PETROLEUM GEOLOGY OF PROVIDENCE OIL FIELD, CENTRAL UTAH THRUST BELT

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ABSTRACT

Providence field, Sanpete County, was discovered in 2008 and confirmed the hydrocarbon development potential in the central Utah thrust belt, or "Hingeline," proving that the region contains the right components (trap, reservoir, seal, source, and migration history) for large accumulations of oil and gas. The producing reservoir at Providence field is the eolian, Jurassic Navajo Sandstone. The basic trap is an elongate, symmetric, northeast-trending fault-bend fold with a hanging wall splay along the Salina thrust. The Navajo Sandstone is repeated with both the "First" and "Second" Navajo Sandstones being oil and gas productive. The trap for the First Navajo is formed by the main fault-bend fold along the thrust. The Second Navajo trap is a relatively small, isolated fault splay under the main fault-bend fold.

In general, the Navajo Sandstone reservoir consists of very well to well-sorted, very fine to medium-grained, subangular to subrounded sand or silt grains cemented by silica cement. The typical sandstone is 97% white or clear quartz grains (most frosted) with varying amounts of K-feldspar and lithics. The porosity and permeability values are moderate to low; water saturation ranges from 33 to 49%. Mudstone, siltstone, and thin and argillaceous carbonate intervals within the Sinawava Member of the Jurassic Temple Cap Formation serve as the seal for the First Navajo. The seal for the Second Navajo is formed by a hanging-wall cutoff placing the reservoir in contact with undifferentiated Permian strata and the impermeable Triassic Moenkopi Formation.

Oil from the First Navajo is a reddish brown, low-volatile crude; the solution gas is composed of approximately 81% carbon dioxide, 6% nitrogen, and only 13% hydrocarbons. The Second Navajo oil is a yellow, high-volatile crude; the gas is composed of approximately 80% methane and higher hydrocarbons, 12% nitrogen, and 8% carbon dioxide. The hydrocarbons were generated from Carboniferous source rocks within the Salina thrust plate. Hydrocarbon migration occurred 70 to 80 million years ago, concurrent with the creation of the Providence structure. Differential thermal stress accounts for variations between the hydrocarbon components of the First and Second Navajo Sandstones. The presence of non-hydrocarbon gases at Providence field suggests an independent source and migration event for the gases.

The original oil in place for the field is estimated at 10.7 million stock tank barrels (1.7 million m^3); estimated in place gas reserves are estimated at nearly 32 billion cubic feet (0.9 BCM) including the large component of carbon dioxide and nitrogen. The estimated ultimate recovery of oil and gas, and the economic feasibility of the field will be determined from additional reservoir testing which will lead to a long-term production plan for Providence.

INTRODUCTION

In 2004, Michigan-based Wolverine Gas & Oil Corporation (herein referred to as Wolverine) announced the most significant Utah oil discoveries in nearly 30 years – Covenant field in the central Utah thrust belt (figure 1). This region, often referred to by many geologists as "the Hingeline," had seen petroleum exploration for over 50 years but with no success. Explorationists viewed the geology as a natural extension of producing plays in the Utah-Wyoming-Idaho salient of the Sevier thrust belt to the north. This view changed as the Covenant discovery showed that, in actuality, a number of significant geologic differences exist between the two regions and introduced a new play concept. The hydrocarbon potential in the central Utah thrust belt went from hypothetical to proven with the play containing all the right components (trap, reservoir, seal, source, and migration history) for large accumulations of oil and gas. In 2008, Wolverine added a second discovery on the trend 20 miles (32 km) to the northeast, Providence field (figure 1), confirming that Covenant field was not just what some might call a "one-

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field wonder" (see Chidsey and others [2007]; Chidsey, in preparation, for a complete description of Covenant).

Providence field is located about 5 miles (8 km) southwest of the small town of Mayfield and 3.5 miles (5.6 km) east of Utah Highway 89 in Sanpete County, Utah (figure 1). The producing oil and gas reservoir is the eolian, Jurassic Navajo Sandstone (figure 2), which therefore is the primary focus of this field description that includes structural geology and trap mechanism, stratigraphy, depositional environments, and reservoir characteristics. We also briefly describe the completion practices, estimated petroleum reserves, and potential hydrocarbon source/migration history of Providence field.

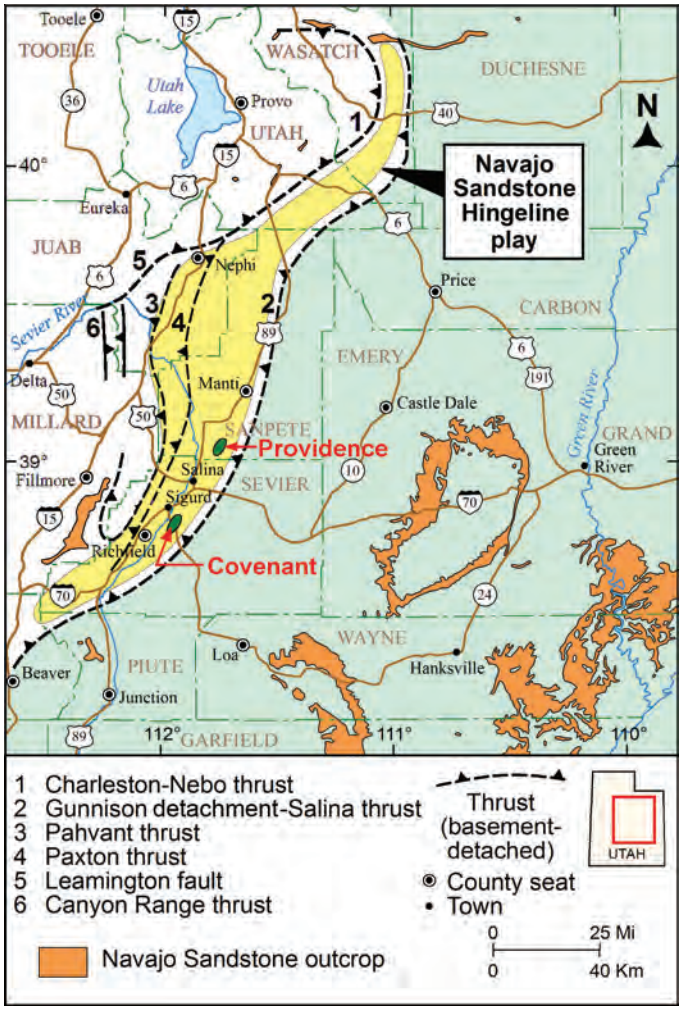

Figure 1. *Location of Providence and Covenant oil fields, uplifts, and selected thrust systems in the central Utah thrust belt province. Numbers and sawteeth are on the hanging wall of the corresponding thrust system. Yellow shaded area shows the potential extent of the Jurassic Navajo Sandstone "Hingeline" 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).*

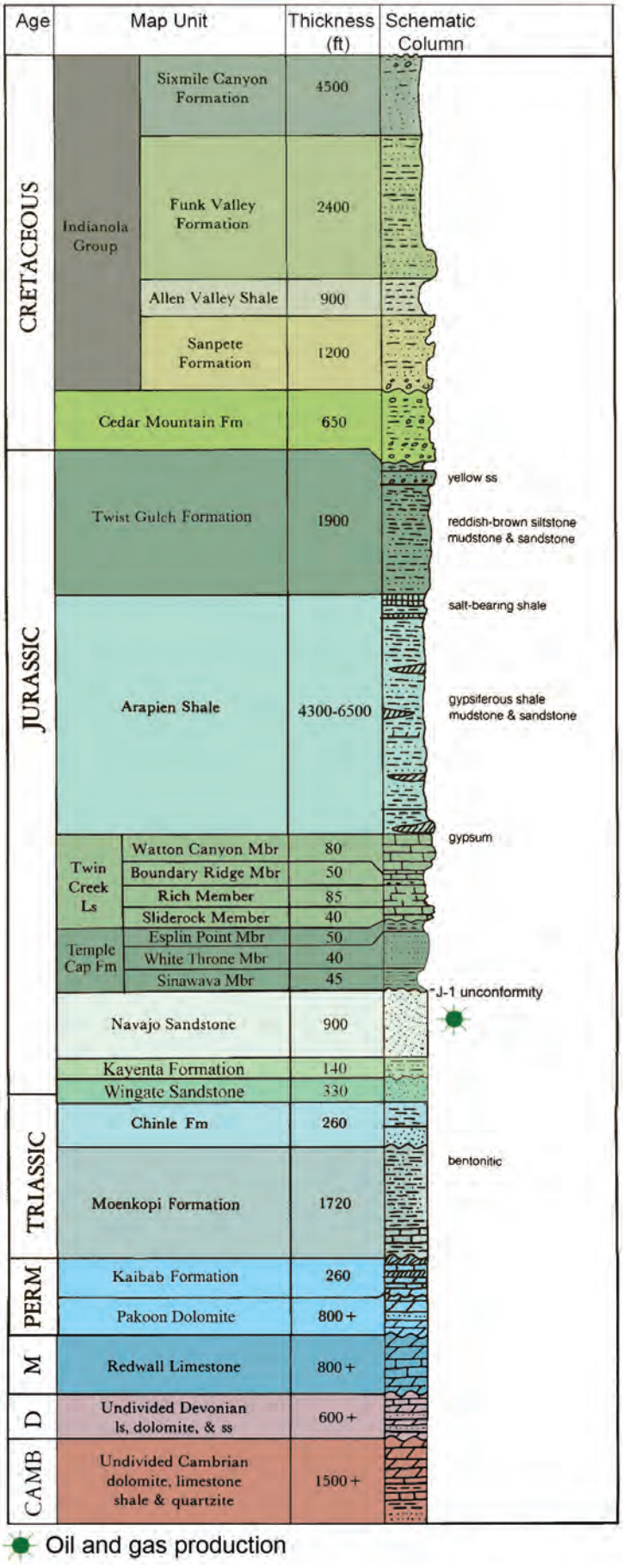

Figure 2. *Stratigraphic column of a portion of the Paleozoic and Mesozoic section in central Utah. Modified from Hintze and Kowallis (2009).*

STRUCTURE

Regional Geologic Setting

The central Utah thrust belt or Hingeline is more than 100 miles (160 km) wide and is part of the Sevier thrust belt, which extends through the entire state. 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 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 represented 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. At present it forms the general boundary in central Utah between the Basin and Range and Colorado Plateau physiographic provinces.

In reality, the Hingeline is a zone rather than a sharp boundary, 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 carbonate rocks thicken westward across the Hingeline area (which represented a passive continental margin during the Paleozoic) from thin eastern cratonic deposits. The Upper Cretaceous section in the Hingeline area includes thick synorogenic deposits reflecting proximity of the Sevier orogenic belt to the west; these rocks also thin to the east. 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, 2007). 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, 2007; 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).

Major thrust faults in central Utah (from west to east) include the Canyon Range thrust, Leamington fault, Pahvant thrust, Paxton thrust (Royse, 1993), Charleston-Nebo thrust system, Gunnison detachment, and Salina thrust (Villien and Kligfield, 1986; Schelling and others, 2007) (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). Eastern 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 the Albian, the Paxton thrust was emplaced in the Santonian, and the Gunnison detachment-Salina thrust was active from late Campanian through early Paleocene time (DeCelles and Coogan, 2006). The Ephraim fault and other high-angle, basement-involved faults in central Utah 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 detachment-Salina thrust. The Pahvant, Paxton, and Gunnison detachment-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, and ramp anticlines (fault-bend folds) such as the huge fold that makes up most of Mount Nebo (near the town 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 up to 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 western plates (Willis, 1999). Basement-involved extensional faults in the region, such as the Ephraim, determined the position of these ramp anticlines and associated duplexes along thrust systems by acting as buttresses to plate movement (Schelling and others, 2005, 2007). 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 décollement form fault-propagation and fault-bend folds, creating some of the producing anticlines on the Wasatch Plateau.

Deformation related to compression continued to about 41 Ma in central Utah and was quickly followed by pre-Basin and Range extension (Judge, 2007). It was during this early extension period (middle to late Eocene) that the Wasatch monocline and associated structures formed, likely as a result of relaxation (reversed movement) along the back thrust system on the east side of the San Pitch Mountains (Weiss and Sprinkel, 2002; Cline and Bartley, 2007; Judge, 2007; Judge and others, this volume). Continued extension in the Neogene likely reactivated movement along some thrust ramps, splays, and associated back thrusts which formed listric normal faults. Other normal faults related to Basin and Range extension dissected thrust plates into additional, compartmentalized

blocks (Schelling and others, 2005, 2007). Some local, tectonically driven ductile deformation of Jurassic evaporites further complicated the structural picture of the region (Witkind, 1982; Schelling and others, 2007).

Internal deformation within large-scale thrust plates includes frontal and lateral duplex zones. The deformation front along the leading edge of these major thrusts, particularly the Paxton and Gunnison detachment-Salina thrusts, includes complex back thrusting, tectonic-wedge formation, triangle zones, fault-propagation and fault-bend folds, and passive-roof duplexing (Schelling and others, 2005, 2007). Low-amplitude, fault-bend anticlines in the hanging walls of thrusts associated with these features form multiple structural traps—the targets of the Covenant and Providence discoveries. These features are obscured by complex surface geology that includes: (1) major folds, (2) angular unconformities, (3) Oligocene volcanic rocks, (4) pre-Basin and Range (middle to late Eocene) to Basin and Range (Miocene-Holocene) listric(?) normal faulting, and (5) local diapirism. Basement-involved 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, 2007; Strickland and others, 2005).

Providence Field

Surface Geology

Providence field is located within the White Hills (figure 3), a major north-northeast to south-southwest-trending exposure and type area of the Middle Jurassic Arapien Shale. It is expressed as a classic example of badland topography. The Arapien consists mainly of thin-bedded mudstone and calcareous mudstone, muddy limestone, and siltstone. Gypsum and rock salt (halite) are present in several units, often as thick (300 to 450 feet [100-150 m]) pods in the axes of folds (Weiss, 1994). Bedding is commonly contorted and red, white, or light gray in color. One small outcrop of the Middle to Upper Jurassic Twist Gulch Formation, reddish-brown mudstone and siltstone, has been mapped 1 mile (1.6 km) southwest of the field (figure 3) (Witkind and others, 1987).

Tertiary rocks are exposed both east and west of Providence field (figure 3). They include the Eocene Green River and Crazy Hollow Formations; exposures of the Paleocene Flagstaff Limestone and Eocene Colton Formation are also present in the area (figure 3). The Green River consists of light to greenish-gray lacustrine shale, calcareous mudstone, and limestone deposited in Lake Uinta. The Crazy Hollow was a non-lacustrine fill, mainly red mudstone, of the southwest arm of Lake Uinta (Weiss, 1994). Unconsolidated Tertiary and Quaternary deposits in the field area include pediment mantle, alluvial fans, earth flow, slope wash, and alluvium (figure 3).

Structurally, the Arapien Shale in the White Hills represents the core of the Sanpete-Sevier Valley antiform. The core is an overturned anticline with multiple thrusts (including back thrusts) resulting from Cretaceous- to Eocene-age lateral compression of the Sevier orogeny (Standlee, 1982; Lawton, 1985; Weiss, 1994; Weiss and Sprinkel, 2002; Judge, 2007). The contact between the Arapien Shale and the Green River Formation west of Providence field is a west-directed back thrust, with a possible component of relaxation, that strikes north-south through the area (figure 3). Similar structural features involving the Arapien have been mapped and described throughout the region (Lawton and Weiss, 1999; Weiss and Sprinkel, 2002; Judge, 2007; Morris and others, 2007; Schelling and others, 2007). Subsequent local diapirism within the Arapien has also occurred (Witkind, 1982). East of the field, the dominant structural feature is the west-dipping Wasatch monocline. It forms the west flank of the Wasatch Plateau, exposing strata of the Green River, Colton, and Flagstaff Formations (figure 3). A series of north-northeast to south-southwest-trending, high angle and down-to-east, normal faults cut the monocline (figure 3) (Witkind and others, 1987; Weiss, 1994). These faults are likely antithetic with small throws and die out in the thick Cretaceous section or the Arapien at depth.

Trapping Mechanisms

Providence field (figure 1) is located along the east flank of the Sanpete-Sevier Valley antiform. In this area, thrust imbricates or imbricate fans above the Salina thrust and antiformal stacks of horses forming a duplex below the thrust create multiple, potential drilling targets (Villien and Kligfield, 1986; Schelling and others, 2005, 2007; Strickland and others, 2005). The Ephraim fault east of these features served to buttress movement of the Salina plate, thus causing thrust imbrication.

Providence field lies on trend with, and has a trap similar to Covenant field to the southwest—an elongate, symmetric, northeast-trending fault-bend anticline (figures 4 and 5). The structure formed above a series of splay thrusts in a passive roof duplex along the Salina thrust, west of a probable frontal triangle zone within the Arapien Shale (figure 5), and west of the Ephraim fault (not shown on figure 5). The Federal Arapien Valley No. 24-1 discovery well (SW1/4NW1/4 section 24, T. 20 S., R. 1 E., Salt Lake Base Line and Meridian [SLBL&M]) was drilled in 2008 based on geophysical seismic data. The Navajo Sandstone is repeated with both sections being oil and gas productive (figure 5 and 6). The well penetrated Navajo sections at the drilled depths of 8936 feet (2724 m; sub-sea-level depths of -3356 feet [-1023 m]) and 12,121 (3695 m; -6541 feet [-1994 m]), respectively (figures 5 and 6).

The upper Navajo ("First" Navajo) trap is formed by the main fault-bend fold along the Salina thrust (figures 4 and 5). The amount of structural closure has yet to be fully defined; the height of the hydrocarbon column is about 350 feet (107 m). The lower Navajo ("Second" Navajo) trap is a relatively small, isolated fault splay under the main fault-bend fold. The height of the lower hydrocarbon column is about 280 feet (85 m). Unlike Covenant field, no back thrust is present within the trap by the current interpretation. The dipmeter in the Arapien Valley No. 24-1 well indicates that the First Navajo was encountered on the crest of the structure while the Second Navajo dips steeply east perhaps due to drag along the overlying thrust splay. The

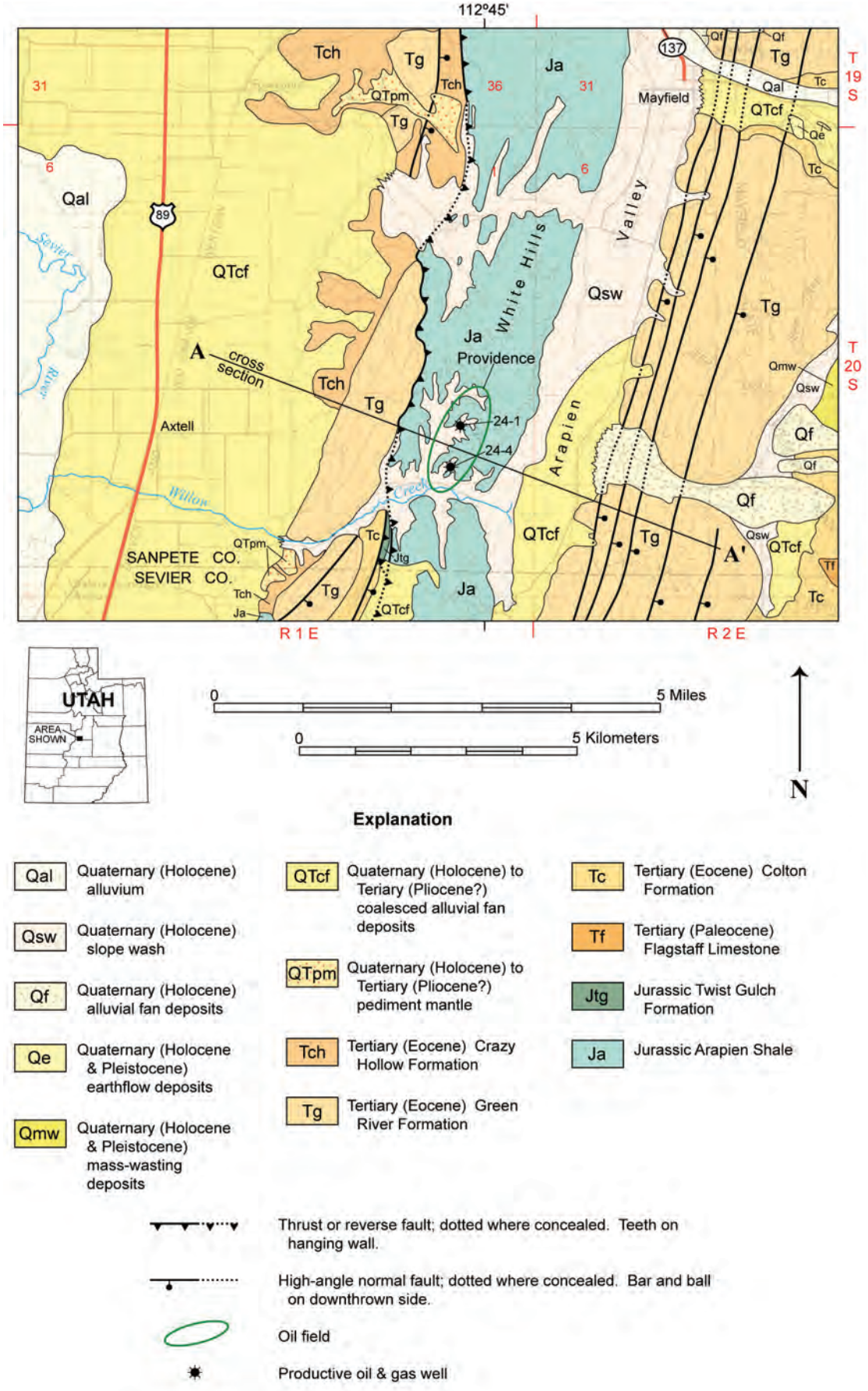

Figure 3. *Geologic map showing surficial strata, sediments, and faulting in the Providence field area, Sanpete and Sevier Counties. Modified from Witkind and others (1987). Cross section A-A' shown on figure 5.*

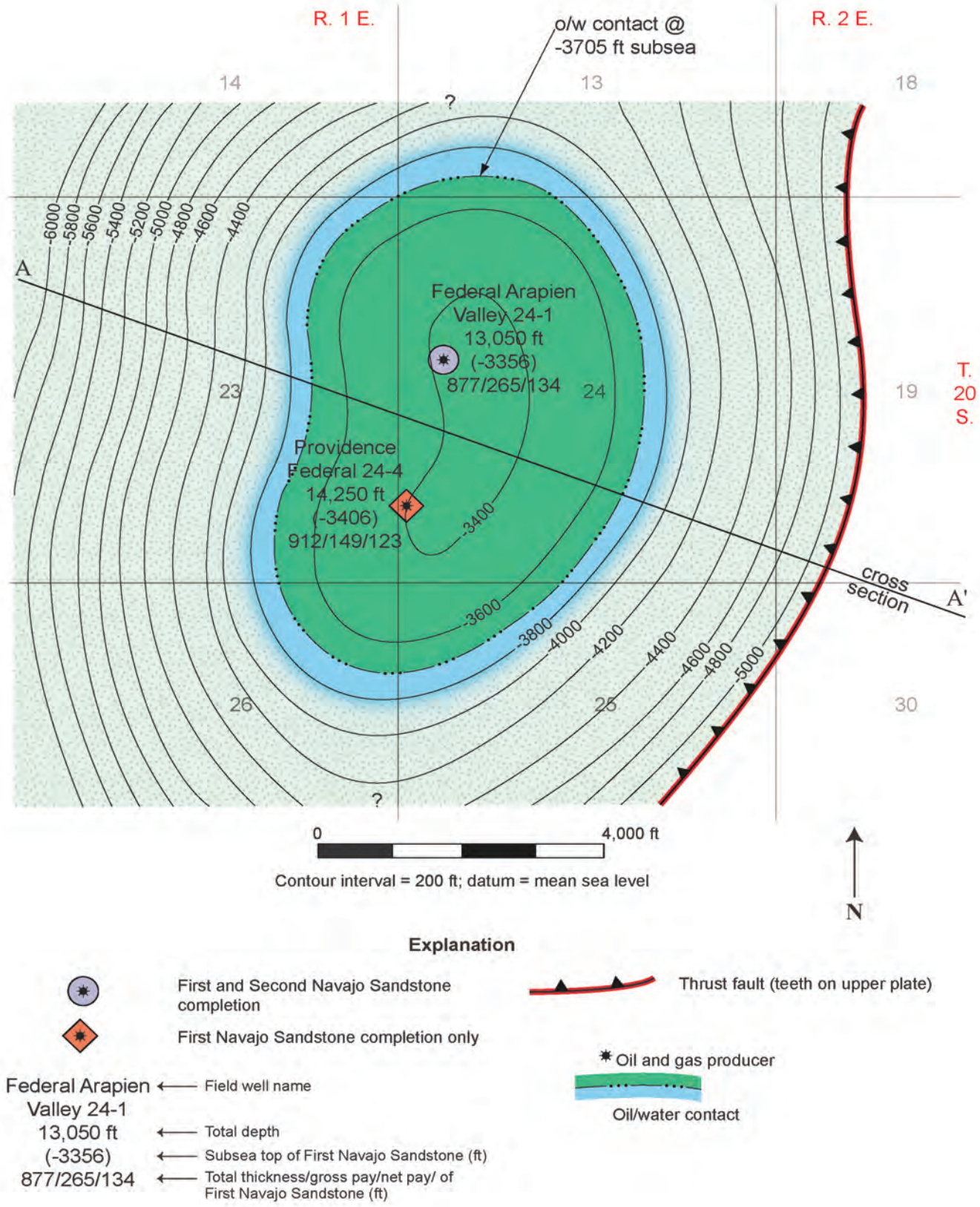

Figure 4. *Structure contour map of the top of the First Navajo Sandstone, Providence field, based on subsurface well control and the structural cross section (note: this interpretation was produced by the Utah Geological Survey and may not represent that of Wolverine Gas & Oil Corp.). Contour interval = 200 feet, datum = mean sea level. Cross section A-A', which extends beyond the edges of this figure, is shown on figure 5.*

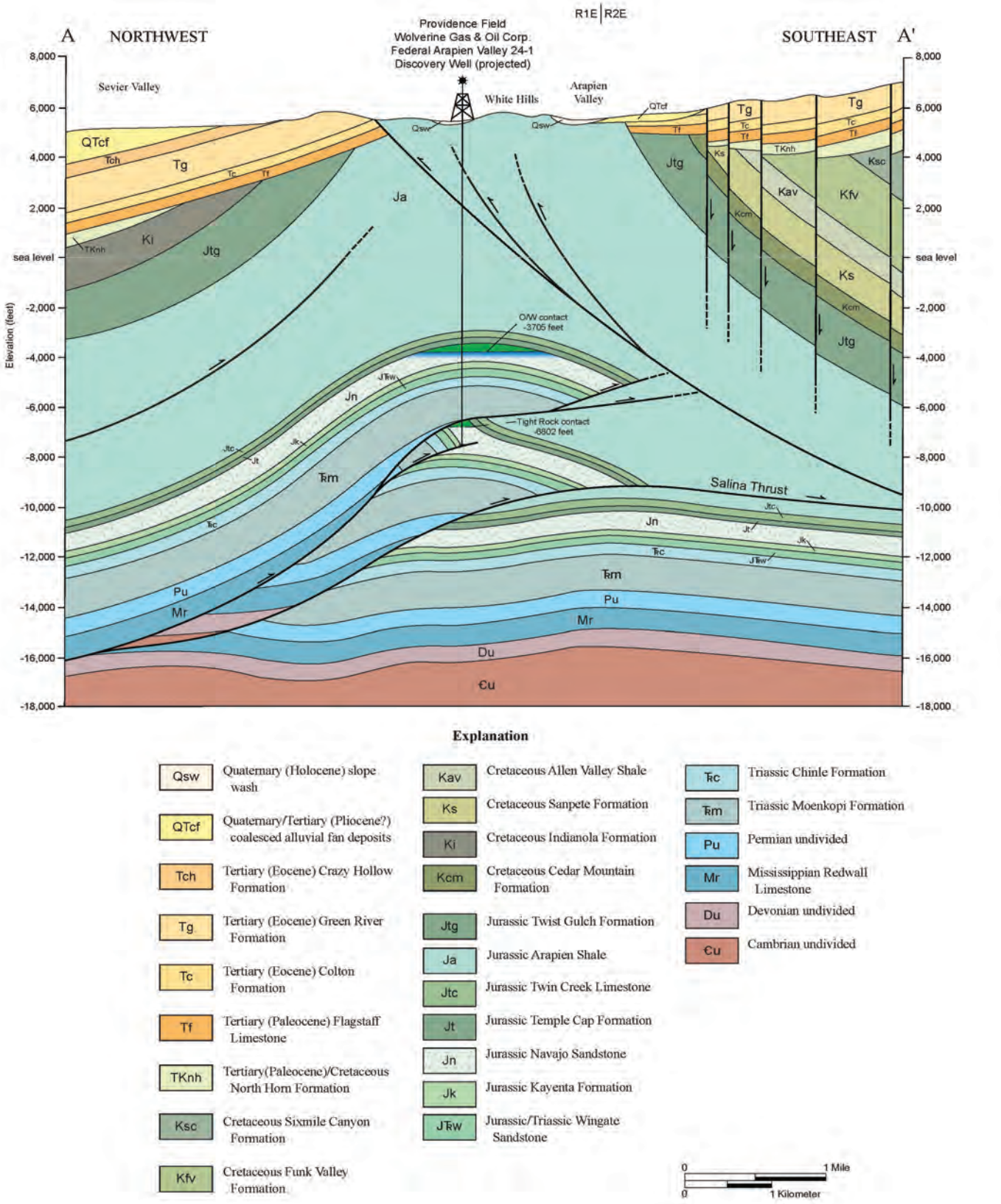

Figure 5. *Northwest-southeast structural cross section through Providence field. Note small splay thrust through the anticline that results in a repeated Navajo Sandstone section. A small horse consisting of Temple Cap Formation present above the Second Navajo Sandstone (see figure 6) is not shown due to the scale of the cross section. Line of cross section shown on figures 3 and 4. Surface geology modified from Witkind and others (1987); subsurface interpretation modified from an unpublished section constructed by D. Schelling and a hearing exhibit from the Utah Division of Oil, Gas, and Mining (2010a).*

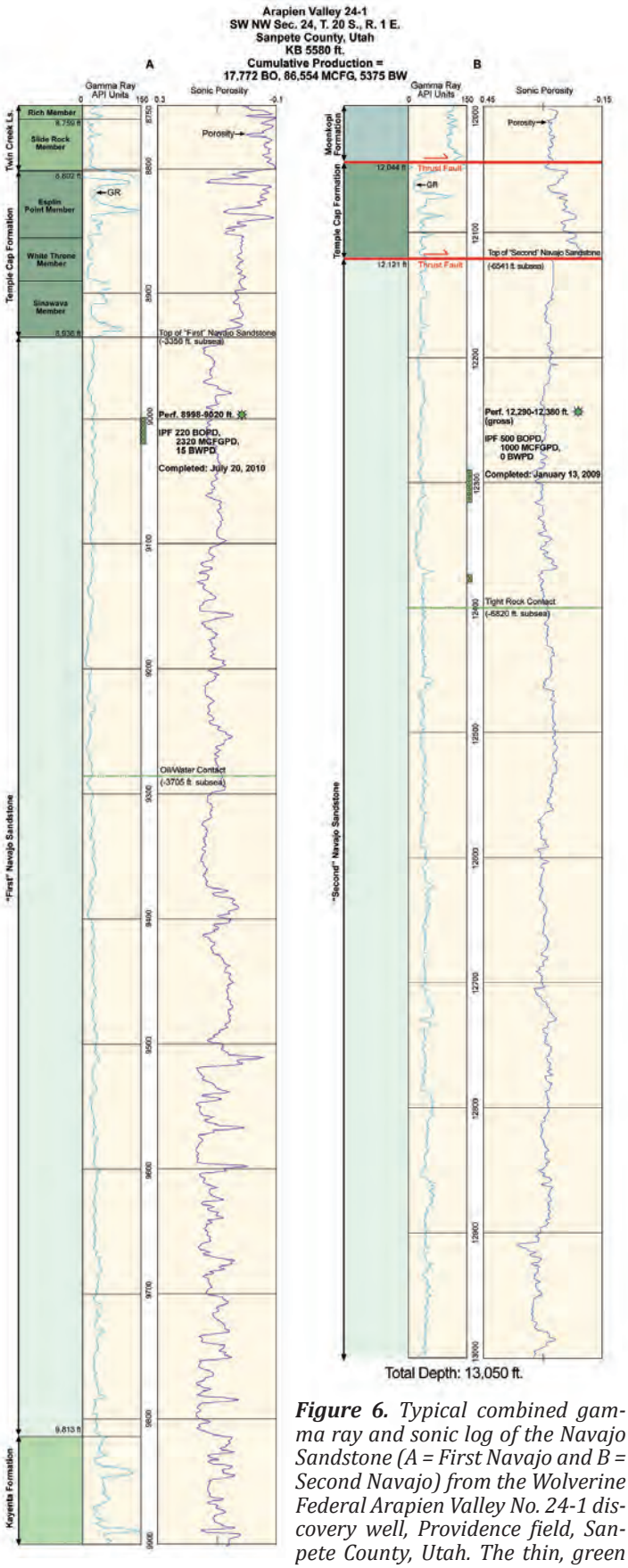

Figure 6. *Typical combined gamma ray and sonic log of the Navajo Sandstone (A = First Navajo and B = Second Navajo) from the Wolverine Federal Arapien Valley No. 24-1 discovery well, Providence field, Sanpete County, Utah. The thin, green vertical bars on the logs indicate producing (perforated) intervals.*

Second Navajo in the Arapien Valley No. 24-1 well is 2033 feet (-620 m) structurally higher than the Second Navajo in the Providence No. 24-4 well, about 0.3 miles (0.5 km) southwest. The Providence structure extends to greater depths than the Navajo (figure 5), however, the section has been penetrated to the Triassic Moenkopi Formation above the Salina thrust fault with no productive zones in the Triassic and lower Jurassic sandstones.

Seal

The principal regional seal for the Navajo producing zones consists of salt, gypsum, and mudstone in the overlying Arapien Shale (figure 2). Mudstone, siltstone, and thin argillaceous carbonate intervals within the Sinawava Member of the Jurassic Temple Cap Formation (figure 2) serve as the seal for the First Navajo at Providence field (figure 5). The seal for the Second Navajo is formed by a hanging-wall cutoff placing the reservoir in contact with the impermeable Moenkopi Formation and a small horse block of the Sinawava and White Throne Members of the Temple Cap (figure 5). Interdunal and other low permeability lithofacies within the Navajo Sandstone, and possible unrecognized splay and back-thrust faults may act as local seals, barriers, or baffles to fluid flow.

STRATIGRAPHY

Thickness, Age, and Regional Correlation

The Navajo Sandstone is 610 to 1620 feet (190-490 m) thick in the region (Hintze and Kowallis, 2009) and has a characteristic geophysical log response (figure 6). The Navajo is Early Jurassic (Pliensbachian/Toarcian) in age and forms many of the spectacular canyons in the parks of southern Utah (Zion Canyon National Park and Glen Canyon National Recreation Area, for example). It is also exposed east and west of Providence 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).

The Navajo Sandstone is underlain by fluvial channel deposits of the Lower Jurassic Kayenta Formation (figure 2). The Navajo is overlain by Early to Middle Jurassic (Pliensbachian to Bajocian) Temple Cap Formation in central Utah (Sprinkel and others, 2010; Kowallis and others, 2011) (figure 2). The Temple Cap is divided into the three members: the Sinawava (basal), White Throne, and an unnamed upper member (Sprinkel and others, 2009; Biek and others, 2010). Sprinkel and others (Utah Geological Survey, verbal communications, 2011) plan to propose the name Esplin Point for the unnamed upper member in a formal publication that is in progress; thus, we will use that name in this article. In this part of central Utah, the J-1 unconformity is found at the contact between the Navajo and Temple Cap, and corresponds to a gap of 2 to 3 million years (Pipiringos and O'Sullivan, 1978).

Depositional Environment

In Early Jurassic time, Utah had an arid climate and lay 15º north of the equator (Smith and others, 1981). The Navajo Sandstone and age-equivalent rocks were deposited in an extensive dune field (erg) 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. The eolian deposits included dunes, interdunes, and sand sheets (Picard, 1975; Fryberger, 1990; Dalrymple and Morris, 2007). Navajo dunes were large (widths up to 2200 feet [670 m]) to small, straight-crested to sinuous, coalescing, transverse barchanoid ridges as suggested by large-scale cross-bedding (Picard, 1975; Fryberger, 1990; Hartwick, 2010). Regional analyses of the mean dip of dune foreset beds indicate paleocurrent and paleowind directions were dominantly from the north and northwest (Kocurek and Dott, 1983).

Research on the geochronology of detrital zircon grains in the Navajo/Nugget Sandstone suggests that most of the sand was eroded from the ancestral Appalachian Mountains, transported to the west by a continental-scale river system to the western shore of North America during the Jurassic, and then blown southward into the Nugget/Navajo dune field (Dickinson and Gehrels, 2003, 2010; Rahl and others, 2003; Biek and others, 2010). The massive thickness of Navajo/Nugget sand was preserved because of basin subsidence associated with Early Jurassic compressional deformation near the west margin of North America (Allen and others, 2000; Biek and others, 2010). This deformation caused the continental interior to flex downward, creating accommodation space for sand and other sedimentary accumulations (Biek and others, 2010).

In addition to a "sea" of wind-blown sand dunes, the Navajo erg system included interdune playas and oases (Dalrymple and Morris, 2007). A high water table produced oases; deposition occurred when spring 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.

In late Early to Middle Jurassic time, a shallow seaway spread south from Canada to south-central and southwestern Utah (Blakey, 1994; Peterson, 1994; Hintze and Kowallis, 2009; Biek and others, 2010; Kowallis and others, 2011). The Sinawava Member immediately above the Navajo Sandstone signifies a change from eolian conditions to coastal sabkha and tidal flat environments. The overlying White Throne Member represents a brief return to eolian conditions along a coastal dune field (Blakey, 1994; Peterson, 1994); it is productive at Covenant field but not at Providence.

RESERVOIR AND HYDROCARBON CHARACTERISTICS

Lithologic and Petrophysical Properties

At Providence field, the Navajo Sandstone is about 880 feet (270 m) thick. On geophysical well logs it appears as massive, homogeneous sandstone (figure 6). However, the Navajo actually has heterogeneous reservoir properties because of (1) cyclic dune/interdune lithofacies with better porosity and permeability in certain dune morphologies, (2) fracturing, and (3) minor diagenetic effects. For example, a tight streak is present within the middle of the pay zone (9160 feet [2790 m]) of the First Navajo in the Arapien Valley No. 24-1 well (figure 6). These characteristics can also be observed in outcrops east of Providence field and in cores from Covenant field (figure 1; Chidsey and others, 2007; Dalrymple and Morris, 2007). In general, the Navajo consists of very well to well-sorted, very fine to medium-grained (1/16 mm to ½ mm), subangular to subrounded sand or silt grains cemented by silica cement. 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 First and Second Navajo Sandstone at Providence field is 10.7% and 5.5%, respectively, based on core-plug analysis. Sandstone likely contains significant secondary porosity in the form of fracturing. Fractures are related to fault-propagation folding during the Sevier orogeny after deep burial (Royse and others, 1975). Permeabilities in the First and Second Navajo from the core data are 8 millidarcies (mD) and less than 3.6 mD, respectively. The best permeability within Navajo dune deposits is along foreset bedding, with preferred directions along the dip and strike of the individual slipfaces 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.

Reservoir and Hydrocarbon Characteristics

First Navajo Sandstone

The First Navajo Sandstone maximum gross-pay thickness is 262 feet (80 m) and net-pay thickness is 134 feet (41 m) at Providence field, a net-to-gross ratio of 0.51. The reservoir temperature is 193ºF (89ºC). The average water saturation is 49%, and produced water resistivity (Rw) from the Federal Arapien Valley No. 24-1 well is 0.265 ohm-m at 70ºF (21ºC). The initial reservoir pressure averages about 3545 pounds per square inch (psi) (24,443 kPa). The reservoir drive mechanism is gas expansion with water drive. Geophysical well logs show a transition zone near the base of the pay (9195 feet [2803 m]; -3615 feet [-1102 m] subsea) in terms of water saturation above the oil/water contact (-3705 feet [-1129 m]) (figure 6). Perforations confirmed the highest water cuts are at the base of the pay zone in the Arapien Valley No.

24-1 well. No gas cap was found as additional perforations tested the well up hole.

The First Navajo oil is a reddish brown, high-volatile crude. The API gravity of the oil is 48.3º; the corresponding specific gravity is 0.7869 at 60ºF (16ºC) and molecular weight is 139. The pour point is -20ºF (-29ºC). The weight percent of paraffin is 2.4 to 2.5. Distillation results show the (1) gasoline fraction = 47% at 375ºF (191ºC), (2) naphtha fraction = 8% at 425ºF (218ºC), (3) kerosene fraction = 19% at 550ºF (288ºC), and (4) fuel oil (bottoms) fraction = 25% at +550ºF (+288ºC).

The producing solution gas to oil ratio (GOR) is 10,607 standard feet^3/stock tank barrels (SCF/STB) in the First Navajo. The gas is composed of approximately 81% carbon dioxide (CO_2), 6% nitrogen (N_2), 6% methane, 2% ethane, 2% propane, and 3% higher hydrocarbon components; hydrogen sulfide (H_2S) is 32 parts per million (ppm). The gas heating value is 306 British thermal units/feet^3 (Btu/ft^3). It has a specific gravity of 1.47, which is heavier than most produced solution gases because of the significant amount of heavier CO_2 rather than lighter methane. The viscosity of the solution gas was higher than expected, also due to the CO_2 content (Thomas W. Zadick, consulting reservoir engineer to Wolverine Gas & Oil Corp., verbal communication, February 24, 2010; Utah Division of Oil, Gas, and Mining, 2010b). The CO_2 in the field is interpreted to originate from a high temperature inorganic source by virtue of the carbon isotope signatures (-5.5 to -6.4‰), which is quite similar to that measured in CO_2 produced from the Navajo Sandstone at Farnham Dome field 10 miles (16 km) southeast of Price in Carbon County.

Second Navajo Sandstone

The Second Navajo Sandstone maximum gross-pay thickness is 279 feet (85 m) and net-pay thickness is 96 feet (29 m), a net-to-gross ratio of 0.34. The reservoir temperature is 244ºF (118ºC). The average water saturation is 33%, and the Rw of the produced water from the Federal Arapien Valley No. 24-1 well is the same as the First Navajo (0.265 ohm-m at 70ºF [21ºC]). The initial reservoir pressure averages about 4930 psi (33,990 kPa). The reservoir drive mechanism is gas expansion with limited (?) water drive. Geophysical well logs show a tight rock contact within the sandstone at -6820 feet (-2079 m) (figure 6). As in the First Navajo, no gas cap is present in the Second Navajo.

The Second Navajo oil is a yellow, high-volatile crude. The API gravity of the oil is 54.9º; the corresponding specific gravity is 0.7593 at 60ºF (16ºC) and molecular weight is 117. The pour point is -6 to -4ºF (-21 to -20ºC). The weight percent of paraffin is 4.4 to 4.6. Distillation results show the (1) gasoline fraction = 54% at 375ºF (191ºC), (2) naphtha fraction = 6% at 425ºF (218ºC), (3) kerosene fraction = 17% at 550ºF (288ºC), and (4) fuel oil (bottoms) fraction = 22% at +550ºF (+288ºC).

The producing GOR is 5702 SCF/STB. The produced gas is composed of approximately 63% methane, 8% ethane, 4% propane, 5% higher hydrocarbon components, 8% CO_2, and 12% N_2; H_2S is 1000 ppm. It has a specific gravity of 0.84 and the heating value is 1075 Btu/ft^3.

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 USA acquired nine seismic lines in the area of what would become the Wolverine Federal Unit, along with a swath survey over the Chevron USA Salina Unit No. 1 well (about 3.5 miles [5.6 km] north of the Covenant discovery well). These lines provided a complement to a very coarse seismic grid that Chevron acquired in the 1980s. In 2000, Wolverine Gas & Oil Corporation bought Chevron's leases and the 1990 vintage seismic data in the central Utah thrust belt. Wolverine reprocessed these seismic data along with Utah COCORP Line 3, mapped the structure 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, one drillable structure, and three single seismic line potential structures, although the first models predicted the frontal end of the thrust belt would be gas prone since the structure of interest (now known as Covenant field) formed after the primary oil migration event. In order for oil to be present in this particular structure, the presence of a paleo-trap was required (Wavrek and others, 2010). 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, and the Prospect Exchange in Calgary, Alberta (Johnson and others, 2007) 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 the Wolverine Federal Unit, Wolverine made its first discovery in the area—Covenant field—in late 2004.

Following the success at Covenant field, Wolverine invested significant capital by conducting extensive seismic programs, additional lease acquisitions, and exploratory drilling in the region. Little to no modern seismic data had been acquired over the northern portion of the Wolverine Federal Unit and no seismic data were ever acquired over the Providence field structure prior to Wolverine's 2005 program. The Federal Arapien Valley No. 24-1 well (figures 3 and 4) was spudded on November 9, 2007, and reached a total depth of 13,050 feet (3977 m). The Second Navajo Sandstone was completed on January 13, 2009, with an initial flowing potential (IPF) of 500 barrels of oil per day (BOPD) (80 m^3/d), 1000 thousand cubic feet of gas per day (MCFGPD) (28 m^3/d), and no water, from a gross perforated interval between 12,290 to 12,380 feet (3746-3773 m). The First Navajo was completed July 20, 2010, with an IPF of 220 BOPD (35 m^3/d), 2320 MCFGPD (66 m^3/d), and 15 barrels of water per day (2.4 m^3/d) from a perforated interval between 8998 to 9020 feet (2742-2749 m).

The Providence discovery has continued the interest

and exploratory drilling activity throughout the central Utah thrust belt that was renewed with the discovery of Covenant field. As was the case with the discovery of Covenant field, the drill sites are located close to small towns such as Salina and Mayfield. Thus, it has been again impossible to keep drilling and completion operations, as well as early production, completely away from both a curious industry and excited local citizens.

Completion Practices

Logging practice at Providence field is to run a full suite including gamma ray, spontaneous potential, laterolog, density, neutron, sonic, digital spectral, photoelectric, temperature, and x-tended range micro-imager geophysical logs, as well as rotary sidewall cores. The Arapien Valley No. 24-1 well was completed with 13-3/8-inch (34 cm) surface casing set to a depth of approximately 2000 feet (600 m), 9-5/8-inch (24.5 cm) intermediate casing set in the First Navajo at 10,370 feet (3160 m), and 5-1/2-inch (14 cm) production casing landed and cemented through the Navajo Sandstone at 12,755 feet (3888 m). The intermediate casing is set below the Arapien Shale to prevent possible salt flowage. The casing and wellhead are designed to accommodate CO_2 and small amounts of hydrogen sulfide. The production casing was perforated in selected Navajo intervals with six jet shots per foot. The perforations were broken down using small, 2% potassium chloride brine treatments, primarily to clean perforations of clays from drilling mud. The First Navajo was fracture stimulated with 26,000 gallons (98,000 L) of fluid and 10,120 pounds (lbs) (4590 kg) of 100 mesh and 60,000 lbs (27,000 kg) 20/40 mesh high-strength proppant (HSP [bauxite]); the Second Navajo was fracture stimulated with 29,148 gallons (110,325 L) of fluid and 50,000 lbs (23,000 kg) of 30/50 mesh HSP.

The White Throne Member of the Temple Cap Formation, productive at Covenant field, was also tested through perforations. However, it failed to flow any fluids and is considered non-productive at Providence field.

Production Analysis

Cumulative field production as of July 1, 2011, was 70,636 barrels of oil (BO) (11,231 m^3), 595,004 MCFG (16,851 MCMG), and 22,425 barrels of water (BW) (2969 m^3) (Utah Division of Oil, Gas, and Mining, 2011a). The field was shut in on February 22, 2011, for further testing and evaluation. Prior to that, daily production averaged 237 BO (38 m^3), 2601 MCFG (74 MCMG), and 72 BW (11 m^3) (Utah Division of Oil, Gas, and Mining, 2011b). There are no current well spacing orders for the field.

The field currently has two productive wells, drilled from separate pads. The Arapien Valley No. 24-1 discovery well is completed in the First and Second Navajo Sandstone zones. Cumulative production as of July 1, 2011, was 52,459 BO (8341 m^3), 492,212 MCFG (13,939 MCMG), and 10,102 BW (1606 m^3) (Utah Division of Oil, Gas, and Mining, 2011c). Prior to shut in, daily production averaged 199 BO (32 m^3), 2361 MCFG (67 MCMG), and 32 BW (5.1 m^3) (Utah Division of Oil, Gas, and Mining, 2011b). The Providence No. 24-4 well is only completed in the First Navajo; the Second Navajo is structurally below the oil/water contact. Cumulative production as of July 1, 2011, was 17,412 BO (2769 m^3), 97,788 MCFG (2769 MCMG), and 11,364 BW (1807 m^3) (Utah Division of Oil, Gas, and Mining, 2011c). Prior to shut in, daily production averaged 39 BO (6.2 m^3), 240 MCFG (6.8 MCMG), and 40 BW (6.4 m^3) (Utah Division of Oil, Gas, and Mining, 2011b).

Oil is trucked to Salt Lake City or other markets in the western U.S. The gas is flared while extended production testing is being conducted.

Oil and Gas Reserves

Although the productive area for Providence field has not been fully defined, original oil in place (OOIP) reserves are estimated at 10,740,310 stock tank barrels (STB) (1,707,709 m^3). The OOIP for First Navajo is estimated at 10,199,420 STB (1,621,708 m^3) and 540,890 STB (86,002 m^3) for the Second Navajo Sandstone. Estimated in place gas reserves are 31.6 billion cubic feet (BCF) (0.89 BCM) based on GORs from pressure/volume/temperature (PVT) analysis. Most of the gas reserves are from the First Navajo, estimated at 30.3 BCF (0.86 BCM) using a PVT-derived GOR of 2975: CO_2 = 24.5 BCF (0.69 BCM), N_2 = 1.7 BCF (0.05 BCM), methane = 1.8 BCF (0.051 BCM), ethane = 0.6 BCF (0.02 BCM), and the remainder other components. Estimated gas reserves for the Second Navajo are 1.3 BCF (0.04 BCM) using a PVT-derived GOR of 2380: methane = 0.8 BCF (0.02 BCM), N_2 = 0.15 BCF (0.004 BCM), ethane = 0.1 BCF (0.003 BCM), CO_2 = 0.1 BCF (0.003 BCM), and the remainder other components.

As of early 2011, Providence was continuing an extended production test that began in 2010 to validate the economic feasibility of the field. The ultimate configuration of production (that is, whether the gas will need to be re-injected or allowed to continue to flare) will be determined later in 2011. Thus, it is difficult to address an estimated ultimate recovery (EUR) of oil and gas at this stage without a long-term plan for the field in place.

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; Chidsey and others, 2007); 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 Providence and Covenant fields, a viable source rock is proven in the central Utah thrust belt. Several source candidates are present in the region (Wavrek and others, 2007, figure 7). 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; Chidsey and others, 2007), and the Permian Park City/Phosphoria Formation (Claypool and others, 1978; Sprinkel and others, 1997; Peterson, 2000, 2001). Representative source rock profiles from key wells on the Paxton and Aurora/Valley Mountain thrust plates to the west indicate that hundreds of feet of effective (>2% total organic carbon [TOC]) source rock are present (figure 8).

Comprehensive geochemical characterization of Covenant- and Providence-produced oil (figures 9 through 11) and Carboniferous (Mississippian-Pennsylvanian) source rock extracts show a good correlation by molecular and isotopic methods (Wavrek and others, 2005, 2007, 2010; Chidsey and others, 2007). It is acknowledged, however, that the samples from the correlative source-rock facies (i.e., anoxic sediment starved to slope facies) are all thermally overmature (e.g., the Carboniferous section at the Paxton, Sunset Canyon, and Barton wells [figure 8] have vitrinite reflectance values of 1.2, 1.6, and 2.0%, respectively) which requires differential thermal stress to be included into the interpretation process. The Carboniferous source rocks that are at moderate levels of thermal maturity (e.g., east of Ephraim fault) are from a different organic facies (i.e., shelfal condensed zone).

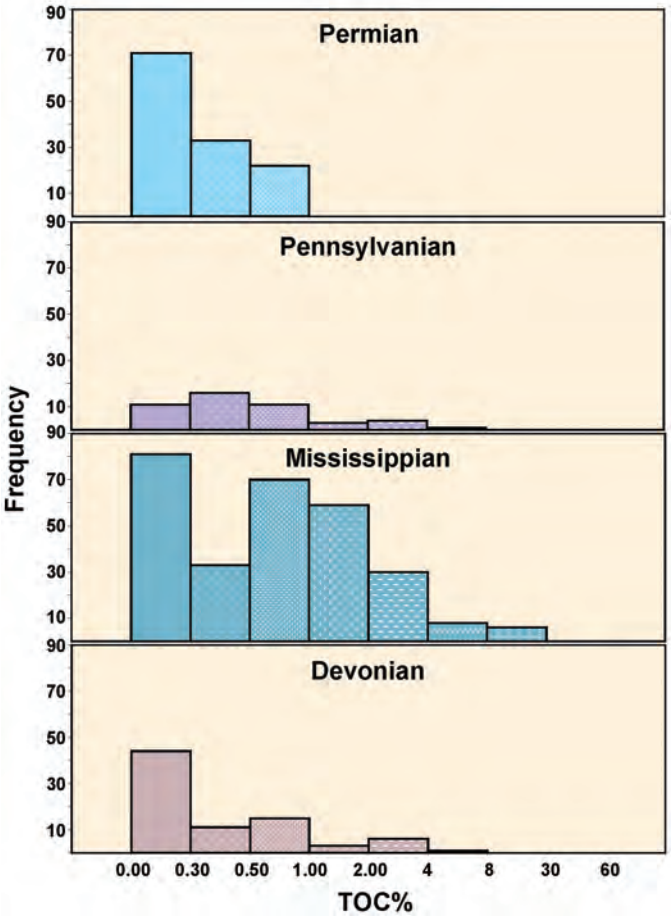

Figure 7. *Histograms of measured TOC data (n = 574) for Permian, Pennsylvanian, Mississippian, and Devonian source rocks from central and western Utah (Wavrek and others, 2007). Samples with evidence of staining from migrated hydrocarbons (particularly prevalent in the Permian section) have been removed from this display.*

Wavrek and others (2010) conducted a detailed analysis of the hydrocarbon charge at Providence field. Their work indicates a Carboniferous source within the Salina thrust plate and that hydrocarbon migration occurred 70 to 80 Ma, concurrent with the creation of the Providence structure. Hydrocarbons were then expelled and subsequently migrated into the trap, primarily along fault planes or through porous Paleozoic and Mesozoic carrier beds. Differential thermal stress and secondary alteration processes explain the differences in hydrocarbon constituents between the First and Second Navajo Sandstones (Wavrek and others, 2010). Finally, the isotopic composition of CO_2 and N_2 at Providence field likely represents a mixing event from inorganic sources separate from those responsible for the hydrocarbon charge (Wavrek and others, 2010). These inorganic components could have been generated and migrated from the Tertiary (Oligocene) volcanic activity that occurred in the region south of the Covenant and Providence field areas.

SUMMARY

1. The 2008 discovery of Providence field confirmed the hydrocarbon development potential in the central Utah thrust belt that began with the 2004 Covenant field discovery, proving that the region contains the right components (trap, reservoir, seal, source, and migration history) for multiple large accumulations of oil and gas.
2. The basic Providence trap is an elongate, symmetric, northeast-trending fault-bend fold with a hanging wall splay along the Salina thrust. The eolian Jurassic Navajo Sandstone is repeated, and both are oil and gas productive. The trap for the First Navajo is formed by the main fault-bend fold along the thrust. The Second Navajo trap is a relatively small, isolated fault splay under the main fault-bend fold. Mudstone, siltstone, and thin argillaceous carbonate intervals within the Sinawava Member of the Jurassic Temple Cap Formation serve as the seal for the First Navajo. The seal for the Second Navajo is formed by a hanging-wall cutoff placing the reservoir in contact with undifferentiated Permian strata and the impermeable Triassic Moenkopi Formation.
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. In general, the Navajo consists of very well to well-sorted, very fine to medium-grained, subangular to subrounded sand

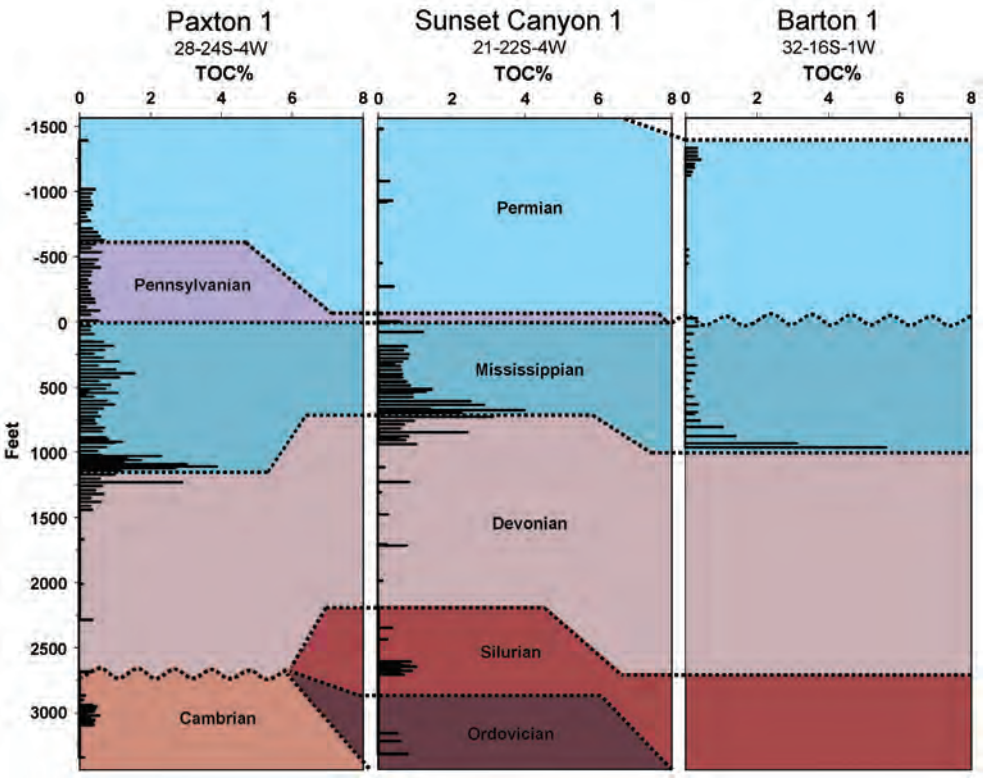

Figure 8. *Down-hole profiles of measured TOC for three key wells on the Paxton and Aurora/Valley Mountain thrust plates in the central Utah thrust belt with the datum at the top of the Mississippian section (Wavrek and others, 2007). The results demonstrate that the interval with highest source rock potential is located at the base of the Mississippian depositional sequence.*

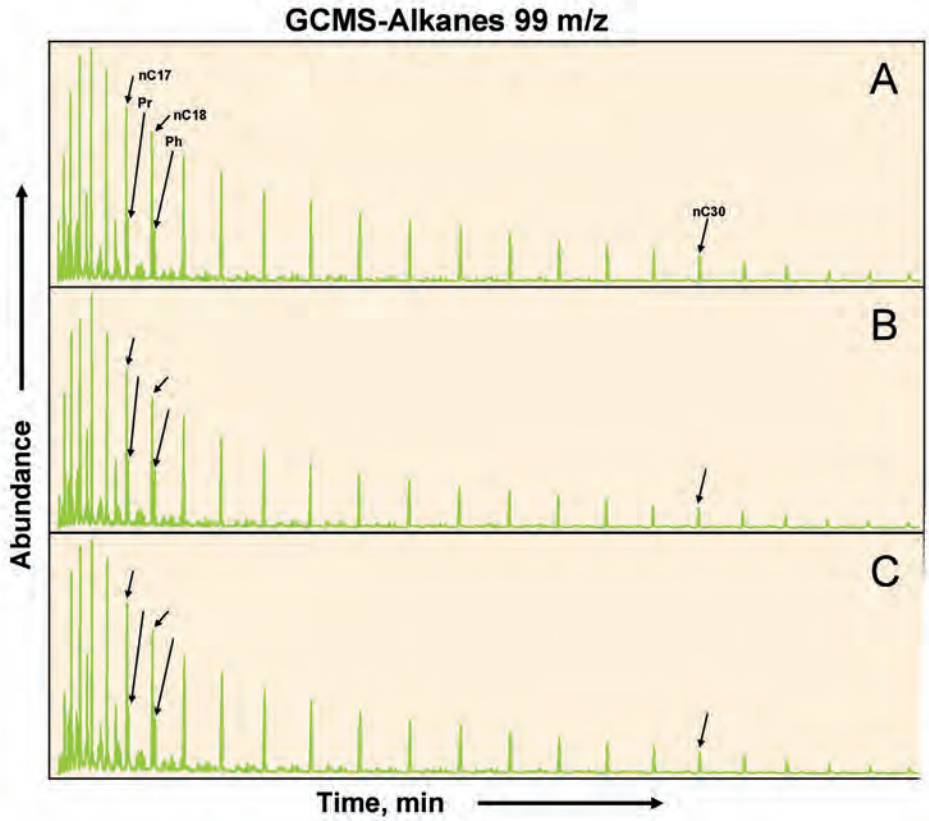

Figure 9. *Alkane profiles with key peak identities for Covenant (A), Providence First Navajo (B), and Providence Second Navajo (C) produced oils. Data are extracted from mass-to-charge ratio (m/z) 99 collected during saturate fraction gas chromatography-mass spectroscopy (GC-MS) analysis.*

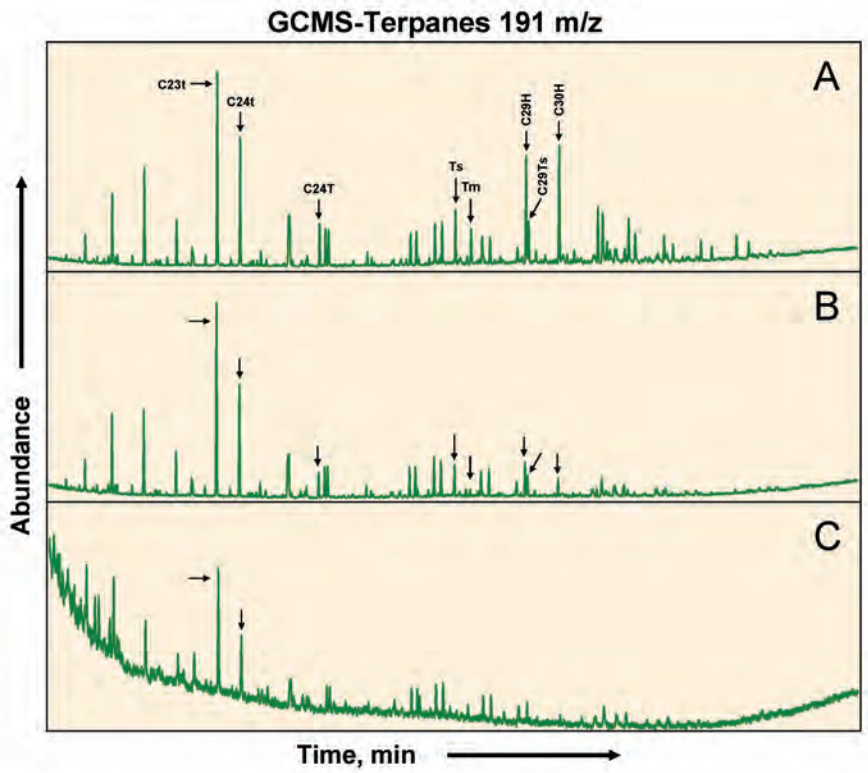

Figure 10. *Terpane profiles with key peak identities for Covenant (A), Providence First Navajo (B), and Providence Second Navajo (C) produced oils. These samples represent genetically related oils that have been subjected to progressively higher generation temperatures (i.e., A-C respectively, at 0.9-1.0, 1.1-1.2, and 1.2-1.3 vitrinite reflectance equivalence; Wavrek and others, 2010) that are manifested in differential thermal destruction of biomarker compounds. Data are extracted from m/z 191 collected during saturate fraction GC-MS analysis.*

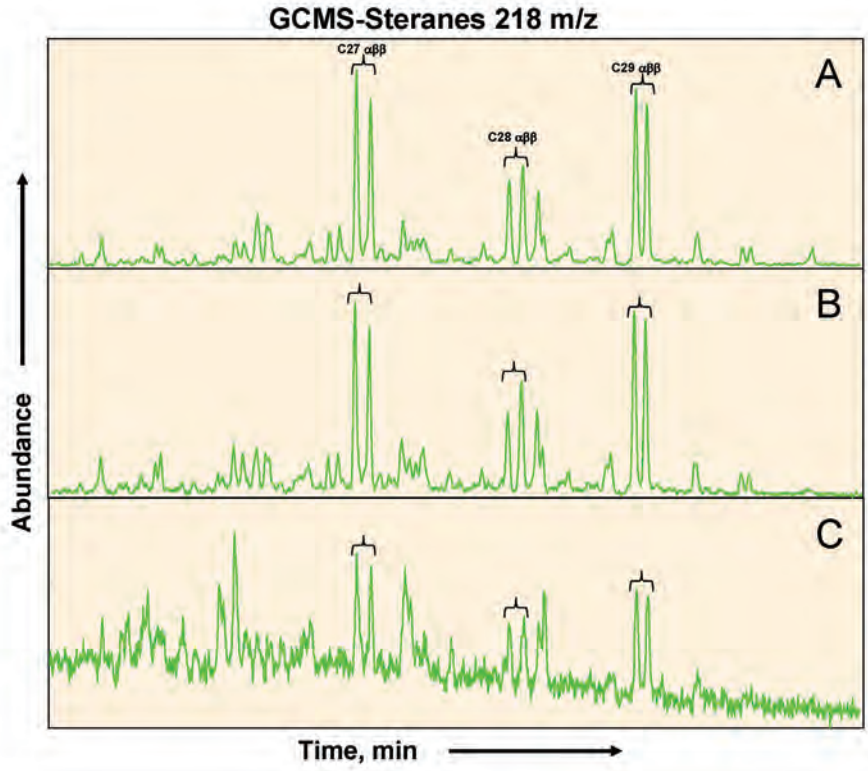

Figure 11. *Sterane profiles with key peak identities for Covenant (A), Providence First Navajo (B), and Providence Second Navajo (C) produced oils. Data are extracted from m/z 218 collected during saturate fraction GC-MS analysis.*

or silt grains cemented by silica cement. The typical sandstone is 97% white or clear quartz grains (most frosted) with varying amounts of K-feldspar and lithics.

4. The First Navajo Sandstone at Providence field has 134 feet (41 m) of net pay, an average of 10.7% porosity, 8 mD of permeability, an average water saturation of 49%, and a reservoir drive mechanism of gas expansion with water drive. The Second Navajo Sandstone has 96 feet (29 m) of net pay, an average of 5.5% porosity, 3.6 mD of permeability, an average water saturation of 33%, and a reservoir drive mechanism of gas expansion with limited water drive.
5. The First Navajo oil is a reddish brown, high-volatile crude with an API gravity of 48.3º. The producing solution GOR is 10,607 SCF/STB. The gas is composed of approximately 81% CO_2, 6% N_2, 6% methane, 2% ethane, 2% propane, and 3% higher hydrocarbon components. The Second Navajo oil is a yellow, high-volatile crude with an API gravity of 54.9º. The producing solution GOR is 5702 SCF/STB. The gas is composed of approximately 63% methane, 8% ethane, 4% propane, 5% higher hydrocarbon components, 8% CO_2, and 12% N_2. Minor amounts of H_2S are present in both units.
6. Cumulative field production as of July 1, 2011, was 70,636 BO (11,231 m^3), 595,004 MCFG (16,851 MCMG), and 22,425 BW (2969 m^3) from two wells; only one well is productive in the Second Navajo Sandstone. In early 2011, the field was shut in for additional testing and evaluation. Prior to shut in, daily production averaged 237 BO (38 m^3), 2601 MCFG (74 MCMG), and 72 BW (11 m^3). The OOIP for the field is estimated at 10,740,310 STB (1,707,709 m^3); 10,199,420 STB (1,621,708 m^3) and 540,890 STB (86,002 m^3) for the First and Second Navajo, respectively. The in-place gas reserves are estimated at 31.6 BCF (0.89 BCM; 30.3 BCF (0.86 BCM) and 1.3 BCF (0.04 BCM) for the First and Second Navajo, respectively. The EUR of oil and gas, and the economic feasibility of the field will be determined from additional reservoir testing, which will lead to a long-term production plan for Providence.
7. According to Wavrek and others (2010), hydrocarbons in the Navajo Sandstone reservoir were generated from Carboniferous source rocks within the Salina thrust plate. Hydrocarbon migration occurred 70 to 80 Ma, concurrent with the creation of the Providence structure. Differential thermal stress accounts for variations between the hydrocarbon components of the First and Second Navajo Sandstones. The isotopic composition of non-hydrocarbon gases at Providence field suggests an independent inorganic source and migration event.

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