This section describes the seismic surveys that were performed in the Gas Plant area to evaluate the subsurface geologic structure and potential gas migration pathways. A 3-D seismic survey was performed in 1996, several years prior to the accidental gas release, to provide information pertaining to operation of the CIG gas storage facility. Data from that survey were reanalyzed by Miller Consulting Services (Miller) and URS for this study. Based on the reanalysis of the three-dimensional (3-D) survey data, a subsequent 2-D seismic survey was performed in 2007 to evaluate the geologic structure at shallow depths in the area of the gas release, including Gas Storage Well No. 26 and surface disruption areas adjacent to the Gas Plant.

4.1 THREE-DIMENSIONAL SEISMIC REFLECTION SURVEY

In 1996, CIG performed a 3-D seismic reflection survey to further assess the structural characteristics of the underground gas storage reservoir at the Fort Morgan Unit, which occurs below a depth of 5,000 feet bgs in the Dakota Sandstone. The layout for this survey is shown on Figure 4-1. Subsequent to the accidental gas release from Gas Storage Well No. 26 on October 22, 2006, these 3-D seismic data were reevaluated with a focus on the shallow geologic structure and potential gas migration. URS retained Miller, a firm specializing in seismic data analysis and geologic interpretation, to perform the reanalysis with the specific objective of mapping the shallowest horizons using the 3-D data.

Results of the 1996 3-D seismic reflection data reevaluation were presented in the *Interim Phase II Report* (URS 2007). In summary, the effort found that four reflector horizons could be mapped at depth intervals ranging from approximately 1,500 to 2,900 feet bgs. However, there are areas of substantial missing data at depths above 1,000 feet, which limited the usefulness of the 1996 survey to identify potential gas release migration pathways.

Despite the limitations of the 1996 data, reevaluating it was useful for identifying several shallow geologic structures (e.g., faults) that could represent zones of structural weakness in the upper Pierre Shale beneath the Gas Plant. For example, Figure 4-2 shows the 3-D seismic data interpretation along a north to south section, Crossline 118, through Gas Storage Well No. 26, which indicates fault displacements in the Shallow 4 reflector (about 2,800 feet deep) that may extend upward into overlying strata. (Figure 4-2 is a copy of Figure 5-14 from Miller [2007]). The reanalyzed 1996 survey data were used to plan the 2007 high-resolution seismic survey to maximize its effectiveness.

4.2 HIGH-RESOLUTION TWO-DIMENSIONAL SEISMIC SURVEY

In October and November 2007, a high-resolution 2-D seismic survey was performed by Bay Geophysical under URS direction. This survey involved collecting and evaluating high-resolution seismic data along the 2-D transect lines shown on Figure 4-3. This map also shows the surface projections of faults interpreted using the 3-D seismic data and elevation contours of the subsurface bedrock topography which were described in the *Interim Phase II Report* (URS 2007). The objective of the 2-D seismic survey was to further evaluate the gas migration routes from the casing leak at 846 feet in depth in Gas Storage Well No. 26 to the areas around the Gas Plant where the gas surfaced. The survey focused on pathways that could be related to geologic structures such as faults and fractured zones. Identification of geologic structures that might have served as gas conduits helps identify areas potentially containing residual gas in shallow strata, and aid in selecting future monitoring well locations.

URS retained Miller to analyze the 2007 high-resolution seismic data and to work closely with URS to evaluate the shallow geologic structure and gas migration pathways. The data analysis also considered the results of the 1996 3-D seismic survey and available geophysical logs of the upper Pierre Shale from nearby oil and gas wells. The principal findings of the 2-D high-resolution seismic survey are described below.

There is a very good correlation between the 1996 3-D survey data and the 2007 high-resolution 2-D data, which is illustrated on Figure 4-4. The 2-D data provide much better definition of strata in the shallower section of the Pierre Shale, which are pertinent to evaluating gas migration pathways adjacent to and above the casing leak depth of 846 feet. Three strong seismic reflectors are discernable from the 2-D data in the upper Pierre Shale at depths of approximately 320 feet, 680 feet and 1,020 feet, which are designated UP1, B/UP2 and UP3 respectively. All of these reflector horizons are at shallower depths than the uppermost reflector seen on the 3-D survey, Shallow1, which occurs at a depth of 1,500 feet. Thus, the shallowest reflector that occurs in both surveys is Shallow1. These shallow reflectors correlate well with coarser-grained sedimentary deposits (silty, fine-grained sandstones) in the upper Pierre Shale, as illustrated on borehole geophysical logs of Gas Storage Well No. 26 (Figure 4-4).

The seismic reflection data from the high-resolution 2-D survey are of excellent quality. Unfortunately, the seismic refraction data that were also acquired along several of these lines were not usable because of shallow ground noise attributable to operations at the plant. However, the 2-D seismic reflection data are very useful for evaluating subsurface geologic structure at shallow depths because four strong reflector horizons are consistently seen in the upper Pierre Shale (UP1, B/UP2, UP3, and Shallow 1) that correlate with specific geologic strata in well logs for this area.

Of these reflectors, the UP1 reflector horizon is particularly valuable for structural geologic analysis. UP1 is correlated with an interval composed primarily of fine, silty sandstone that was deposited in the uppermost Pierre Shale (Figure 4-4). This interval of fine sandstone is seen in all of the geophysical logs throughout the study area, and reflects a near-shore marine or pro-delta depositional environment. The widespread consistency in thickness and physical character of UP1 make it the best horizon for mapping geologic structures and bedding orientations in the upper Pierre Shale section beneath the Gas Plant.

Each of the four major reflectors in the upper Pierre Shale are identified on the high-resolution 2-D survey profiles, which are shown in Figures 4-5 through 4-13 and briefly summarized below.

Figure 4-5 illustrates the continuous and coherent reflection events along Line D, running north to south, just west of the Gas Plant. There appear to be only minor disruptions in lateral continuity of reflectors UP1 and B/UP2 on the ends of Line D.

The interpreted data profile along Line A, an east–west line running through Gas Storage Well No. 26, is shown on Figure 4-6. Minor disruptions in lateral continuity appear in UP1 and B/UP2 several hundred feet to the east of the well, which appear to indicate slump faulting and a reduction in thickness of the stratigraphic section between UP3 and UP1. A similar but less pronounced structural feature affects UP1 several hundred feet to the west of the well.

Line C is a northeast–southwest trending profile crossing Gas Storage Well No. 26 and is shown on Figure 4-7. The reflection events along this line are continuous and coherent, with no obvious disruptions, even at Gas Storage Well No. 26.

Line E is a northeast–southwest profile that lies between Gas Storage Well No. 26 and the Gas Plant and is shown on Figure 4-8. This profile shows no obvious disruptions of any of the reflectors. In the central portion of the line, UP1 appears to have some minor deformation.

Line F is an east–west profile (Figure 4-9) along CR N immediately north of the Gas Plant. The eastern third of this profile shows severe disruption of the upper Pierre Shale, extending vertically through reflectors UP1, B/UP2 and UP3 on both sides of Gas Well No. 12 (FM12). The deeper reflector, Shallow1, appears to be disrupted east of Gas Well No. 12, but to a lesser degree than the shallower reflectors.

Line G is a northwest–southeast profile (Figure 4-10) located to the southwest of the Gas Plant. The only obvious disruptions are those where UP1 and B/UP2 appear displaced on the southeast end of the profile, south of the Gas Plant. The disruption of UP1 is consistent with slump faulting caused by loss in mass or material volume in the stratigraphic section between UP1 and UP3.

Line H (Figure 4-11), which runs northeast to southwest immediately east of the Gas Plant, shows an intensely disrupted UP1 along most of the line. The deeper reflectors B/UP2 and UP3 are also disrupted in the northeastern half of the profile, but to a lesser degree than UP1. The Shallow1 reflector shows only minor disruption, if any. The spatial pattern of these disruptions is consistent with faulting caused by slumping, or collapse, of the shallower strata into a zone of post-depositional mass removal from the stratigraphic interval between UP1 and UP3.

Figure 4-12 shows Line I, a northeast–southwest profile that lies southeast of the Gas Plant. This profile shows a similar pattern of disruptions as Line H, but with a less extensive zone of lateral disruption. The vertical extent of the disruption area is essentially the same as shown on Line H. Again, this pattern of disruptions is consistent with slump faulting or collapse of the shallower strata into a zone of post-depositional mass removal from the depth interval between UP1 and UP3.

The seismic reflection profile along Line J is shown as Figure 4-13. This line runs north to south along CR 18 east of the Gas Plant and shows severe disruption of the upper Pierre Shale. Reflector UP1 is the most intensively disrupted, with the degree and lateral extent of disruption diminishing with depth. Shallow1 is hardly disrupted, if at all. As for lines H, I and J, the spatial pattern of the disrupted strata is consistent with slump faulting caused by downward movement of the shallower strata into deeper zones where rock mass has been removed within the interval below UP1 but above Shallow1. The amount of post-depositional mass removal appears greatest between UP1 and UP3 in the center of Line J. More recent deposition of thicker sediments above UP1 is also evident in the central portion of Line J.

The origin of geologic structures in the upper Pierre Shale is clarified by comparing the pattern of disruptions on the 2-D profiles to those of the 1996 3-D seismic survey, which were obtained many years prior to the accidental gas release from Gas Storage Well No. 26. Figure 4-14 is a structure contour map of UP1 that was prepared based on the 1996 3-D data and available borehole geophysical logs showing the elevation of UP1 at existing wells. On Figure 4-14, the higher elevation areas of UP1 are shown in orange and yellow while the lower elevations are in pink and blue. The red arrows indicate the up-dip directions from Gas Storage Well No. 26 as inferred from the mapped elevation contours of the UP1 reflector. Figure 4-15, is a 3-D perspective diagram created from the same data used to prepare Figure 4-14. On both these figures, the blue areas south and southeast of the plant show large depressions in the top surface of UP1, while the yellow-orange area east and northeast of the plant is a structural high.

Considering the relatively low resolution of the shallow reflectors in the 3-D seismic data, it is only possible to discern the general shape and extent of the UP1 structural features from that survey. Nonetheless, the general shapes and trends of several UP1 structures seen in the 3-D survey are similar to the structural trends derived from the high-resolution 2-D data. Figure 4-16 shows the UP1 structure contour map based on the 2-D data and well logs and shows patterns comparable to those on Figure 4-14 and Figure 4-15. Of particular note are the large depressions in UP1 located just to the east, southeast and south of the Gas Plant, are reflected in the seismic data collected prior to and after the accidental gas release from Gas Storage Well No. 26. This indicates the general nature of these geologic structures existed prior to the release.

The structural features in the upper Pierre Shale in the areas just east, south and southeast of the Gas Plant show a spatial distribution of faulting and bedding orientations that are consistent with post-depositional slump faulting into a depression created after the UP1 stratum was deposited. The concentric pattern of the slump faulting and downward displacement of UP1, with more recent infilling of sediment above, is evidence of post-depositional mass removal from the Pierre Shale by dissolution of soluble sedimentary material. Lateral continuity of Shallow 4 below is evidence that the interval from which sediment was removed lies above Shallow 4.

Dissolution of limestone and subsequent collapse of overlying strata into the dissolution cavities create similar patterns, both laterally and vertically, to those observed just east and southeast of the Gas Plant. Localized limestone deposits attributable to sea-floor methane seeps have been reported in the upper Pierre Shale along the southwestern margin of the Denver Basin. Shapiro and Fricke (2002) and Kauffman (1996) provide detailed descriptions of the lithofacies distribution and biochemical characteristics of the Tepee Buttes mounds. Figure 4-17 illustrates the lithologic and geochemical character and stratigraphic occurrence of a typical Tepee Butte limestone mound.

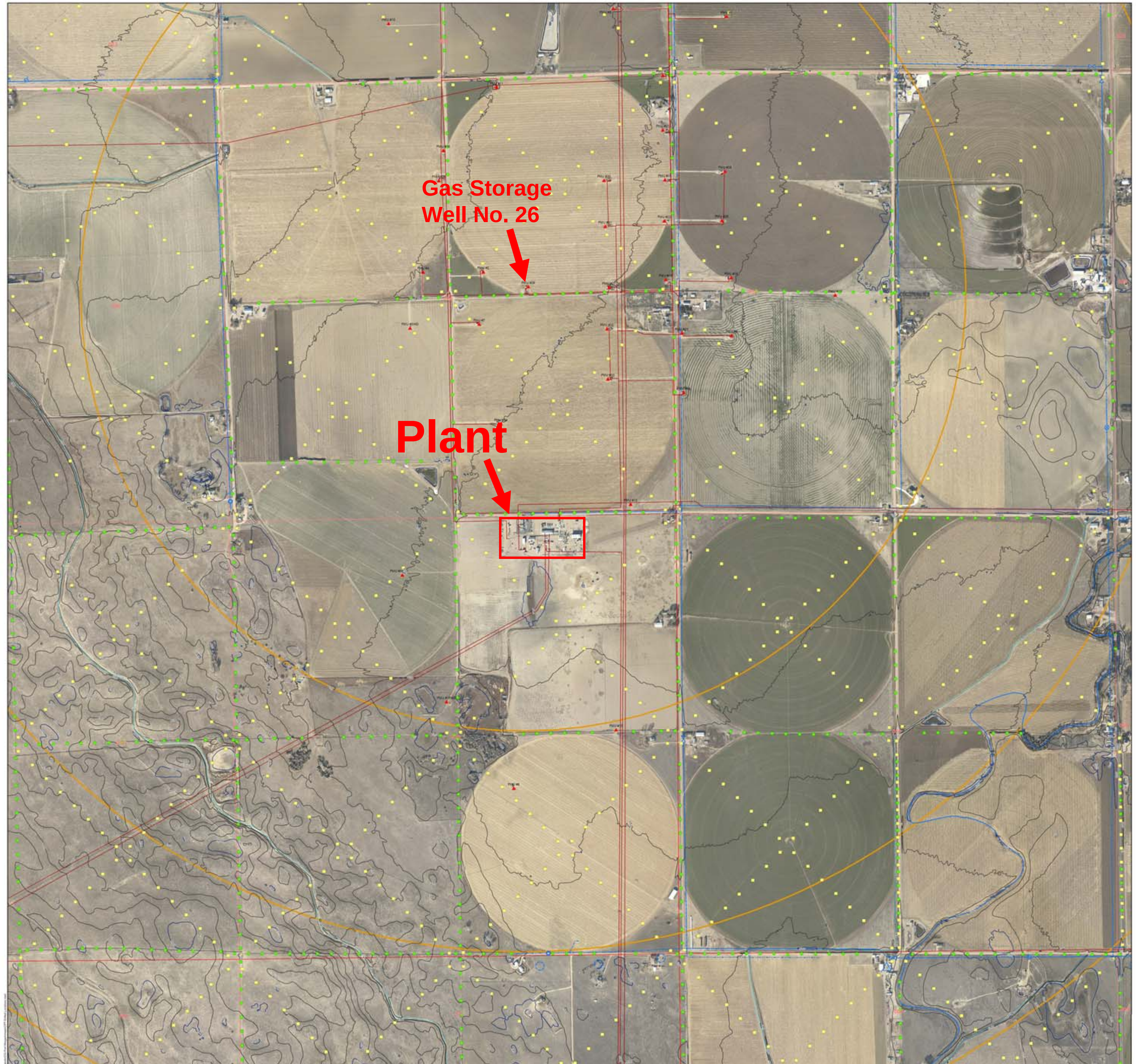
Several northwest-trending faults east and southeast of the Gas Plant seen in the 1996 3-D seismic reflection data coincide with the major disruption zones seen in the 2007 seismic data. However, the 2-D data also reveal a pronounced area of low velocity in UP1 coinciding with the most severely disrupted area to the east and south of the Gas Plant, as shown on Figure 4-18. A low velocity area of this proportion is consistent with increased fractures and gas-filled pore volume, which are likely attributable to the migration and surface eruptions of the natural gas in those areas during the October 2006 release.

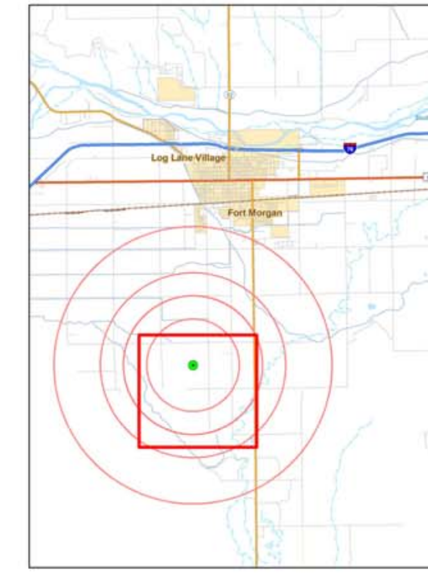
4.3 CONCLUSIONS

Important conclusions can be derived from the seismic survey results:

- The 2-D and 3-D seismic reflection survey data are of excellent quality and provide a strong technical basis for defining the spatial orientations and continuity of strata in the upper Pierre Shale in areas near Gas Storage Well No. 26 and locations of land surface disruptions caused by the natural gas leak.
- Subsurface mapping of reflector horizons based on the 1996 3-D seismic survey and well log data collected prior to the accidental gas release, show the upper Pierre Shale beds dip generally toward the west, and to the northeast, in the immediate vicinity of Gas Storage Well No. 26. The general up-dip directions from Gas Storage Well No. 26 are eastward and southwestward as illustrated on Figure 4-14.
- The 3-D data show displacements of the deeper reflectors in the upper Pierre Shale, particularly Shallow4 (about 2800 feet bgs), which indicate several normal faults exist near Gas Storage Well No. 26 and southward (Figure 4-2). Projecting these faults to shallower depths is somewhat uncertain, but reasonable to consider, and the projected surface locations are shown on Figure 4-3. The 3-D data also show large depressions in the upper Pierre Shale beds immediately south and southeast of the Gas Plant and a structural high to the east and northeast of the Gas Plant.
- The 2-D seismic data provide even better resolution of the geologic structure of the upper Pierre Shale at depths ranging between 300 and 1,000 feet bgs.
- Figure 4-16 is based on an evaluation of the 2-D data in conjunction with available borehole geophysical logs of wells, as well as the general trends shown in the 3-D surveys. Thus, Figure 4-16 provides the most definitive representation of bedding orientations and geologic structure of the upper Pierre Shale.
- Vertical profiles of the 2-D data in Figures 4-5 through 4-13 best illustrate the bedding continuity in the undisturbed areas and the patterns of bedding displacements with depth in the disrupted areas.
- The remarkably well-defined, low-velocity area observed in the 2-D data east of the Gas Plant is shown on Figure 4-18. This low velocity zone reflects a combination of physical factors: increased fracture porosity caused by subsurface disruption in the upper Pierre Shale due to the gas release and larger amounts of gas filled pore space compared to the surrounding rock. The low-velocity area likely coincides with the principal source of residual methane leakage into the alluvium from the gas release.

- The spatial pattern of faulting and anomalous bedding orientations in the upper Pierre Shale south, east and southeast of the CIG Plant are likely the result of post-depositional slump faulting caused by dissolution of a localized limestone mound, similar to those reported in the Tepee Buttes area east of Colorado Springs (Shapiro and Fricke 2002, Kauffman 1996).





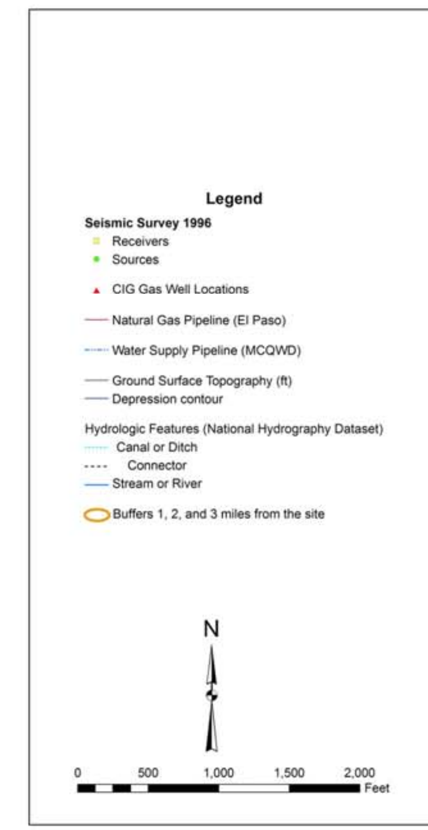


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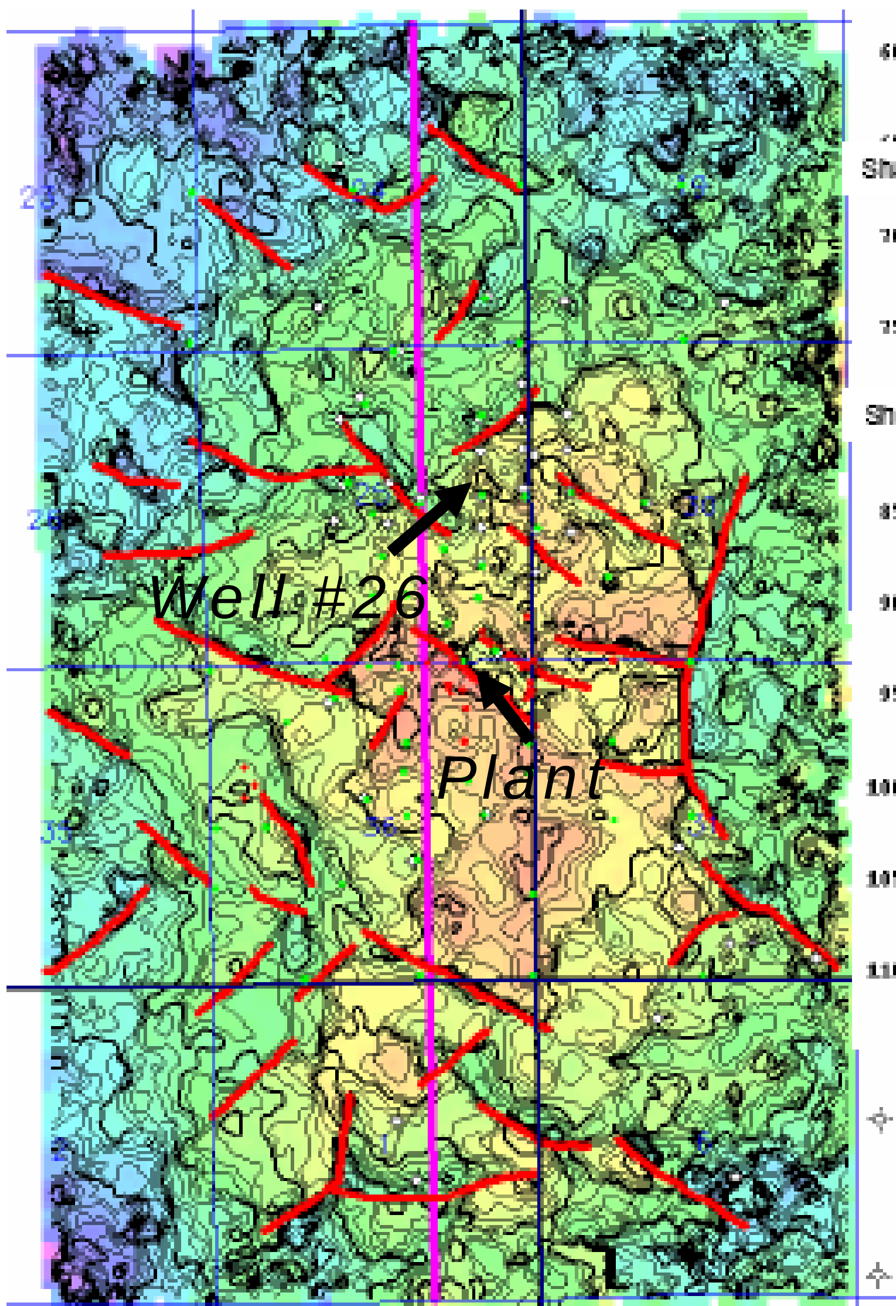
Figure 4-1
1996 3-D Seismic Survey Lines

Crossline 118 through the FMU #26 well showing the seismic data through the Shallow4 horizon. The fault interpretation is shown through this horizon.

Shallow 1 ~ 1,500 ft

Shallow4 time structure contour interval: .001 sec



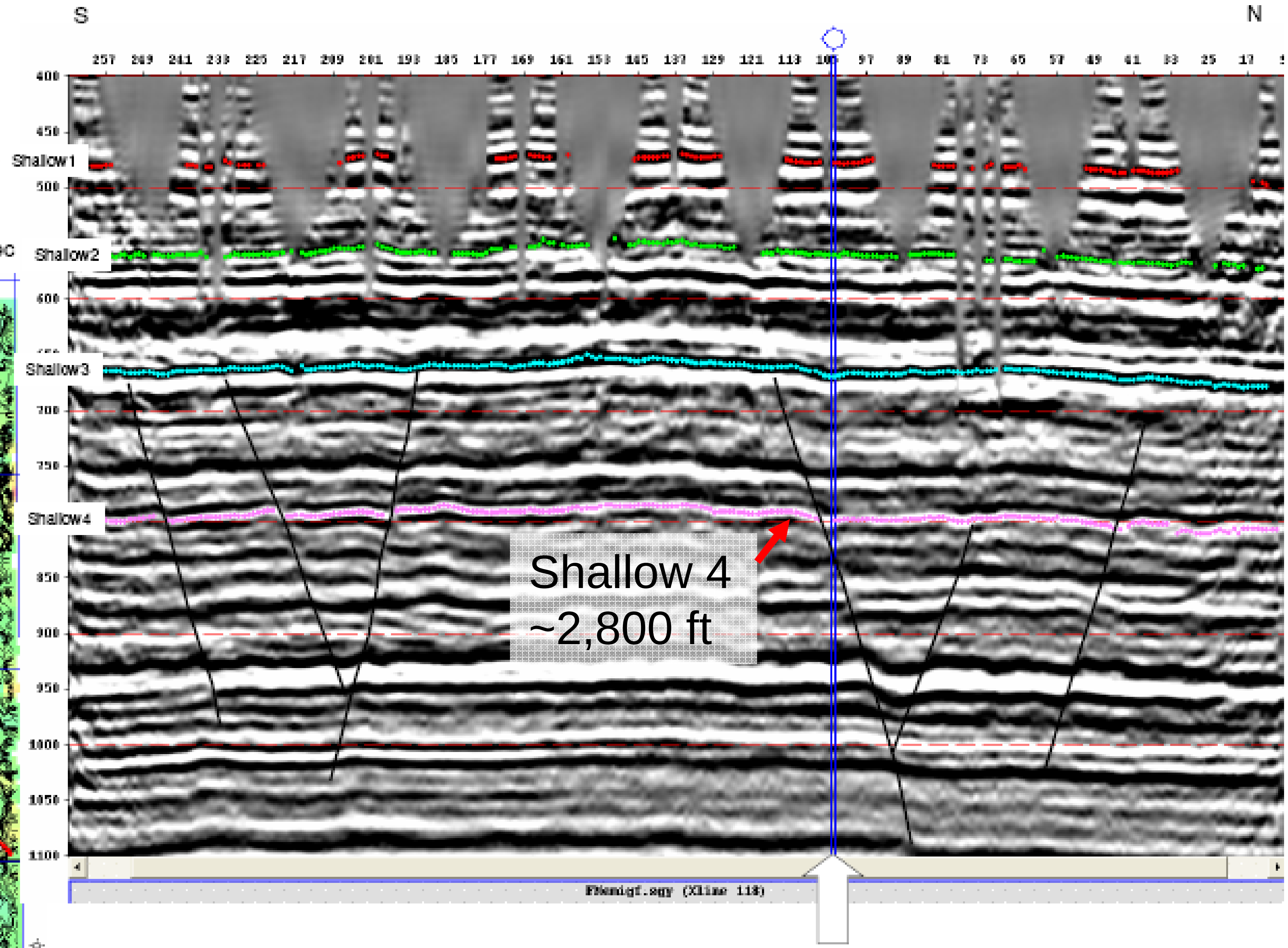


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Figure 4-2
3-D Seismic Data Interpretation, Crossline 118 through Gas Storage Well No. 26

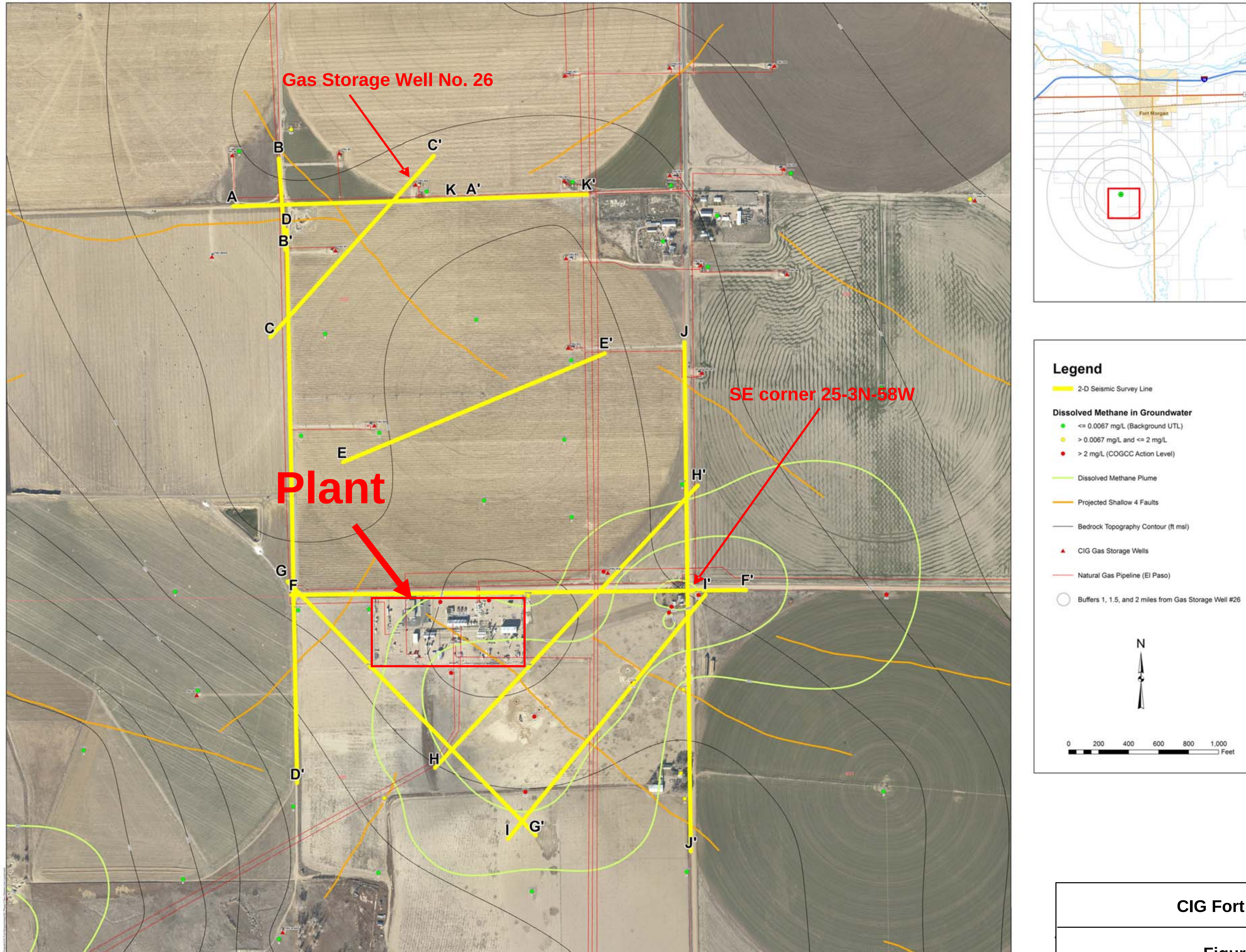

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Figure 4-3
2007 2-D Seismic Survey Lines

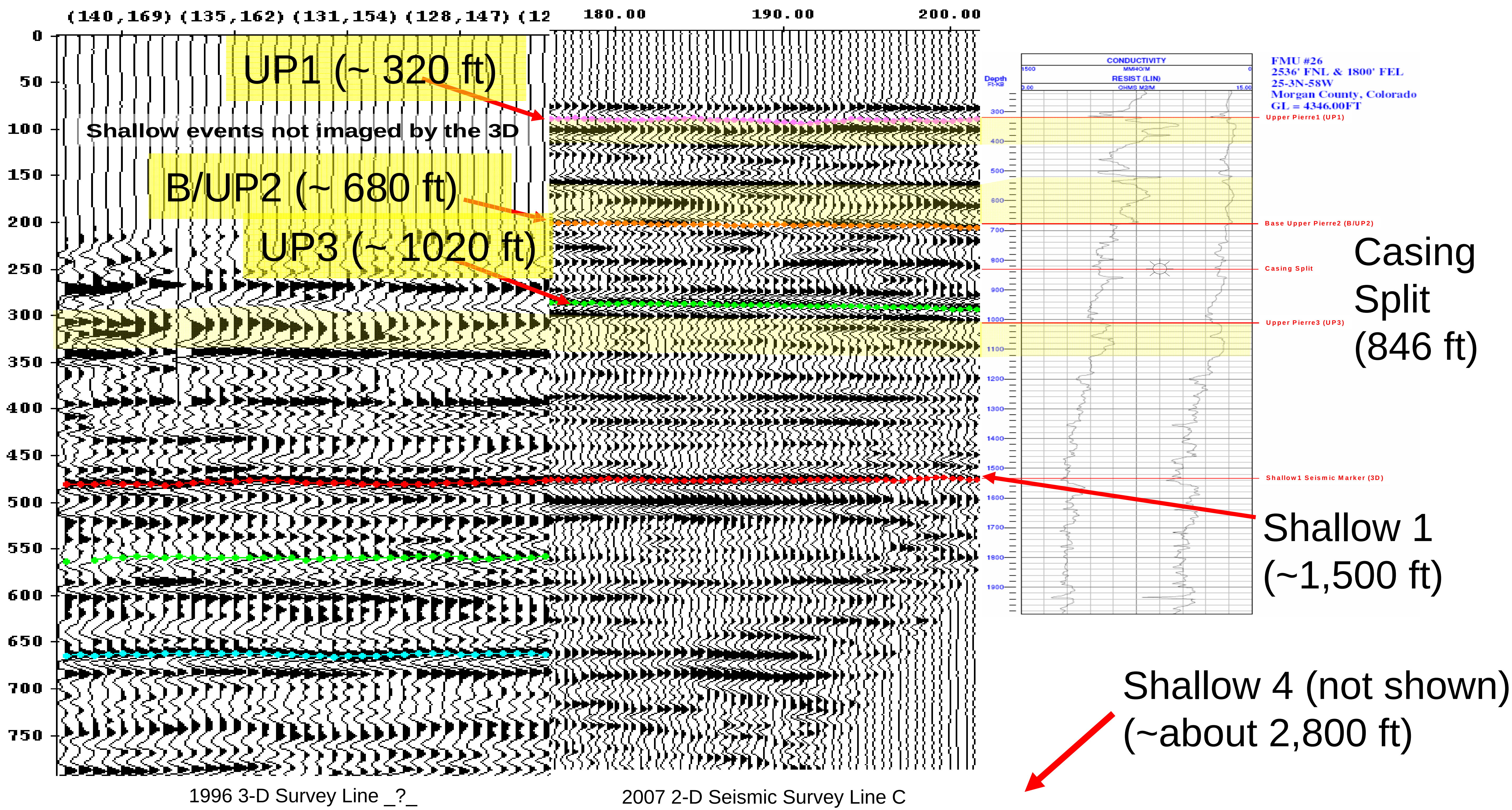

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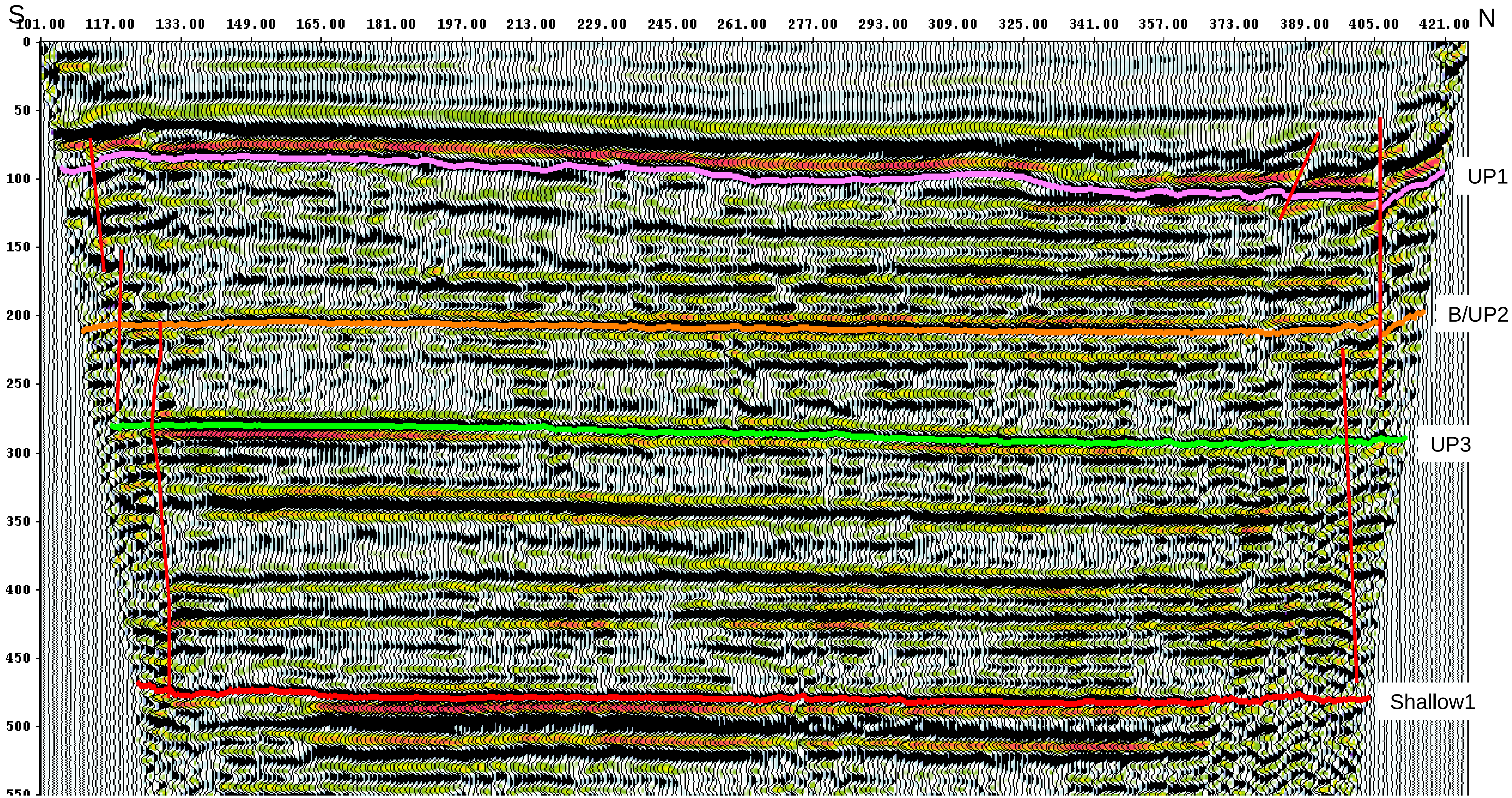
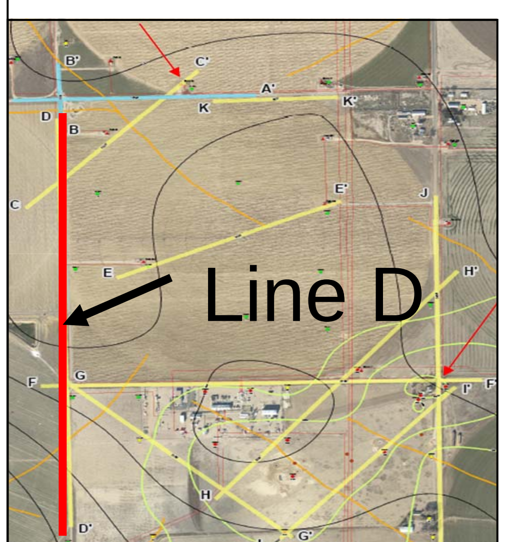
Figure 4-4
Correlation of 1996 3-D Survey Data and 2007 High-Resolution 2-D Data
Gas Storage Well No. 26





Line D-This N-S line for the large part has continuous and coherent reflection events with no obvious disruptions. Minor disruptions are evident at the north and south ends of this line.

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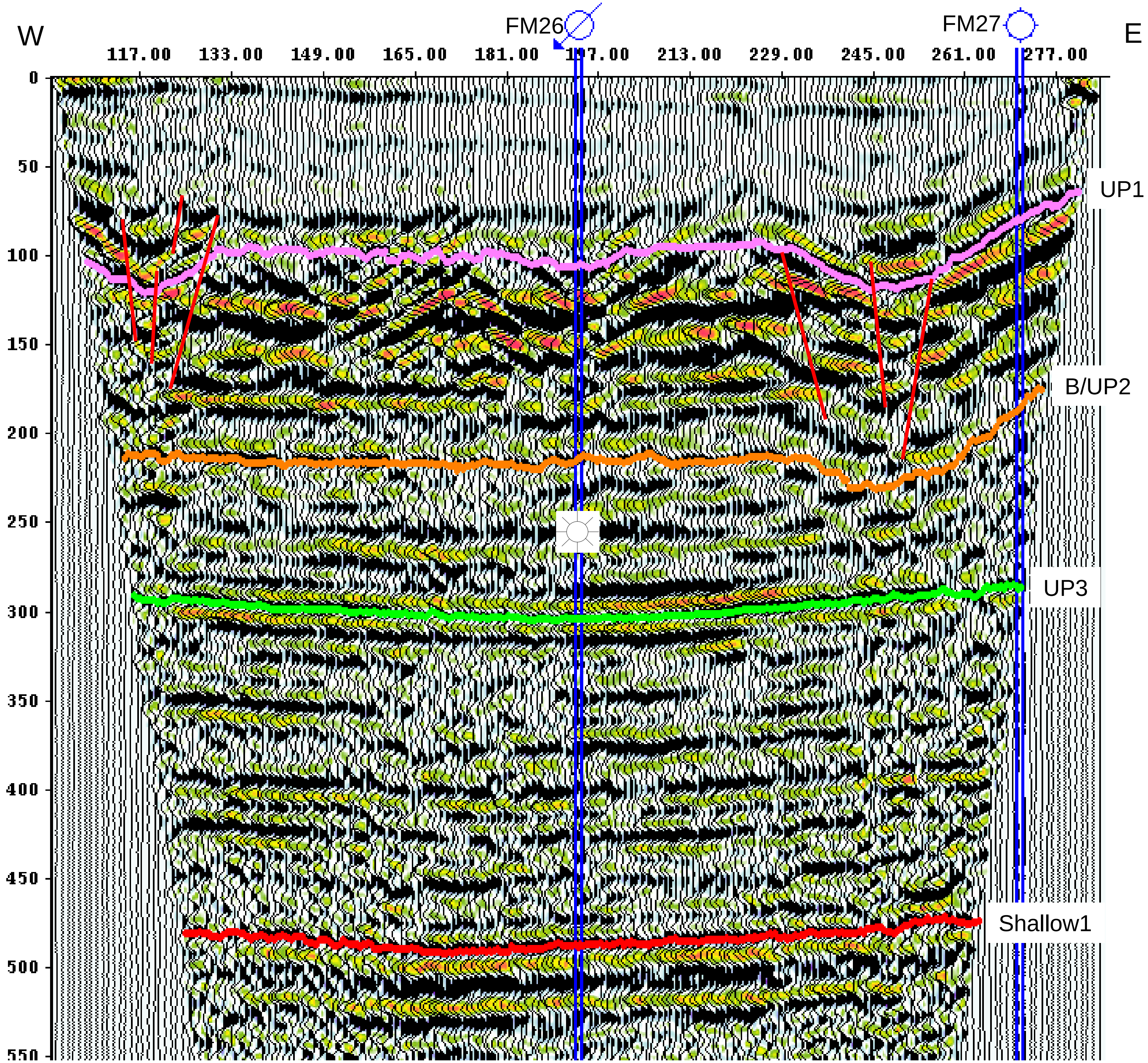
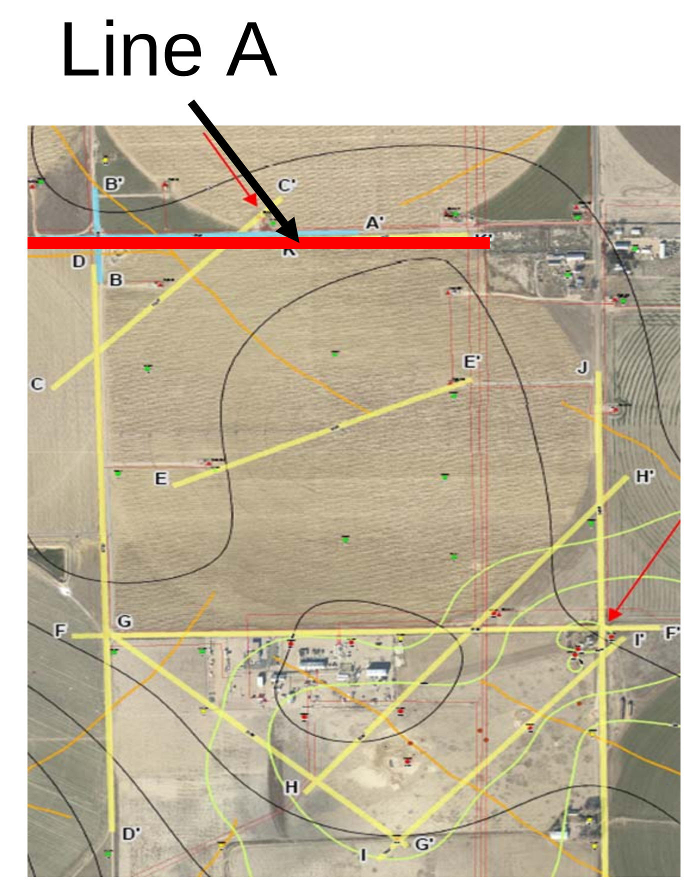
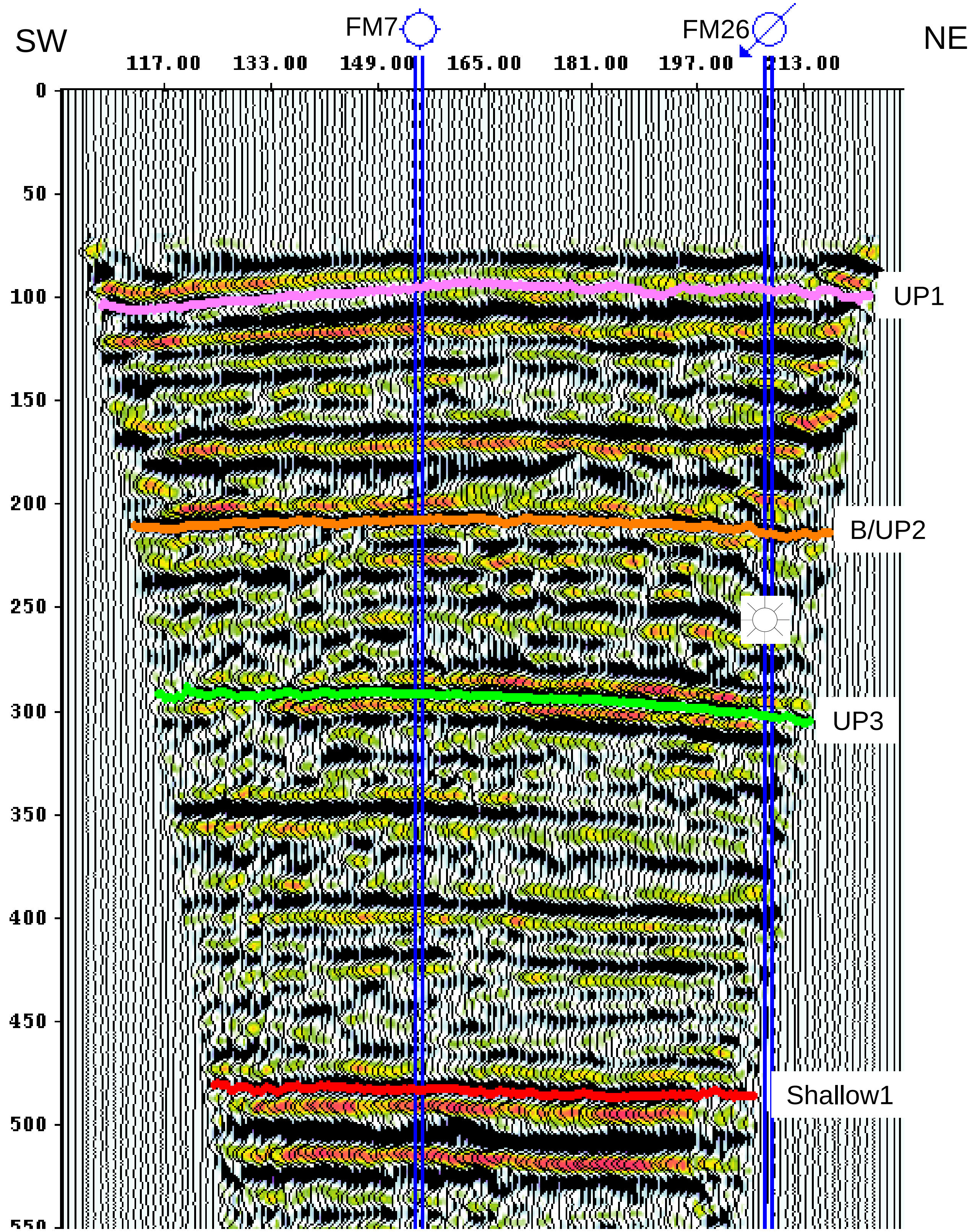
Figure 4-5
2-D Seismic Reflection Profile – Line D

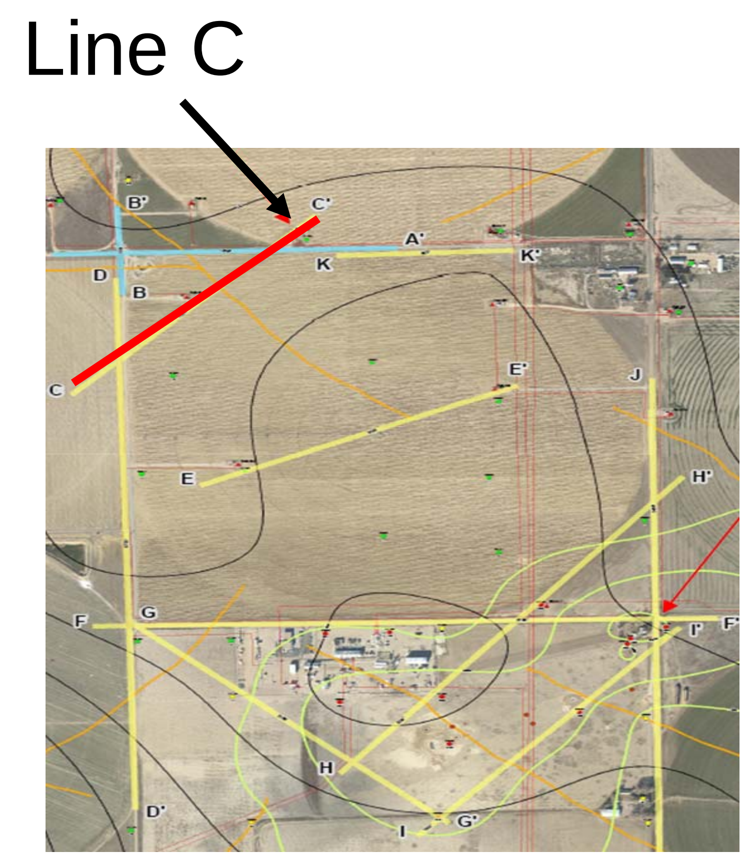




Line A-This E-W line ties the Gas Storage Well No. 26 well, and the location of the casing split is indicated on the welllbore path. Cathodic protection was on during the recording of this line which affected the shallow data quality, but was turned off for the recording of the remaining lines. Distinct sags in the UP1 event and disruption of the event continuity in the Upper Pierre 1&2 section is noticeable at the west end of the line as well as the east end centered around shotpoint 250.

CIG Fort Morgan
Figure 4-6 **2-D Seismic Reflection Profile – Line A**

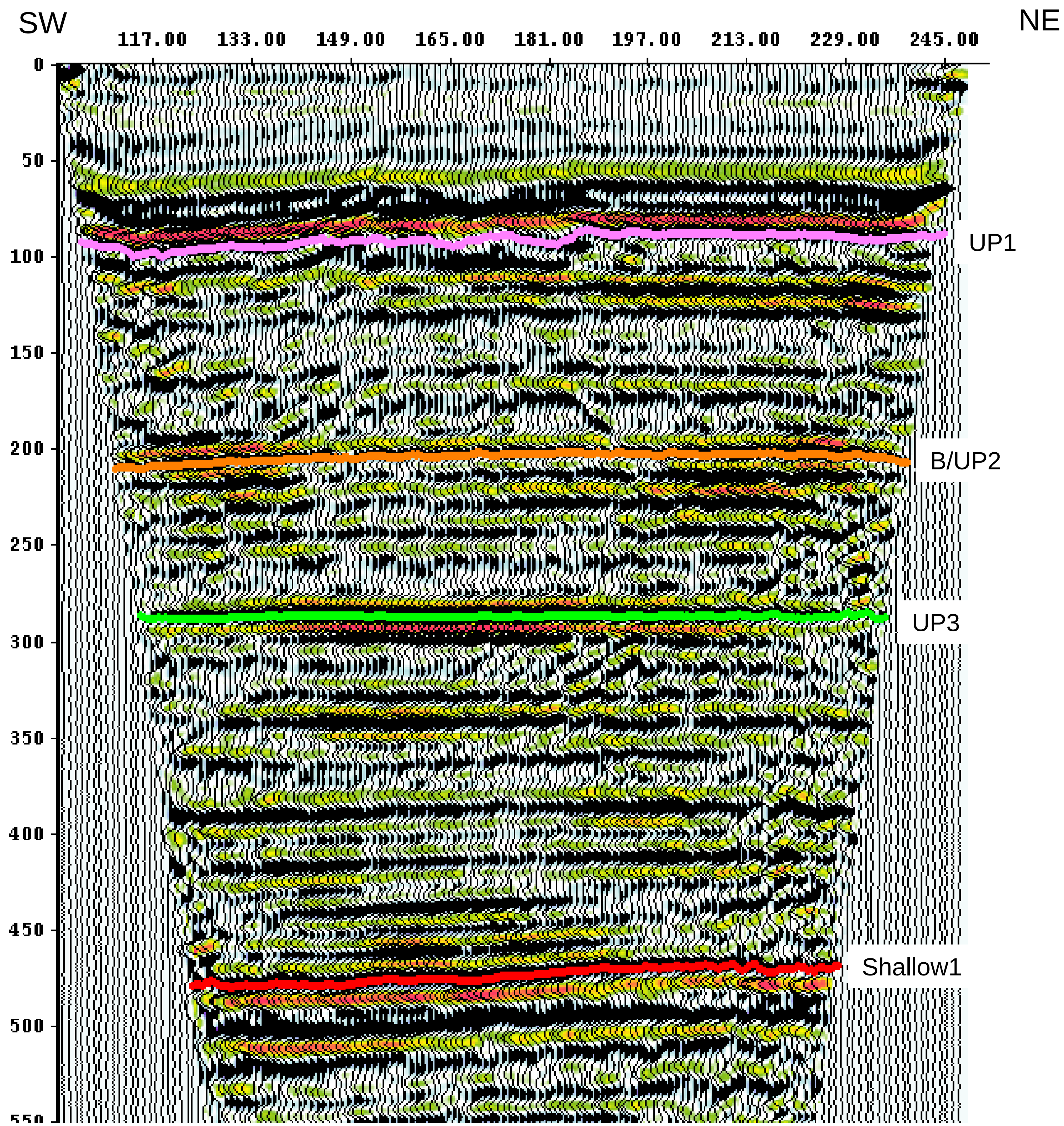




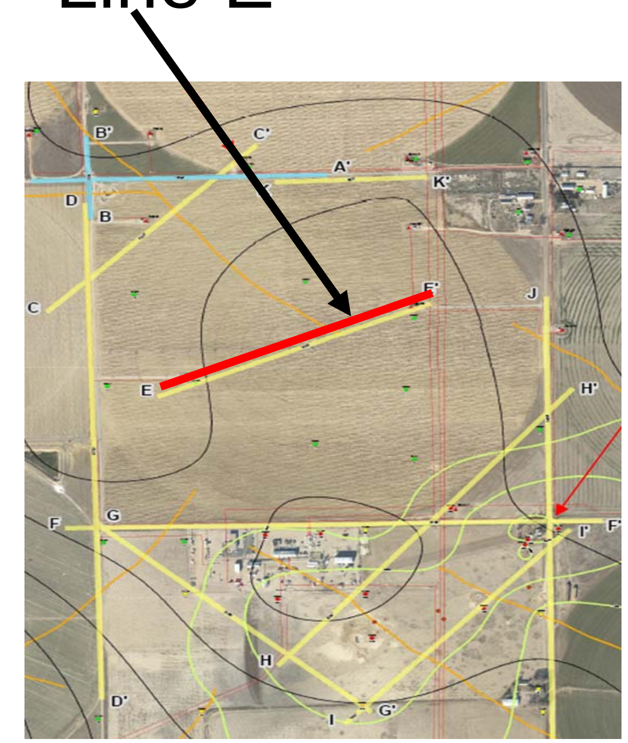
Line C-This NE-SW line also ties the Gas Storage Well No. 26 well, and the location of the casing split is indicated on the welllbore path. The reflection events are continuous and coherent with no obvious disruptions, including at the Gas Storage Well No. 26 location.

CIG Fort Morgan

Figure 4-7
2-D Seismic Reflection Profile – Line C

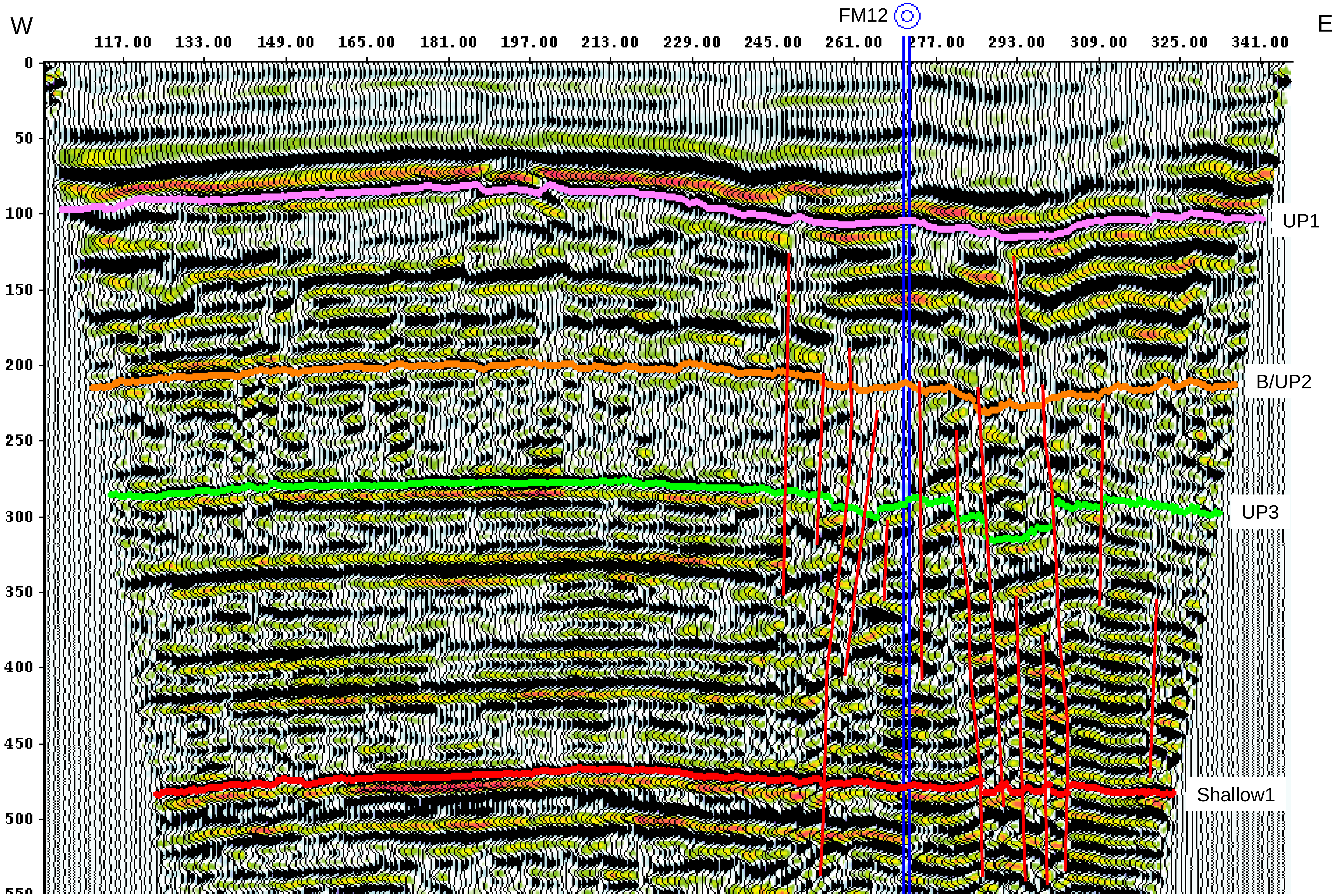


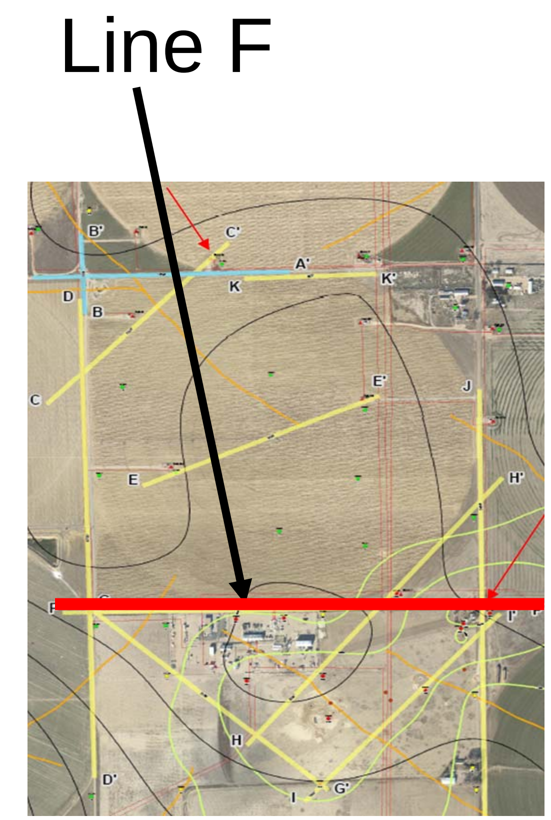
Line E



<u>Line E</u>-This NE-SW line has continuous and coherent reflection events with no obvious disruptions.

CIG Fort Morgan
Figure 4-8 **2-D Seismic Reflection Profile – Line E**

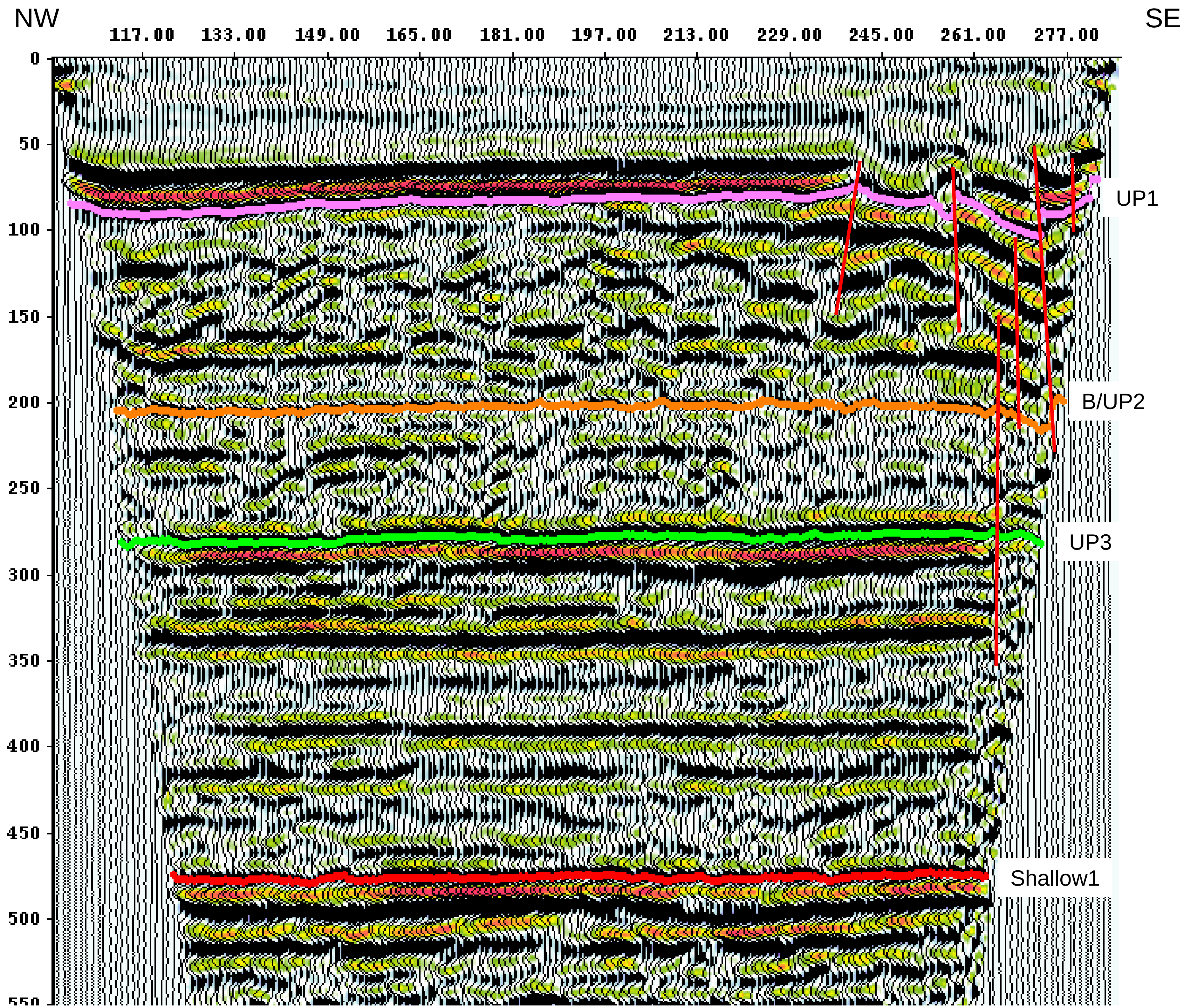


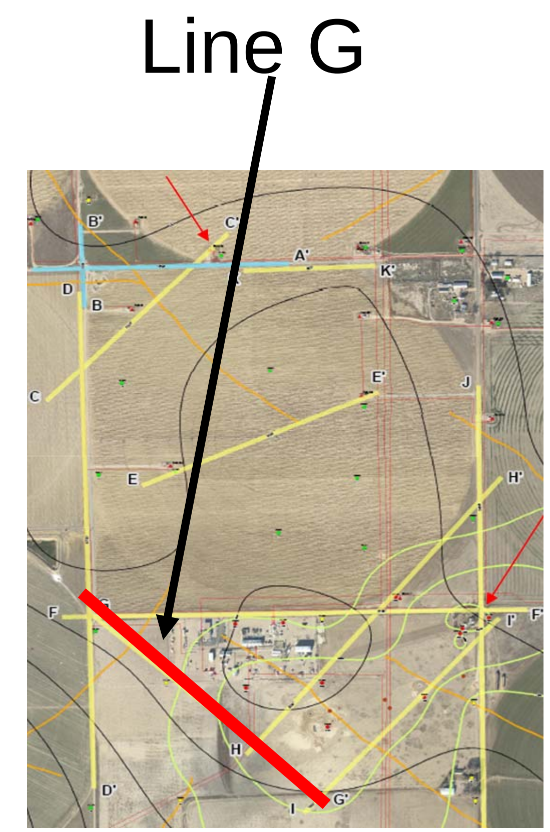


Line F-This E-W line runs along County Road N has continuous and coherent reflection events over the west half of the line, but the east half of the line displays severe disruption of the Upper Pierre and deeper seismic events from shotpoints 250-340. The CIG plant is at approximately shotpoints 155-230, and the intersection with line J (SE corner of section 25) is at shotpoint 317.

CIG Fort Morgan

Figure 4-9
2-D Seismic Reflection Profile – Line F

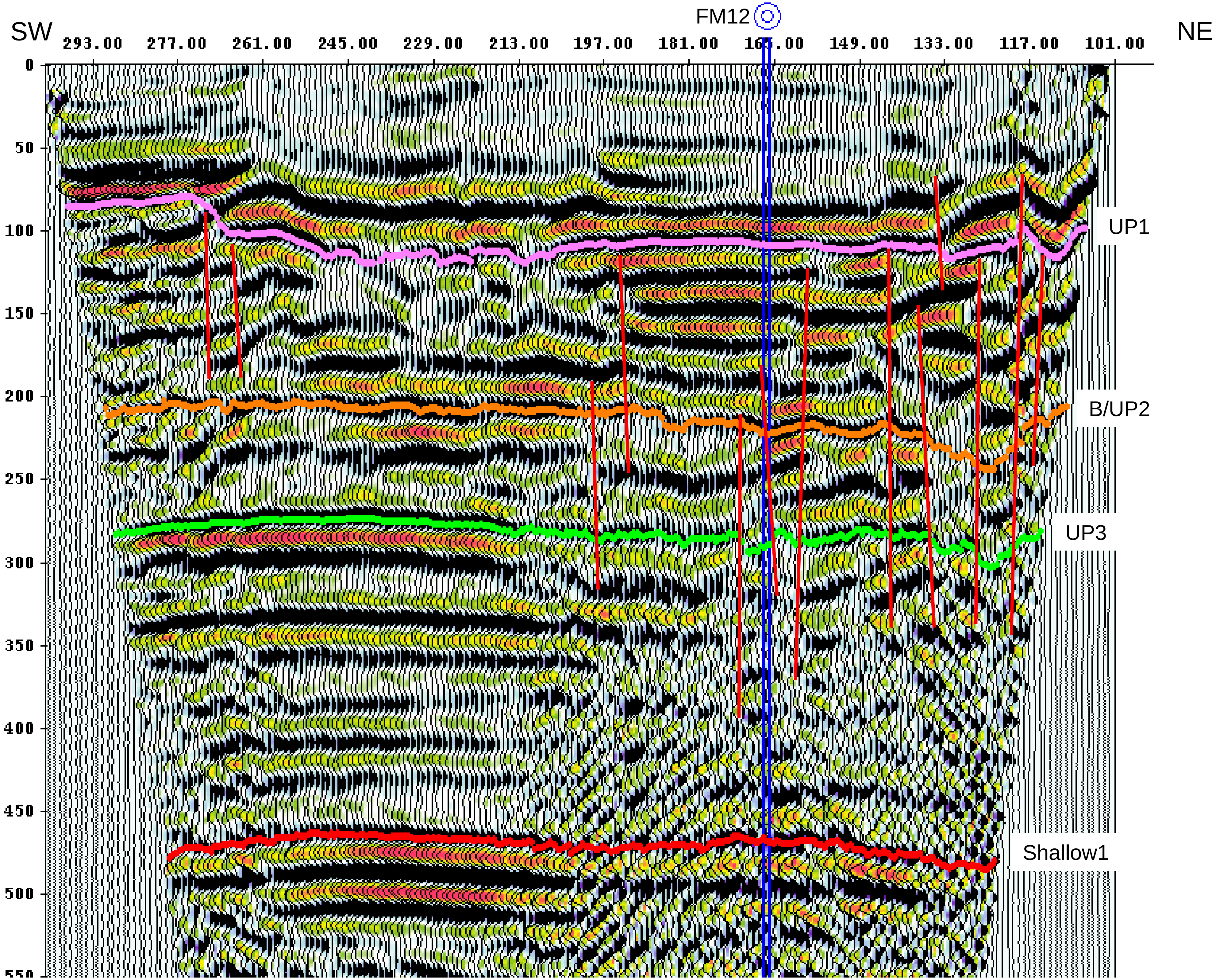


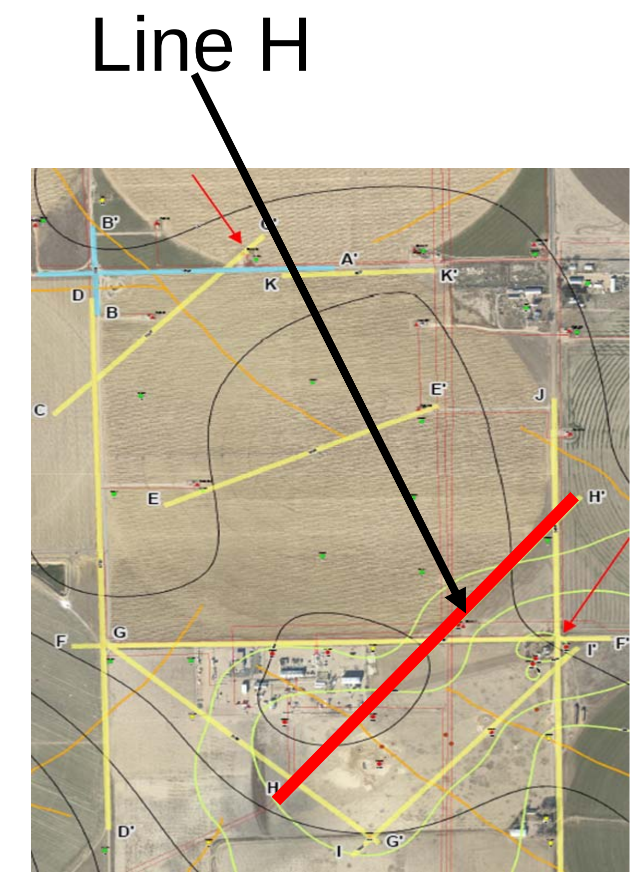


Line G-This NW-SE line for the large part has continuous and coherent reflection events with no obvious disruptions except between shotpoints 240-285 where disruptions are evident in the Upper Pierre section.

CIG Fort Morgan

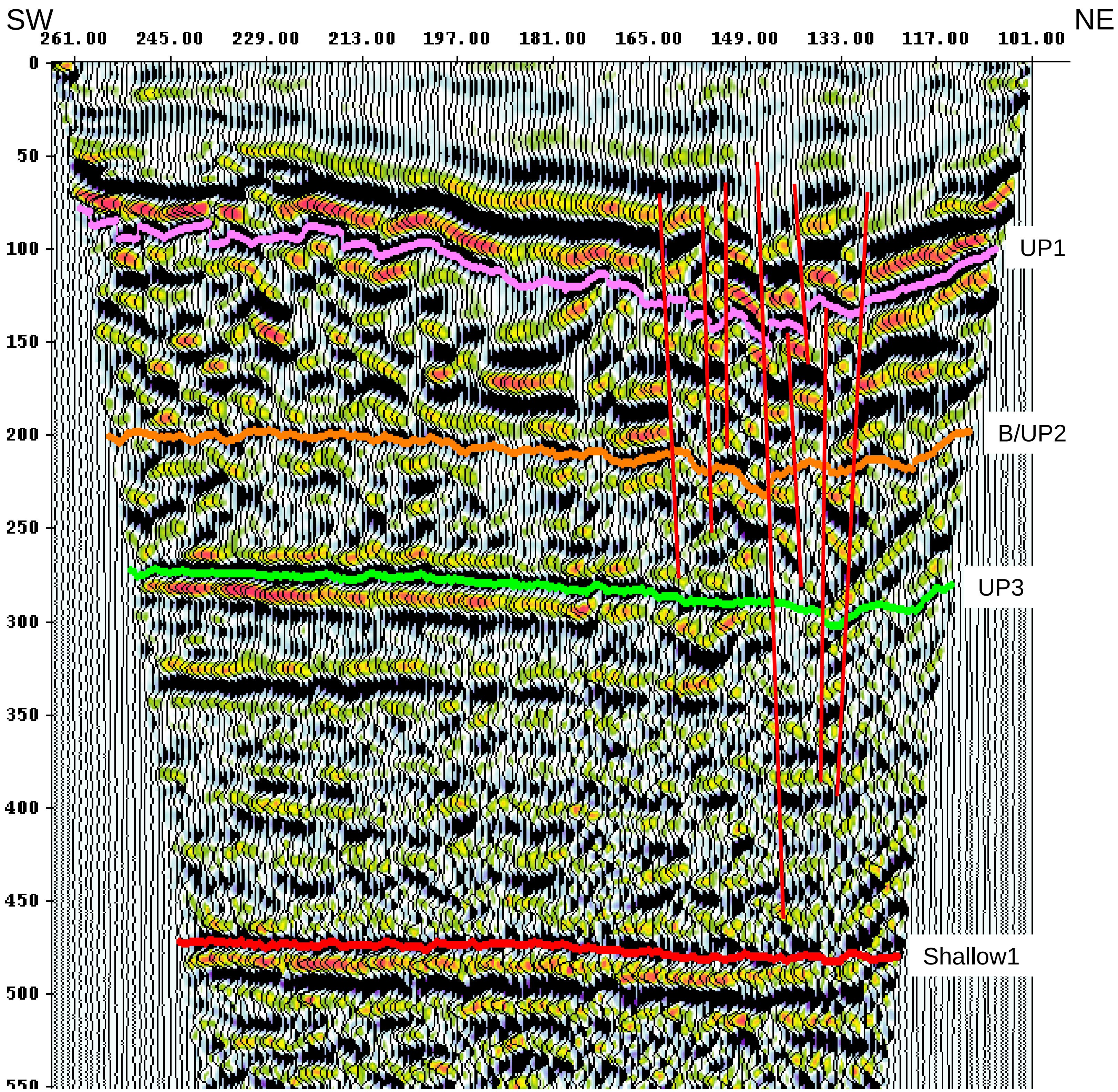
Figure 4-10
2-D Seismic Reflection Profile – Line G

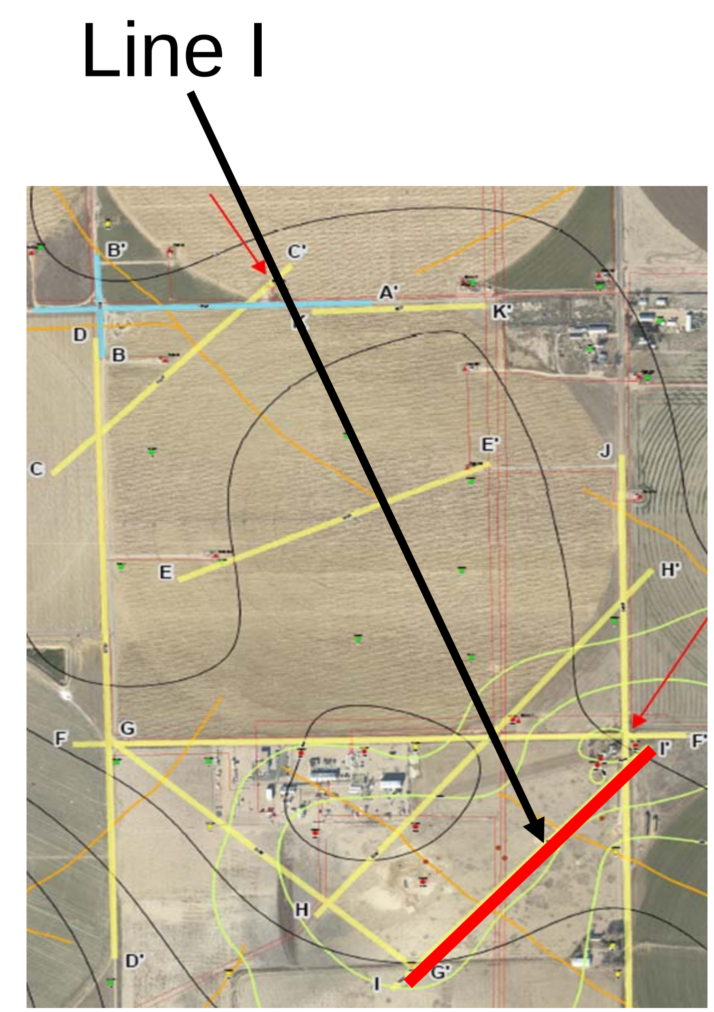




Line H-This NE-SW line displays significant disruption of the Upper Pierre seismic events from shotpoints 101-200. There is also an attenuation of the deeper seismic signal under this area. There is an area of signal loss in the Upper Pierre from shotpoints 205-250 but the event continuity does not appear to be too disrupted.

CIG Fort Morgan
Figure 4-11 **2-D Seismic Reflection Profile – Line H**

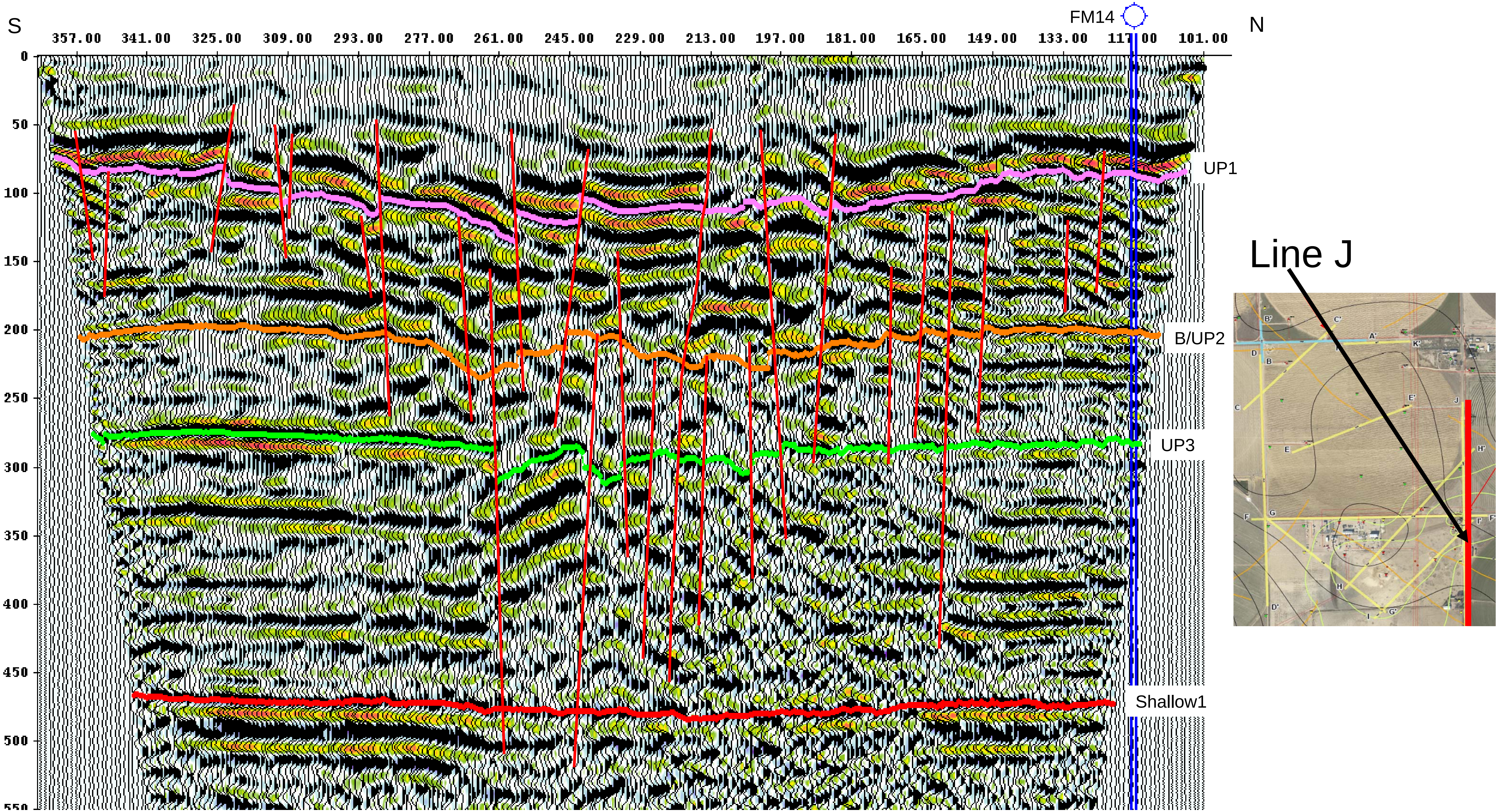




Line I-This NE-SW line displays severe disruption of the Upper Pierre and deeper seismic events from shotpoints 101-170.

CIG Fort Morgan

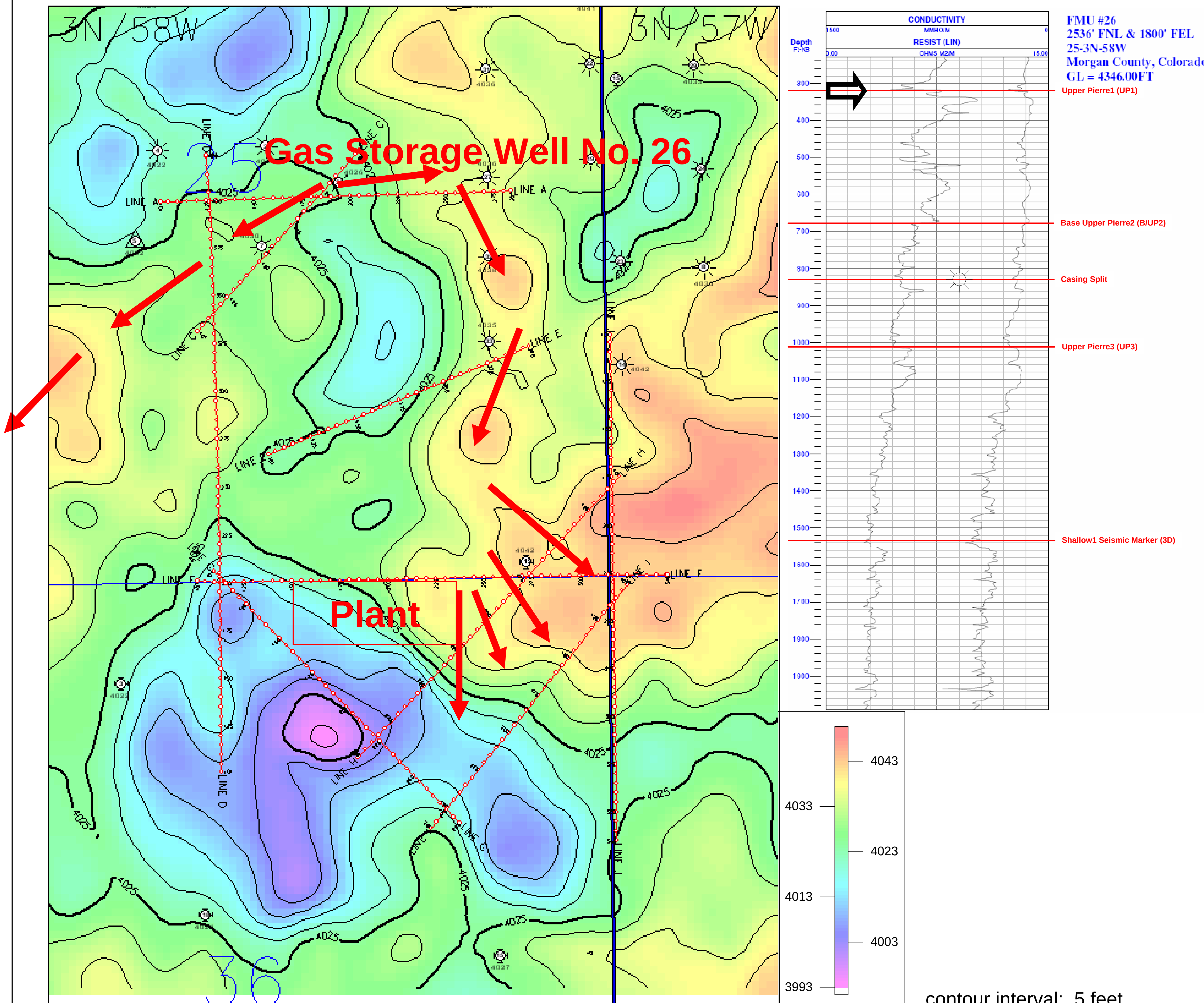
Figure 4-12
2-D Seismic Reflection Profile – Line I



Line J-This N-S line runs along County Road 18 and displays severe disruption of the Upper Pierre and deeper seismic events from shotpoints 150-310. The intersection with line F (SE corner of section 25) is at shotpoint 225.

CIG Fort Morgan

Figure 4-13
2-D Seismic Reflection Profile – Line J



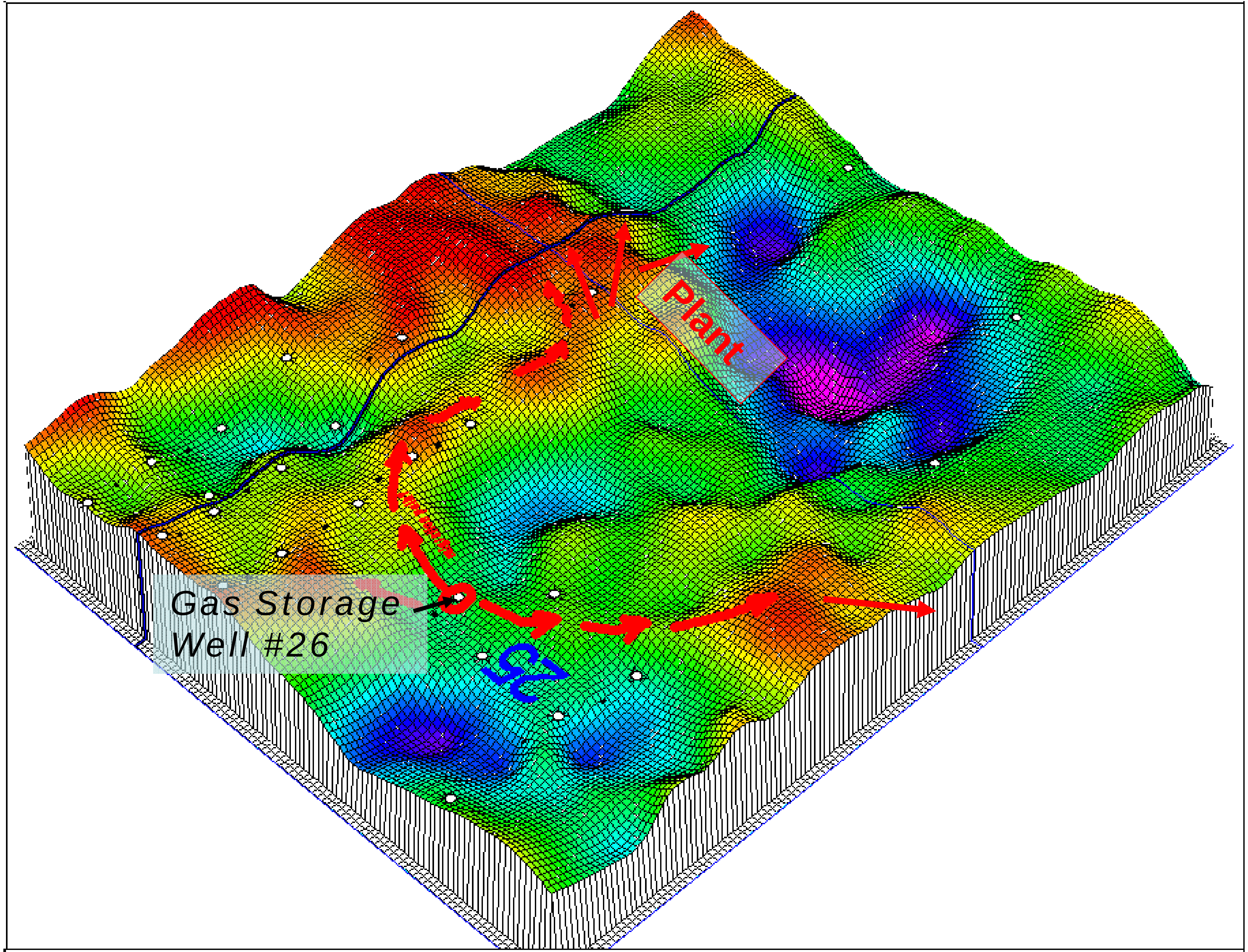
contour interval: 5 feet

<u>UP1 Depth Structure from 3D</u>-This map was also generated from the Ft Morgan 3-D which was previously interpreted. The Gas Storage Well No. 26 borehole log shows the depth of this mapped interval. The 3-D data did not map this UP1 formation directly as it was designed to map the deeper field reservoir and did not image very shallow events. The Shallow1 horizon shown on the log was mappable from the 3-D and converted to depth structure using a contoured velocity field calculated from the well to seismic ties. The geologic isopach interval, determined from the well logs, from the Upper Pierre1 (UP1) down to the Shallow1 horizon was then added on top of the Shallow1 depth structure to estimate the depth structure of the UP1 horizon. The Upper Pierre1 subsea values are posted at the wells where borehole logs were available (note that these are positive datums above sea level). The structurally highest area is at the SE corner of section 25 of T3N-R58W.

It is important to note that this was mapped with data acquired years before the casing split in the Gas Storage Well No. 26 well, which occurred in October 2006.

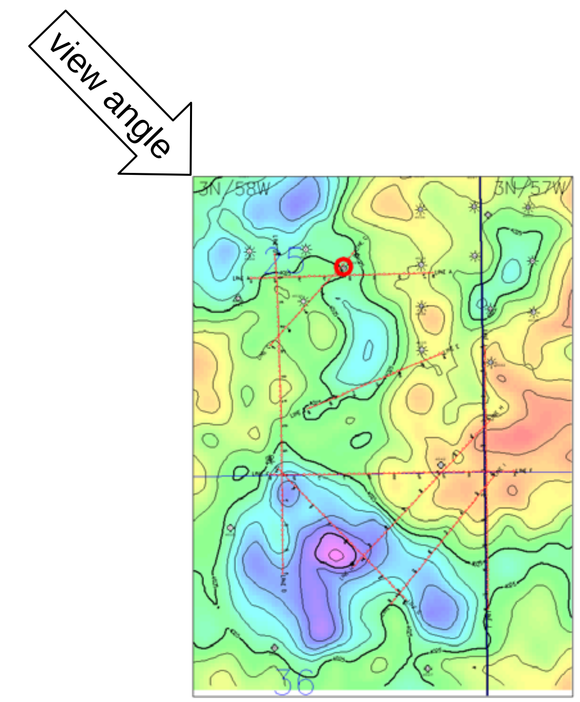
CIG Fort Morgan

Figure 4-14
Structure Contour Map of UP1
(based on 3-D seismic data and well logs)



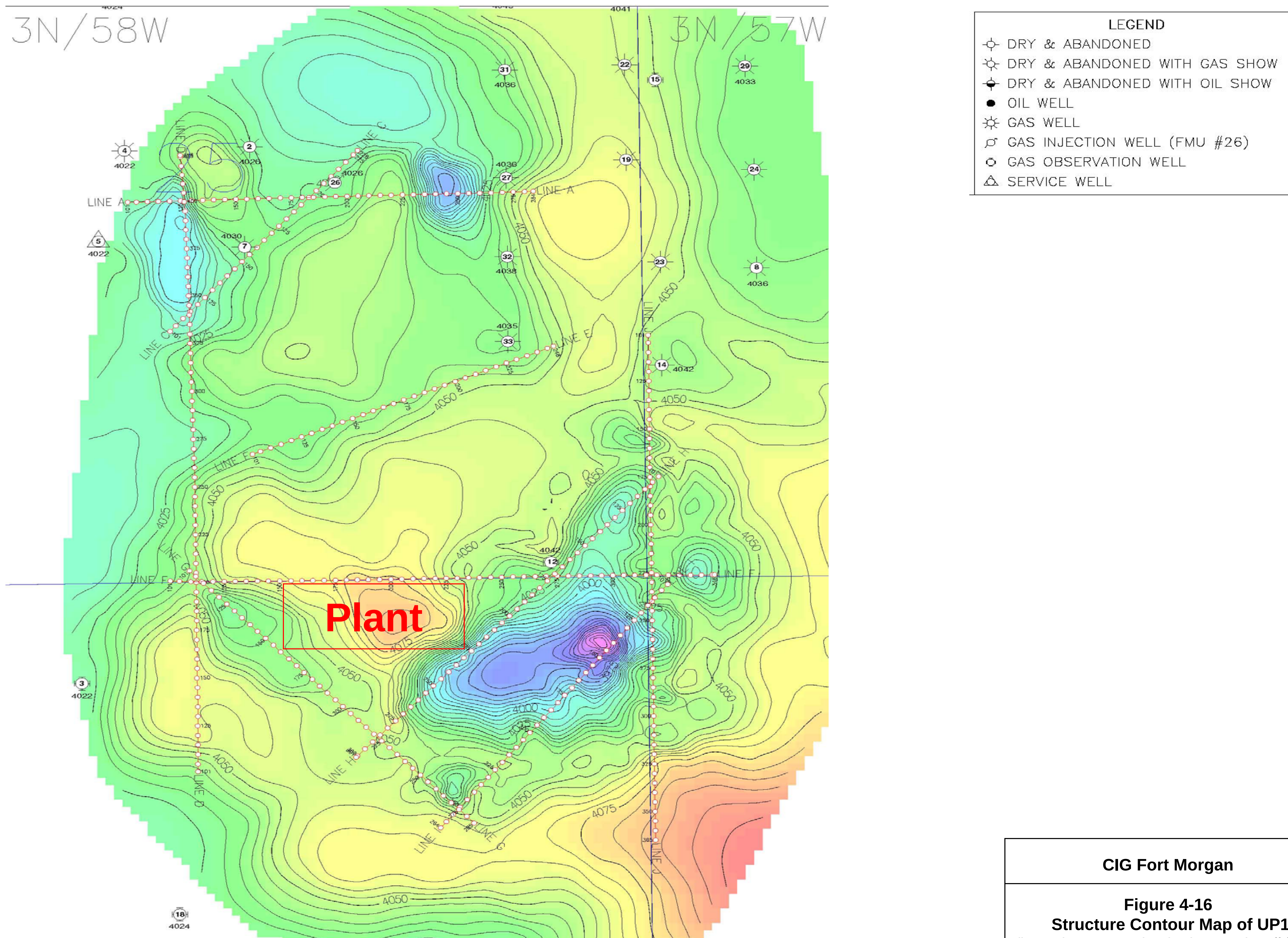
UP1 Depth Structure 3-D Perspective map with notes- The possible gas migration pathways have been added to the 3-D perspective map of the UP1 depth structure derived from the 3-D interpretation. This helps visualize the potential pathways of gas migration from the Gas Storage Well No. 26 borehole to the highest structure.

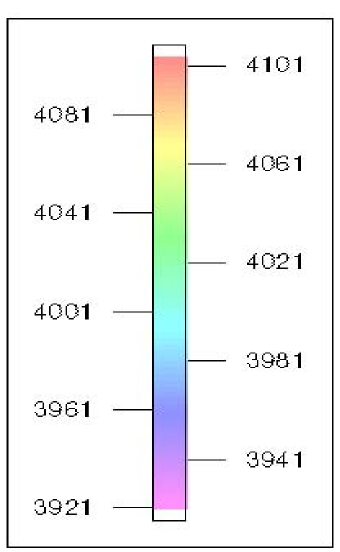
This mapped data was acquired many years prior to the Gas Storage Well No. 26 casing split. The newly acquired 2-D were not used in the generation of this map.



CIG Fort Morgan

Figure 4-15
Perspective View of UP1 Structure
(based on 3-D seismic data and well logs)





Contour Interval: 5 feet

CIG Fort Morgan

Figure 4-16
Structure Contour Map of UP1
(based on 2-D seismic data and well logs)

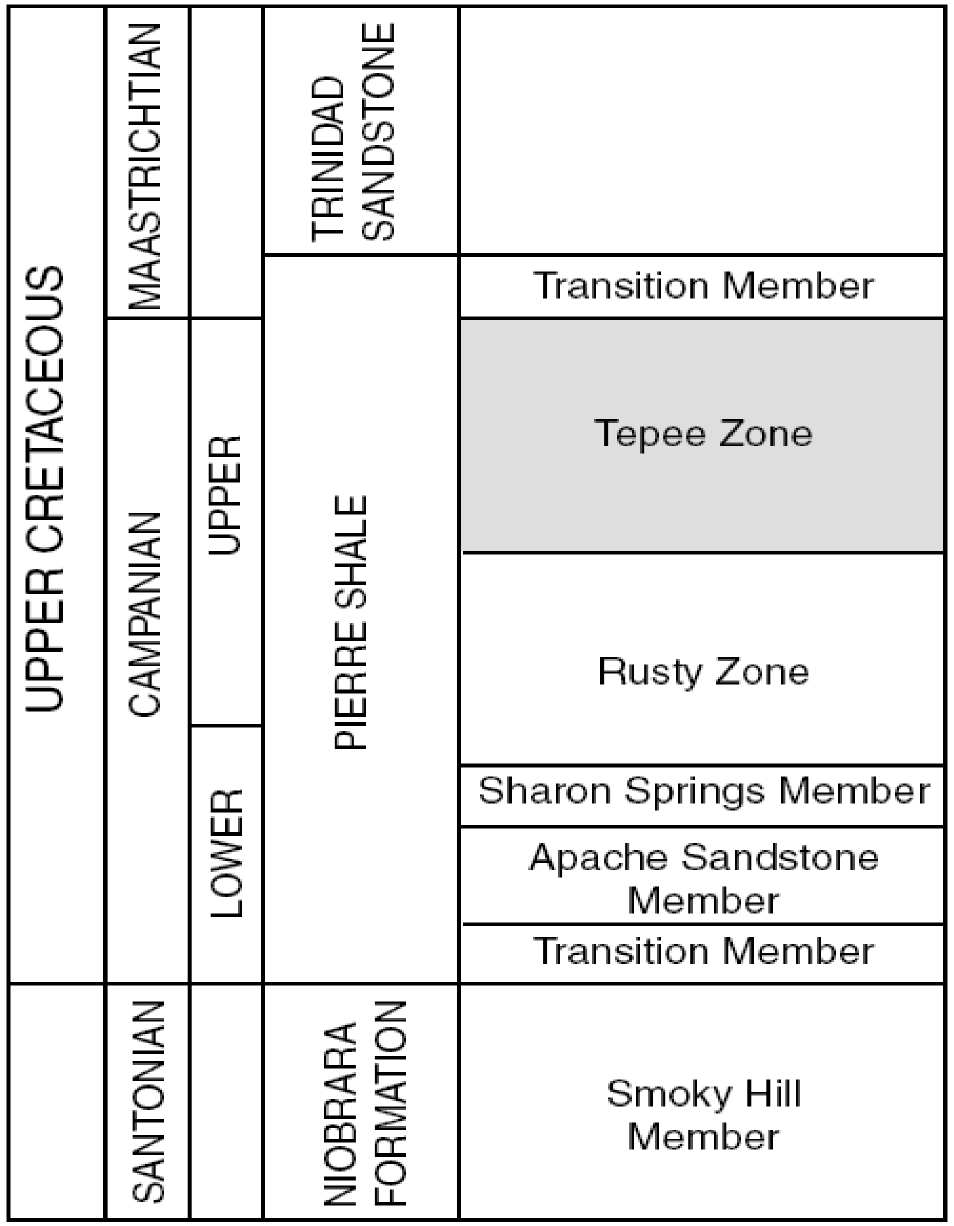


Figure 3. Stratigraphic position of the Tepee Buttes within the Upper Cretaceous of the Western Interior Seaway. The buttes occur within the *Baculites scotti* and *Didymoceras nebrascense* fossil assemblage zones. From Howe (1987).

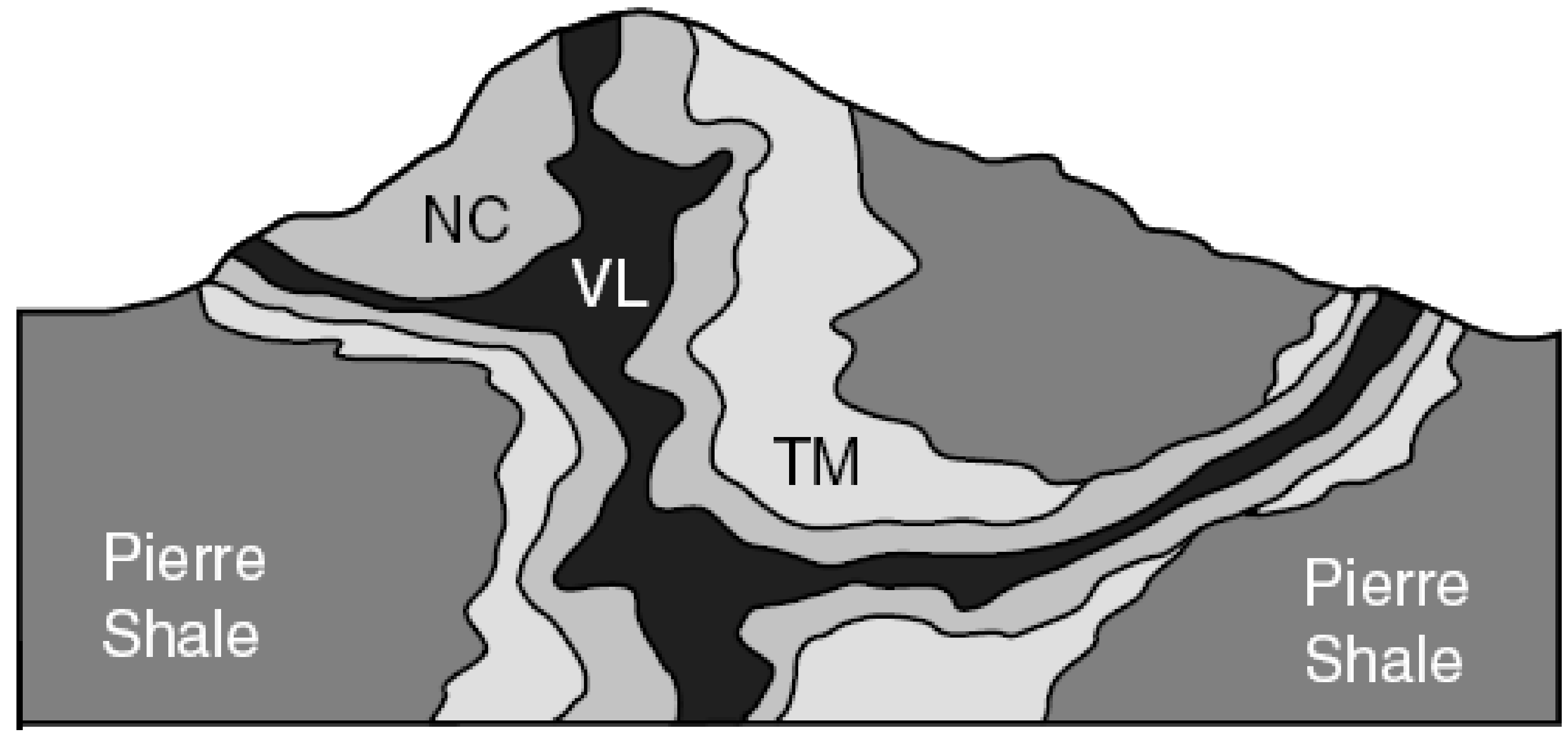


Figure 4. Simplified distribution of lithofacies of a typical Tepee Butte within the Pierre Shale (modified from Kauffman et al., 1996, figure 3). The central vent (in black) is defined by vuggy limestone (VL) and *Nymphalucina* coquinas (NC). Surrounding these central facies is the "pelletoid micrite facies" of Howe (1987) that we interpret to be thrombolitic microbialite (TM).

From Shapiro and Fricke (2002) and Kauffman et al (1996)

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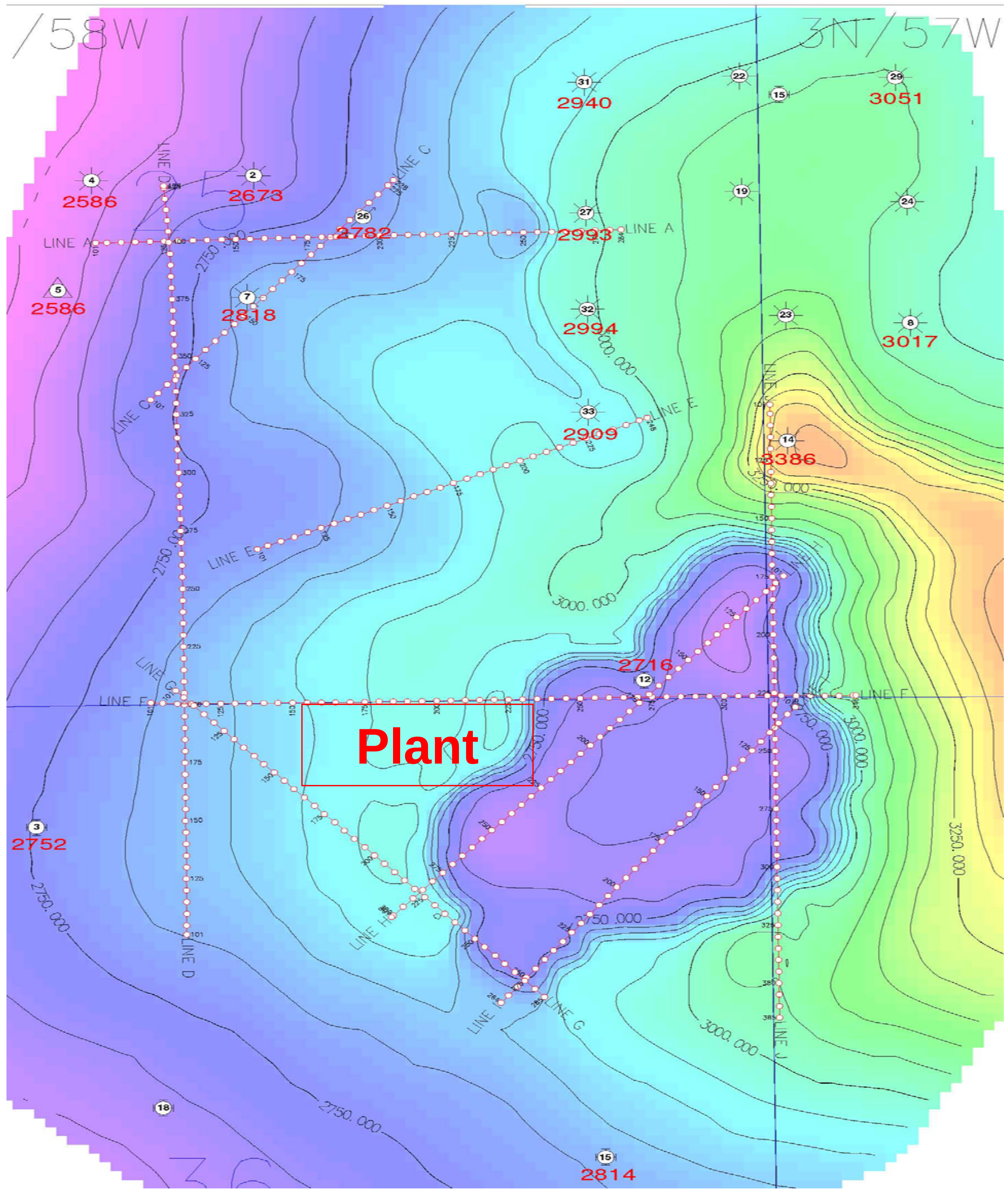
Figure 4-17 **Limestone Mounds in Upper Pierre Shale**



	3433
3333	
	3233
3133	
	3033
2933	
	2833
2733	
	2633
2533	

Contour Interval: 5 feet

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Figure 4-18
Upper Pierre (UP1) Average Velocity
(based on 2-D seismic data)

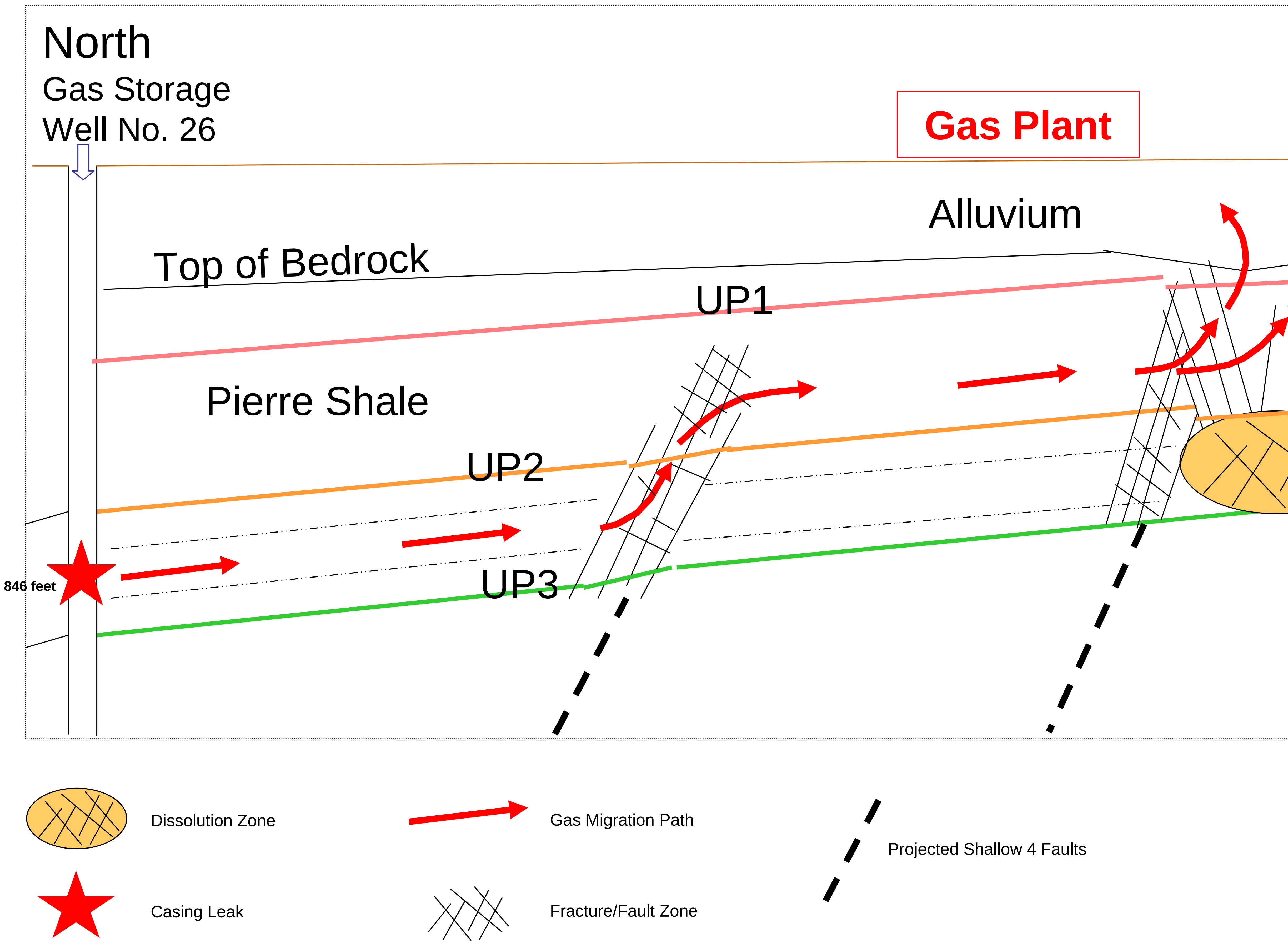

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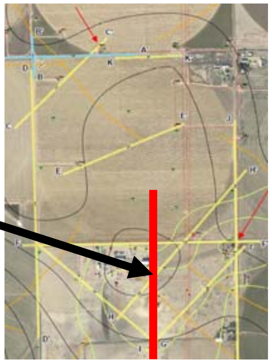
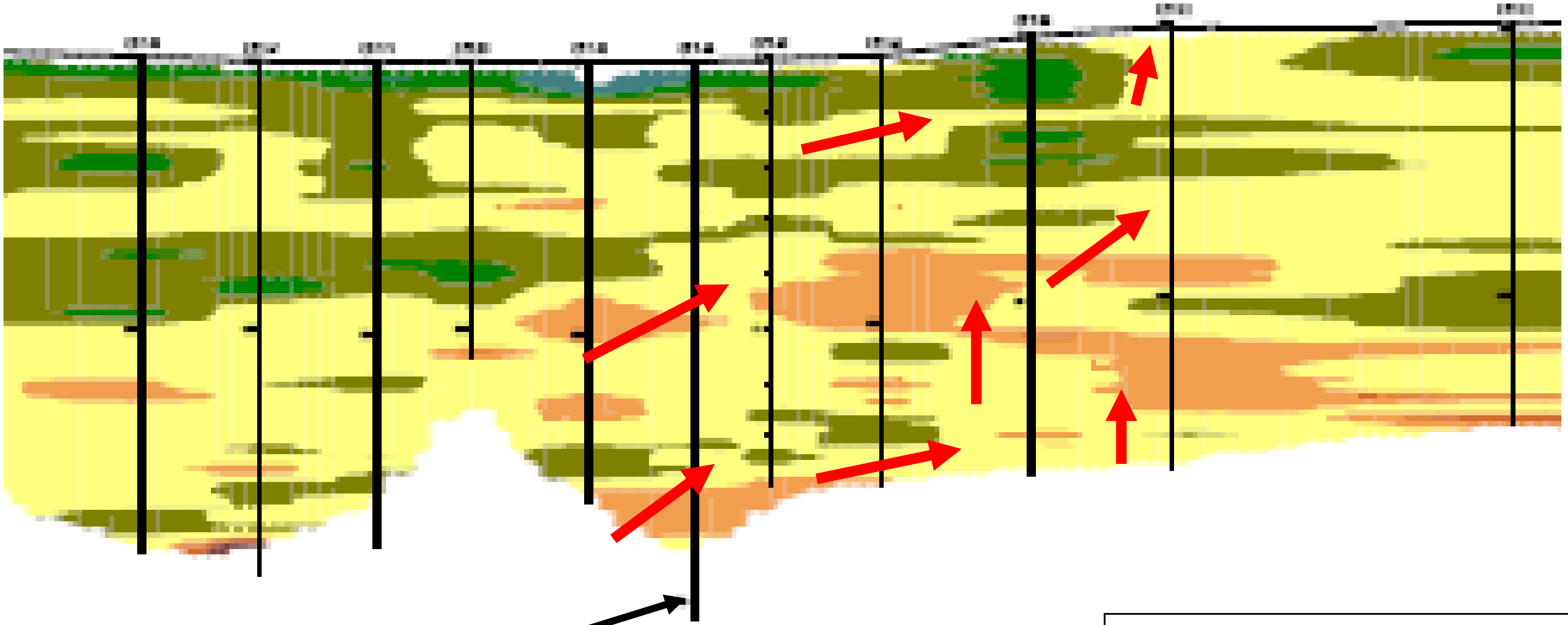
Figure 4-19
Conceptual Model of Gas Migration

Cross-section L-L’





100 feet deep, beneath SE corner of Gas Plant

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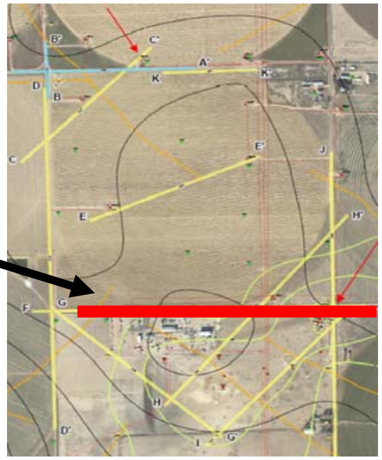
Figure 4-20
Conceptual Gas Migration Paths in Alluvium, Cross-section L-L’

Cross-section D-D’



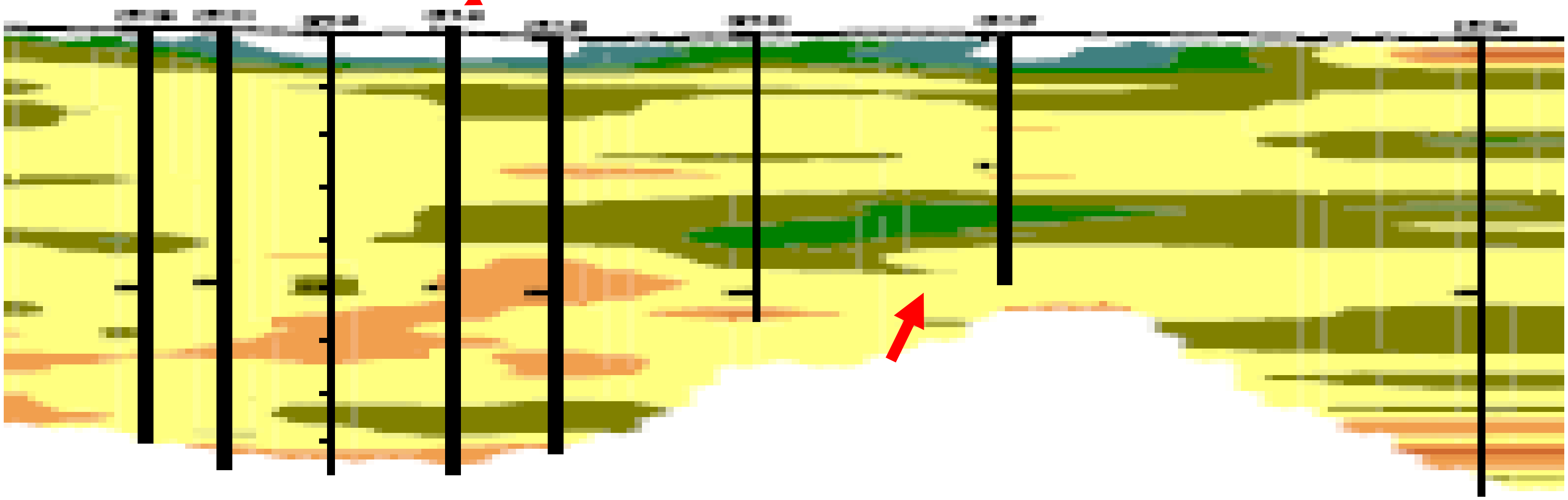


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Figure 4-21
Conceptual Gas Migration Paths in Alluvium, Cross-section D-D’

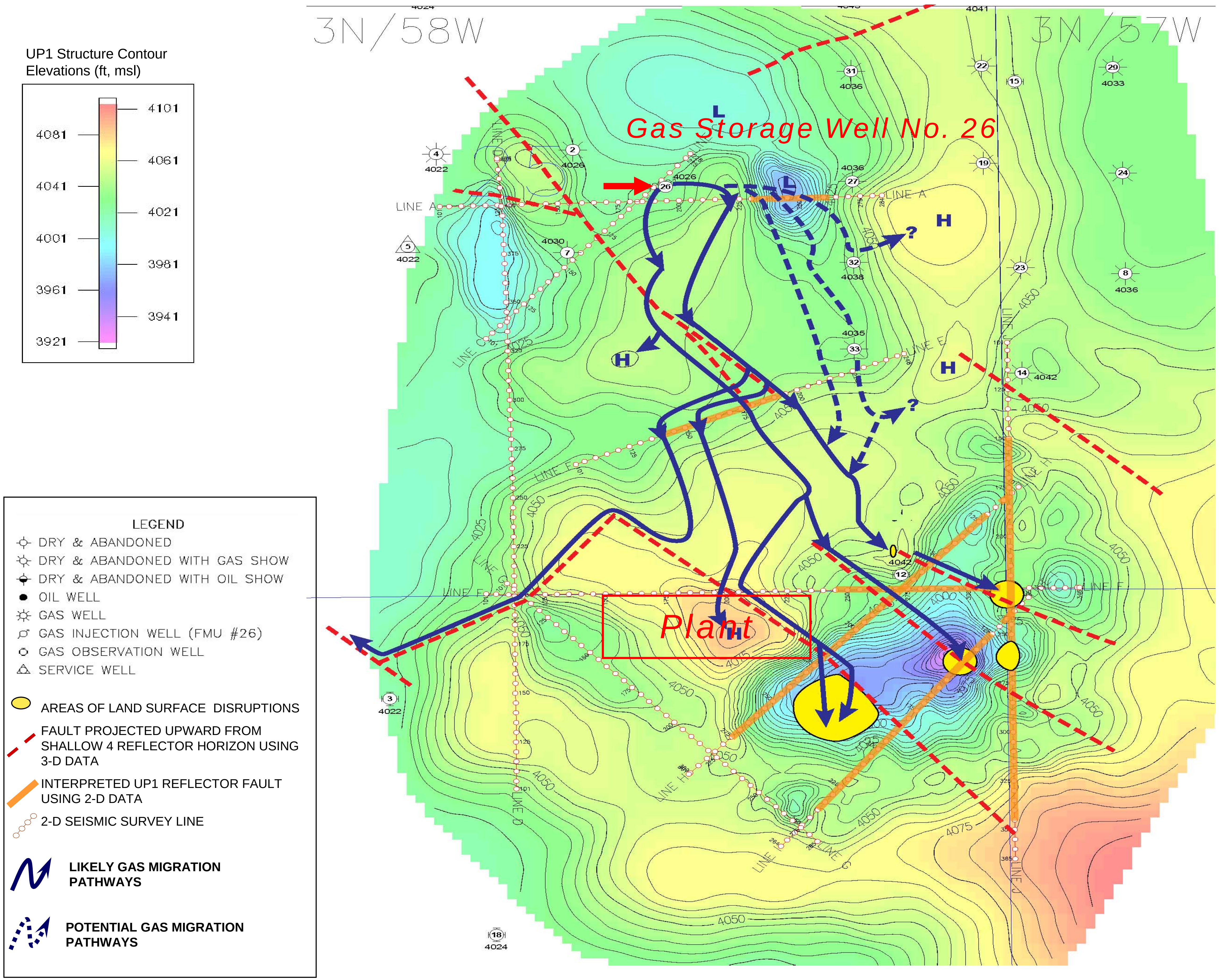

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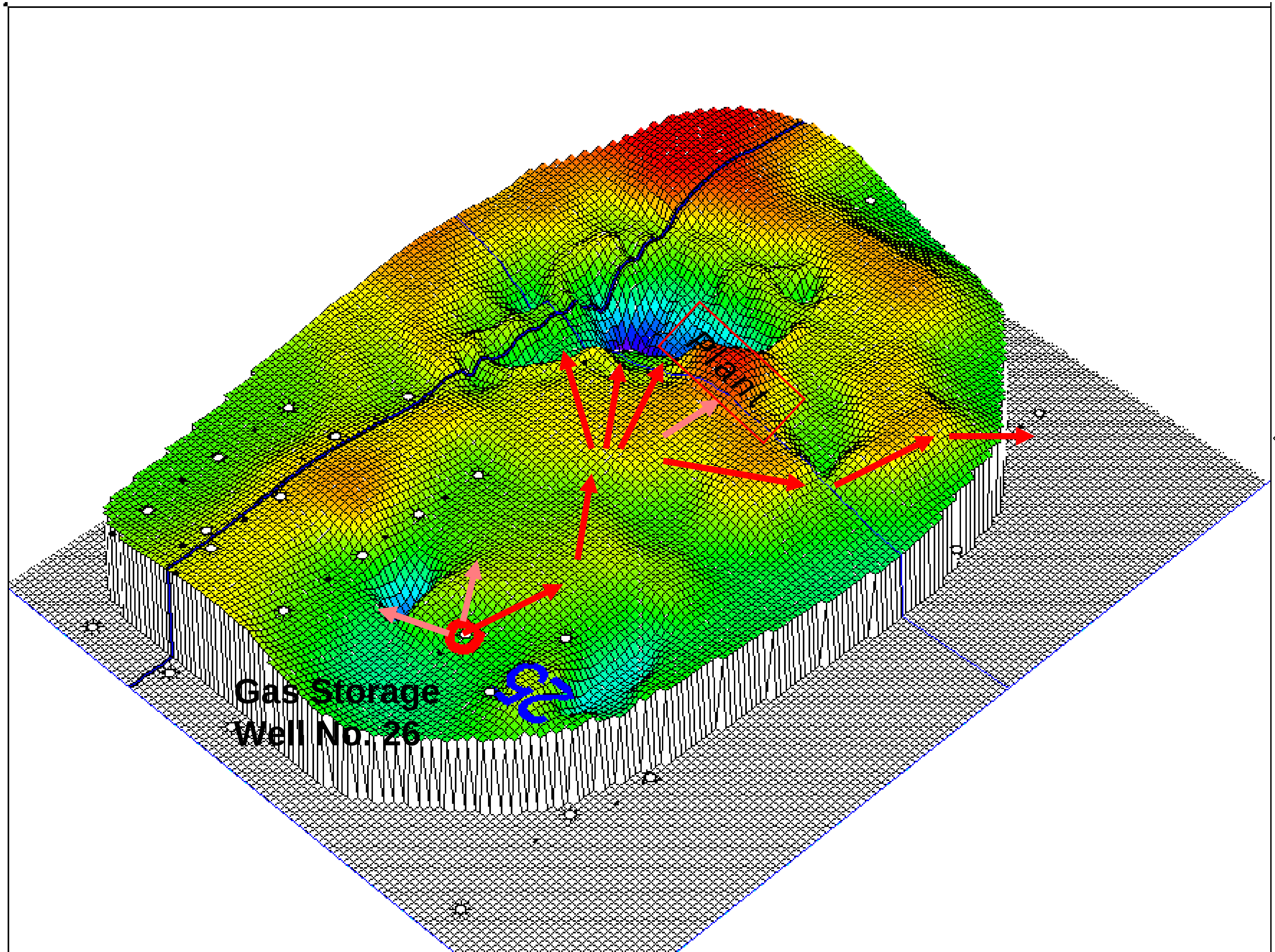
Figure 4-22
Map View of Conceptual Model of Gas Migration Pathways



UP1 2-D Depth Structure 3-D Perspective map-The calculated depth structure of the UP1 formation mapped from the 2-D data is shown in a 3-D perspective map. The viewing angle is from the NW. The structural high is to the SE from the Gas Storage Well No. 26, which is circled. The structural low that remains in the NE of section 36 is a result of an even lower average velocity existing than that predicted by the calculations at the well ties.

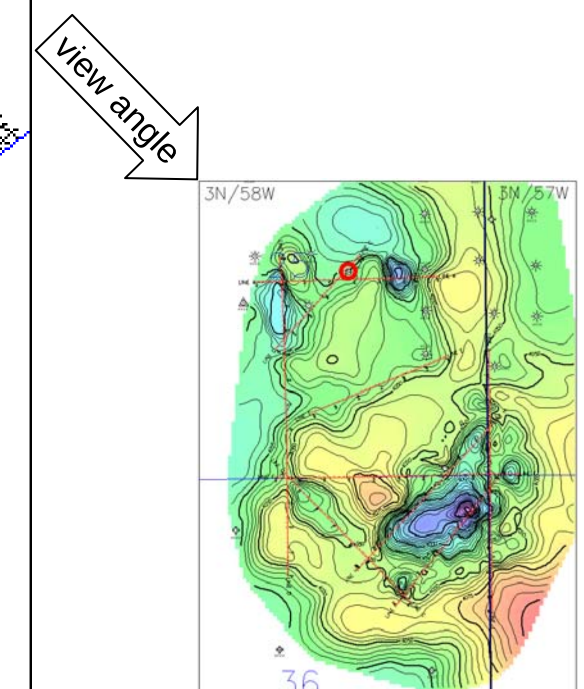


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Figure 4-23
Perspective View of Gas Migration Paths on UP1 Structure