UINTA ENIGMA

The Duchesne Fault Zone and Its Impact on the Development of the Uinta Basin

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BY RILEY BRINKERHOFF

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It's easy to believe that there is not much left to discover in geology, especially in the continental U.S., where so many aspects of geology have been studied many times over by many great geologists. That impression is usually reinforced by the constant influx of journal articles that focus on a particular facet of a much larger stratigraphic or structural story. It is further strengthened by the hundreds of citations of previous work by geologists that have re-examined the same geologic feature. But the truth is that the Earth is a massive place and has only been cursorily explored in most places. Utah is no different! Since the investigations by the early great surveys of the western U.S., thousands of geologists have crawled all over the West, researching everything from economic resources like mining, oil and gas, and hydrothermal prospects to regional stratigraphy and structural geology. Discoveries from these endeavors have been published in journals, government reports and maps. Moreover, Utah has an excellent state survey that regularly publishes new research. Even with all these publications and surveys, there are many well-exposed geologic features left to be fully researched.

A great example is the Duchesne Fault Zone (DFZ). Located just south of the center of the Uinta Basin of northeastern Utah, the surface exposure is a 40 mile long system of en-echelon grabens that cut through the middle of the Green River oil play (figures 1 and 2). The en-echelon pattern was formed early in the DFZ's history through compressional and transpressional shear on individual faults being progressively transferred to the adjoining right-stepping faults within the system. Approximately 2,100 oil wells have been drilled within a mile of one of the surface strands of the fault zone, but little has been published concerning its structural history, kinematics, or effects on oil and gas production. Fortunately, it was not difficult to find the features that point to a long structural history that drove large syndepositional sedimentary trends of the Eocene Green River Formation within the ancient

UINTA BASIN, UTAH

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Lake Uinta, recorded the changes in stress regimes in the Uinta Basin. These factors are crucial in driving oil production trends in this area, as described in this article.

GENERAL CHARACTERISTICS

The DFZ is not a subtle feature. The grabens and related faults are clearly visible on aerial photographs and satellite imagery **(figure 2)**. The DFZ is also unmistakable on the ground, as the grabens are bounded by topographical escarpments of up to 20 feet in some areas. The fault zone changes character along the length of its traces from west to east. In the western part of the fault system, the grabens are wider and well-defined. The eastern part lacks the well-defined grabens and consists mostly of narrow, parallel vertical normal faults, surface parallel and oblique lineaments, and transpressional ridges. A prominent asymmetrical footwall syncline closely parallels most of the graben along the DFZ's southern margin. Sandstone beds adjacent to the DFZ are commonly saturated with dead oil, and the easternmost traces of the DFZ are pervasively intruded with gilsonite. Springs and oil seeps are found along traces of the DFZ. Early oil and gas prospectors could not help but notice the hydrocarbon indicators along the fault zone, and a few small discoveries were made in the fractured rocks within the DFZ.

Slickensides, fractures, and fault-plane data indicate a complex kinematic history along the DFZ **(figure 3)**. Slickenside orientation ranges from horizontal and oblique, recording strike-slip compressional-transpressional movement, to the more prominent vertical dip-slip slickensides recording extensional movement. In a few places, the horizontal and oblique slickensides are overprinted by vertical slickensides, which strongly suggest that the stress regime that influenced fault motion changed

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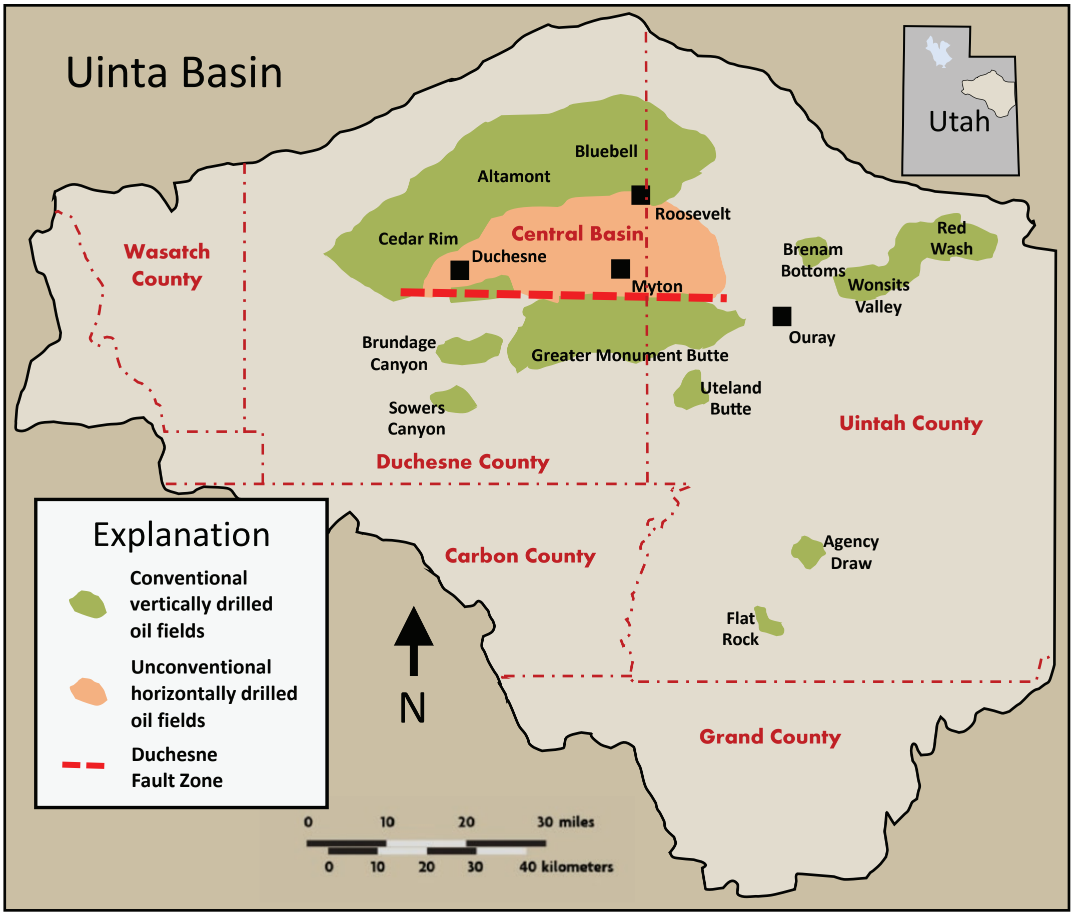

FIGURE 1: Location map of the Uinta Basin within northeastern Utah, showing the position of the Duchesne fault zone (DFZ) in red. Note that the DFZ separates the older, vertically drilled conventional fields to the south from the newer, horizontally drilled unconventional oil fields to the north.

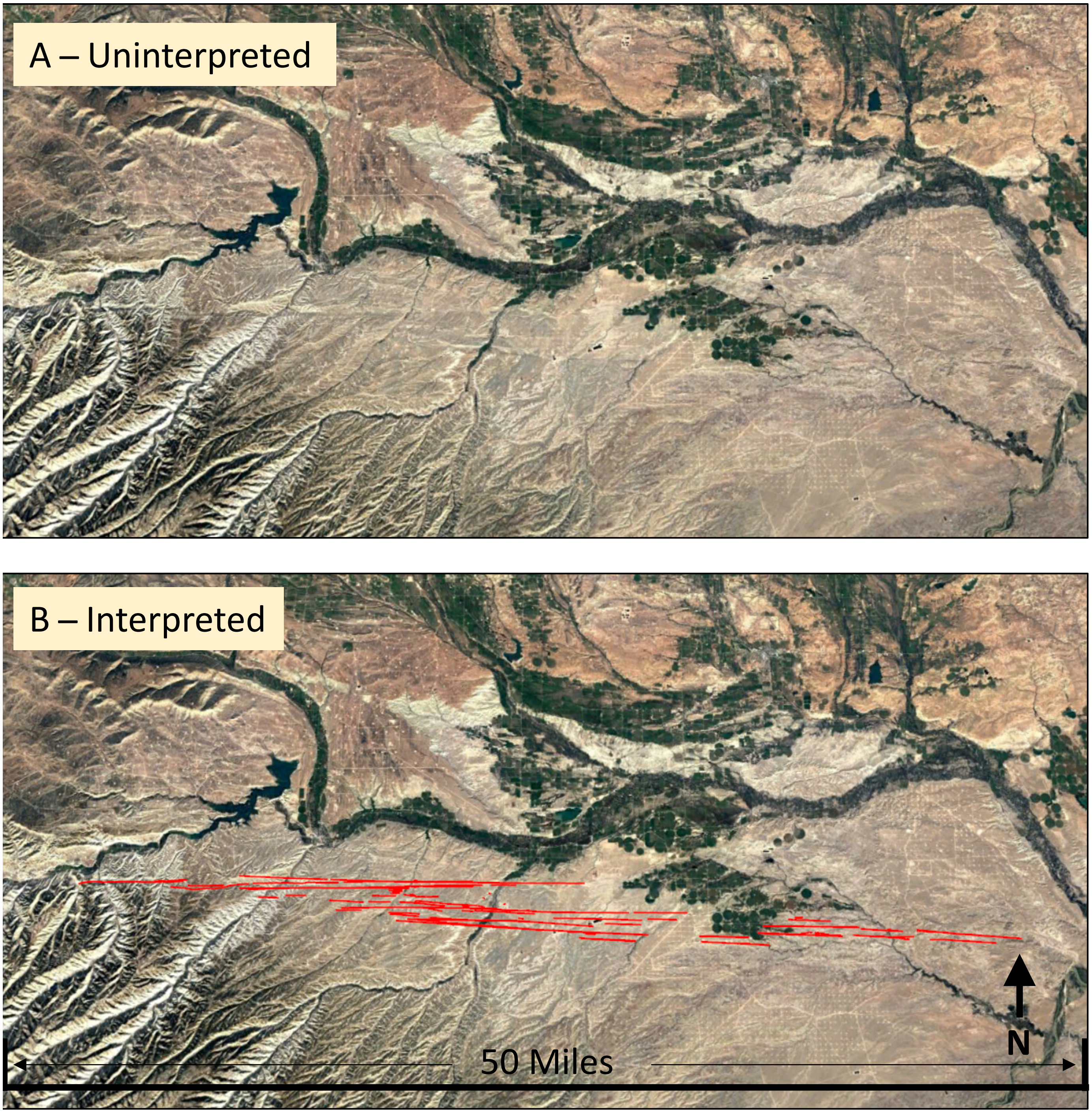

FIGURE 2: Satellite imagery of the central part of the Uinta Basin showing fault traces in the DFZ. (A) The DFZ is a 40-mile-long east-west-trending fault system. (B) The fault traces of the DFZ are marked in red. Note the en-echelon pattern. Some of the fault traces appear to be discontinuous because they are concealed by surficial deposits and modern agriculture. Also note the generally straight, east-west nature of the fault zone. This generally parallels the trend of the Uinta Mountain structure to the north. Individual oil well pads are visible as small, light-colored dots on a grid pattern.

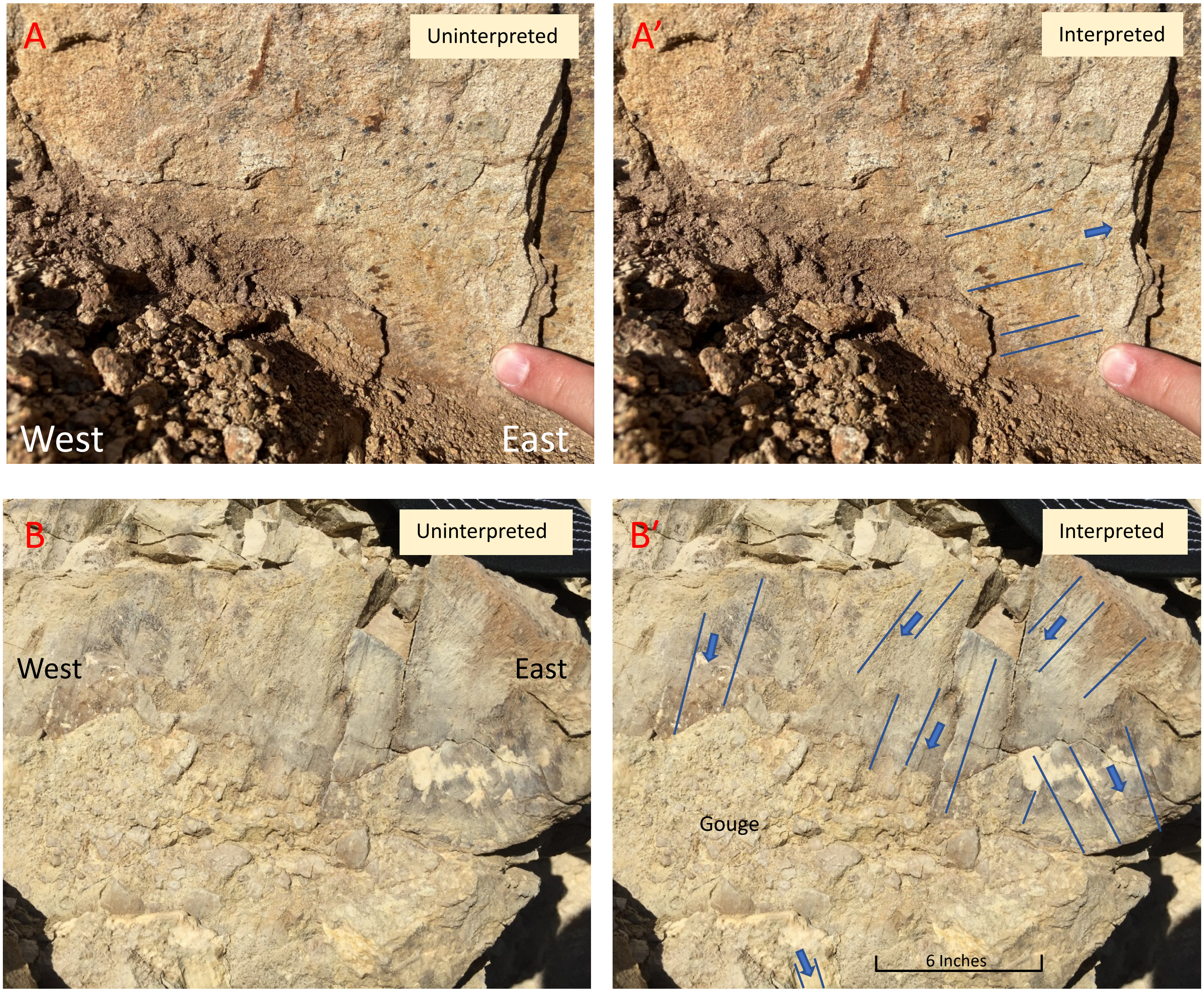

FIGURE 3: Most of the slickensides preserved on fault planes in the DFZ record dip-slip movement as part of the latest phase of fault relaxation during Neogene extension. However, slickensides preserved on fault planes at some locations have horizontal and oblique orientations that indicate an earlier phase of strike-slip and oblique-slip motion. (A) Uninterpreted fault surface with slickensides. View is to the north. (A′) Interpretation of same fault surface showing nearly horizontal slickensides created from lateral slip. Slickensides are highlighted with blue lines, with arrow showing direction of motion. (B) Uninterpreted fault surface showing multiple set sets of slickensides. (B′) Interpretation of same fault surface highlighting the slickensides with blue lines to show different periods of motion. One set show predominantly extensional dip-slip movement overprinted on transpressional oblique-slip movement. Arrows show the direction of motion. We interpret the dextral-oblique slip as the older phase, which then rotates nearly 90° to slightly sinistral-oblique slip.

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over time. Similarly, Riedel shears appear to have been formed from lateral movements of the fault, even though many are now found adjacent to normal faults that formed under extension. Fault-plane data indicate the average strike is 267° whereas the average strike of conjugate faults and Riedel shears are about 40°. Average fault-plane dip is 69° with maximum and minimum dips of 89° and 14°, respectively. Fault-plane geometry also changes from west to east. Fault-plane attitudes in the western grabens exhibit classic graben or half graben geometries: the faults that form the south margin dip north and the faults on the north margin dip south. In contrast, the faults on both margins of the narrow grabens dip north in the eastern part of the DFZ.

Previous work on the DFZ suggested that vertical offset in the fault zone dies out at a shallow depth based on two models discussed in Groeger and Bruhn (2001). Using their detachment fault model, Groeger and Bruhn (2001) estimated that the master fault becomes listric and dies out at about 3,000 feet into shaley beds of the Green River Formation. In contrast, using a planar master fault model, they estimated the depth that the fault dies out to be about 4,500 feet. However, we think the DFZ penetrated basement rocks at depths greater than 20,000 feet based on well data, stratigraphic thickness to basement, and anomalous spikes in helium and hydrogen oil-gas data across several fault traces in the DFZ (Jones and Pirkle, 1981; Sprinkel, 2018a). The relative movement across the fault zone was complex as the amount of slip within any single fault decreased along its length as shear strain was transferred to adjoining, right-stepping faults. This complex transcurrent movement created small sag basins, also called pull-apart basins **(figure 4)**. Careful correlation of markers within the Green River Formation shows distinct zones of remarkable growth strata, usually with 50 to 100 feet of additional thickness over an area of one to two miles. These sag basins only occur in distinct zones within the lower Green River Formation, particularly within the Uteland Butte member, the Long Point Bed, and the Carbonate Marker member, which provides evidence of punctuated intervals of movement along the fault zone in early Eocene time.

GEOLOGIC HISTORY

The DFZ is likely an ancient structure, possibly originating as a weak point during the assembly of Proterozoic terrains in Utah. Structural offset has been observed in seismic data along the fault zone in Mississippian rocks (Madison Limestone) dating from the early movement of the Late Paleozoic ancestral Rocky Mountain orogeny. During the late Mesozoic to early Paleogene Sevier orogeny, the DFZ was active again, with structural offset visible in Cretaceous marine stratigraphy. However, the focus of our research is on the slip that occurred during the Paleogene to Oligocene Laramide orogeny and deposition of the Eocene Green River Formation. At that time, the regional deformation was caused by an eastward push of a descending slab of oceanic crust under western North America (Smith and others, 2014). The North American continent did not respond to this compression evenly, with weak places getting thrust upwards as mountains while adjacent regions descended as foreland basins. The Uinta Mountains rose as the largest Laramide block in Utah, causing the crust south of the mountains to subside and form the Uinta Basin. Continental stress and mountain building eventually caused the ancient weak zone along the DFZ to rupture and begin to slip parallel to the rising east-west-trending Uinta Mountain block. We know from horizontal slickensides and offset channel deposits within the Eocene Uinta Formation, which overlies the Green River Formation, that the fault slipped in a dextral motion, meaning that the northern block moved to the east **(figure 5)**.

INTERPRETATION

The DFZ is an important structural feature that aids the interpretation of many phenomena within the Uinta basin. Tightly spaced contours on structure maps clearly show that there is a sharp increase in structural dips of Green River stratigraphy at the fault zone, perhaps most easily shown by calculating a first-derivative structure map **(figure 6)**. We observed in seismic reflection data that there is a change in dip of the stratigraphic section across the DFZ with shallow-dipping beds south of the DFZ and

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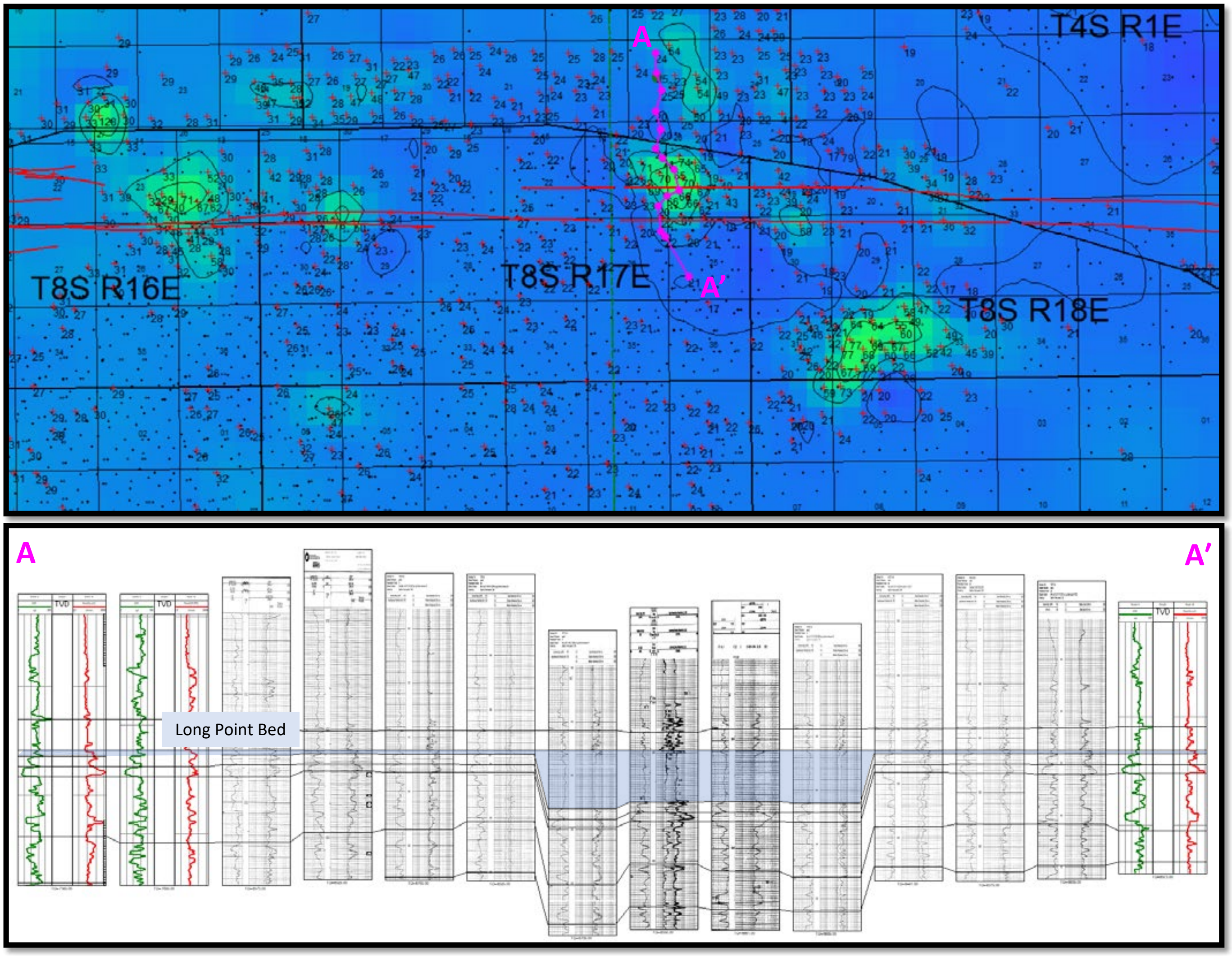

FIGURE 4: Isopach map and associated cross section of the Long Point Bed of the lower Green River Formation. Note the small basins that syndepositionally opened along the DFZ. We characterize these as small sag basins or pull-apart basins associated with strike-slip movement along the fault zone.

Explanation

- ● Oil wells
- +25 Isopach of Long Point Bed
- — Traces of the DFZ
- ▱ Sag basins on cross-section
- 🟩 Sag basins isopach map with 20′ contours

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steeper-dipping beds to the north. Our interpretation is that the DFZ acted as a hinge during basin development. The increase in dip within the stratigraphic section reinforces the concept that the fault zone penetrated basement rocks and accommodated extensive subsidence in the developing Uinta Basin. Today, the DFZ is the southern boundary for the deep, overpressured portion of the petroleum system in the basin. Since fault movement on the DFZ was syndepositional with the Green River Formation, it significantly influenced depositional trends. Shallow deltaic sediments tend to characterize deposition south of the DFZ whereas hyperpycnites (lacustrine turbidites) and deeper lacustrine mudstones dominate north of it. The Sunnyside delta was the largest deltaic system during Green River time, grading into the open-lacustrine facies of the

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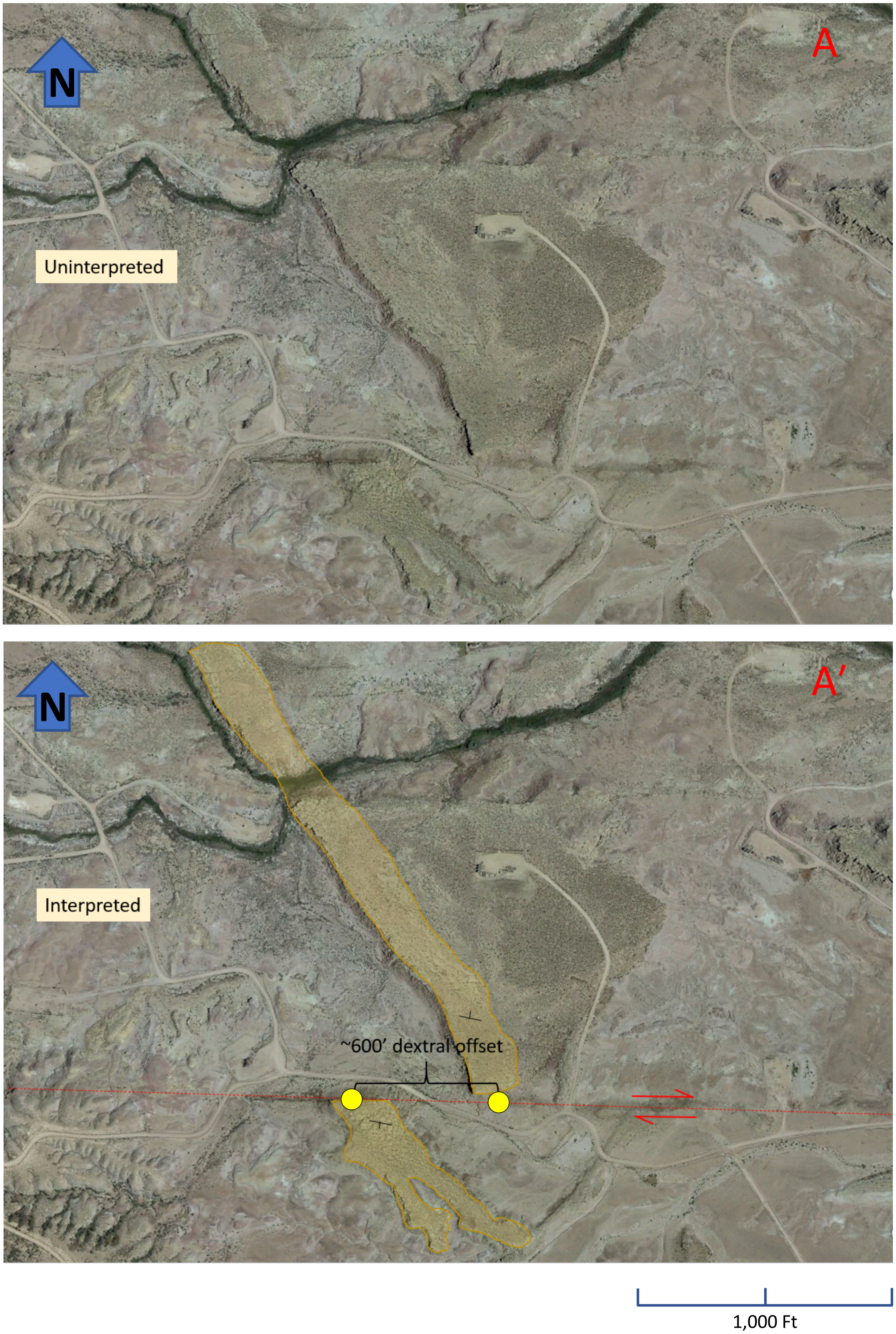
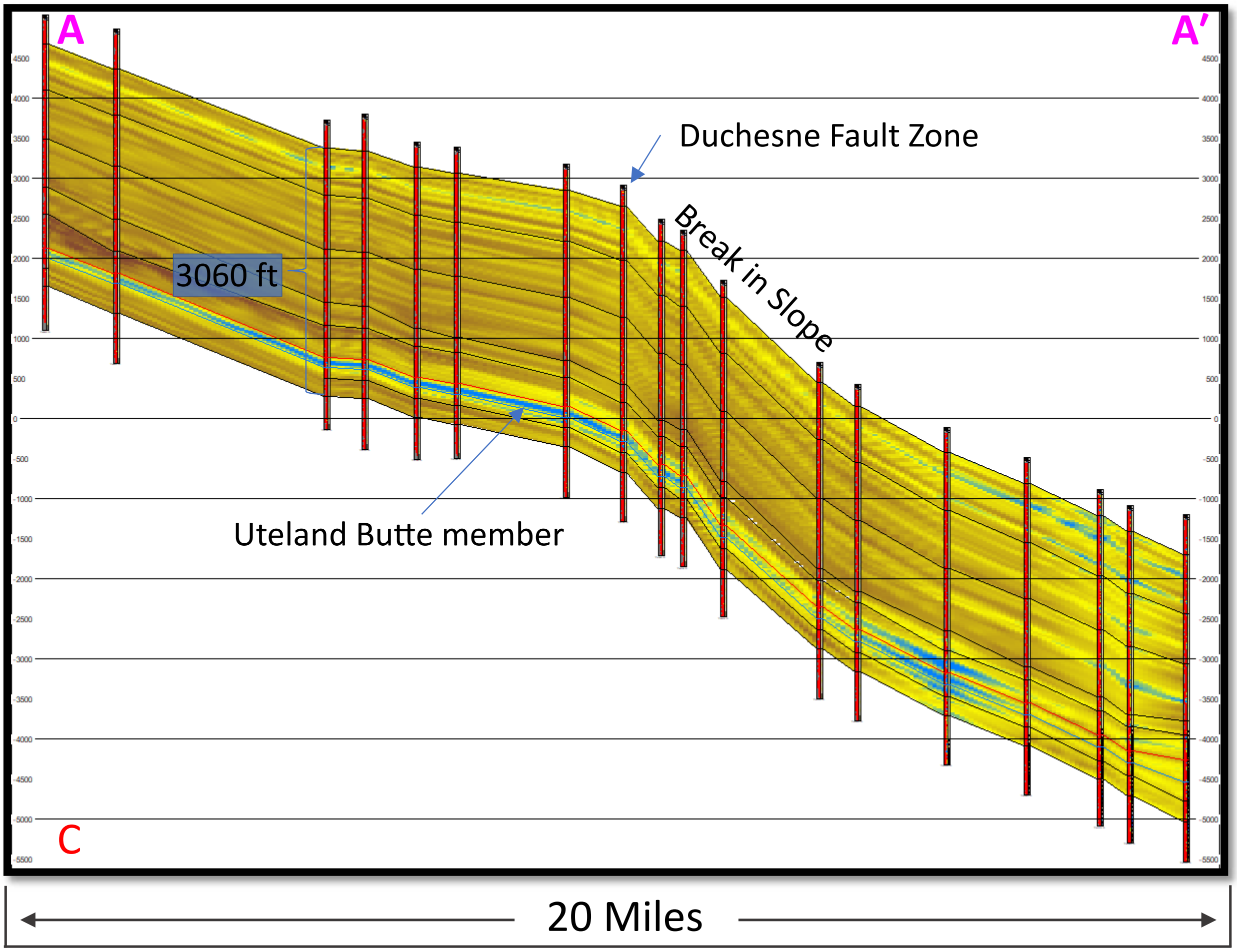
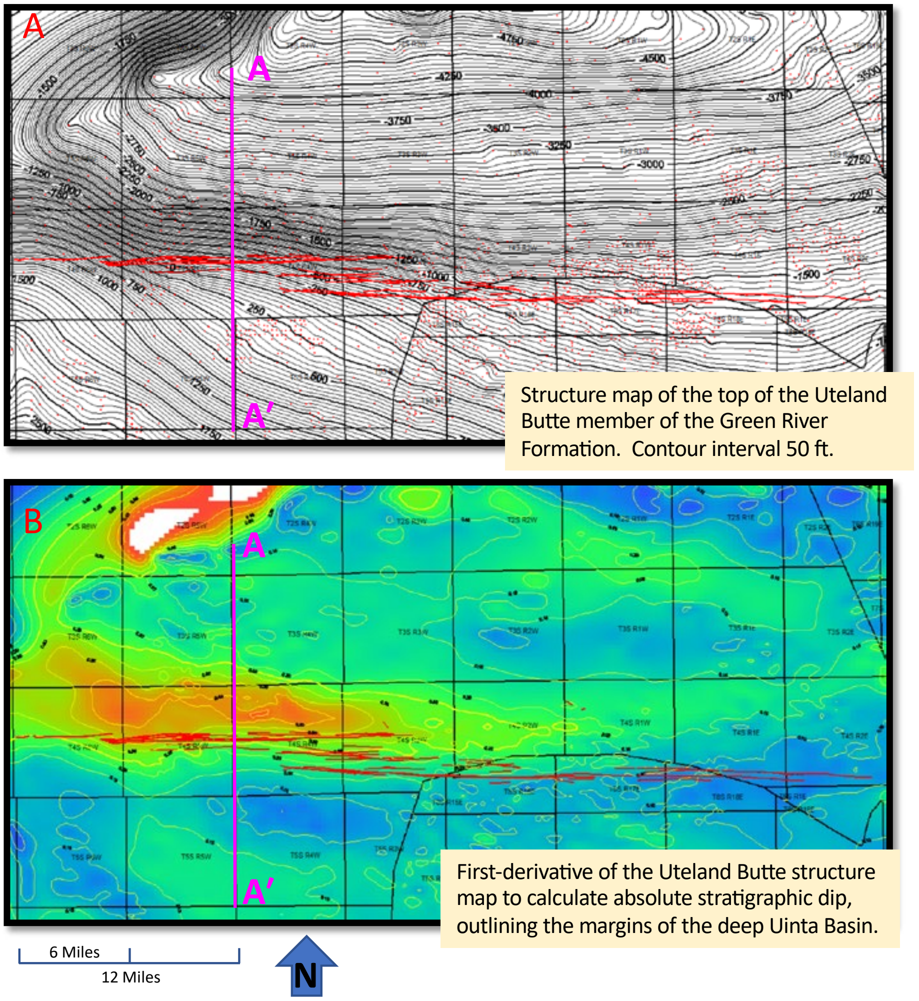


FIGURE 5: (A) Google image showing a fault segment that cuts the Eocene Uinta Formation. (A′) Annotated photo shows the interpretation of right-lateral (dextral) movement along the fault segment with the offset of an exhumed channel in the Uinta Formation. The laterally offset features, called "pin points" by structural geologist, allow us to measure fault offset. This fault offset the exhumed channel ~600 ft. The roads and cleared areas are oil well pads within the Greater Monument Butte field.

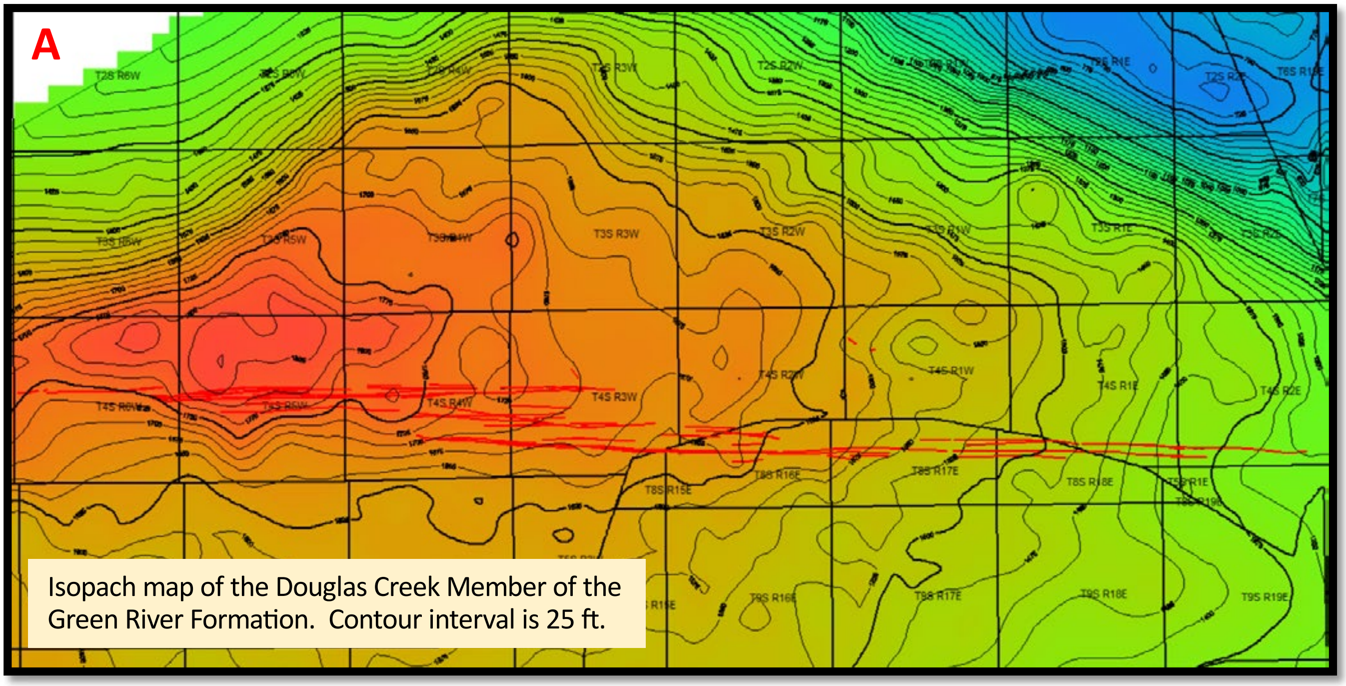




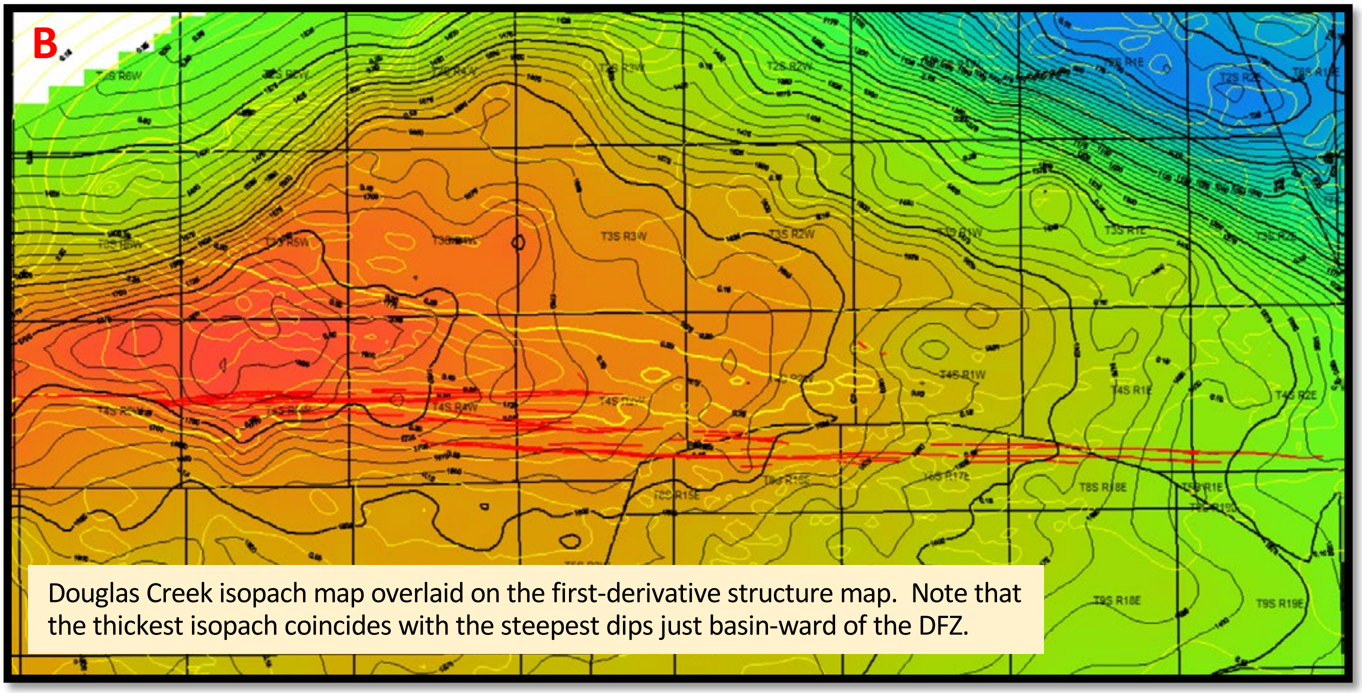
Structure map of the top of the Uteland Butte member of the Green River Formation. Contour interval 50 ft.

First-derivative of the Uteland Butte structure map to calculate absolute stratigraphic dip, outlining the margins of the deep Uinta Basin.

FIGURE 6: (A) Subsea-true-vertical-depth (SSTVD) structure contour map on the top of the Uteland Butte member of the Eocene Green River Formation. (B) First-derivative structure contour map on the Uteland Butte member. (C) Interpretive gamma-ray well cross section (A-A′) demonstrate the DFZ's influence on the greater structural and depositional trends in the Uinta Basin. The DFZ acted as a hinge point in the developing Uinta Basin, with steeper (warmer colors inset B) stratigraphic dips to the north of the fault zone. The more rapid subsidence of the basin north of the fault created greater accommodation, resulting in much thicker stratigraphic thicknesses just basinward of the fault. Today the DFZ marks the southern boundary of the deep, overpressured part of the Uinta Basin petroleum system.

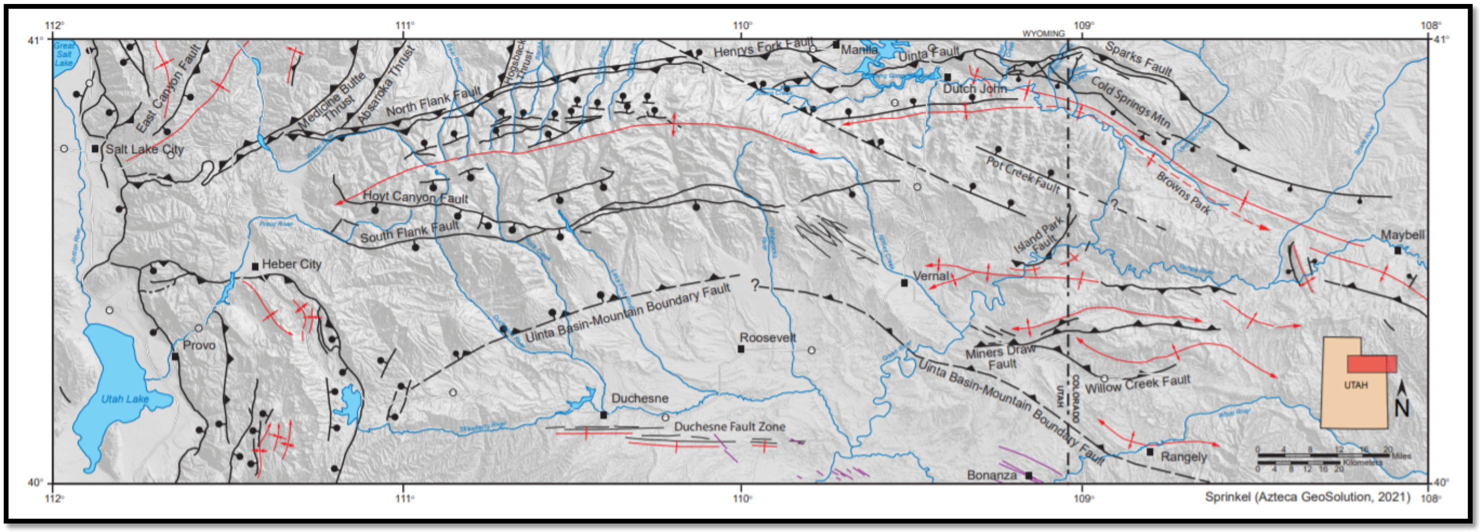


Isopach map of the Douglas Creek Member of the Green River Formation. Contour interval is 25 ft.



Douglas Creek isopach map overlaid on the first-derivative structure map. Note that the thickest isopach coincides with the steepest dips just basin-ward of the DFZ.

FIGURE 7: Structurally influenced sedimentation: (A) Douglas Creek Member of the Green River Formation (and equivalents) isopach map and (B) isopach map overlain on first-derivative structure-contour map. The increased accommodation space created as the basin subsided more rapidly to the north of the DFZ allowed greater volumes of lacustrine sediments to accumulate near the fault zone. This is well illustrated by map A. Note that the unit thickens just to the north and along the fault zone. Map B is an overlay of A with contours from the first derivative of the Uteland Butte structure map (map B of figure 7) to show the correlation of steepest dips related to the DFZ and the greatest accumulation of sediments, strongly suggesting that movement was syndepositional.



Sprinkel (Azteca GeoSolution, 2021)

FIGURE 8: A tectonic-structure map of northeastern Utah and northwestern Colorado. Note that the DFZ lies in the center of the Uinta Basin, paralleling the general structure of the Laramide aged Uinta Mountain uplift. To the west lie normal faults, some reactivating Sevier aged thrust faults, related to Neogene Basin and Range extension. To the east of the DFZ are Laramide thrusts and uplifts that have not undergone extension. The Uinta Basin-Mountain Boundary Fault to the north of the DFZ shows the transition from Basin and Range extension on the west to relict Laramide compression on the east.

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Douglas Creek Member. This unit reached its greatest thicknesses on the north side of the DFZ structural hinge (figure 7A). Accommodation developed rapidly on the north side of the DFZ hinge point, forcing rivers in the prograding system to drop their sedimentary loads. By overlaying the first-derivative structure contour map on an isopach of the Douglas Creek interval (figure 7B), it is apparent that the member is thickest where the structural dips are the highest.

Studying the DFZ is just one piece of the tectonic puzzle in understanding the regional structural history of the Uinta Basin and Uinta Mountains **(figure 8)**. The change in stress fields from compression-transpression to extension occurs at about the center of the DFZ. The wide grabens that characterize the western part of the fault zone are within the extended part of the basin. The eastern part of the DFZ includes the narrow grabens transpressional ridges and anticlines, and the vertical to steeply dipping north faults that reflect the relict Laramide stress regime. The changing tectonic stress fields within the DFZ are a microcosm of the regional stress change that has affected the Uinta Basin and Uinta Mountains as a whole. The western part of the basin is currently undergoing Neogene extension-driven Basin and Range deformation; however, Neogene extension does affect the eastern Uinta Mountains (Sprinkel, 2014, 2018b). In the western part of the basin, many of the reverse and thrust faults from the Sevier and Laramide orogenies

The Uinta Basin-Mountain boundary fault zone (UB-MBFZ), about 20 miles north of the DFZ **(figure 8)**, is a great example of this changing stress field. The eastern part of the UB-MBFZ still exhibits a compressional thrust orientation, whereas the western side of the fault has experienced significant extension (Sprinkel, 2018a). Modern stress data, mostly from image log-derived borehole-breakout data, show this change in stress **(figure 9)**. Maximum horizontal stress on the eastern side of the basin trends northwest to southeast, parallel to the relict Laramide stresses. On the west side of the basin, maximum horizontal stress runs directly north-south, like the adjacent Basin and Range province.

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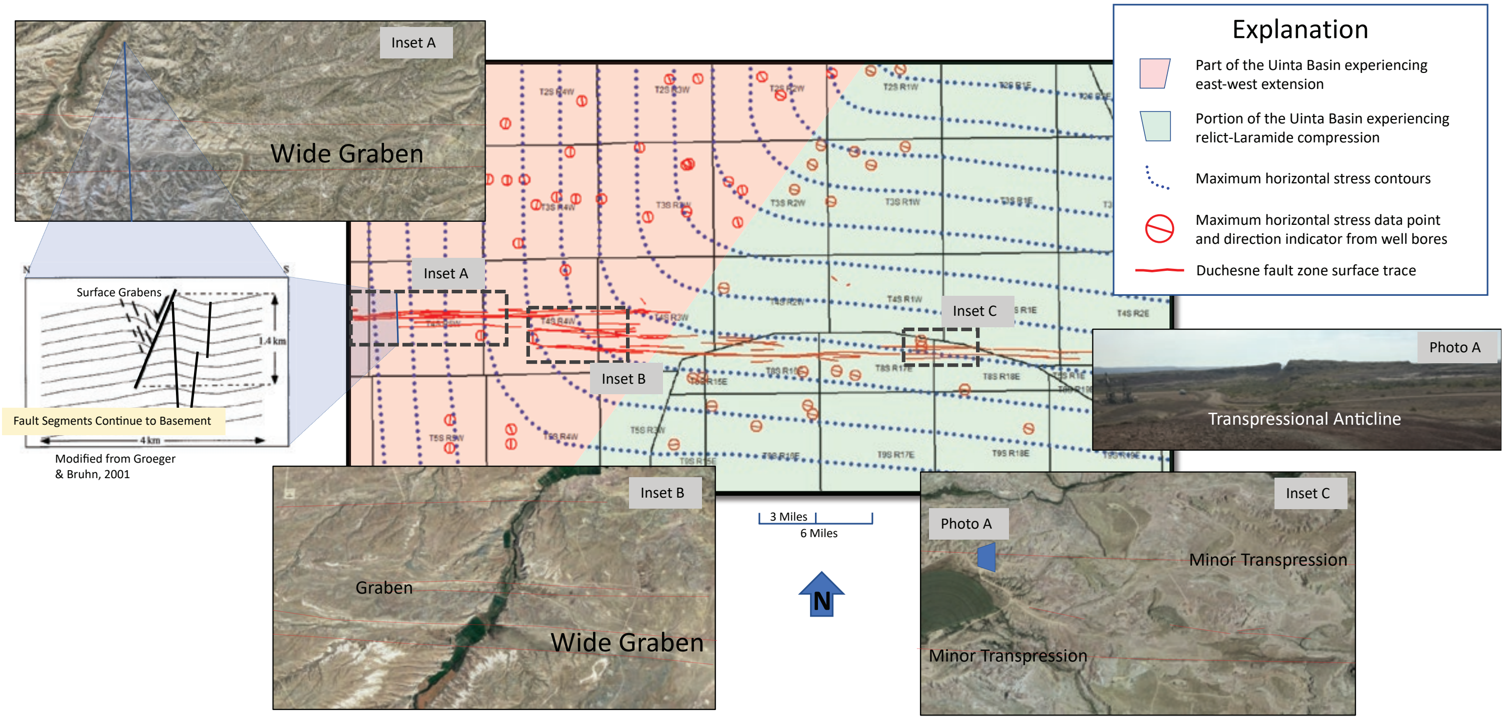

FIGURE 9: Mapped traces of the DFZ overlain on the maximum horizontal stress contours (map centered in the figure). Contours demonstrate the "stress swing" (blue dotted lines changing orientation) in the center of the Uinta Basin. Note that the part of the basin experiencing east-west extension (shown in pink) have north-south-directed maximum stress and have developed wide grabens within the DFZ (insets A and B). Cross section (below inset A) illustrates the general geometry of the DFZ graben. The line of section is shown as a blue line on inset A and the horizontal stress contour map. Farther east, (inset C) extension has not yet modified the DFZ, and relict-Laramide stresses still dominate (shown in green). Here Eocene-aged transpressional features such as anticlines, synclines, and compressional ridges can be found in surface expression (Photo A).

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IMPLICATIONS FOR OIL AND GAS DEVELOPMENT

The development of horizontal drilling allowed operators to target tight limestone reservoirs north of the DFZ within the central overpressured part of the Uinta Basin. Although the current unconventional oil development is north of the DFZ **(figure 1)** in the overpressured area, there is active conventional oil development south of and within the DFZ. The best production from conventional oil development is south of the DFZ within the deltaic reservoirs. Since deltaic sediments north of the DFZ are poorly organized and sand-poor, conventional drilling struggled to find significant reservoir beyond relatively minor turbidite flows. Unfortunately, vertical drilling within the DFZ itself has its own problems that have made oil and gas development economically difficult **(figure 10)**. Vertical-well completions within the fault zone tended to initially produce at impressive rates (figure 10B), but oil production would rapidly fall off as gas production rose. Careful mapping of faults in these oil fields show that reservoirs were tightly compartmentalized. Natural fracturing associated with the fault zone likely created better total reservoir permeability, leading to the impressive initial production. However, as the total reservoir boundaries are limited by the tightly spaced faults in the DFZ, individual reservoirs would rapidly deplete. As these reservoirs are small, even moderate production led to a rapid decline of reservoir pressure, making them reach the bubble point early. At the bubble point, natural gas that is dissolved in the oil comes out of solution, leading to rapidly rising gas production rates and sharply falling oil production. Newfield, the operator that drilled

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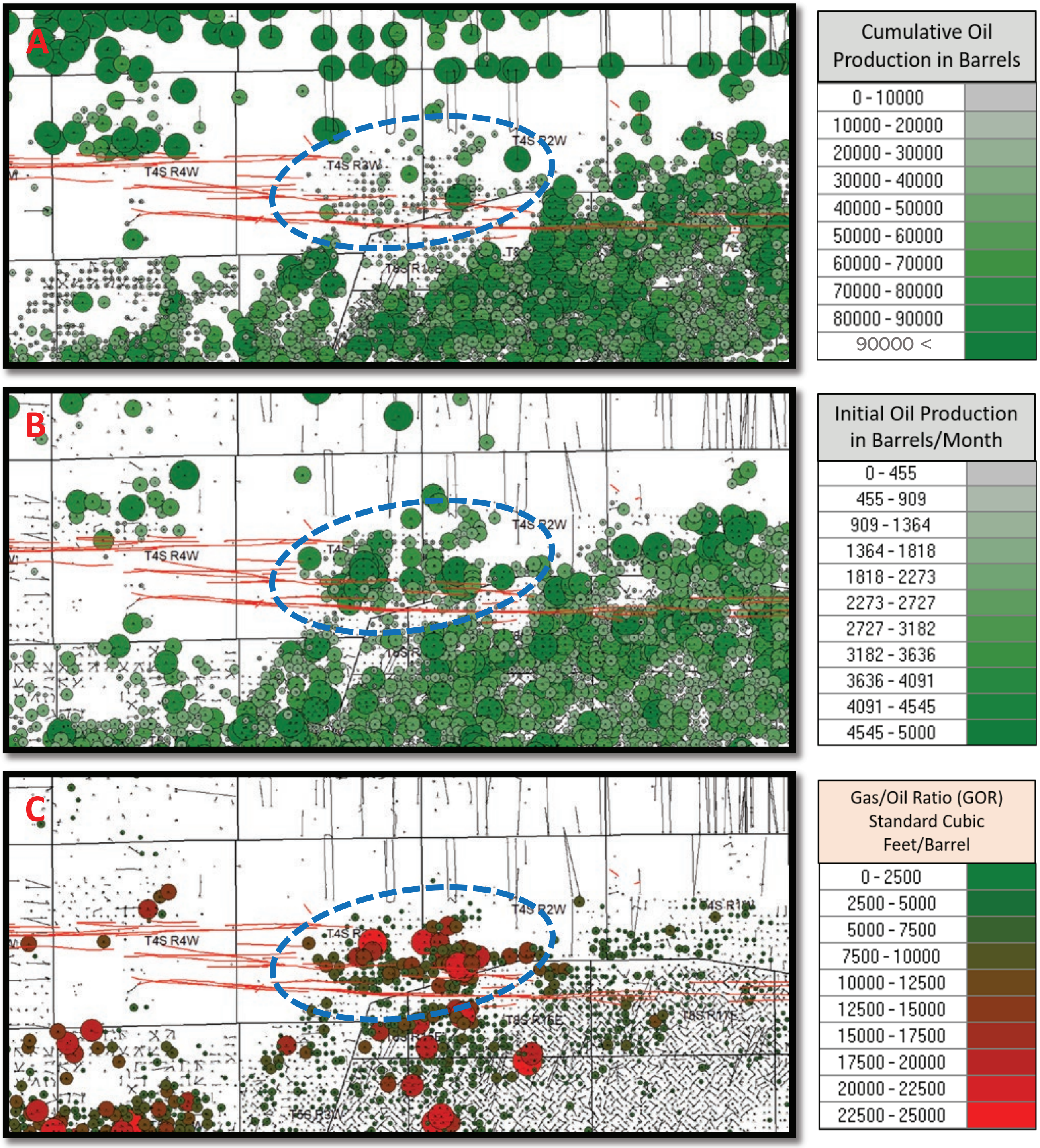

FIGURE 10: Production bubble maps from wells along the DFZ. Production is undifferentiated and represents all commingled perforations within the Green River Formation of the well's historical tabulation of cumulative oil (A), first month's oil (IP) (B), and gas/oil ratio (GOR) (C). The wells in the blue oval indicate that wells in the DFZ while having higher initial oil production and higher GOR, are ultimately lower cumulative oil producers during the total life of the well. These series of maps demonstrate the DFZ's influence on oil and gas production from the Green River Formation. Note the wells within the blue oval have much higher GOR's than normal. Our interpretation of this data is that the DFZ compartmentalized the reservoirs these wells access. Natural fracturing from the DFZ likely enhanced permeability, leading to strong IP's. However, compartmentalization led to these wells reaching bubble point early, which forced two-phase flow, and ultimately to poor production.

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many of the wells within this area, approved the development program based on the early-time, high initial production (IP) rates. Unfortunately, it only became clear after drilling 45 wells that the IPs were misleading, and the entire project became something of an economic disaster for the company.

CONCLUSIONS

After pulling together all the disparate information about the DFZ, we constructed a timeline for the structural history of the fault and summarized potential oil development.

The DFZ began as a weak point in deep basement rocks, possibly related to the accretion and assembly of Precambrian terrains in Utah.

The DFZ is reactivated when large-scale tectonic stresses are placed on northeastern Utah, particularly during uplift of the Ancestral Rocky Mountains, the Sevier and Laramide orogenies, and Neogene Basin and Range extension.

The DFZ was active during deposition of the Green River Formation. Shear stresses related to the Laramide uplift of the Uinta Mountain Block and coincidental subsidence of the Uinta Basin created dextral shearing on the DFZ. The DFZ responded by becoming a hinge point for differential shearing on the DFZ hinge point, which created a larger accommodation space, resulting in thicker lacustrine deposits. Sag or pull-apart basins also formed adjacent to and within the fault zone.

Compressional-transpressional movement on the DFZ ceased at end of the Laramide orogeny.

Neogene Basin and Range extension resulted in dip-slip movement along faults within the DFZ, creating the graben and half-graben geometries, and the noticeable topographic escarpment, especially in the western part of the fault system.

The Uinta Basin horizontal oil play is rapidly developing across the DFZ. The previous vertical well development has shown that while reservoirs have not experienced large vertical offsets from the fault, they have been compartmentalized. Operators would be wise to carefully model the DFZ as they plan wellbore placement and frac jobs, as it will likely exert a strong influence on the completion results.

The famous geologists of a century ago did great work, but they only scratched the surface of all the geology in the Rockies. Exploring the Duchesne Fault Zone ended up being a lot of fun, especially finding evidence for lateral motion, such as the offset paleochannels, that had not been documented before. The deeper we dive into the details of the amazing geology around us, the more firsts that we can find and document ourselves.

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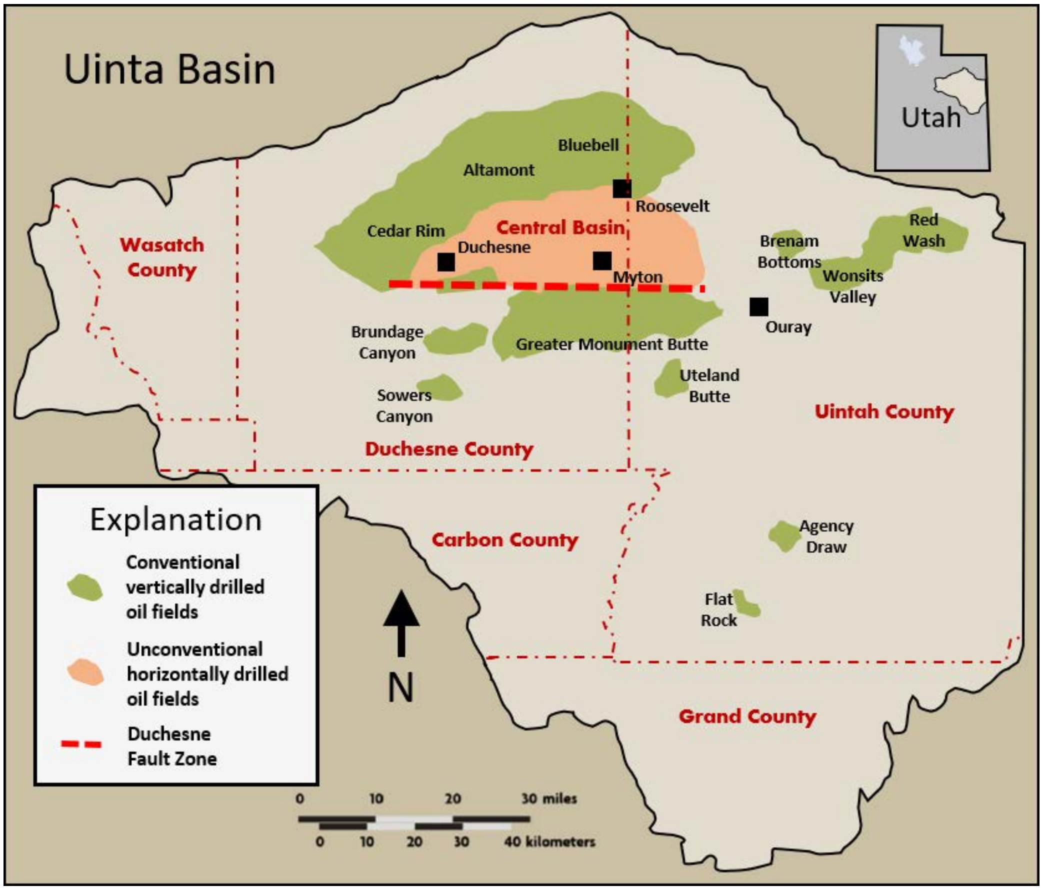
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Bluebell
Altamont
Roosevelt
Cedar Rim
Central Basin
Duchesne
Myton
Wasatch County
Brenam Bottoms
Red Wash
Wonsits Valley
Ouray
Brundage Canyon
Greater Monument Butte
Uteland Butte
Sowers Canyon
Uintah County
Duchesne County
Carbon County
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Explanation
Conventional vertically drilled oil fields
Unconventional horizontally drilled oil fields
Duchesne Fault Zone
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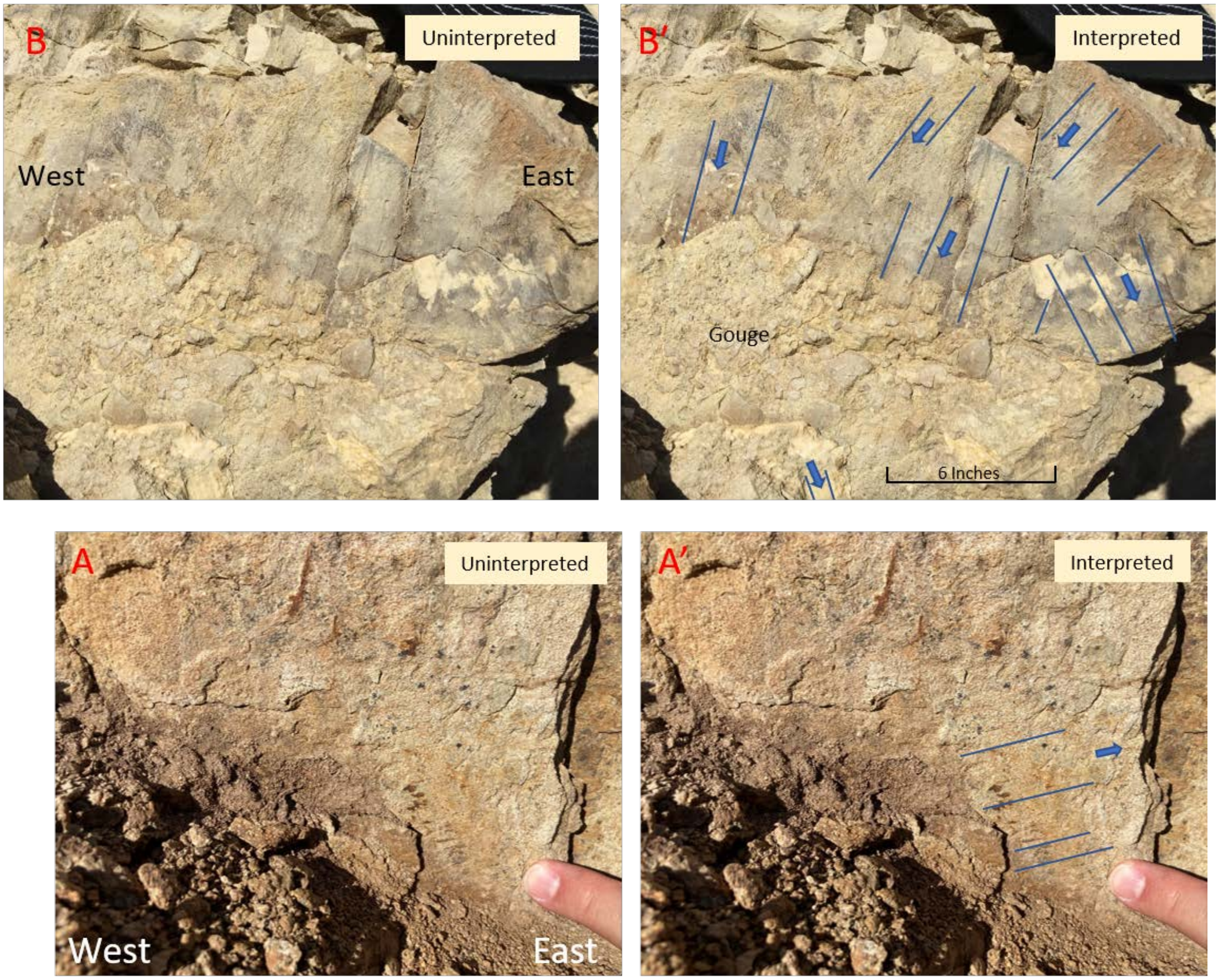
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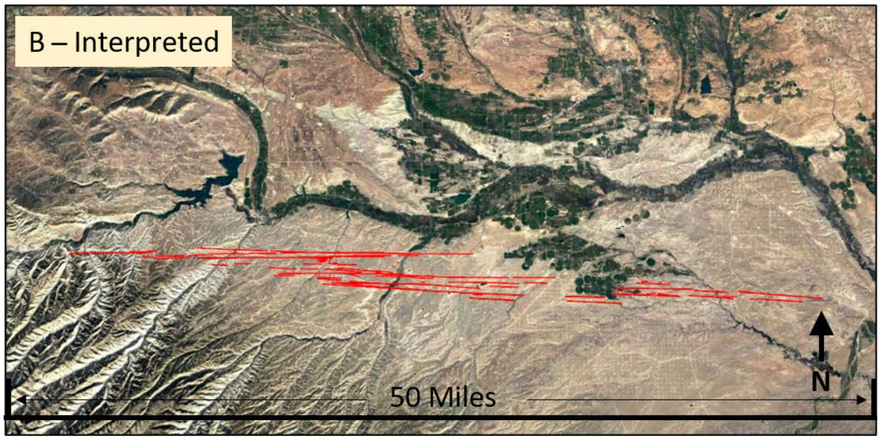

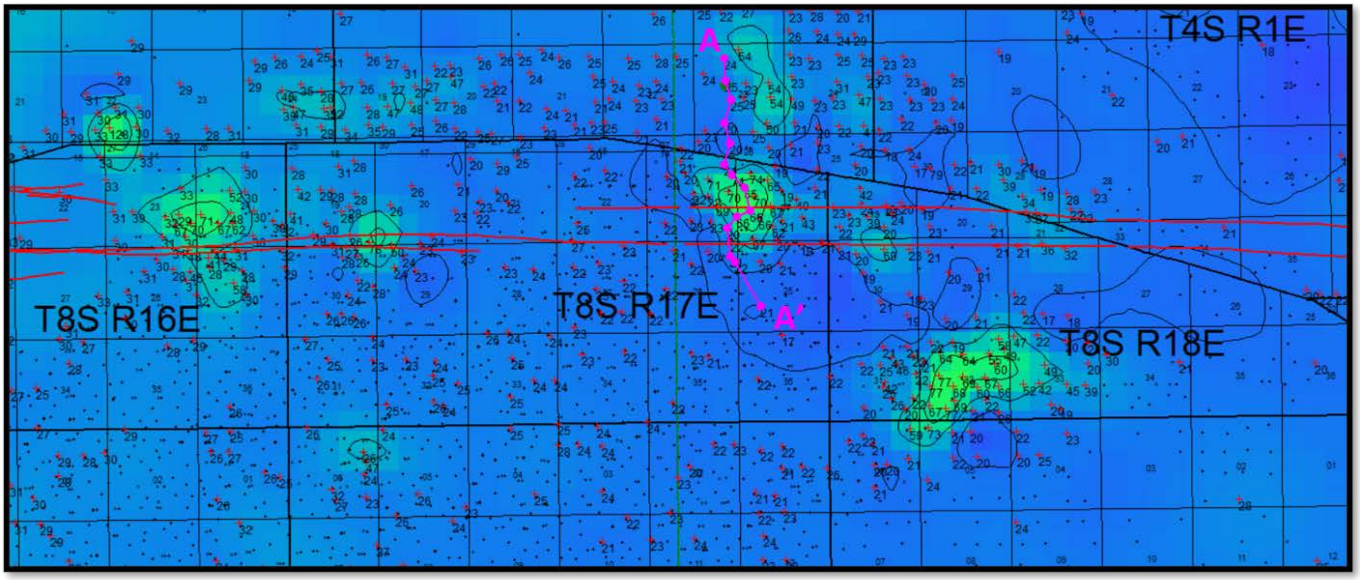

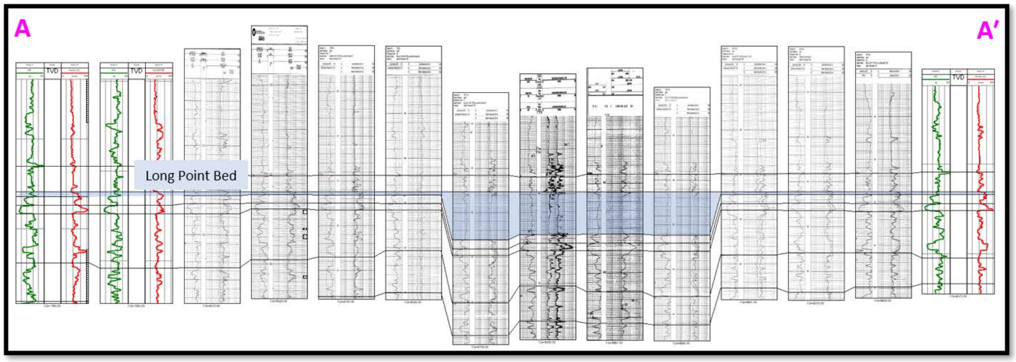

Explanation

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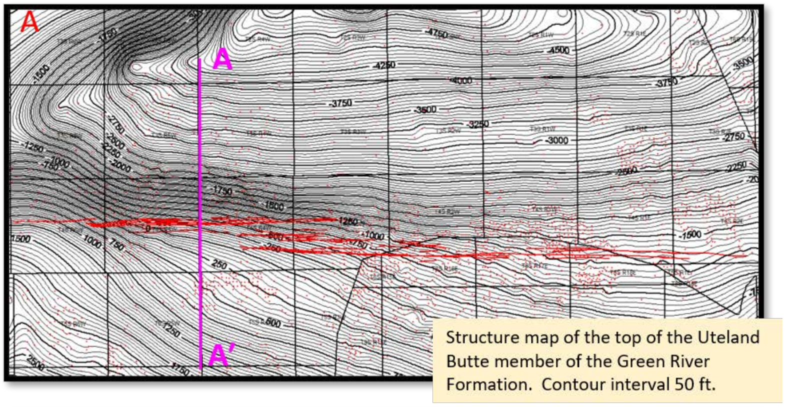
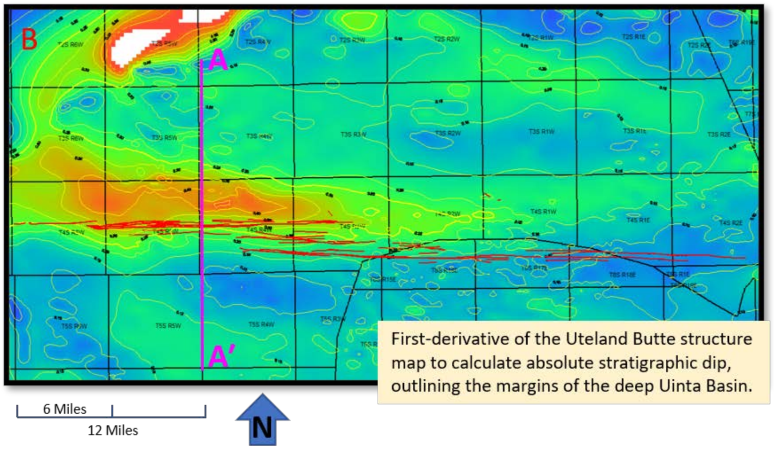
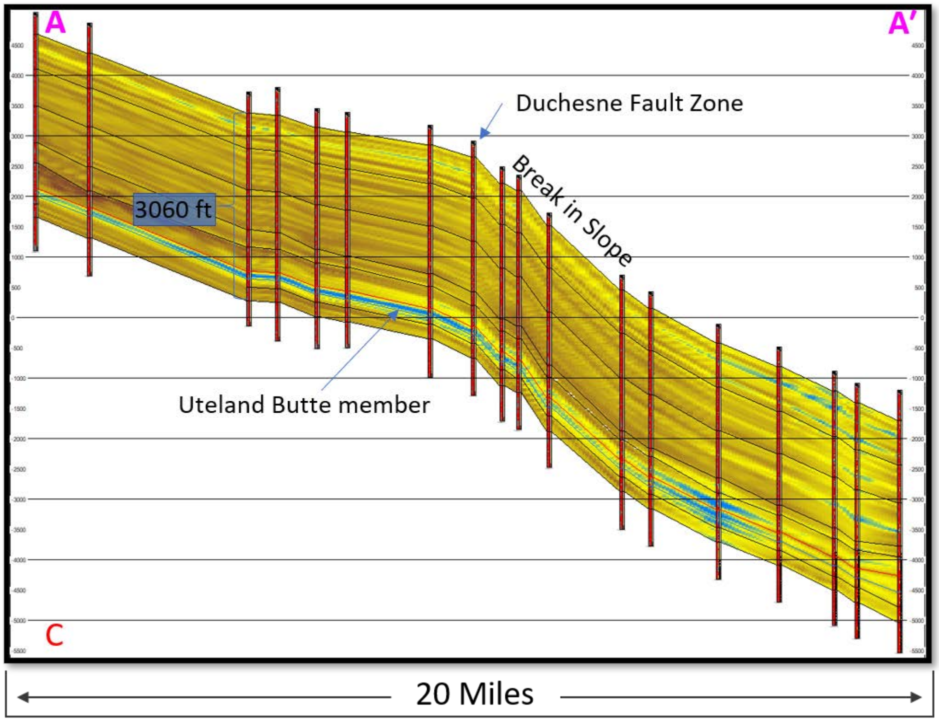
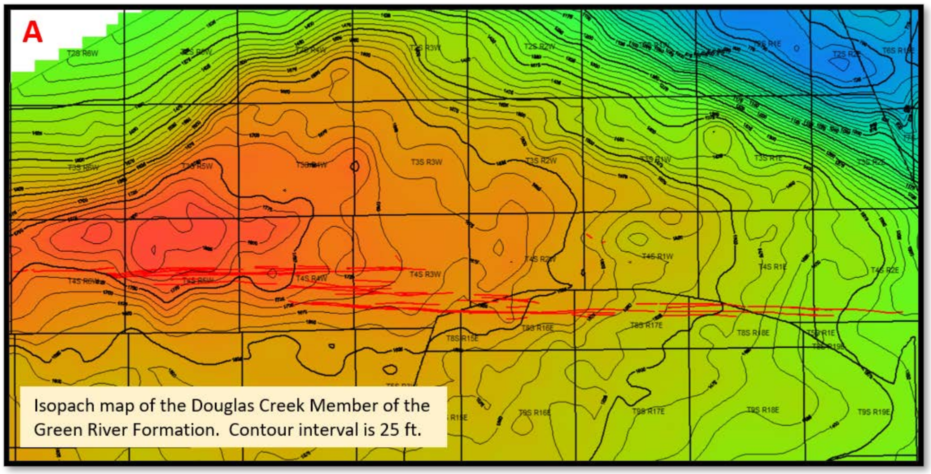


Structure map of the top of the Uteland Butte member of the Green River Formation. Contour interval 50 ft.

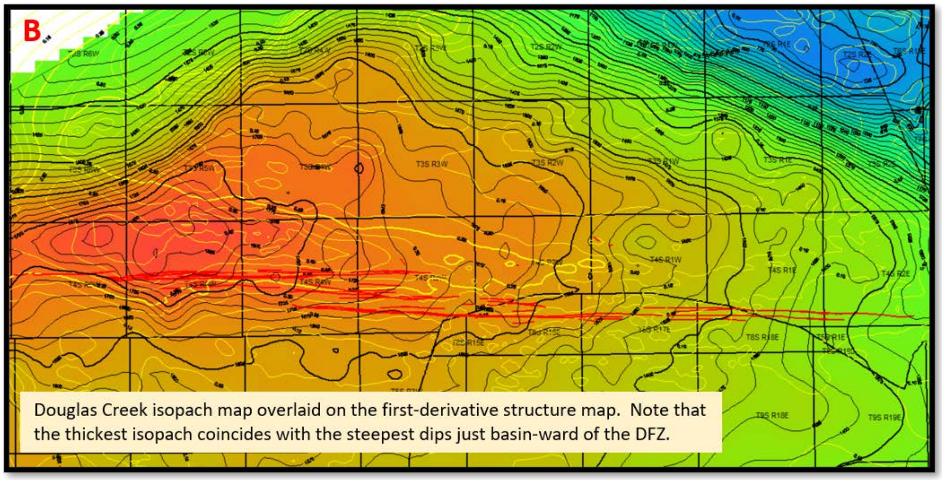


First-derivative of the Uteland Butte structure map to calculate absolute stratigraphic dip, outlining the margins of the deep Uinta Basin.

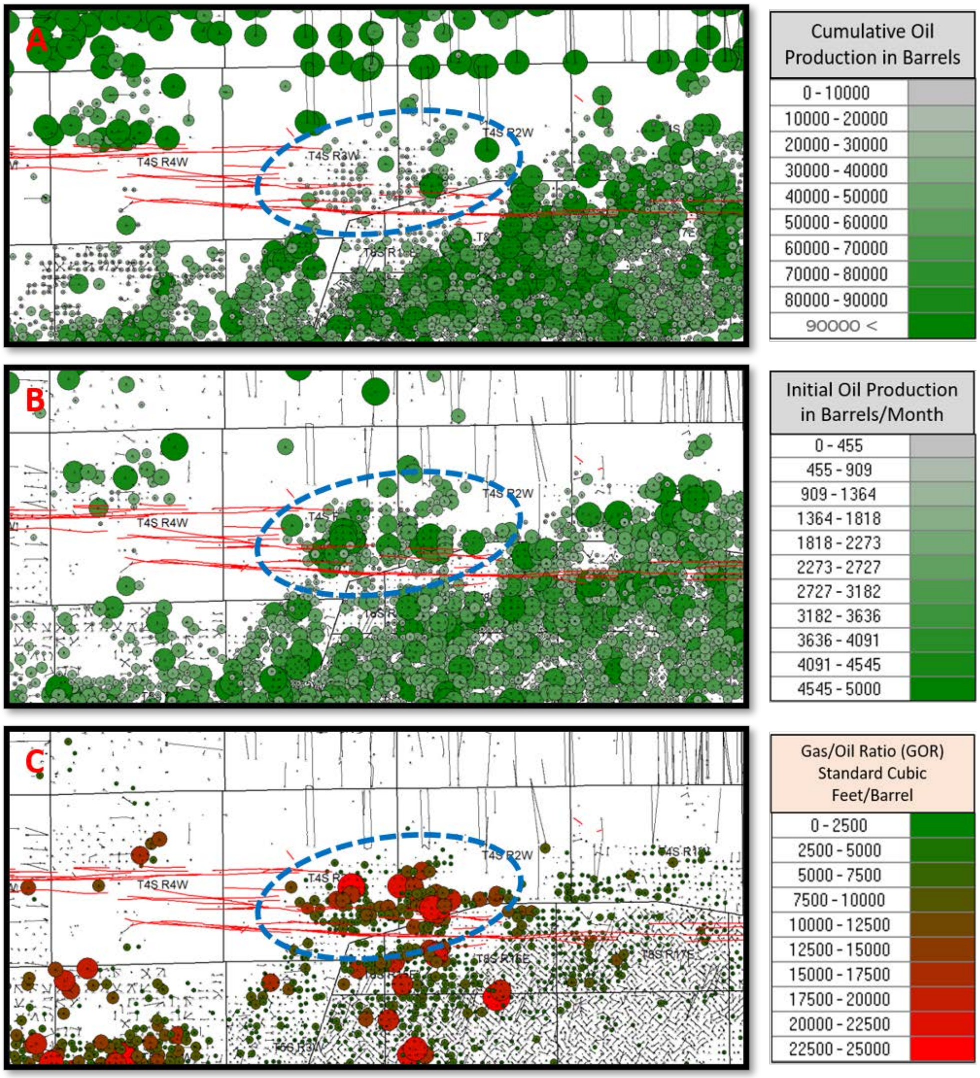


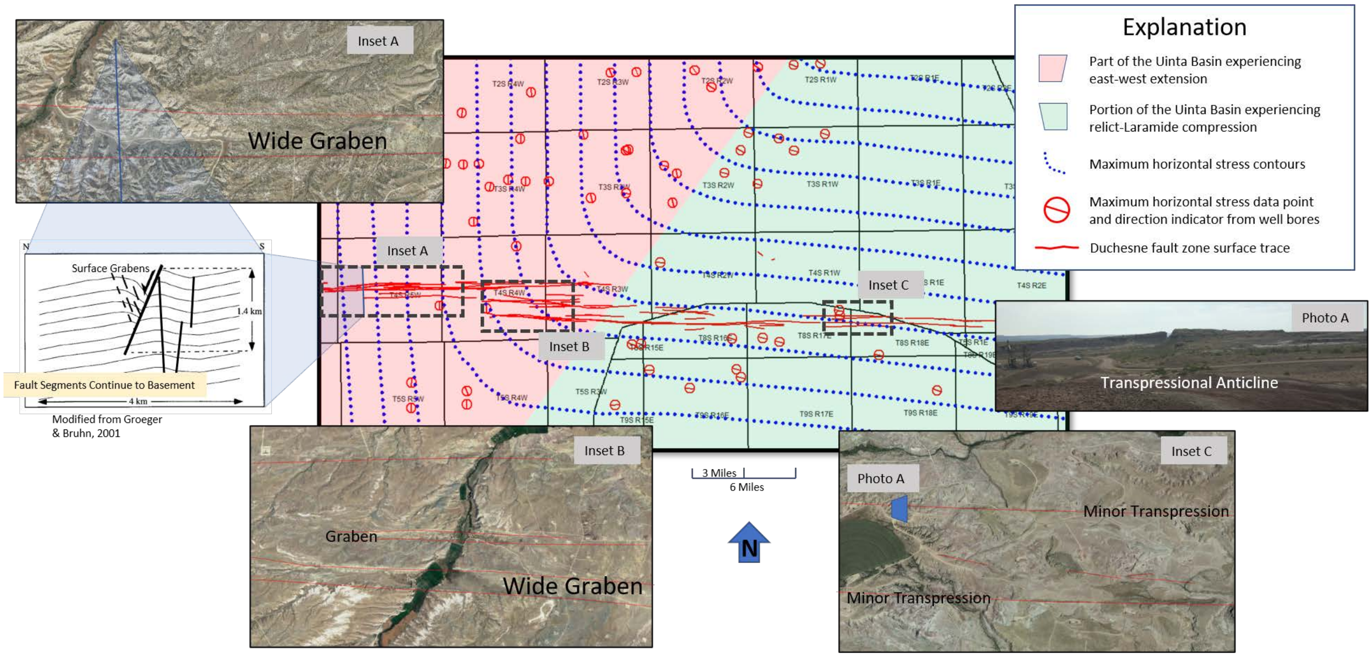


Isopach map of the Douglas Creek Member of the Green River Formation. Contour interval is 25 ft.



Douglas Creek isopach map overlaid on the first-derivative structure map. Note that the thickest isopach coincides with the steepest dips just basin-ward of the DFZ.


A
T4S R4W
T4S R3W
T4S R2W
T8S R1
Cumulative Oil Production in Barrels
0 - 10000
10000 - 20000
20000 - 30000
30000 - 40000
40000 - 50000
50000 - 60000
60000 - 70000
70000 - 80000
80000 - 90000
90000 <
B
T4S R4W
T4S
T4S R2W
Initial Oil Production in Barrels/Month
0 - 455
455 - 909
909 - 1364
1364 - 1818
1818 - 2273
2273 - 2727
2727 - 3182
3182 - 3636
3636 - 4091
4091 - 4545
4545 - 5000
C
T4S R4W
T4S R2W
T4S R1W
T8S R15E
T8S R17E
T9S R15E
Gas/Oil Ratio (GOR) Standard Cubic Feet/Barrel
0 - 2500
2500 - 5000
5000 - 7500
7500 - 10000
10000 - 12500
12500 - 15000
15000 - 17500
17500 - 20000
20000 - 22500
22500 - 25000


Inset A
Wide Graben
N
S
Surface Grabens
1.4 km
Fault Segments Continue to Basement
4 km
Modified from Groeger & Bruhn, 2001
Inset A
Inset B
Inset C
T2S R4W
T2S R3W
T2S R2W
T2S R1W
T2S R1E
T2S R2E
T3S R4W
T3S R3W
T3S R2W
T3S R1W
T3S R1E
T4S R5W
T4S R4W
T4S R3W
T4S R2W
T4S R1W
T4S R1E
T4S R2E
T8S R15E
T8S R16E
T8S R17E
T8S R18E
T8S R19E
T5S R5W
T5S R4W
T5S R3W
T9S R15E
T9S R16E
T9S R17E
T9S R18E
T9S R19E
Explanation
Part of the Uinta Basin experiencing east-west extension
Portion of the Uinta Basin experiencing relict-Laramide compression
Maximum horizontal stress contours
Maximum horizontal stress data point and direction indicator from well bores
Duchesne fault zone surface trace
Photo A
Transpressional Anticline
Inset B
Graben
Wide Graben
3 Miles
6 Miles
N
Inset C
Photo A
Minor Transpression
Minor Transpression