MAJOR OIL PLAYS IN UTAH AND VICINITY

QUARTERLY
TECHNICAL PROGRESS REPORT

Reporting Period
Start Date: April 1, 2003
End Date: June 30, 2003

by
Thomas C. Chidsey, Jr., Principal Investigator/Program Manager,
Craig D. Morgan, Kevin McClure, and Grant C. Willis
Utah Geological Survey

UTAH GEOLOGICAL SURVEY

September 2003

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 P. Lindsey, 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). 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; summaries of the state-of-the-art drilling, completion, and secondary/tertiary techniques for each play; locations of major oil pipelines; descriptions of reservoir outcrop analogs; and identification and discussion of land-use constraints. All play maps, reports, databases, and so forth, produced for the project will be published in interactive, menu-driven digital (web-based and compact disc) and hard-copy formats.

This report covers research activities for the fourth quarter of the first project year (April 1 through June 30, 2003). This work included describing outcrop analogs to the Jurassic Nugget Sandstone and Pennsylvanian Paradox Formation, the major oil producers in the thrust belt and Paradox Basin, respectively. Production-scale outcrop analogs provide an excellent view, often in three dimensions, of reservoir-facies characteristics and boundaries contributing to the overall heterogeneity of reservoir rocks. They can be used as a "template" for evaluation of data from conventional core, geophysical and petrophysical logs, and seismic surveys.

The Nugget Sandstone was deposited in an extensive dune field that extended from Wyoming to Arizona. Outcrop analogs are found in the stratigraphically equivalent Navajo Sandstone of southern Utah which displays large-scale dunal cross-strata with excellent reservoir properties and interdunal features such as oases, wadi, and playa lithofacies with poor reservoir properties. Hydrocarbons in the Paradox Formation are stratigraphically trapped in carbonate buildups (or phylloid-algal mounds). Similar carbonate buildups are exposed in the Paradox along the San Juan River of southeastern Utah. Reservoir-quality porosity may develop in the types of facies associated with buildups such as troughs, detrital wedges, and fans, identified from these outcrops. When combined with subsurface geological and production data, these outcrop analogs can improve (1) development drilling and production strategies such as horizontal drilling, (2) reservoir-simulation models, (3) reserve calculations, and (4) design and implementation of secondary/tertiary oil recovery programs and other best practices used in the oil fields of Utah and vicinity.

During this quarter, technology transfer activities consisted of exhibiting the project plans, objectives, and products at a booth at the 2003 annual convention of the American Association of Petroleum Geologists. The project home page was updated on the Utah Geological Survey Internet web site.

EXECUTIVE SUMMARY

Utah oil fields have produced over 1.2 billion barrels (191 million m^3). 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 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 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 fourth quarter of the first project year (April 1 through June 30, 2003). This work included: (1) describing outcrop analogs to the Jurassic Nugget Sandstone (thrust belt) and Pennsylvanian Paradox Formation (Paradox Basin) and (2) technology transfer activities.

Utah is unique in that it has representative outcrop analogs for each major oil play. Production-scale outcrop analogs provide an excellent view, often in three dimensions, of reservoir-facies characteristics and boundaries contributing to the overall heterogeneity of reservoir rocks. Outcrop analogs can be used as a "template" for evaluation of data from conventional core, geophysical and petrophysical logs, and seismic surveys. When combined with subsurface geological and production data, outcrop analogs can improve development drilling and production strategies, reservoir-simulation models, reserve calculations, and design and implementation of secondary/tertiary oil recovery programs and other best practices used in the oil fields of Utah and vicinity.

The most prolific oil reservoir in the thrust belt is the Jurassic Nugget Sandstone which was deposited in an extensive dune field that extended from Wyoming to Arizona. Outcrop analogs are found in the stratigraphically equivalent Navajo Sandstone of southern Utah. The Navajo in the Glen Canyon National Recreation Area displays large-scale dunal cross-strata and interdunal features such as oases, wadi, and playa lithofacies. Navajo interdune lithofacies have significantly poorer reservoir characteristics than the dune lithofacies and in a reservoir represent potential barriers to flow. Identification and correlation of dune/interdune lithofacies in individual Nugget reservoirs in the thrust belt is critical to understanding their effects on production rates and paths of petroleum movement.

In the Paradox Basin, hydrocarbons are stratigraphically trapped in heterogeneous reservoirs within carbonate buildups (or phylloid-algal mounds) of the Pennsylvanian Paradox Formation. Carbonate buildups are exposed along the San Juan River of southeastern Utah. Reservoir-quality porosity may develop in the types of facies associated with buildups, such as troughs, detrital wedges, and fans, identified from these outcrops. If these facies are in communication with mound-reservoir facies in actual reservoirs, they could serve as conduits facilitating sweep efficiency in secondary/tertiary recovery projects. However, the relatively small size and the abundance of intermound troughs over short distances, as observed along the river, suggests caution should be used when correlating these facies between development wells. Facies that appear correlative and connected from one well to another may actually be separated by low-permeability facies which inhibit flow and decrease production potential.

These outcrop analogs also demonstrate that there are various targets and risks when considering horizontal drilling in the Paradox Basin. Before selecting the optimal location, orientation, and type of horizontal well, the distribution, both laterally and vertically, of phylloid-algal mounds and other associated facies must be carefully evaluated.

During this quarter, technology transfer activities included exhibiting the project plans, objectives, and products at a booth at the 2003 annual convention of the American Association of Petroleum Geologists in Salt Lake City, Utah. The project home page was updated on the Utah Geological Survey Internet 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, 2003). 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 283 million bbls (45 million m^3) (Energy Information Administration, 2001). 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 prices are likely to entice less risk-averse exploration investment (more wildcats), resulting in new discoveries.

Utah still contains large areas that are virtually unexplored. There is significant potential for increased recovery from existing fields by employing improved reservoir characterization and the latest drilling, completion, and secondary/tertiary 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 land-use constraints to development such as wilderness or roadless areas, and national parks within oil plays.

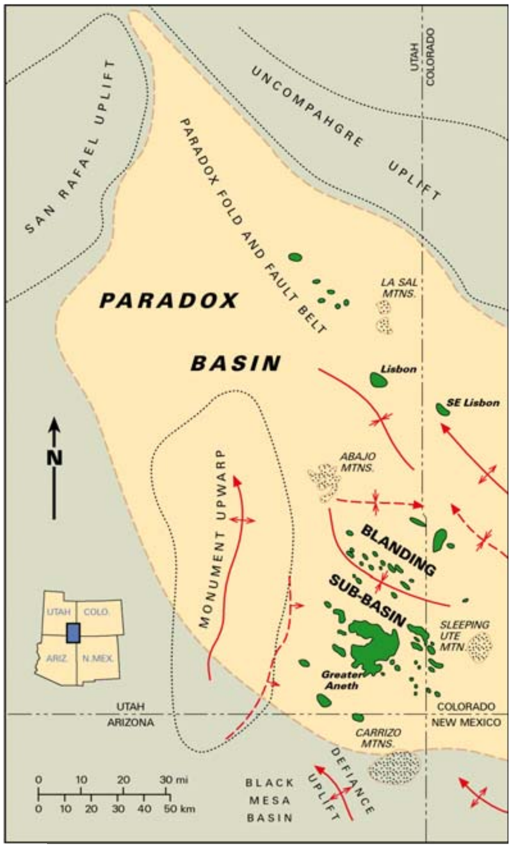
Project Benefits

The overall benefits of this multi-year project will be enhanced petroleum production in the Rocky Mountain region. Specifically, the benefits expected from the project are:

(1) increasing oil production and reserves by improved reservoir characterization,

(2) preventing premature abandonment of numerous small fields in the Paradox and Uinta Basins,

(3) increasing recoverable reserves by identifying the type of untapped compartments created by reservoir heterogeneity (for example, diagenesis and rapid facies changes),



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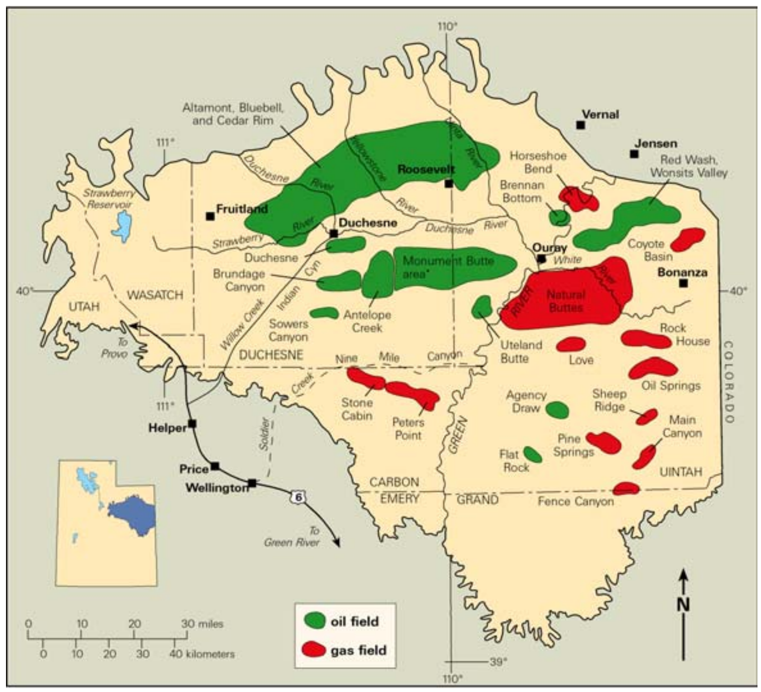

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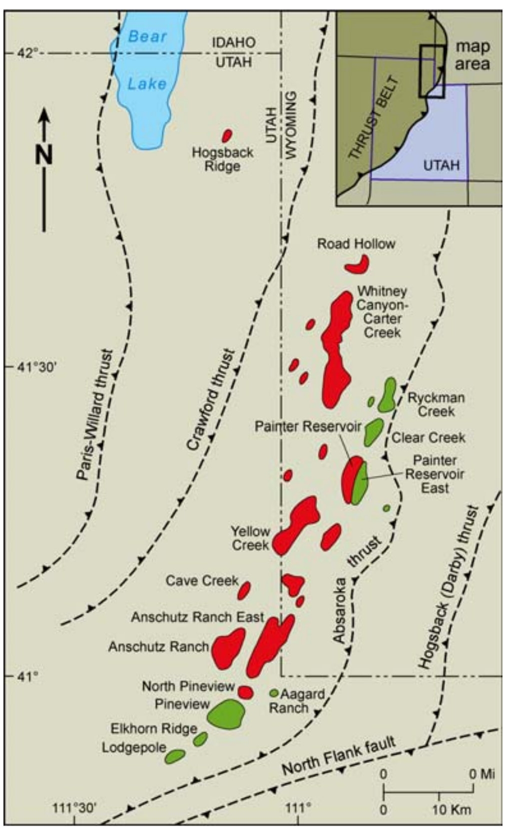


C

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.

(4) increasing deliverability through identifying the latest drilling, completion, and secondary/tertiary techniques,

(5) identifying reservoir trends for field extension drilling and stimulating exploration in producing fairways,

(6) encouraging technology used in other identified basins or trends with similar types of reservoirs,

(7) reducing development costs and risk by reducing the number of wells needed to successfully drain the reservoir,

(8) allowing limited energy investment dollars to be used more productively, and

(9) increasing royalty income to the Federal Government; Utah, Wyoming, and Colorado state and local governments; the Navajo Nation and Ute Mountain Ute Indian Nation; 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 and land-acquisition strategies. 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 Holder Boards, an industry outreach program, and technical presentations at national and regional professional meetings. All of this information will be made public (1) through the Utah Geological Survey (UGS) Internet web site, (2) as an interactive, menu-driven digital product on compact disc, and (3) as hard copy publications in various technical or trade journals.

OUTCROP RESERVOIR ANALOGS – DISCUSSION AND RESULTS

Utah is unique in that representative outcrop analogs (depositional or structural) for each major oil play are present in or near the thrust belt, Uinta Basin, and Paradox Basin. Production-scale analogs provide an excellent view, often in 3D, of reservoir-facies characteristics, geometry, distribution, and the nature of boundaries contributing to the overall heterogeneity of reservoir rocks. The specific objectives of this work are to: (1) increase understanding of vertical and lateral facies variations and relationships within major reservoirs; (2) describe the lithologic characteristics; (3) determine the morphology, internal geometries, and possible permeability and porosity distributions; and (4) identify potential impediments and barriers to fluid flow.

An outcrop-analog model, combined with the details of internal lithofacies characteristics, can be used as a "template" for evaluation of data from conventional core, geophysical and petrophysical logs, and seismic surveys. When combined with subsurface geological and production data, the analog model will improve development drilling and production strategies, reservoir-simulation models, reserve calculations, and design and implementation of secondary/tertiary oil recovery programs and other best practices used in the oil fields of Utah and vicinity. Outcrop analogs for the major oil reservoirs in the thrust belt and Paradox Basin are presented in the following sections.

Thrust Belt

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 oil fields are on the Absaroka thrust plate (figure 1).

Petroleum-trapping mechanisms in Mesozoic-cored structures of the Absaroka thrust consist of long, narrow, doubly plunging anticlines. These anticlines are asymmetric, overturned to the east, and often develop en echelon structures along the leading edge of the Absaroka thrust. Traps form on discrete subsidiary closures along major ramp anticlines. The most prolific oil reservoir in these thrust-belt traps is the Jurassic Nugget Sandstone.

Nugget Sandstone Reservoir

In Early Jurassic time, Utah had an arid climate and lay 15 degrees north of the equator. It was then that the Nugget Sandstone was deposited in an extensive dune field that extended from Wyoming to Arizona comparable to the present Sahara in North Africa or the Alashan area of the Gobi in northern China. Correlative rocks form many of the spectacular canyons in the parks of southern Utah. The Nugget Sandstone and age-equivalent rocks are more than 2,000 feet (600 m) thick. The formation is typically 1,100 feet (335 m) thick in the thrust belt where it is overlain by the Jurassic Twin Creek Limestone and underlain by the Triassic Ankareh Formation.

The Nugget Sandstone is composed of (1) a basal, thin-bedded unit up to 140 feet (40 m) thick, characterized by horizontal stratification and ripple marks and (2) an overlying cyclic dune/interdune sequence (the principal petroleum-bearing section), more than 1,000 feet (300 m) thick, characterized by cross-stratification. The dune/interdune sequence generally consists of fine- to coarse-grained, subangular to subrounded sand or silt grains cemented by calcite (Picard, 1975). The best permeability is along bounding surfaces (bedding planes), with preferred directions along the dip and strike of the individual slipfaces (cross-beds) (Lindquist, 1983).

Dune deposits consist almost entirely of sandstone whereas interdune deposits consist of both sandstone and siltstone with some carbonate and evaporite lithologies. Framework and matrix grains in sandstone (>1/16 mm and 1/16 to 1/256 mm, respectively) and siltstone are commonly composed of more than 90 percent quartz (usually frosted) with varying amounts of K-feldspar, plagioclase, and rock fragments. The typical sandstone contains 11 percent authigenic cement and 2 percent matrix grains, and has an average porosity of 14 percent; the typical siltstone contains 18 percent authigenic cement and 11 percent matrix grains, and has an average porosity of 7 percent (Picard, 1975).

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 (interdune, foresets, and avalanche-slope deposits have different directional permeabilites), (2) diagenetic effects, and (3) fracturing.

Navajo Sandstone Outcrop Analog, Glen Canyon National Recreation Area, Utah

The best outcrop analogs to the Nugget Sandstone are found in the stratigraphically equivalent Navajo Sandstone of southern Utah. The Navajo is famous for its exposures in Zion National Park and Glen Canyon National Recreation Area in southern Utah (figure 2). Navajo dunes were straight-crested to sinuous, coalescing, transverse barchanoid ridges with slipfaces dipping toward the downwind direction (Picard, 1975). Regional analyses indicate paleocurrent and paleowind directions were dominantly from the north and northwest (Anderson and others, 2000; Chidsey and others, 2000b). Outcrops along the shores of Lake Powell in Glen Canyon National Recreation Area display classic eolian bedforms (Ahlbrandt and Frybreger, 1982) such as

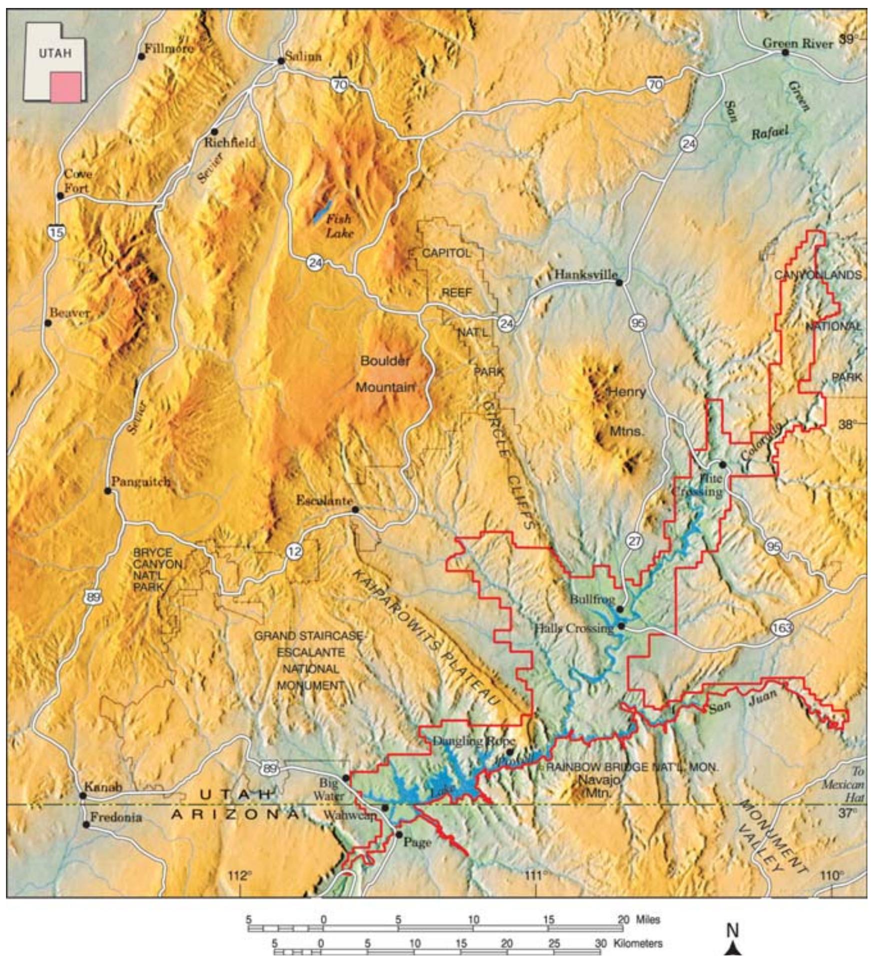


Figure 2. Index map to Glen Canyon National Recreation Area, Utah and Arizona (modified from Hintze, 1997; topographic relief base map modified with permission, courtesy of Chalk Butte, Inc., Boulder, Wyoming).

tabular planar, wedge planar, and large-scale trough cross-strata (figure 3). They occur in sets up to 25 feet (8 m) thick. Dips of cross-beds between set boundaries vary as much as 40 degrees from the nearly horizontal structural attitude of the formation in Glen Canyon National Recreation Area. Dune sand-flow toes often form tangential contacts of cross-beds with the lower bounding surfaces (Ahlbrandt and Frybreger, 1982). Dune lithofacies from the brink to the toe of the dune slipface consist of (1) thin, reverse graded, tabular, pinstriped grainfall laminae, (2) thick, subgraded avalanche laminae, and (3) thin, tightly packed, reworked ripple strata at the dune toe (Lindquist, 1983). Wind ripples or high-index ripples are occasionally preserved on topset deposits. The south shore of Antelope Island in Lake Powell contains some of the best examples of soft-sediment deformation or contorted bedding in the Navajo. The contorted bedding is the result of slumping on the slopes of sand dunes before the sediments were lithified, possibly during earthquakes. Many of the tortuous and twisted beds have weathered in relief, forming eerie-looking outcrops (figure 4).

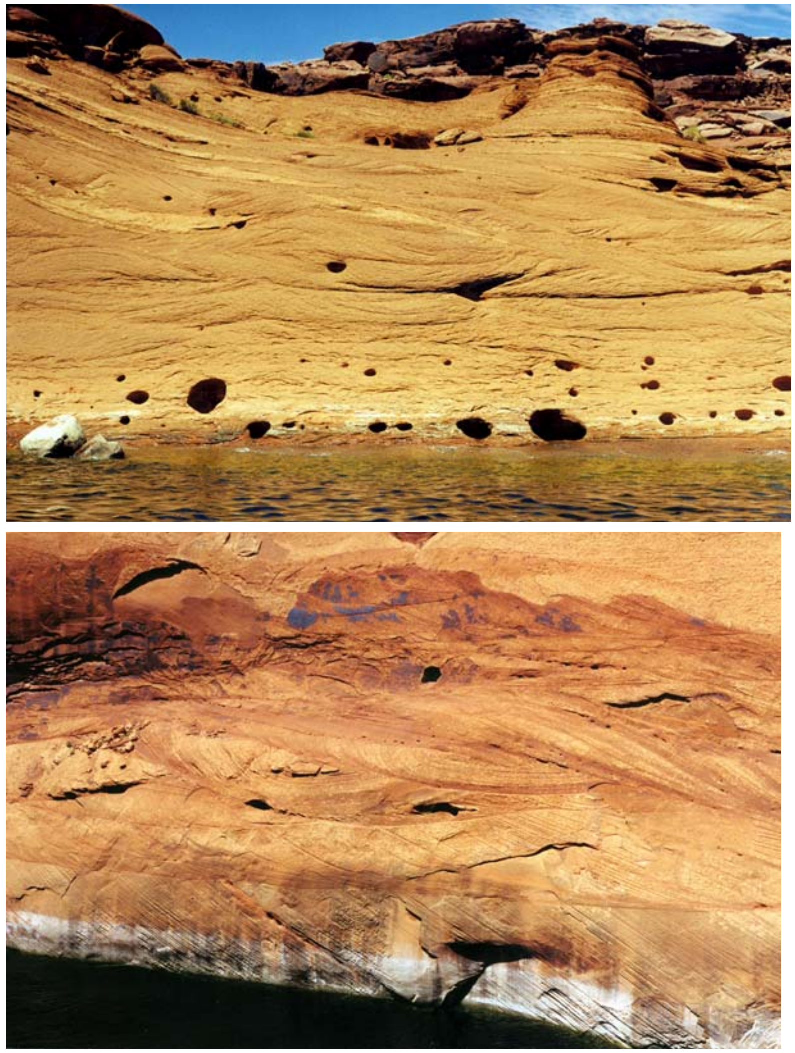


Figure 3. Navajo Sandstone beds display pronounced trough cross-bedding which indicates the paleowinds were from the north and northwest, Lake Powell, Glen Canyon National Recreation Area, Utah.

In addition to "seas" of wind-blown sand dunes, large deserts such as the Sahara and Gobi contain depositional interdune lithofacies, including playas and oases. 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. A playa is a flat-floored bottom of an undrained desert valley that is only occasionally the site of shallow lakes. Within the Navajo Sandstone around Lake Powell in Glen Canyon National Recreation Area are many thin-bedded, lenticular limestone beds that are interpreted as interdune oasis deposits (Anderson and others, 2000; Chidsey and others, 2000a, 2000b). Shallow lacustrine limestone seems to be the most common. Oasis deposits are typically represented by light-gray, 5- to 10-foot-thick (2-3 m), thin and horizontally bedded limestone that commonly contains oscillation ripples and mudcracks (figure 5A and B). They generally pinch out over very short distances (figure 5C),

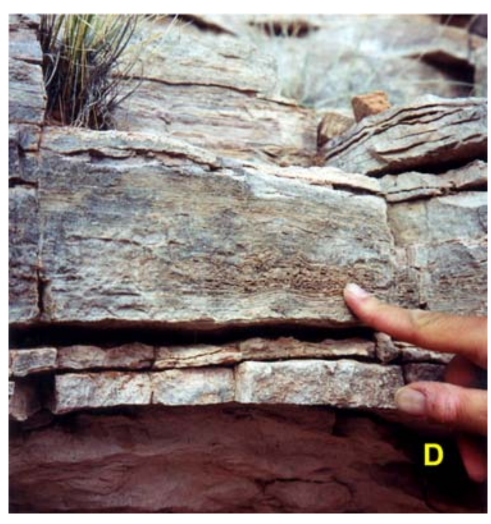
Figure 4. Spectacular contorted bedding in Navajo Sandstone; south side of Antelope Island in Lake Powell, Glen Canyon National Recreation Area, Arizona.

and can be observed on both sides of the narrower canyons (figure 6). Limestone beds in several Navajo outcrops have yielded fossil plants and invertebrates (Stokes, 1991; Santucci, 2000). Many limestone beds also contain cryptalgalaminites (algal laminae) most likely created by coccoid blue-green algal or cyanobacterial processes as organic mats and thrombolites (figures 5D and 7) (D.E. Eby, Eby Petrography & Consulting, Inc., written communication, 2003). Playas or mudflats (some with precipitation of evaporite minerals) are also present in the Navajo around Lake Powell, represented by planar beds composed of mud, silt, and very fine grained sand.

Similar limestone beds along the Colorado River near Canyonlands National Park represent small freshwater lakes based on geochemical analysis (Gilland, 1979). Fresh ground water at a shallow depth had to persist for prolonged periods of time, perhaps many thousands of years, to allow the lake or pond deposits of these oases to develop (Stokes, 1991). The continuous supply of fresh water provided favorable environments for life and the deposition of carbonate rocks (figure 6). The Alashan area of the Gobi Desert contains a high water table producing similar lakes between massive dunes today (Webster, 2002).

Some Navajo interdunes were erosional (deflation) areas associated with running water, such as a wadi or desert wash (Chidsey and others, 2000a, 2000b). An ancient wadi deposit can be observed in the Navajo Sandstone in Rainbow Bridge National Monument, Utah (figure 2) and is represented by several dark, iron-stained channelform features present on the south side of Rainbow Bridge Canyon (figure 8A), a tributary canyon to Glen Canyon and the Colorado River. A wadi is a usually dry streambed or channel in a desert region. A few large blocks of a wadi deposit fell to the terrace bench, near the Rainbow Bridge viewing area, from a channel bed about 3 feet (1 m) thick about 50 feet (15 m) up the cliff. The deposit is a "pudding stone" consisting of tan to reddish-orange, rounded sandstone fragments or clasts, and gray to dark gray, subangular to subrounded dolomitic limestone clasts (figure 8B). Clasts vary from pea to small boulder sized. The matrix is medium- to coarse-grained sandstone cemented with iron-bearing quartz and minor calcite. The fallen blocks are horizontally stratified and have some small-scale cross-beds. They contain rip-up clasts of lime muds; some imbricated rip-up clasts are inclined in the downstream direction. Additional wadi deposits are located in other parts of Rainbow Bridge Canyon and nearby Forbidding Canyon, and possibly belonged to the same ancient wadi system (figure 8C).

Figure 5. Oasis deposits in the Navajo Sandstone, Lake Powell, Glen Canyon National Recreation Area, Utah. A - Typical limestone oasis deposit near the top of the Navajo Sandstone; Forgotten Canyon. B - Mudcracks in oasis limestone mud above bed containing ripple marks; Forgotten Canyon. C - Rapid pinch out of thin limestone bed; Moki Canyon. D – Algal laminae within the limestone oasis beds in the Navajo Sandstone; Moki Canyon.



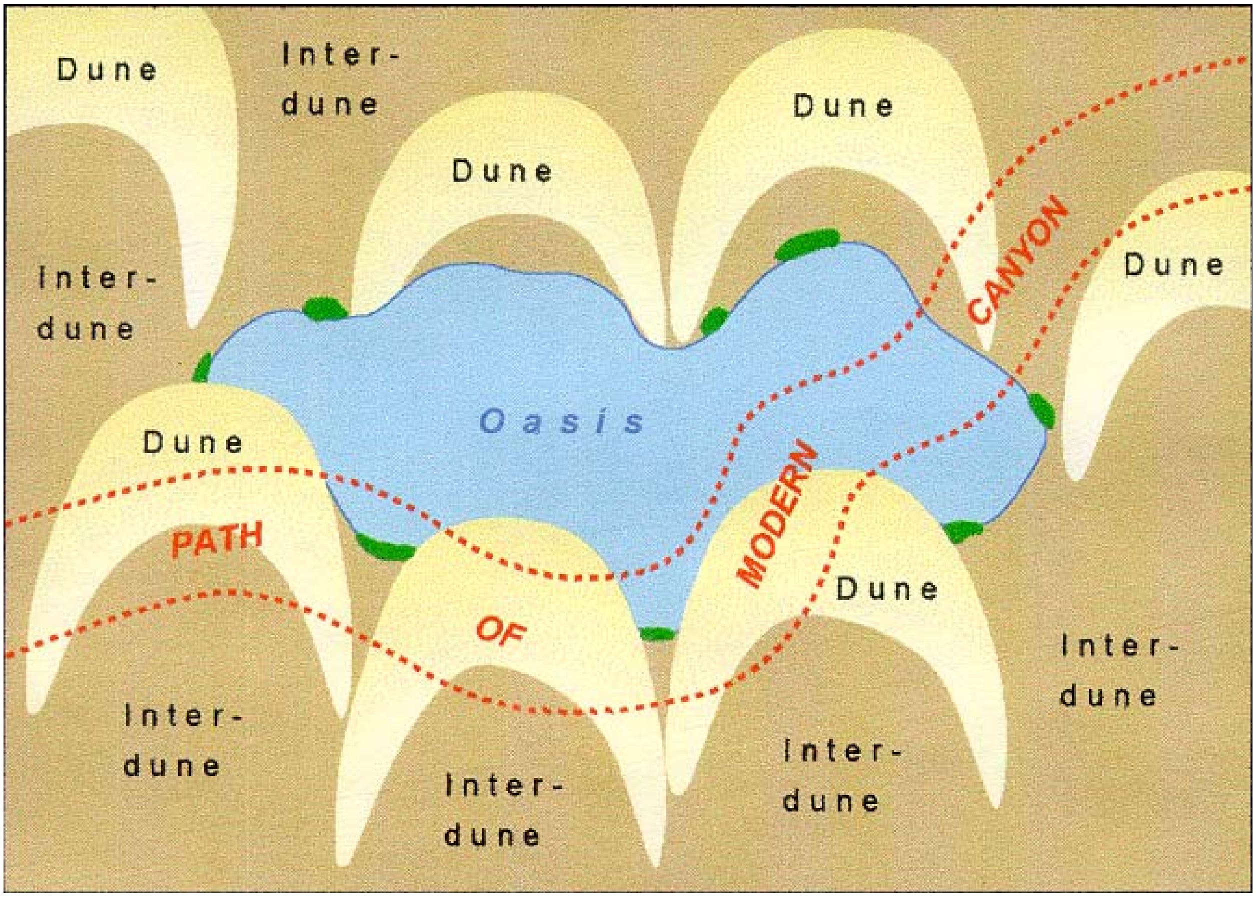


Figure 6. Schematic interpretation, map view, of a Navajo oasis pond surrounded by large dunes. The path of a modern canyon is superimposed to demonstrate the rapid pinch outs of limestones observed along the canyon walls; many of the limestones probably belong to the same oasis deposits.

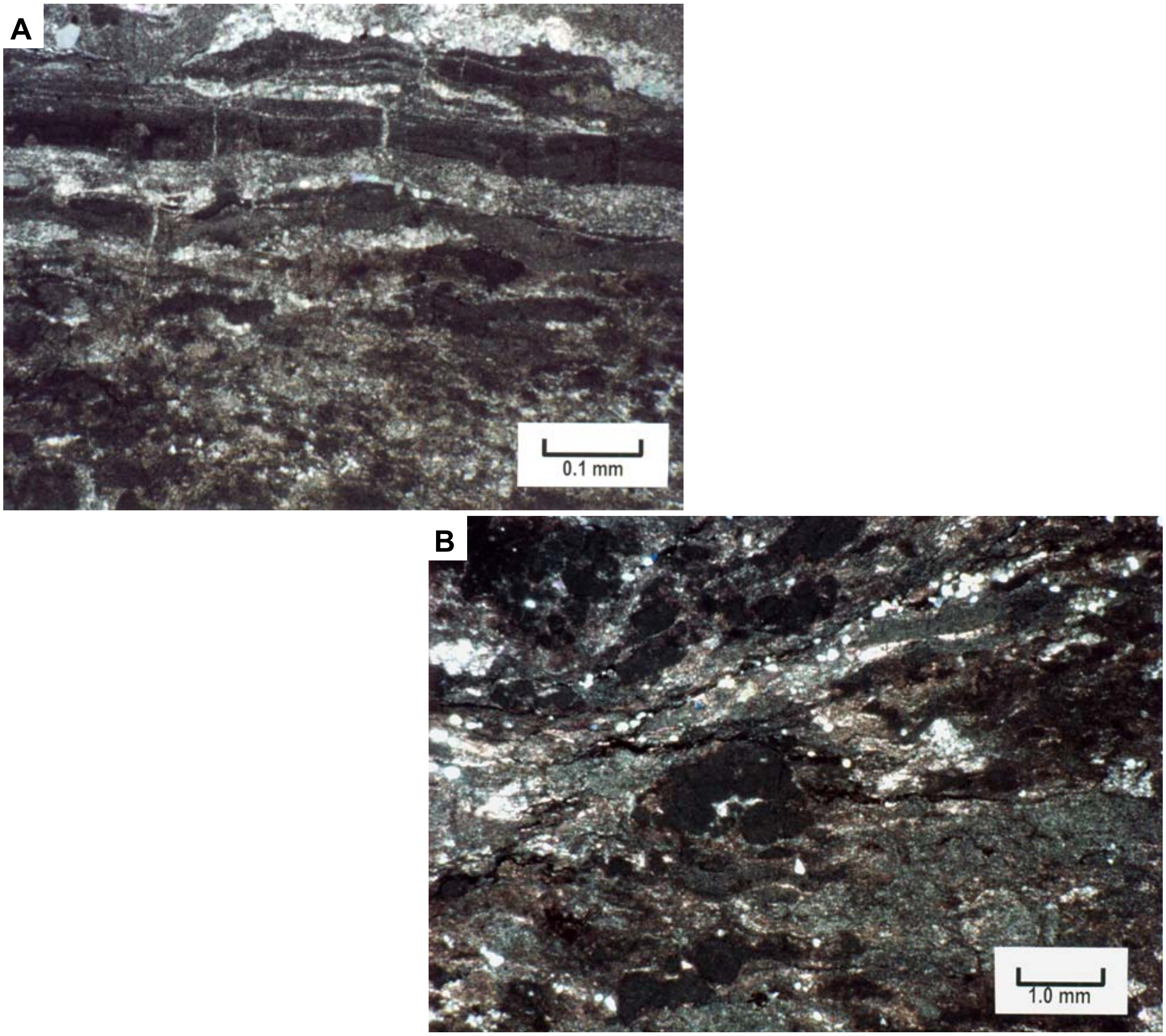


Figure 7. Photomicrographs (crossed nicols) of oasis deposits, Navajo Sandstone, Glen Canyon National Recreation Area, Utah. A - Couplets of alternating cryptalgalaminites and massive microcrystalline layers dominate the upper half of this micrograph. The laminated bands are mostly calcitic (limestones) while the lighter-colored microcrystalline bands are mostly dolomites. These mm-scale couplets are typical of organic blue-green algal or cyanobacterial mats. The lighter-colored, massive or microcrystalline bands are probably the result of dolomitized storm deposits while the microlaminated layers are the result of normal microbial mat trapping and binding activities. The lower half of this image shows a greater concentration of dark-colored rip-up intraclasts. B - Dark-colored clots and pin cushion-like patches of micrite are surrounded by lighter-colored, partially dolomitized detrital sediments and small, white quartz grains. Several of these lumpy clots can be termed "thrombolites." They were most likely created by coccoid blue-green algal or cyanobacterial processes. Such microbial structures could have easily formed in stressed environments that were intermittently desiccated. Salinity stresses, ranging from fresh to hypersaline waters, can promote these types of microbial mini-structures. Photomicrographs and description by D.E. Eby, Eby Petrography & Consulting, Inc., written communication, 2003.

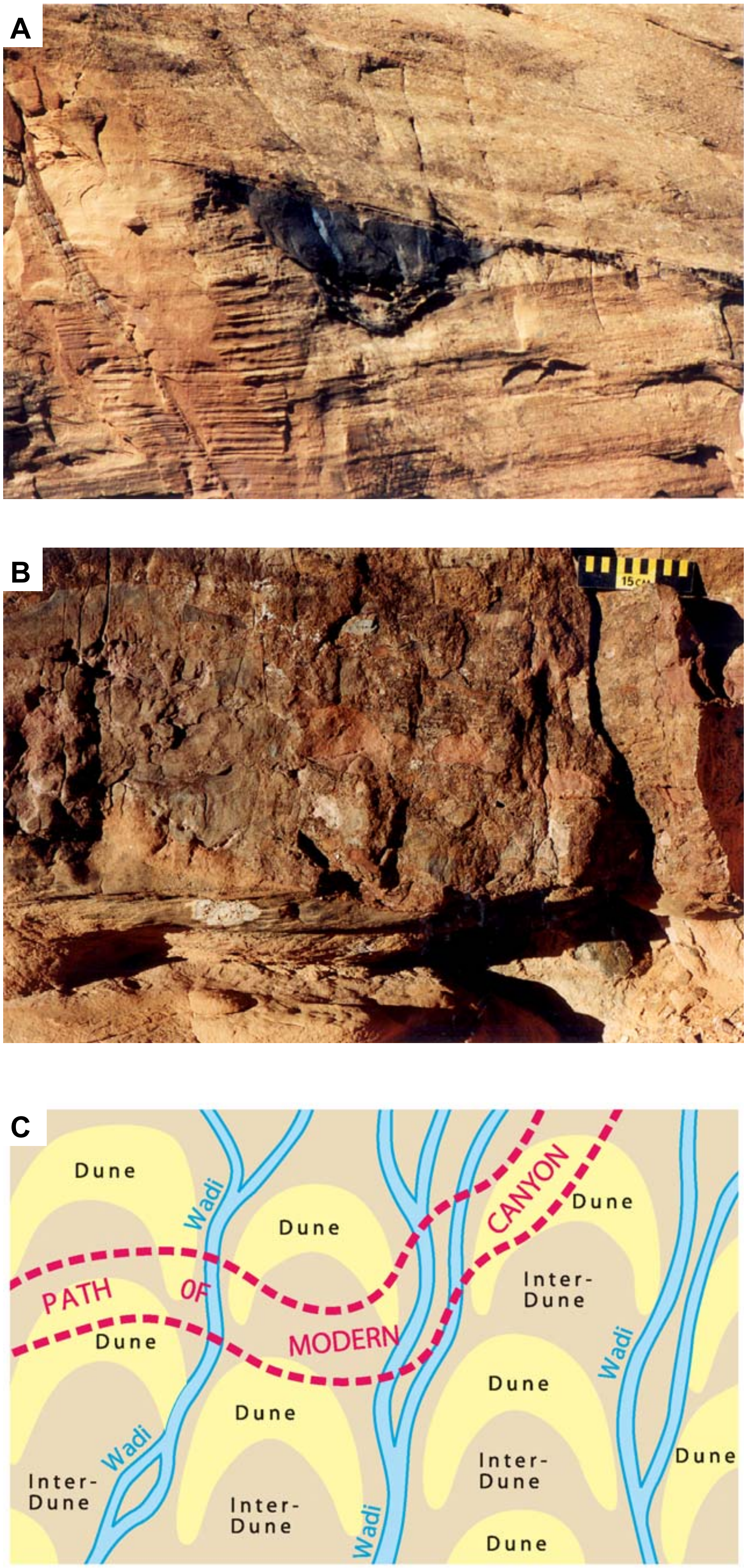


Figure 8. Wadi deposits in the Navajo Sandstone at Rainbow Bridge National Monument, Utah. A – Wadi channel, filled with strongly cemented sand, on the cliff face of the south side of the canyon; channel deposit is about 5 feet (2 m) thick (taken with a telephoto lens). B – Wadi "pudding stone" consisting of sandstone and dolomitic limestone rip-up clasts in a medium- to coarse-grained sandstone matrix. Note horizontal stratification and small-scale cross-beds at base of photo. C - Schematic interpretation, map view, of a Navajo wadi system between large dunes with the path of a modern canyon superimposed.

Navajo interdune lithofacies have significantly poorer reservoir characteristics than the dune lithofacies. The low-permeability interdune lithofacies is a potential barrier to flow. Identification and correlation of dune/interdune lithofacies in individual Nugget reservoirs in the thrust belt is critical to understanding their effects on production rates and paths of petroleum movement (Lindquist, 1983). Avalanche laminae, soft-sediment deformation, and other depositional features can also result in significant reservoir heterogeneity, even within the dune lithofacies.

Paradox Basin

The Paradox Basin (figure 1), located mainly in southeastern Utah and southwestern Colorado, is an elongate, northwest-southeast-trending evaporitic basin that predominately developed during the Pennsylvanian (Desmoinesian), about 330 to 310 million years ago. At this time, uplift of the Ancestral Rockies in the western United States also occurred. The Uncompahgre Highlands (uplift) in eastern Utah and western Colorado initially formed as the westernmost range of the Ancestral Rockies. The southwestern flank of the Uncompahgre Highlands is bounded by a large basement-involved, high-angle reverse fault identified from seismic surveys and exploration drilling. As the highlands rose, an accompanying depression, or foreland basin, formed to the southwest – the Paradox Basin. Rapid subsidence, particularly during the Pennsylvanian and continuing into the Permian, accommodated large volumes of evaporitic and marine sediments that intertongue with non-marine arkosic material shed from the highland area to the northeast (Hintze, 1993). The Paradox Basin is surrounded by other uplifts and basins, which formed during the Late Cretaceous-early Tertiary Laramide orogeny (figure 1).

The Paradox Basin can generally be divided into three areas: the Paradox fold and fault belt in the north, the Blanding sub-basin in the south-southwest, and the Aneth platform in southeasternmost Utah (figure 1). The relatively undeformed Blanding sub-basin and Aneth platform developed on a subtropical shallow-marine shelf and shelf-margin that locally contained algal-mound and other carbonate facies buildups. The codiacean green algae *Ivanovia* was the dominant genus in the algal buildups of the Paradox Formation. Hydrocarbons are stratigraphically trapped in porous and permeable units within carbonate buildups. These units are effectively sealed by impermeable marine mud and/or anhydrite at the base, flank, and top of the buildup.

Paradox Formation Reservoir

The two main producing zones are informal zones of the Paradox Formation, the Ismay and the Desert Creek. The shallow-shelf and shelf-margin facies belts in these zones include carbonate buildups (phylloid algal, coralline algal, bryozoan, and marine-cemented buildups [mounds]), calcarenites (beach, dune, and stabilized grain flats), and platform-interior carbonate muds and sands (Eby and others, 1993; Chidsey and others, 1996b). These facies were deposited at water depths between 0 and 40 feet (0-12 m). Karst characteristics are occasionally present over mounds.

The Ismay zone is dominantly limestone comprising equant buildups of phylloid-algal material with locally variable small-scale subfacies capped by anhydrite. The Ismay produces oil from fields in the southern Blanding sub-basin (figure 1). The Desert Creek produces oil from fields in the central Blanding sub-basin (figure 1). There, the Desert Creek zone is dominantly dolomite comprising regional nearshore shoreline trends with highly aligned, linear facies tracts. Both the Ismay and Desert Creek buildups generally trend northwest-southeast. The Aneth platform contains the largest oil field in Utah, Greater Aneth, as well as several productive satellite buildups. Production at Greater Aneth field is primarily from Desert Creek zone limestone composed of phylloid-algal buildups and overlying oolitic-bank deposits.

With the exception of the Greater Aneth field, most fields in southeastern Utah are small, ranging in size from 0.5 to 1 mile (0.8-1.6 km) wide and 0.5 to 4.5 miles (0.8-7 km) long. They consist of 1 to 8 wells at 20-, 40-, and 80-acre (8-, 16-, and 32-ha) spacing. The principal producing intervals include porous bafflestone, grainstone, packstone, and some wackestone, with pay thickness ranging from 18 to 100 feet (6-30 m). Porosity ranges from 8 to 12 percent in moldic, vuggy, intercrystalline, and shelter pore-type networks. Permeability averages 25 millidarices (md), but ranges from less than 1 to greater than 500 md. Diagenesis includes early marine cementation, dolomitization (early and late), freshwater dissolution and cementation, and anhydrite and bitumen plugging.

Three factors create reservoir heterogeneity within productive mound-core and supra-mound intervals: (1) variations in lithotypes and facies, (2) mound relief and flooding surfaces, and (3) diagenesis. The extent of these factors and how they are combined affect the degree to which they create barriers to fluid flow. At the reservoir production scale (less than 0.5 mile [0.8 km]), reservoir heterogeneity is the major cause of low recovery rates, particularly in the upper parts of the buildups.

Paradox Formation Outcrop Analog, San Juan River, Utah

Carbonate buildups exposed in outcrops of the Paradox Formation along the San Juan River of southeastern Utah provide production-scale analogs of reservoir-facies characteristics, geometry, distribution, and the nature of boundaries contributing to the overall heterogeneity of these rocks. Algal buildups in the Ismay zone are exposed at river level 10 river miles (16 km) east of Mexican Hat, Utah, with some of the best examples in the Eight-Foot Rapid area (figure 9). High-resolution, outcrop-based sequence-stratigraphic analysis has been conducted on these rocks by Goldhammer and others (1991, 1994), Simo and others (1994), Best and others (1995), Weber and others (1995a, 1995b), Gianniny and Simo (1996), and Grammar and others (1996). Ten river miles (16 km) west of Mexican Hat, over 1,300 feet (400 m) of Pennsylvanian rocks, including almost the entire Paradox Formation, is exposed through the famous Goosenecks of the San Juan River (figures 9 and 10A) and along the Honaker Trail, which provides access to the river from the canyon rim (figures 9 and 10B). The Honaker Trail section has been extensively studied by Pray and Wray (1963), Wengerd (1963), Weber and others (1995a), Stevenson (2000), Ritter and others (2002), and many other workers.

Eight-Foot Rapid area: Phylloid-algal buildups of the Ismay zone exposed in the Eight-Foot Rapid area were deposited in northwest-trending elongate banks on a shallow carbonate shelf. The Ismay zone is divided into two intervals: the lower Ismay, which consists of a single, thick, shoaling-upward carbonate sequence, and the upper Ismay, which consists of three or more thinner, shoaling-upward, carbonate and carbonate-evaporite cycles.

Figure 9. Location of Paradox Formation outcrops in the Eight-Foot Rapid area and The Goosenecks/Honaker Trail, San Juan River, southeastern Utah.

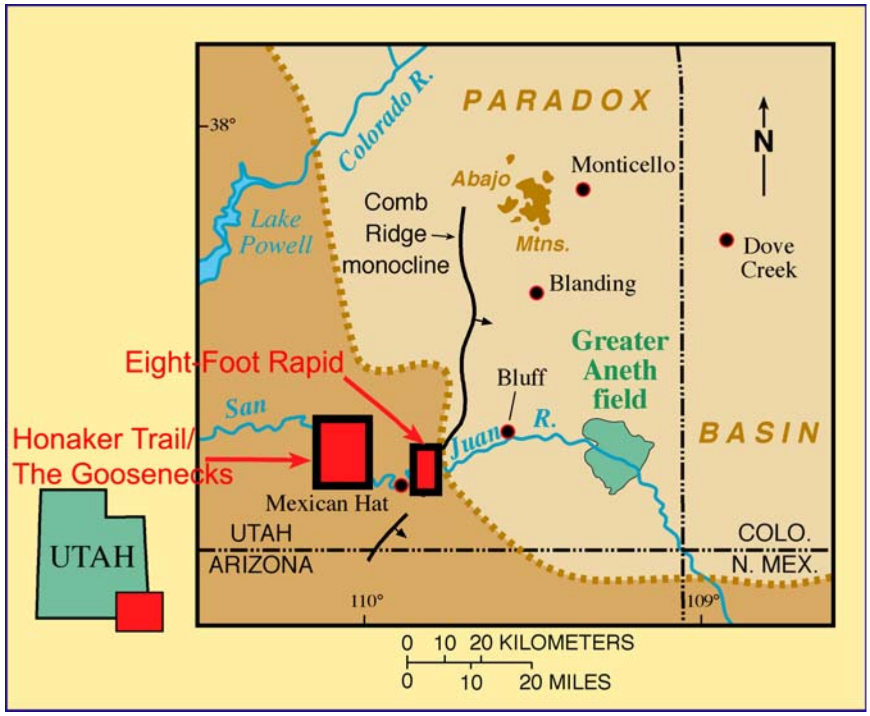


Figure 10. San Juan River, southeastern Utah. A – Goosenecks of the San Juan River. Photograph by Tom Till, courtesy of the Utah Travel Council. B – Pennsylvanian section along Honaker Trail, view looking west.

Recognizing the morphologic variations in this area is critical to understanding controls on deposition. The following terms distinguish buildup geometry (Brinton, 1986). These are shown schematically in figures 11 and 12.

Algal bank: The massive, lenticular, biostromal algal buildups, 30 to 40 feet (10-13 m) thick, exposed for several miles along the canyon walls of the San Juan River.

Interbank: The channel-like feature that separates, or bisects, algal banks.

Algal mound: Secondary, ridge-and-swale or wave-form-like features that define the upper surfaces of the algal banks and impart the wavy topography that characterizes outcrops.

Intermound: The shallow trough region between algal-mound crests.

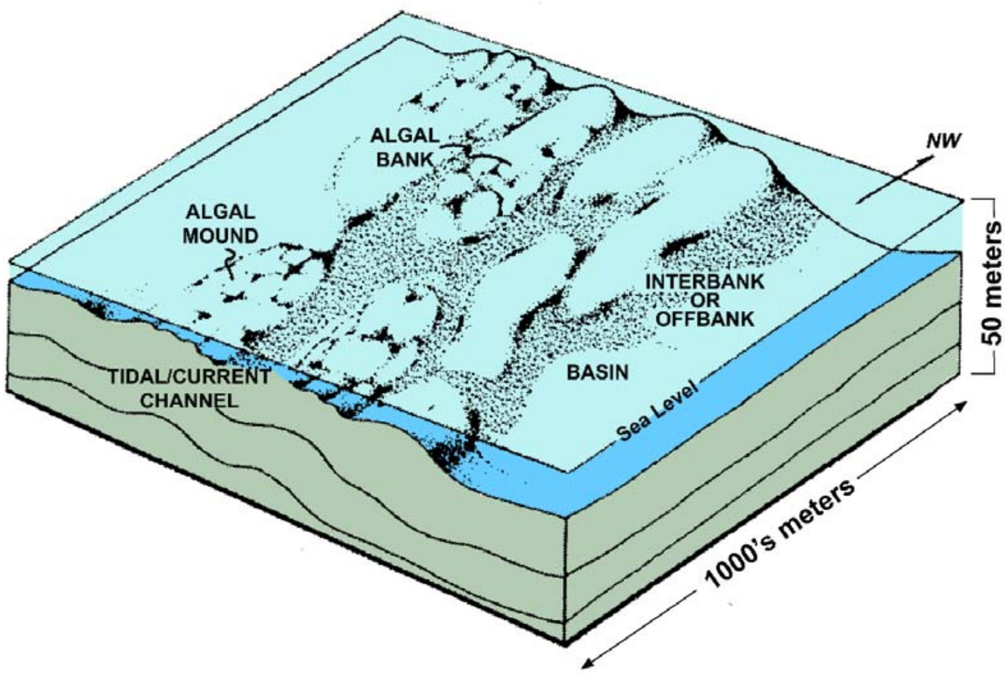


Figure 11. Schematic diagram of Paradox Formation algal banks (from Brinton, 1986).

The lower Ismay zone algal banks or buildups exposed along the San Juan River appear as flat-bottomed, convex-upward lenticular bioherms with undulating, wave-like upper surfaces and relief as great as 50 feet (15 m) (figure 13). The most distinctive feature of buildups and adjacent facies is the undulatory or ridge-and-swale upper surface of the algal banks. The wavy topographic features (mounds and intermounds) extend for miles along the walls of the canyon, displaying regular wavelengths (150 to 200 feet [46-61 m]) and amplitudes (10 to 20 feet [3-6 m]). Mounds appear to be superimposed on the larger-scale algal banks whose length/width ratios are more characteristic of biostromes (Brinton, 1986).

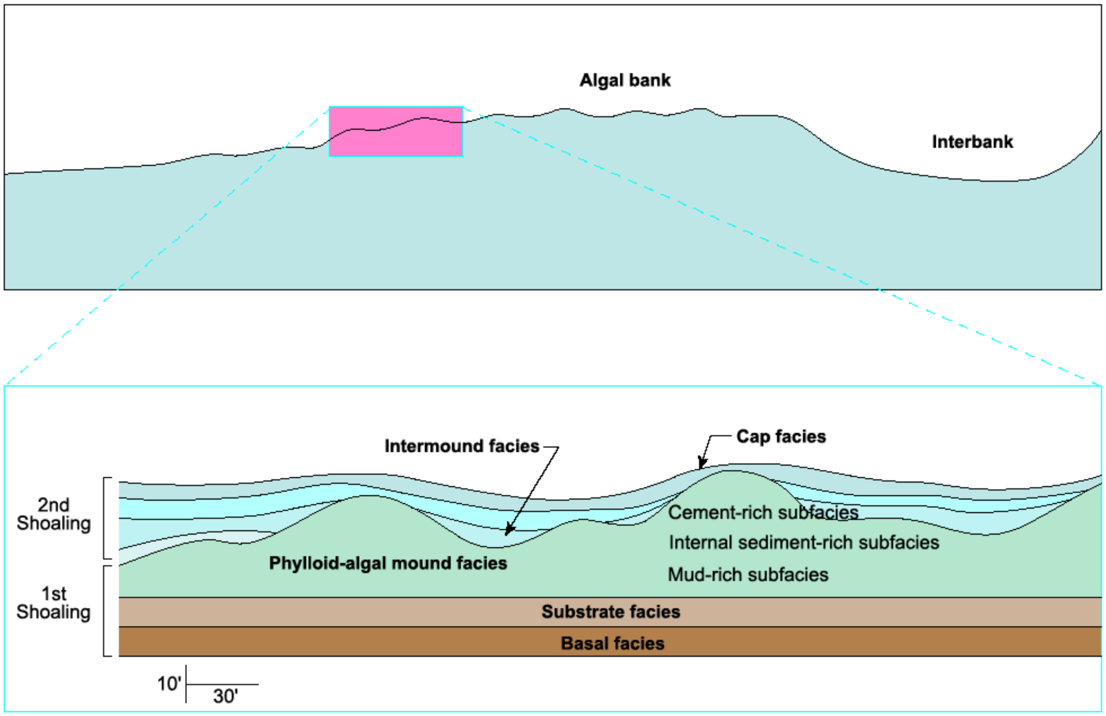


Figure 12. Paradox Formation algal bank/mound topography, morphology, and facies relationships as seen along the San Juan River, Utah (from Brinton, 1986).

Figure 13. Ismay zone algal banks near Eight-Foot Rapid as illustrated in figures 11 and 12.

Cyclic sedimentation is recorded by four dominant facies recognized in a single, shoaling-upward sequence (figure 14): (1) substrate carbonate, (2) phylloid algal, (3) intermound, and (4) skeletal capping (Brinton, 1986; Grammar and others, 1996). An outcrop in the Eight-Foot Rapid area displaying these and additional facies was selected for detailed study (figure 15A) (Chidsey and others, 1996a).

The Eight-Foot Rapid study site is interpreted as consisting of three principal features: (1) a phylloid-algal mound with grainstone buildups deposited at or near sea level, (2) a "reef wall" that formed in a higher energy, more marginal setting than the mound, and (3) a carbonate detrital wedge and fan consisting of shelf debris. Figure 16 is a schematic block diagram illustrating hypothetical facies relationships. This interpretation is not only based on observations made at the outcrop, but also incorporates subsurface core data that are discussed in Chidsey and others (1996b).

Bafflestone and *Chaetetes*- and rugose-coral-bearing grainstone and packstone textures observed in the northern part of the Eight-Foot Rapid complex comprise the main phylloid-algal mound (figure 15B). A flooding surface recognized on top of the buildup and probable low-permeability lithotypes (packstone and cementstone) within the buildup might act as barriers or baffles to fluid flow in the subsurface. The Eight-Foot Rapid outcrop appears to be only a portion of a larger algal-bank complex, or one of a series observed along the San Juan River. Although not documented at this outcrop, observations from cores in other areas in the subsurface suggest an interior-lagoon and other associated facies likely formed to the west as part of this complex (Chidsey and others, 1996b).

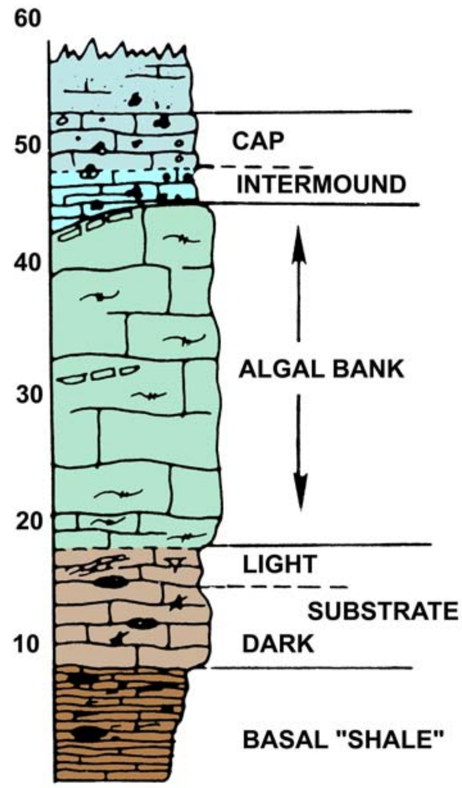


Figure 14. Typical vertical facies succession preserved in the Ismay zone at Eight-Foot Rapid (from Brinton, 1986).

The rudstone, cementstone, and lumpstone depositional textures represent deposits that were part of, or near, what might be interpreted as a "reef wall" (figure 16). The presence of internal sediments in these rocks indicates an influx of mud during storms, or mud routinely distributed by stronger currents. The reef wall records deposition and intense sea-floor cementation as a result of reflux of large pore volumes of water through sediments occupying a high-energy setting that is marginal between shallow-shelf and deeper, open-marine conditions. The reef wall may have served as a barrier behind which algal buildups could develop and thrive in a more protected setting that facilitated preservation of primary shelter porosity. The presence of reef-wall facies in a well core might serve as a proximity indicator for a more prospective algal-buildup drilling target. Examples of this relationship have been observed in the Blue Hogan and Brown Hogan fields to the southwest of the Greater Aneth field (Chidsey and others, 1996b).

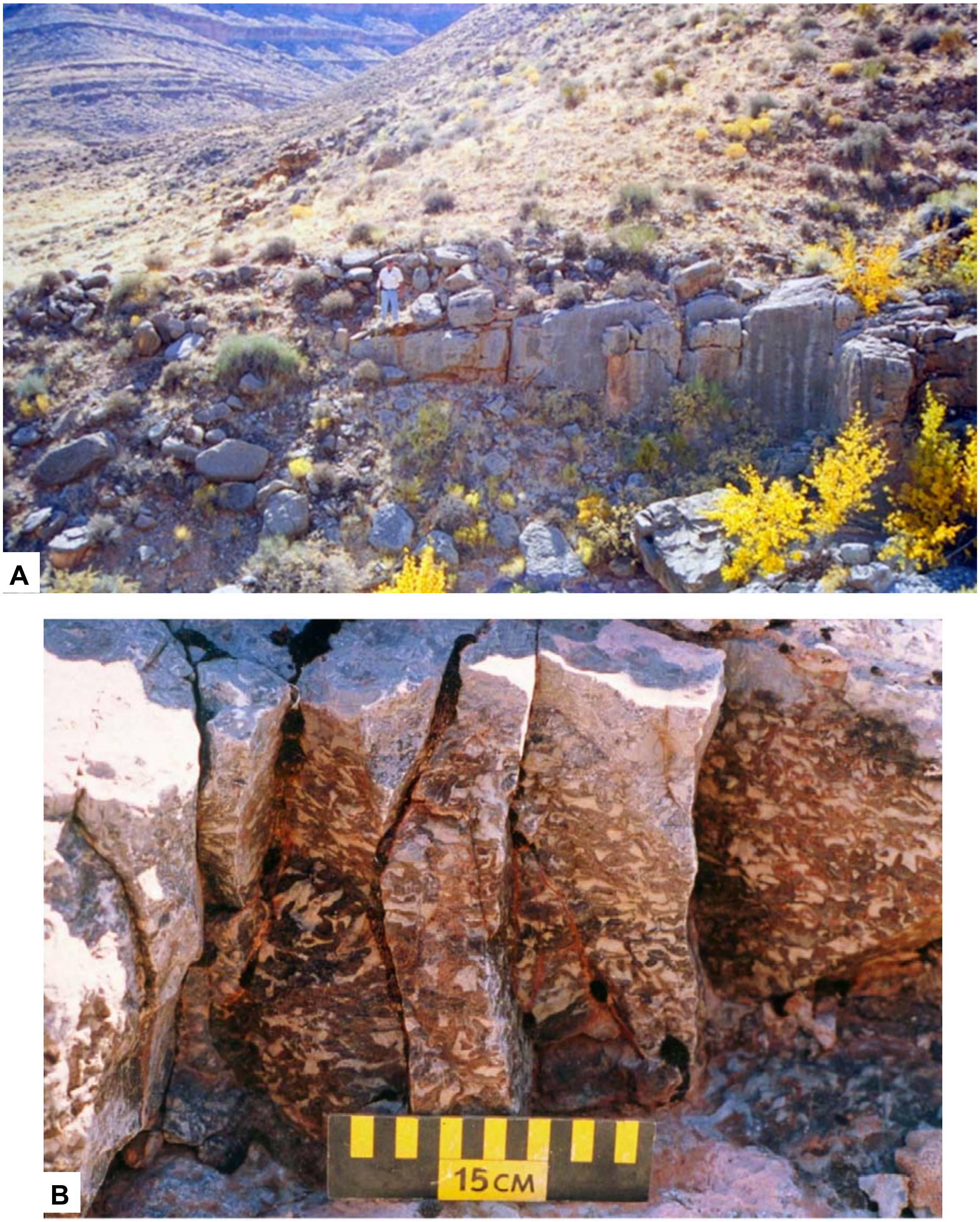


Figure 15. Outcrops in the Ismay zone of the Paradox Formation, Eight-Foot Rapid area near the San Juan River, southeastern Utah. (A) Typical phylloid-algal mound composed of algal bafflestone, skeletal grainstone, and packstone. A flooding surface is present at the top of the mound. (B) Cement-rich algal bafflestone exposed in a phylloid-algal mound. Original sheltered pore spaces were filled with mud; cement rinds are developed around algal plates.

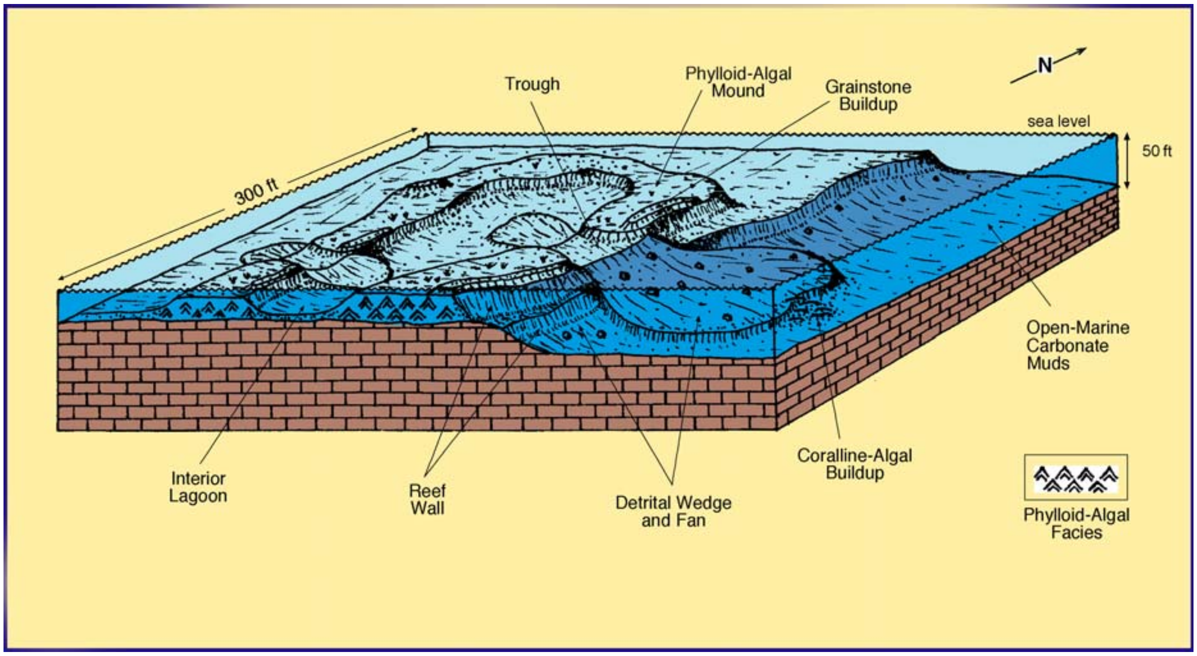


Figure 16. Block diagram displaying depositional interpretation of a mound complex and associated features in the Eight-Foot Rapid area (from Chidsey and others, 1996a). This interpretation is a composite of inferences made from outcrop and subsurface data.

An intermound trough in the center of a mound could represent a tidal channel flowing across the reef wall (figure 16). Material shed from the mound and reef wall was subsequently carried through the tidal channel and might have been deposited as a detrital wedge or fan on open-marine carbonate muds. These features are recorded by the grainstone and transported material observed on the east side of the outcrop complex. Coralline-algal buildups may have also developed near the carbonate detrital fan but were not observed at this locality in the canyon.

Reservoir-quality porosity may have developed in troughs, detrital wedges, and fans identified from core and facies mapping. If these types of deposits are in communication with mound-reservoir facies in the subsurface, they could serve as conduits facilitating sweep efficiency in secondary/tertiary recovery projects. However, the relatively small size and the abundance of intermound troughs over short distances, as observed along the river, suggests caution should be used when correlating these facies between development wells. Facies that appear correlative and connected from one well to another may actually be separated by low-permeability facies which inhibit flow and decrease production potential.

Honaker Trail and The Goosenecks: The Paradox Formation section along the Honaker Trail includes both the Ismay and Desert Creek zones, and the Akah and Barker Creek (at river level) zones as well. The Horn Point marker bed defines the top of the lower Ismay zone. Ritter and others (2002) have identified 30 high-frequency cycles or 5th-order parasequences (Goldhammer and others, 1991) from the Horn Point to the bottom of the section based on conodont sequence biostratigraphy. These cycles are 6 to 21 feet (2-7 m) thick and grade from deeper-water sediments at the base to subtidal and shoaling carbonates at the top (Ritter and others, 2002).

The top of the Horn Point is a flooding surface (figure 17) representing a 4th-order sequence boundary indicated here by (1) evidence of subaerial exposure, (2) regionally traceable surfaces, and (3) the presence of deeper-water black shales at the contact, in this case the Hovenweep shale above the Horn Point (Goldhammer and others, 1991). This type of surface or sequence boundary, as well as parasequence boundaries (also flooding surfaces [figure 18]), is a time-correlative marker in the subsurface. If these surfaces are not recognized and the intervals erroneously correlated lithostratigraphically, the result might be failure to recognize significant fluid-flow barriers, and misinterpretation of reservoir facies geometries and distributions. These surfaces must be recognized in conventional core and/or geophysical logs in order to accurately predict the distribution and continuity of reservoirs (Weber and others, 1995a, 1995b).

The Paradox Formation along the Honaker Trail (Horn Point marker bed of the lower Ismay zone to the base of the section in the Barker Creek zone) displays most of the major facies associated with carbonate buildups observed in the formation at Eight-Foot Rapid. Carbonate fabrics, from deepest to shallowest, include shaley lime mudstone, sponge spicule-bearing wackestone, skeletal (mainly crinoidal and phylloid-algal) and peloidal wackestone to packstone, and oolitic grainstone (Ritter and others, 2002). An unusual cross-bedded, 5-foot-thick (2-m) quartz sandstone unit (figure 19) is present near the top of the lower Ismay above a fossiliferous wackestone. Similar cross-bedded sandstone units have been recognized by Eby and others (2003) in core from wells in the Blanding sub-basin. Large chert nodules, presumably derived from sponge spicules, are common in laminated, deeper-water limestone (figure 20). *Chaetetes* are also commonly associated with fossiliferous wackstone in the skeletal-capping facies above the phylloid-algal facies (figure 21). Peloidal and oolitic grainstone in the cap and intermound facies display well-developed cross-bedding (figure 22).

Distinct phylloid-algal mounds are exposed in the Barker Creek and Akah zones throughout The Goosenecks section of the San Juan River. These mounds vary in length from a few tens of feet to several hundred feet, often rapidly pinching out into non-mound facies (figures 23, 24, and 25). The thickness is also variable from a few tens of feet to well over 50 feet (16 m). Mounds are occassionaly stacked but separated by either mound-cap or substrate facies (figure 26). Mound flanks are well exposed and consist of angular, poorly sorted clasts of mound material (figure 27), whereas intermound channel grainstone deposits show excellent cross-bedding (figure 28).

Horizontal drilling has only been conducted in a few typical fields in the Paradox Basin with no commercial success; the exception is within the atypical Greater Aneth field where horizontal drilling has become a major best practice. Phylloid-algal mounds in The Goosenecks demonstrate that there are various targets and risks when considering potential horizontal drilling in small, heterogeneous reservoirs in the Paradox Basin. Before selecting the optimal location, orientation, and type of horizontal well (for example single or multiple horizontal laterals, radially stacked laterals, splays or branches) (figure 29), the distribution, both laterally and vertically, of the mound or mounds, mound flanks, and other associated facies must be carefully evaluated.

Figure 17. Flooding surface (4th-order sequence boundary) at the top of the Horn Point marker bed, lower Ismay zone of the Paradox Formation along the Honaker Trail. Note abundant intact and fragmented productid brachiopods in the medium gray limestone matrix.

Figure 18. Flooding surface (5th-order parasequence boundary?) at the top of the Barker Creek zone of the Paradox Formation along the Honaker Trail. Note abundant rip-up clasts and sharp contact with the overlying unit.

Figure 19. Very fine grained, cross-bedded quartz sandstone near the top of the lower Ismay zone of the Paradox Formation along the Honaker Trail.

Figure 20. Large chert nodules in laminated lime mudstone, Akah zone of the Paradox Formation along the Honaker Trail.

Figure 21. Chaetetes in fossilerous wack-stone of a skeletal-capping facies, lower Ismay zone of the Paradox Formation along the Honaker Trail.

Figure 22. Well-developed cross-bedding in peloidal and oolitic grainstone in the cap and intermound facies of the Barker Creek zone of the Paradox Formation along the Honaker Trail. Close-up shown in inset photo.

Figure 23. Small phylloid-algal mound in the Barker Creek zone of the Paradox Formation, river mile 44.3, San Juan River.

Figure 24. Medium-sized phylloid-algal mound in the Akah zone of the Paradox Formation, river mile 38.5, San Juan River.

Figure 25. Photomosaic of a large phylloid-algal mound complex in the Barker Creek zone of the Paradox Formation, river mile 40.5, San Juan River.

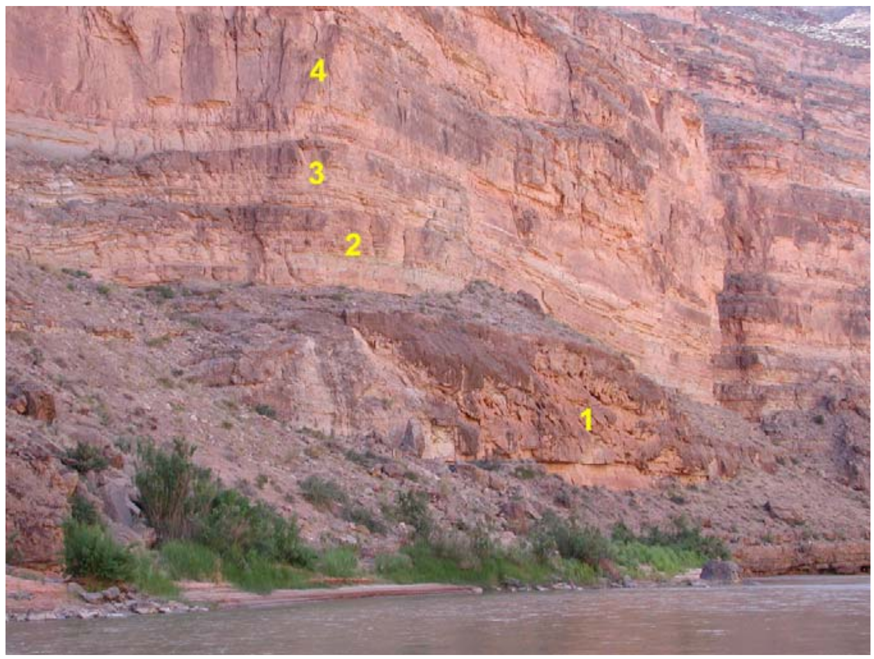


Figure 26. Stacked complex of four phylloid-algal mounds in the Akah and Barker Creek zones of the Paradox Formation, river mile 39.8, San Juan River.

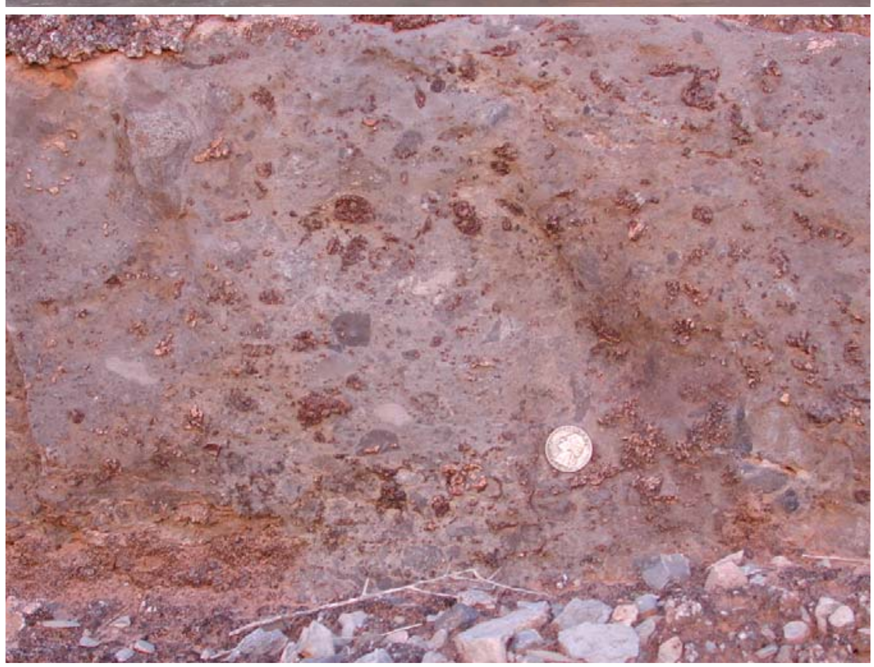


Figure 27. Mound flank material – part of the large phylloid-algal mound complex in the Barker Creek zone shown on figure 25, river mile 40.5, San Juan River.

Figure 28. Cross-bedding in an intermound channel grainstone deposit in the Akah zone of the Paradox Formation, river mile 35.3, San Juan River.

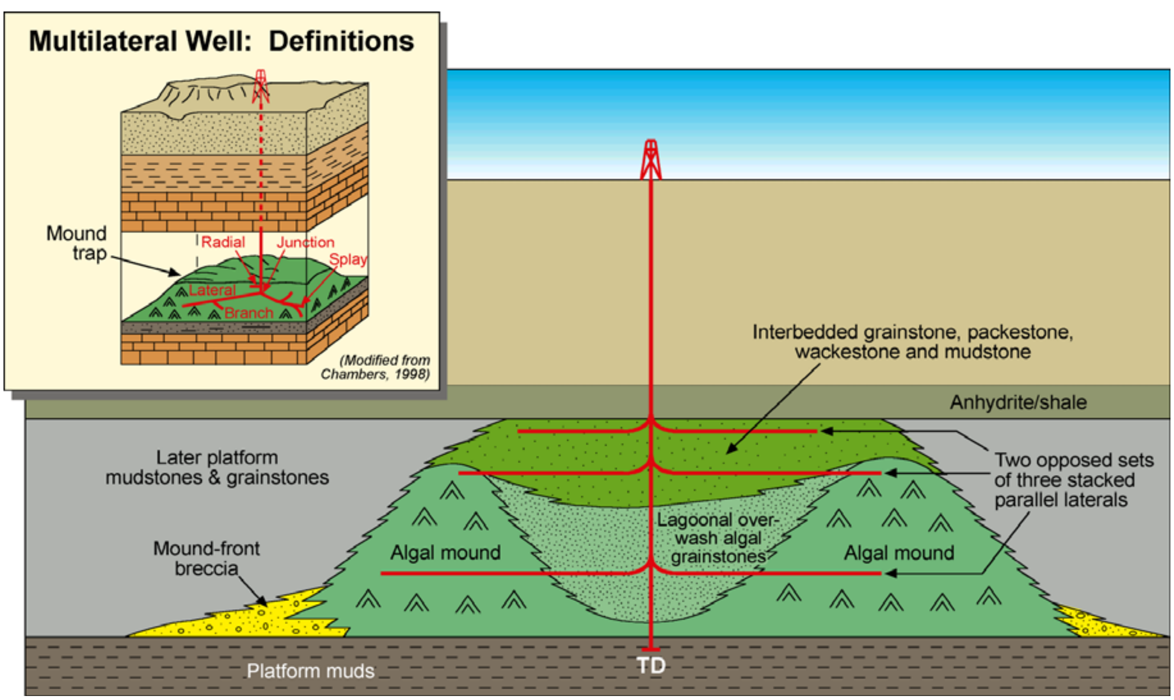


Figure 29. Schematic diagram of drilling targets in a Paradox carbonate buildup by multilateral (horizontal) legs from an existing field well (modified from Chambers, 1998).

TECHNOLOGY TRANSFER

The UGS is the Principal Investigator and prime contractor for the PUMPII project and three other government-industry cooperative petroleum-research projects. These projects are designed to improve recovery, development, and exploration of the nation's oil and gas resources through use of better, more efficient technologies. The projects involve detailed geologic and engineering characterization of several complex heterogeneous reservoirs. Two Class II Oil projects include practical oil-field demonstrations of selected technologies in the Paradox Basin. The third project involves establishing a log-based correlation scheme for the Tertiary Green River Formation in the southwestern Uinta Basin to help identify new plays and improve the understanding of producing intervals. The DOE and multidisciplinary teams from petroleum companies, petroleum service companies, universities, private consultants, and state agencies are co-funding the three projects.

All play maps, reports, databases, and so forth, produced for the PUMPII project will be published as interactive, menu-driven digital (web-based and compact disc) and hard-copy formats by the Utah Geological Survey for presention 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*. This information will also be released through the UGS periodical *Survey Notes* and on the UGS project Internet web page.

The technology-transfer plan included the formation of a Technical Advisory Board and a Stake Holders Board. 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 may 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. They will also provide field and reservoir data, especially data pertaining to best practices.

Utah Geological Survey *Survey Notes* and Internet Web Site

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 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, and (4) quarterly technical progress reports.

Technical Presentation

Project materials, plans, and objectives were displayed as a PowerPoint presentation at the UGS booth during the AAPG Annual Convention, May 11-14, 2003, in Salt Lake City, Utah. Four UGS scientists staffed the display booth at this event. Project displays will be included as part of the UGS booth at professional meetings throughout the duration of the project.

CONCLUSIONS

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 with petroleum potential due to favorable source rock, migration paths, reservoir characteristics, and other factors.

Utah is unique in that representative outcrop analogs for each major oil play are present in or near the thrust belt, Uinta Basin, and Paradox Basin. Production-scale analogs provide an excellent view, often in 3D, of reservoir-facies characteristics (geometry, distribution, and so forth) and the nature of boundaries contributing to the overall heterogeneity of reservoir rocks. Outcrop analogs can be used as a "template" for evaluation of data from conventional core, geophysical and petrophysical logs, and seismic surveys. When combined with subsurface geological and production data, analog models improve development drilling and production strategies, reservoir-simulation models, reserve calculations, and design and implementation of secondary/tertiary oil recovery programs and other best practices used in the oil fields of Utah and vicinity.

The most prolific oil reservoir in the thrust belt is the Jurassic Nugget Sandstone which was deposited in an extensive dune field that extended from Wyoming to Arizona. The best outcrop analogs to the Nugget Sandstone are found in exposures of the stratigraphically equivalent Navajo Sandstone of southern Utah. Outcrops along the shores of Lake Powell display classic eolian bedforms such as large-scale dunal cross-strata, and interdunal features such as oases, wadi, and playa lithofacies. Navajo interdune lithofacies have significantly poorer reservoir characteristics than the dune lithofacies and in a reservoir represent potential barriers to flow. Identification and correlation of dune/interdune lithofacies in individual Nugget reservoirs in the thrust belt is critical to understanding their effects on production rates and paths of petroleum movement.

In the Paradox Basin, hydrocarbons are stratigraphically trapped in heterogeneous reservoirs within carbonate buildups (or phylloid-algal mounds) of the Pennsylvanian Paradox Formation. Carbonate buildups exposed in the Paradox Formation at Eight-Foot Rapid, Honaker Trail, and The Goosenecks along the San Juan River of southeastern

Utah provide excellent outcrop analogs of these reservoir rocks. Reservoir-quality porosity may develop in the types of facies associated with buildups, such as troughs, detrital wedges, and fans, identified from these outcrops. If these facies are in communication with mound-reservoir facies in actual reservoirs, they could serve as conduits facilitating sweep efficiency in secondary/tertiary recovery projects. However, the relatively small size and the abundance of intermound troughs over short distances, as observed along the river, suggests caution should be used when correlating these facies between development wells. Facies that appear correlative and connected from one well to another may actually be separated by low-permeability facies which inhibit flow and decrease production potential. These outcrop analogs also demonstrate that there are various targets and risks when considering potential horizontal drilling in the Paradox Basin. Before selecting the optimal location, orientation, and type of horizontal well, the distribution both laterally and vertically of phylloid-algal mounds and other associated facies must be carefully evaluated.

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