

PETROLEUM GEOLOGY OF COVENANT OIL FIELD, CENTRAL UTAH THRUST BELT

by

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ABSTRACT

After over 50 years of unsuccessful exploration in the central Utah thrust belt, or “Hingeline,” the 2004 discovery of Covenant oil field proved that this region contains the right components (trap, reservoir, seal, source, and migration history) for large accumulations of oil. Covenant has produced over 3.1 million barrels (500,000 m³) of oil and no gas, an average of 5400 barrels (860 m³) of oil per day, from the eolian Jurassic Navajo Sandstone. The original oil in place is estimated at 100 million barrels (15.9 million m³), with an estimated recovery factor of 40% to 50%.

The Covenant trap is an elongate, symmetric, northeast-trending anticline with nearly 800 feet (270 m) of structural closure and bounded on the east by a series of splay thrusts. The structure formed above a series of splay thrusts in a passive roof duplex along the “blind” Gunnison-Salina thrust and west of a frontal triangle zone within the Jurassic Arapien Shale. The Jurassic Navajo Sandstone and overlying Twin Creek Limestone are repeated due to an east-dipping back-thrust detachment within the structure. Only the Navajo in the hanging wall of the back thrust (and possibly the Twin Creek) is productive. The Navajo Sandstone reservoir is effectively sealed by mudstone and evaporite beds in the overlying Jurassic Twin Creek Limestone and Arapien Shale. Oil analysis indicates a probable Carboniferous source—oil derived and migrated from rocks within the Utah Hingeline region.

Cores from the Navajo Sandstone display a variety of eolian facies (dune, interdune, lake/playa, fluvial/wadi), fracturing, and minor faults, which in combination, create reservoir heterogeneity. Reservoir sandstone is 97% frosted quartz grains (bimodal grain size), with some quartz overgrowths and illite. The net reservoir thickness is 424 feet (129 m) over a 960-acre (390 ha) area. Porosity averages 12%; permeability is ≤100 millidarcies. The drive mechanism is a strong water drive; water saturation is 38%. A thorough understanding of all the components that created Covenant field will determine whether it is a harbinger of additional, large oil discoveries in this vast, under-explored region.

INTRODUCTION

The central Utah thrust belt (figure 1) has seen petroleum exploration for the past 50 years because explorationists viewed the geology as a natural extension of successful plays in the Utah-Wyoming-Idaho salient of the Sevier thrust belt to the north. Early efforts tested anticlines identified from surface mapping and seismic reflection data. During the late 1970s to early 1980s companies drilled thrust-belt-style structures in the wake of the 1975 Pineview discovery in northern Utah. Although these efforts failed, companies confirmed that the area is similar in structural style and timing, and reservoir types, to the productive thrust belt to the north. The lack of Cretaceous hydrocarbon source beds below the thrust structures seemingly was to blame for the earlier exploration failures; however, oil and gas shows were commonly noted in Mississippian, Permian, Triassic, and Jurassic rocks. The 2004 discovery of Covenant field (figure 1) by Michigan-based Wolverine Gas & Oil Corporation (herein referred to as Wolverine) changed the oil development potential in the central Utah thrust belt from hypothetical to proven and showed that

the region contains all the right components (trap, reservoir, seal, source, and migration history) for large accumulations of oil.

Covenant field is located about 2 miles (3 km) southeast of the small town of Sigurd in Sevier County, Utah, along Utah Highway 24 (figure 1). Cumulative production is over 3.1 million barrels (bbls [500,000 m³]) of oil, averaging nearly 170,000 bbls (27,000 m³) per month (Utah Division of Oil, Gas and Mining, 2006). The producing oil reservoir is the eolian Jurassic Navajo Sandstone (figure 2), which therefore is the primary focus of this field description, including stratigraphy, depositional environments, and reservoir characteristics. We also briefly describe the structural geology and trap mechanism, hydrocarbon source, completion practices, and potential petroleum reserves of Covenant field.

STRUCTURE

Regional Geologic Setting

The central Utah thrust belt is part of the Sevier thrust belt that trends through the entire state, also referred to

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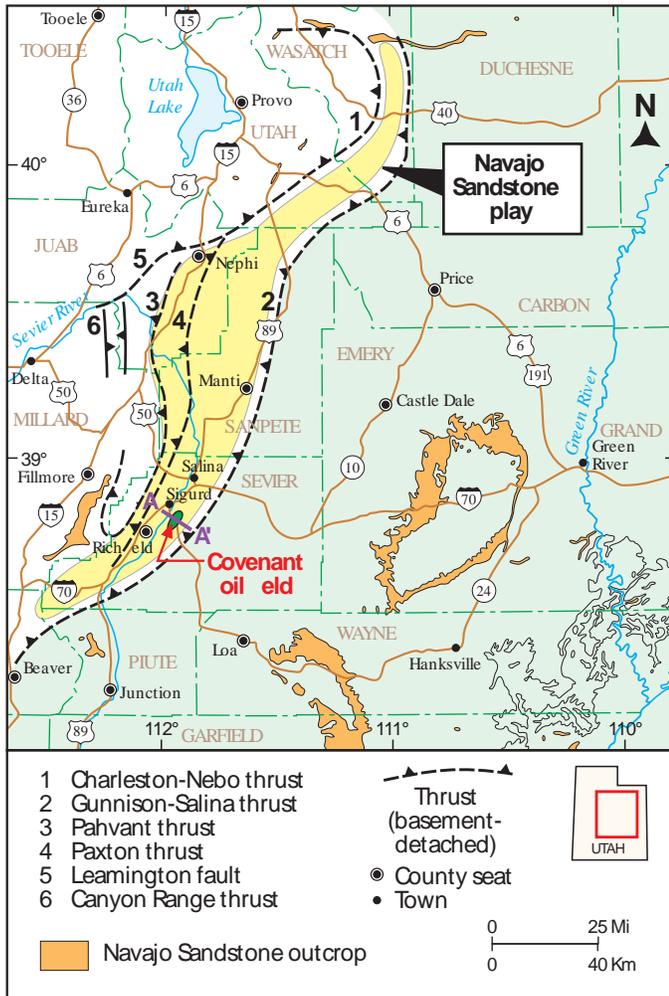


Figure 1. Location of Covenant oil field, uplifts, and selected thrust systems in the central Utah thrust belt province. Numbers and sawteeth are on the hanging wall of the corresponding thrust system. Shaded area shows the potential extent of the Jurassic Navajo Sandstone “Hingeline” play in the central Utah thrust belt as defined by Sprinkel and Chidsey (2006). Modified from Hintze (1980), Sprinkel and Chidsey (1993), and Peterson (2001). Cross section A-A' shown on figure 4.

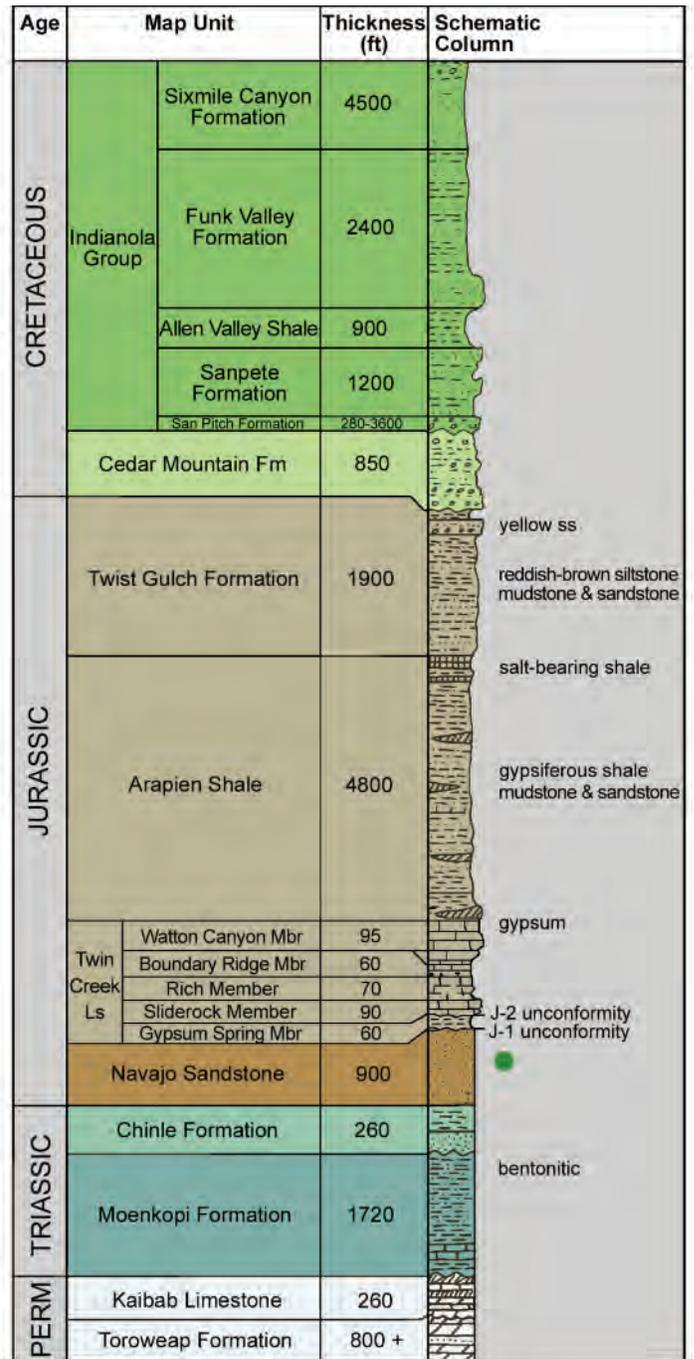


Figure 2. Stratigraphic column of a portion of the upper Paleozoic and Mesozoic section in central Utah. Modified from Hintze (1993).

by many geologists as “the Hingeline.” It is loosely defined as the portion of the thrust belt south of the Uinta Mountains of northeastern Utah, trending through central Utah to the Marysvale–Wah Wah volcanic complex of south-central Utah. Classic papers describing and interpreting the geology of the Hingeline region include those of Eardley (1939), Kay (1951), Armstrong (1968), and Stokes (1976). Throughout this area’s geologic history, the Hingeline has marked a pronounced boundary between different geologic terranes and processes. From Late Proterozoic to Triassic time, it marked the boundary between a very thick succession of sediments deposited in western Utah and a thin succession deposited in eastern Utah. During Cretaceous and early Tertiary time, the Hingeline coincided with and influenced thrusts at the eastern edge of the Sevier orogenic belt. Today in central Utah it marks the general boundary between the Basin and Range and Colorado Plateau physiographic provinces.

In reality, the Hingeline is an area rather than a line, and includes geologic features common in both the Basin and Range and Colorado Plateau physiographic provinces: Sevier orogenic thrust faults, basement-cored Late Cretaceous–Oligocene Laramide uplifts (plateaus and the Wasatch monocline), and Miocene to Holocene normal faults. Paleozoic rocks thicken westward across the Hingeline area from thin cratonic deposits, whereas the Upper Cretaceous section includes thick synorogenic deposits reflecting proximity of the Sevier orogenic belt to the west. Several depositional environments during the Mississippian and Permian produced organic-rich deposits capable of generating hydrocarbons.

An extensional fault system, including the high-angle, basement-involved “ancient Ephraim fault,” was located in central Utah during the Middle Jurassic (Moulton, 1976; Schelling and others, 2005). In the Late Jurassic, Utah was mostly a forebulge high (Willis, 1999). In central Utah, large-scale thrust sheets were emplaced during latest Jurassic through early Tertiary time by compression of the actively evolving foreland basin (Schelling and others, 2005; DeCelles and Coogan, 2006). The youngest evidence of thrust faulting is 40 million years old in central Utah (Lawton, 1985; DeCelles and others, 1995; Lawton and others, 1997; Willis, 1999; Constenius and others, 2003; DeCelles, 2004; DeCelles and Coogan, 2006). Thrusting extended westward for more than 100 miles (160 km).

Major thrust faults in central Utah (from west to east) include the Canyon Range thrust, Leamington fault, Pahvant thrust (Royse, 1993), Paxton thrust, Charleston-Nebo thrust system, and the Gunnison-Salina thrust (Villien and Kligfield, 1986; Schelling and others, this volume) (figure 1). These thrust faults represent detached, thin-skinned, compressional styles of deformation, with eastward combined movement of greater than 90 miles (140 km) for the Canyon Range and Pahvant thrusts (DeCelles and Coogan, 2006). Easternmost thrust systems moved less than western thrust systems and are generally younger; the Canyon Range thrust was

emplaced during latest Jurassic–Early Cretaceous time, the Pahvant thrust was emplaced in Albian time, the Paxton thrust was emplaced in Santonian time, and the Gunnison-Salina thrust was active from late Campanian through early Paleocene time (DeCelles and Coogan, 2006). The Ephraim fault and other Middle Jurassic faults may have also experienced additional Laramide-age (Maastrichtian through Eocene) movement.

Surface traces of the thrust faults generally trend in a north-northeast direction. Some of the thrust faults do not extend to the surface, and the term “blind” thrust is applied to buried faults like the Gunnison-Salina thrust. The Pahvant, Paxton, and Gunnison-Salina thrust systems contain Lower Cambrian through Cretaceous strata. Jurassic shale, mudstone, and evaporite beds serve as the main glide planes along the hanging-wall flats of these thrust systems.

The leading edges of the thrust faults are listric in form and structurally complex. They include numerous thrust splays, back thrusts, duplex systems (particularly in eastern thrusts), fault-propagation folds (fault-bend folds), and ramp anticlines such as the huge fold that makes up most of Mount Nebo (near the city of Nephi) along the Charleston-Nebo thrust system where overturned upper Paleozoic and attenuated Triassic and Jurassic rocks are spectacularly displayed. The duplex systems are similar to those found in the Alberta Foothills in the eastern Canadian Rocky Mountains (Dahlstrom, 1970); these types of features are not present in the Utah-Wyoming-Idaho salient of the thrust belt to the north.

Central Utah thrust plates, like the Canyon Range thrust plate, are as much as 36,000 feet (12,000 m) thick (DeCelles and Coogan, 2006), although eastern plates tend to be thinner. The eastern plates also deformed into smaller-amplitude fault-propagation folds and ramp anticlines than did western plates (Willis, 1999). Middle Jurassic extensional faults, such as the Ephraim and similar faults in the region, determined the position of these ramp anticlines and associated duplexes along thrust systems by acting as buttresses to plate movement (Schelling and others, 2005). However, a blind, low-angle thrust fault continues east of the Ephraim fault within the Jurassic Arapien Shale–Carmel Formation under the Wasatch Plateau (Neuhauser, 1988). Smaller imbricate faults from the decollement form fault-propagation/fault-bend folds, which are some of the producing anticlines on the Wasatch Plateau.

Neogene reactivated movement along many thrust ramps, splays, and associated back thrusts formed listric normal faults. Other normal faults related to basin-and-range extension dissected thrust plates into additional, compartmentalized blocks (Schelling and others, 2005). The Wasatch monocline and other monoclinical structures formed at this time. Some local ductile deformation of Jurassic evaporites further complicated the structural picture of the region (Witkind, 1982).

Internal deformation within large-scale thrust plates includes frontal and lateral duplex zones. The deforma-

tion front along the leading edge of these major thrusts, particularly the Paxton and Gunnison-Salina thrusts, includes complex back thrusting, tectonic-wedge formation, triangle zones, and passive-roof duplexing (Schelling and others, 2005). Fault-propagation/fault-bend folds and low-amplitude anticlines in both the hanging walls and footwalls of thrusts associated with these features form multiple structural traps—the targets of the Covenant discovery. These features are obscured by complex surface geology that includes (1) major folds, (2) angular unconformities, (3) Oligocene volcanic rocks, (4) basin-and-range (Miocene–Holocene) listric(?) normal faulting, and (5) local diapirism. Jurassic extensional faults, including the Ephraim fault, may be the key to hydrocarbon migration pathways and to locating antiformal stacks that contain traps along thrusts (Schelling and others, 2005; Strickland and others, 2005).

Covenant Field

Covenant field (figure 1) is located along the east flank of the Sanpete–Sevier Valley antiform, where the Gunnison-Salina thrust is primarily a bedding-plane fault developed in weak mudstone and evaporite beds of the Arapien Shale. In this area, thrust imbricates or imbricate fans above the Gunnison-Salina thrust and antiformal stacks of horses forming a duplex below the thrust create multiple potential drilling targets (Villien and Kligfield, 1986). The Ephraim fault east of these features served to buttress movement of the Gunnison-Salina plate, thus causing thrust imbrication.

The Kings Meadow Ranches No. 17-1 discovery well (SE $\frac{1}{4}$ NW $\frac{1}{4}$ section 17, T. 23 S., R. 1 W., Salt Lake Base Line and Meridian [SLBL&M]) was drilled in 2004 updip from two abandoned wells located about 2 miles (3 km) to the north: the Standard Oil of California Sigurd Unit No. 1 (NE $\frac{1}{4}$ SE $\frac{1}{4}$ section 32, T. 22 S., R. 1 W., SLBL&M) drilled in 1957, and the Chevron USA Salina Unit No. 1 (NE $\frac{1}{4}$ NE $\frac{1}{4}$ section 33, T. 22 S., R. 1 W., SLBL&M) drilled in 1980. The Navajo Sandstone was encountered at sub-sea-level depths of -3390 feet (-1033 m) and -2973 feet (-906 m), respectively, in these wells. The dipmeter in the Salina Unit No. 1 well showed 16° structural dip to the northwest in the Navajo. This dip, combined with seismic data, indicated a structural high to the south. The Kings Meadow Ranches No. 17-1 well penetrated the Navajo at a sub-sea-level depth of -94 feet (-29 m) (figure 3).

The Covenant field trap is an elongate, symmetric, northeast-trending, fault-propagation/fault-bend anticline with nearly 800 feet (270 m) of structural closure with a 450-foot (150 m) oil column (figure 3). The oil-charged Navajo reservoir covers about 960 acres (390 ha). The structure formed above a series of splay thrusts in a passive roof duplex along the Gunnison-Salina thrust and west of a frontal triangle zone within the Arapien Shale (figure 4), west of the Ephraim fault (not shown on figure 4). The Covenant structure extends to greater depths

above the Gunnison-Salina thrust fault (figure 4) with untested potential in the Permian Kaibab Limestone (which has produced oil for more than 40 years at Upper Valley field 70 miles [110 km] south in the Kaiparowits basin [Garfield County]). As of mid-2007, Wolverine plans to test the Kaibab with a 14,500-foot (4420 m) infield wildcat, the Federal No. 17-8 well (NE $\frac{1}{4}$ SW $\frac{1}{4}$ section 17, T. 23 S., R. 1 W., SLBL&M).

The Navajo Sandstone and Twin Creek Limestone are repeated below the producing interval due to an east-dipping back-thrust detachment within the structure; a salt water disposal well drilled northwest of the field encountered a repeated Arapien section but penetrated only the Navajo in the footwall of the back thrust (figure 4). This back thrust forms a hanging-wall cutoff along the west flank and north-plunging nose of the fold. Only the Navajo in the hanging wall of the back thrust (and possibly the Twin Creek, based on mudlog/cutting shows and a drill-stem test in the Federal No. 17-2 well) is productive. Other small, minor faults likely divide the Covenant reservoir into segments. As possible evidence of these faults, the sub-sea-level value of the oil/water contact varies in field wells from -588 to -704 feet (-179 to -215 m). In addition, fractures and deformation bands (Davis, 1999) (open and bitumen-filled), brecciation, and slickensides (representing a fault or shear zone along a deformation band) are observed in cores (figures 5 and 6).

The principal regional seal for the Navajo producing zones consists of salt, gypsum, and mudstone in the Jurassic Arapien Shale (figure 2). Mudstone and argillaceous limestone intervals within the Jurassic Twin Creek Limestone may serve as additional seals. Interdunal shale and mudstone within the Navajo Sandstone, and splay and back-thrust faults may act as local seals, barriers, or baffles to fluid flow (fault gouge is cemented with silica [figure 5C]).

STRATIGRAPHY

Thickness, Age, and Regional Correlation

The Navajo Sandstone is 740 to 1700 feet (230–520 m) thick in the area (Hintze, 1993) and has a characteristic geophysical log response (figure 7). The Navajo is Early Jurassic (Toarcian) in age and forms many of the spectacular canyons in the parks of southern Utah (Zion National Park and Glen Canyon National Recreation Area, for example). It is also exposed east and west of Covenant field (figure 1). The Navajo is stratigraphically equivalent to part of the highly productive Nugget Sandstone in the thrust belt fields of northern Utah and southwestern Wyoming (Chidsey, 1993). At Covenant field, the Navajo is divided into lower, middle, and upper units based on core and geophysical log analysis (figures 6 and 7). The lower and upper units have subtle but distinct characteristic geophysical log responses; the middle unit has a high gamma-ray profile recognized on other logs regionally. The depth below ground surface to the

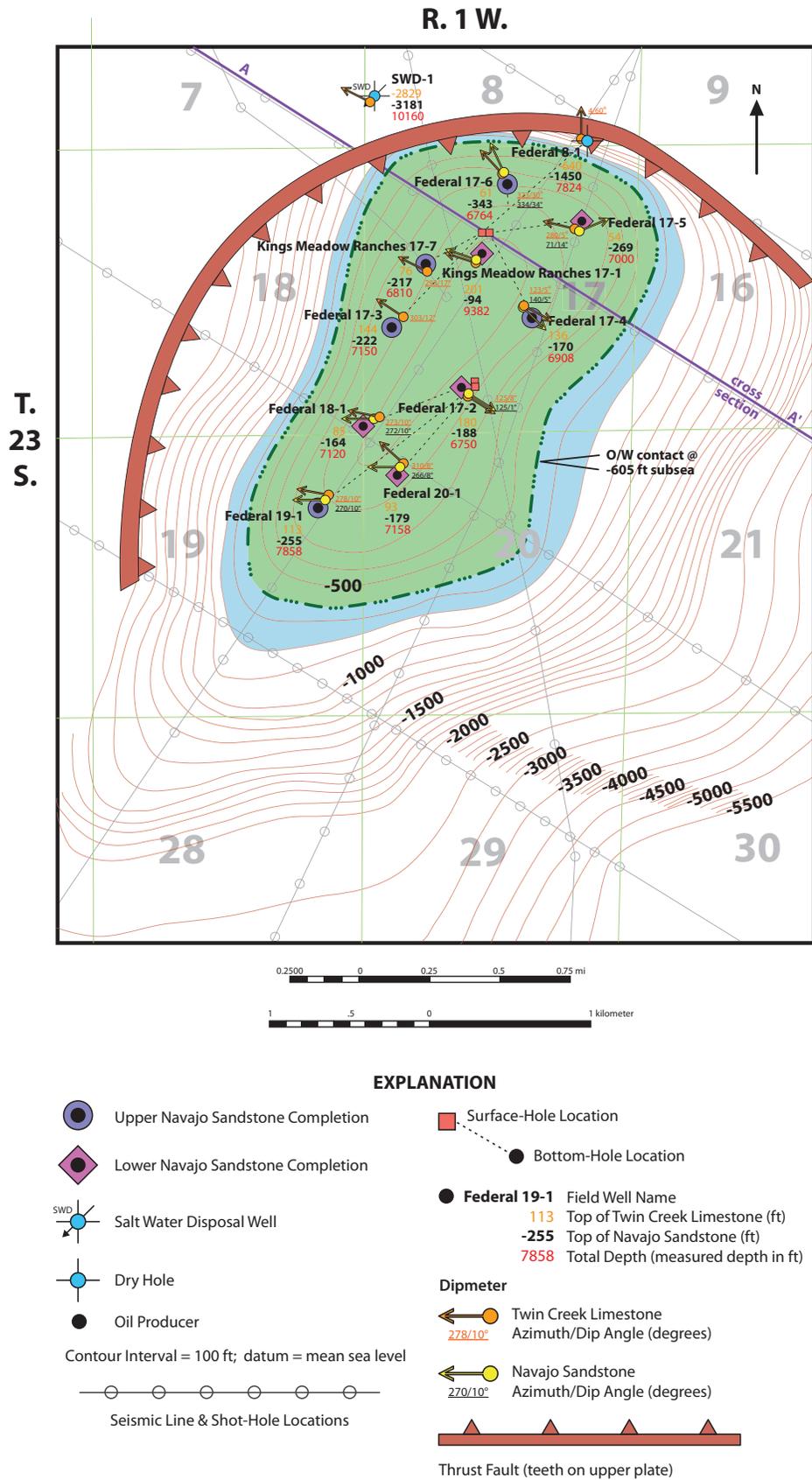
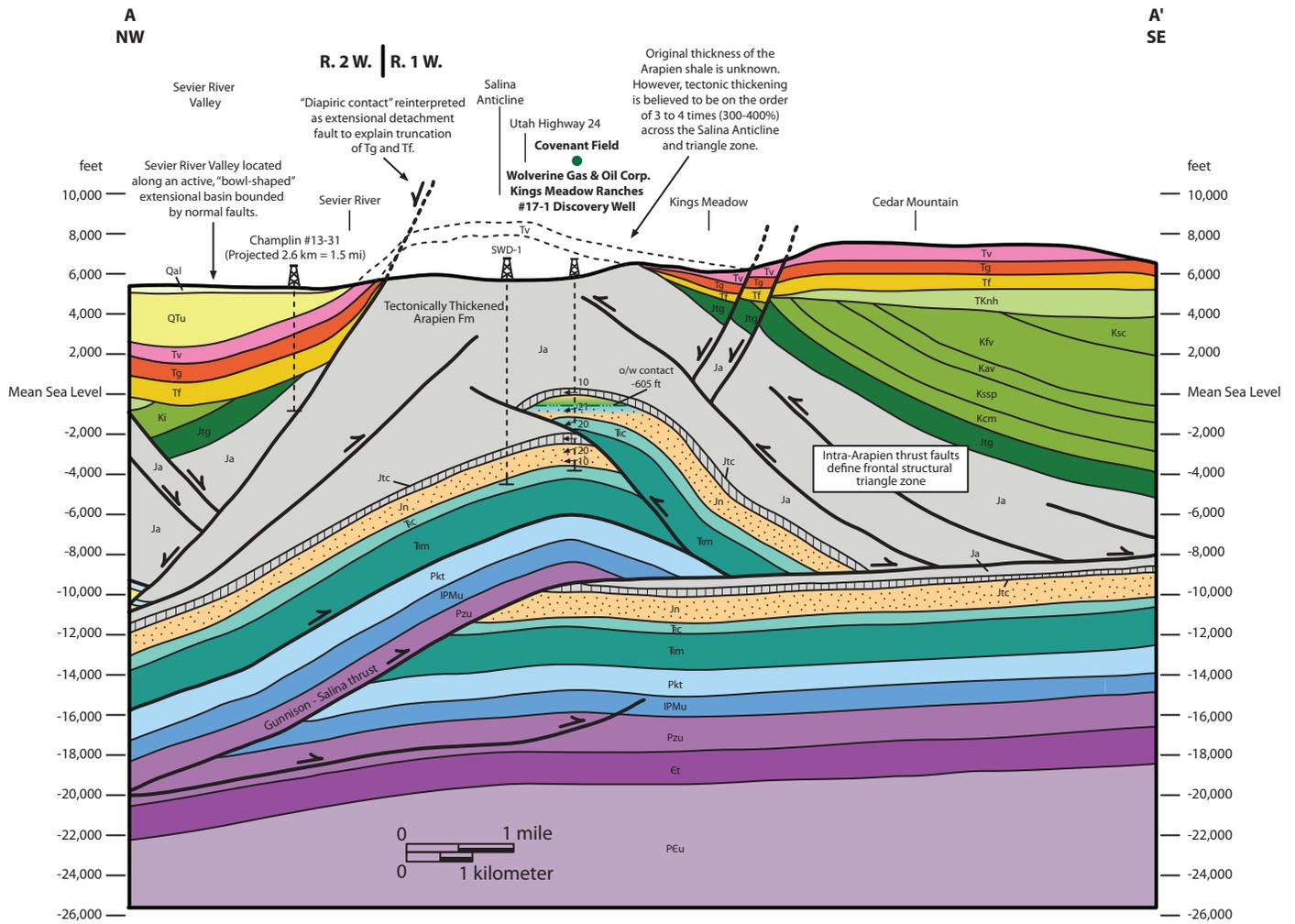


Figure 3. Structure contour map of the top of the Navajo Sandstone, Covenant field, based on subsurface well control and seismic data. Contour interval = 100 feet, datum = mean sea level. Line of cross section A-A', which extends beyond the edges of this figure, is shown on figures 1 and 4.



EXPLANATION

Qal Quaternary alluvium/colluvium	Jtg Jurassic Twist Gulch Formation
QTu Quaternary/Tertiary undivided alluvial fan, lacustrine, tuffs, etc.	Ja Jurassic Arapien Shale
Tv Tertiary volcanics	Jtc Jurassic Twin Creek Limestone
Tg Tertiary Green River Formation	Jn Jurassic Navajo Sandstone
Tf Tertiary Flagstaff Limestone	Trc Triassic Chinle Formation
TKnh Tertiary/Cretaceous North Horn Formation	Trm Triassic Moenkopi Formation
Ki Cretaceous Indianola Group	Pkt Permian Kaibab Limestone & Toroweap Formation
Ksc Cretaceous Sixmile Canyon Formation	IPMu Pennsylvanian/Mississippian undivided
Kfv Cretaceous Funk Valley Formation	Pzu Lower Paleozoic undivided
Kav Cretaceous Allen Valley Shale	Et Cambrian Tintic Quartzite
Kssp Cretaceous Sanpete & San Pitch Formations	PEu Precambrian undivided
Kcm Cretaceous Cedar Mountain Formation	

Figure 4. Northwest-southeast structural cross section through Covenant field. Note small back thrust through the anticline that results in a repeated Navajo Sandstone section. Line of cross section shown on figures 1 and 3.

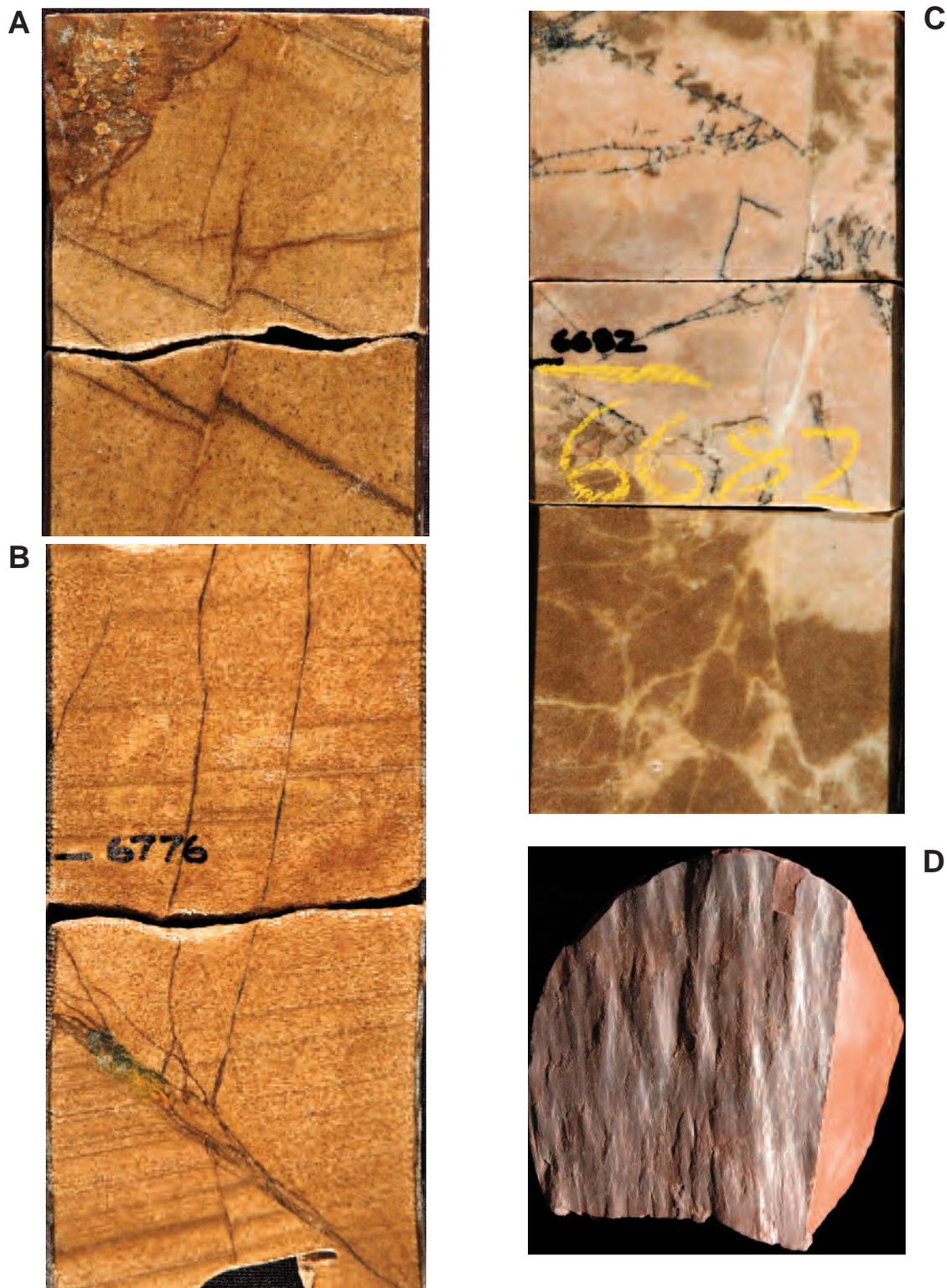


Figure 5. Fractures and deformation within the Navajo Sandstone from the Wolverine Federal No. 17-3 well. (A) Bitumen-filled fractures with slight offsets; slabbed core from 6660 feet (measured depth [MD]). (B) Swarm of intense microfractures or deformation band as well as bitumen-filled vertical fractures; slabbed core from 6776 feet (MD). (C) Silica-impregnated brecciation and fault gouge; slabbed core from 6682 feet (MD). (D) Slickensides representing a fault or shear zone along a deformation band; slabbed core from 6756 feet (MD).

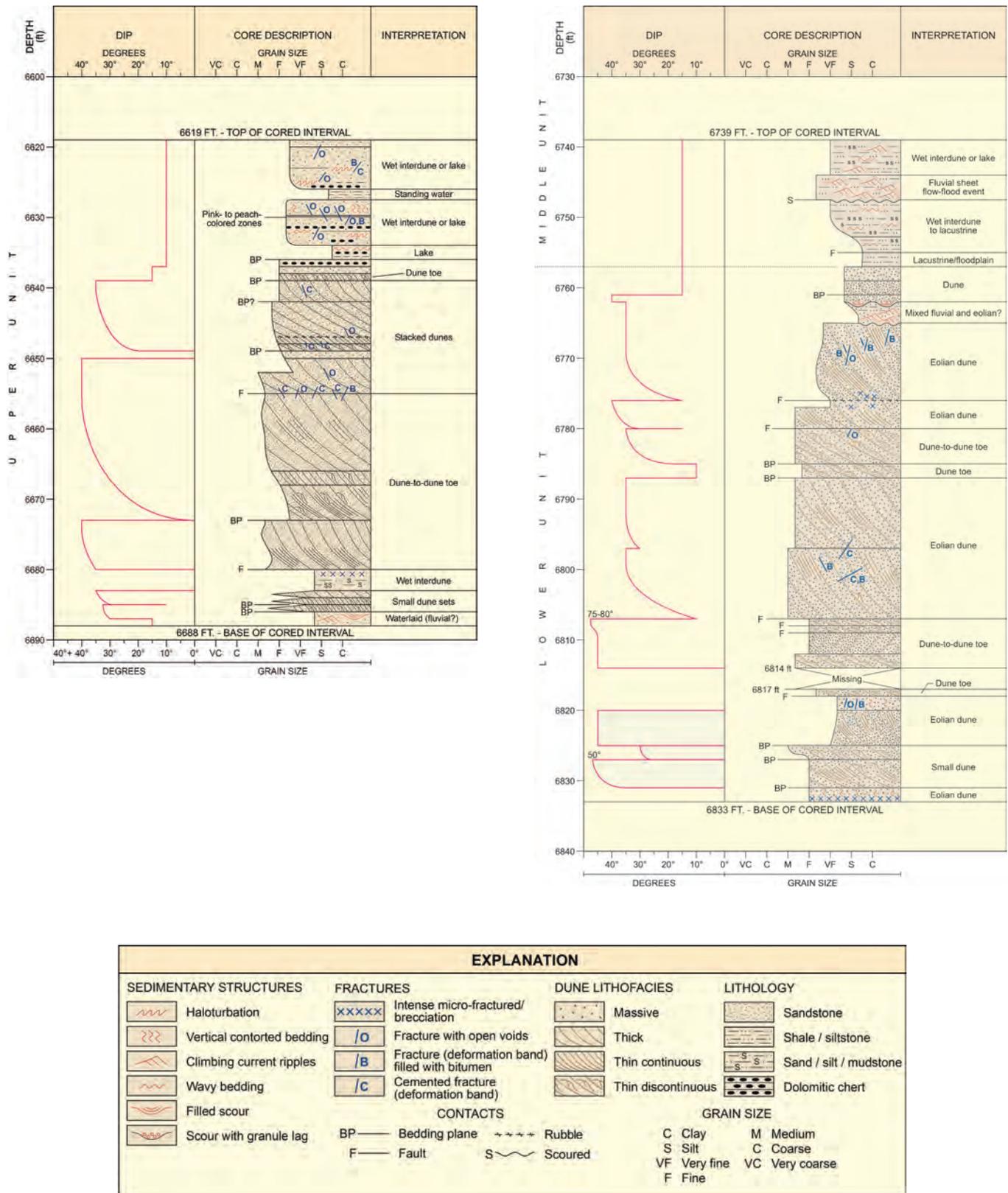


Figure 6. Core description (measured depth) of the Navajo Sandstone from the Wolverine Federal No. 17-3 well, Covenant field.

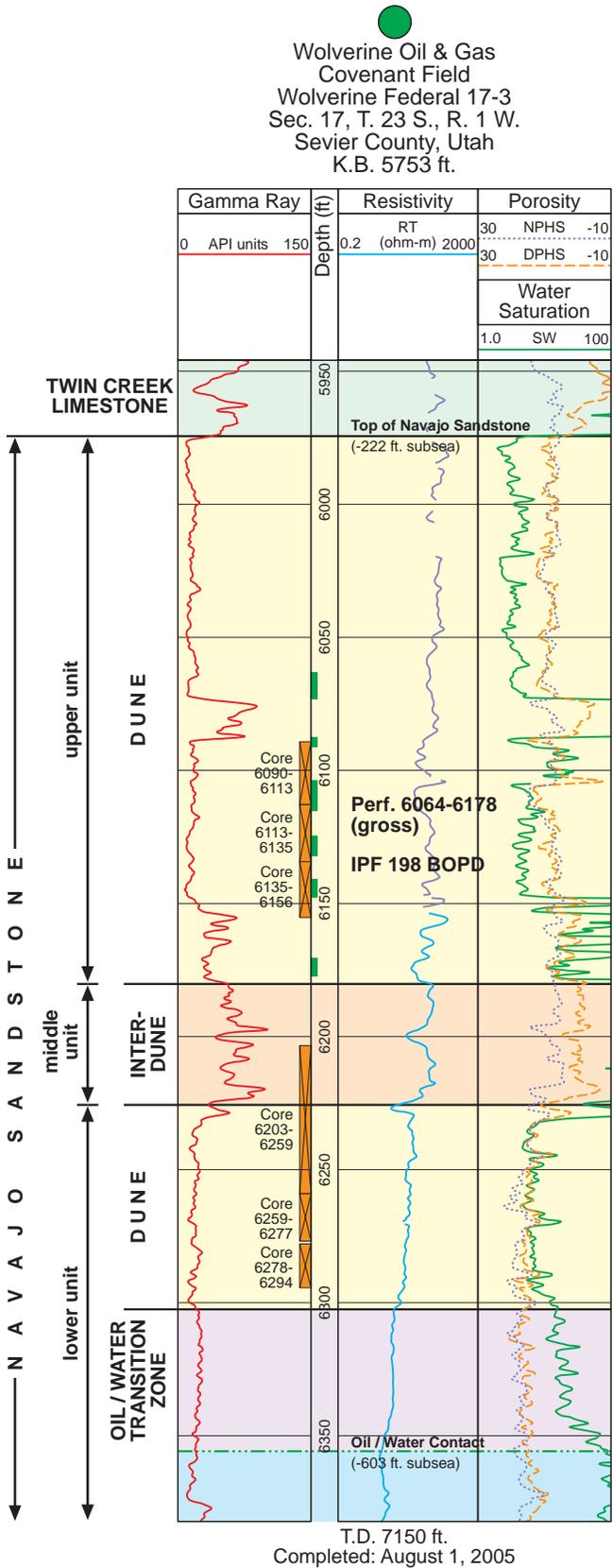


Figure 7. Typical combined gamma ray, resistivity, and neutron-density log of the Navajo Sandstone from the Wolverine Federal No. 17-3 well, Covenant field, Sevier County, Utah. The thin, vertical bars between depths of 6064 and 6178 feet (true vertical depth [TVD]) on the log indicate producing (perforated) intervals.

Navajo in Covenant field is about 5840 feet (1780 m).

The Navajo Sandstone is overlain by predominantly marine carbonates of the Middle Jurassic (Bajocian through Bathonian) Twin Creek Limestone (figure 2). The Twin Creek in central Utah includes the lower five of the seven members typical to northern Utah. In ascending order they are the Gypsum Spring, Sliderock, Rich, Boundary Ridge, and Watton Canyon Members; the Sliderock, upper Rich, and Watton Canyon Members are productive in several fields in northern Utah. In this part of central Utah, the J-1 unconformity is found at the contact between the Navajo and Twin Creek, and represents a gap of 2 to 3 million years (Pipiringos and O’Sullivan, 1978). The J-2 unconformity is found within the Twin Creek at the contact between the Gypsum Spring and Sliderock Members, and divides the Lower Jurassic from the Middle Jurassic representing a gap of 1 million years (Pipiringos and O’Sullivan, 1978). The Navajo is underlain by river floodplain deposits of the Upper Triassic (Carnian-Norian) Chinle Formation (figure 2).

Depositional Environment

In Early Jurassic time, Utah had an arid climate and was positioned 15° north of the equator (Smith and others, 1981). The Navajo Sandstone and age-equivalent rocks were deposited in an extensive dune field (eolian erg environment), which extended from present-day Wyoming to Arizona, and was comparable to the Sahara desert in North Africa or the Alashan area of the Gobi desert in northern China. Multiple sand sources were likely for the Navajo. The sand was likely recycled from Paleozoic and Triassic sandstone exposed to the north in western Montana or Alberta, Canada, with some reworked from local sources (Peterson, 1988; Biek and others, 2003). An additional source was perhaps as far away as the ancestral Appalachian area in the eastern United States, based on zircon similarities (Rahl and others, 2003). The eolian deposits included dunes, interdunes, and sand sheets. Navajo dunes were large to small, straight-crested to sinuous, coalescing, transverse barchanoid ridges as suggested by large-scale cross-bedding (Picard, 1975; Fryberger, 1990). Regional analyses of the mean dip of dune foreset beds indicate paleocurrent and paleowind directions were dominantly from the north and north-

west (Kocurek and Dott, 1983), with the exception of the upper Navajo unit where dip of the foreset beds indicates winds from the northeast.

In addition to a “sea” of wind-blown sand dunes, the Navajo erg system included interdune playas and oases (see Dalrymple and Morris, this volume). A high water table produced oases; deposition occurred when springs and lakes existed for relatively long periods of time. The high water table also resulted in early soft-sediment deformation in overlying dune sands (Sanderson, 1974; Doe and Dott, 1980). Some Navajo interdunes were erosional (deflation) areas associated with running water, such as a wadi or desert wash (a wadi is a usually dry streambed or channel in a desert region). Sand sheets represented by low-relief, poorly drained, vegetated or gravel pavement deposits were also common (Lindquist, 1988). These areas acted as sand transport surfaces.

RESERVOIR AND HYDROCARBON CHARACTERISTICS

Lithologic and Petrophysical Properties

Lithofacies, Porosity, and Permeability

The Navajo Sandstone has heterogeneous reservoir properties because of (1) cyclic dune/interdune lithofacies with better porosity and permeability in certain dune morphologies, (2) fracturing, and (3) diagenetic effects. These characteristics can be observed in outcrops to the east and west of Covenant field (figure 1; Dalrymple and Morris, this volume). In general, the lower and upper units of the Navajo consist of very well to well-sorted, very fine to medium-grained ($\frac{1}{16}$ mm to $\frac{1}{2}$ mm), subangular to subrounded sand or silt grains cemented by silica cement. However, some intervals show a bimodal grain-size distribution representing silty laminae between sand beds. The typical sandstone is 97% white or clear quartz grains (most frosted) with varying amounts of K-feldspar and lithics.

The average porosity for the Navajo Sandstone at Covenant field is 12%; the average grain density is 2.651 g/cm³ based on core-plug analysis. Sandstone exhibits significant secondary porosity in the form of fracturing. Permeabilities in the Navajo from the core data are upwards of 100 millidarcies (mD). The best permeability within Navajo dune deposits is along foreset bedding, with preferred directions along the dip and strike of the individual slip faces or lee faces (cross-beds) (Lindquist, 1983). Porosity and permeability should be greatest in thickly laminated avalanche deposits (Hunter, 1977; Schenk, 1981). Navajo interdunes, as expected, have significantly poorer reservoir characteristics than the dune lithofacies and represent significant barriers to fluid flow.

At Covenant field, the productive lower unit of the Navajo Sandstone is about 240 feet (70 m) thick; the pro-

ductive upper unit is about 200 feet (60 m) thick. The middle unit of the Navajo is a more heterogeneous, 50-foot-thick (15 m) interdunal section. On geophysical well logs both lower and upper units appear as massive, homogeneous sandstone (figure 7). However, cores from Covenant field (figures 6 and 8), combined with outcrop observations, reveal these units are actually heterogeneous with a variety of eolian lithofacies (described below).

Thick (figures 8A and 9A): fine to medium-grained sandstone containing the large-scale, trough, planar, or wedge-planar cross-beds (35° to 40°) commonly recognized as classical eolian dune features; contorted bedding, wind ripples, and small-scale cross-beds are also common (Sanderson, 1974). The sand grains are very well to well-sorted, dune and avalanche deposits. Sand layers are greater than 0.2 inches (0.5 cm) thick in core. The “thick” classification is correlated to avalanche deposits (Lindquist, 1983). The brink to the toe of the dune slip face consists of thin, graded, tabular grainfall laminae (rarely preserved in the core) and thick, subgraded, avalanche laminae. Porosity ranges from 5% to 15%, and permeabilities typically range from 7 to 300 mD (figures 10 and 11).

Thin continuous (figures 8B and 9B): continuously bedded, fine- to medium-grained sandstone layers containing trough, planar, or wedge-planar cross-beds with less inclination (20° to 35°) than the thick lithofacies, and less than 0.2 inches (0.5 cm) thick in core. This lithofacies is moderately well to poorly sorted with more clay cementation than the thin discontinuous lithofacies described below. The thin continuous lithofacies can occur within the thick and thin discontinuous lithofacies, making the thin continuous lithofacies a transitional or gradational phase. All thin continuous lithofacies porosities are under 12% and permeabilities generally range from 1 to 30 mD, with a few over 100 mD (figures 10 and 11).

Thin discontinuous (figures 8C and 9C): fine-grained sandstone with flat-lying bedding less than 0.2 inches (0.5 cm) thick in core containing wind ripples and some cross-bedding (0 to 20°). This lithofacies is moderately to poorly sorted with greater carbonate cement than thin continuous lithofacies. It is commonly closest to the base of a bedding plane in core. Thin discontinuous also contain tightly packed, reworked ripple strata representative of the dune toe. Low porosities and permeabilities are characteristic (figures 10 and 11).

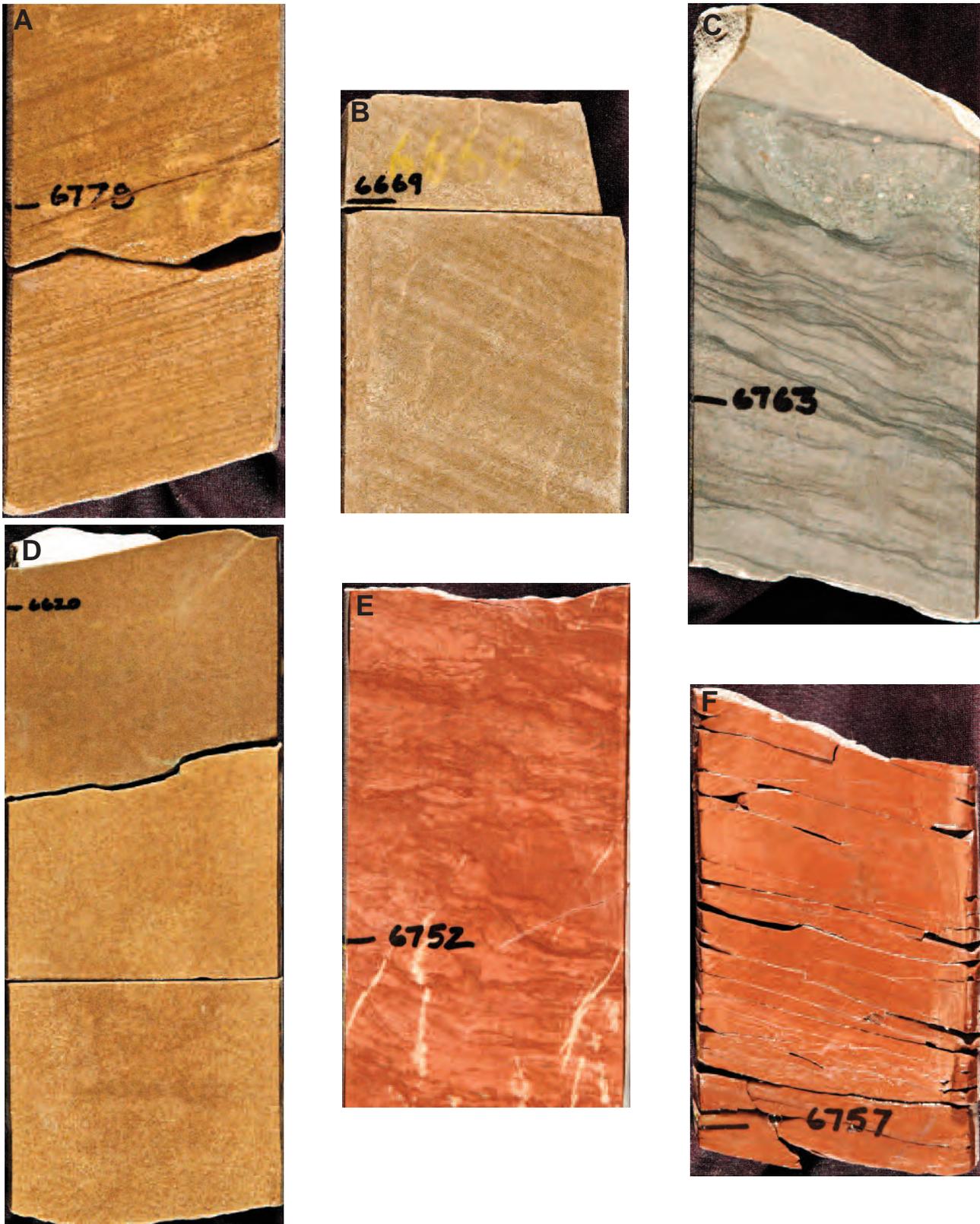


Figure 8. Typical eolian lithofacies in the Navajo Sandstone from the Wolverine Federal No. 17-3 well. MD = measured depth. (A) Thick lithofacies; slabbed core from lower unit at 6778 feet (MD). (B) Thin continuous lithofacies; slabbed core from the upper unit at 6669 feet (MD). (C) Thin discontinuous lithofacies; slabbed core from the lower unit at 6763 feet (MD). Note scour with granule lag. (D) Massive lithofacies; slabbed core from the upper unit at 6620 feet (MD). (E) Interdune lithofacies showing siltstone laminae and mudstone representing a wet interdunal or lacustrine depositional environment; slabbed core from the middle unit at 6752 feet (MD). (F) Interdune lithofacies consisting of shale representing playa or floodplain depositional environment; slabbed core from the middle unit at 6757 feet (MD).

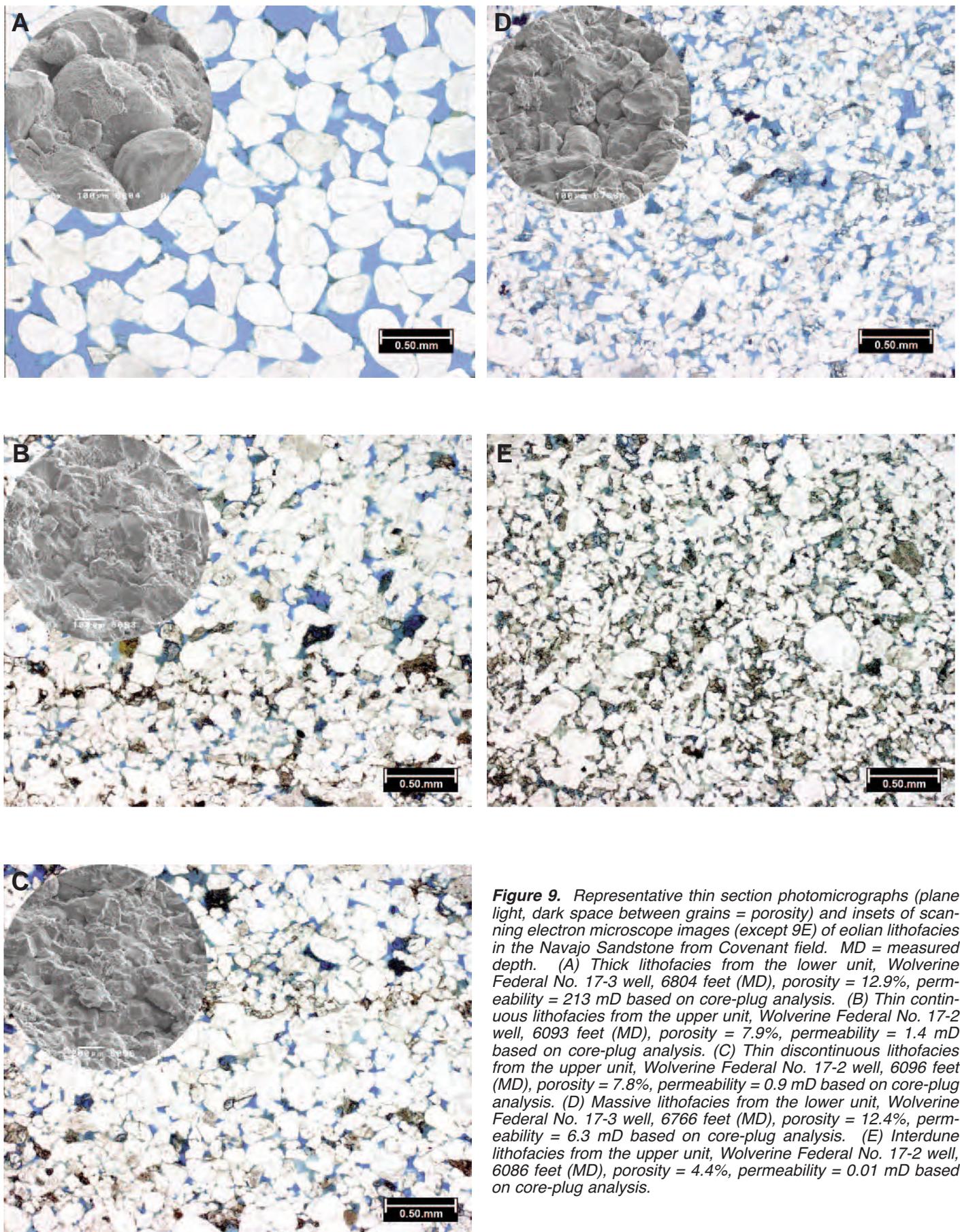


Figure 9. Representative thin section photomicrographs (plane light, dark space between grains = porosity) and insets of scanning electron microscope images (except 9E) of eolian lithofacies in the Navajo Sandstone from Covenant field. MD = measured depth. (A) Thick lithofacies from the lower unit, Wolverine Federal No. 17-3 well, 6804 feet (MD), porosity = 12.9%, permeability = 213 mD based on core-plug analysis. (B) Thin continuous lithofacies from the upper unit, Wolverine Federal No. 17-2 well, 6093 feet (MD), porosity = 7.9%, permeability = 1.4 mD based on core-plug analysis. (C) Thin discontinuous lithofacies from the upper unit, Wolverine Federal No. 17-2 well, 6096 feet (MD), porosity = 7.8%, permeability = 0.9 mD based on core-plug analysis. (D) Massive lithofacies from the lower unit, Wolverine Federal No. 17-3 well, 6766 feet (MD), porosity = 12.4%, permeability = 6.3 mD based on core-plug analysis. (E) Interdune lithofacies from the upper unit, Wolverine Federal No. 17-2 well, 6086 feet (MD), porosity = 4.4%, permeability = 0.01 mD based on core-plug analysis.

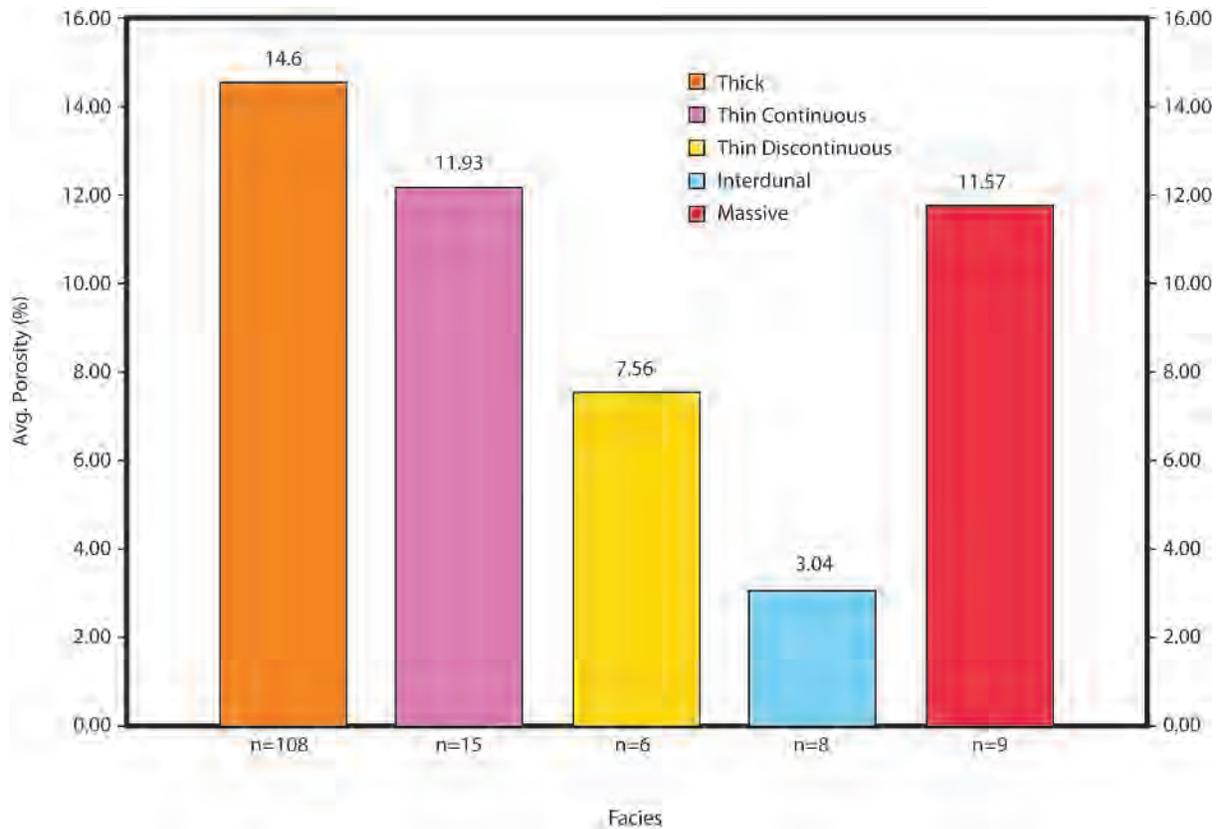
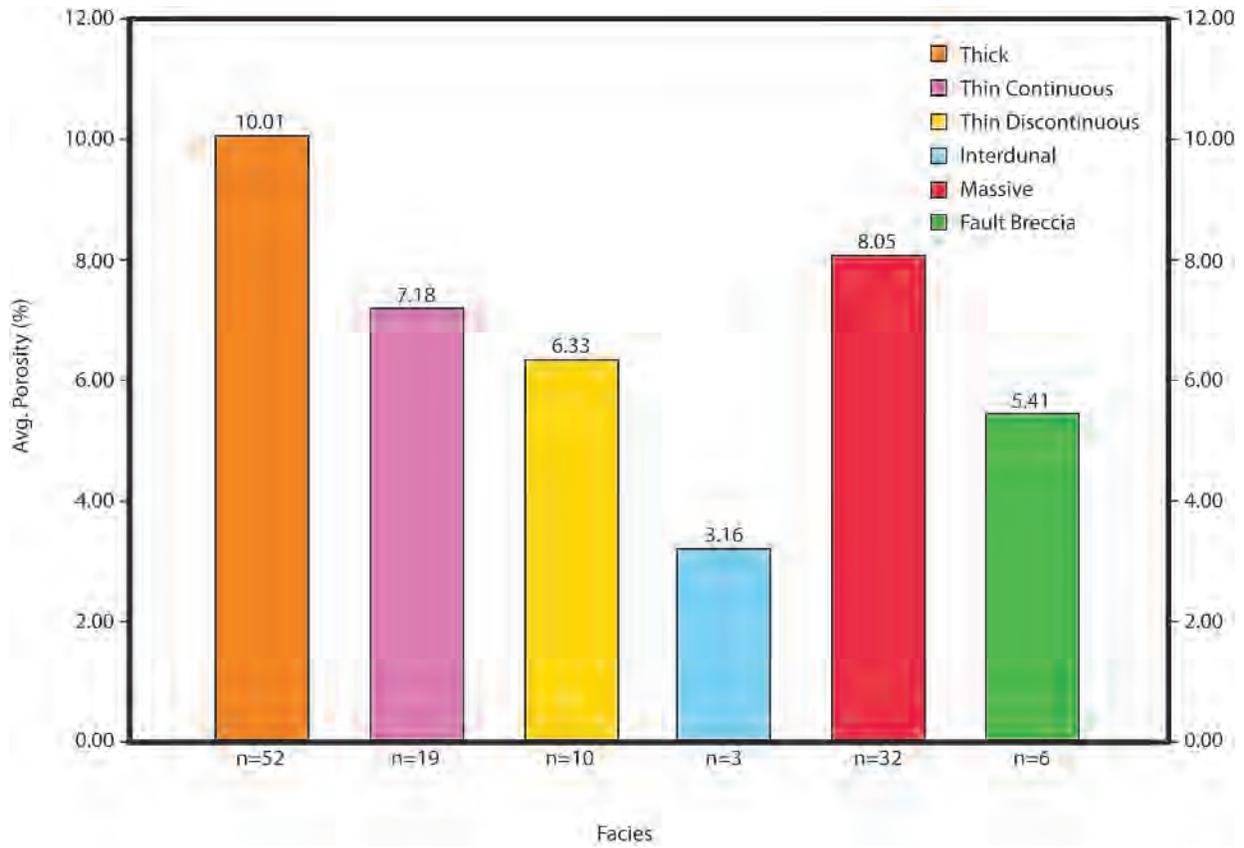


Figure 10. Average porosity by lithofacies from the upper (A) and lower (B) units of the Navajo Sandstone in Covenant field, based on core-plug analysis from the Wolverine Federal No. 17-3 well, showing gradational changes in reservoir quality within the various dune lithofacies and transitional changes to interdune lithofacies; zones of brecciation from faulting are also plotted.

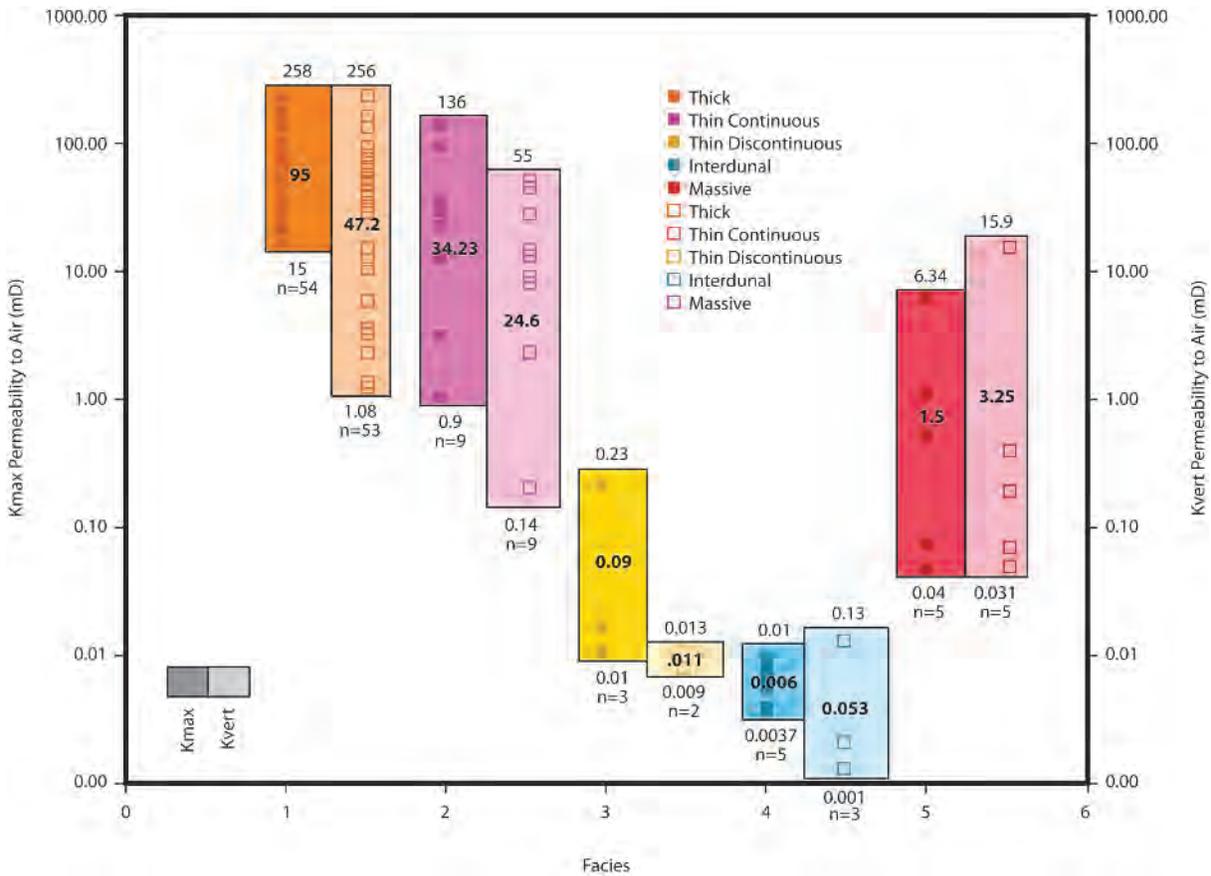
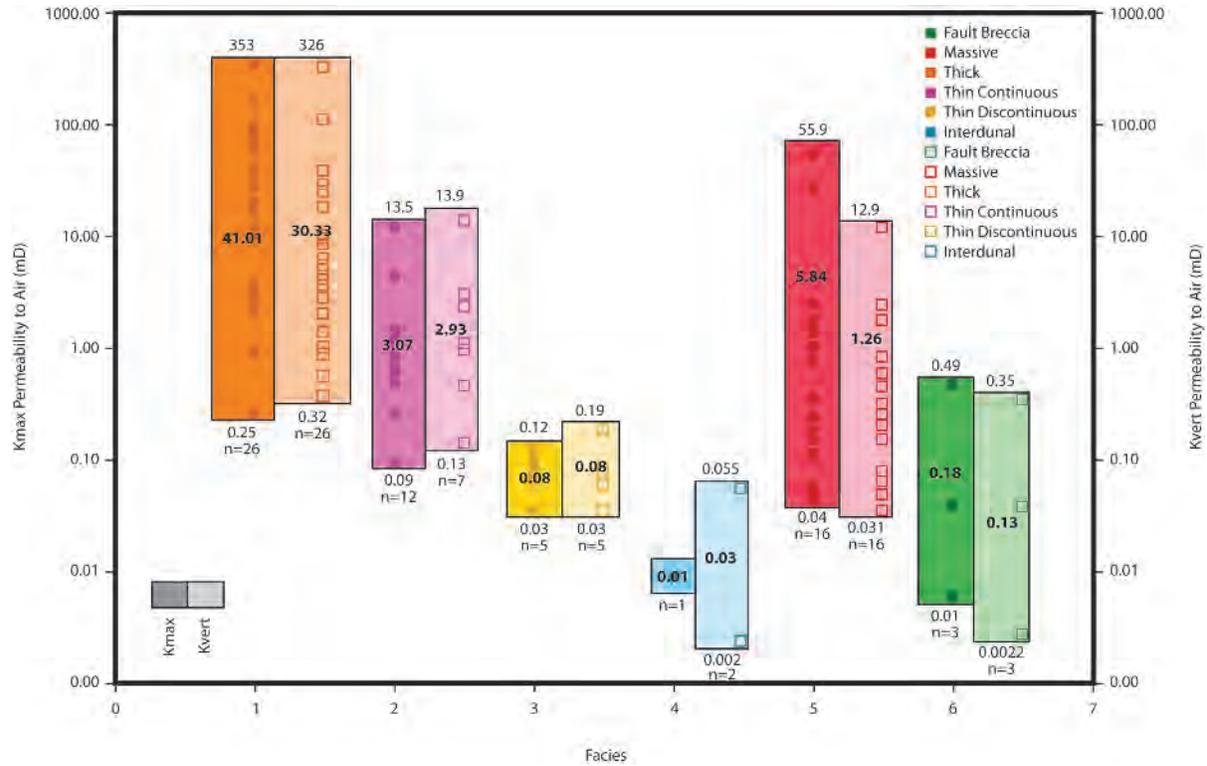


Figure 11. Permeability by lithofacies from the upper (A) and lower (B) units of the Navajo Sandstone in Covenant field, based on core-plug analysis from the Wolverine Federal No. 17-3 well, showing gradational changes in reservoir quality within the various dune lithofacies and transitional changes to interdune lithofacies; zones of brecciation from faulting are also plotted.

Massive (figures 8D and 9D): homogenized, very fine to fine-grained sandstone layers showing few distinct sedimentary structures or laminations with the exception of occasional contorted bedding. Porosity varies but can be as high as 12%, however, permeabilities are generally lower than thick and thin continuous lithofacies (figures 10 and 11). Massive lithofacies probably formed by water-saturated sand (Sanderson, 1974).

Interdunal (figures 8E, 8F, and 9E): low-angle to horizontal laminae or distorted bedding consisting of very fine to fine-grained, thin, poorly sorted sandstone, siltstone, and shale dominated by carbonate cement. Dolomitic chert is also common. Beds may be wavy and contain haloturbation, some wind ripples, or fluvial characteristics such as small scour-filled channel deposits and current ripples. Typical porosities and permeabilities are very low (figures 10 and 11). Interdunal fluvial characteristics indicate sheet flow or flooding events in a fluvial/

wadi setting while other deposits suggest wet, playa, or lacustrine conditions.

Plotting porosity versus permeability shows gradational changes in reservoir quality within the various dune lithofacies and transitional changes to interdune lithofacies (figure 12). The thick lithofacies is more variable in the upper Navajo unit than in the lower unit. The porosity ranges are about the same for the massive lithofacies in the upper and lower units. However, the permeability ranges are broader in the upper unit than in the lower unit for the massive lithofacies. The other lithofacies are generally similar in both units. These graphs provide a means for estimating eolian lithofacies in wells where there are no cores. This in turn aids in mapping dune lithofacies prior to a well completion, which results in identifying zones of maximum drainage effects.

Bounding Surfaces

Genetic units of eolian sandstone deposits are separated by 1st-order bounding surfaces formed by interdune deposits or major diastems. Internal bounding surfaces are also found within dune cross-beds (Ahlbrandt

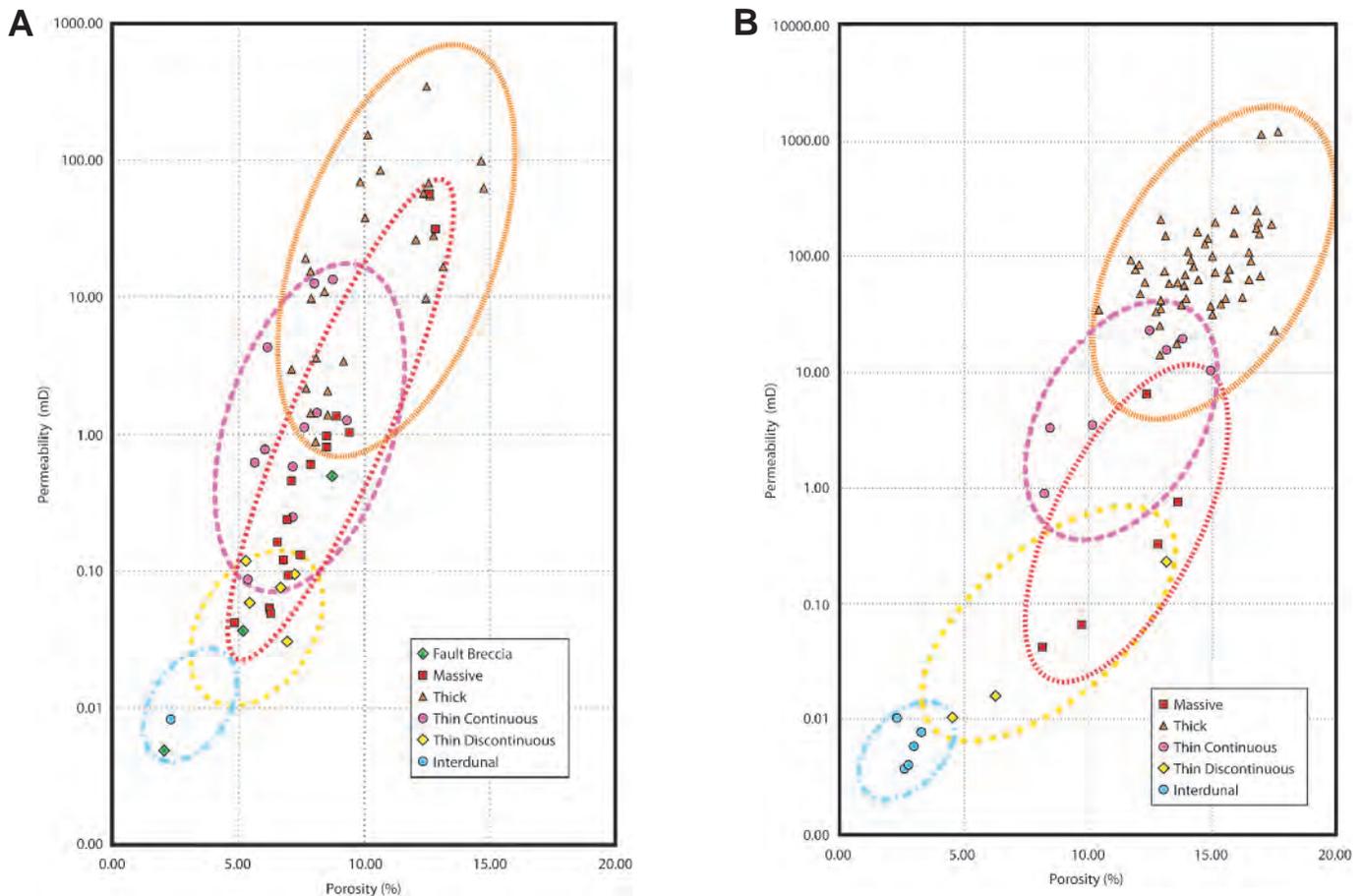


Figure 12. Porosity versus permeability (K_{max} from figure 11) by lithofacies cross plot from the upper (A) and lower (B) units of the Navajo Sandstone in Covenant field, based on core-plug analysis from the Wolverine Federal No. 17-3 well, showing gradational changes in reservoir quality within the various dune lithofacies and transitional changes to interdune lithofacies; zones of brecciation from faulting are also plotted.

and Fryberger, 1981; Fryberger, 1990; Ciftci and others, 2004). Stacking surfaces or 2nd-order bounding surfaces (superposition surfaces) within a single genetic unit can divide the cross-strata of two dunes and are formed by migrating dunes superimposed on the slip faces of the underlying dunes (Fryberger, 1990; Ciftci and others, 2004; Morris and others, 2005). Growth surfaces, or 3rd-order bounding surfaces, are high-angle reactivation surfaces dividing sets of ripple strata related to the advance of a single dune (Fryberger, 1990; Ciftci and others, 2004). These bounding surfaces represent possible barriers or baffles to fluid flow, both vertically and horizontally, within the Navajo reservoir. Identification and correlation of the numerous bounding surfaces, as well as recognition of fracture set orientations and lithofacies in the Navajo reservoir, are critical to understanding their effects on production rates, petroleum movement pathways, directionally drilled well plans, and any future pressure maintenance program at Covenant field.

Fracturing and Diagenesis

Fracturing and diagenetic effects can both reduce and enhance the reservoir permeability of the Navajo Sandstone. Fractures are related to fault-propagation folding during the Sevier orogeny after deep burial

(Royse and others, 1975). Fractures in the Navajo Sandstone at Covenant field consist of four types: (1) fractures with open voids, (2) bitumen-filled fractures, (3) intense micro-fractures or deformation bands, and (4) gouge-filled, silica-cemented, impermeable fractures and brecciated zones (figures 5 and 6). Fracture intensity and brecciation increase, as expected, closest to fault zones running through the core from the Wolverine Federal No. 17-3 well. Fractures with voids and some micro-fractures likely provide additional permeable flow paths for oil migration. Development of bitumen-filled and silica-cemented fractures and deformation bands locally reduce reservoir permeability. However, these fractures may have been open when oil migration occurred. Later dissolution of silicate minerals and the development of open fractures increased reservoir permeability.

Diagenetic effects in the Navajo reservoir are relatively minor at Covenant field based on thin-section analysis and scanning electron microscopy from core samples (figure 13). There are only minor overgrowths of quartz and very little clay. Authigenic clay mineralization has occurred in the form of grain-coating, pore-bridging, and fibrous illite. Some ferroan(?) dolomite cementation and fractured, corroded K-feldspar are also present.

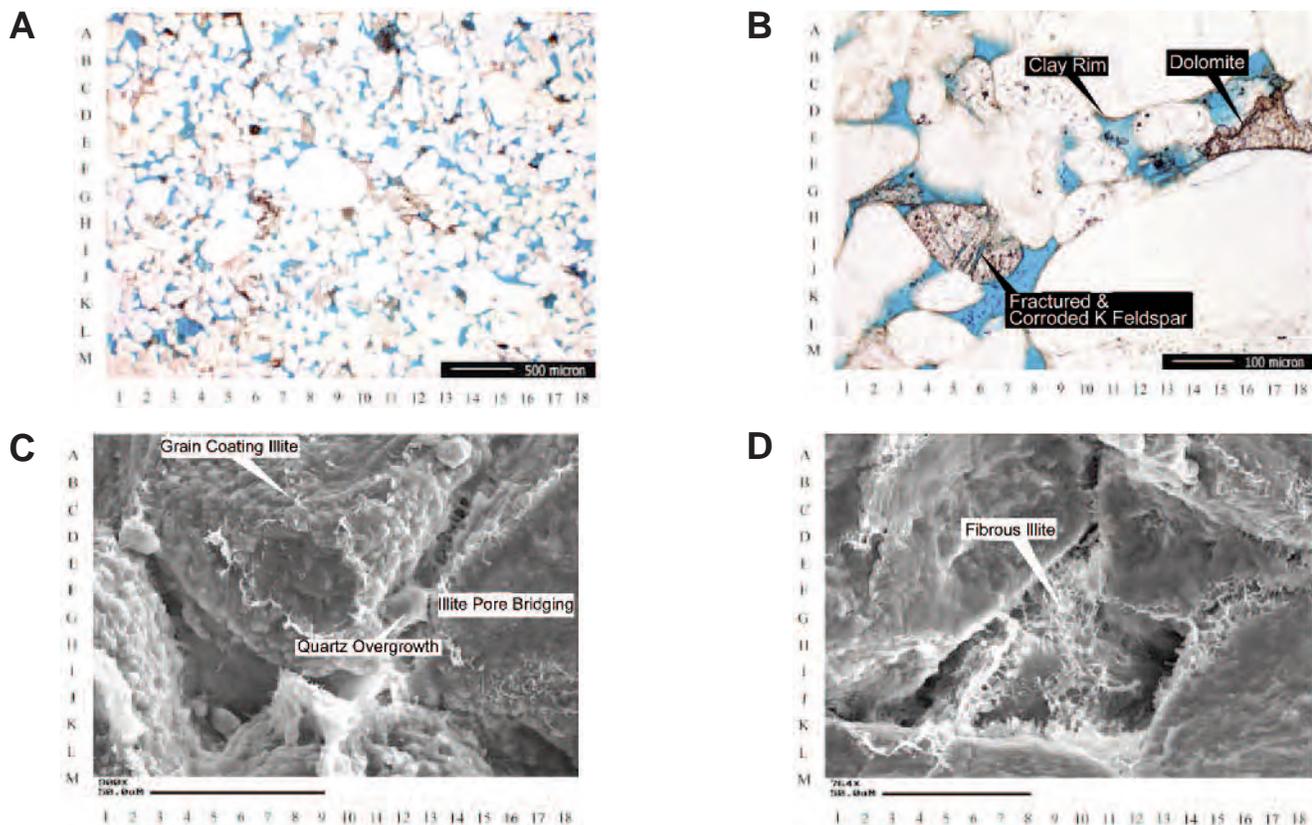


Figure 13. Thin-section photomicrographs (plane light) and scanning electron microscope images of diagenetic effects in the Navajo Sandstone, Kings Meadow Ranches No. 17-1 well, 8495 feet (measured depth). (A) Overview photomicrograph representative of typical Navajo showing bimodal distribution of subangular to subrounded quartz sand and silt. Dark area is intergranular porosity. (B) Close-up photomicrograph of clay rims on quartz grains, fractured and corroded K feldspar grains, and dolomite cement filling pore spaces. (C) Scanning electron microscope image displaying quartz overgrowth, grain-coating illite, and illite pore bridging. (D) Scanning electron microscope image displaying fibrous illite lining a pore.

Reservoir and Oil Characteristics

Navajo Sandstone gross-pay thickness at Covenant field is 487 feet (148 m) and net-pay thickness is 424 feet (129 m), a net-to-gross ratio of 0.87. The Navajo reservoir temperature is 188°F (87°C). Average water saturation is 38%, and produced water resistivity (R_w) from the Kings Meadow No. 17-1 well is 0.281 ohm-m at 77°F (25°C), containing 28,400 mg/L total dissolved solids (calcium = 428 mg/L, magnesium = 41 mg/L, sodium = 10,080 mg/L, potassium = 220 mg/L, barium = trace, iron = 12 mg/L, silica = 46 mg/L, bicarbonate = 518 mg/L, sulfate = 3000 mg/L, and chloride = 14,100 mg/L). The produced water has a pH value of 6.45 with a specific gravity of 1.0208 at 67°F (19°C). The initial reservoir pressures average about 2630 pounds per square inch (18,134 kPa). The reservoir drive mechanism is a strong active water drive. Geophysical well logs show a transition zone in terms of water saturation above a very sharp oil/water contact (figure 7).

Covenant field's Navajo oil is a dark brown, low-volatile crude. The API gravity of the oil is 40.5°; the specific gravity is 0.8280 at 60°F (16°C). The viscosity of the crude oil is 4.0 centistokes (cst) at 77°F (25°C) and the pour point is 2.2°F (-16.5°C). The average weight percent sulfur of produced Navajo oil is 0.48; nitrogen content is 474 parts per million. The weight percent of paraffin is 4.9 to 5.0; the weight percent of asphaltenes is 0.1. Stable carbon-13 isotopes are -29.4‰ and -29.0‰ for saturated and aromatic hydrocarbons, respectively. The pristane/phytane ratio is 0.96 (Baseline DGSI, 2005). Distillation results show the (1) gasoline fraction = 33% at 375°F (191°C), (2) naphtha fraction = 7% at 425°F (218°C), (3) kerosene fraction = 19% at 550°F (288°C), and (4) fuel oil (bottoms) fraction = 41% at +550°F (+288°C).

PRODUCTION AND RESERVES

Field Discovery

Beginning in the late 1950s, Standard Oil of California (later Chevron USA) explored the hydrocarbon potential in the Sevier Valley of the central Utah thrust belt and drilled several wells. They maintained the leases on about 80,000 acres [32,000 ha]. In 1995 and 1997, Chevron acquired a fairly large seismic data grid in the region. In 2000, Wolverine Gas & Oil Corporation bought Chevron's leases and seismic data in the central Utah thrust belt. Wolverine acquired available seismic in the area, and conducted a large source-rock and hydrocarbon-migration timing study. These data and studies indicated the possibility of a viable hydrocarbon system and several drilling prospects, although the first models predicted the frontal end of the thrust belt would be gas prone. Wolverine then looked for a drilling partner, the central Utah thrust belt being a particularly difficult place to sell deals based on past drilling failures. A drilling

deal was shown to 65 companies and twice taken to the North American Prospect Expo in Houston, Texas, with no success in finding a partner. Wolverine's management decided to break the deal down into small interests and sell it to various investors, some having never been involved with oil and gas before. Forming a federal unit, Wolverine was ready to drill its first well in the area—the Kings Meadow Ranches No. 17-1 beginning in late 2003.

The Kings Meadow Ranches No. 17-1 well (figure 4) was spudded on November 11, 2003, and reached a total true vertical depth (TVD) of 9382 feet (2860 m). The well was completed a year later on November 3, 2004, with an initial flowing potential of 708 bbls (113 m³) of oil per day, 1000 cubic feet (28 m³) of gas per day, and 20 bbls (3 m³) of water per day from a gross perforated interval between 6100 and 6225 feet (1859–1897 m) in the lower Navajo unit. As of January 1, 2007, the No. 17-1 well had produced 739,065 bbls (117,511 m³) of oil, 91,125 bbls (14,489 m³) of water, and no gas (Utah Division of Oil, Gas and Mining, 2006).

Wolverine invested significant capital in leasehold, seismic acquisition, drilling, and completion up through the discovery well. With the drill site located along Utah Highway 24, it was impossible to keep drilling and completion operations, as well as early production, away from both a curious industry and excited local citizens. Ultimately, the Covenant discovery led to a frenzied lease play, extensive seismic acquisition, and renewed exploratory drilling throughout the central Utah thrust belt.

Completion Practices

The latest development wells drilled in Covenant field have been completed with 13-3/8-inch surface casing set to depths of approximately 2000 feet (600 m), 9-5/8-inch intermediate casing set in the Twin Creek Limestone, and 7-inch production casing landed and cemented through the Navajo Sandstone at approximately 6700 feet (2000 m) TVD. The production casing was perforated in selected Navajo intervals with four jet shots per foot. The perforations were broken down using small, 7.5% hydrochloric acid treatments with additives, primarily to clean perforations of clays from drilling muds. Electrical submersible pumps were then installed to artificially lift fluids and the wells were placed in production (Ellis M. Peterson, Wolverine Gas & Oil Corporation, written communication, March 12, 2007).

Production Analysis

Covenant field wells produce oil (84%) and water (about 16% since the field was discovered), and no gas. Cumulative production as of January 1, 2007, was 3,106,099 bbls (493,870 m³) of oil and 578,074 bbls (91,914 m³) of water (Utah Division of Oil, Gas and Mining, 2006). Daily oil production averages 5400 bbls (860 m³) of oil and 1700 bbls (270 m³) of water; no gas has been produced at Covenant field. Production stead-

ily increased through July 2006 as new development wells and infrastructure were completed; a slight decline is shown beginning in August 2006 (figure 14). The field currently has 10 producing wells and one dry hole, drilled from two pads. The well spacing is about 40 acres (16 ha) within the Covenant unit.

Five wells are completed in the lower Navajo unit and five in the upper Navajo unit; none are commingled (Ellis M. Peterson, Wolverine Gas & Oil Corporation, verbal communication, February 2007). Production facilities at the site include two 10,000-barrel (1600 m³) storage tanks. Oil is trucked to Salt Lake City or to a pipeline at Montezuma Creek in southeastern Utah. The fully developed cost for this first field will be around \$56.3 million.

Reserves and Additional Potential

Original oil in place (OOIP) reserves are estimated at 100 million bbls (15.9 million m³). A 40 to 50% recovery of the OOIP may be achieved with efficient operations and completion techniques. Secondary and tertiary recovery programs may include nitrogen injection and/or a carbon dioxide flood. Additional reserves may be present in the Twin Creek Limestone, the untested Kaibab Limestone and deeper Paleozoic formations.

The fact that no associated gas is produced at Covenant field suggests the possibility that sediment or thrust-plate loading may have driven the gas off during hydrocarbon migration (Wavrek and others, 2005) or faults acting as baffles caused gas to migrate along different paths than oil. Thus, potential gas-charged traps may be present in the region.

HYDROCARBON SOURCE

The lack of good Cretaceous source rocks was blamed for earlier exploration failures in the central Utah thrust belt (Sprinkel and Chidsey, 2006); however, oil and gas shows were common in Mississippian, Permian, Triassic, and Jurassic rocks. Although some coaly beds are present in the Upper Cretaceous rocks in the eastern part of central Utah, the Cretaceous strata become more fluvial and nonmarine to the west and probably are only gas-prone. Therefore, unlike the producing structures of the thrust belt in northern Utah and southwestern Wyoming, the structures and faults of central Utah are not in contact with high-quality Cretaceous source rocks.

With the discovery of Covenant field, a viable source rock is proven in the central Utah thrust belt; however, the exact geochemical correlation between the oil pro-

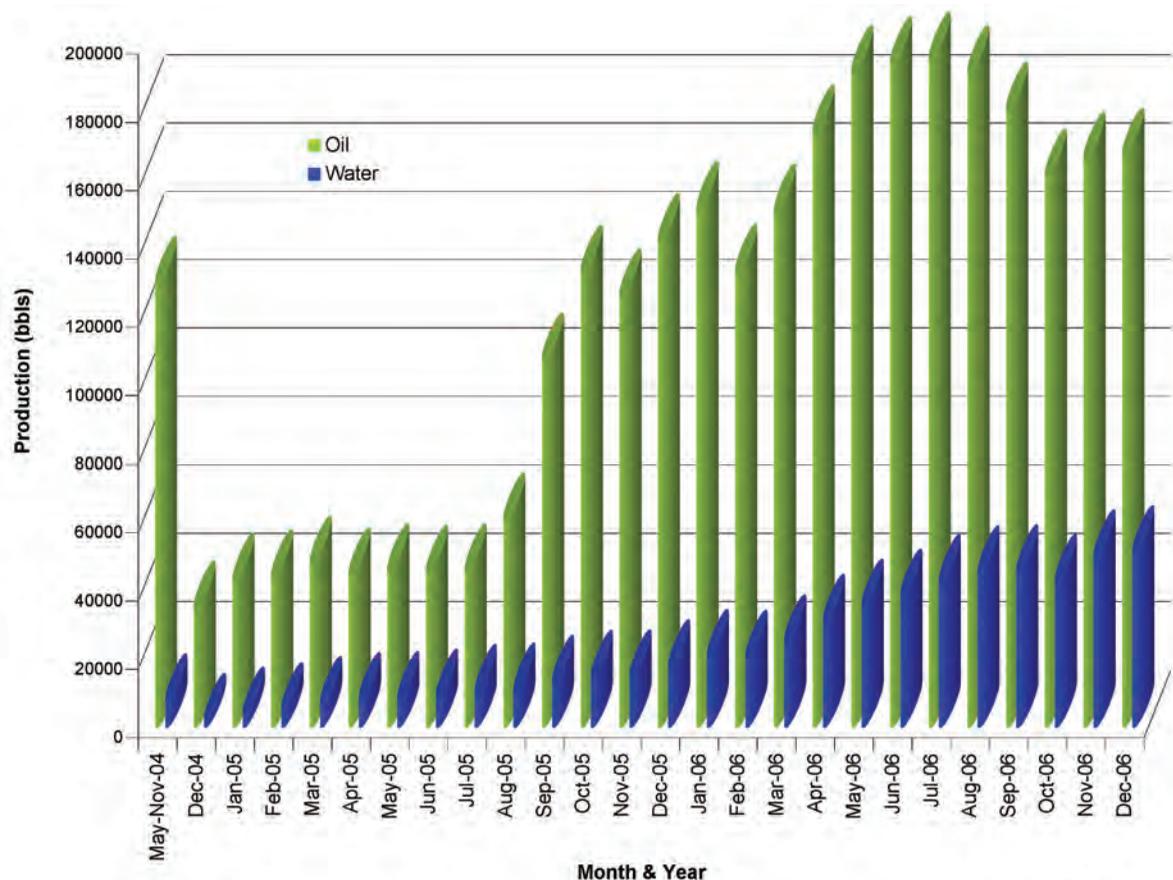


Figure 14. Monthly oil and water production from wells in Covenant field as of January 1, 2007 (Utah Division of Oil, Gas and Mining, 2006).

duced at Covenant and the formation containing the potential source rock has not been demonstrated. Several source candidates are present in the region. They include the Mississippian Delle Phosphatic Member of the Deseret Limestone and equivalent formations (Sandberg and Gutschick, 1984), the Mississippian Chainman Shale (Poole and Claypool, 1984; Sandberg and Gutschick, 1984), the Mississippian Long Trail Shale of the Great Blue Limestone (Poole and Claypool, 1984), the Mississippian Doughnut Formation (Swetland and others, 1978), the Mississippian-Pennsylvanian Manning Canyon Shale (Swetland and others, 1978; Poole and Claypool, 1984), and the Permian Park City/Phosphoria Formation (Claypool and others, 1978; Sprinkel and others, 1997; Peterson, 2000, 2001). Total organic carbon for some units within these rocks is 15%. The regional distribution of these formations is shown by Peterson (2001).

What we do know about the possible correlation between the Covenant field oil and its source is based on limited or negative evidence. A graph (figure 15) plotting stable carbon-13 isotopes of saturated versus aromatic hydrocarbons from the Covenant field oil with other well-documented Mississippian and Permian oils shows the Covenant oil was derived from marine source beds. This is based on its canonical variable (CV) of less than 0.47 (Sofer, 1984). We eliminated known marine Cretaceous source beds because they are not found in central Utah and the geochemistry of the Covenant oil is

similar to known Paleozoic oils that have been correlated to source beds in the region (table 1). Furthermore, we believe we can eliminate the Mississippian Chainman Shale and the Permian Phosphoria Formation as possible sources based on a graph plotting canonical variable (CV) versus pristine/phytane values (figure 16). Thus, the Covenant field oil is likely derived from a Carboniferous source (see Wavrek and others, 2005, in press).

As stated earlier, thrusting in this area is Cretaceous to early Tertiary in age. Most of the hydrocarbon generation and migration probably occurred during this period; however, some could have started as early as Permian or Triassic time in the older Paleozoic rocks and as late as Tertiary time in Mesozoic rocks. Hydrocarbons were then expelled and subsequently migrated into the overlying traps, primarily along fault planes or through porous Paleozoic and Mesozoic carrier beds. Late Tertiary extension in this area may have disrupted the traps more than in the productive thrust belt of northern Utah and southwestern Wyoming.

Oil migrating from the Mississippian Chainman Shale in western Utah requires a post-Sevier-orogeny, long-distance migration, and must have circumvented the Sevier arch where no Mississippian rocks are present. Potential hydrocarbon sources in the Mississippian Delle Phosphatic Member and Mississippian-Pennsylvanian Manning Canyon Shale (containing 2% to 15% total organic content) would have to have been generated outside the Pennsylvanian-Permian Oquirrh basin to the north

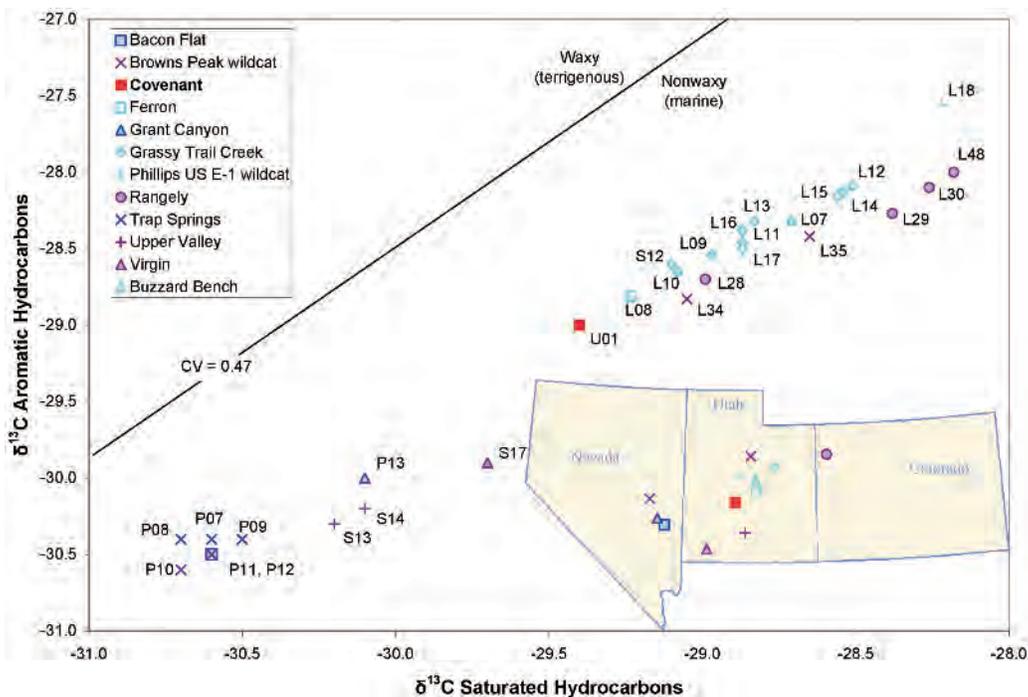


Figure 15. Stable carbon-13 isotope of saturated versus aromatic hydrocarbons from the Covenant field oil and other key oils from Utah, Colorado, and Nevada (see inset for field locations). Units on both axes of the graph depict the carbon isotopes measured in the oil versus the Pee Dee Belemnite (PDB) standard in parts per thousand; a negative value implies the oil sample is depleted in the heavy isotope relative to the standard. The line labeled CV = 0.47 (CV = canonical variable) divides waxy (terrigenous) and nonwaxy (marine) sources (Sofer, 1984), and shows that oils in this region are derived from marine sources.

Table 1. Geochemistry of oils from Utah, Colorado, and Nevada (see figure 15 for field locations).

ID	Field	Reservoir	Reservoir Age	Oil Type	API ¹	Sulfur ²	$\delta^{13}\text{C Sat}^3$	$\delta^{13}\text{C Aro}^4$	CV ⁵	Pr/Ph ⁶	CPI ⁷	Well Name	County	State	Depth (ft)	Data Source
P12	Bacon Flat	Gulmette Formation	D	Mississippian Chairman	24.0	0.5	-30.60	-30.50	-1.94	1.50	1.50	Bacon Flat 1	Nye	Nevada	5316-5333	Poole and Claypool, 1984
L34	Browns Peak wildcat	Entrada Sandstone?	J	Permian Phosphoria	30.8	0.74	-29.05	-28.83	-2.16	0.91	1.00	Browns Peak Unit 1-G24	Utah	Utah	5788-5812	Lillis and others, 2003
L35	Browns Peak wildcat	Entrada Sandstone?	J	Permian Phosphoria	35.5	0.74	-28.65	-28.42	-2.25	0.91	0.97	Browns Peak Unit 1-G24	Utah	Utah	5788-5812	Lillis and others, 2003
L07	Buzzard Bench	Moenkopi Formation	Tr	Uncertain Paleozoic	n.d.	n.d.	-28.71	-28.31	-1.86	0.83	0.99	Federal 41-33	Emery	Utah	9462-9472	Lillis and others, 2003
U01	Covenant	Navajo Sandstone	J	Carboniferous	40.5	0.48	-29.40	-29.00	-1.65	0.96	1.00	Kings Meadow Ranches 17-1	Sevier	Utah	6215-6225	Baselma DGSI, 2005
L08	Ferion	Kaibab Limestone	P	Uncertain Paleozoic	35.0	n.d.	-29.23	-28.81	-1.69	0.94	0.97	Pan Am 3 (Ferron Unit 42-21)	Emery	Utah	7154-7178	Lillis and others, 2003
P13	Grant Canyon	Gulmette Formation	D	Mississippian Chairman	27.0	0.5	-30.10	-30.00	-2.10	1.40	1.00	Grant Canyon 1	Nye	Nevada	4374-4426	Poole and Claypool, 1984
L09	Grassy Trail Creek	Moenkopi Formation	Tr	Uncertain Paleozoic	n.d.	n.d.	-28.97	-28.54	-1.71	0.89	0.98	Federal 11-23	Emery	Utah	3910-3940	Lillis and others, 2003
L10	Grassy Trail Creek	Moenkopi Formation	Tr	Uncertain Paleozoic	n.d.	n.d.	-28.08	-28.65	-1.68	0.97	1.01	Federal 11-33	Emery	Utah	3420-3906	Lillis and others, 2003
L11	Grassy Trail Creek	Moenkopi Formation	Tr	Uncertain Paleozoic	n.d.	n.d.	-28.87	-28.46	-1.79	0.90	0.98	Federal 11-14	Emery	Utah	3687-4010	Lillis and others, 2003
L12	Grassy Trail Creek	Moenkopi Formation	Tr	Uncertain Paleozoic	n.d.	n.d.	-28.51	-28.09	-1.88	1.00	1.00	Federal 11-41	Emery	Utah	3540-3911	Lillis and others, 2003
L13	Grassy Trail Creek	Moenkopi Formation	Tr	Uncertain Paleozoic	36.5	0.33	-28.83	-28.32	-1.58	1.12	0.97	Federal 11-41	Emery	Utah	3540-3911	Lillis and others, 2003
L14	Grassy Trail Creek	Moenkopi Formation	Tr	Uncertain Paleozoic	n.d.	n.d.	-28.54	-28.13	-1.99	1.00	0.99	Federal 11-42	Emery	Utah	3453-3654	Lillis and others, 2003
L15	Grassy Trail Creek	Moenkopi Formation	Tr	Uncertain Paleozoic	n.d.	n.d.	-28.55	-28.16	-1.91	0.91	0.99	Federal 11-43	Emery	Utah	3382-3996	Lillis and others, 2003
L16	Grassy Trail Creek	Moenkopi Formation	Tr	Uncertain Paleozoic	n.d.	n.d.	-28.87	-28.38	-1.81	0.93	0.98	Federal 12-32	Emery	Utah	3627-3970	Lillis and others, 2003
L17	Grassy Trail Creek	Moenkopi Formation	Tr	Uncertain Paleozoic	n.d.	n.d.	-28.87	-28.50	-1.88	0.88	0.99	State 2-43X	Emery	Utah	3669-4182	Lillis and others, 2003
S12	Grassy Trail Creek	Moenkopi Formation	Tr	Uncertain Paleozoic	42.5	n.d.	-29.10	-28.60	-1.52	0.90	n.d.	Grassy Trail 1-33 Federal	Emery	Utah	3420-3906	Spinkel and others, 1997
L18	Phillips US E-1 wildcat	Sinbad Mbr. of Moenkopi Fm	Tr	Uncertain Paleozoic	n.d.	n.d.	-28.22	-27.56	-1.44	0.95	0.98	United States E-1	Sanpete	Utah	16,115-16,425	Lillis and others, 2003
L28	Rangely	Weber Sandstone	IP	Permian Phosphoria	33.1	0.73	-28.99	-28.70	-2.02	0.95	1.02	Equity Federal 1-7	Rio Blanco	Colorado	6505-6535	Lillis and others, 2003
L29	Rangely	Weber Sandstone	IP	Permian Phosphoria	32.8	n.d.	-28.38	-28.27	-2.61	0.96	1.00	Equity Federal 1-7	Rio Blanco	Colorado	6505-6535	Lillis and others, 2003
L30	Rangely	Weber Sandstone	IP	Permian Phosphoria	34.5	n.d.	-28.28	-28.10	-2.53	1.06	1.00	Pennell-Hayes 1-31	Rio Blanco	Colorado	6175-6345	Lillis and others, 2003
L48	Rangely	Morrison Formation	J	Permian Phosphoria-Cretaceous Mancos mix	33.3	n.d.	-28.18	-28.00	-2.51	1.25	1.01	McLaughlin Stuart 2	Rio Blanco	Colorado	3225-3237	Lillis and others, 2003
P07	Trap Springs	Garrett Ranch Group	T	Mississippian Chairman	30.0	0.6	-30.60	-30.40	-1.72	1.50	1.00	Britton 13-21	Nye	Nevada	3976-4140	Poole and Claypool, 1984
P08	Trap Springs	Garrett Ranch Group	T	Mississippian Chairman	29.0	0.6	-30.70	-30.40	-1.47	1.50	1.00	Trap Springs 19	Nye	Nevada	3374-4100	Poole and Claypool, 1984
P09	Trap Springs	Garrett Ranch Group	T	Mississippian Chairman	21.0	0.6	-30.50	-30.40	-1.97	1.50	1.00	Zuspan 24-1	Nye	Nevada	4910-4944	Poole and Claypool, 1984
P10	Trap Springs	Garrett Ranch Group	T	Mississippian Chairman	19.0	0.6	-30.70	-30.80	-1.91	1.50	1.00	Trap Springs 1	Nye	Nevada	4220-4853	Poole and Claypool, 1984
P11	Trap Springs	Garrett Ranch Group	T	Mississippian Chairman	24.0	0.5	-30.60	-30.50	-1.94	1.50	1.00	Trap Springs 3	Nye	Nevada	3269-4083	Poole and Claypool, 1984
S13	Upper Valley	Kaibab Limestone	P	Permian	26.6	2.71	-30.20	-30.30	-2.51	0.60	n.d.	Upper Valley Unit 31	Garfield	Utah	6895-7020	Spinkel and others, 1997
S14	Upper Valley	Kaibab Limestone	P	Permian	19.9	2.94	-30.10	-30.20	-2.54	0.80	n.d.	Little Valley 1	Garfield	Utah	7806-7630	Spinkel and others, 1997
S17	Virgin	Kaibab Limestone	P	Permian	n.d.	n.d.	-29.70	-29.90	-2.80	0.60	n.d.	tank battery	Washington	Utah	surface	Spinkel and others, 1997

¹ oil gravity in degrees API² weight percent sulfur³ $\delta^{13}\text{C}$ saturates in Pee Dee Belemnite (PDB) standard in parts per thousand⁴ $\delta^{13}\text{C}$ aromatics in Pee Dee Belemnite (PDB) standard in parts per thousand⁵ canonical variable (Sofer, 1984)⁶ pristane/phytane⁷ carbon preferential index (Hunt, 1979)

n.d. = no data

T - Tertiary

J - Jurassic

Tr - Triassic

P - Permian

IP - Pennsylvanian

D - Devonian

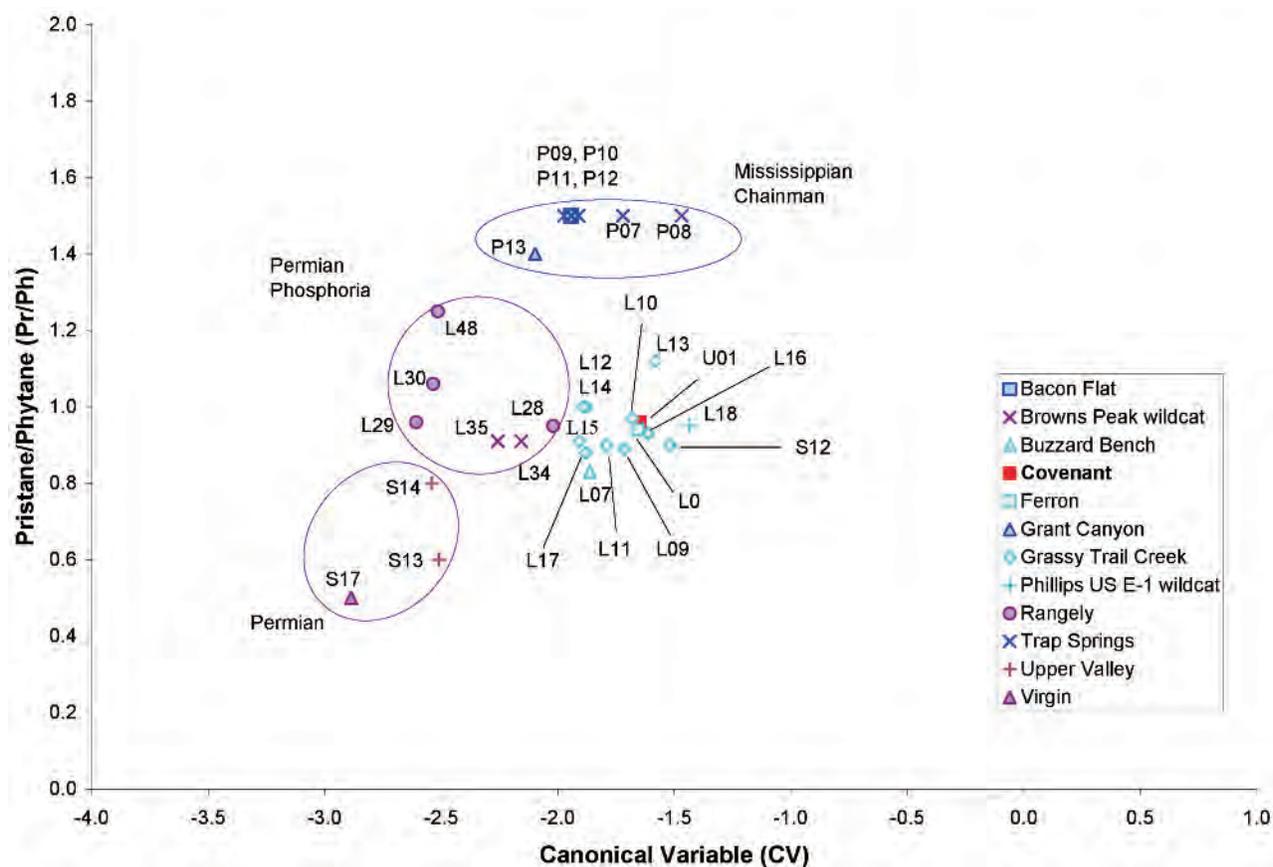


Figure 16. Canonical variable (CV) versus pristane/phytane values from the Covenant field oil and other key oils from Utah, Colorado, and Nevada (see figure 15 for field locations). The plot suggests the Covenant field oil is not likely derived from the Mississippian Chainman Shale, a major source of oil in Nevada, or the Permian Phosphoria Formation, a source of oil in Wyoming, northwestern Colorado, and northeastern Utah. This does not preclude the source of oil in the Covenant field from being a local Carboniferous organic-rich source bed. Correlation presented here is based on this plot only; other geochemical parameters should be used to fully evaluate the correlation of oils.

where they would have been deeply buried and too highly “cooked,” resulting in the migration of hydrocarbons prior to the formation of the thrust belt traps. In central Utah, the question remains whether these rocks have been buried deep enough on the western parts of the hanging walls of the thrust faults to generate hydrocarbons. However, at least as far east as the Paxton thrust (figure 1), the Mississippian section lies just below the basal décollement in the footwall where thrust loading could have generated hydrocarbons. Finally, just south of the Covenant field area, heat from Tertiary (Oligocene) volcanism may have provided an extra mechanism to stimulate hydrocarbon generation.

SUMMARY

1. The 2004 discovery of Covenant field changed the oil development potential in the central Utah thrust belt (part of the Sevier thrust belt [Utah’s Hingeline]) from hypothetical to proven and showed that the region contains the right components (trap, reservoir, seal, source, and migration history) for large accumulations of oil.

2. The Covenant trap is an elongate, symmetric, north-east-trending anticline, with nearly 800 feet (270 m) of structural closure and bounded on the east by a series of splay thrusts in a passive roof duplex along the “blind” Gunnison-Salina thrust; the producing reservoir is the eolian Jurassic Navajo Sandstone. The Navajo is repeated due to an east-dipping back-thrust detachment within the structure. Only the Navajo in the hanging wall of the back thrust is currently productive; future production is possible from the overlying Jurassic Twin Creek Limestone or deeper Paleozoic strata. The Navajo reservoir is effectively sealed primarily by mudstone and evaporite beds in the Jurassic Arapien Shale.
3. The Navajo Sandstone was deposited in an extensive dune field that extended from Wyoming to Arizona. Playas, mudflats, and oases developed in interdune areas. The Navajo has heterogeneous reservoir properties because of (1) cyclic dune/interdune lithofacies with variable porosity and permeability that developed in certain dune morphologies, (2) fracturing, and (3) minor diagenetic effects. At Covenant field, the

- Navajo is divided into lower, middle, and upper units. On geophysical well logs both lower and upper units appear as massive, homogeneous sandstone. Cores and outcrop observations reveal these units are heterogeneous, containing a variety of eolian lithofacies: thick, thin continuous, thin discontinuous, massive, and interdune; each lithofacies has characteristic petrophysical properties.
4. The Navajo Sandstone at Covenant field has 424 feet (129 m) of net pay, an average of 12% porosity, as much as 100 mD of permeability, an average water saturation of 38%, and a strong water drive. Cumulative production from 10 wells, as of January 1, 2007, was 3,106,099 bbls (493,870 m³) of oil, averaging 5400 bbls (860 m³) of oil per day; there has been no gas produced at Covenant field. The original oil in place is estimated at 100 million bbls (15.9 million m³); the estimated recovery factor is 40% to 50%.
 5. Hydrocarbons in the Navajo Sandstone reservoir were most likely generated from Carboniferous source rocks during Cretaceous to early Tertiary time. The source rocks began to mature after loading or overridding by thrust plates. Hydrocarbons were then generated, expelled, and subsequently migrated into

the overlying trap, primarily along fault planes or through porous Paleozoic and Mesozoic carrier beds.

6. The lack of associated gas at Covenant field suggests the possibility that gas-charged traps may be present in the central Utah thrust belt.

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