MAJOR OIL PLAYS IN UTAH AND VICINITY

QUARTERLY
TECHNICAL PROGRESS REPORT

Reporting Period
Start Date: October 1, 2004
End Date: December 31, 2004

by
Thomas C. Chidsey, Jr., Principal Investigator,
and Douglas A. Sprinkel
Utah Geological Survey

March 2005

Contract No. DE-FC26-02NT15133

Submitting Organization: Utah Geological Survey
1594 West North Temple, Suite 3110
P.O. Box 146100
Salt Lake City, Utah 84114-6100
Ph.: (801) 537-3300/Fax: (801) 537-3400

Rhonda Jacobs, Contract Manager
U.S. Department of Energy
National Petroleum Technology Office
1 West 3rd Street
Tulsa, OK 74103-3532

DISCLAIMER

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ABSTRACT

Utah oil fields have produced over 1.2 billion barrels (191 million m^3) of oil from 241 million barrels (38.3 million m^3) of proved reserves. However, the 13.7 million barrels (2.2 million m^3) of production in 2002 was the lowest level in over 40 years and continued the steady decline that began in the mid-1980s. The Utah Geological Survey believes this trend can be reversed by providing play portfolios for the major oil-producing provinces (Paradox Basin, Uinta Basin, and thrust belt) in Utah and adjacent areas in Colorado and Wyoming. Oil plays are geographic areas with petroleum potential caused by favorable combinations of source rock, migration paths, reservoir rock characteristics, and other factors. The play portfolios will include descriptions and maps of the major oil plays by reservoir; production and reservoir data; case-study field evaluations; locations of major oil pipelines; identification and discussion of land-use constraints; descriptions of reservoir outcrop analogs; and summaries of the state-of-the-art drilling, completion, and secondary/tertiary recovery techniques for each play.

This report covers research activities for the tenth quarter of the project (October 1 through December 31, 2004). This work included (1) describing the Jurassic Nugget Sandstone thrust belt play, and (2) technology transfer activities.

The most prolific oil reservoir in the Utah/Wyoming thrust belt province is the eolian, Jurassic Nugget Sandstone, having produced over 288 million barrels (46 million m^3) of oil and 5.1 trillion cubic feet (145 billion m^3) of gas. Traps form on discrete subsidiary closures along major ramp anticlines where the depositionally heterogeneous Nugget is also extensively fractured. Hydrocarbons in Nugget reservoirs were generated from subthrust Cretaceous source rocks. The seals for the producing horizons are overlying argillaceous and gypsiferous beds in the Jurassic Twin Creek Limestone, or a low-permeability zone at the top of the Nugget.

The Nugget Sandstone thrust belt play is divided into three subplays: (1) Absaroka thrust - Mesozoic-cored shallow structures, (2) Absaroka thrust - Mesozoic-cored deep structures, and (3) Absaroka thrust - Paleozoic-cored shallow structures. Both Mesozoic-cored structures subplays represent a linear, hanging wall, ramp anticline parallel to the leading edge of the Absaroka thrust. Fields in the shallow Mesozoic subplay produce crude oil and associated gas; fields in the deep subplay produce retrograde condensate. The Paleozoic-cored structures subplay is located immediately west of the Mesozoic-cored structures subplays. It represents a very continuous and linear, hanging wall, ramp anticline where the Nugget is truncated against a thrust splay. Fields in this subplay produce nonassociated gas and condensate. Traps in these subplays consist of long, narrow, doubly plunging anticlines. Prospective drilling targets are delineated using high-quality, two-dimensional and three-dimensional seismic data, forward modeling/visualization tools, and other state-of-the-art techniques.

Future Nugget Sandstone exploration could focus on more structurally complex and subtle, thrust-related traps. Nugget structures may be present beneath the leading edge of the Hogsback thrust and North Flank fault of the Uinta uplift. Potential also exists for locating oil reserves in the stratigraphically equivalent Jurassic Navajo Sandstone in the central Utah thrust belt. A new, major Navajo oil discovery in the region indicates reservoir and structural characteristics may be similar to the productive play area to the north.

As part of technology transfer activities during this quarter, project team members joined Utah Stake Holders Board Members in attending the Uinta Basin Oil and Gas Collaborative Group meeting in Vernal, Utah. The project home page was updated on the Utah Geological Survey Web site.

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EXECUTIVE SUMMARY

Utah oil fields have produced over 1.2 billion barrels (191 million m^3) of oil from 241 million barrels (38.3 million m^3) of proved reserves. However, the 13.7 million barrels (2.2 million m^3) of production in 2002 was the lowest level in over 40 years and continued the steady decline that began in the mid-1980s. The overall objectives of this study are to (1) increase recoverable oil from existing field reservoirs, (2) add new discoveries, (3) prevent premature abandonment of numerous small fields, (4) increase deliverability through identifying the latest drilling, completion, and secondary/tertiary recovery techniques, and (5) reduce development costs and risk.

To achieve these objectives, the Utah Geological Survey is producing play portfolios for the major oil-producing provinces (Paradox Basin, Uinta Basin, and thrust belt) in Utah and adjacent areas in Colorado and Wyoming. This research is partially funded by the Preferred Upstream Management Program (PUMPII) of the U.S. Department of Energy, National Petroleum Technology Office (NPTO) in Tulsa, Oklahoma. This report covers research activities for the tenth quarter of the project (October 1 through December 31, 2004). This work included (1) describing the Jurassic Nugget Sandstone thrust belt play, and (2) technology transfer activities.

A combination of depositional and structural events created the right conditions for oil generation and trapping in the major oil-producing provinces (Paradox Basin, Uinta Basin, and thrust belt) in Utah and adjacent areas in Colorado and Wyoming. Oil plays are specific geographic areas having petroleum potential due to favorable source rock, migration paths, reservoir characteristics, and other factors. The most prolific oil reservoir in the Utah/Wyoming thrust belt province is the Jurassic Nugget Sandstone, having produced over 288 million barrels (46 million m^3) of oil and 5.1 trillion cubic feet (145 billion m^3) of gas.

The Nugget Sandstone was deposited in an extensive dune field (an eolian environment) which extended from Wyoming to Arizona, and was comparable to the present Sahara in North Africa or the Alashan area of the Gobi in northern China. Playas, mudflats, or oases developed in interdune areas. Traps form on discrete subsidiary closures along major ramp anticlines where the Nugget is extensively fractured. Hydrocarbons in Nugget reservoirs were generated from subthrust Cretaceous source rocks. The seals for the producing horizons are overlying argillaceous and gypsiferous beds of the Jurassic Twin Creek Limestone or a low-permeability zone at the top of the Nugget Sandstone.

The Nugget Sandstone has heterogeneous reservoir properties because of (1) cyclic dune/interdune lithofacies with better porosity and permeability in certain dune morphologies, (2) diagenetic effects, and (3) fracturing. Identification and correlation of barriers and baffles to fluid flow, and recognition of fracture set orientations in individual Nugget reservoirs in the thrust belt is critical to understanding their effects on production rates, petroleum movement pathways, horizontal well plans, and pressure maintenance programs.

The Nugget Sandstone thrust belt play is divided into three subplays: (1) Absaroka thrust - Mesozoic-cored shallow structures, (2) Absaroka thrust - Mesozoic-cored deep structures, and (3) Absaroka thrust - Paleozoic-cored shallow structures. Both Mesozoic-cored structures subplays represent a linear, hanging wall, ramp anticline parallel to the leading edge of the Absaroka thrust. Fields in the shallow Mesozoic subplay produce crude oil and associated gas; fields in the deep subplay produce retrograde condensate. The Paleozoic-cored shallow structures subplay is located immediately west of the Mesozoic-cored structures

subplays. The subplay represents a very continuous and linear, hanging wall, ramp anticline also parallel to the leading edge of the Absaroka thrust. The eastern boundary of the subplay is defined by the truncation of the Nugget against a thrust splay. Fields in this subplay produce nonassociated gas and condensate. Traps in these subplays consist of long, narrow, doubly plunging anticlines.

Prospective drilling targets in the Nugget Sandstone thrust belt play are delineated using the following: high-quality, two-dimensional and three-dimensional seismic data, forward modeling/visualization tools, well control, dipmeter information, surface geologic maps, and incremental restoration of balanced cross sections to assess trap geometry. Determination of the timing of structural development, petroleum migration, entrapment, and fill and spill histories are critical to successful exploration.

Future Nugget Sandstone exploration could focus on more structurally complex and subtle, thrust-related traps. Nugget structures may be present beneath the leading edge of the Hogsback thrust and North Flank fault of the Uinta uplift. Potential also exists for locating oil reserves in the stratigraphically equivalent Jurassic Navajo Sandstone in the central Utah thrust belt. A new, major Navajo oil discovery in the region indicates reservoir characteristics may be similar to the productive reservoirs to the north. Anticlines associated with the Gunnison thrust, a blind thrust in the region, form multiple structural traps that could contain hydrocarbons generated from Mississippian or Permian source rocks.

As part of technology transfer activities during this quarter, the project team joined Utah Stake Holder Board members in attending the Uinta Basin Oil and Gas Collaborative Group meeting in Vernal, Utah. Project team members published a quarterly report detailing project progress and results. The project home page was updated on the Utah Geological Survey Web site.

INTRODUCTION

Project Overview

Utah oil fields have produced over 1.2 billion barrels (bbls) (191 million m^3) (Utah Division of Oil, Gas and Mining, 2004). However, the 13.7 million bbls (2.2 million m^3) of production in 2002 was the lowest level in over 40 years and continued the steady decline that began in the mid-1980s (Utah Division of Oil, Gas and Mining, 2002). Proven reserves are relatively high, at 241 million bbls (38.3 million m^3) (Energy Information Administration, 2003). With higher oil prices now prevailing, secondary and tertiary recovery techniques should boost future production rates and ultimate recovery from known fields.

Utah's drilling history has fluctuated greatly due to discoveries, oil price trends, and changing exploration targets. During the boom period of the early 1980s, activity peaked at over 500 wells per year. Sustained high petroleum prices are likely to provide the economic climate needed to entice more high-risk exploration investments (more wildcats), resulting in new discoveries.

Utah still contains large areas that are virtually unexplored. There is also significant potential for increased recovery from existing fields by employing improved reservoir characterization and the latest drilling, completion, and secondary/tertiary recovery technologies. New exploratory targets may be identified from three-dimensional (3D) seismic surveys. Development of potential prospects is within the economic and technical capabilities of both major and independent operators.

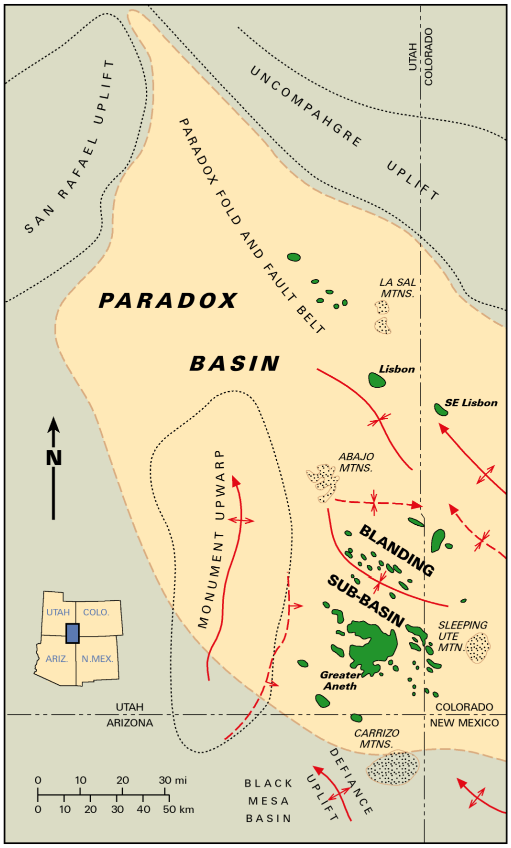
The primary goal of this study is to increase recoverable oil reserves from existing field reservoirs and new discoveries by providing play portfolios for the major oil-producing provinces (Paradox Basin, Uinta Basin, and thrust belt) in Utah and adjacent areas in Colorado and Wyoming (figure 1). These play portfolios will include descriptions (such as stratigraphy, diagenetic analysis, tectonic setting, reservoir characteristics, trap type, seal, and hydrocarbon source) and maps of the major oil plays by reservoir; production and reservoir data; case-study field evaluations; summaries of the state-of-the-art drilling, completion, and secondary/tertiary techniques for each play; locations of major oil pipelines; and descriptions of reservoir outcrop analogs for each play. Also included will be an analysis of land-use constraints on development, such as wilderness or roadless areas, and national parks within oil plays.

This report covers research activities for the tenth quarter of the project (October 1 through December 31, 2004). This work included (1) describing the Jurassic Nugget Sandstone thrust belt play, and (2) technology transfer activities.

Project Benefits

The overall goal of this multi-year project is enhanced petroleum production in the Rocky Mountain region. Specifically, the project goal will benefit from the following projects:

(1) improved reservoir characterization to prevent premature abandonment of numerous small fields in the Paradox and Uinta Basins,



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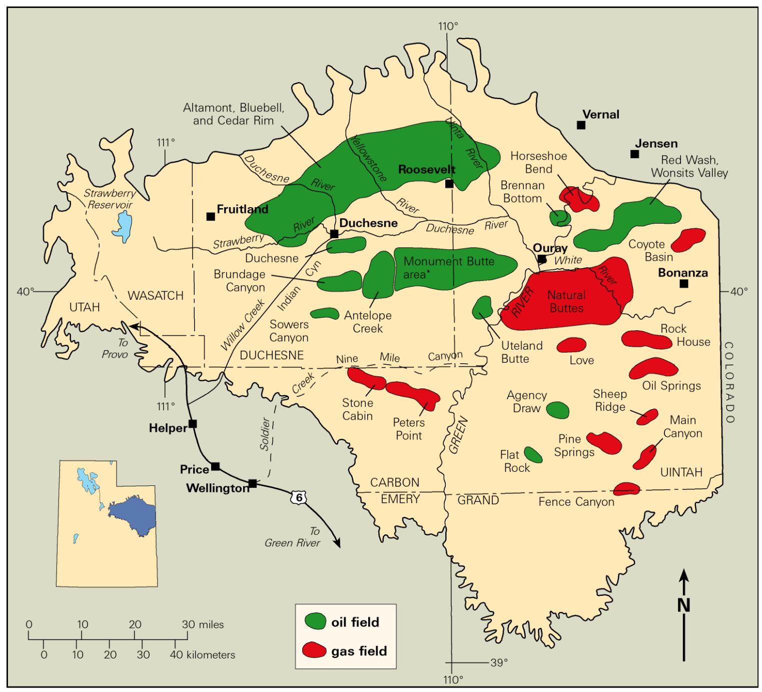

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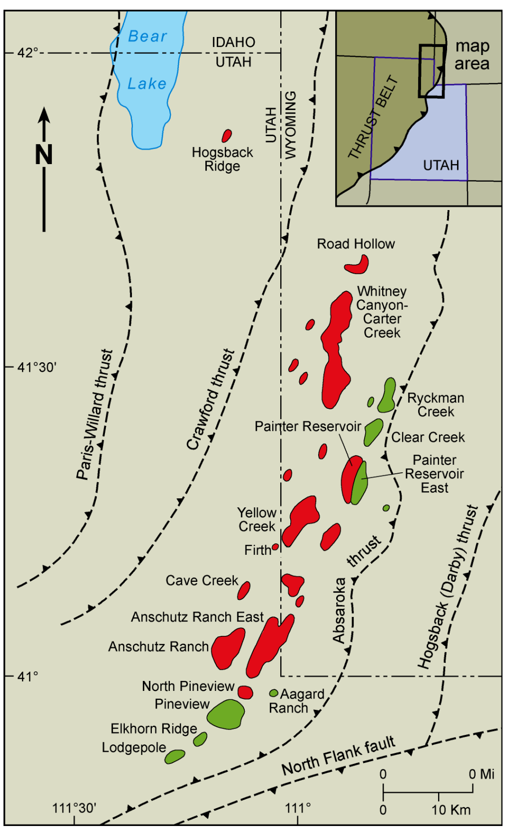

C

Figure 1. Major oil-producing provinces of Utah and vicinity. A - Oil and gas fields in the Paradox Basin of Utah and Colorado. B - Oil and gas fields in the Uinta Basin of Utah. C - Oil and gas fields, uplifts, and major thrust faults in the Utah-Wyoming thrust belt.

(2) identification of the type of untapped compartments created by reservoir heterogeneity (for example, diagenesis and rapid facies changes) to increase recoverable reserves,

(3) identification of the latest drilling, completion, and secondary/tertiary techniques to increase deliverability,

(4) identification of reservoir trends for field extension drilling and stimulating exploration in undeveloped parts of producing fairways,

(5) identification of technology used in other identified basins or trends with similar types of reservoirs that might improve production in Utah,

(6) identification of optimal well spacing/location to reduce the number of wells needed to successfully drain a reservoir to reduce development costs and risk, and allow limited energy investment dollars to be used more productively, and

(7) technology transfer to encourage new development and exploration efforts and increase royalty income to the federal, state, local, Native American, and fee owners.

The Utah play portfolios produced by this project will provide an easy-to-use geologic, engineering, and geographic reference to help petroleum companies plan exploration, land-acquisition strategies, and field development. These portfolios may also help pipeline companies plan future facilities and pipelines. Other users of the portfolios will include petroleum engineers, petroleum land specialists, landowners, bankers and investors, economists, utility companies, manufacturers, county planners, and numerous government agencies.

The results of this project will be transferred to industry and other interested parties through establishment of Technical Advisory and Stake Holders Boards, an industry outreach program, and technical presentations at national and regional professional society meetings. All of this information will be made public through (1) the Utah Geological Survey (UGS) Web site, (2) an interactive, menu-driven digital product on compact disc, and (3) hard copy publications in various technical or trade journals and UGS publications.

JURASSIC NUGGET SANDSTONE THRUST BELT PLAY – DISCUSSION AND RESULTS

Thrust Belt Overview

The Utah-Wyoming-Idaho salient of the Cordilleran thrust belt is defined as the region north of the Uinta Mountains of northeastern Utah and south of the Snake River Plain of Idaho, with the Green River basin of Wyoming forming the eastern boundary. Thrusting extends westward into the Great Basin for more than 100 miles (160 km). There are four major thrust faults in the region (from west to east): the Paris-Willard, Crawford, Absaroka, and Hogsback (Darby). These thrust faults represent detached (not involving basement rock), compressional styles of deformation. The thrusts generally trend in a north-northeast direction. The leading edges of these faults are listric in form and structurally complex, with numerous folds and thrust splays.

The Absaroka thrust moved in Late Cretaceous time (pre-mid-Santonian to pre-Campanian-Maestrichtian according to Royse and others, 1975). Most thrust belt oil fields are on the Absaroka thrust plate (figure 1C). Traps form on discrete, seismically defined, subsidiary closures along strike on major ramp anticlines (Lamerson, 1982).

Nugget Sandstone Thrust Belt Play Description

The most prolific oil and gas play confined to the hanging wall of the Abasroka thrust system is the Jurassic Nugget Sandstone thrust belt play (figure 2). The Nugget has produced over 288 million barrels (46 million m^3) of oil and 5.1 trillion cubic feet of gas (TCFG [145 billion m^3]); however, much the gas included in the production figures is cycled gas, including nitrogen, for pressure maintenance (Utah division of Oil, Gas and Mining, 2004; Wyoming Oil & Gas Conservation Commission, 2004). Pineview field, Summit County, Utah, was the first to produce oil and gas from the Nugget in 1975 (Conner and Covlin, 1977; Petroleum Information, 1981) and led the way for additional discoveries over the next eight years. There are currently 13 Nugget fields, with eight entirely in Wyoming, four entirely in Utah, and one (Anschutz Ranch East) in both Utah and Wyoming. Geologic data for individual fields in the play are summarized in table 1.

The play outline represents the maximum extent of petroleum potential in the geographical area as defined by producing reservoirs, hydrocarbon shows, and untested hypotheses. The attractiveness of the Nugget Sandstone thrust belt play (and other thrust belt plays) to the petroleum industry depends on the likelihood of successful development, reserve potential, pipeline access, drilling costs, oil and gas prices, and environmental concerns. When evaluating these criteria, certain aspects of the Nugget play may meet the exploration guidelines of major oil companies while other aspects meet the development guidelines of small, independent companies.

Prospective drilling targets in the Nugget Sandstone thrust belt play are delineated using high-quality two-dimensional (2-D) and three-dimensional (3-D) seismic data, 2-D and 3-D forward modeling/visualization tools, well control, dipmeter information, high-quality surface geologic maps, and detailed analyses of structural geometry (Chidsey, 1999; Meneses-Rocha and Yurewicz, 1999). Incremental restoration of balanced cross sections is one of the best methods to assess trap geometry (Meneses-Rocha and Yurewicz, 1999). Several techniques can be used to determine the timing of structural development, petroleum migration, and entrapment, and to decipher fill and spill histories. These techniques include illite age analysis, apatite fission track analysis, and use of fluid inclusions (Meneses-Rocha and Yurewicz, 1999).

The Jurassic Nugget Sandstone thrust belt play is in the southwest Wyoming and northern Utah thrust belt (figure 2). The play area is bounded by truncations of the Nugget against the leading edge of the Absaroka thrust on the east, the Crawford thrust on the west, the North Flank fault of the Uinta uplift on the south, and the Little Muddy Creek transverse ramp on the north where the Nugget is exposed (figures 2 and 3). The Nugget Sandstone thrust belt play is productive along three principal anticlinal trends, and thus divided into three subplays (figure 3): (1) Absaroka thrust - Mesozoic-cored shallow structures, (2) Absaroka thrust - Mesozoic-cored deep structures, and (3) Absaroka thrust - Paleozoic-cored shallow structures.

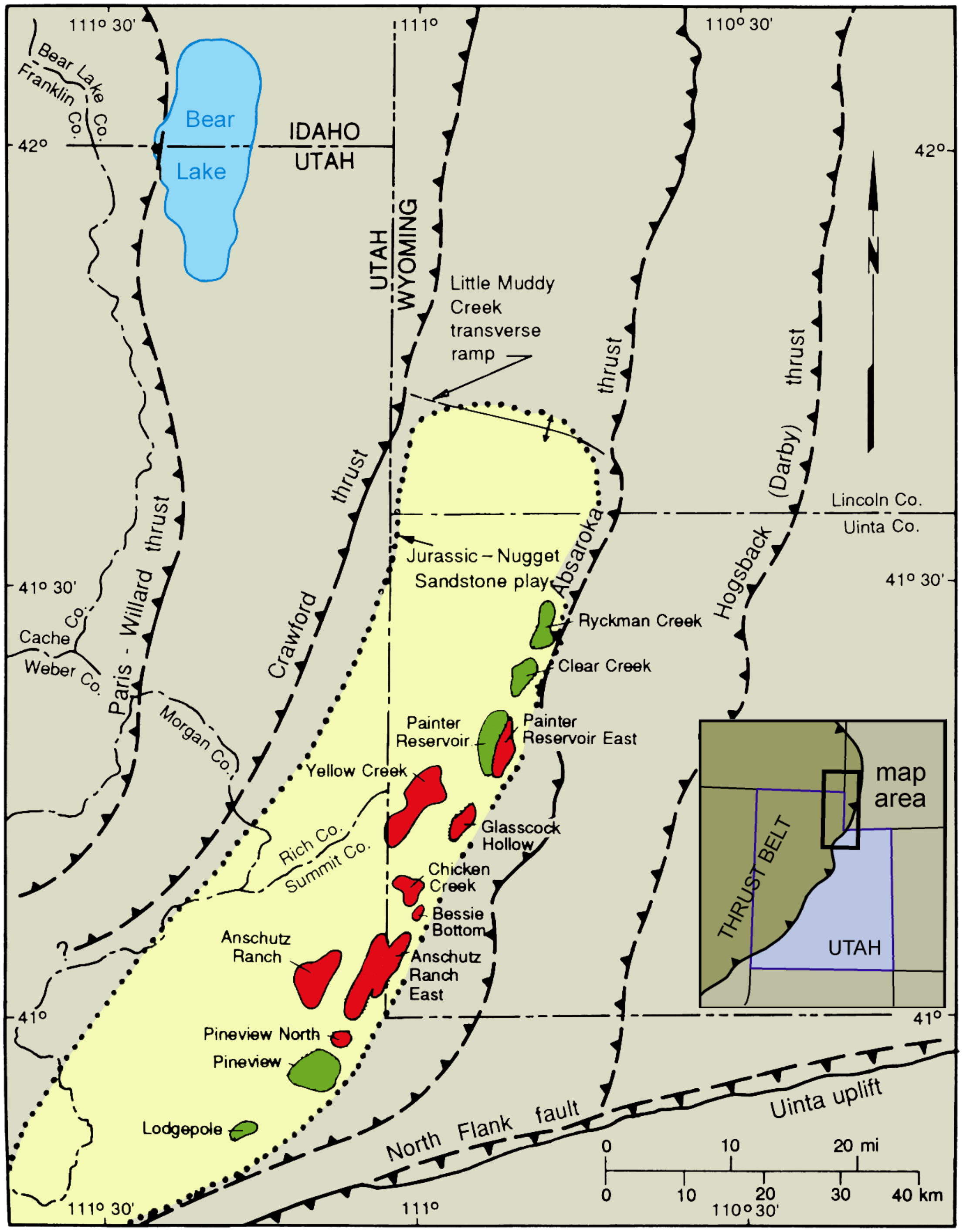

Figure 2. Location of reservoirs that produce oil (green) and gas and condensate (red) from the Jurassic Nugget Sandstone, Utah and Wyoming; major thrust faults are dashed where approximate (teeth indicate hanging wall). The Nugget Sandstone thrust belt play area is dotted. Modified from Chidsey (1993).

Table 1. ***Geologic, reservoir, and production data for fields in the Jurassic Nugget Sandstone thrust belt play. Data compiled from Loucks (1975), Conner and Covlin (1977), Kelly and Hine (1977), Jones (1979), Moklestad (1979), Petroleum Information (1981, 1984), Frank and Gavlin (1981), Frank and others (1982); Sercombe (1989), Chase and others (1992a, 1992b), Holm (1992), Mullen (1992a, 1992b), Powers (1992), Benson (1993), Cook and Dunleavy (1993), Chidsey (1993), Lindquist and Ross (1993), Utah Division of Oil, Gas and Mining (2004, and well records), and Wyoming Oil & Gas Conservation Commission (2004).***

State	County	Field	Discovery Date	Active Producers	Abandoned Producers	Acres	Spacing (acres)	Pay (feet)	Porosity (%)	Perm. (mD)	Temp. (°F)	Initial Reservoir Pressure (psi)	Average Monthly Production		Cumulative Production	
													Oil (bbl)	Gas (MCF)	Oil (bbl)	Gas (BCF)
Utah	Summit	Pineview	1975	7	5	2180	80	135	11	50	200	4200	8045	11,975	22,239,591	28.7
Utah	Summit	Pineview North	1982	1	3	1200	80	400	12	1.3	205	2000	824	12,793	783,614	8.9
Utah	Summit	Lodgepole	1976	2	5	640	160	43	10	229	188	4474	10	0	247,340	0.2
Utah	Summit	Anschutz Ranch	1979	2	2	1680	160	300	11	16	146	2915	0	0	555,367	43.1
Utah/ Wyoming	Summit/ Uinta	Anschutz Ranch East	1979	55	2	4500	80	W-300 E-501	W-10.1 E-9	W-3 E-2	W-215 E-230	W-5310 E-5902	32,627	1,802,251*	129,700,899	2943.3*
Wyoming	Uinta	Ryckman Creek	1976	1	37	1200	40	22	15	34	129	2900	0	0	18,951,863	259.7
Wyoming	Uinta	Clear Creek	1979	13	1	1200	80	30	13	5.4	138	3443	0	0	5,747,743	142.3
Wyoming	Uinta	Painter Reservoir	1977	54	10	1666	40	450	12	7.1	164	4020	6139	847,394	38,100,316	717.8
Wyoming	Uinta	East Painter Reservoir	1987	48	1	1200	80	900	12	5.4	170	NA	118,862	6,676,222	67,847,486	937.3
Wyoming	Uinta	Yellow Creek	1976	0	3	480	160	300	NA	NA	117	NA	0	0	221,048	0.3
Wyoming	Uinta	Glasscock Hollow	1980	6	5	915	none	110	11	65	220	5620	4245	97,390	2,831,528	17.0
Wyoming	Uinta	Chicken Creek	1983	3	4	430	160	200	11	NA	219	6021	998	5204	938,231	5.7
Wyoming	Uinta	Bessie Bottom	1983	1	0	160	160	170	8.5	0.6	242	6227	713	4180	160,356	1.5

NA = Not Available
For Anshcutz Ranch East field, W = West Lobe and E = East Lobe
*Includes cycled gas

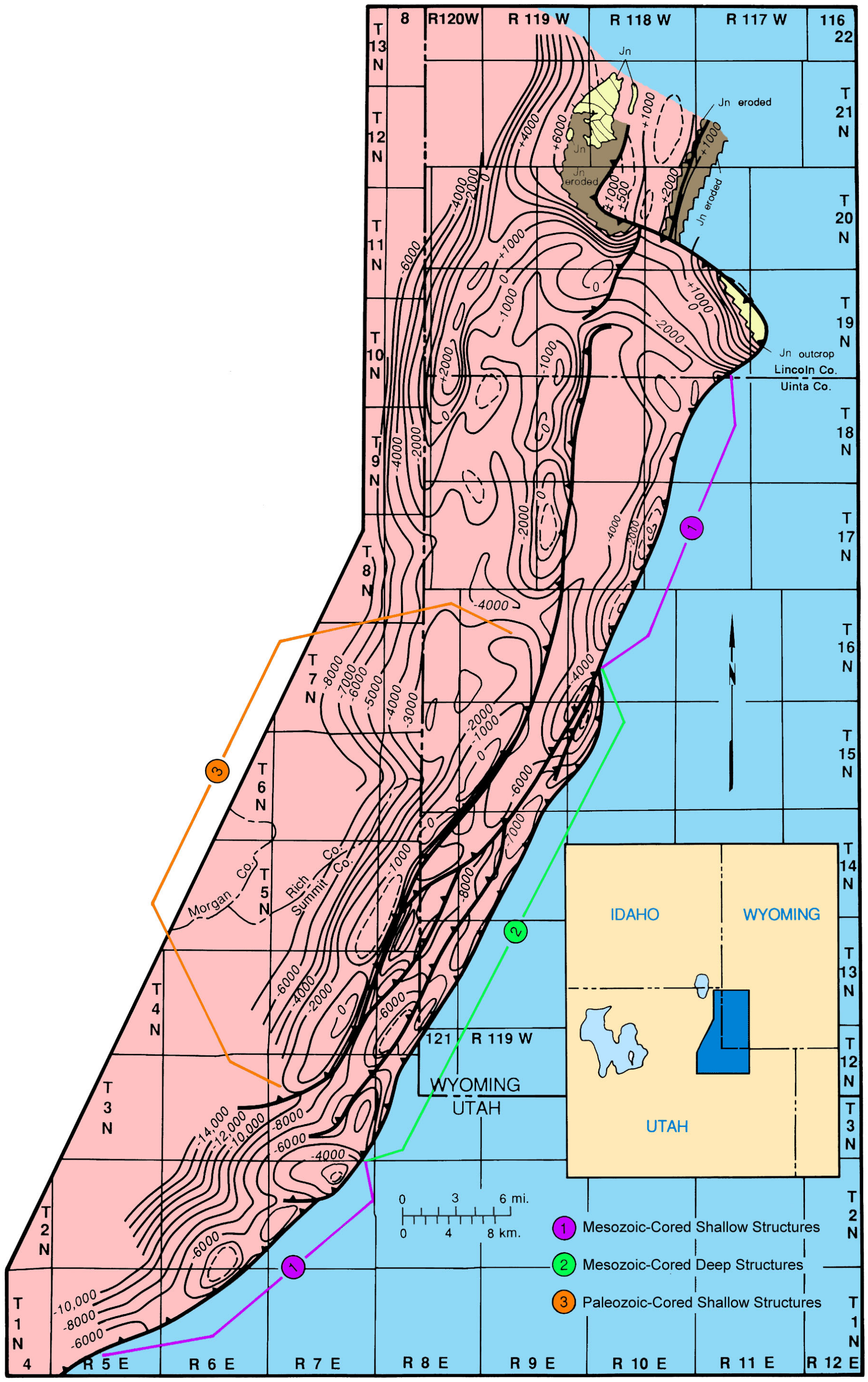

Figure 3. Generalized structure contour map of the top of the Jurassic Nugget Sandstone on the southern Absaroka thrust plate, Utah-Wyoming thrust belt. The three principal anticlinal trends, which define the subplays, are indicated based on their location with respect to the leading edge of the Absaroka thrust, the presence of imbricate thrusts which separate the trends, and the depth to the Nugget. Datum mean sea level, contour interval 1000 feet, dashed where approximate. Modified from Lamerson (1982).

Each subplay has its own unique structural characteristics, average depth, and type and nature of petroleum. Each requires different engineering and completion techniques. Depths to individual reservoirs are related to their position with respect to (1) the northeast-trending leading edge of the Absaroka thrust and associated imbricate thrusts (fields shallower to the west), and (2) two east-trending transverse ramps (fields deeper in the center, shallower to the north and south). Nugget thickness, lithology, lithofacies, reservoir properties, and diagenetic effects are generally the same for all three subplays.

Depositional Environment

In Early Jurassic time, Utah had an arid climate and lay 15° north of the equator (Hintze, 1993). The Nugget Sandstone and age-equivalent rocks were deposited in an extensive dune field (eolian environment) which extended from Wyoming to Arizona (figure 4), and was comparable to the present Sahara in North Africa or the Alashan area of the Gobi in northern China. Navajo dunes were large to small, straight-crested to sinuous, coalescing, transverse barchanoid ridges (Picard, 1975). Regional analyses of the mean dip of dune foreset beds indicate paleocurrent and paleowind directions were dominantly from the north and northwest (figure 4) (Kocurek and Dott, 1983).

An oasis is a vegetated area in desert regions where springs or lakes are present for relatively long periods of because the water table is close to the surface. 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. Low-relief, eolian sand sheets with poor drainage were also common (Lindquist, 1988).

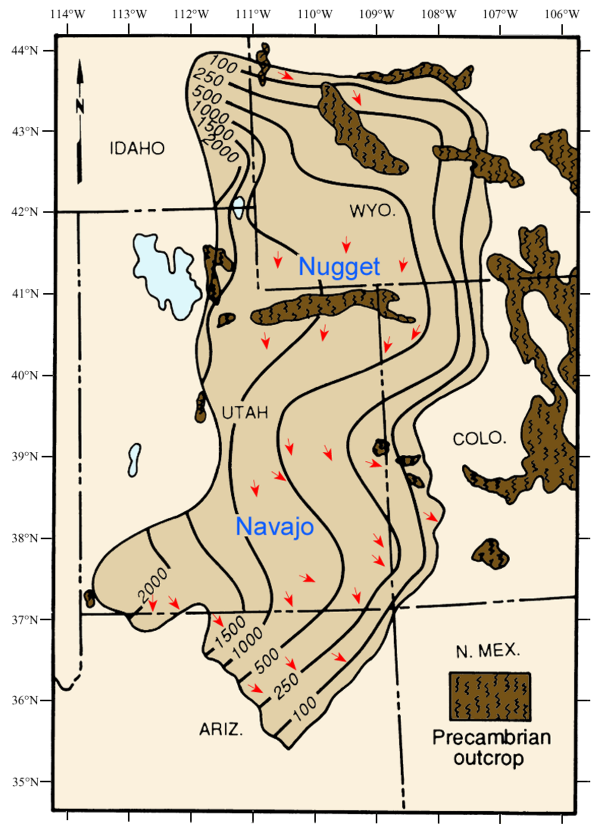

Figure 4. Regional isopach map of the Nugget/Navajo Sandstone based on measured sections and well data. Paleowind generally from the north and northwest is shown by arrows. Contours are in feet. Modified from Picard (1975); Kocurek and Dott (1983).

Stratigraphy and Thickness

The Nugget Sandstone is typically 1100 feet (340 m) thick in the play area (Hintze, 1993) and has a characteristic geophysical log response (figure 5). Lindquist (1988) identified lower, middle, and upper units in the Nugget from core and geophysical log analysis of wells in Anschutz Ranch East field (figures 2 and 6). Each unit has a subtle but distinct characteristic geophysical log response.

The Nugget Sandstone is overlain by the Jurassic Twin Creek Limestone and underlain by the Triassic Ankareh Formation (figure 5). Average depth to the Nugget for all the thrust belt fields is 10,633 feet (3240 m).

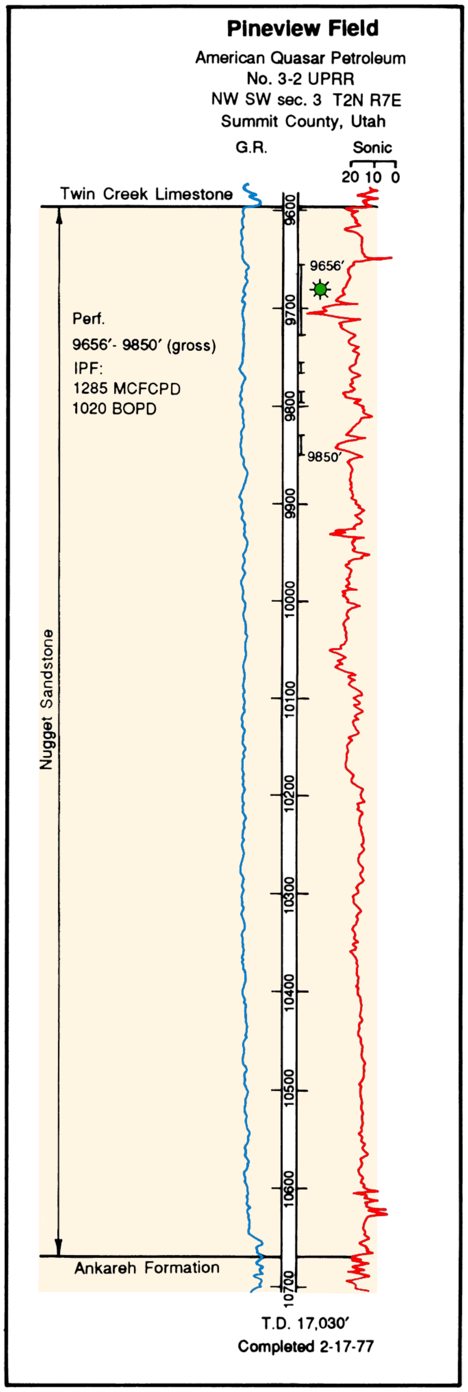

Figure 5. Typical gamma ray-sonic log of the Nugget Sandstone. Example from a development well in the Pineview field, Summit County, Utah. The vertical lines between depths of 9656 and 9850 feet on the log indicate producing (perforated) intervals.

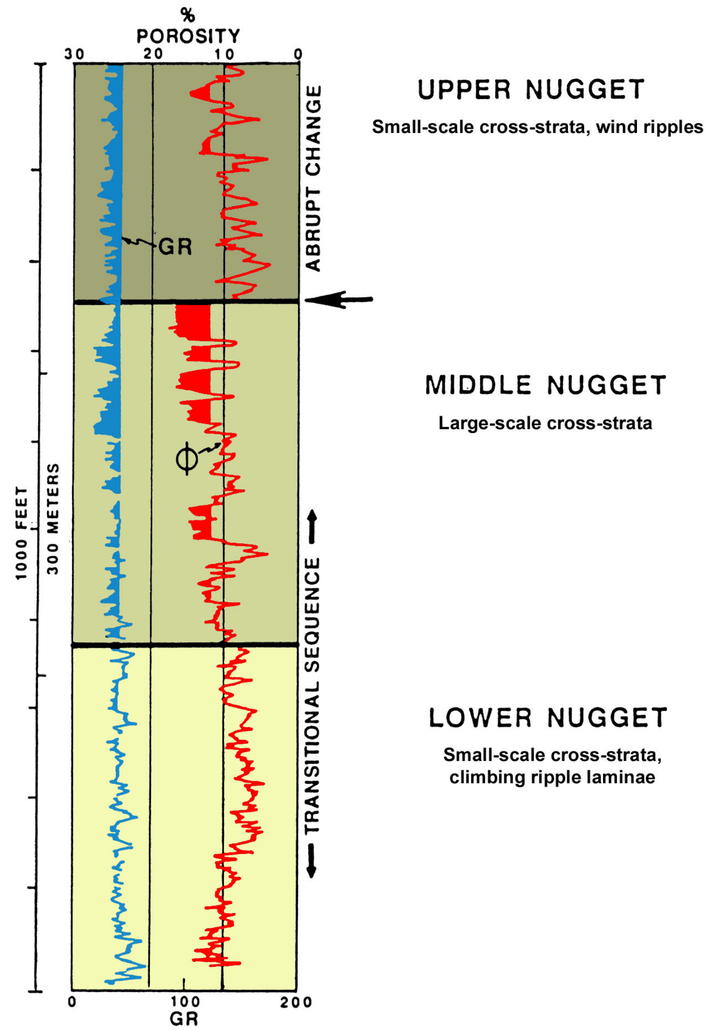

Figure 6. Reservoir quality of the Nugget Sandstone based on porosity and gamma ray characteristics, ARE No. W29-12 well (NWSW section 29, T. 4 N., R. 8 E., SLBL), Anschutz Ranch East field, Summit County, Utah. Modified from Lindquist (1988).

Lithology and Fracturing

The lower Nugget Sandstone is composed of (1) a basal, thin-bedded unit about 140 feet (47 m) thick, characterized by horizontal stratification and ripple marks, and (2) an overlying 220-foot-thick (67 m) section dominated by climbing ripple laminae and small-scale cross-beds (Picard, 1975; Lindquist, 1988). The middle and upper units consist of a cyclic dune/interdune sequence (the principal petroleum-bearing section) more than 740 feet (250 m) thick, characterized by cross-stratification (figure 7). The middle unit is dominated by large-scale, planar or wedge-planar cross-beds (up to 35°) (Conner and Covlin, 1977), and is about 390 feet thick (130 m). The upper unit is dominated by wind ripples and small-scale cross-beds, and is about 350 feet thick (115 m). The boundary between the lower and middle units is transitional, where as between the middle and upper units it is abrupt (figure 6) (Lindquist, 1988).

Figure 7. Typical Nugget Sandstone, from the Champlin No. 1 McDonald 31-3 well (NWNE section 3, T. 2 N., R. 7 E., SLBL, slabbed core from 9872 feet), Pineview field (figure 2), showing cross-bedding in fine-grained sandstone deposited in a dune environment.

The dune/interdune sequence generally consists of fine- to coarse-grained, subangular to subrounded sand or silt grains cemented by calcite (Picard, 1975). Dune deposits consist almost entirely of sandstone, whereas interdune deposits consist of both sandstone and siltstone with some carbonate and evaporite lithologies. Dune lithofacies from the brink to the toe of the dune slipface consist of (1) thin, graded, tabular grainfall laminae (rarely preserved), (2) thick, subgraded avalanche laminae, and (3) thin, tightly packed, reworked ripple strata at the dune toe (Lindquist, 1983). Interdune lithofacies consist of fine-grained, thin, low-angle to horizontal laminae with zones of bioturbation (Lindquist, 1983).

Framework and matrix grains in sandstone (>1/16 mm and <1/16 mm, respectively) and siltstone (1/16 to 1/256 mm and <1/256 mm, respectively) are commonly composed of more than 90 percent quartz (usually frosted) with varying amounts of K-feldspar, plagioclase, and rock fragments (figure 8A). The typical sandstone contains 11 percent authigenic cement and 2 percent matrix grains; the typical siltstone contains 18 percent authigenic cement and 11 percent matrix grains (figure 8B) (Picard, 1975).

Fractures in the Nugget Sandstone consist of two types: (1) early, gouge-filled, silica cemented, impermeable fractures (figure 9), and (2) later, typically open (little gouge or cement), permeable fractures (Conner and Covlin, 1977). The later fractures are related to fault-propagation folding during the Sevier orogeny after deep burial (Royce and others, 1975; Conner and Covlin, 1977; Dixon, 1982; Lamerson, 1982).

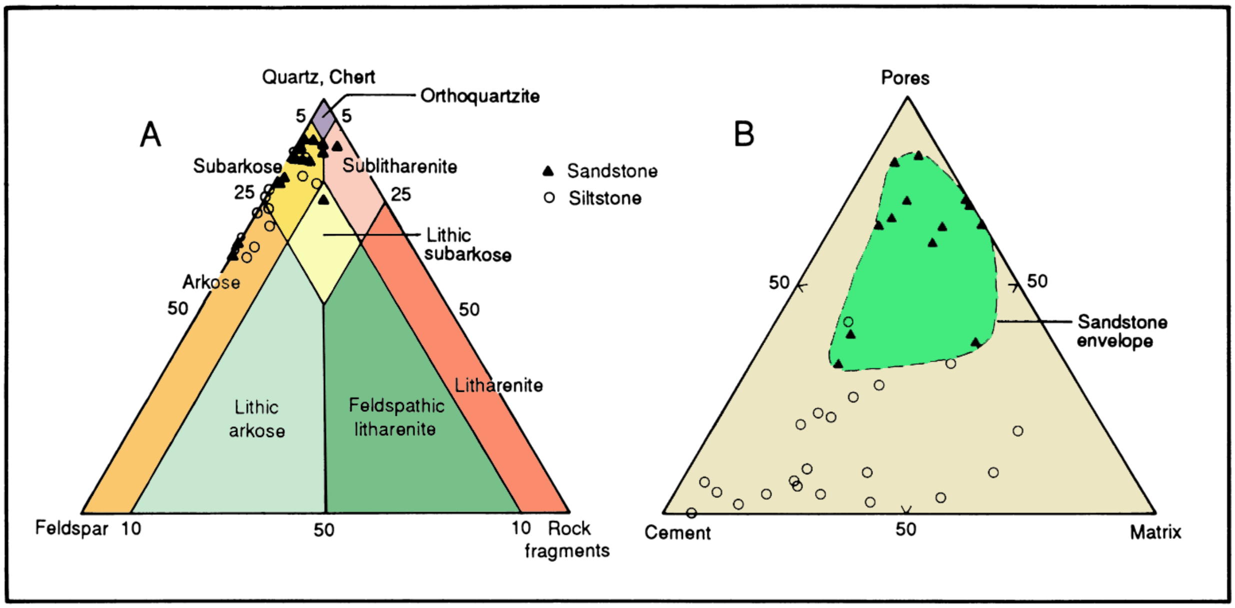

Figure 8. Trilinear plots of (A) quartz, feldspar, and rock fragments and (B) pores, cement, and matrix of sandstone and siltstone in the Nugget Sandstone. Matrix grains are <1/16 mm for sandstone and <1/256 mm for siltstone (after Picard, 1975).

Hydrocarbon Source and Seals

Hydrocarbons in Nugget Sandstone reservoirs were generated from subthrust Cretaceous source rocks (Warner, 1982). These include organic-rich units in the Bear River, Aspen (Mowry equivalent [Nixon, 1973]), and Frontier Formations. The source rocks began to mature after being overridden by thrust plates. Hydrocarbons were then generated, expelled, and subsequently migrated, primarily along fault planes, into overlying traps. Many structures in the hanging wall have juxtaposed the Nugget directly over these source rocks. Fracture systems developed along thrust imbrications may have provided secondary migration routes (Lamerson, 1982).

Burtner and Warner (1984) evaluated the hydrocarbon generation from the Mowry Shale in the Green River Basin (overridden in the western part by the thrust belt) and other northern Rocky Mountain basins. Their study showed that the Mowry ranges from 0.7 to 4.1 weight percent total organic content (TOC) and contains a mixture of type II (marine) and type III (terrestrial) organic matter. In the Green River Basin, Mowry areas having T_{max} values (the temperature during pyrolysis of peak hydrocarbon generation) greater than 435ºC coincide with areas anomalously low in TOC, indicating that hydrocarbons and CO_2 were generated and subsequently migrated out of the source beds (Burtner and Warner, 1984).

The seals for the Nugget producing zones are the overlying argillaceous and gypsiferous beds of the Gypsum Spring Member of the Jurassic Twin Creek Limestone, or a 10- to 60-foot-thick (3-30 m), low-permeability zone at the top of the Nugget Sandstone. Hydrocarbons in the Nugget/Twin Creek system are further sealed by salt beds within the overlying Jurassic Preuss Formation.

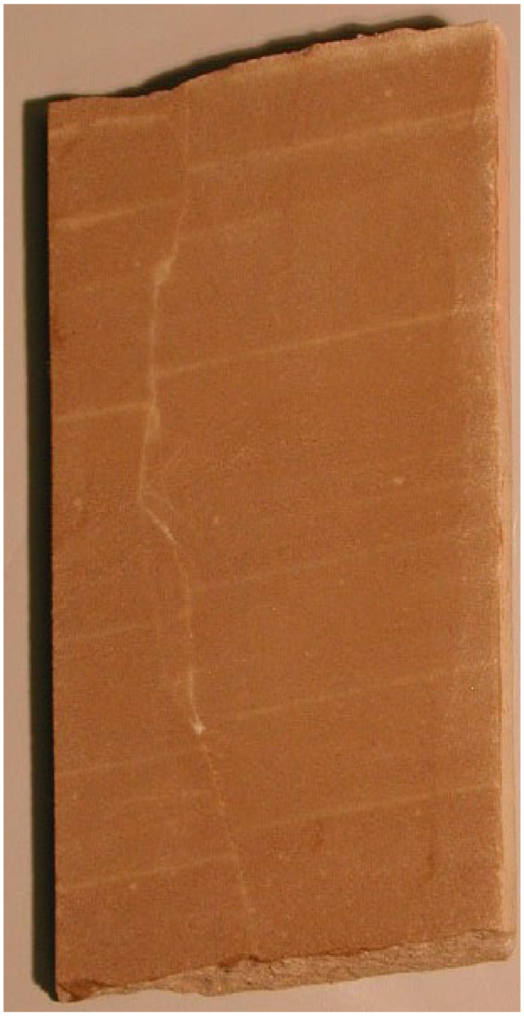

Figure 9. Early, gouge-filled and cemented fractures, with slight offsets, in the Nugget Sandstone, from the Champlin No. 1 McDonald 31-3 well (NWNE section 3, T. 2 N., R. 7 E., SLBL, slabbed core from 9898.5 feet), Pineview field (figure 2).

Structure and Trapping Mechanisms

Absaroka thrust – Mesozoic-cored shallow structures subplay: The Nugget Sandstone Absaroka thrust - Mesozoic-cored shallow structures subplay is located in the western part of Summit County, Utah and Uinta County, Wyoming (figure 10). The subplay represents a linear, hanging-wall, Mesozoic-cored, ramp anticline parallel to the leading edge of the Absaroka thrust (figure 11). Average depth to the Nugget in the shallow subplay is 9300 feet (3100 m). Two broad structural highs (culminations), separated by a structural low (depression), are present along the ramp anticline (Lamerson, 1982; Chidsey, 1993) where individual traps are formed by closure on subsidiary anticlines (figure 3). These culminations may be due to proximity to transverse ramp features. The north culmination is related to the Little Muddy Creek transverse ramp along the north border of the Nugget play area and contains Painter Reservoir (figure 12), Clear Creek, and Ryckman Creek fields (figures 2 and 10). The south culmination is related to a transverse ramp associated with the Uinta uplift along the south border of the play area and contains Pineview and Lodgepole fields (figures 2 and 10). The eastern boundary of the subplay is defined by the truncation of the Nugget against the leading edge of the Absaroka thrust. The western boundary is defined by a branch line representing the intersection of the thrust planes of the Absaroka thrust and a large imbricate thrust (Boyer and Elliott, 1982). The southern part of the Absaroka thrust plate trends southwest toward the Wasatch Range where the Nugget Sandstone play area terminates. The subplay is mapped as two 5-mile-wide (8 km) bands (figure 10).

Potential petroleum-trapping mechanisms in the Nugget Sandstone Absaroka thrust - Mesozoic-cored shallow structures subplay consist of long, narrow, doubly plunging anticlines (figure 13) (Royce and others, 1975; Conner and Covlin, 1977; Dixon, 1982; Lamerson, 1982). These anticlines are asymmetric, overturned to the east, and often develop en echelon structures along the leading edge of the Absaroka thrust because of variations in the competence and thickness of the stratigraphic sequence (West and Lewis, 1982). Pineview field, Summit County, Utah, exemplifies the traps in the subplay (figures 10, 13, and 14). The Nugget reservoir covers approximately 1280 acres (572 ha) and has more than 1000 feet (300 m) of structural closure.

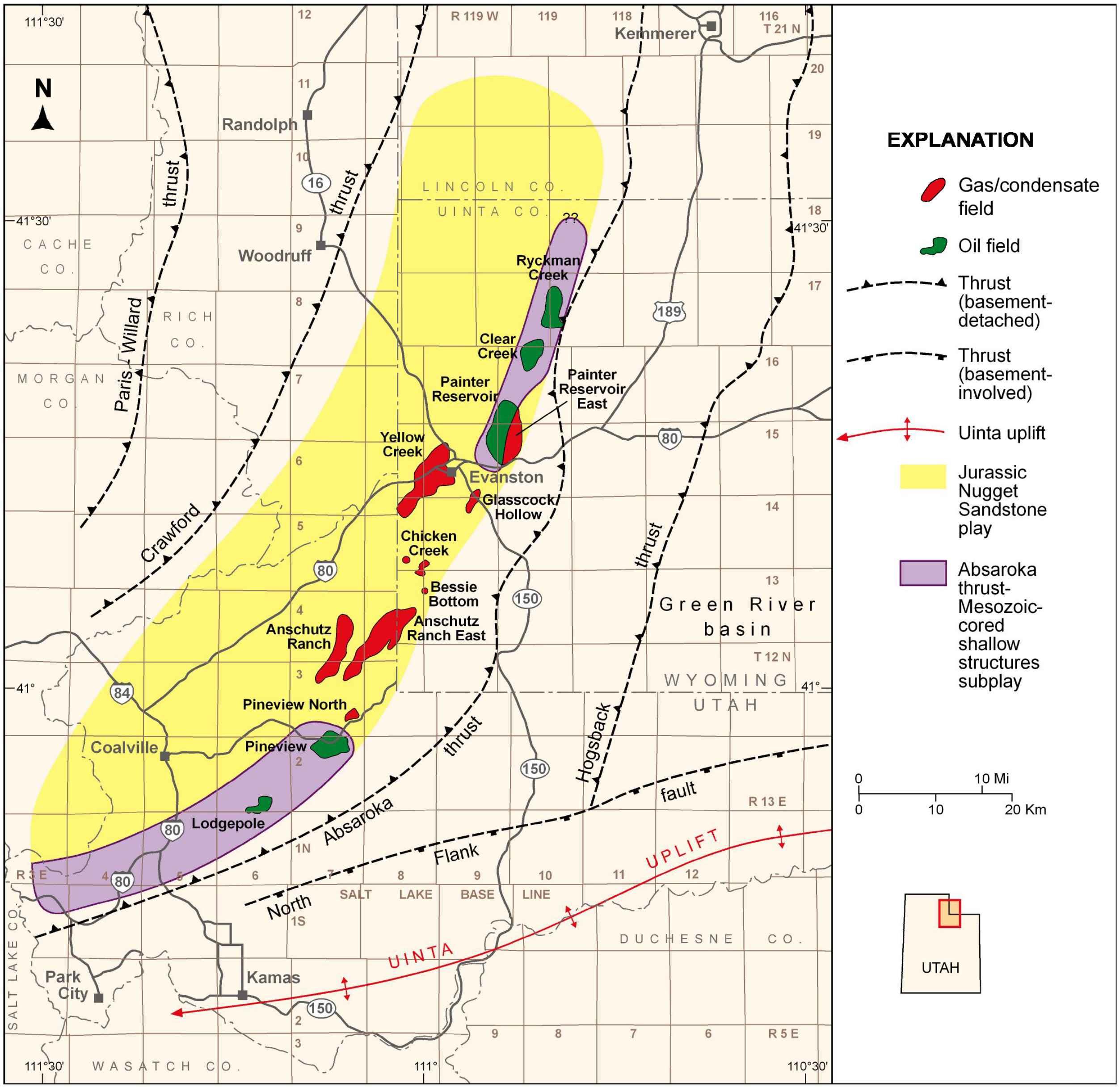

Figure 10. Location of the Nugget Sandstone Absaroka thrust - Mesozoic-cored shallow structures subplay, Summit County, Utah and Uinta County, Wyoming.

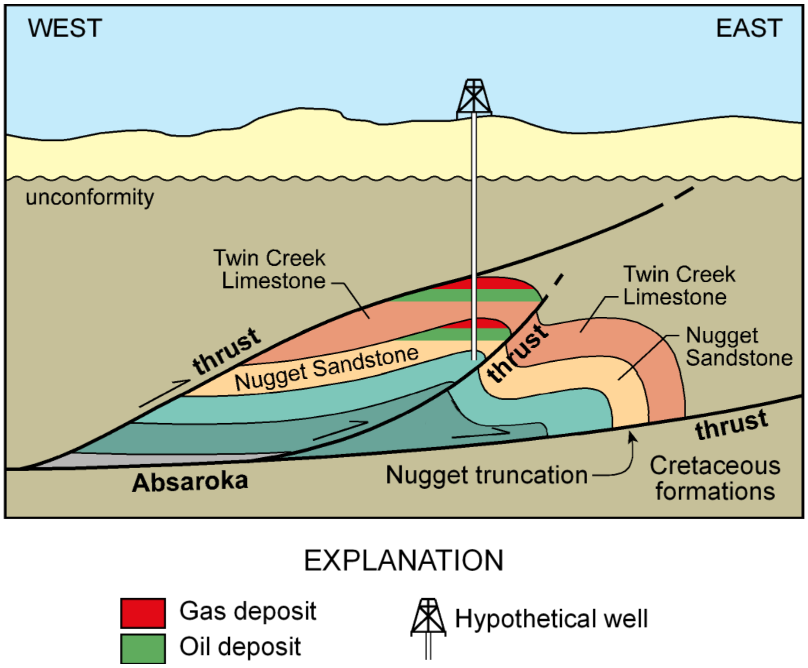

Figure 11. Schematic cross section of traps in the Nugget Sandstone Absaroka thrust - Mesozoic-cored shallow and deep structures subplays.

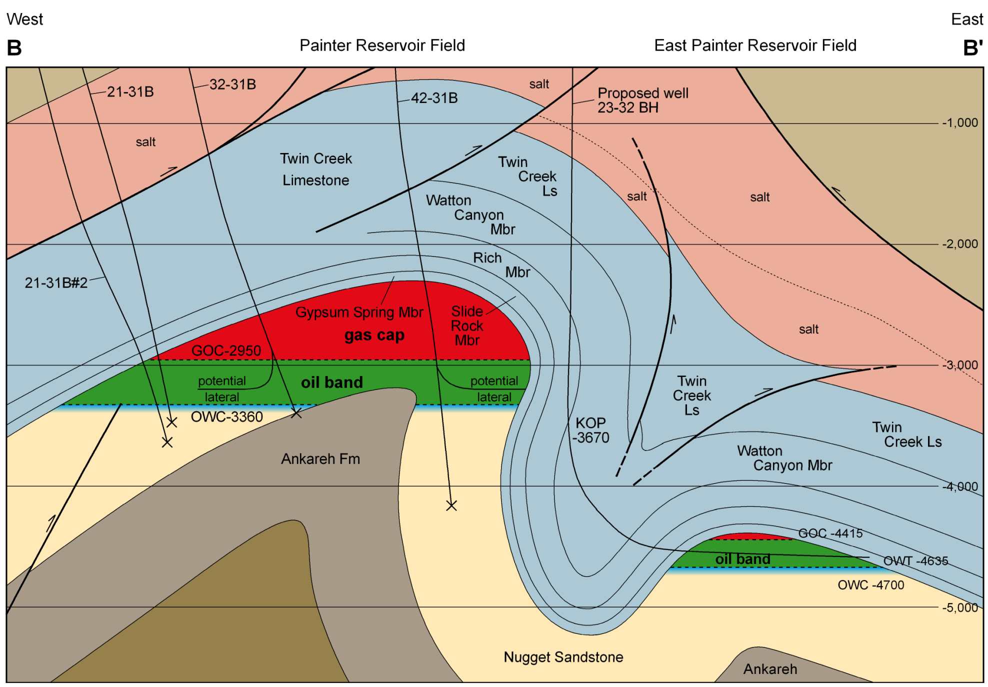

Figure 12. East-west structural cross section through the Painter Reservoir and East Painter Reservoir fields, Uinta County, Wyoming, showing typical traps for Nugget Sandstone fields. The cross section also shows the geometry of the structure in the shallow (Painter Reservoir) and deep (Painter Reservoir East) Mesozoic-cored structure subplays. Depth in feet, datum = mean sea level. Modified from Wyoming Oil and Gas Conservation Commission (1998).

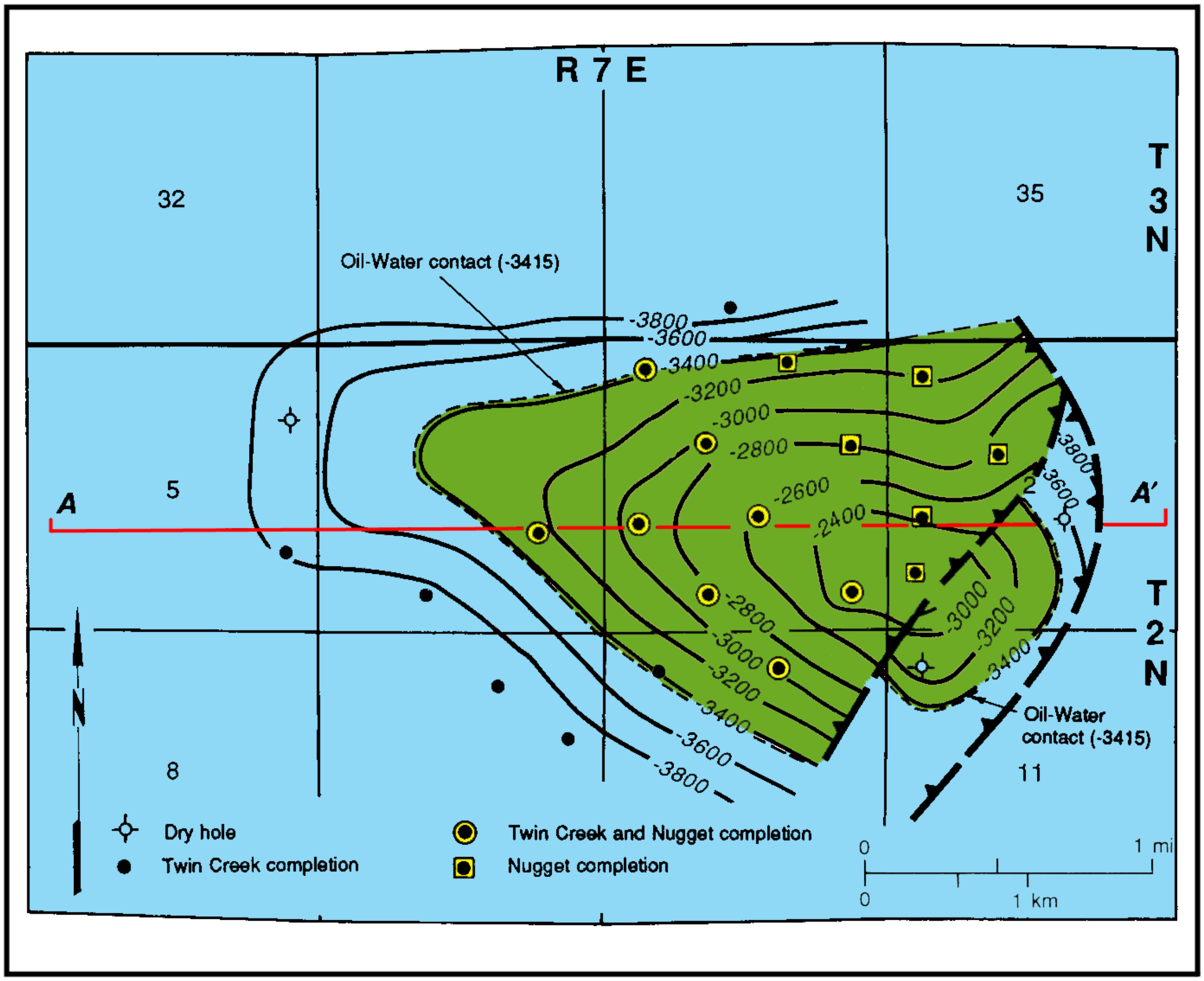

Figure 13. Structure contour map of the top of the Nugget Sandstone, Pineview field, Summit County, Utah, typical of the geometry of Mesozoic-cored shallow structures on the southern culmination, Jurassic Nugget Sandstone thrust belt play. Oil is trapped in an asymmetrical thrusted anticline in the hanging wall of the Absaroka thrust system. Contour interval = 200 feet, datum = mean sea level. After Utah Division of Oil, Gas and Mining (1978). Cross section A-A' shown on figure 14.

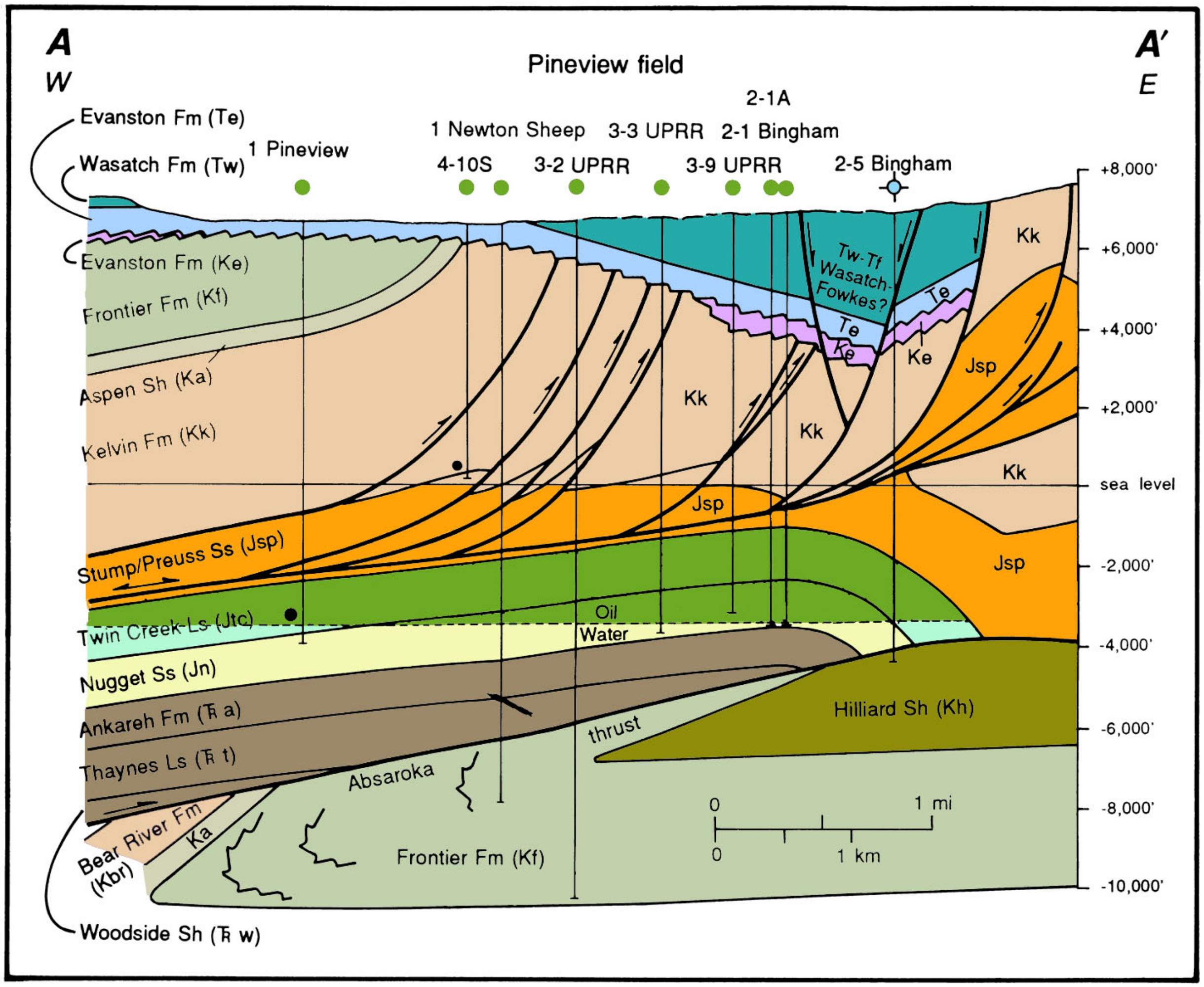

Figure 14. East-west cross section through the Pineview structure. Line of section shown on figure 13. Note that the field also produces oil from the Jurassic Twin Creek Limestone that has a common oil/water contact with the Nugget. Reservoir zones are juxtaposed against Cretaceous source rocks in the subthrust along the east flank of the structure. After Lamerson (1982).

Absaroka thrust – Mesozoic-cored deep structures subplay: The Nugget Sandstone Absaroka thrust - Mesozoic-cored deep structures subplay is also located in the western part of Summit County, Utah and Uinta County, Wyoming (figure 15). The subplay represents a linear, Mesozoic-cored ramp anticline developed in the structural low (depression) between the north and south culminations of the shallow structures subplay and along the truncation of the Nugget against the Absaroka thrust (figures 3 and 11) (Lamerson, 1982). The Mesozoic-cored shallow and deep structures subplays are also separated by imbricate thrusts along strike, and backlimb thrust faults are present locally (figures 11 and 12). Average depth to the Nugget in the deep subplay is 12,810 feet (3900 m). Discrete anticlinal closures form Pineview North, Anschutz Ranch East, Bessie Bottom, Chicken Creek, Glasscock Hollow, and Painter Reservoir East fields (figures 2 and 15). The subplay extends north as a 5-mile-wide (8 km) band into Uinta County, Wyoming (figure 15).

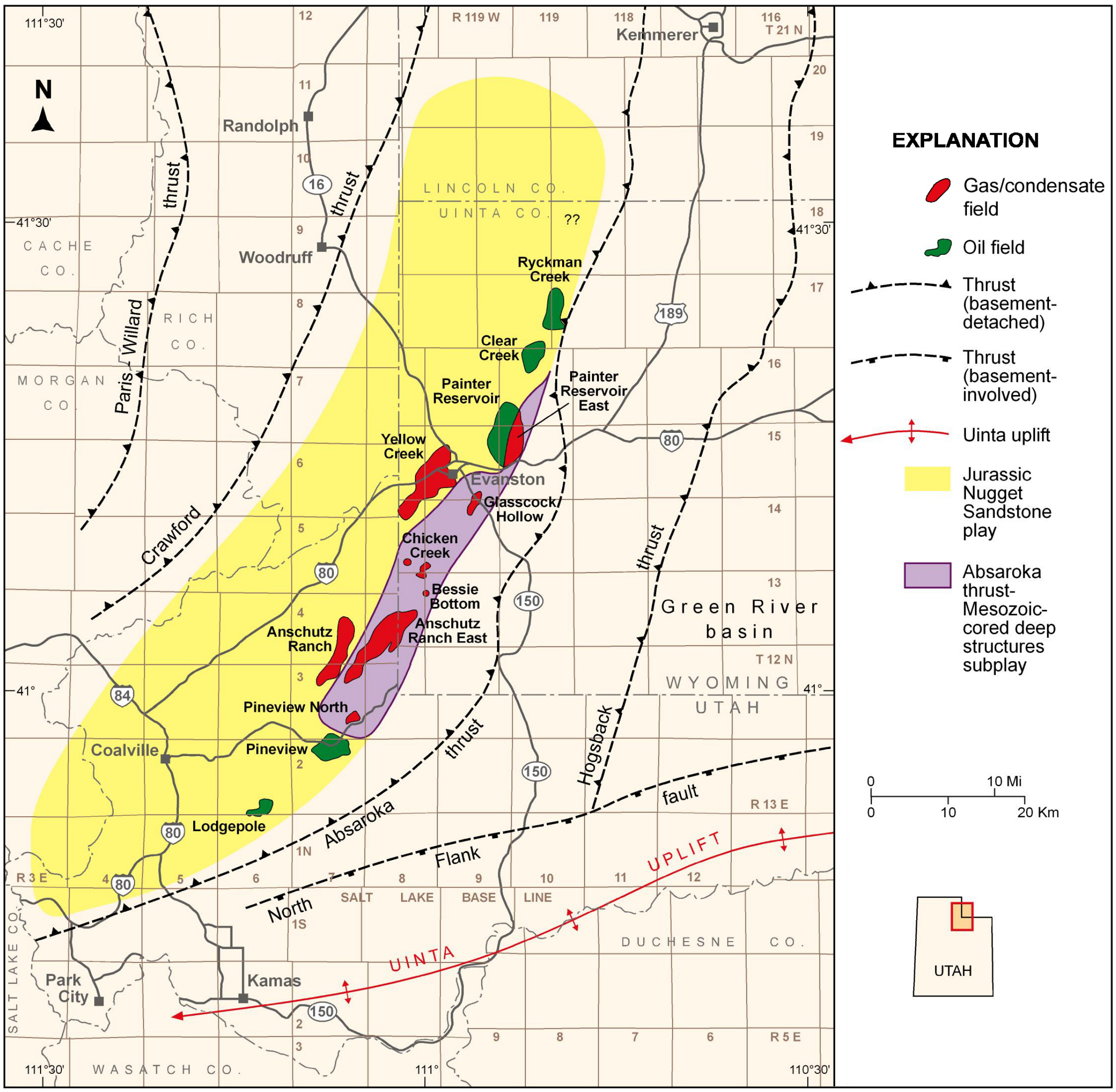

Figure 15. Location of the Nugget Sandstone Absaroka thrust - Mesozoic-cored deep structures subplay, Summit County, Utah and Uinta County, Wyoming.

Similar to the Absaroka thrust - Mesozoic-cored shallow structures subplay, potential petroleum-trapping mechanisms in the Nugget Sandstone Absaroka thrust - Mesozoic-cored deep structures subplay also consist of long, narrow, doubly plunging anticlines (figures 16 and 17) (Royce and others, 1975; Conner and Covlin, 1977; Dixon, 1982; Lamerson, 1982). These anticlines are asymmetric and overturned to the east as well. Splay faults and salt near the anticlinal axes are common, complicating drilling operations and compartmentalizing productive zones (figure 17).

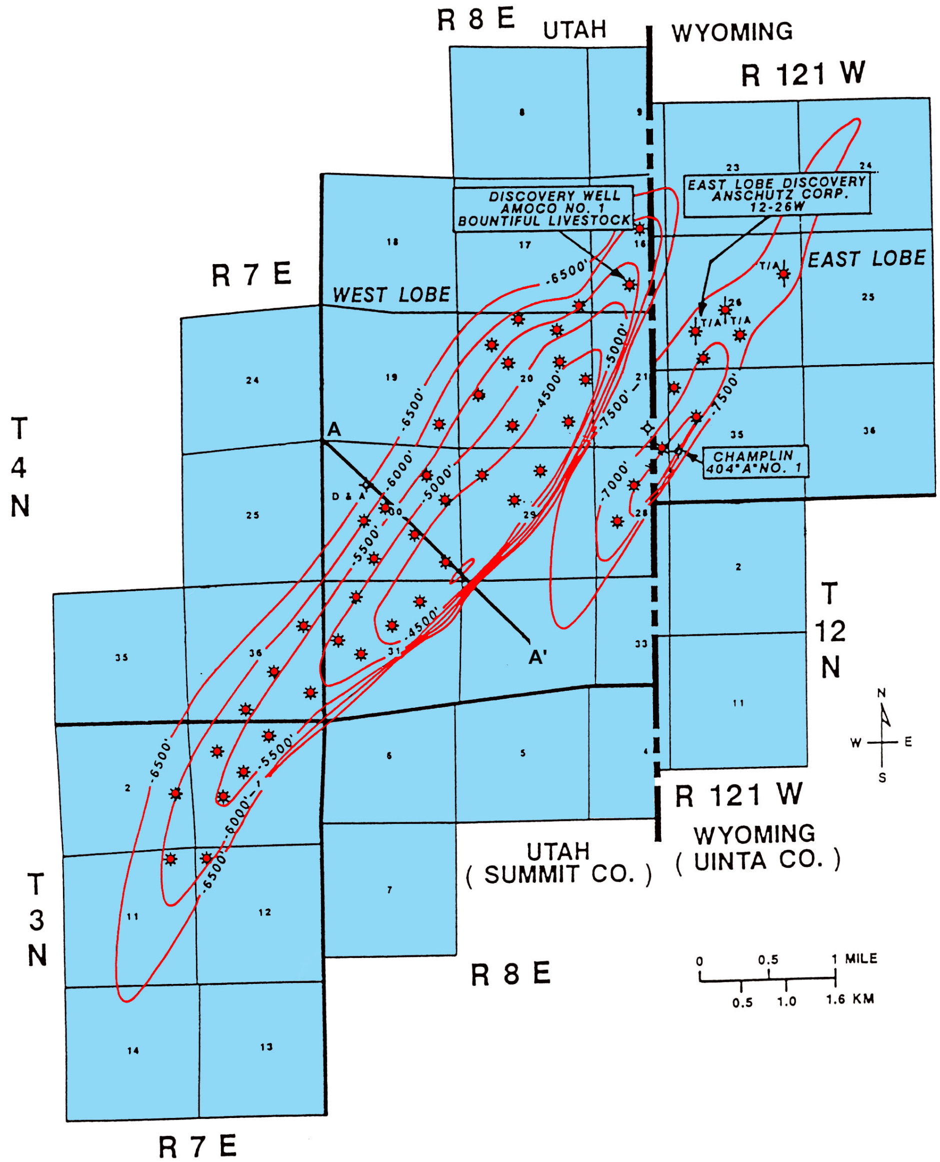

Figure 16. Structure contour map of the top of the Nugget Sandstone, Anschutz Ranch East field, Summit County, Utah and Uinta County, Wyoming, typical of the geometry of Mesozoic-cored deep structures, Jurassic Nugget Sandstone thrust belt play. Retrograde condensate and gas are trapped in east and west lobes of a large northeast-southwest-trending, thrusted anticline in the hanging wall of the Absaroka thrust system. Contour interval = 500 feet, datum = mean sea level. After Lelek (1982). Cross section A-A' shown on figure 17.

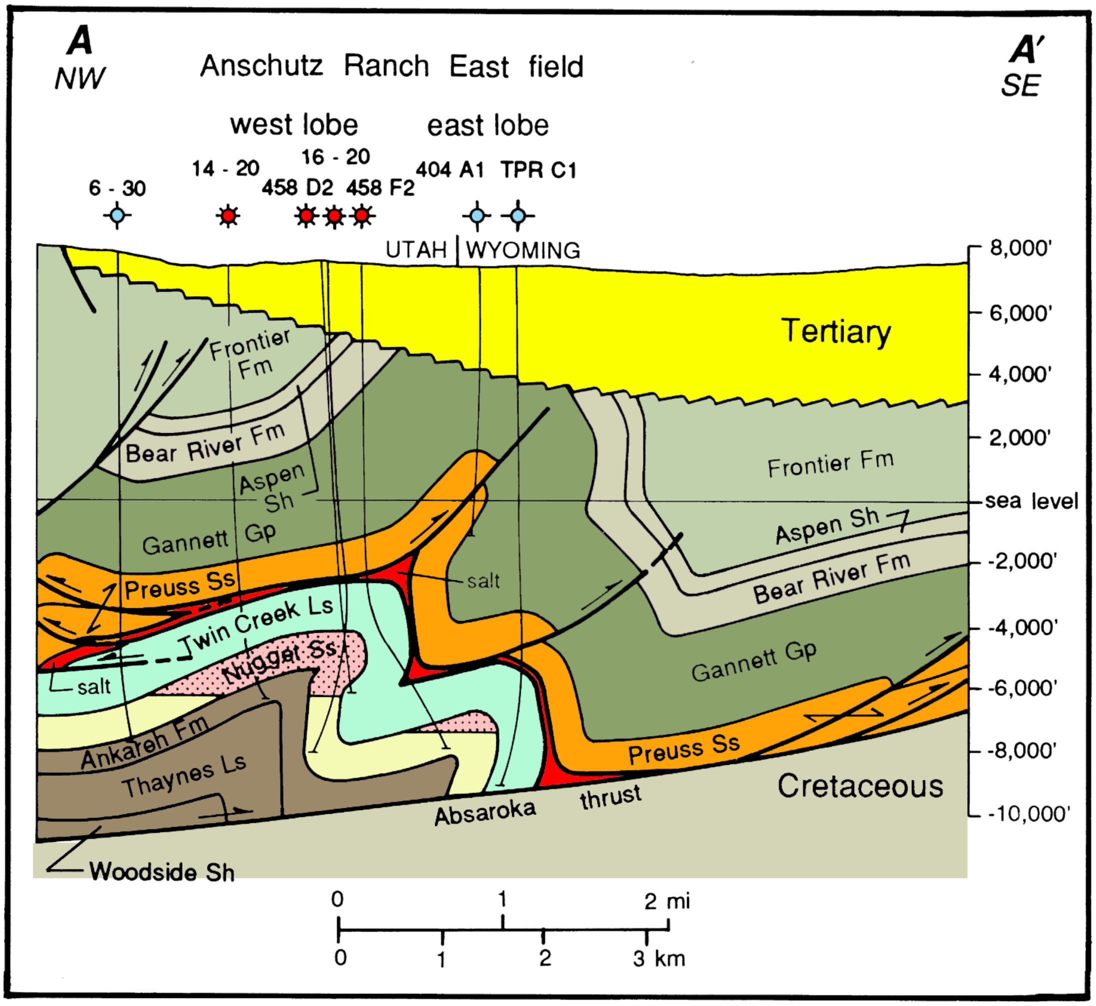

Figure 17. Northwest-southeast cross section through the Anschutz Ranch East structure showing the large west lobe and the deeper, smaller east lobe (base of pink stippled area represents the gas-water contact. Line of section shown on figure 16. After West and Lewis (1982).

Anschutz Ranch East field is an excellent example of Mesozoic-cored deep structures (figure 2). It is the largest field in the subplay in terms of hydrocarbon column thickness, cumulative production and reserves, and areal extent (figures 16 and 17). The reservoir covers approximately 4620 acres (1870 ha) and is divided into two structural lobes. The larger west lobe is a narrow, elongate anticline overturned to the east (Lelek, 1982). Average depth to the Nugget Sandstone in the west lobe is 12,900 feet (4300 m) with more than 2100 feet (700) of closure. When the west lobe reservoir was discovered in 1979, the hydrocarbon column was near the spill point. The smaller east lobe has the same general configuration as the west lobe, and is separated from it by an overturned syncline (Lelek, 1982). Average depth to the Nugget Sandstone in the east lobe is 14,325 feet (4775 m), and it has more than 1000 feet (330 m) of closure. When the east lobe reservoir was discovered in 1981, the hydrocarbon column was also near the spill point (Petroleum Information, 1984).

Absaroka thrust – Paleozoic-cored shallow structures subplay: The Nugget Sandstone Absaroka thrust - Paleozoic-cored shallow structures subplay is located immediately west of the Mesozoic-cored structures subplays (figure 18). The subplay represents a very continuous and linear, hanging-wall, Paleozoic-cored, ramp anticline parallel to the leading edge of the Absaroka thrust (figure 19). The eastern boundary of the subplay is defined by the truncation of the Nugget against a thrust splay. The western boundary is defined as the point at which the dips on the west flank of the ramp anticline begin to flatten out. The southern part of this ramp anticline trends southwest toward the Wasatch Range where the play area terminates. The play extends north as a 3-mile-wide (4.8 km) band through Summit County, Utah and into western Uinta County, Wyoming (figure 18).

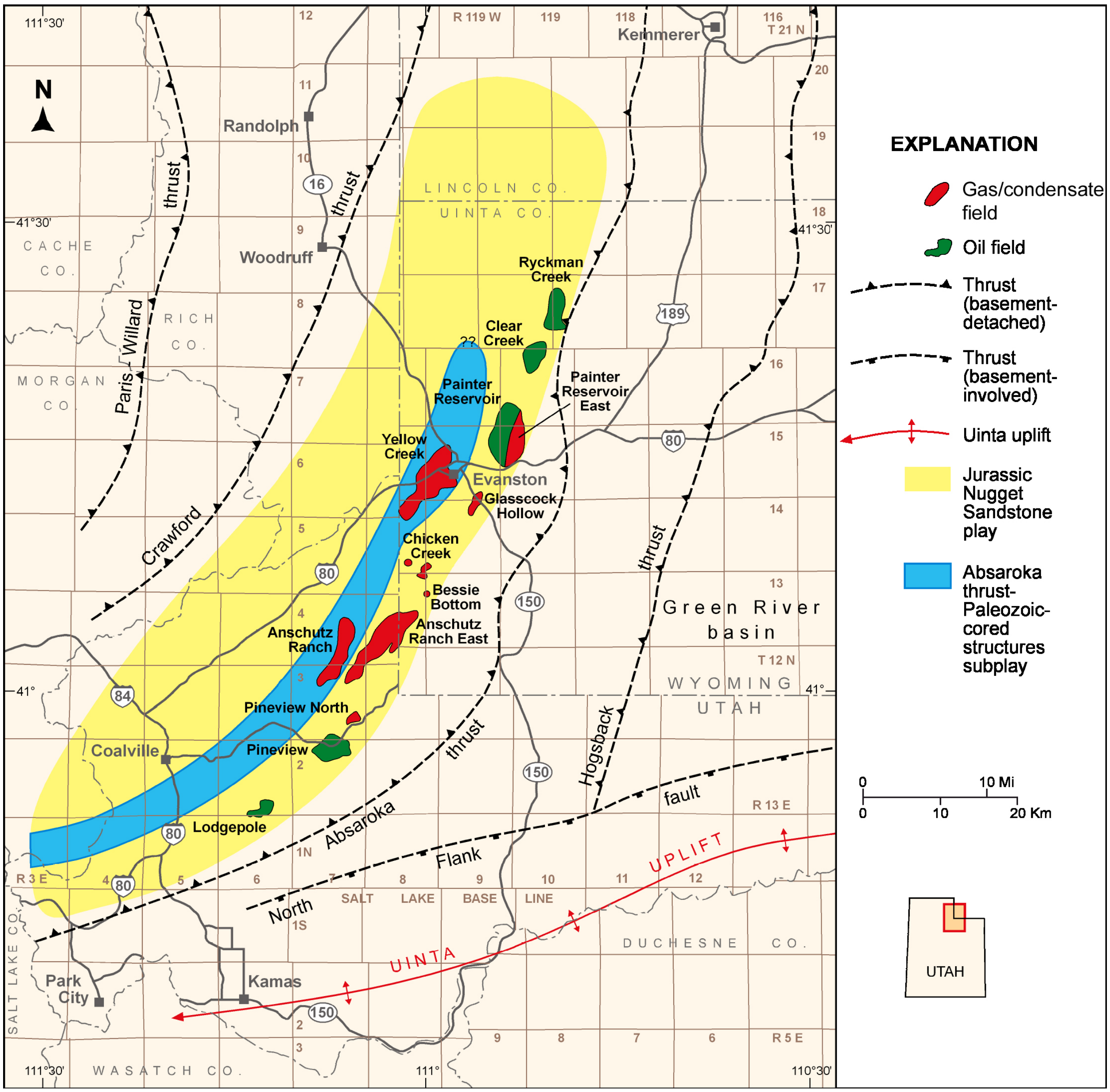

Figure 18. Location of the Nugget Sandstone Absaroka thrust - Paleozoic-cored shallow structures subplay, Summit County, Utah and Uinta County, Wyoming.

Potential petroleum-trapping mechanisms in the Nugget Sandstone Absaroka thrust - Paleozoic-cored shallow structures subplay also consist of long, narrow, doubly plunging anticlines that trend north to northeast (figures 20 and 21) (Royce and others, 1975; Conner and Covlin, 1977; Petroleum Information, 1981; Dixon, 1982; Lamerson, 1982). These anticlines are also asymmetric and overturned to the east. There are just two fields in the Nugget Sandstone Absaroka thrust - Paleozoic-cored shallow structures subplay: Anschutz Ranch in Summit County, Utah, and Yellow Creek in Uinta County, Wyoming (figure 18). For example, Anschutz Ranch field consists of a large, elongate anticline with more than 7100 feet (2164 m) of structural closure involving Jurassic through Ordovician rocks; the reservoir covers approximately 2880 acres (1170 ha). However, hydrocarbons are trapped only on the very crest of the structure, as is the case at Yellow Creek field.

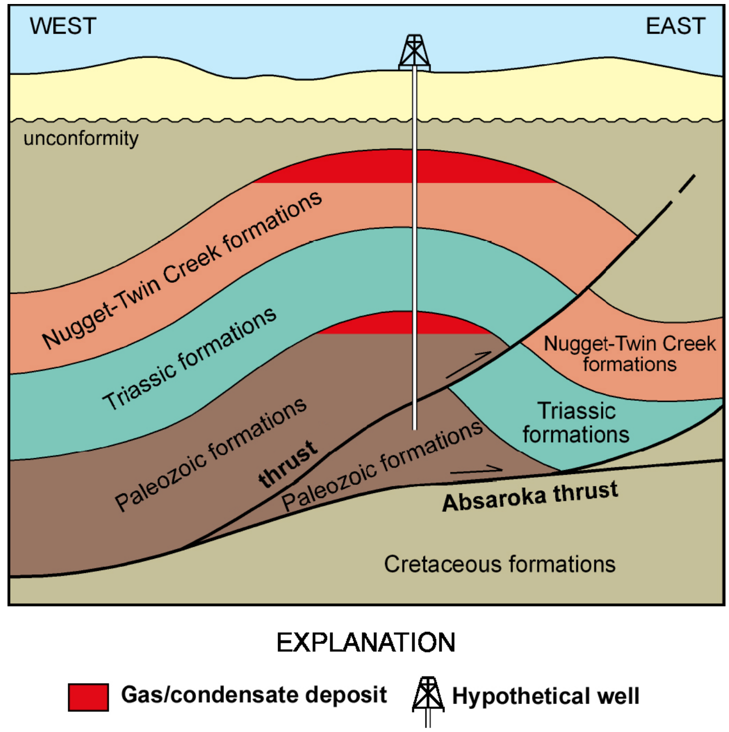

Figure 19. Schematic cross section of traps in the Nugget Sandstone Absaroka thrust - Paleozoic-cored shallow structures subplay.

Reservoir Properties

The Nugget Sandstone has heterogeneous reservoir properties because of (1) cyclic dune/interdune lithofacies with better porosity and permeability that developed in certain dune morphologies, (2) diagenetic effects, and (3) fracturing. The typical sandstone has an average porosity of 14 percent; the typical siltstone has an average porosity of 7 percent (figure 8B; Picard, 1975). They exhibit significant secondary porosity in the form of fracturing. Permeabilities in the Nugget range from 1 to more than 200 millidarcies (mD). The best permeability within Nugget dune deposits is along bounding surfaces (bedding planes), with preferred directions along the dip and strike of the individual slipfaces (cross-beds) (figure 22A; Lindquist, 1983). Porosity and permeability is greatest in thickly laminated avalanche deposits (Hunter, 1977; Schenk, 1981). Nugget interdunes, however, have significantly poorer reservoir characteristics than the dune 1ithofacies (figure 22B). In Painter Reservoir, for example, the average porosity and permeability is only 9.7 percent and 1.5 mD in interdune lithofacies, but 13.6 percent and 16.5 mD in dune lithofacies (Tillman, 1989). The low-permeability interdune lithofacies is a potential barrier to flow (figure 22B). Identification and correlation of dune/interdune lithofacies in individual Nugget reservoirs is critical to understanding the effects on production rates and paths of petroleum movement. Natural fractures also affect permeability, and control hydrocarbon production and injection fluid pathways (Parra and Collier, 2000).

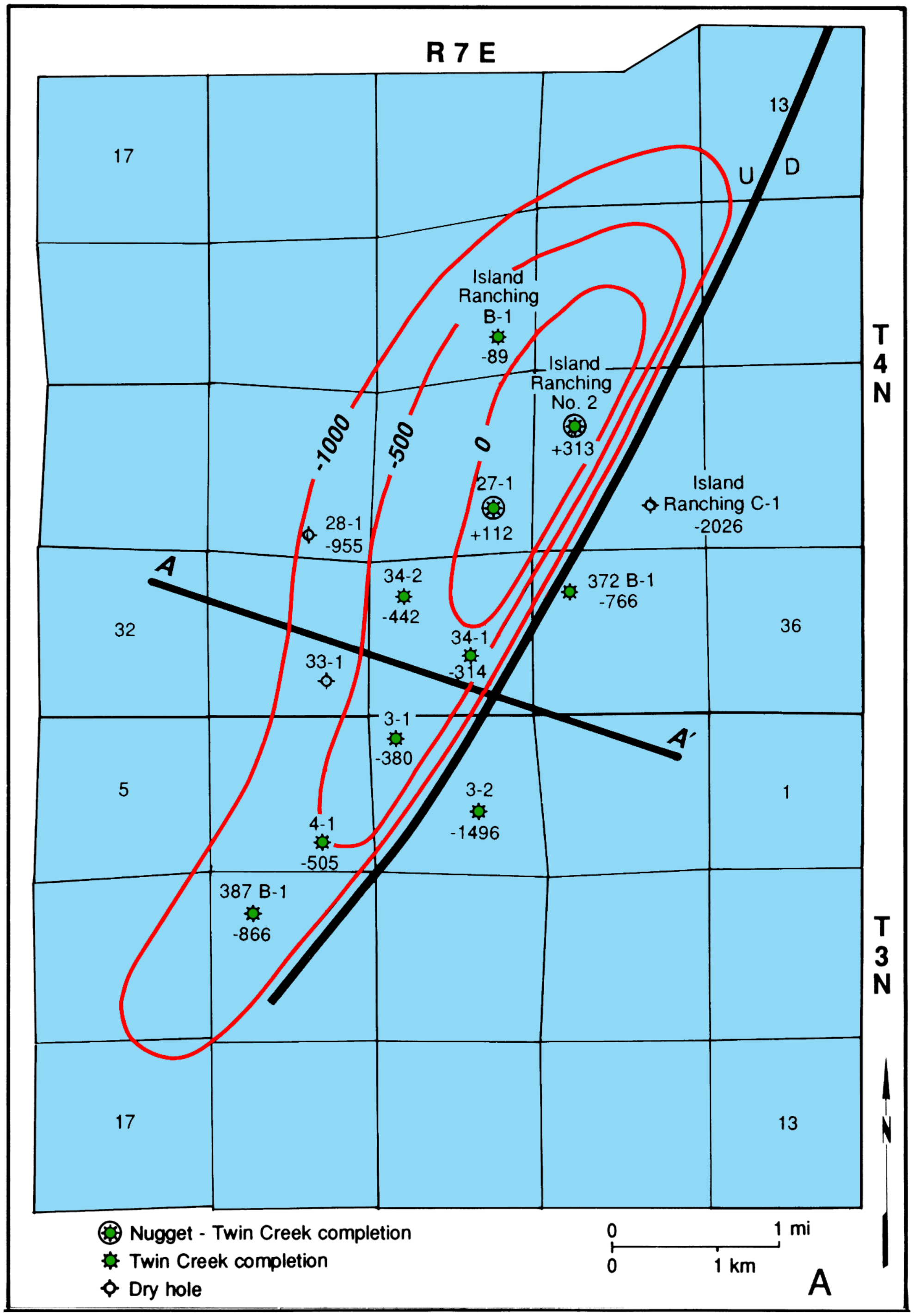

Figure 20. Structure contour map of the top of the Nugget Sandstone, Anschutz Ranch field, Summit County, Utah, typical of the geometry of Paleozoic-cored shallow structures in the Jurassic Nugget Sandstone thrust belt play. Gas and condensate are trapped only on the very crest of a large northeast-southwest-trending, doubly plunging, asymmetric, thrusted anticline in the hanging wall of the Absaroka thrust system. Contour interval = 500 feet, datum = mean sea level. Modified from Utah Division of Oil, Gas and Mining (1980a). Cross section A-A' shown on figure 21.

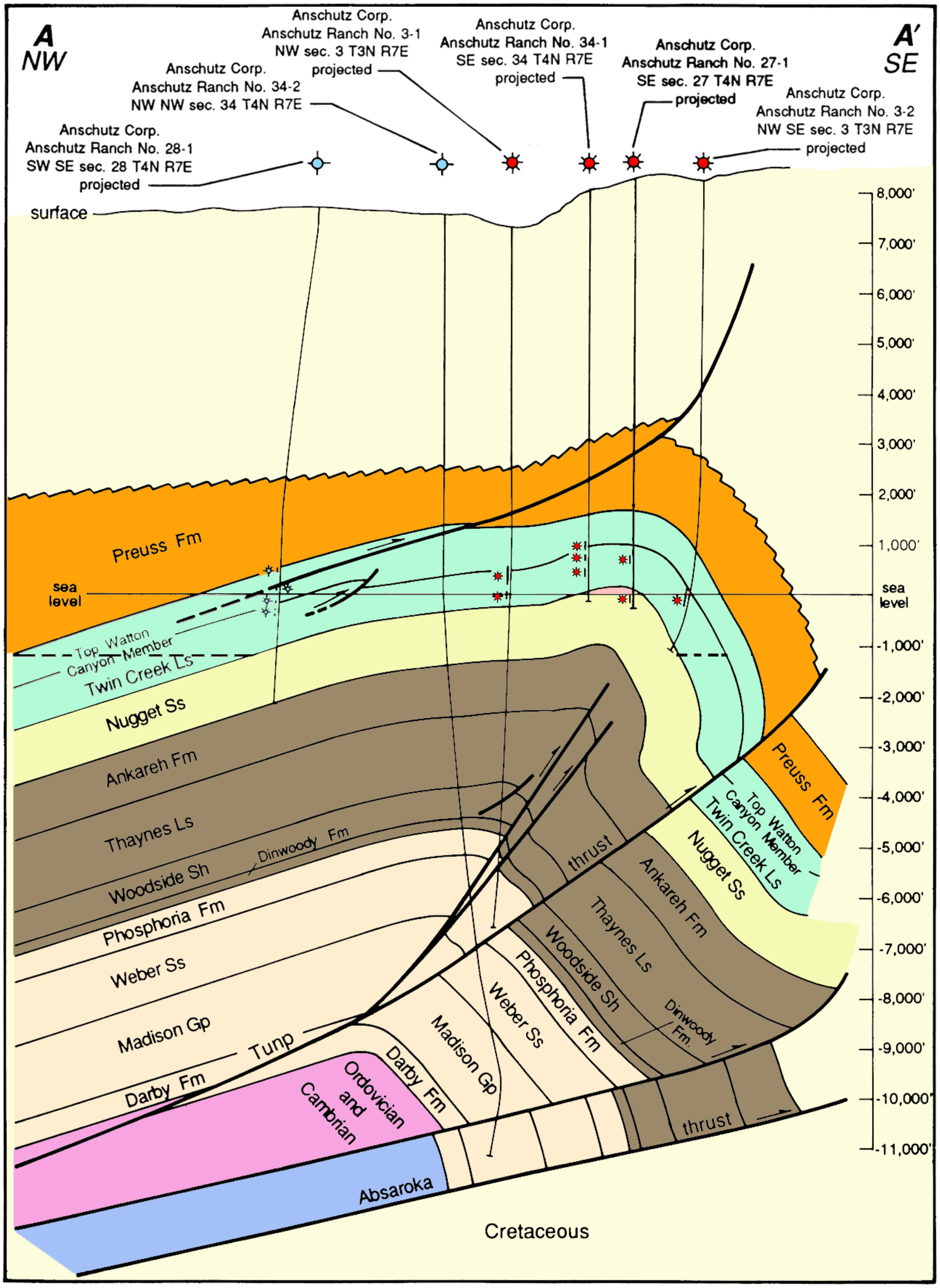

Figure 21. Northwest-southeast cross section through the Anschutz Ranch structure. Line of section shown on figure 20. Cretaceous formations in the footwall of the Absaroka thrust system charge the overlying, fractured sandstone units of the Nugget Sandstone with gas and condensate. Modified from Utah Division of Oil, Gas and Mining (1980b).

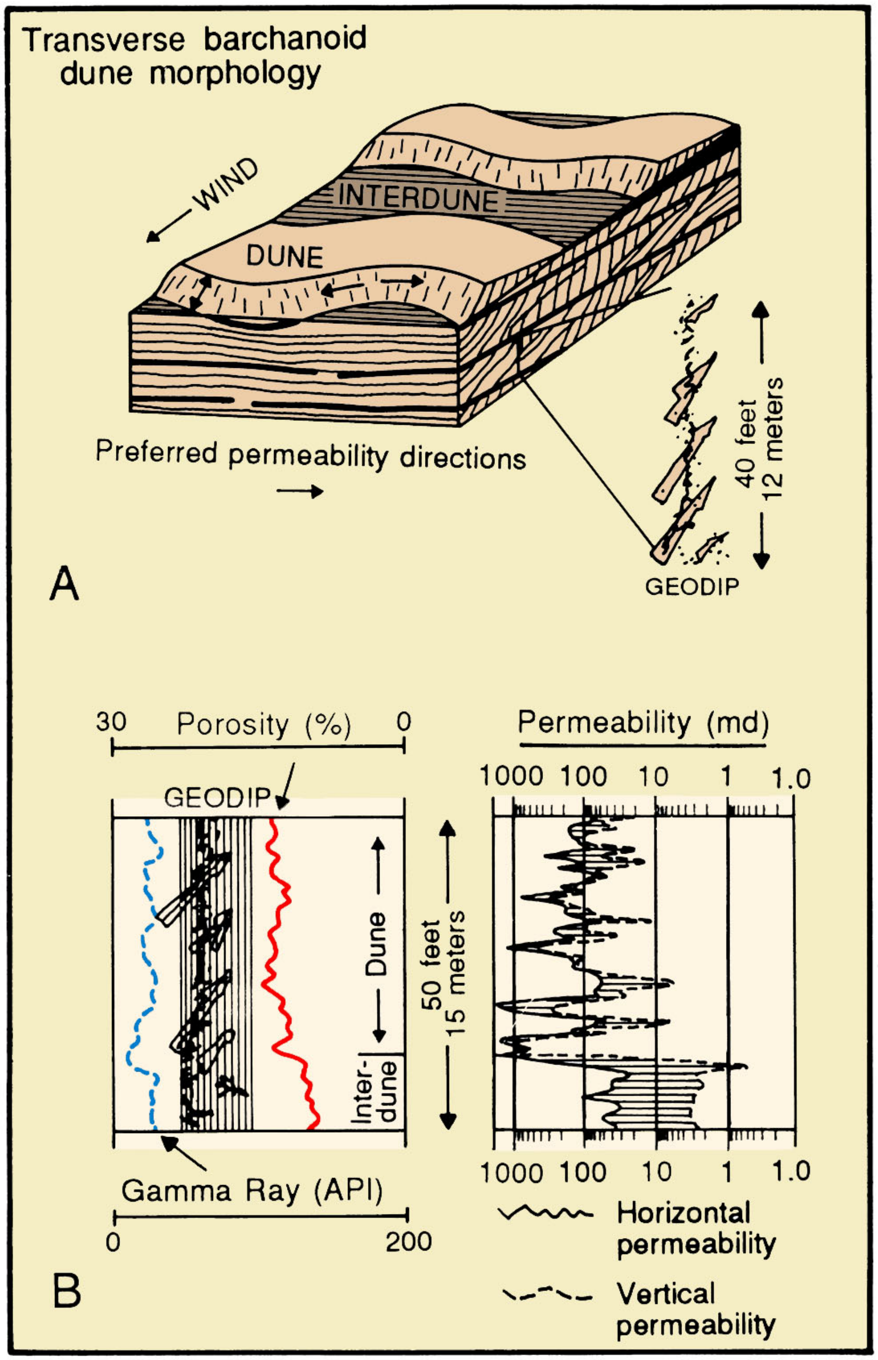

Figure 22. Transverse barchanoid dune morphology. A - Schematic dune/interdune sequence in the Nugget Sandstone correlating transverse barchanoid dune morphology to structurally corrected stratigraphic dipmeter data (Geodip). The slipface of a dune (surface between the dune brink and toe), on which deposits form cross-beds, dips in the downwind, dune-migrating direction. Arrows indicate preferred permeability directions along the dip and strike of dune slipfaces (cross-beds). B - Geophysical logs demonstrate the differences in porosity and directional permeability between the dune and interdune lithofacies. Lined area indicates vertical and horizontal permeability contrasts particularly within the interdune lithofacies (after Lindquist, 1983).

Diagenetic effects and fracturing have both reduced and enhanced the reservoir permeability of the Nugget Sandstone. Overgrowths of quartz and feldspar, authigenic clay mineralization (illite and chlorite), ferroan dolomitization, emplacement of asphaltenes, and the development of gouge and calcite-filled fractures locally have reduced reservoir permeability (Lindquist, 1983). Dissolution of silicate minerals and the development of open fractures have increased reservoir permeability (Lindquist, 1983).

Nugget net-pay thickness is variable, depending on fracturing, and ranges from 22 to 900 feet (7-300 m). The average Nugget reservoir temperature is 185ºF (85ºC). Water saturations range from 22 to 45 percent, and average resistivity (R_w) is 0.284 ohm-m at 68ºF (20ºC). Initial reservoir pressures average about 3900 pounds per square inch (26,890 kPa). The reservoir drive mechanisms include pressure depletion, active water drive, and solution gas.

Reservoir data for individual fields in the Jurassic Nugget Sandstone thrust belt play are summarized in table 1. For details see Loucks (1975), Conner and Covlin (1977), Kelly and Hine (1977), Jones (1979), Moklestad (1979), Petroleum Information (1981, 1984), Frank and Gavlin (1981), Frank and others (1982), Chase and others (1992a, 1992b), Holm (1992), Mullen (1992a, 1992b), Powers (1992), Benson (1993), Cook and Dunleavy (1993), Chidsey (1993), and Lindquist and Ross (1993).

Oil and Gas Characteristics

In major reservoirs, the produced Nugget oil and retrograde condensate are rich, volatile crudes. The API gravity of the oil ranges from 43º to 48º; the gas-oil ratio ranges between 300 and 640 cubic feet/bbl. The API gravity of the condensate ranges from 47º to 63º; the gas-oil ratio ranges from 3800 and 7750 cubic feet/bbl. Oil colors vary from light to dark brown, and condensate can be clear to various shades of yellow, orange, and brown. In some cases, color can change with location or structural position within a single field. In Anschutz Ranch East field (figure 2), for example, the color of the condensate oil changes with the structural position of the producing wells. Condensate on the crest is pale yellow, turning darker shades (yellow through brown) with increasing depth (figure 23). The color change is likely the result of gravity segregation within the reservoir where condensate at the top of structure contains more dissolved gas than at the bottom. The viscosity of the crude oil is 2.18 centistokes (cst) at 104ºF (40ºC); in Saybolt Univeral Seconds (sus) the viscosity averages 33.2 sus at 104ºF (40ºC). The viscosity of the condensate averages 1.09 cst and 29.4 sus at 104ºF (40ºC). The pour point of the crude oil is 15ºF (9.4ºC). The average weight percent sulfur and nitrogen of produced Nugget hydrocarbon liquids are 0.04 and 0.004, respectively.

Figure 23. Color changes in retrograde condensate from Anschutz Ranch East field, Summit County, Utah. Sample bottles are labeled with subsea structural elevation.

In the Mesozoic-cored shallow structures subplay, the three Wyoming fields on the northern culmination produce associated gas that is very uniform in composition: 74 to 80 percent methane, 11 to 15 percent ethane, 5 to 7 percent propane, 2 percent butane, 0.4 percent pentane, and 2 percent nitrogen (Frank and Gavlin, 1981). Heating values average 1252 British thermal units/cubic foot (Btu/ft^3). Pineview field on the south culmination produces associated gas that is significantly different in composition: 35 percent methane, 10 percent ethane, 9 percent propane, 8 percent butane, 4 percent pentane, 2 percent hexane, 31 percent heptanes (and higher hydrocarbon fractions), 0.6 percent nitrogen, and 0.7 percent carbon dioxide (Petroleum Information, 1984). The heating value is 2964 Btu/ft^3. Fields on the Mesozoic-cored deep structures subplay produce nonassociated gas that is remarkably uniform in composition: 74 to 79 percent methane, 12 to 15 percent ethane, 5 percent propane, 2 percent butane, <1 percent pentane, and 2 percent nitrogen (Frank and Gavlin, 1981; Moore and Sigler, 1987). Heating values average 1216 Btu/ft^3. The Nugget reservoir in Anschutz Ranch field (figure 2) on the Paleozoic-cored shallow structures subplay produces nonassociated gas (with condensate) that is somewhat different in composition than gas produced on the Mesozoic-cored shallow and deep structures subplays. The gas contains 81 percent methane, 8 percent ethane, 3 percent propane, 1.5 percent butane, 0.6 percent pentane, and 6 percent nitrogen, making it a low-quality gas (Utah Geological Survey field files). The heating value is 1101 Btu/ft^3. Gas produced from the reservoirs in the Nugget Sandstone thrust belt play contains no hydrogen sulfide.

Production

Five fields in the Jurassic Nugget Sandstone Absaroka thrust - Mesozoic-cored shallow structures subplay have produced crude oil and associated gas. Pineview, Lodgepole, Painter Reservoir, Clear Creek, and Ryckman Creek fields (figure 2) have combined to produce 85 million bbls of oil (MMBO [14 MMCMO]) and 1.15 TCFG (32 BCMG) from the Nugget (Utah Division of Oil, Gas and Mining, 2004; Wyoming Oil & Gas Conservation Commission, 2004) (table 1). There are currently 77 active producers and 58 abandoned Nugget producers in this subplay (table 1).

Six fields in the Jurassic Nugget Sandstone Absaroka thrust - Mesozoic-cored deep structures subplay have produced retrograde condensate and nonassociated gas. Pineview North, Anschutz Ranch East, Bessie Bottom, Chicken Creek, Glasscock Hollow, and East Painter Reservoir fields (figure 2) have combined to produce 202 million bbls of condensate (MMBC [32 MMCMC]) and 3.9 TCFG (111 BCMG) from the Nugget (Utah Division of Oil, Gas and Mining, 2004; Wyoming Oil & Gas Conservation Commission, 2004) (table 1). There are currently 114 active producers and 15 abandoned producers in this subplay (table 1).

Two fields in the Jurassic Nugget Sandstone Absaroka thrust - Paleozoic-cored shallow structures subplay have produced nonassociated gas and condensate. Anschutz Ranch and Yellow Creek fields (figure 2) have combined to produce 776,415 bbls of condensate (123,459 BC) and 43 billion cubic feet of gas (BCFG [1.2 BCMG) from the Nugget (Utah Division of Oil, Gas and Mining, 2004; Wyoming Oil & Gas Conservation Commission, 2004) (table 1). There are currently two active and five abandoned Nugget producers in this subplay (table 1).

In 2004, the monthly production from the Nugget Sandstone averaged 172,463 bbls of oil (and condensate) (27,422 MCMO) and 9.5 BCFG (0.3 BCMG) (Utah Division of Oil, Gas and Mining, 2004; Wyoming Oil & Gas Conservation Commission, 2004). Monthly production peaked in 1979, and has generally declined since then. However, in the 1990s, the intensely fractured and depositionally heterogeneous zones of the Nugget in Lodgepole, Pineview, and Painter Reservoir fields were successfully exploited using horizontal-drilling techniques. Lodgepole field was sub-commercial prior to the horizontal-drilling program.

Exploration Potential and Trends

Future exploration in the Nugget Sandstone thrust belt play could focus on more structurally complex and subtle, thrust-related traps that overlie organic-rich Cretaceous strata. Possible structural targets include complex traps formed by true duplexes, overlapping ramp anticlines, and hybrid duplexes (Mitra, 1986). In these structures, naturally fractured sandstone beds and the overlying seals of the Twin Creek Limestone are repeated many times. Other thrust-related structural traps include subtle fault-propagation folds formed by imbricate thrust faults or stacked imbricate faults. These traps may be developed along secondary fault-propagation folds, along backlimb thrust faults, or between imbricate splays on the forelimb of anticlines (Mitra, 1986, 1990). Nugget structures may be present beneath the leading edge of the Hogsback thrust and North Flank fault of the Uinta uplift (Chidsey, 1999). Minor irregularities along the Nugget truncation against major thrusts may also be the locations for untested structures, particularly in the Mesozoic-cored shallow and deep structures subplays on the Absaroka thrust system.

Major oil reserves also exist in the stratigraphically equivalent Jurassic Navajo Sandstone in the central Utah thrust belt – often referred to as the "Utah Hingeline" (figure 24). In addition, producing members (Sliderock and Watton Canyon) of the Twin Creek Limestone are correlated with limestone beds that separate overlying mudstone and evaporite beds of the Jurassic Arapien Shale from the underlying Navajo (Sprinkel, 1982, 1991; Sprinkel and Waanders, 1984). Exploration for oil should be confined to a belt east of the inferred surface trace of the Charleston-Nebo thrust system and the subsurface trace of the Pavant thrust (Hintze, 1980, 1993; Willis, 1999). Along this belt, the Navajo should have reservoir characteristics similar to the productive reservoirs to the north. Anticlines associated with blind thrusts (Gunnison thrust of Villien and Kligfield, 1986, and Paxton thrust of Royse, 1993) should form multiple structural traps (Sprinkel, 1990).

The Gunnison thrust in this area (Sanpete and Sevier Valleys) is primarily a bedding-plane fault within weak mudstone and evaporite beds of the Arapien Shale. Thrust imbricates, or imbricate fans above, and antiformal stacks of horses forming a duplex below the Gunnison thrust create multiple potential drilling targets (figure 25) (Villien and Kligfield, 1986). These features are obscured by complex surface geology which includes (1) angular unconformities, (2) Oligocene volcanic rocks, (3) Basin and Range-age (Miocene-Holocene) listric normal faulting, and (4) local diapirism. The Gunnison thrust represents, perhaps, the youngest and last of the Sevier-age thrusts in central Utah. It continues eastward under the Wasatch Plateau along the Arapien Shale; however, the complex duplex thrusting remains west of the seismically defined, probable Laramide-age, basement-involved, down-to-the-west, Ephriam fault (figure 25; Royse, 1993). We suggest that, unlike the Nugget Sandstone thrust belt play to the north, the structures and faults are not in contact with Cretaceous source rocks. Rather, potential source rocks include the Mississippian Delle Phosphatic Member of the Deseret Limestone (Sandberg and Gutschick, 1984), Mississippian Chainman Shale, Mississippian-Pennsylvanian Manning Canyon Shale, and Permian Park City/Phosphoria Formation (Sprinkel and others, 1997; Peterson, 2000, 2001), all requiring migration of hydrocarbons from the north or west.

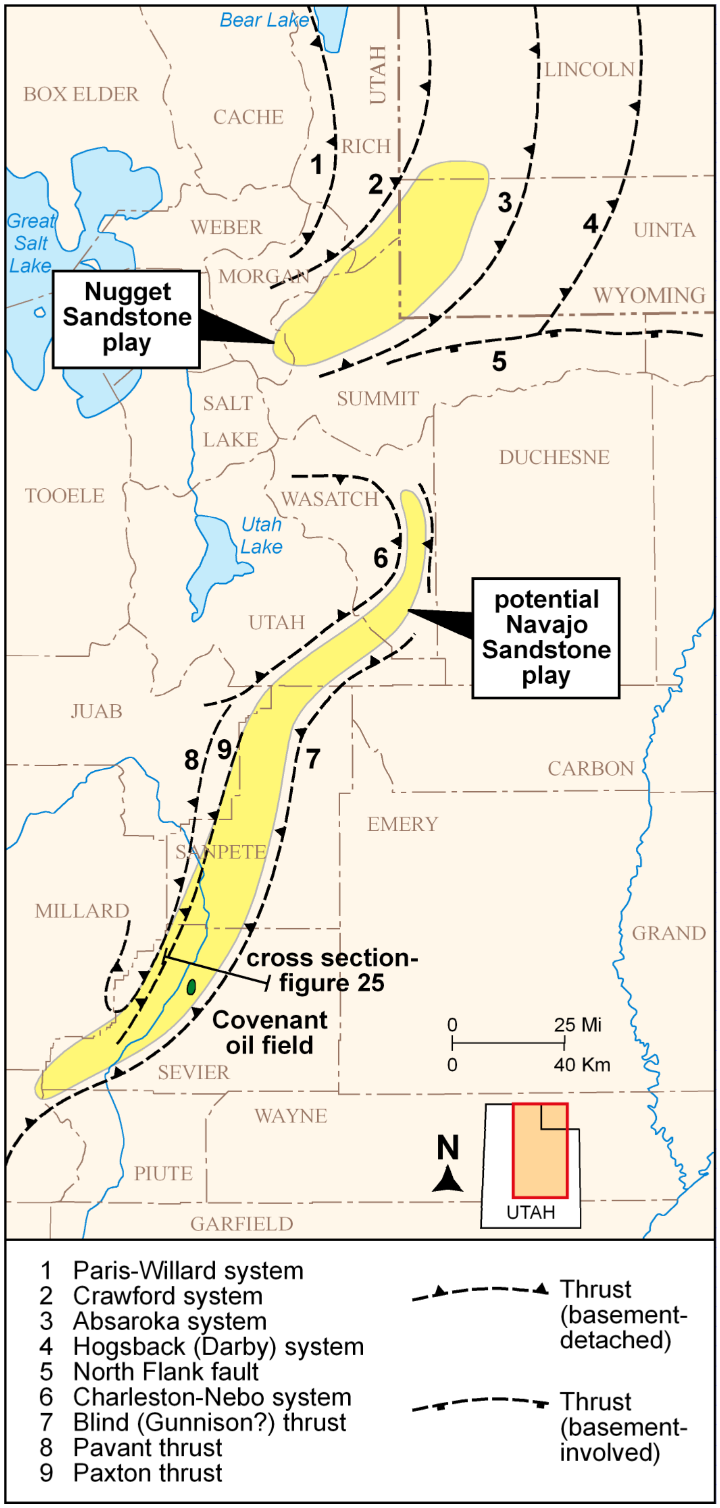

Figure 24. Selected thrust systems of southwestern Wyoming-northern Utah and central Utah (Hintze, 1980; Sprinkel and Chidsey, 1993; Peterson, 2001). Numbers and saw teeth are on the hanging wall of the corresponding thrust system. Colored (light yellow) areas show present and potential Jurassic Nugget/Navajo Sandstone thrust belt plays; Covenant oil field, Sevier County, Utah, shown in green.

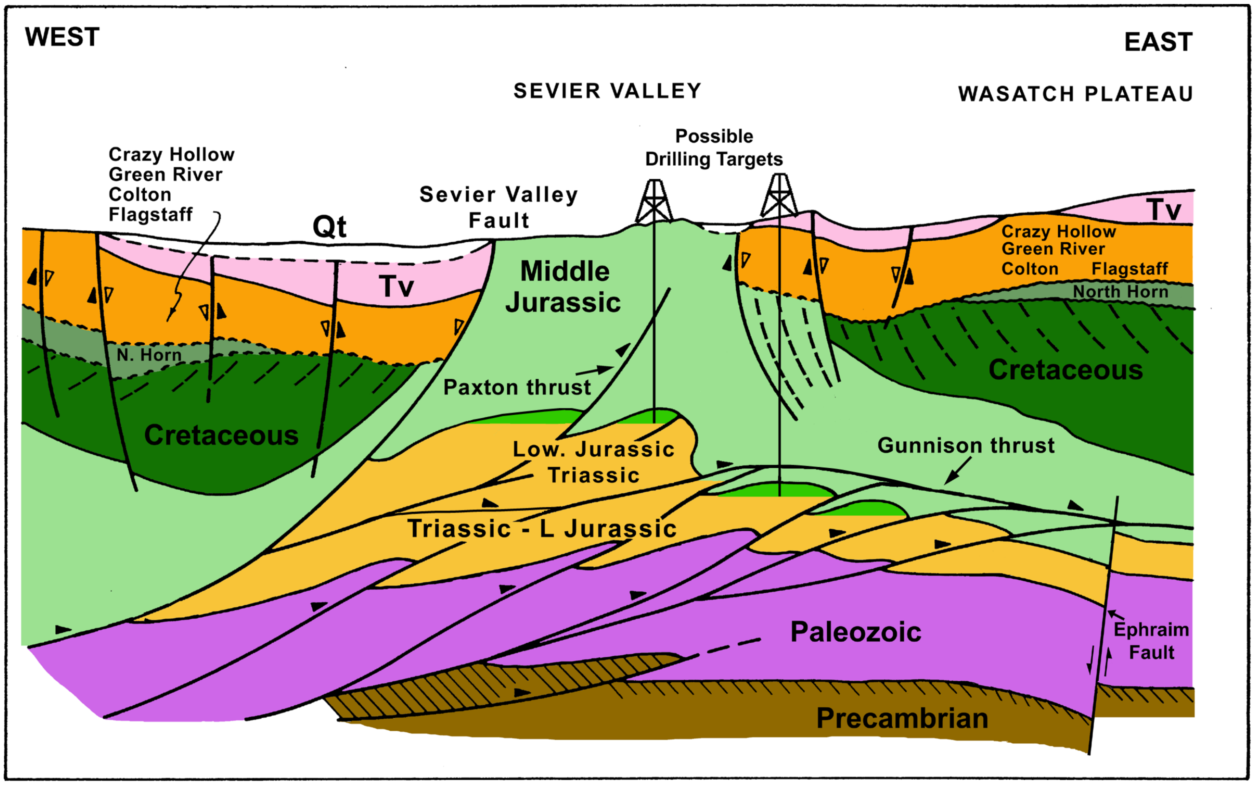

Figure 25. Schematic east-west structural cross section through Sevier Valley, Utah (line of section shown on figure 24), just north of the 2004 discovery of Covenant field (Jurassic Navajo Sandstone), showing potential Lower Jurassic exploratory drilling targets in thrust imbricates and duplexes above and below the Gunnison thrust. Modified from Villien and Kligfield (1986).

As a result of the complex geology, unsuccessful exploration for petroleum in the central Utah thrust belt has continued in cycles for over 50 years. Finally, in 2004, Wolverine Oil & Gas Company's No. 17-1 Kings Meadow Ranches well (SE1/4NW1/4 section 17, T. 23 S., R. 1 W., SLBLM, Sevier County) reportedly tested nearly 1000 bbls (159 m^3) of oil per day and has produced over 100,000 bbls (15,900 m^3) from the Navajo Sandstone in this trend (Petroleum Information/Dwights Drilling Wire, 2004a, 2004b). This major discovery, now Covenant field (figure 24), is leading to increased exploration, and possible, additional Navajo discoveries.

TECHNOLOGY TRANSFER

The Utah Geological Survey (UGS) is the Principal Investigator and prime contractor for the PUMPII project. All play maps, reports, databases, and other deliverables produced for the PUMPII project will be published in interactive, menu-driven digital (Web-based and compact disc) and hard-copy formats by the UGS for presentation to the petroleum industry. Syntheses and highlights will be submitted to refereed journals, as appropriate, such as the *American Association of Petroleum Geologists (AAPG) Bulletin* and *Journal of Petroleum Technology*, and to trade publications such as the *Oil and Gas Journal*.

The technology-transfer plan included the formation of a Technical Advisory Board and a Stake Holders Board. These boards meet annually with the project technical team members. The Technical Advisory Board advises the technical team on the direction of study, reviews technical progress, recommends changes and additions to the study, and provides data. The Technical Advisory Board is composed of field operators from the oil-producing provinces of Utah that also extend into Wyoming or Colorado. This board ensures direct communication of the study methods and results to the operators. The Stake Holders Board is composed of groups that have a financial interest in the study area including representatives from the State of Utah (School and Institutional Trust Lands Administration and Utah Division of Oil, Gas and Mining) and the federal government (Bureau of Land Management and Bureau of Indian Affairs). The members of the Technical Advisory and Stake Holders Boards receive all quarterly technical reports and copies of all publications, and other material resulting from the study. Board members will also provide field and reservoir data, especially data pertaining to best practices. During the quarter, project team members joined Utah Stake Holders Board members in attending the Uinta Basin Oil and Gas Collaborative Group meeting in Vernal, Utah, on December 7, 2004. Project activities, results, and recommendations were presented at this meeting.

Utah Geological Survey *Survey Notes* and Web Site

The UGS publication *Survey Notes* provides non-technical information on contemporary geologic topics, issues, events, and ongoing UGS projects to Utah's geologic community, educators, state and local officials and other decision-makers, and the public. *Survey Notes* is published three times yearly. Single copies are distributed free of charge and reproduction (with recognition of source) is encouraged. The UGS maintains a Web site on the Internet, http://geology.utah.gov. The UGS site includes a page under the heading *Utah Geology/Oil, Coal, and Energy*, which describes the UGS/DOE cooperative studies (PUMPII, Paradox Basin [two projects], Ferron Sandstone, Bluebell field, Green River Formation), and has a link to the DOE Web site. Each UGS/DOE cooperative study also has its own separate page on the UGS Web site. The PUMPII project page, http://geology.utah.gov/emp/pump/index.htm, contains (1) a project location map, (2) a description of the project, (3) a reference list of all publications that are a direct result of the project, (4) poster presentations, and (5) quarterly technical progress reports.

Project Publication

Chidsey, T.C., Jr., and Sprinkel, D.A., 2004, Major oil plays in Utah and vicinity – quarterly annual technical progress report for the period July 1 to September 30, 2004: U.S. Department of Energy, DOE/FC26-02NT15133-9, 26 p.

CONCLUSIONS AND RECOMMENDATIONS

1. A combination of depositional and structural events created the right conditions for oil generation and trapping in the major oil-producing provinces (Paradox Basin, Uinta Basin, and thrust belt) in Utah and adjacent areas in Colorado and Wyoming. Oil plays

are specific geographic areas having petroleum potential due to favorable source rock, migration paths, reservoir characteristics, and other factors.

2. The most prolific oil play in the Utah/Wyoming thrust belt province is the Jurassic Nugget Sandstone thrust belt play, having produced over 288 million bbls (46 million m^3) of oil and 5.1 TCFG (145 billion m^3). The Nugget Sandstone was deposited in an extensive dune field that extended from Wyoming to Arizona. Playas, mudflats, or oases developed in interdune areas. Traps form on discrete subsidiary closures along major ramp anticlines where the Nugget is extensively fractured. The seals for the producing horizons are overlying argillaceous and gypsiferous beds within the Jurassic Twin Creek Limestone, or a low-permeability zone at the top of the Nugget Sandstone.

3. Hydrocarbons in Nugget Sandstone reservoirs were generated from subthrust Cretaceous source rocks. The source rocks began to mature after being overridden by thrust plates. Hydrocarbons were then generated, expelled, and subsequently migrated into overlying traps, primarily along fault planes.

4. The Nugget Sandstone has heterogeneous reservoir properties because of (1) cyclic dune/interdune lithofacies with better porosity and permeability that developed in certain dune morphologies, (2) diagenetic effects, and (3) fracturing. Identifying and correlating barriers and baffles to fluid flow, and recognizing fracture set orientations in individual Nugget reservoirs in the thrust belt are critical to understanding their effects on production rates, petroleum movement pathways, horizontal well plans, and pressure maintenance programs.

5. The Nugget Sandstone thrust belt play is divided into three subplays: (1) Absaroka thrust - Mesozoic-cored shallow structures, (2) Absaroka thrust - Mesozoic-cored deep structures, and (3) Absaroka thrust - Paleozoic-cored shallow structures. Mesozoic-cored structures subplays both represent a linear, hanging-wall, ramp anticline parallel to the leading edge of the Absaroka thrust. This ramp anticline is divided into a broad, shallow structural high (culmination) and a deep, structural low (depression). Fields in the shallow subplay produce crude oil and associated gas. Fields in the deep subplay produce retrograde condensate. The Paleozoic-cored shallow structures subplay is located immediately west of the Mesozoic-cored structures subplays. This subplay represents a very continuous and linear, hanging-wall, ramp anticline, that is also parallel to the leading edge of the Absaroka thrust. The eastern boundary of the subplay is defined by the truncation of the Nugget against a thrust splay. Fields in this subplay produce nonassociated gas and condensate. Traps in these subplays consist of long, narrow, doubly plunging anticlines.

6. Prospective drilling targets in the Nugget Sandstone thrust belt play are delineated using high-quality 2-D and 3-D seismic data, 2-D and 3-D forward modeling/visualization tools, well control, dipmeter information, surface geologic maps, and incremental restoration of balanced cross sections to access trap geometry. Determination of the timing of structural development, petroleum migration, entrapment, and fill and spill histories is critical to successful exploration.

7. Future Nugget Sandstone exploration could focus on more structurally complex and subtle, thrust-related traps. Nugget structures may be present beneath the leading edge of the Hogsback thrust and North Flank fault of the Uinta uplift. Major oil reserves also exist in the stratigraphically equivalent Jurassic Navajo Sandstone in the central Utah thrust belt. Exploration for oil should be confined to a belt east of the inferred surface trace of the Charleston-Nebo thrust system where the Nugget should have reservoir characteristics similar to the productive reservoirs to the north. Anticlines associated with the Gunnison thrust, a blind thrust in the region, should form multiple structural traps containing hydrocarbons possibly generated from Mississippian or Permian source rocks.

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