The Duchesne Fault Zone's Impact on Horizontal Development Within the Burgeoning Green River Oil Play, Uinta Basin, Northeastern Utah, USA

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Abstract

With the continuing advancement in horizontal drilling for oil and gas, complex fault zones have been identified as an important geologic risk in unconventional oil developments. This study analyzed the Duchesne fault zone (DFZ) in the Uinta Basin, Utah, to evaluate its impact on the burgeoning horizontal oil play in the Eocene Green River Formation. Whereas many horizontal wells have been drilled both north and south of the DFZ, operators are hesitant to target reserves within the fault zone for fear of its effects on well completions (out of zone fracture propagation), changes in stratigraphic dips, cut-out target zones, and poor production due to anonymously low bubble points related to reservoir compartmentalization. Our work on the DFZ demonstrates dextral oblique, syndepositional motion on faults during Green River deposition. Moreover, the DFZ acted as a hinge between the deeper central Uinta Basin and the more shallow-dipping southern flank. First derivative calculations on data-rich structure maps reveal these changes in stratigraphic dip and their relationship to the DFZ. Multiple traces within the fault zone accommodated oblique movement, with relays transferring strain between faults. Differences in motion between discreate faults created small pull-apart basins, today identifiable as anomalous lacustrine strata up to 60 ft thick, varying in area from as small as a quarter mile in diameter to well over two miles. These small basins are easily recognizable as growth strata bound by widespread marker beds within the Green River Formation. Discrete stratigraphic zones tend to contain many of these small pull-apart basins, indicating motion on the fault was not continuous but instead highly episodic. These basins lie between and adjacent to traces within the DFZ and are the best indicator for areas where vertical offsets of subjacent strata can be expected. Pop-up structures are also found but were poorly preserved and are difficult to identify in well data. Vertical offsets appear to be uncommon in most drilling target zones outside of these pull-apart basins; however, proximity to the DFZ ties nicely with a drop in oil productivity in vertical wells, which we attribute to reservoir compartmentalization of fault blocks. Field data shows intense vertical fracturing in bands within the DFZ even where no vertical movement has occurred. Our modeling suggests that hydraulic frac jobs likely were not able to access reservoir rock across these fracture bands due to rapid fluid leak-off into the vertical fractures and an inability to reach breakdown pressures across the fracture bands. Operators planning horizontal wells within the DFZ would benefit from incorporating detailed mapping of the zone into their development plans. Well orientation, stage planning, frac volumes, fluid rheology, and wellbore directional planning will all need to be tailored to the individual drilling units within the DFZ.

Introduction

Located just south of the center of the Uinta Basin of northeastern Utah, the surface exposure of the Duchesne Fault Zone (DFZ) is a 40-mile-long system of en-echelon faults and associated grabens (Groeger and Bruhn, 2001) that cut through the middle of the Green River oil play (Figure 1). Approximately 2100 oil wells have been drilled within a mile of one of the surface strands of the fault zone. During the past decade nearly 300 horizontal wells have been drilled within the Uinta Basin, with the most success being found in the deep center of the basin north of the DFZ (Figure 2). Perhaps surprisingly, little has been published concerning the DFZ's structural history, kinematics, or effects on oil and gas production (Groeger and Bruhn, 2001). The fault zone has a long structural history that drove large syndepositional sedimentary trends of the Eocene Green River Formation within the ancient Lake Uinta, as well as recorded the changes in stress regimes in the Uinta Basin. Understanding these factors is crucial to the efficient and economic development of the Green River oil reserves that lie within the fault zone.

Green River Oil Play

The horizontal Green River oil play has only really come into its own during the last several years. In-basin sand made large frac jobs much more economic and the market for the basin's waxy crude has greatly expanded with the development of rail-transfer facilities. To date the most successful target of the Green River system has been the Uteland Butte Member, followed by the evenly matched Castle Peak Member and the Wasatch Formation (Figure 3). Developing targets include the Douglas Creek Member and the Lower Black Shale. While many horizontal wells have been drilled south of the DFZ, lower pore pressure, higher fluid viscosity and lower reservoir temperatures have generally resulted in these wells being much less successful. As of mid-2021, only one horizontal well has been drilled into the DFZ, with only marginal results, possibly due to its small frac size.

Characteristics of the Duchesne Fault Zone

The DFZ is a major structural feature within the Uinta Basin that has moved during multiple tectonic events (Brinkerhoff and Sprinkel, 2021) and recently published evidence suggests that the DFZ has moved during the Quaternary (Howe and Klinger, 2021). The grabens and related faults are clearly visible on aerial photographs and satellite imagery. The DFZ is also unmistakable on the surface, due to the grabens being bounded by topographical escarpments of up to 20 feet in some areas. Springs and oil seeps are found along traces of the DFZ. Sandstone beds adjacent to the DFZ are commonly saturated with dead oil, and the easternmost traces of the DFZ are pervasively intruded with gilsonite, strong evidence of vertical fluid flow along the fault zone. Early oil and gas and gas prospectors could not help but notice all the hydrocarbon indicators along the fault zone, and a few small discoveries were made in the fractured rocks within the DFZ in the 1950's and 60's (Cashion, 1967).

Subsurface structural mapping of Green River sediments across the Uinta Basin shows a pronounced change in dip at the DFZ (Figure 3) (Sprinkel, 2009, 2018). The Uinta Basin formed as a Laramide foreland flexure related to the uplift of the Uinta Mountains to the north. 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 steeper-dipping beds to the north. Our interpretation is that the DFZ acted as a hinge during basin development, separating the deep basin from its shallower southern limb (Figure 4). This change in structural dip is perhaps best illustrated by taking the first derivative in the dip direction on the structure map. The resulting map will have its highest values in where structural dip is the highest (Figure 5), which neatly ties with deformation on the DFZ. In Eocene time, the increase in structural dip at the DFZ was expressed as an increase in depositional accommodation space. 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. Many stratigraphic units within the Green River Formation show significant growth at the fault zone. Figure 6A shows how the Douglas Creek Member achieves its maximum thickness just north of the fault zone. The contours of the first derivative structure map from Figure 5 neatly parallel the isopach contours in the thick. Similar features can be found on individual stratigraphic sequences, such as an isopach map of sandstones with a single sequence of the Castle Peak Member. Delta fronts are consistently located along the DFZ, where the increase of accommodation space forced fluvial systems to drop their sedimentary loads as prograding mouth-bars into the lake (Figure 6B).

Seismic and well data show much of this deformation was accommodated by folding, but dextral slip on the DFZ, coupled with the vertical stress associated with the subsiding basin created a complex series of sub-vertical faults with variable amounts of oblique and vertical throw. This deformation is associated with intense, tightly spaced fractures. Natural fractures in the DFZ can be divided into three groups, the joint sets that trend NW-SE, which are related to far-field Laramide stresses and are found across the Uinta Basin, an associated cross-set, and E-W trending sets that are tightly tied to deformation on the DFZ (Figure 7). In carbonates and sandstones these DFZ fractures are tightly spaced and accommodate vertical fluid migration, as shown by the springs and oil seeps found associated with them. Pore-pressure data from the Uteland Butte Member shows that the DFZ is the southern edge of the Green River overpressure cell in the deep Uinta Basin (Figure 4). Deeper, hotter Green River sediments experience more thermal stress north of the fault zone and generated large volumes of hydrocarbons. Hydrocarbons that migrated up-dip to the south were partially captured and lost into the fractures and faults of the DFZ, resulting in normally pressured reservoirs south of the DFZ.

The Uinta Stress Field

Studying the DFZ is just one piece of the tectonic puzzle in understanding the regional structural history of the Uinta Basin. Modern day in-situ stress fields transfer from compression-transpression to extension 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, whereas the east 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 as a whole. The western part of the basin is currently undergoing Neogene extension related Basin and Range deformation, whereas the eastern part of the basin still exhibits a compressional orientation (Sprinkel, 2018a). Modern stress data, mostly from image logs derived borehole-breakout data, show this change in stress (Figure 9). Maximum horizontal stress on the east 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. This stress-swing has important implications to the development of Green River oil reserves using horizontal wells since these wells need to be drilled perpendicular to the maximum horizontal stress to access the reservoir most efficiently. Note in Figure 3 that horizontal wells drilled on the east side of the basin are oriented north-south, while on the west side wells are laid out east-west. Much of the DFZ lies west of the stress-swing, where horizontal wells would ideally be oriented east-west from a purely in-situ stress perspective. However, if wells within the DFZ are laid out east-west, they will parallel the intensive fracturing related to the fault zone. Our modeling shows that an induced hydraulic fracture is much more likely to propagate along the east-west trending DFZ fracture sets, as these planes of weakness dominate over the in-situ stress field. A wellbore drilled in an east-west orientation would likely only stimulate rocks near the wellbore and break out of zone badly in a vertical direction. Deformation within the DFZ is intense enough that horizontal wells should be drilled north-south across the fault zone regardless of the stress-swing.

Reservoir Compartmentalization within the DFZ

Although most of the current unconventional oil development is north of the DFZ (Figure 2) in the overpressured portion of the Uinta Basin, there is an active conventional (vertical) 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 rapidly grade into poorly organized and sand poor reservoir units, conventional drilling struggled to find significant reservoir beyond relatively minor turbidite flows in the deep basin. Unfortunately, vertical drilling within the DFZ itself has its own problems that has 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 oil production falling sharply. Newfield, the operator that drilled 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 IP's were misleading, and the entire project became something of an economic disaster for the company.

Development Opportunities within the DFZ

Understanding that Green River reservoirs are compartmentalized by the DFZ and that frac jobs are likely to propagate parallel to the fault zone rather than across it allows operators to engineer development programs to allow for and take advantage of those conditions. Our study suggests that the DFZ has demonstrated that the reservoirs contain relatively high total system permeabilities, as demonstrated by the high IP's the vertical wells experienced. The problem is connecting the separated reservoirs, which could be done with a horizontal wellbore-oriented north-south, crossing the various fault blocks and deformation bands. Frac jobs will propagate in an east-west direction, away from the wellbore, connecting the targeted reservoirs to the well. Stage-lengths would ideally be small to avoid having any single, high perm fault or fracture set absorb too much of the induced frac energy. Reservoir pressure will be lower than the basin center, but this will be compensated by the higher system permeabilities provided by the highly fractured rock within the fault zone.

Potential Development Hazards

Drilling horizontal wells across the DFZ is likely to encounter several structural and stratigraphic complexities that could create operational problems. Obvious hazards include drilling out of zone due to crossing faults with significant throw. As much of the lower Green River in this area has a high volume of mechanically weak mudstone and claystone beds, finding the BHA significantly out of zone could rapidly lead to wellbore stability issues. In a related fashion, extensive damage zones near faults could have shattered rocks which may also result in wellbore collapse. These same faults and fracture zones may also be permeable enough to swallow significant volumes of drilling mud, creating well-control issues. Well-control issues may also be found when drilling across fault blocks that likely have different pore-pressures, leading to rapid mud volume losses or gains, depending on the differences in pressure between blocks. Similar issues may happen when attempting to cement in the casing if too much cement is swallowed by the faults and fractures.

Completing a well within the DFZ may also encounter difficulties. If the fault and related fracture zones are not as permeable as our modeling suggests, frac jobs may propagate north-south, parallel to both the in-situ stresses and the wellbore, leading to an ineffective frac job and likely poor well performance. Conversely, the faults and fractures may be permeable enough that the frac job cannot reach sufficient stress necessary to fracture new rock, so only the existing fracture network is available for production. It is also very likely that the existing faults and fracture bands within the DFZ contain significant volumes of water. We consider it likely that water cuts from the DFZ will be higher than typical lower Green River wells, perhaps significantly so.

Stratigraphic hazards include rapid stratigraphic growth in “sag basins.” The relative fault 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 6). Careful correlations 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 1 to 2 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. The sag basins are drilling hazards, particularly in Uteland Butte wells as wellbores will be out of zone after crossing a sag-related fault.

Conclusions

The DFZ was active during deposition of the Green River Formation. Shear stresses related to the Laramide uplift of the Uinta Mountain block coincidental subsidence of the Uinta Basin created dextral shearing on the DFZ. Moreover, the DFZ responded by becoming a hinge point for differential subsidence within the basin. In general, there is an increase rate of subsidence north of 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. Neogene Basin and Range extension resulted in dip-slip movement along faults within the DFZ, created the graben and half-graben geometries, and the noticeable topographic escarpment, especially in the western part of the fault system. This same extension from the west created a stress-swing at about the center of the DFZ, with the west being in extension while the east half is still in relict Laramide compression. The Uinta Basin horizontal oil play is rapidly developing toward 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.

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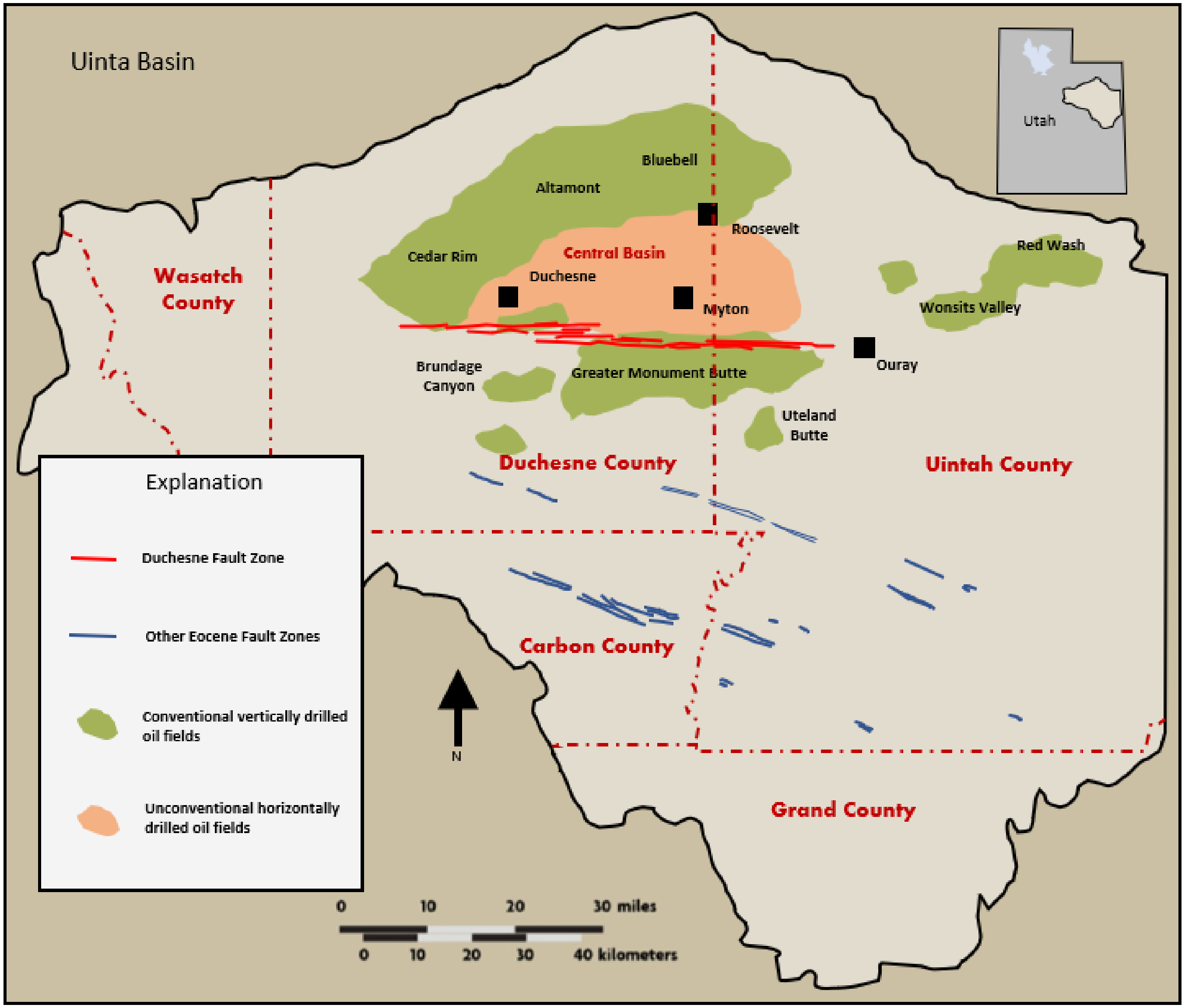

Figure 1. The Uinta Basin, with surface traces of the Duchesne Fault Zone shown in red, cutting through the center of the basin. Note that up to now, most horizontal wells have been drilled north of the fault zone.

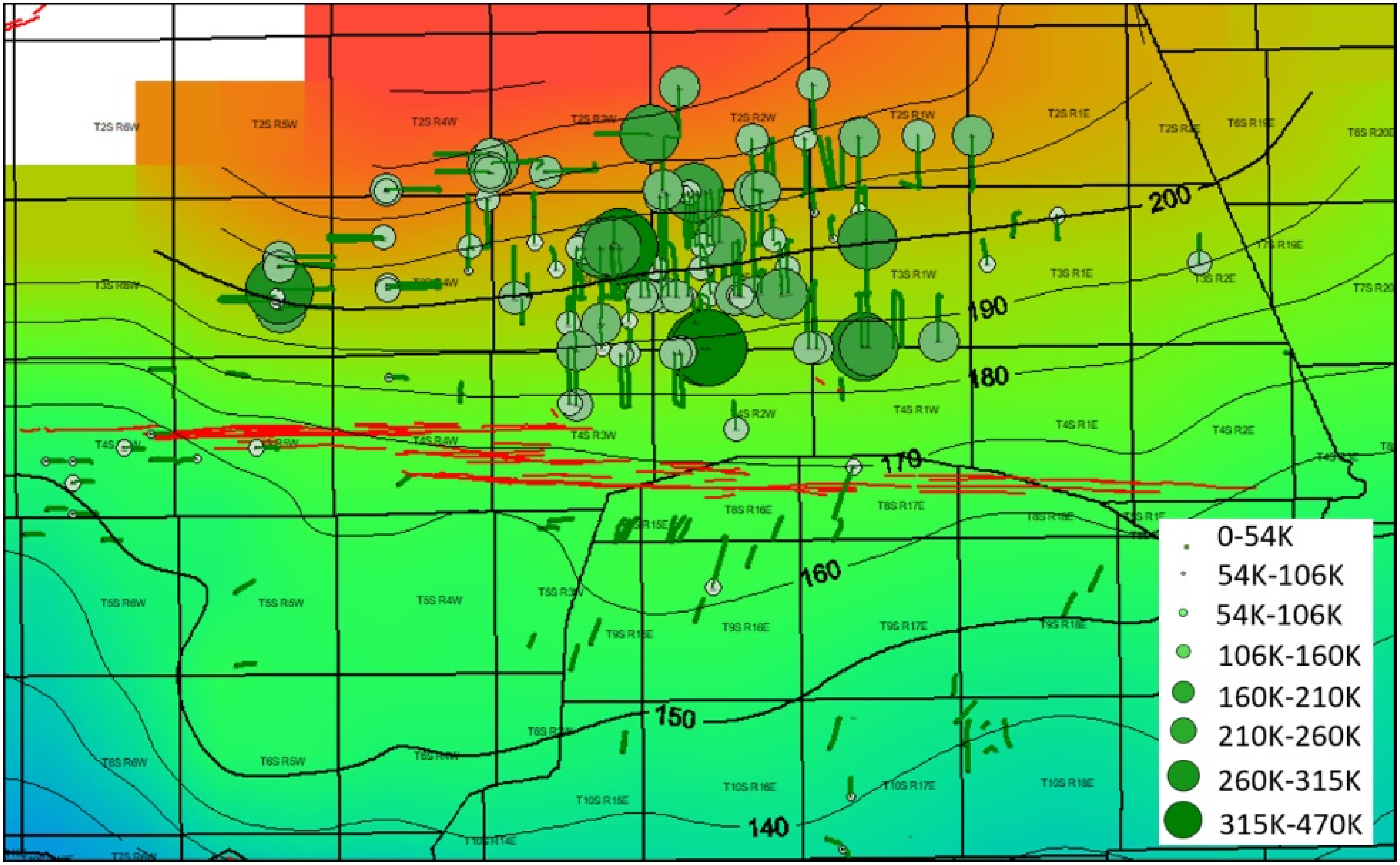

Figure 2 Cumulative production bubble map for Uteland Butte horizontals overlaid on a reservoir temperature map of the Uteland Butte. Note the relatively poor production horizontal wells have south of the DFZ as compared to wells north of the DFZ.

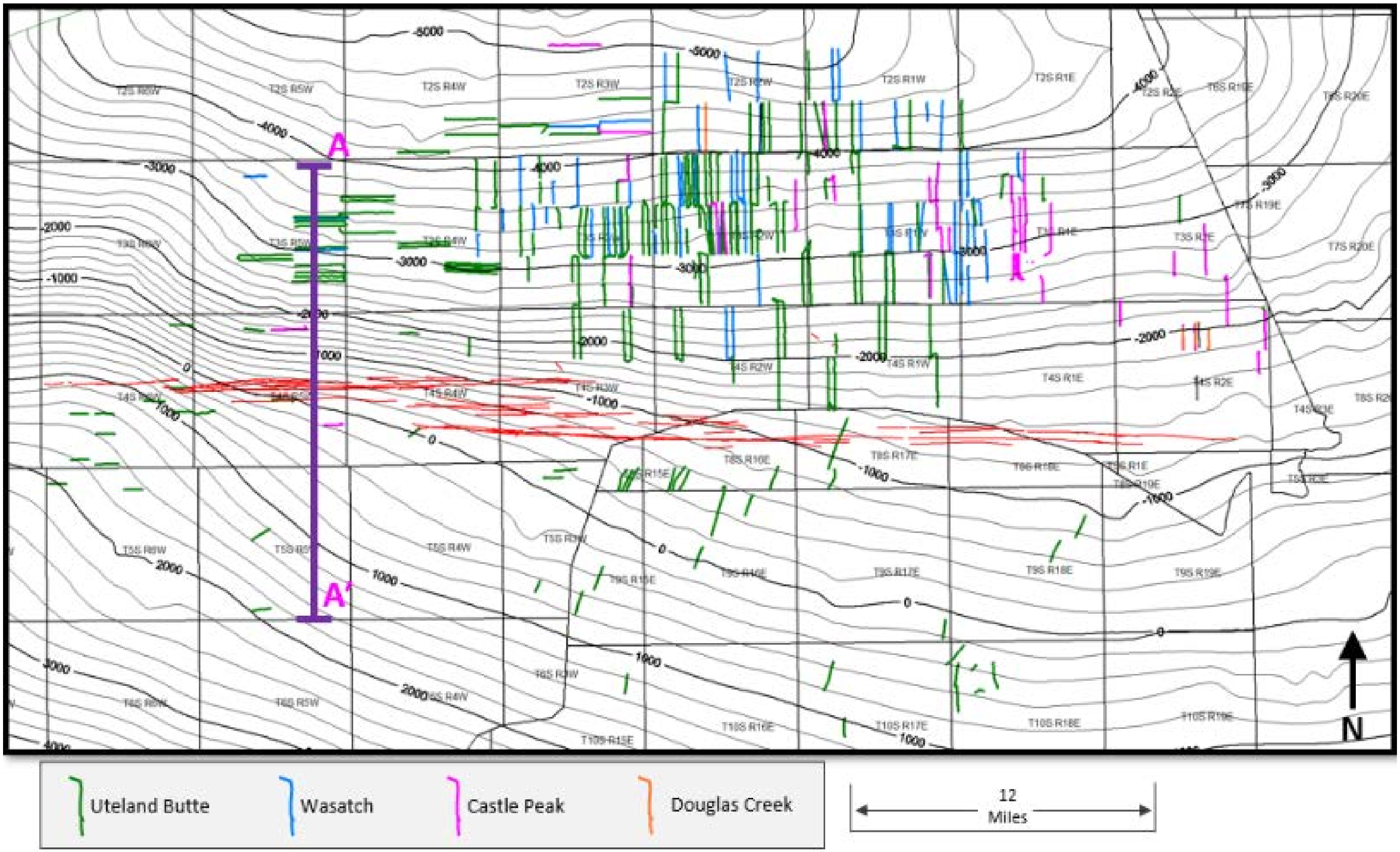

Figure 3. Sub-sea-true-vertical-depth (SSTVD) structure map on the Uteland Butte Member of the Green River Formation. Horizontal wells are differentiated by target. Note that drilling has been much more successful north of the DFZ than to the south.

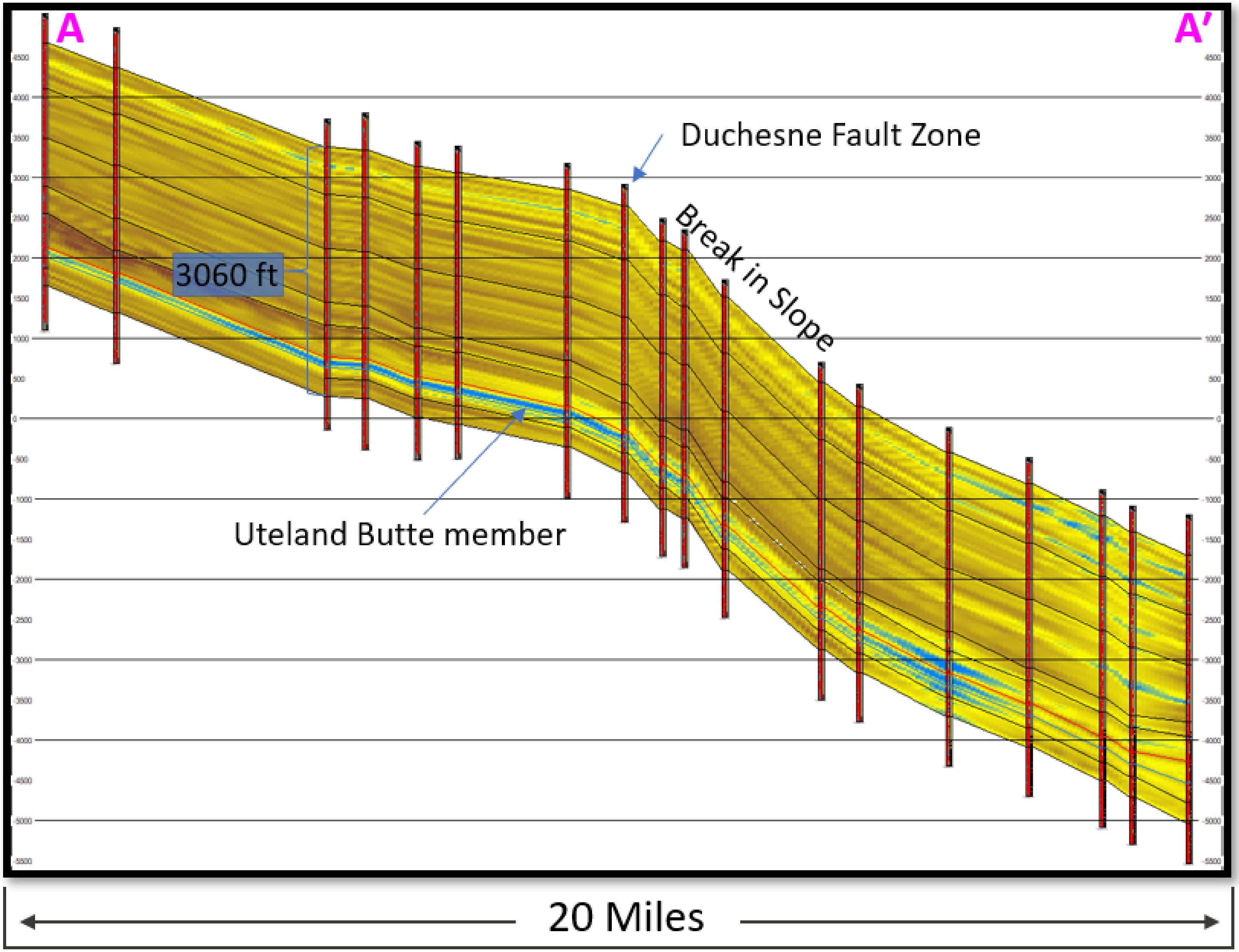

Figure 4. Cross-section of the lower Green River Formation across the DFZ with substantial vertical exaggeration. Note the break in slope at the DFZ, separating the deep Uinta Basin from the shallower southern flank. The line of cross-section is shown on Figure 3.

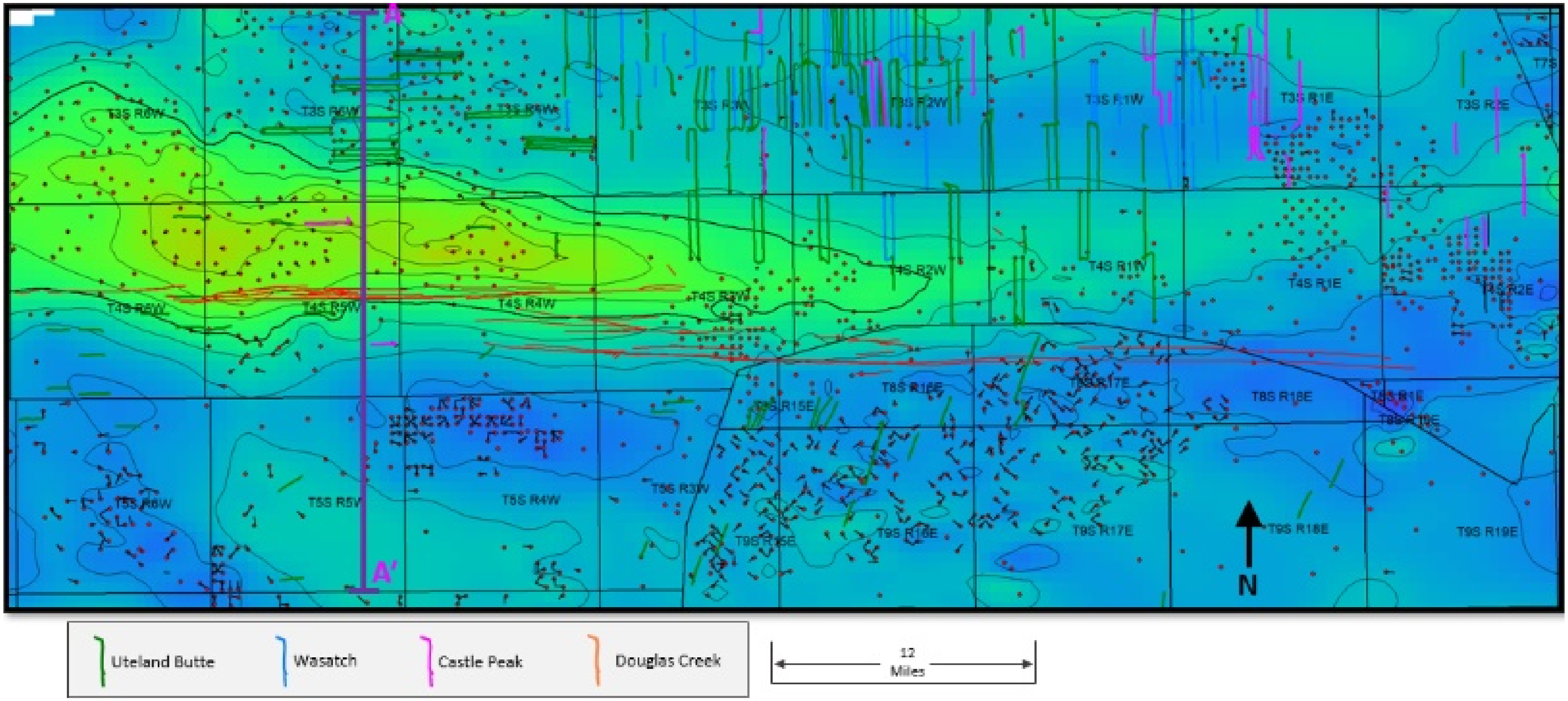

Figure 5. First-derivative map of the SSTVD Uteland Butte structure map (Figure 2). Note the much higher values on the northern margin of the DFZ, demonstrating the rapid change in dip there. The higher dips gradually die out to the east as deformation on the fault zone decreases.

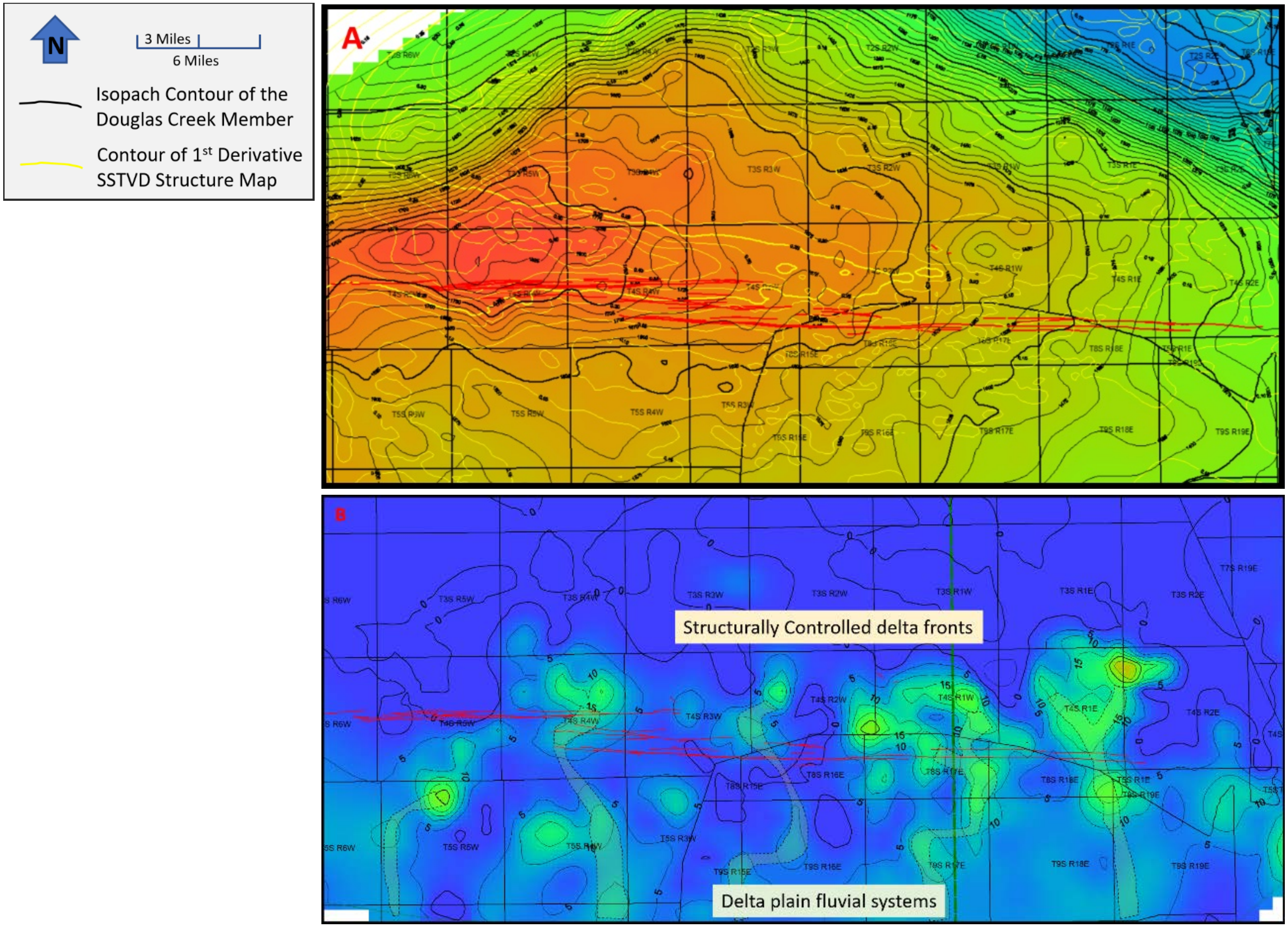

Figure 6. Structurally influenced sedimentation: (A) Douglas Creek Member of the Green River Formation (and equivalents) isopach map overlain on first-derivative structure-contour map. The increased accommodation space created as the basin subsided more rapidly to the north of the DFZ allowed greater volumes of lacustrine sediments to accumulate near the fault zone. Note that the unit thickens just to the north and along the fault zone. Overlaying the contours from the first derivative of the Uteland Butte structure map (Figure 5) shows the correlation of steepest dips related to the DFZ and the greatest accumulation of sediments, strongly suggesting that movement was syndepositional. Map B shows how the development of delta fronts within a discreet parasequence in the Castle Peak Member were controlled by the increase in accommodation space at the DFZ.

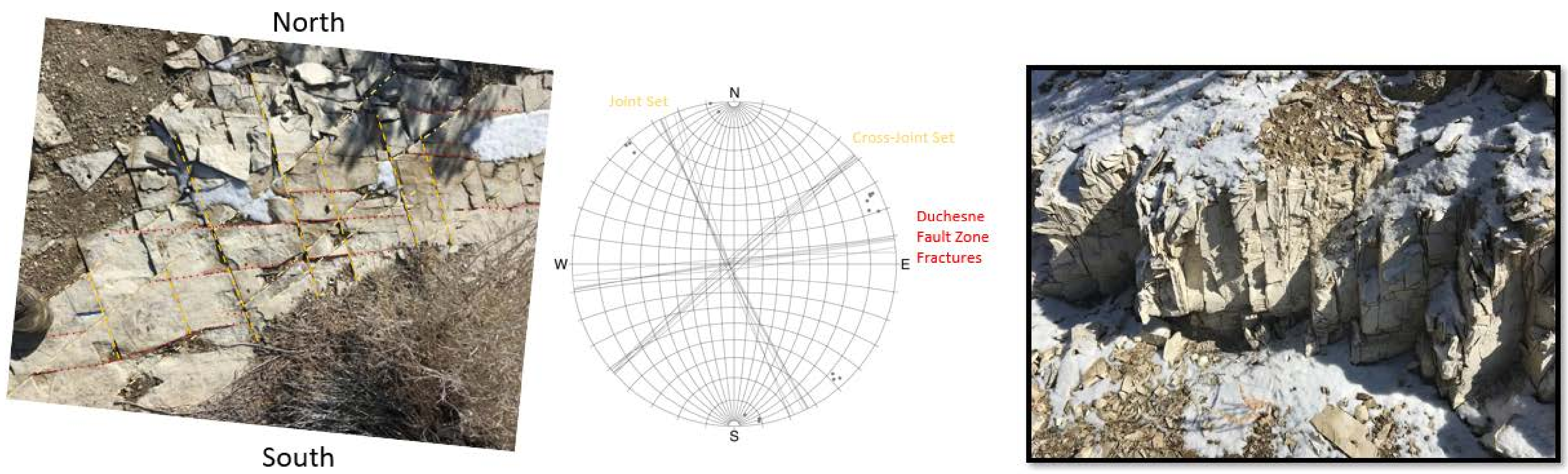

Figure 7. Outcrop of limestones in the upper Green River Formation within the DFZ. Fractures are highlighted in both the outcrop photo and their orientations noted in the half-hemisphere plot. The east-west fracture density related to deformation in the DFZ is high through out the fault zone and is particularly intense adjacent to faults.

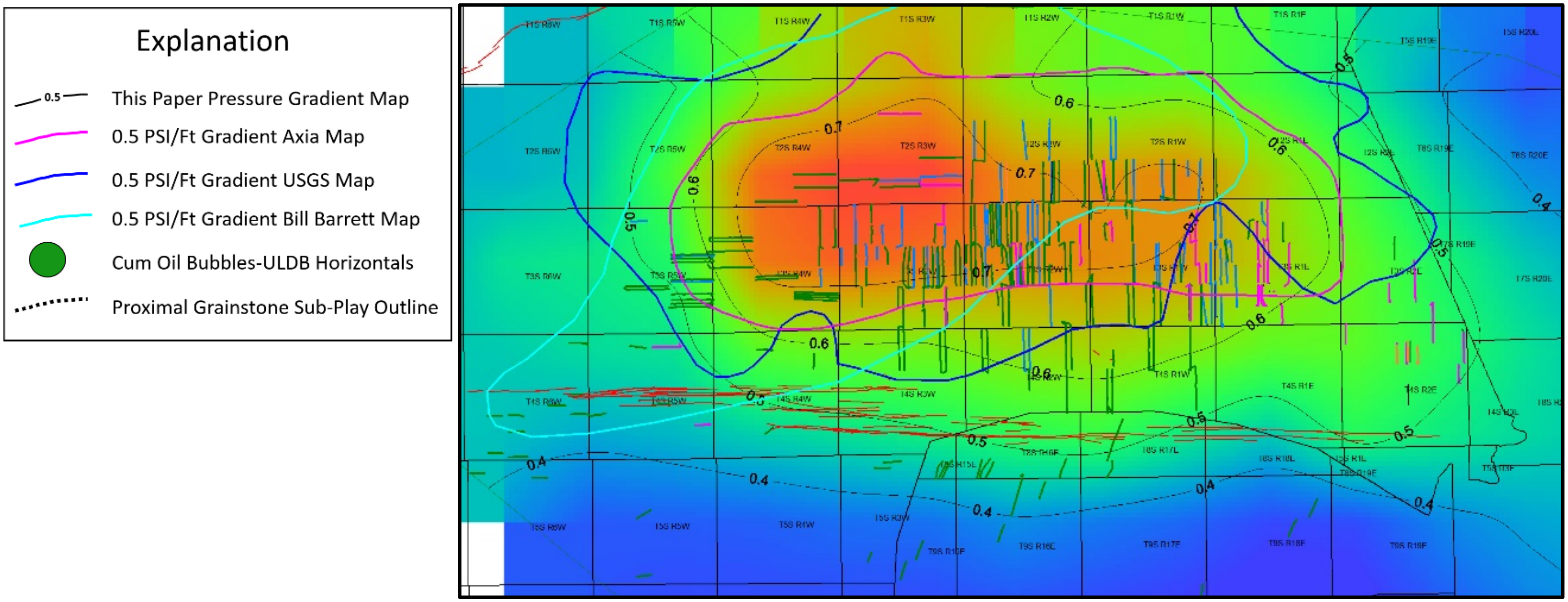

Figure 8. Uteland Butte pore-pressure map, showing the limits of overpressure from both this study and from maps released by Axia, Bill Barrett Corp. and the USGS.

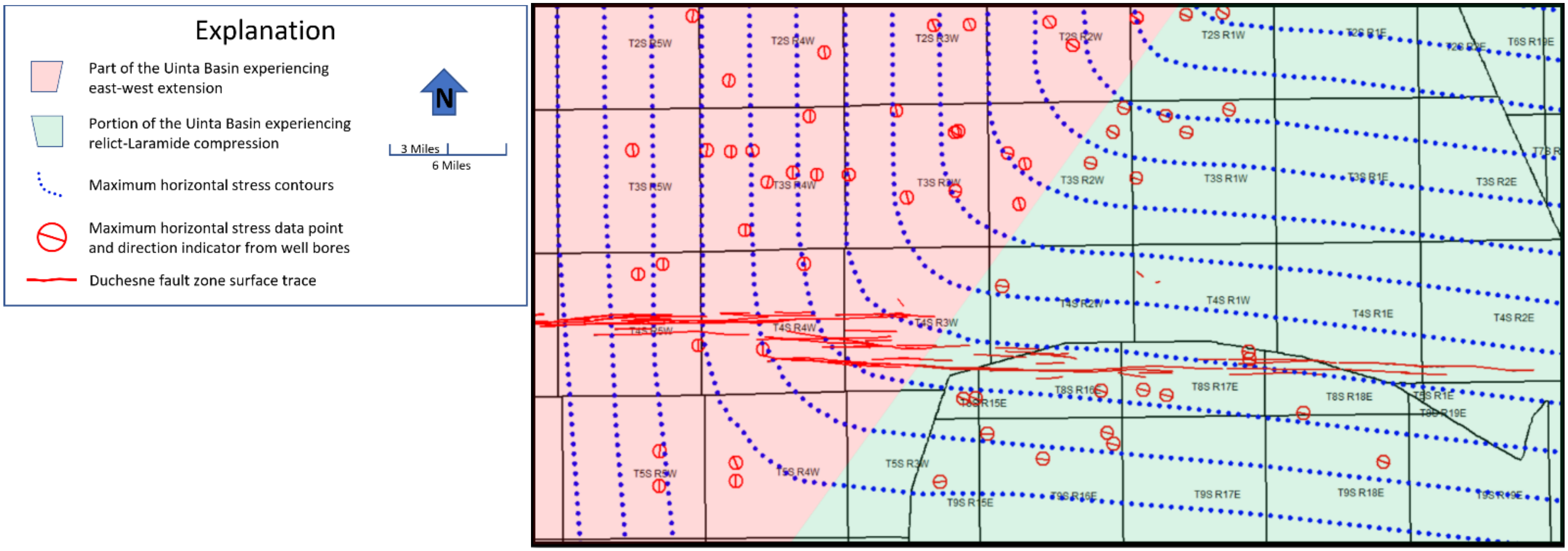

Figure 9. Mapped traces of the DFZ overlain on the maximum horizontal stress contours. Contours demonstrate the “stress swing” (blue dotted lines changing orientation) in the center of the Uinta Basin. Note that the part of the basin experiencing east-west extension (shown in pink) have north-south-directed maximum stress and have developed wide grabens within the DFZ.

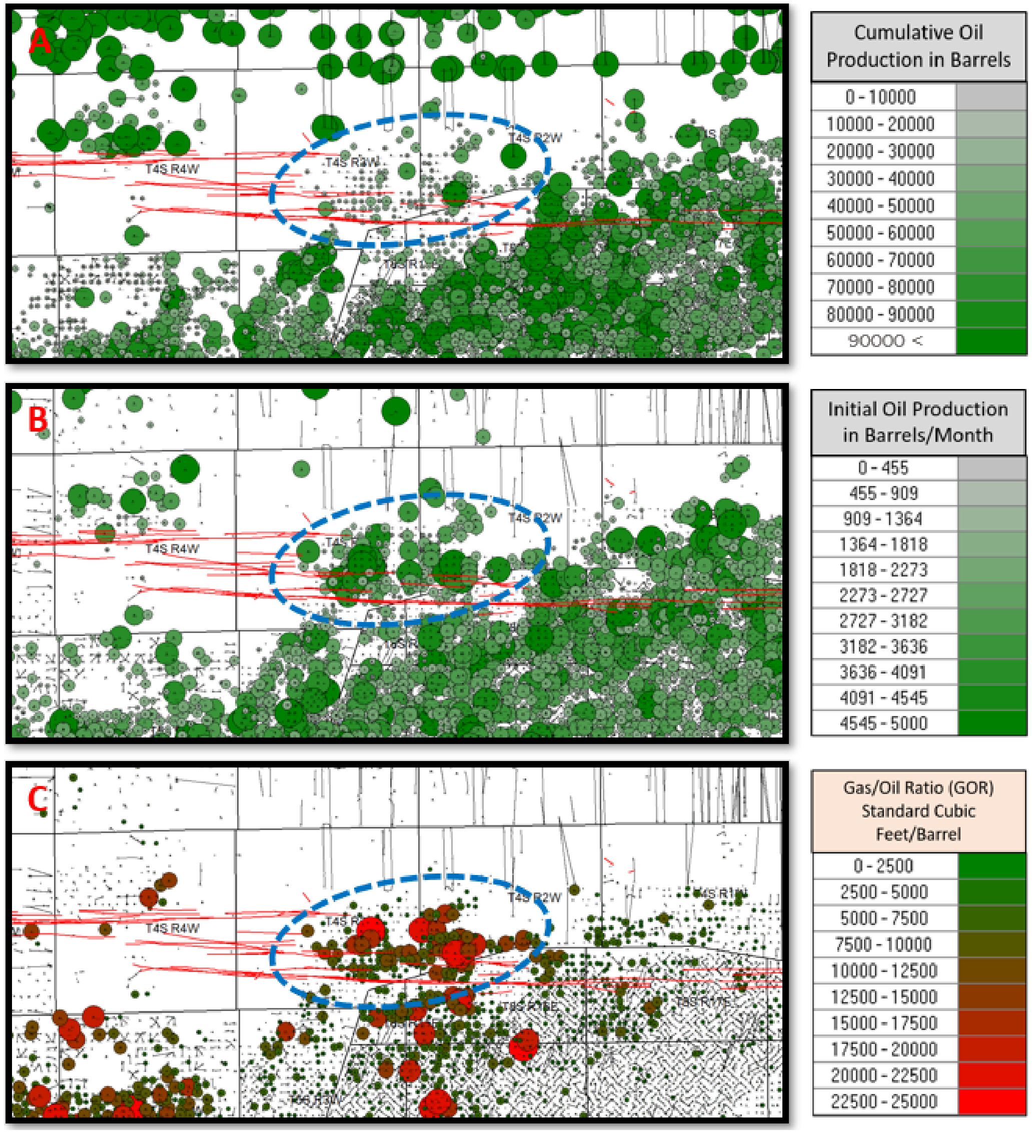

Figure 10. Production bubble maps from wells along the DFZ. Production is undifferentiated and represents all commingled perforations within the Green River Formation of the well's historical tabulation of cumulative oil (A), first month's oil (IP) (B), and gas/oil ratio (GOR) (C). The wells in the blue 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.

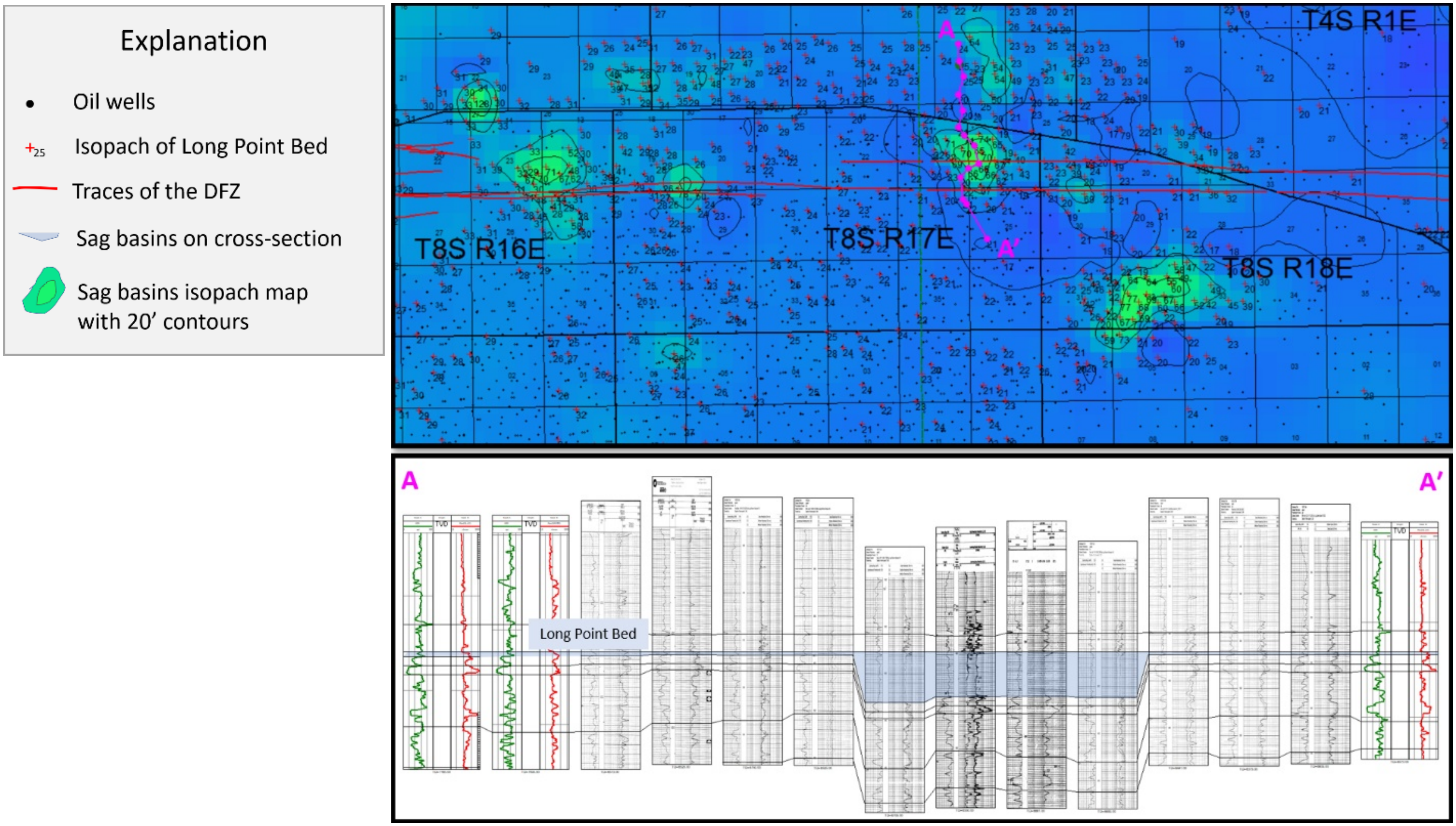

Figure 11. Isopach map and associated cross section of the Long Point Bed of the lower Green River Formation. Note the small basins that syndepositionally opened along the DFZ. We characterize these as small sag basins or pull-apart basins associated with strike-slip movement along the fault zone.