, 3.4%; Resins and NSO compounds, 28.8%; and Asphaltenes, 45.5%.

The surface bitumen samples are much heavier and more degraded than the 11.1° API oil from core that was analyzed by Bunker and others (1979; table 3). The Tar Sand Triangle bitumen is very close in composition and physical properties to the Canadian Athabasca bitumen used for comparison, but it differs substantially from the more saturate-rich heavy oil from Utah's northwest Asphalt Ridge in the Uinta Basin. The Tar Sand Triangle bitumen has a relatively low (1.44) H/C ratio and high asphaltene (26.0%) and sulfur (4.38%) contents, as well as a very high carbon residue. All of these factors will make upgrading the heavy oil difficult and expensive. However, the oil does have favorable nitrogen and metals contents. A bitumen sample extracted from Sagadahoc-Skyline State 1 core (API 4305530008; section 16, T. 30 S., R. 16 E.) had an API gravity of 8.5° and a total sulfur content of 5.47 wt%. A note in the analytical report indicated that the API gravity may be 3 to 5 degrees low due to the method used for bitumen extraction (report from Utah DOGM files).

The viscosity of the Tar Sand Triangle oil is the lowest of any heavy oils and bitumens in Utah (figure 14), although it is slightly more viscous than the Athabasca oil (table 3). At a reservoir temperature of 100°F, the viscosity of the oil is about 50,000 centipoise (cp). By conventional Andrade extrapolation, a viscosity of 100 cp would be reached in this oil at just 230°F and 10 cp would be reached at 290°F. These temperatures are within the range of thermal recovery processes, such as steam stimulation, currently in widespread use. Note, however, that the Tar Sand Triangle bitumen is considerably more viscous than the typical heavy oil (figure 14) of the Midway-Sunset field, southern San Joaquin basin, California, that requires thermal stimulation to be produced commercially.

Based on biomarker analysis of many heavy oils in southern Utah (Tar Sand Triangle, Circle Cliffs, San Rafael Swell, and others), Dembicki and others (1986) and Wenrich and Palacas (1990) conclude that all oils have been derived from the same carbonate source rock(s). They note as evidence for the carbon-

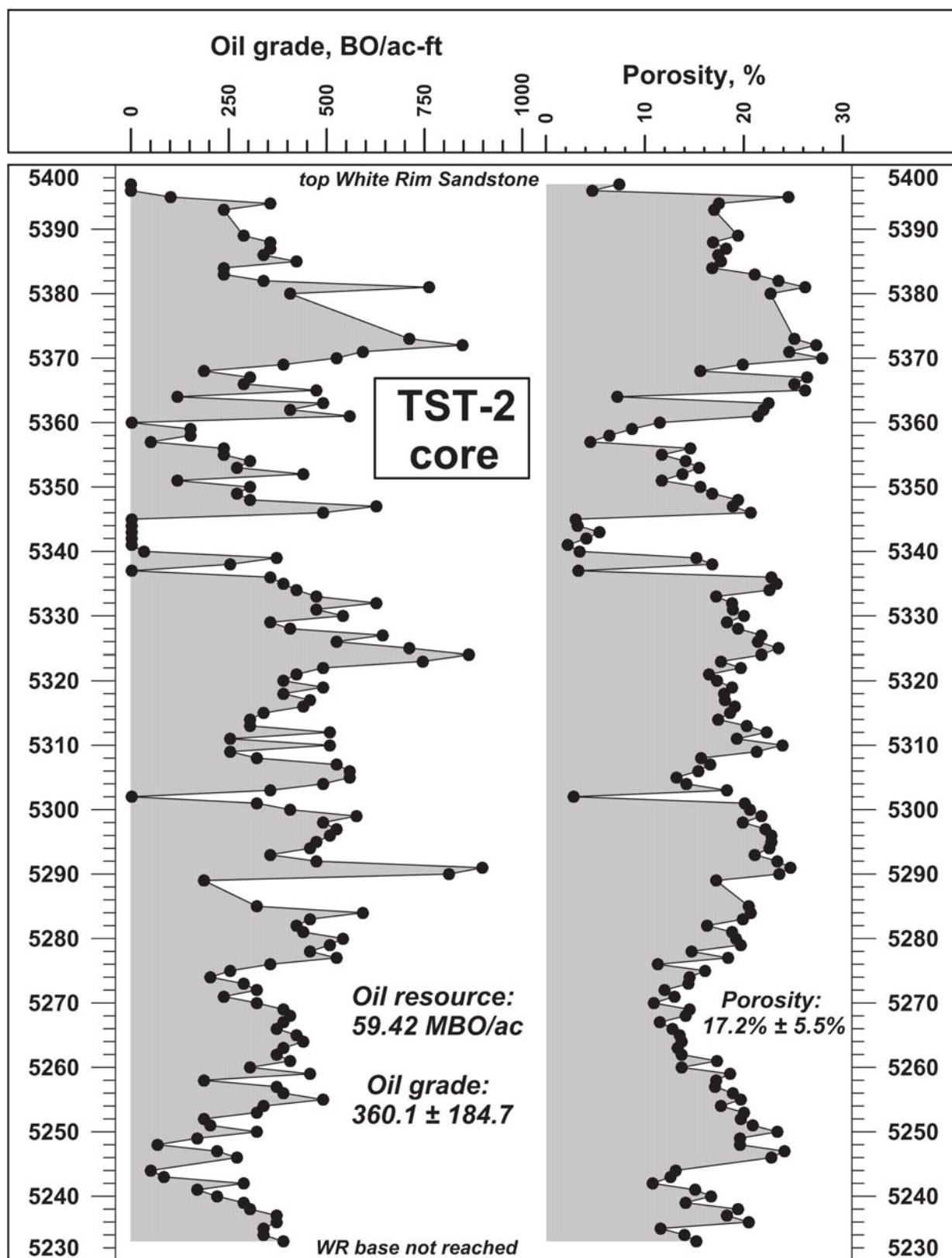


Figure 7. Vertical variations of oil grade and porosity of the White Rim Sandstone bitumen reservoir in core TST-2 (API 4301730163). Refer to figure 2 and table 2 for location of the core hole. Depths in the core are shown as elevations in feet msl. The average porosity after bitumen-extraction is $17.2 \pm 5.5\%$. The bitumen-impregnated interval is 165 feet thick. The oil grade is highly variable, averaging 360.1 ± 184.7 barrels of oil per acre-foot (BO/ac-ft). The bitumen resource measured in this core is 59.42 thousand barrels of oil (bitumen) per acre (MBO/ac). Data from Dana and others (1984).

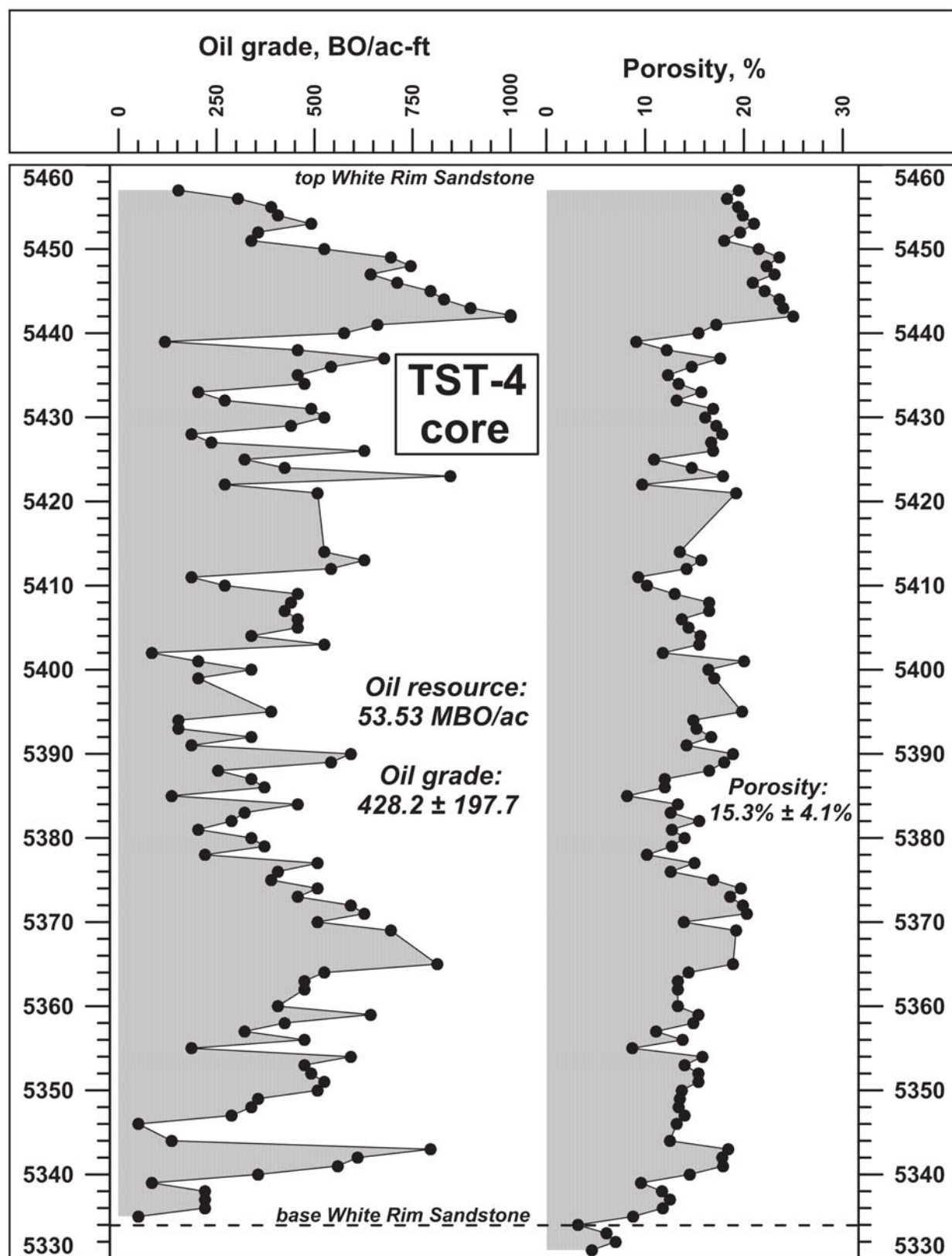


Figure 8. Vertical variations of oil grade and porosity of the White Rim Sandstone bitumen reservoir in core TST-4 (API 4301730144). Refer to figure 2 and table 2 for location of the core hole. Depths in the core are shown as elevations in feet msl. The average porosity after bitumen-extraction is $15.3 \pm 4.1\%$. The bitumen-impregnated interval is 125 ft thick. The oil grade is highly variable, averaging 428.2 ± 197.7 BO/ac-ft. The bitumen resource measured in this core is 53.53 MBO/ac. Data from Dana and others (1984).

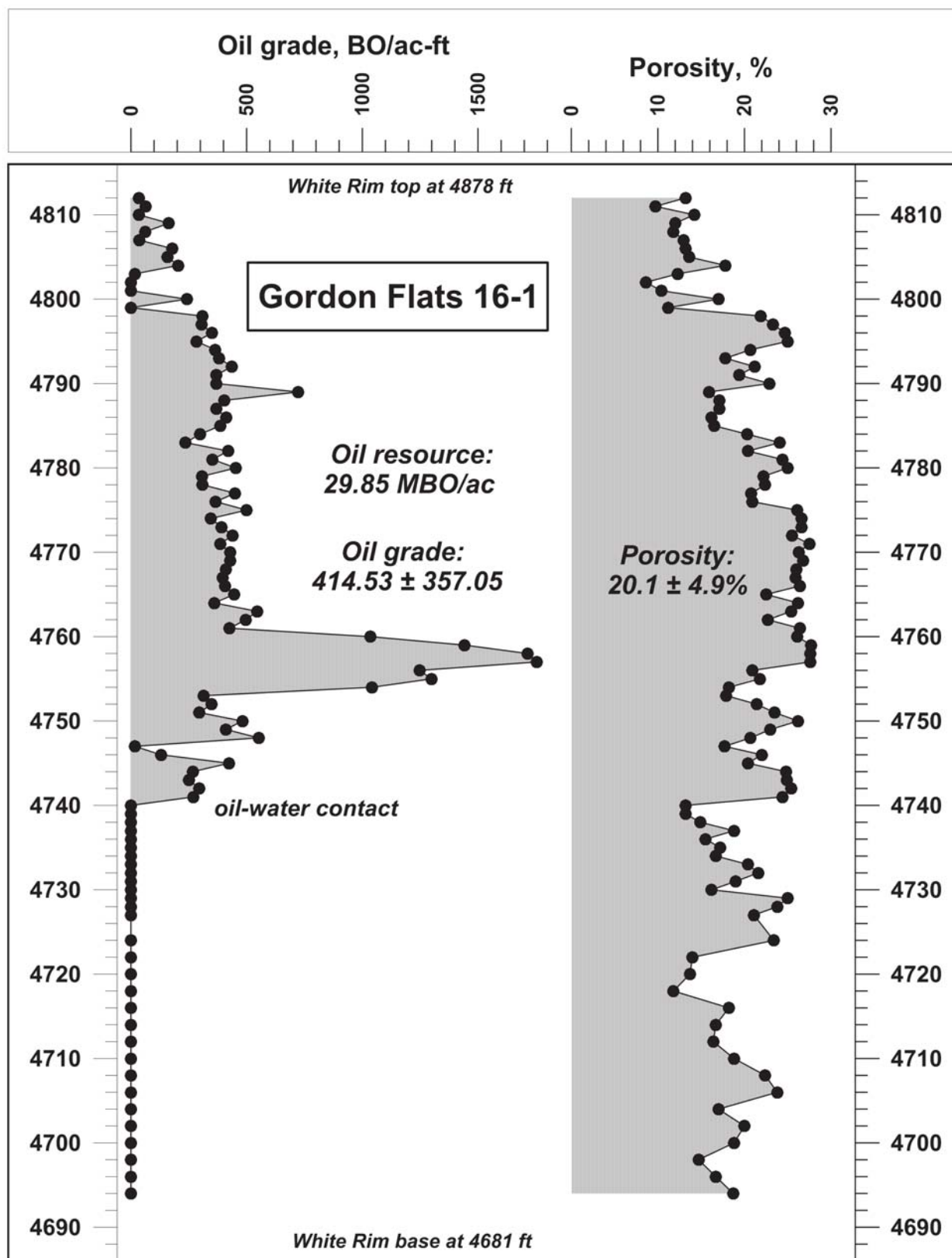


Figure 9. Vertical variations of oil grade and porosity of the White Rim Sandstone bitumen reservoir in Gordon Flats 16-1 core (API 4305530015). Refer to figure 2 and table 2 for location of the core hole. Depths in the core are shown as elevations in feet msl. The average porosity after bitumen-extraction is $20.1 \pm 4.9\%$. The bitumen-impregnated interval is 72 ft thick. The oil grade is highly variable, averaging 414.5 ± 357.1 BO/ac-ft. The bitumen resource measured in this core is 29.85 MBO/ac. The oil-water contact is at an elevation of 4,740 feet. Data from a well completion report in Utah DOGM files.

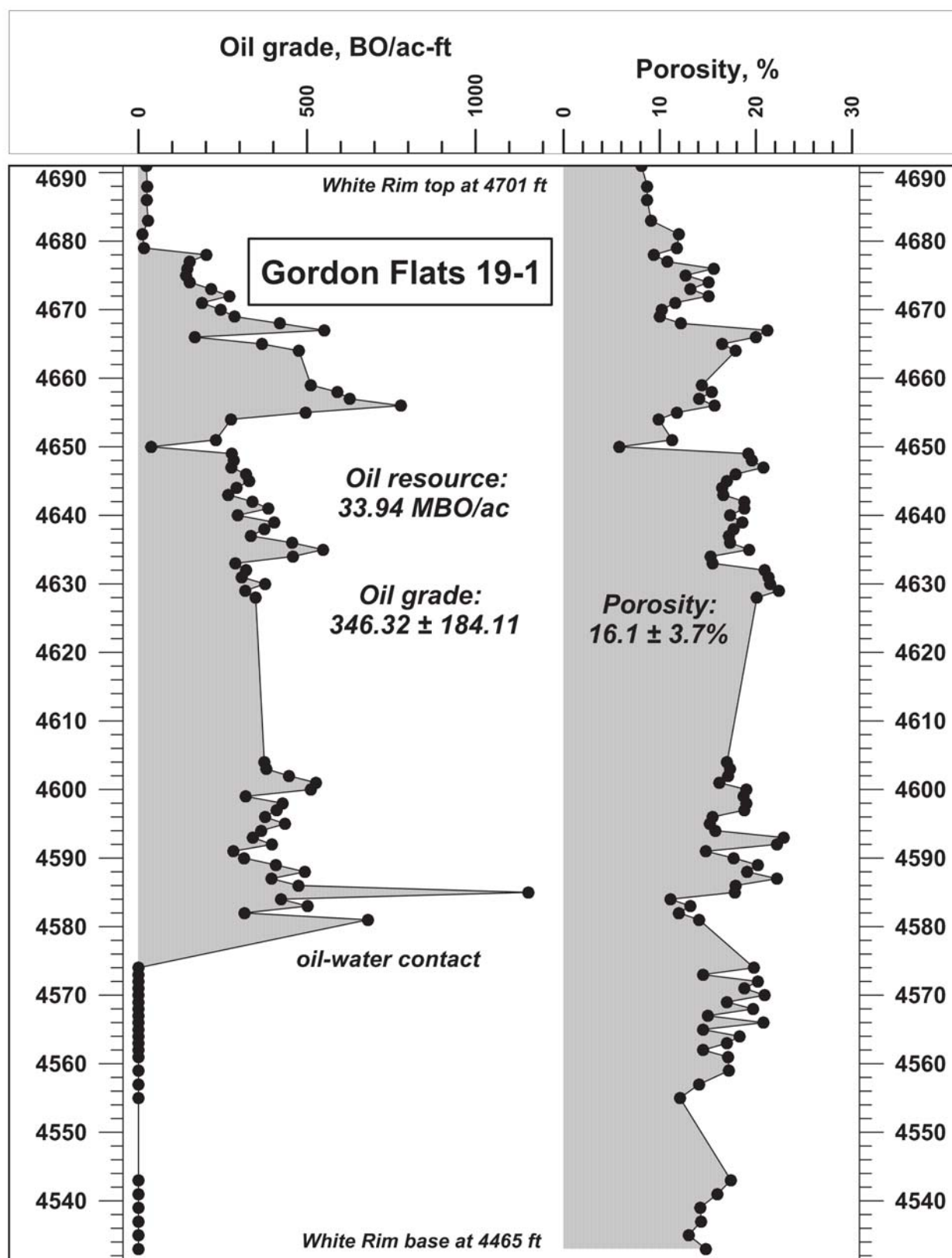


Figure 10. Vertical variations of oil grade and porosity of the White Rim Sandstone bitumen reservoir in Gordon Flats 19-1 core (API 4305530016). Refer to figure 2 and table 2 for location of the core hole. Depths in the core are shown as elevations in feet msl. The average porosity after bitumen-extraction is $16.1 \pm 3.7\%$. The bitumen-impregnated interval is 98 feet thick. The oil grade is highly variable, averaging 346.3 ± 184.1 BO/ac-ft. The bitumen resource measured in this core is 33.94 MBO/ac. The oil-water contact is at an elevation of 4,580-4,585 feet. Data from a well completion report in Utah DOGM files.

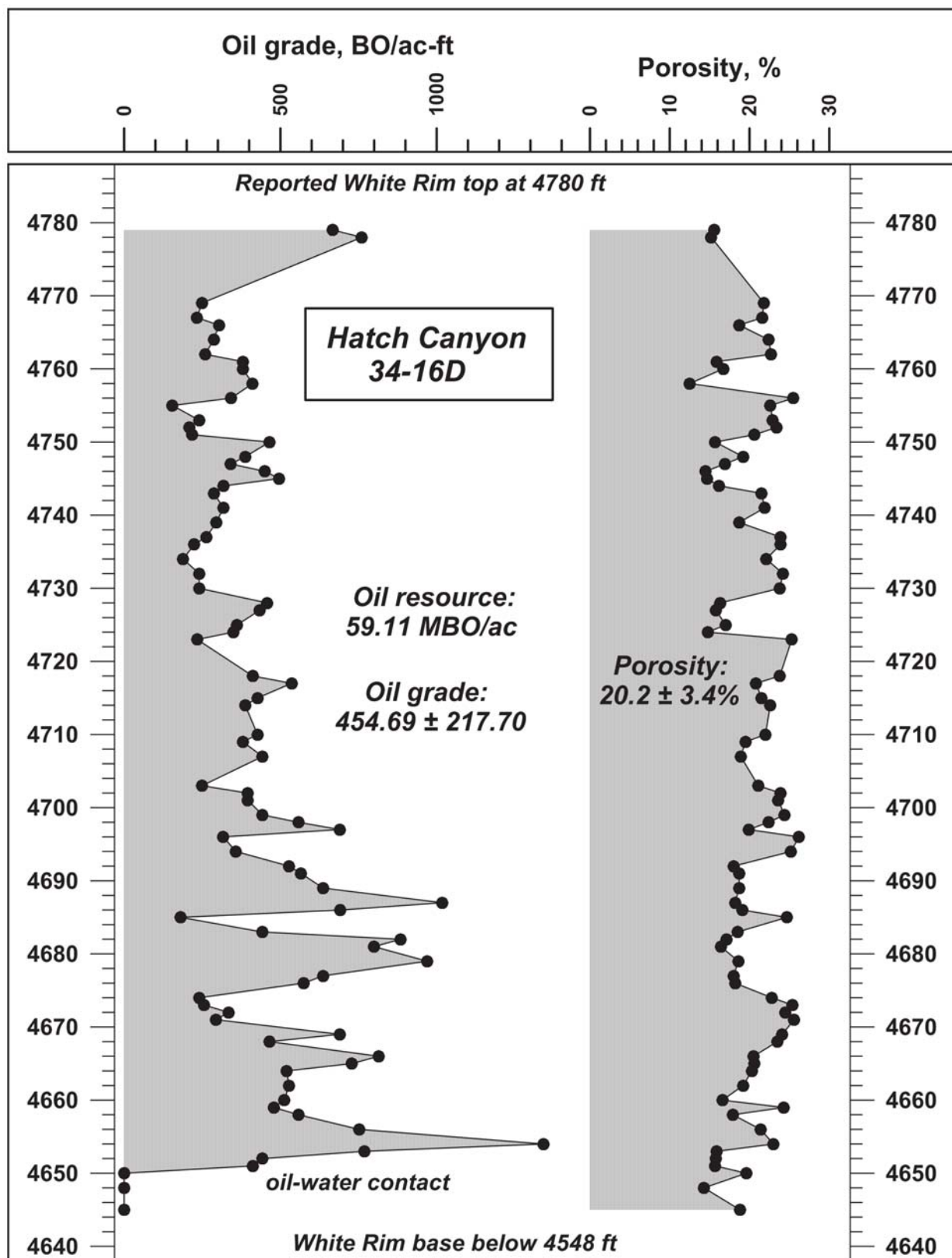


Figure 11: Vertical variations of oil grade and porosity of the White Rim Sandstone bitumen reservoir in Hatch Canyon 34-16D core (API 4301730109). Refer to figure 2 and table 1 for location of the core hole. Depths in the core are shown as elevations in feet msl. The average porosity after bitumen-extraction is 20.2 ± 3.4%. The bitumen-impregnated interval is 130 ft thick. The oil grade is highly variable, averaging 454.7 ± 217.7 BO/ac-ft. The bitumen resource measured in this core is 59.11 MBO/ac. The oil-water contact is at an elevation of 4,650 ft. Data from a well completion report in Utah DOGM files.

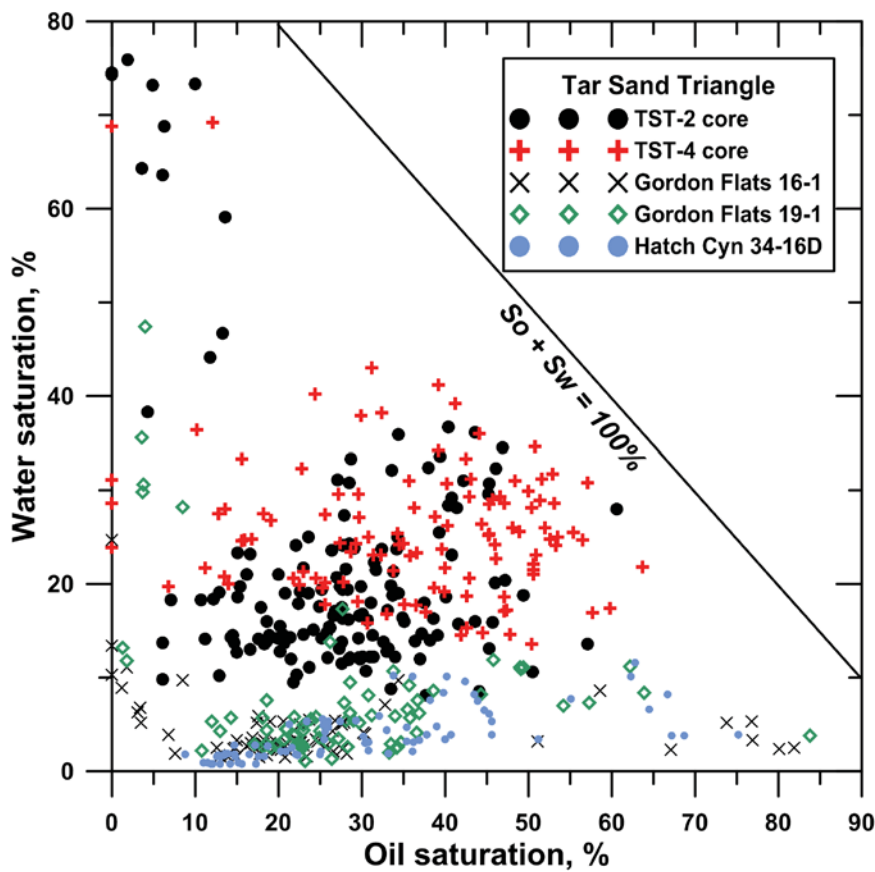


Figure 12: Fluid saturations measured in core samples of the bitumen-impregnated White Rim Sandstone. Note that none of the samples have oil and water saturations summing to 100%. The third fluid is air existing in the sandstone prior to coring, or introduced during handling and storage of the core. Data are from Dana and others (1984) and Utah DOGM files.

Figure 13: Relationship of oil grade, in units of barrels of oil per acre-feet (BO/ac-ft), and porosity of the White Rim Sandstone reservoir after the bitumen is extracted. This relationship is dependent on the oil saturation. Oil grade is determined from the weight of bitumen extracted, the parameter used to calculate oil saturation. Very few of the core samples have more than 60% oil saturation. This seriously limits the bitumen resource potential in the deposit.

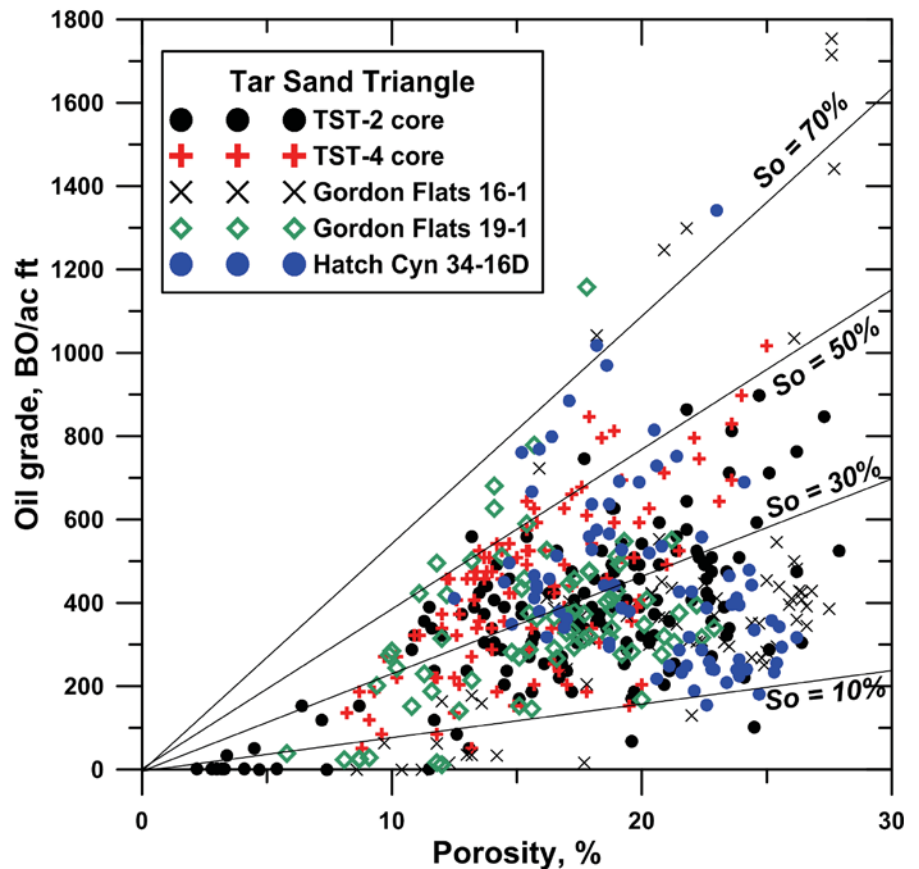


Table 3. Properties of the Tar Sand Triangle (TST) bitumen compared with those of Asphalt Ridge Northwest in Uintah Co., Utah (AR NW) and the Athabasca tar sands in northeast Alberta. Data from Bunger and others (1979).

Property	TST	AR NW	Athabasca
API gravity	11.1	14.4	11.6
H/C atomic ratio	1.44	1.64	1.48
Saturated HC (wt %)	25.7	21.6	27.8
Aromatic HC (wt %)	31.9	38.1	26.9
Asphaltenes (wt %)	26	6.3	16.4
Carbon residue (wt %)	21.6	3.5	16.1
Sulfur (wt %)	4.38	1.02	4.85
Nitrogen (wt %)	0.46	0.59	0.47
Va + Ni (ppm)	161	145	292
Dyn. viscosity (poise)	12,990	29,500	6,380
Heating value Btu/lb)	17,900	18,800	17,700

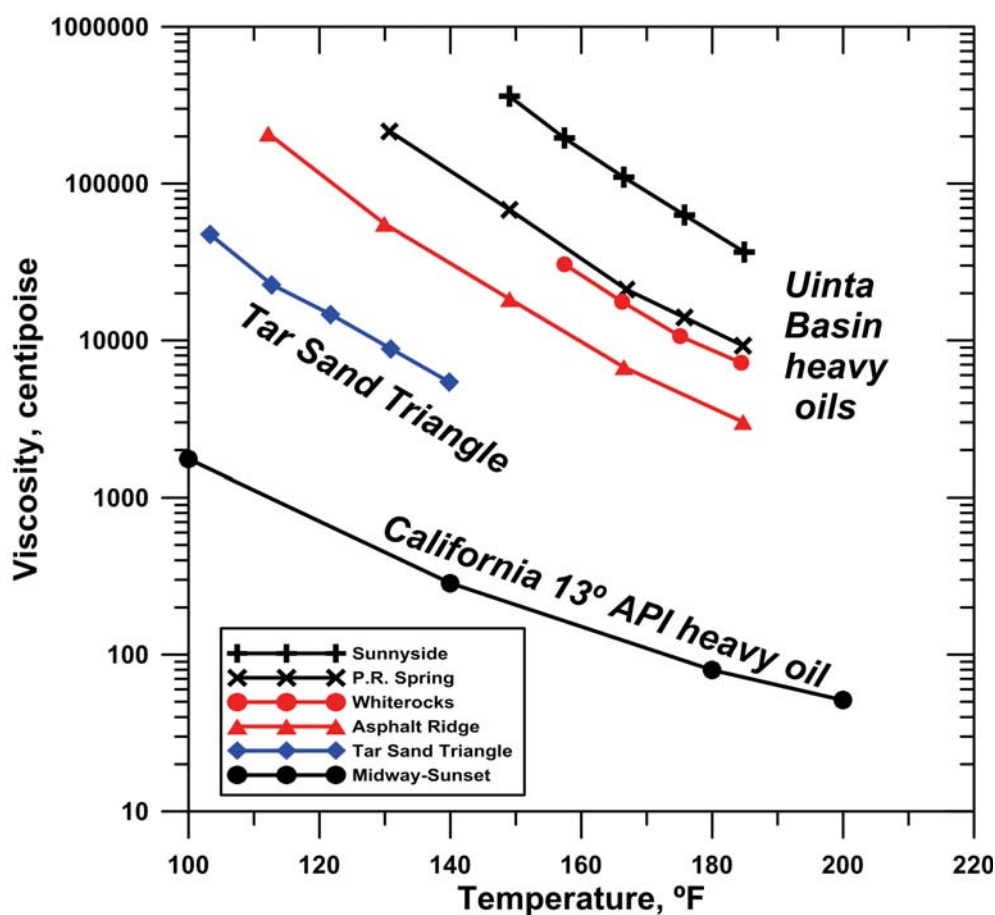


Figure 14: Viscosity profile of representative bitumen from the Tar Sand Triangle deposit relative to those of bitumen and heavy oils in various Uinta Basin deposits and a southern San Joaquin Basin (central California) oil produced in situ by steam stimulation. Data from Oblad and others (1987) and Schamel (2009).

ate source the low disterane concentrations and the predominance of norhopane over hopane, pristine-phytane ratios less than 1, the predominance of even alkanes, C35 > C34, and the high sulfur content.

The black calcareous shales of the Paradox Formation (Pennsylvanian) in the Paradox Basin and the

Manning Canyon-Doughnut Shale (Mississippian-Pennsylvanian) in western and north-central Utah are equally plausible source rocks for the Tar Sand Triangle bitumen. Both nearby source rock units are marine and contain interbedded limestone. The Paradox black “shale” is known to be the source for hydrocarbons in

the Paradox Basin (Nuccio and Condon, 1996). Huntoon and others (1999) propose the Delle Phosphatic Member of the Deseret Limestone (Mississippian) in western Utah being the Tar Sand Triangle source rock, but this unit is thin, discontinuous, and very distant. At present, the source of the oil remains uncertain.

Size of Total Bitumen Resources

Curiously, for all of the test drilling that was done in the Tar Sands Triangle deposit in the 1970s and early 1980s, only limited data in the public domain document the volume of oil in place. However, the published estimates are remarkably consistent. Campbell and Ritzma (1979) cite an average oil grade of 482.5 BO/ac ft based on 121 core samples from four Santa Fe Energy wells in the Gordon Flats area. Phillips (1987) reports an oil grade of 487.9 BO/ac ft from the Black Ledge (32S-16E-18) sector of the Tar Sand Triangle. The median grades in the TST-2 and TST-4 cores reported in Dana and others (1984) are 355.7 and 423.5 BO/ac ft, respectively. Were these values representative of the entire deposit, the average bitumen resource for the reported average 124.9 ft thick bitumen-impregnated reservoir would be in the range 53.36 to 73.49 MBO/ac.

To date, the most rigorous estimate of the bitumen resource is a study conducted by the Laramie Energy Technology Center in the early 1980s (Dana and others, 1984). Using public domain and proprietary well data, the thickness of the bitumen-impregnated White Rim Sandstone reservoir was compiled for 28 wells penetrating the full resource interval (table 1). Eight of the wells had adequate oil grade data from core samples to calculate a bitumen resource value for the well. These values ranged from a high of 244.0 MBO/ac for Gordon Flats 27-1 (section 27, T. 30 S., R. 16 E.) to a low of 29.0 MBO/ac in Saga.-Skyline State 1 (section 16, T. 30 S., R. 16 E.). Using the 28 bitumen-impregnated thickness values, a "resource-thickness" isopleth map was constructed. The eight bitumen resource values then were used to sketch out four concentric zones having the general shape of the isopleths map. The zones having areas of 26, 61, 55, and 56 square miles (sections) size are assigned average bitumen resource values of 110, 75, 35, and 10 MBO/ac, respectively. The total in-place bitumen resource for the deposit is calculated as 6.3 BBO. Although substantially less than the 12.5 to 16.0 BBO reported by Ritzma (1979), the 6.3 BBO estimated by Dana and others (1984) is based on optimistic projection of just a few unusually large well values of bitumen resource.

The approach taken in this paper expands on the database and methodology of Dana and others (1984), adding and revising the control wells and adopting a more rigorous analysis of the data. Three additional bitumen resource control wells were added to the original set of eight (table 1): Gordon Flat 16-1 (figure 9), Gordon Flat 19-1 (figure 10), and Hatch Canyon 34-16D (figure 11) substituting for the immediately adjacent "A" well in Dana and others (1984). Also, the resource-thickness and bitumen resource of the TST-2 and TST-4 wells were revised slightly to reflect the data presented in the logs of figures 7 and 8. Using just 14 oil grade values reported in Utah DOGM files for the Saga.-Skyline State 1 well, the bitumen resource for this well would be 10.92 MBO/ac, not the 29.0 MBO/ac reported in Dana and others (1984). In the absence of core analyses for the other wells, the data reported in Dana and others (1984) are accepted as the best available. It is not known to what extent the bitumen resource values are determined from close-spaced analysis of core or by other, less representative, methods.

The oil resource values are plotted against the resource-thickness for the 11 control wells in table 1 (figure 15). While most data points cluster, one well stands far apart from the others. This well is Gordon Flats 27-1 with a bitumen resource value of 244.0 MBO/ac, the equivalent to an oil grade of 1244.9 BO/ac ft. An immediately adjacent control well in section 27, T. 30 S., R. 16 E., Shell 9, has an even thicker resource-thickness, but bitumen resource of just 85.8 MBO/ac (344.7 BO/ac ft). A linear regression for all 11 control wells yields an average oil grade equivalence of 718.7 BO/ac ft and a correlation coefficient (R^2) of 0.42 (figure 15). Excluding this clear outlier, the linear regression for the remaining 10 wells has an average oil grade equivalence of 460.3 BO/ac ft, a value exceeding the upper range for all but a few of the control wells. The R^2 for this regression is 0.74. By excluding two additional wells, Gordon Flats Fed Unit 1 and Utah S-Govt 22-19, the linear regression for the remaining eight wells has an average oil grade equivalence of 386.0 BO/ac ft and an R^2 of 0.92. The linear regressions serve as the basis for three alternative bitumen resource models (table 4). Model A, the more conservative, is based on eight wells and has a very good correlation. Model B, a plausible alternative, is based on 10 wells. Model C is calculated, but it is considered improbable. The average and median bitumen resource values for the three models are shown in table 4.

The model values of bitumen resource are the

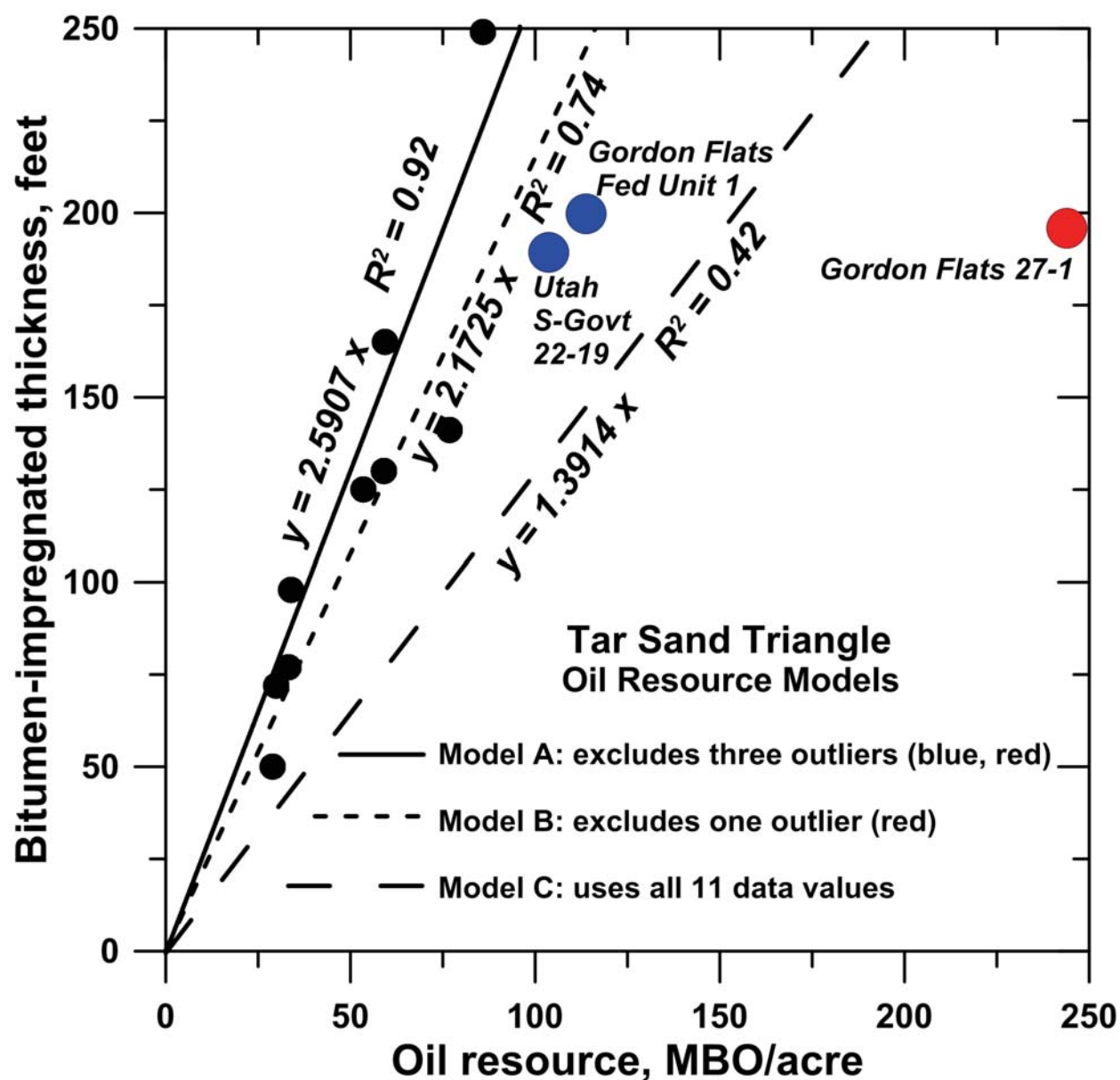


Figure 15. Crossplot of independently reported (Dana and others, 1984) bitumen resource vs. the thickness of the bitumen impregnated White Rim Sandstone reservoir in the test well. See tables 1 and 4 for the identity of the test wells. Oil resource models are developed from linear regressions of all or subsets of the resource-thickness data values. See text for a full discussion of the figure.

Table 4. Measured and model-predicted bitumen resource for wells in the Tar Sand Triangle deposit as reported in this paper and Dana and others (1984). The table presents the measured bitumen resource (MBO/ac) for the 11 wells used to do the resource modeling and the modeled resource values for all 28 wells. The modeled values are used to construct the resource isopleths maps in figures 16 and 17. The UTM NAD83 coordinates of the wells are from Utah DOGM online records, with the exception of Gordon Flats 27-1, which were digitized from a geo-referenced basemap.

Well	E-NAD83	N-NAD83	Impr. ft	MBO/ac	Model A	Model B	Model C
Saga.-Skyline State 1	571119	4228821	50	29.00	19.30	23.01	35.94
Gordon Flats 16-1	570615	4227888	72	29.85	27.79	33.14	51.75
Gordon Flats 19-1	567444	4226851	98	33.94	37.83	45.11	70.43
Skyline State 2	572215	4227473	89		34.35	40.97	63.96
Gordon Flats Fed Unit 1	572571	4227291	200	113.42	77.20	92.06	143.74
French Seep 1	572097	4225606	115		44.39	52.93	82.65
Robbers Roost 41-33	571800	4220756	185		71.41	85.16	132.96
TST-2	574171	4220679	165	59.42	63.69	75.95	118.59
Technology 14-36	555324	4212821	14		5.40	6.44	10.06
White Rim 44-4	561606	4221560	156		60.22	71.81	112.12
Magnum 23-8	559325	4219693	57		22.00	26.24	40.97
Garfield 44-15	563414	4217593	124		47.86	57.08	89.12
Winfield 21-15	565795	4218967	186		71.80	85.62	133.68
Remington 14-15	562051	4217670	169		65.23	77.79	121.46
State 34-16	561043	4217567	175		67.55	80.55	125.77
Utah S-Govt 22-19	557043	4216866	190	103.55	73.34	87.46	136.55
Monroe 22-20	558821	4217048	86		33.20	39.59	61.81
Cromwell 33-29	559265	4214533	60		23.16	27.62	43.12
TST-4	571830	4215518	125	53.53	48.25	57.54	89.84
State 11-2	563799	4212614	84		32.42	38.67	60.37
State 31-16	561043	4209398	26		10.04	11.97	18.69
USA Federal A-1	561132	4204497	80		30.88	36.82	57.50
Hatch Cyn U 34-16B	560806	4217593	178		68.71	81.93	127.93
Shell 7	567978	4228692	77	33.21	29.72	35.44	55.34
Shell 1 Sentinel	571237	4227473	161		62.15	74.11	115.71
Gordon Flats 27-1	573134	4225243	196	244.00	75.66	90.22	140.87
Shell 9	572630	4225891	249	85.83	96.11	114.61	178.96
Hatch Canyon 34-16D	561340	4217567	130	59.11	50.18	59.84	93.43
<i>Median:</i>			125	59.11	48.06	57.31	89.48
<i>Average</i>			124.9	76.80	48.21	57.49	89.76

products of the resource-thickness times the average oil grade equivalence associated with each model. This yields 28 values for each model. These values are gridded by Kriging on a 100 x 100 node array and contoured in Surfer 11™. The Model A bitumen resource isopleths are displayed on a township basemap in figure 16. The band of highest values trends north-east-southwest across the deposit as would be expected from the northwest dip of the White Rim Sandstone reservoir and its thinning to the southeast. However, the richest portions of the deposit lie within the Glen Canyon NRA. The comparable resource isopleths map for Model B (figure 17) shows an expansion of the richer portions of the deposit. In this model, there is a relatively narrow northeast-trending zone in which bitumen resource values are greater than 60 MBO/ac. A substantial portion of that area is west of the Glen Canyon NRA.

An alternative way of viewing the models is to compare the cumulative planar areas represented by successively lower bitumen resource thresholds (figure 18). The area of the deposit having a bitumen re-

source equal or greater than 10 MBO/ac is 180 sections (square miles) in size in Model A and 189 sections in Model B. The areas having bitumen resource equal or greater than 60 MBO/ac are 30.5 and 51.7 sections in Model A and B, respectively. The total in-place bitumen resource for the deposit in areas modeled as greater than 10 MBO/ac is 4255 MMBO in Model A and 5149 MMBO in Model B (figure 19).

The total in-place bitumen resource estimate may attract the attention of speculators, but is in most respects a meaningless number for an operator. If the resource is too lean for commercial exploitation, it can never become booked reserves and future produced hydrocarbons. With no experience actually producing the Tar Sand Triangle bitumen, it is not presently productive to speculate on the level of reservoir richness where commercially-viable production is possible. Consequently, the in-place bitumen resource is indicated for specific MBO/ac thresholds (figure 19). For instance, at the 60 MBO/ac richness threshold, the in-place resource is 1301 MMBO in Model A and 2459 MMBO in Model B. Note that for threshold val-

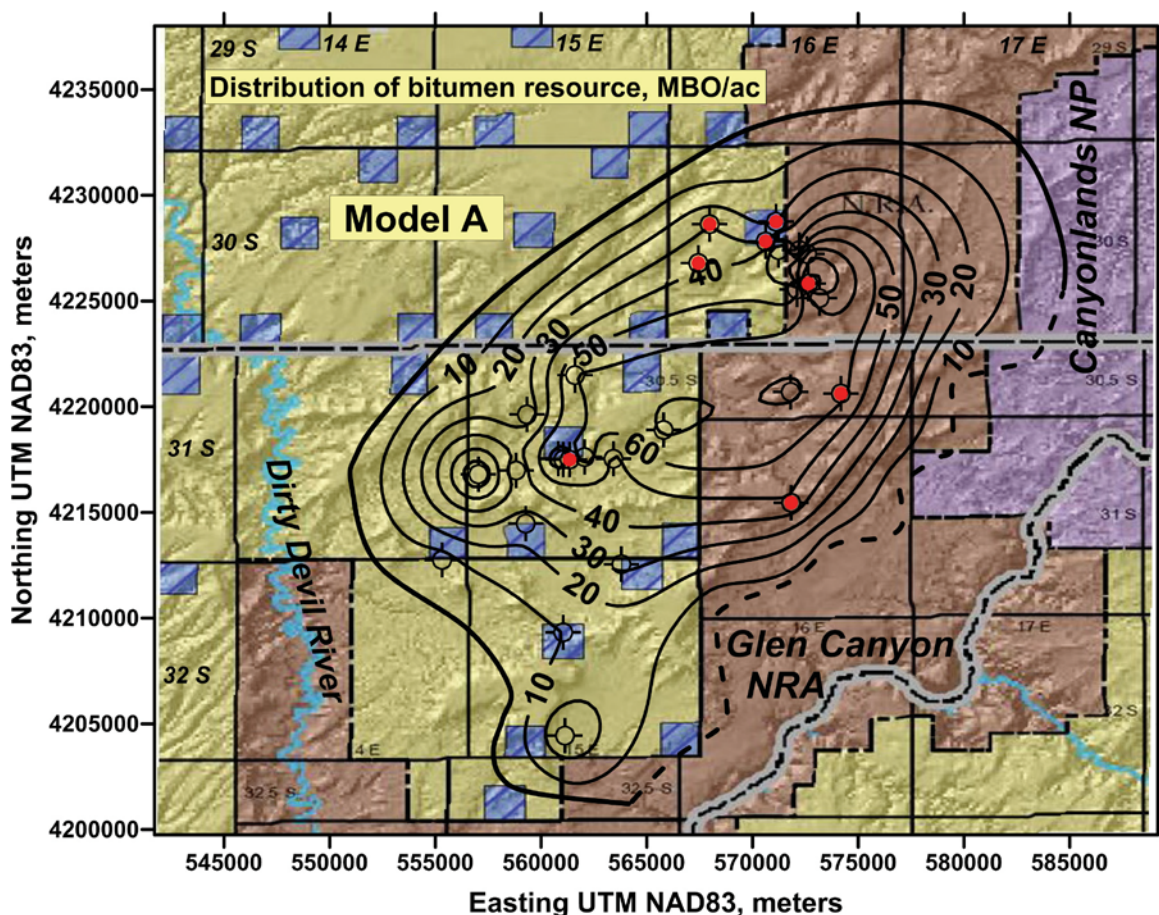


Figure 16. Township and range map showing the distribution of bitumen resource (MBO/ac) within the Tar Sand Triangle deposit as calculated from Model A. The contour interval is 10 MBO/ac. Note that the region with bitumen resource values greater than 60 MBO/ac is primarily restricted to the Glen Canyon NRA.

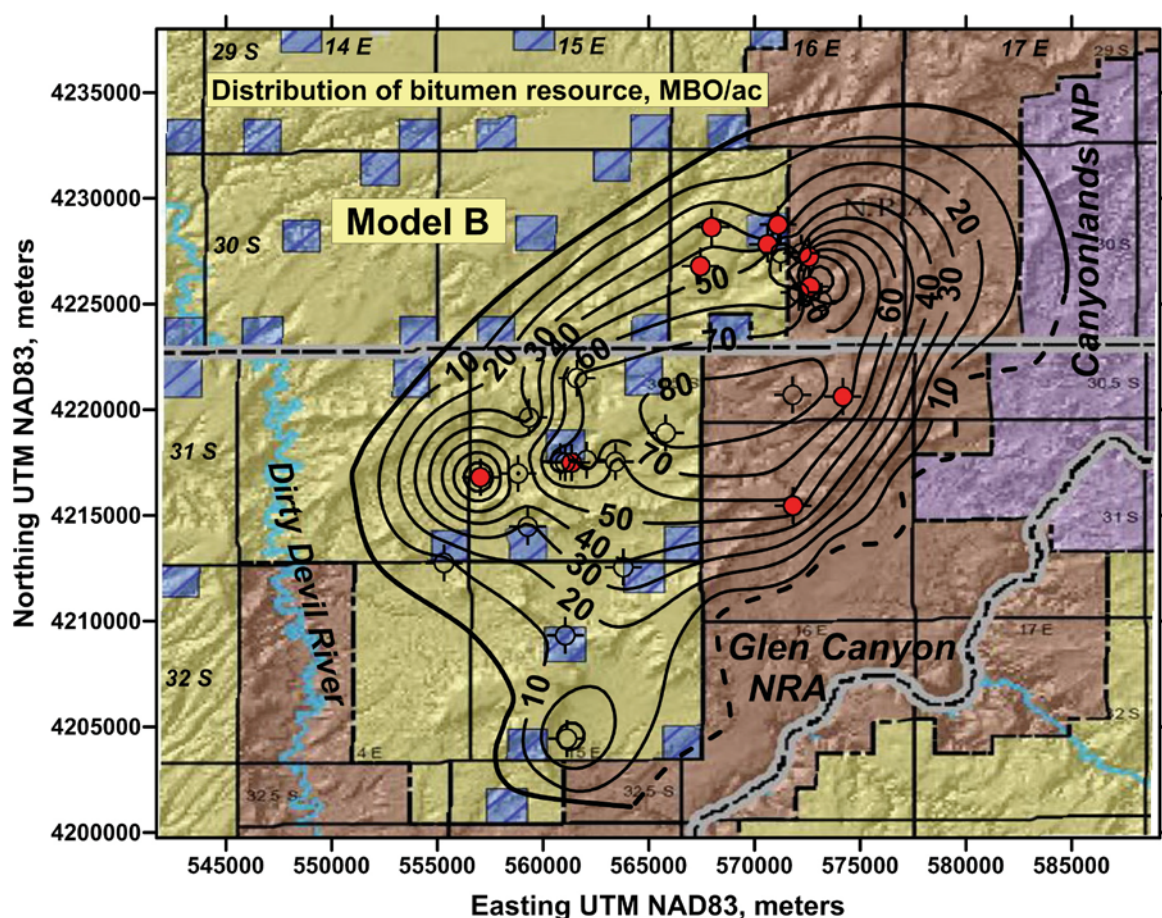


Figure 17. Township and range map showing the distribution of bitumen resource (MBO/ac) within the Tar Sand Triangle deposit as calculated from Model B. The contour interval is 10 MBO/ac. In this model, there is a relatively narrow northeast-trending band in which the resource values are greater than 60 MBO/ac. A substantial portion of that area is west of the Glen Canyon NRA.

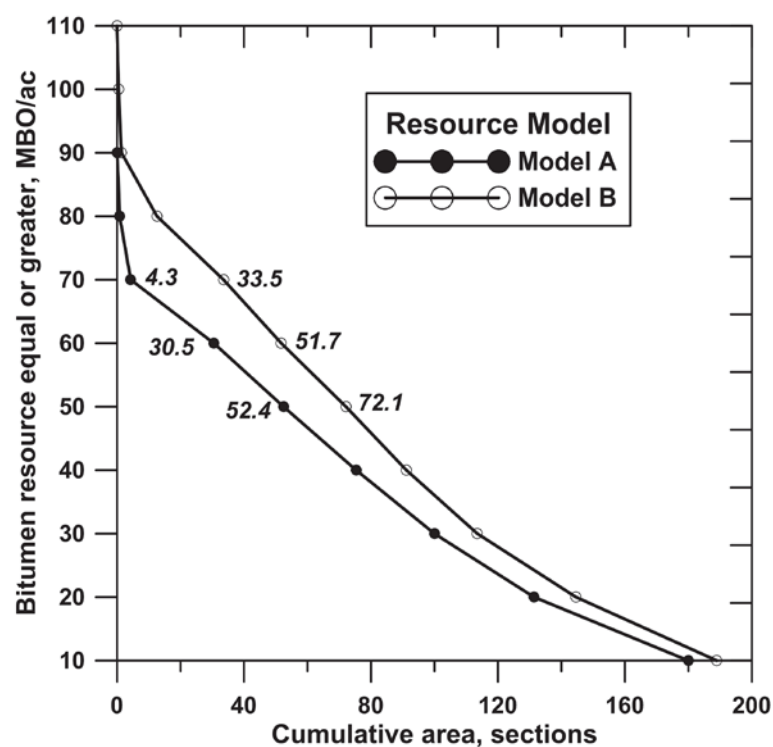


Figure 18. Crossplot of cumulative area in sections (square miles) as a function of bitumen resource values equal or greater than a given value. For instance, for Model A, 30.5 square miles (sections) have bitumen resource values equal to or greater than 60 MBO/ac, whereas for Model B that area is 51.7 sections. The planar areas for the range of bitumen resource levels are determined from the contouring grid using a tool in Surfer 11™.

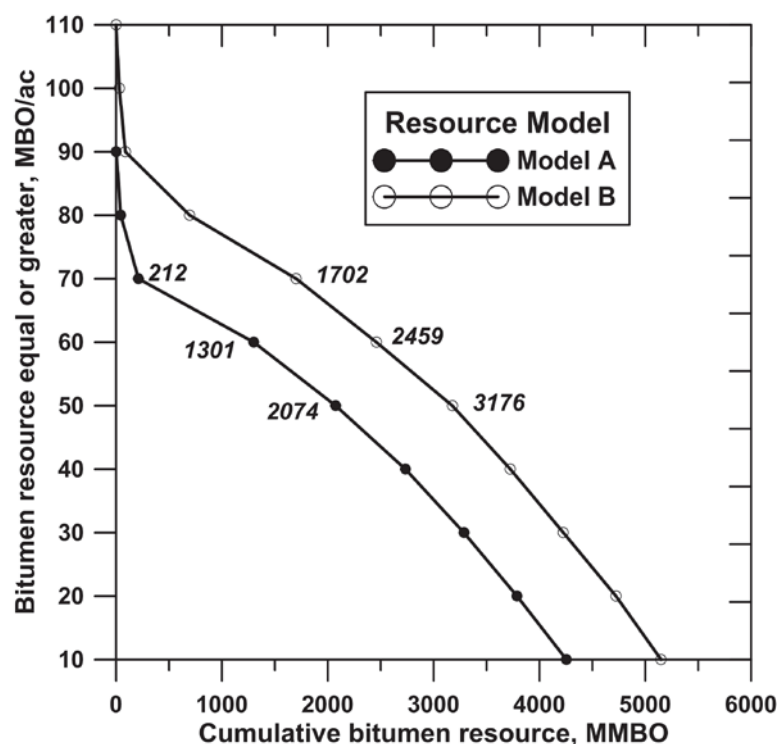


Figure 19. Crossplot of the total cumulative bitumen resource in millions of barrels for bitumen resource thresholds greater or equal to given values. The cumulative planar areas shown in Figure 18 are used to calculate the total cumulative bitumen resource at specific resource thresholds within the deposit. For instance, Model A predicts 1.3 BBO at a threshold equal or richer than 60 MBO/ac, whereas Model B predicts 2.5 BBO at that same threshold of resource concentration.

ues greater than 70 to 80 MBO/ac, the total bitumen resource diminishes rapidly, reflecting the contraction of the area (figure 18) having these larger bitumen grades.

Although the bitumen resource estimates are developed by a rigorous, established analytical procedure, the limited number of control wells diminishes their level of confidence. Twenty-eight wells across an area of approximately 200 square miles is a data density of just one well per 7.2 square miles. Additionally, the majority of the control wells are clustered on the Gordon Flats, on the southeast of The Big Ridge, and in North Hatch Canyon (figure 16), reducing the effective data density.

Discussion

The bitumen in the Tar Sand Triangle deposit is reseroured in a several-hundred-foot-thick eolian sandstone, the White Rim Sandstone (Lower Permian). Across an area of 84 square miles, the thickness of the bitumen-impregnated sandstone exceeds 100 ft. The strata are gently dipping and otherwise unstructured. Average porosity and permeability of the sandstone reservoir are in the range of 15-20% and 200-500 md, respectively. The oil saturation is con-

sistently low, averaging 30-35%. The bitumen has an API gravity less than 8° at the surface and just over 10° in core. It has a high asphaltene and sulfur content, and it is saturate-poor. Although very viscous at reservoir temperatures, the bitumen is a few orders of magnitude less viscous than the Uinta Basin heavy oils. This study estimates a total in-place bitumen resource between 4.7 to 5.6 BBO in a deposit exceeding 200 square miles in size.

The principal operational issue for the Tar Sand Triangle is accessibility. Fortunately, a very large part of the most resource-rich portion of the deposit can be reached by an existing road network that follows the ridge that links the top of the Orange Cliffs with The Big Ridge (figure 3). This road-accessible high plateau provides a suitable platform for reaching into the central parts of the deposit. Directional drilling can extend the exploitable parts of the deposit for some distance beyond the rims of the plateau segments. Some older wells have been spudded below the canyon rim, so at least in the past, the intermediate Moenkopi bench has been reached by roads off the higher plateau. This bench in the North Hatch Canyon immediately south of The Big Ridge is traversed by road #730.

Despite the high aridity of the region, water is

available in the nearby rivers and subsurface aquifers (Glassett and Glassett, 1976; U.S. Department of Interior, 1984). There are an estimated 9.8 million ac-ft in the Colorado, Green, and Dirty Devil Rivers; 210 million ac-ft of groundwater in the Navajo, Wingate, and Coconino Sandstone aquifers of the lower Dirty Devil River basin; and 25 million ac-ft maximum storage in Lake Powell (Pyper, 1983). However, all water in the area is fully appropriated by existing rights, so water required for in situ recovery or mining extraction would have to be purchased or leased.

A large area in which the bitumen-impregnated interval is in excess of 100 ft thick, an apparently homogeneous, relatively porous reservoir, and relatively low viscosity of the oil all would suggest that steam-based thermal in situ recovery methods could be successful in the Tar Sand Triangle (Holmes and others, 1986; Schamel, 2009). However, the close proximity to a national park and a national recreation area, as well as limited access to water resources, would favor a recovery process that has little water demand, has a very small surface footprint, and generates minimal air pollutants. THAI™ (toe-to-heel air injection) in situ combustion (Xia and others, 2002) might be applied very effectively in this deposit, particularly as the deposit has generally low oil saturation. Solvent extraction is an alternative technology, and electrical heating might prove effective on the intermediate benches where the deposit is relatively close to the surface. The overall remoteness of the deposit, limited water resources (Pyper, 1983), lack of essential infrastructure, large distance to oil refineries, and generally poor quality of the bitumen could delay its development for many decades. In-reservoir upgrading made possible with in situ combustion might solve the last of these impediments.

ACKNOWLEDGMENTS

This paper greatly expands on a chapter describing the Tar Sands Triangle bitumen deposit in the Utah Geological Survey Open-File Report 551, *Strategies for in situ recovery of Utah's heavy oil and bitumen resources* (Schamel, 2009). That report was prepared, in part, with a UGS research contract managed by Craig Morgan. Wally Gwynn and Gene Van Dyke provided valuable assistance to earlier investigations of the Tar Sand Triangle bitumen deposit enabling the open-file report and this paper. Bryce Tripp, Thomas Morris, David Tabot, and Andrew Rupke are gratefully acknowledged for their careful and thorough reviews of the paper.

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