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STRUCTURE AND STRATIGRAPHY OF THE GRASSY TRAIL CREEK FIELD, CARBON AND EMERY COUNTIES, UTAH

Susan Juch Lutz, University of Utah Research Institute, Salt Lake City, Utah

M. Lee Allison, Utah Geological Survey, Salt Lake City, Utah

ABSTRACT

The Grassy Trail Creek field produces 40 gravity oil and minor gas from shallow-marine sandstones of the Triassic Moenkopi Formation on the north-plunging nose of the San Rafael Swell in central Utah. Production is controlled by a combination of stratigraphic heterogeneities, fractures, and minor north-south trending faults. The faults are normal, near-vertical, discontinuous, and run roughly parallel to the axis of the San Rafael Swell. Although fracture permeability enhances production of the reservoir, some faults appear to act as barriers to fluid migration, segmenting the area into productive and dry fault blocks. Horizontal drilling techniques developed in this field in the early 1980's resulted in an approximately 500 percent increase in production.

Isochore map patterns from log analyses and lithofacies descriptions from core analyses enable the interpretation of the depositional facies and their distribution within producing units of the field. The A and B zones in the Torrey Member of the Moenkopi contain fractured, ripple cross-laminated, dolomite-cemented sandstone beds, 2-12 ft (.7-4 m) thick. The fining-upward (fine to very fine grained) beds have massive to intraclast-rich bases which are in erosive contact with underlying rippled to bioturbated micaceous siltstones and mudstones. The productive A and B sandstone bodies are interpreted to represent tidal channels that cut into intertidal deposits.

Log analyses indicate that the main reservoir is a complex stack of thin tidal channel sandstones. Isochore maps of the A and B zones indicate thickened meanders that form localized pods which are vertically offset. The channelized sandstone bodies are concentrated parallel to a northwest-southeast trending shoreline. The location of the channels appears to have been controlled by the distribution of the highs of the underlying Sinbad Limestone, an oolitic barrier island complex.

The C zone in the Black Dragon Member of the Moenkopi also contains graded, dolomite-cemented sandstone beds. But, in contrast to the A and B zones, the sandstone occurs in thick beds (up to 20 ft, 6.7 m), is predominantly medium-grained, vaguely cross-bedded, and contains calcite rather than anhydrite cement. Shale drapes are common at the tops of the sandstone beds and Thalassinoides trace fossils are present in shale beds within or overlying the C zone. The C sandstones are interpreted to represent distributary channel to possibly, estuarine channel

deposits. The C zone can be correlated to oil-impregnated sandstones in both outcrop and in the subsurface throughout the northern San Rafael Swell. The regional distribution of hydrocarbon stained sandstones in the Black Dragon Member suggests a north to northwest trending channel to mouthbar sequence in a large tidal delta.

There is a limited potential for field extensions of the A and B tidal channel sandstones parallel to the northwest to westward trending paleoshoreline in the Torrey Member. The C zone could be marginally productive if stimulated throughout most of the northern San Rafael Swell. Thicker sandstones within the C zone (possible mouthbar deposits) are present to the west of the Grassy Trail Creek field and have the potential to be good producers if they are naturally fractured or artifically hydro-fractured.

INTRODUCTION

The Grassy Trail Creek field is located at the northern end of the San Rafael Swell in Carbon and Emery counties, Utah (Figure 1). Wells in the field (Figure 3) produce from three zones in the Triassic Moenkopi Formation at approximately 3,900 ft depth. The A and B zones produce from the Torrey Member and the C zone produces from the upper Black Dragon Member beneath the Sinbad Limestone Member (Figure 4).

The geology of the Grassy Trail Creek field has not been fully studied. A UGMS study of the field (Peterson, 1972) listed the only existing geologic data and presented a very simplified structure map. The primary objectives of this paper are to describe from core analysis the lithofacies that characterize the reservoir units in the Grassy Trail Creek field, to determine the distribution and significance of the productive facies from isochore maps and to interpret structural features within the field. Based on the lithologic and depositional patterns revealed in the Grassy Trail Creek field, a reconstruction of the paleogeographic setting and petroleum potential of the Moenkopi Formation in the northern San Rafael Swell is also presented.

PRODUCTION HISTORY

The Grassy Trail Creek discovery well, Cities Service #1 Government (located in section 1, T16S, R12E), was a recompletion (in 1961) of a wildcat well drilled to the Mississippian by Cities Service in 1953. Cities Service then drilled five wells, which produced about 141,000 bbl of oil between 1961 and 1976.

In 1982, Skyline Oil initiated a development drilling program using the then-experimental Texas Eastern Drilling Systems Inc. (Tedsi) technology for lateral borehole completions (horizontal drilling). Sixteen new wells were drilled in the field by Skyline. Thirteen of the sixteen wells have produced 397,00 bbl of oil (through 1990).

Texas Eastern (which took over Skyline Oil) drilled a total of 68 short-radius laterals in 18 wells that totalled 17,000 ft in length. Of this, 12,000 ft of laterals in 10 wells proved to be productive; about half were drilled in the Black Dragon Member and half in the Torrey Member. The productive laterals average 332 ft in length. According to Mitchell and others (1989a), the best well in the field is well 11-33 which averaged 336 barrels of oil per day and 112 Mcf of gas per day after two laterals were drilled. Horizontal drilling effectively quintupled the ultimate cumulative production from the field (Chidsey and Morgan, 1991).

In 1987, Texas Eastern Development Co. sold the leases and production to Samedan. In 1989, Seeley Oil bought the field from Samedan and is presently the sole operator of the Grassy Trail Creek field. In all, twenty two wells have produced oil on 40-acre spaced wells. The field size is 880 acres. Total cumulative production (through 1990) is about 538,000 bbl of oil, 153,000 Mcf of gas and 62,000 bbl of water.

GEOLOGIC SETTING AND STRATIGRAPHY

During the lower Triassic, Moenkopi sediments were deposited in a coastal setting along the eastern margin of the late Paleozoic miogeosyncline (Stokes, 1986). The deepest part of the Triassic basin lay in northwestern Utah and southeastern Idaho. The Moenkopi Formation thickens from a pinchout along the Colorado-Utah border to over 2,000 ft (641m) in western Utah (Stewart and others, 1972).

In the San Rafael Swell area, sedimentation was controlled by remnants of the northwest-trending Uncompahgre Uplift of western Colorado, and local topographic relief on the Permian Kaibab Limestone and the White Rim Sandstone (Figure 3; and Mitchell, 1985).

The Triassic Moenkopi Formation commonly is divided into four members; in ascending order, the Black Dragon, the Sinbad Limestone, the Torrey and the Moody Canyon (Blakey, 1974). The stratigraphic members are easily correlated by log character in the subsurface.

The Black Dragon and Sinbad Limestone members have been interpreted to represent shallow shelf and coastal environments (Blakey, 1974) or tidal to fluvial environments (Ochs and Chan, 1990). The Torrey and Moody Canyon members have been interpreted as deltaic (Blakey, 1974) or restricted marine (sabkha) in origin (Mitchell, 1985).

In the San Rafael Swell, the Moenkopi Formation is approximately 787 ft (240 m) thick (Stokes, 1986). The Black Dragon Member is about 115 ft (38 m) thick, the Sinbad Limestone is about 50 ft (17 m) thick, the Torrey Member is about 260 ft (87 m) thick and the Moody Canyon member about 160 ft (53 m) thick in the Grassy Trail Creek field. The Moody Canyon Member is non-petroliferous and appears to act as a caprock or seal.

FACIES DESCRIPTION AND ANALYSIS FROM CORE

Seven cores of productive intervals of the Moenkopi Formation were studied. Five of the cores are from Grassy Trail Creek wells (#4-32, 11-13, 11-33, 2-43x and 36-2) and two are from wells north and south of the field (Fig.): Arco Chambers #1 is located just three miles to the northeast and Arco Dusty Trail #1 is located about two miles to the southeast of the field.

Distinct lithofacies are identified in the cores on the basis of rock type and mineralogy, types and abundance of sedimentary and biogenic structures and their distribution.

Torrey Member

Six lithofacies are present in cores from the Torrey Member are: 1) red-brown bioturbated mudstone, 2) dark gray dolomitic sandstone, 3) mottled anhydritic sandstone, 4) thin-bedded sandstone and shale, 5) greenish gray dolomudstone and 6) intraclast-rich siltstone.

The red-brown bioturbated mudstone facies consists of anhydritic siltstone and micaceous shale which overlie the thick sandstone beds in the lower portion of the Torrey Member and may be similar to the lithology of the Moody Canyon Member. The mudstone occurs in medium to thick beds which have gradational contacts. A disrupted, nodular fabric characterizes this facies along with the reddish color.

The chaotic mud and evaporite mixture and small blebs of anhydrite suggest dessication and evaporitic conditions during deposition. The mudstone facies is interpreted to represent upper intertidal (especially where bioturbated) to supratidal deposits (where anhydrite-rich) perhaps even from a sabkha-like environment. The mudstone facies most likely acts as a reservoir seal to underlying units.

The dolomite-cemented sandstones are mostly very fine to fine-grained with some medium-grained and are arkosic to subarkosic. The sandstones occur in well-sorted, upward-fining graded beds with shale intraclast-rich bases and rippled tops. Most of the beds are from 2 to 12 ft (.7 to 4 m) thick. Thicker beds have massive-appearing bases with some evidence for medium-scale cross-stratification (pervasive cementation has obscured some of the original stratification). Some convoluted zones are also present. The basal contacts are sharp and overlie either the interbedded sandstone and shale facies or the anhydritic shale facies. The upper contacts are gradational into thinner-bedded rippled sandstones or mudstone. Ripple cross-lamination is the dominant sedimentary structure preserved in this facies. White patches of dolomite cement in the coarser-grained bases of the beds create a speckled appearance to the dark gray sandstone.

Both the productive A and B zones in the Grassy Trail Creek field are represented by the dark gray dolomitic sandstone facies.

The sandstones are interpreted to be subtidal channel sandstones which cut into intertidal or lagoonal deposits.

The intertidal deposits are represented by the flaser to wavy bedded sandstone and shale facies. Some subaerial exposure of the tidal flat is indicated by sand-filled desiccation cracks in the shale beds. The position of this facies between the A and B zones suggests that it was probably dissected and reworked by the tidal channels. The lagoonal deposits are represented by both the dolomudstone and intraclast-rich siltstone facies, and occur between the underlying Sinbad limestone and the B zone.

Although the dolomitic sandstone facies contains the productive sandstones, the reservoir quality is low to moderate because measured porosities and permeabilities are low, the average grain size is fine, and cementation is pervasive. Permeabilities average about .51 millidarcies (md) and the average porosity is about 3.7 percent.

The anhydritic sandstone facies is characterized by a mottled appearance in cores caused by the presence of light gray anhydrite cement in dark gray dolomitic sandstone. This facies occurs in cores of the B zone in wells 2-43x, 11-13, and Chambers #1 where the zone is thin and overlies topographic highs in the Sinbad Member. This facies is interpreted to represent deposition marginal to the main tidal channels.

Sinbad Limestone Member

Two lithofacies have been identified in cores of the Sinbad Member: 1) oolitic cross-bedded limestone, and 2) fossififerous limestone to packstone.

The oolite occurs in high angle planar cross-stratified beds, 2 to 3 ft (.7 to 1 m) thick, at the top of the Sinbad in core from the north (Chambers #1) and from the south (Dusty Trail #1) of the field. The oolitic grainstones were deposited as shoals along a high to moderate energy shoreline.

In thin-section, the concentric banding of the oolitic structure is partially obscured by recrystallization to ferroan dolomite. Minor intraparticle porosity has developed by the preferential dolomitization of the ooids. Intergranular porosity is still high despite quartz and minor calcite cementation. Strong reddish-brown hydrocarbon residue is evident in the pores between ooids in thin-section.

Sample 4515 ft from Chambers #1 has measured porosities of 10 percent and measured horizontal and vertical permeabilies in the .52 to .88 md range. Oil saturation is about 20 percent.

The fossiliferous limestone facies is composed of 1 to 2 ft (.7 to 1 m) thick coquina beds of various types of gastropods and bivalves and the cephalopod Meekocerus which form wackestones to packstones.

Porosity types are moldic and shelter, and are visible in core samples. Measured porosities are in the 1-2 percent range and horizontal permeabilities are only .01 to .02 md.

Black Dragon Member

Two facies are present in cores of the Black Dragon Member. They are 1) shaly siltstone and 2) coarse-grained sandstone.

Vague crossbedding can be recognized in the siltstones which are also calcareous. More shaly beds are apparently featureless except for the presence of a few isolated pyrite-filled burrows. Some of the thinner beds contain sand-filled mudcracks.

Thicker beds (2 to 3 ft, .7 to 1 m thick) of the shaly siltstone facies contain large sand-filled Thalassinoides (a common marine trace fossil). The presence of Thalassinoides indicates shallow marine or marginal marine deposition of the siltstone.

This facies occurs interbedded with the coarse-grained sandstone facies in the upper portions of the C zone in the Black Dragon Member.

The coarse-grained sandstone facies is composed of dark gray, coarse to medium-grained sandstone in well-sorted and graded beds up to 20 ft (7 m) thick. The bases of the beds contain large shale intraclasts up to 2 in (5 cm) in diameter which are overlain by apparently massive coarse-grained micaceous and arkosic sandstone. Some pyrite nodules are present in the massive sandstone. The beds have a speckled appearance due to lighter-colored dolomite cement in the dark gray, heavily oil-stained sandstone.

High-angle crossbedding can be discerned in the middle of the sandstone beds above the massive bases. Some beds exhibit bidirectional crossbedding. Ripple cross lamination is common at the tops of the beds. Silty shale beds separate the sandstone beds and the lithologic contacts are sharp.

This facies is interpreted to represent distributary channel sandstones or possibly, estuarine channel deposits in a large tidal delta system. The silty shale interbeds may represent mud drapes over the crossbedded sandstone beds. The close lateral association with the Thalassinoides-containing siltstone facies suggests deposition in a marine or marginal marine environment.

The C zone produces from the coarse-grained sandstone facies. Laterals were drilled into rocks of this facies in the Black Dragon Member in at least nine of the productive wells in the Grassy Trail Creek Field (Mitchell, 1989b).

Although the coarse-grained sandstone facies at first appears to be similar to the dolomite-cemented sandstone facies of the Torrey Member, there are significant textural and mineralogic differences between these facies. The channel sandstones in the

Black Dragon Member are coarse- to medium-grained and thick-bedded, are trough crossbedded rather than ripple laminated, and contain calcite cement rather than anhydrite cement.

In general, the porosities are higher in the distributary or estuary channel sandstones than in the fine-grained tidal channel facies. Measured porosities and permeabilities from the C zone in Dusty Trail #1 to the south of the field range from 3 to 4 percent and .1 to .2 md at the medium-grained tops of beds, to 5 to 6 percent and .2 to .3 md from the coarse-grained bases of the beds. From thin-section analysis, primary porosities of the well-sorted sandstones may have been 20 percent before cementation. Local dissolution of the calcite and dolomite cement may have created secondary porosity in these sandstones.

Heavy oil staining of this sandstone facies indicates it has fair to good reservoir quality. This facies probably constitutes the tar sand deposits noted by several workers in outcrops in the northern San Rafael Swell (Blakey, 1974; Mitchell, 1989b; Ochs and Chan, 1990). Ochs and Chan (1990) have interpreted this facies (their XCS facies, located about 100 feet or 33 meters below the base of the Sinbad) as representing fluvial or possibly, estuarine deposits in the Cottonwood Draw area, about 30 miles (48 kilometers) south of the Grassy Trail Creek Field. They indicate paleocurrent directions to the north and northwest.

FACIES DISTRIBUTION FROM ISOCHORE MAPS

The distributions of the productive sand bodies within the Torrey Member were determined through interpretation of isochore maps, constructed from stratigraphic picks on the well logs. Isochore maps were constructed for the following intervals within the Torrey and Sinbad Members: top of the Sinbad to the top of the C, top of the B to top of the Sinbad, top of the A to top of the B, and from the base of the lower bentonite marker bed within the upper Torrey Member to the top of the A (Figures 5 through 8, respectively).

The maps of isochore thicknesses indicate characteristic depositional patterns for the productive sandstone bodies within the Grassy Trail Creek field. Starting with the lowest unit stratigraphically, the Sinbad interval contains a 20 ft thick in the central part of the field (Figure 5). The thickest portions of the Sinbad describe a curved form, oriented approximately NNE to SW, with crosscutting saddles or thins. Because the Sinbad has been interpreted as oolitic shoal or barrier island deposits, the shape of the isochore thicks may represent the highest point of the outer shelf. The position of the Grassy Trail Creek Field is two townships northward and on depositional strike with the Sinbad oolite belt described by Mitchell (1985, see Figure 9).

The isochore map of the B interval (Figure 6) overlying the Sinbad reveals a well-defined linear and meandering thick, the shape of which can easily be interpreted as representing a channel.

From the isochore map, the channel could be up to 18 ft thick. Core analysis of the B zone has indicated some areas with thick dolomitic sandstone beds, or other areas with much thinner strongly anhydritic-mottled very fine-grained sandstone. For example, the B zone in well 2-43x is predominantly anhydritic siltstone and is located within the thin on the isochore map. Note that this thin is positioned directly over the Sinbad thick which indicates that the Sinbad shoal was present as a topographic high during deposition of the B sandstones. Also note that the B channel form (thick) meanders around the Sinbad thick and cuts through (has created?) the saddle in the Sinbad thick.

The isochore map of the A interval (Figure 7) also reveals a channelized thick in the central portion of the field. Although it is not as thick as the B (only 10 to 15 ft thick), the shape of the interval still appears to wrap around the Sinbad high located near wells 2-43x and 3-12. Another channel segment may exist to the west in the vicinity of well 4-32.

Core analysis of the A zone has indicated the presence of thick sandstone units, but the beds appear to lack the sharp bases and basal intraclast lags of the B sandstone beds. Correlation of A sandstone units from the well logs suggests that the A is more laterally continous than the B, occurring in a several mile-wide belt. The A sandstone is envisioned as having been deposited by gently meandering tidal channels which produced a blanket of tidal channels sediment in a large area oriented roughly parallel to the shoreline. The pattern of thicknesses for both the A and B zone sandstones indicate a shoreline generally oriented to the northwest-southeast in the vicinity of the Grassy Trail Creek field.

The isochore map of the mudstone interval (Figure 8) in the upper Torrey Member above the productive A and B sandstone facies illustrates that the mudstone thins to the east onto a high of the A, B and Sinbad isochore thicks. The thickened mudstone interval surrounding the thin area may be a result of infilling of topographic lows produced by the greater compaction of the underlying clayey intertidal sediments around the coarser grained channel sands.

Facies analysis from cores indicates that the upper Torrey Member mudstones are composed of evaporitic upper intertidal to supratidal deposits. The vertical succession of facies in the Torrey Member from subtidal channel sandstones upward to supratidal mudstones suggests progradation of the entire tidal wedge seaward. The classic stratigraphic trap of reservoir-quality sandstones being overlain by an impermeable mudrock seal has been created by the progradation of the tidal deposits.

Additional evidence for the progradation of the tidal deposits comes from detailed log correlations. Mudstone units identified as X, Y and Z from above the A zone pinchout to the south-southwest within the field (Figure 4). Sucessively higher stratigraphic units pinch out progressively farther south indicating a south to southwestern progradation of the tidal deposits over the shoreline deposits.

This southward direction of progradation is not consistant with the generally northward paleocurrent orientations and deepening depositional facies described by other workers (Blakey, 1974) for the Torrey Member in the southern San Rafael Swell. The presence of the remnants of the Uncompahgre Uplift to the northeast of the Grassy Trail field may have controlled the position of the shoreline in the vicinity of the field.

DISCUSSION

Sinbad and Torrey Members

What emerges from our analyses of the facies distributions of sandstone units within the Torrey Member is a marginal mound model for a broad, shallow shelf. This model envisions the Sinbad as an oolitic shoal complex being the highest point of the outer shelf. The shoal would provide a locus of increased current activity and control the location of tidal channels. Subsequent progradation of tidal flat deposits over lagoonal sediments and through the shoal caused tidal channels to be formed around the topographically high, and probably intensely cemented, older carbonate shoals.

At the Grassy Trail Creek field, the A and B tidal channel sandstones occur in a 2 to 4-mile wide region, oriented northwest to southeast. Individual porous beds are thin and discontinous, but these beds occur stacked within thicker packages that can be traced for several miles parallel to the strike of the shelf margin.

Black Dragon Member

Although a local thickness (isochore) map of the C zone was not constructed, the regional distribution of equivalent oil-stained facies in the Black Dragon Member has been illustrated by Mitchell and others (1989b). Their maps are a compilation of surface and subsurface data from descriptions of oil-staining in outcrop and from data on free oil occurrences in more than 50 wells. The subsurface samples were rated by the strength of the show and assigned a thickness value accordingly.

Ochs and Chan (1990) interpreted the cross-stratified sandstone (XCS) facies as being fluvial to possibly estuarine in origin, trending north to northwest, and within the most tidally-influenced portion of the Black Dragon succession, 30 miles (48 kilometers) south of the Grassy Trail Creek field. We interpret the coarse-grained sandstone facies to represent estuarine or tidally-influenced distributary channels. Thus, the distribution of oil-stained sandstones in the Black Dragon Member illustrated in Figure 9 appears to represent a large tidal delta system and the generally northward transition from amalgamated fluvial channels to distributary-estuary channels to mouthbar-shoreface deposits seaward. The channelized portion of the delta is relatively straight-reached, trending north to northwestward across the clayey tidal flats from its landward pinchout to the point where it becomes a wave-reworked mouthbar at the shoreface.

Although in the Grassy Trail Creek field the C zone is composed of fining-upward channelized sandstone beds, logs from wells to the west of the field appear to have a thick coarsening-upward unit that can be correlated to the C zone (oral communication, Kim Seeley, 1989). This coarsening-upward sequence may represent mouthbar deposits.

Mitchell and others (1989b) note that the Black Dragon Member is productive in a well (Texas International Petroleum Federal 41-33) in Section 33 of T18S-R7E. The location of this well to the east of the town of Ferron places it at the western edge of oil-impregnated sandstones that can be interpreted as mouthbar deposits of a separate deltaic lobe. Entrapment may be a result of facies changes along the seaward pinchout of the mouthbar sandstones into prodelta shales and siltstones.

EXPLORATION MODEL

If Mitchell's sample staining maps accurately portray the extent of the A, B, and C sandstone units, several interpretations can be made concerning the regional distribution of the porous and potentially productive units.

Hydrocarbon staining in the Torrey member (Figure 10) forms an arcuate map shape near the Grassy Trail Creek field (Mitchell and others, 1989b). The kidney-bean shape is similar to the combined thicks of the A and B intervals (Figures 6 and 7) if they were mapped as a net sand isopach. The tidal channels in the A and B zones are interpreted to represent net sand deposition parallel to the northwest-trending shoreline. From the sample staining map, this shoreline could actually trend more east-west than in the immediate vicinity of the field.

Sample staining in the Torrey Member in the northern San Rafael Swell is thick only near the Grassy Trail Creek field. This suggests that sandstone units coarse and thick enough to be oil-stained are not present in nearby areas; i.e., there may not be any other tidal channels. This suggests that the potential for the existence of similarly productive units within the Torrey Member is limited.

Because the Black Dragon Member is productive from both estuary channel sandstones in the Grassy Trail Creek field and from possible distributary mouthbar sandstones in Section 33 of T18S-R7E, regional exploration for additional traps or fields in the C interval should identify the most porous and thickest of the sandstones. It should be emphasized that even though C interval sandstones exhibit strong oil shows in wells throughout the northern San Rafael Swell, they still may not produce without significant stimulation and the role of fracturing may be more important than the stratigraphic thickness. Strong regional hydrocarbon staining of the oolitic facies of the Sinbad also suggests rather leaky sealing of the C sandstones by overlying shales.

STRUCTURE

The Grassy Trail Creek field lies on the north plunging nose of the San Rafael Swell, a broad upwarp of Laramide age. The swell trends NNE-SSW through central Utah. To the northeast, the Precambrian-cored Uncompahgre Uplift trends NW-SE. Faults are common throughout the San Rafael Swell and San Rafael Desert to the southeast. The faults vary in trend from roughly east-west (parallel to the swell axis) to northwest-southeast (parallel to the Uncompaghre Uplift).

Faults

Numerous faults of apparent small offset are visible at the surface in the field area. They run parallel to the swell axis and are discontinuous. No faults are actually present on the electric logs of the wells in the field but are inferred based on trying to contour smoothly between the wells (Figure 11). Mitchell and others (1989a) coutour without faults and their map shows a number of irregularities of contours. There is no way to determine which is the correct structural interpretation but the rational for the faulted version will be explained. The five subsurface faults shown are NNE-SSW trending normal faults like those at the surface. Structural contour maps constructed at each major stratigraphic boundary exhibit similar offsets through the geologic section without intersecting any of the wells. Therefore, the subsurface faults must be near vertical, presuming the well locations, both surface and subsurface, are correct. The faults likely originated as extension features over the crest of the uplifting San Rafael Swell.

Faults with greater offsets are located on the margins of the field. The southeasternmost fault, which trends more easterly than the others, delineates an offset of more than 700 feet between the central portion of the field and well #13-11 to the southeast. This fault could trend in a slightly more east-west direction than shown in Figure 11. The fault may represent a downdropped block along the crest of the swell which explains the presence of oil to the northwest while there are only gas shows to the east.

The westernmost fault delineates an offset of about 100 feet, with the west side down. Only the Skyline Federal 4-32 well is productive in the western fault block. Wells updip and downdip from this well are dry, implying a stratigraphic control on production as well.

Three faults within the field may act as fluid barriers, accounting in part for the differences in production between wells.

For example, wells 11-13 and 11-23 are only separated by a few hundred feet and stratigraphic thicknesses and sedimentary facies of the producing intervals are virtually identical in the two wells. The 11-13 well is about 50 feet structurally higher than the 11-23 well, yet the latter has produced about 42,000 barrels of oil, double that of the 21,000 barrels on the 11-13 well.

Fracturing

Because of the low porosity and permeability of producing units in the Moenkopi, fracturing plays a critical role in production. Mitchell and others (1989a) believe that two producing regimes are at work in the field. The first is represented by a hyperbolic decline rate due to gas expansion in the fractures at the borehole with produced fluids being replaced by matrix rock near the borehole. The second regime shows an expotential decline due to gravity drainage of fractures at a distance from the well. The replacing fluids would come from matrix rock near the fractures. According to calculations by Mitchell and others (1989a), about three-quarters of the production would be may be from fractures and the rest from matrix. They also determined that about 29 percent of the production is from fractures near the wellbores and 71 percent is from fractures far from the well and from the matrix.

Mitchell and others (1989a) describe fracture spacing in 19 laterals in nine producing wells. They counted a total of 47 fractures over a length of 6608 feet of laterals for an average fracture spacing of 140 feet. Fracture spacing in different laterals averaged about 100-200 feet. The origin of their data was not given.

Mitchell and others (1989a) assume the subsurface fracture orientations run parallel to those measured at the surface in the Cretaceous Ferron and Dakota-Cedar Mesa Formations; i.e., at N15W and N80E. These directions are inconsistent with fractures measured by Terra Tek Core Services (1984) in oriented core from the ARCO Grassy Trail 36-2 well, cut through the Moenkopi section (Figure 12). Fractures from four 3.5-inch diameter cores totalling 111 feet in length from depths of 4008-4119 feet were divided by them into four categories based on morphological differences. Of the 64 fractures measured, there are 6 open, 25 open with slickensides, 28 gouge-filled and 5 calcite-filled.

The open fractures dominantly trend N5E with a scatter of 40-50 degrees in azimuth (Terra Tek, 1984). A secondary set trends N65W-S65E with minor azimuthal variation. Dips of these fractures range from 10 to 81 degrees but both the average and median dips are around 35 degrees for both azimuthal sets.

The filled fractures are widely scattered in azimuth with one set trending N65W-S65E being the most prominent. The calcite-filled fractures also trend NW-SE, so the scatter is due to the gouge-filled fractures. The other main gouge-filled fracture directions are N5W and N50E.

The common denominator among all the fracture groups is the strong N65W trend. This trend is parallel to the axis of the Uncompahgre Uplift to the northeast and the other WNW-ESE regional fault trends in the San Rafael Swell area. The filled fractures are probably older than the open fractures and have steep to near vertical dips. Open fractures in this trend must have formed after the fracture filling materials were emplaced. The lower dips of the open fractures also suggest that they could have formed at a different time. They may represent incipient fractures or zones of weakness developed along with the other NW-SE trending "Uncompahgre" fractures. Then, during the compressional event that created the San Rafael Swell, these fractures propagated at low dip angles.

Most open fractures run parallel to the trend of the San Rafael Swell structural axis. They are interpreted as extensional fractures as the swell arched up. Regional horizontal compression that formed the swell may account for the low angle dips of the fractures.

The number of filled fractures in each set other than the two discussed above are minor but collectively account for three-quarters of all filled fractures. They could be the result of local stress field variations, differences in rock properties, interference of structural regimes, or additional tectonic events not discussed.

HYDROCARBON SOURCE

Although the Grassy Trail Creek field is the only major Moenkopi producer in Utah, there are an estimated 2 billion barrels of hydrocarbons in surface accumulations of the Moenkopi in and around the San Rafael Swell (Mitchell and others, 1989a).

It has been commonly assumed that the Moenkopi is self-sourced although this widely held belief has not been adequately documented. Mitchell and others (1989a) conclude that the Moenkopi is self-sourced because 1) hydrocarbons are not present in underlying porous units, 2) the dark color of the Torrey and Black Dragon Members implies high organic content, and 3) vertical or long-distance migration would not be possible though the tight Moenkopi rocks.

More quantitative work by Chidsey and others (1990) found the total organic content of the Moenkopi near the Grassy Trail Creek field to be extremely low and inadequate to account for the reserves. In addition, geochemical analysis of the produced oil showed it to be different from the Moenkopi organic material as well as from all the other known or potential source rocks near the north end of the San Rafael Swell. Chidsey and others (1990) report that Precambrian Chuar Group rocks sampled in the Grand Canyon could be a source of the Moenkopi oil in the Grassy Trail Creek field. Subsequent work, particularly biomarker analysis by the USGS (Palacas, personal communication, 1991), has indicated that Precambrian rocks cannot be the source of the Grassy Trail Creek oil, however, no other source has been postively identified. Proprietary oil company analyses suggest the black shales in the Pennsylvanian Paradox Formation as a possible source. Other workers have suggested long distance migration from a Park City-Phosphoria equivalent facies.

Mitchell and others (1989a,b) note that the oils at Grassy Trail Creek and Ferron fields are very similar in gravity, pour point, sulfur content, color, and nitrogen content. Chidsey and others (1990) found that the Ferron and Grassy Trail Creek oils are geochemically similar as well. No other fields have been found with these similarities in Utah.

CONCLUSIONS

Production from the Grassy Trail Creek field is the result of a set of interacting parameters including complex stratigraphic heterogeneities, fracture permeability, faults acting as fluid barriers, and the use of multiple horizontal laterals in some wells. The relative importance among the structure, stratigraphy, and laterals to production has not been determined.

The stratigraphic and structural conditions that contribute to the presence of an economically viable oil accumulation at the Grassy Trail Creek field exist over a larger area than is presently being produced. There appears to be opportunity for expansion, field extensions, or new field discoveries in nearby areas, especially within the Black Dragon Member.

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FIGURE CAPTIONS

Figure 1. Geologic map of the San Rafael Swell area and location of the Grassy Trail Creek field. Modified from Lawton, 1989.

Figure 2. Well locations in the Grassy Trail Creek field. The locations of south-north and west-east cross-sections are indicated.

Figure 3. Paleogeographic reconstruction of intermountain west during Early Traissic, modified after Ochs and Chan, 1990. Arrows indicate paleoflow directions in estuarine facies of the Black Dragon Member. Southward arrow indicates paleoflow directions in tidal channel facies of the Torrey Member.

Figure 4. Stratigraphic cross-sections across the Grassy Trail Creek field, from correlated well logs.

Figure 5. Isochore map of the Sinbad Limestone Member. Contours in feet.

Figure 6. Isochore map of the B zone, above the Sinbad Limestone. Contours in feet.

Figure 7. Isochore map of the A zone, above the B zone. Contours in feet.

Figure 8. Isochore map of the mudstone interval above the A zone. Note that the shape represents a thin rather than a thick.

Figure 9. Distribution of hydrocarbon stained facies in the Black Dragon Member, modified after Mitchell and others, 1989b. Facies interpretation based on core analysis from Grassy Trail Creek wells. Black outline is location of present-day San Rafael Swell.

Figure 10. Distribution of hydrocarbon stained facies in the Torrey Member, modified after Mitchell and others, 1989b. Black outline is location of present-day San Rafael Swell.

Figure 11. Structural contour map on the top of the A zone, Torrey Member, Grassy Trail Creek field. Contour interval is 50 feet.