RIVERTON DOME GAS EXPLORATION AND STIMULATION TECHNOLOGY DEMONSTRATION, WIND RIVER BASIN, WYOMING

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ABSTRACT

The new exploration technology for basin center gas accumulations developed by R.C. Surdam and Associates at the Institute for Energy Research, University of Wyoming, was applied to the Riverton Dome 3-D seismic area. Application of the technology resulted in the development of important new exploration leads in the Frontier, Muddy, and Nugget formations. The new leads are adjacent to a major north-south trending fault, which is downdip from the crest of the major structure in the area.

In a blind test, the drilling results from six new Muddy test wells were accurately predicted. The initial production values, IP, for the six test wells ranged from < one mmcf/day to four mmcf/day. The three wells with the highest IP values (i.e., three to four mmcf/day) were drilled into an intense velocity anomaly (i.e., anomalously slow velocities). The well drilled at the edge of the velocity anomaly had an IP value of one mmcf/day, and the two wells drilled outside of the velocity anomaly had IP values of < one mmcf/day and are presently shut in. Based on these test results, it is concluded that the new IER exploration strategy for detecting and delineating commercial, anomalously pressured gas accumulations is valid in the southwestern portions of the Wind River Basin, and can be utilized to significantly reduce exploration risk and to increase profitability of so-called basin center gas accumulations.

Most importantly, this study strongly suggests that a prime exploration prospect exists in the Riverton Dome 3-D seismic survey area. At this location, the new IER conceptual model and exploration technology can be tested in three targeted formations (i.e., the Frontier, Muddy, and Nugget formations) in a single well. At the prospect, in each of the formations there is an intense velocity anomaly that is 1800 to 1900 ms slower than would be predicted by the regional velocity - depth gradient. A velocity anomaly of this magnitude can only be explained by the presence of significant gas accumulations. *Thus, it is concluded that a well drilled at CDP 124896 in the Riverton Dome 3-D seismic survey is not only an ideal test of the IER exploration technology, but also the highest priority drill site for so-called basin center gas accumulations within the survey area.*

INTRODUCTION

A primary objective of the Institute for Energy Research (IER)-Santa Fe Snyder Oil Company-DOE Riverton Dome project is to test the validity of a new conceptual model and resultant exploration paradigm for so-called "basin center" gas accumulations (Surdam, 1997; see Figure 1). This paradigm and derivative exploration strategy suggest that the two most important tasks crucial to the development of prospects in the deep, gas-saturated portions of Rocky Mountain Laramide Basins are (1) the determination and, if possible, three-dimensional evaluation of the pressure boundary between normal and anomalous pressure regimes (i.e., this boundary is typically expressed as a significant inversion in both sonic and seismic velocity-depth profiles), and (2) the detection and delineation of porosity/permeability "sweet spots" (i.e., areas of enhanced storage capacity and deliverability) in potential reservoir targets below this boundary (Figure 1). There are other critical

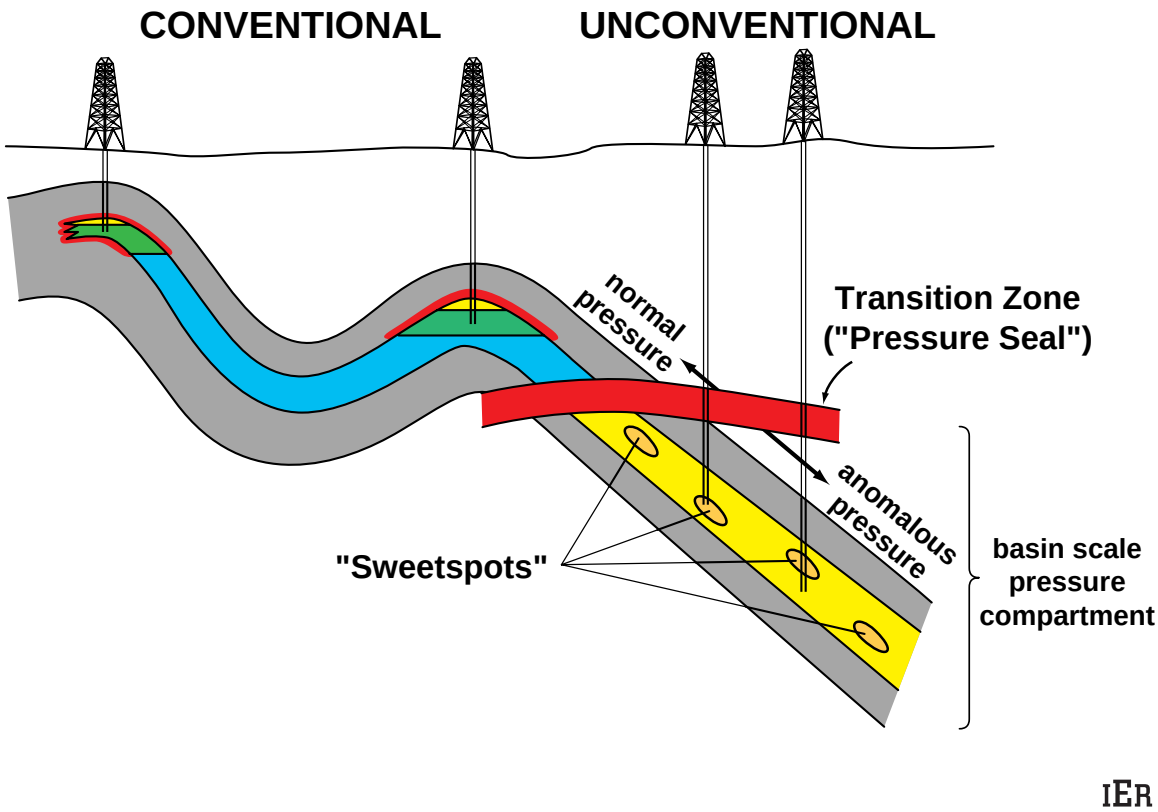


Figure 1. Conceptual model for basin-center, anomalously pressured gas accumulations. Key elements are (1) the regional pressure seal expressed as a sonic or seismic velocity inversion (i.e., regional boundary that separates normally pressured rocks above from anomalously pressured rocks below), and (2) production sweet spots below the regional pressure seal (i.e., domains characterized by enhanced porosity and permeability). Blue is fluid that is dominantly water (simple phase); yellow is fluid containing a significant free gas phase (multiphase) and red are capillary seals.

aspects in searching for basin center gas accumulations, but completion of these two tasks is essential to the successful exploration for the unconventional gas resources present in anomalously pressured rock/fluid systems in the Rocky Mountain Laramide Basins (RMLB).

The southern Wind River Basin, in particular the Riverton Dome area, is a neat location for testing this exploration paradigm (Figure 2). Preliminary work within the Wind River Basin has demonstrated that there is a regionally prominent pressure surface boundary that can be detected by inversions in sonic velocity-depth gradients in individual well log profiles (Figure 3) and that can be seen as a velocity inversion on seismic lines (Figure 4). Also, the Wind River Basin in general — and the Riverton Dome area specifically — are characterized by a significant number of anomalously pressured gas accumulations (Figure 5). Most importantly, Santa Fe Snyder Oil Company has provided the study with sonic logs, a 3-D seismic study (40 mi^2), and a variety of other necessary geological and geophysical information.

DATA SET AND METHODOLOGY

The most important portion of the available data set is the 3-D Riverton Dome seismic study, for it allows not only a three-dimensional velocity evaluation, but it also facilitates the application of new and/or modified existing technologies developed at IER to detect, visualize, and delineate basin center gas accumulations.

In this study, Echo Geophysical-processed seismic data were used as the basis for the velocity analysis. The processing stream included true amplitude recovery, surface consistent deconvolution, time variant spectral whitening, statics and applied residual statics. The data were summed in 500×550 ft bins with maximum offsets of 15,000 ft and then

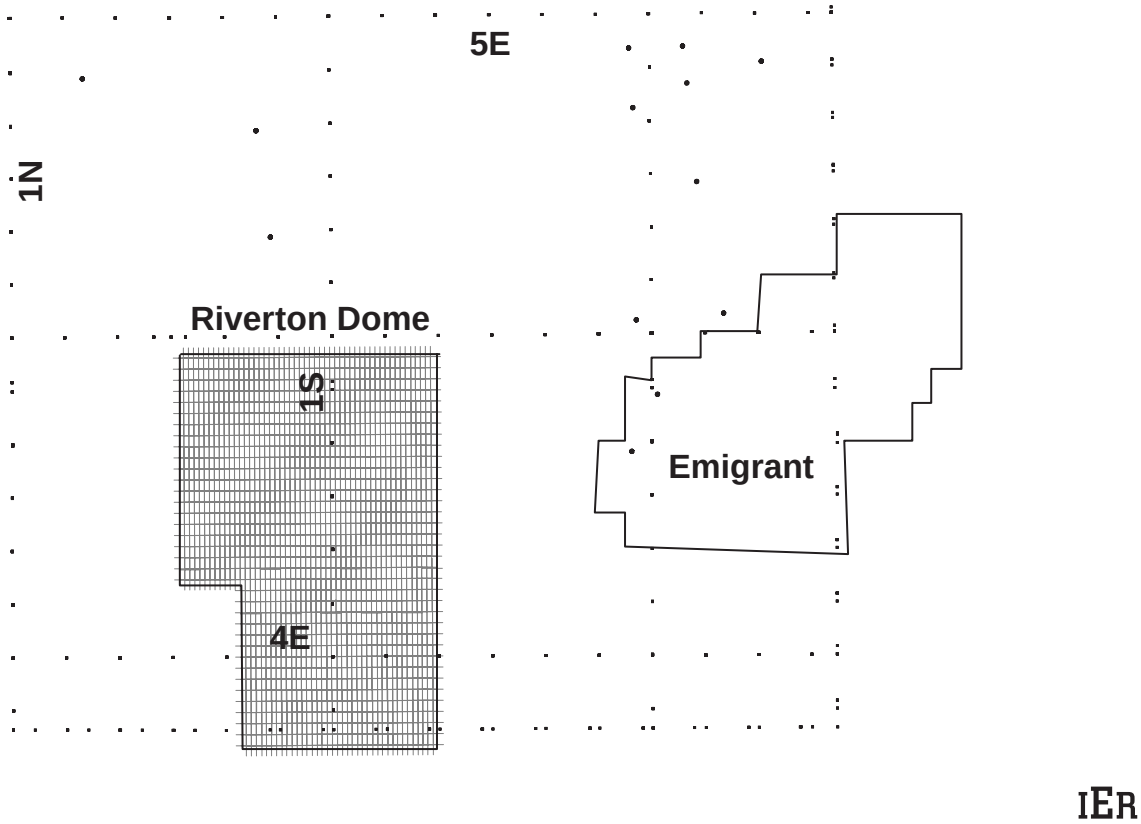


Figure 2. Index map for the Riverton Dome area, Wind River Basin, Wyoming.

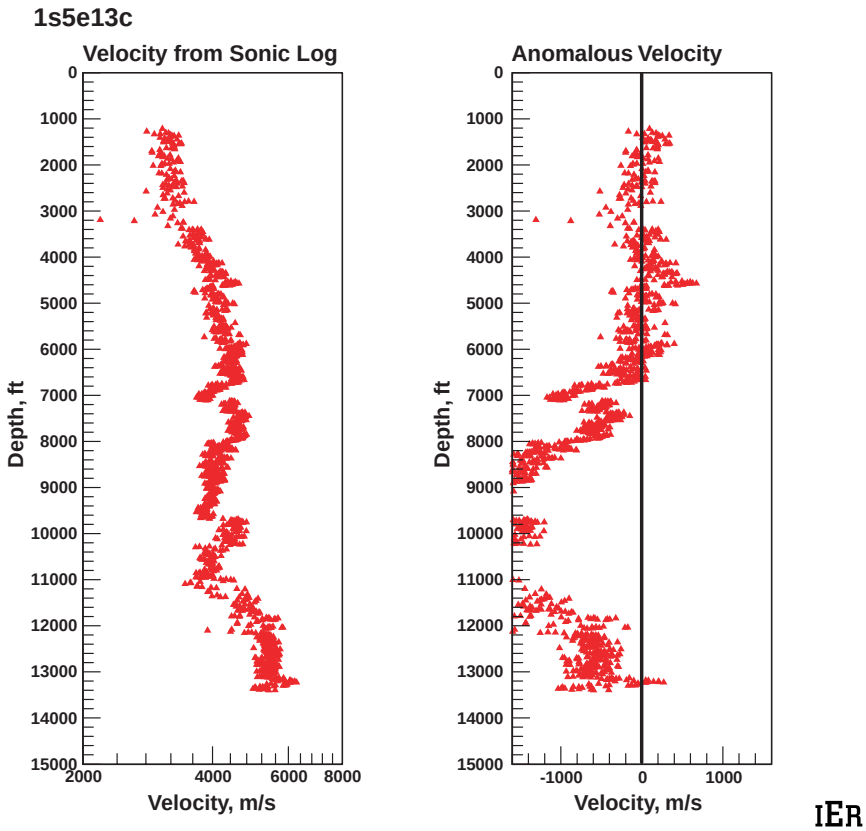


Figure 3. Sonic velocity log, and anomalous sonic velocity-depth profile after removal of normal regional velocity-depth gradient. This example is from within the Riverton Dome 3-D seismic survey area.

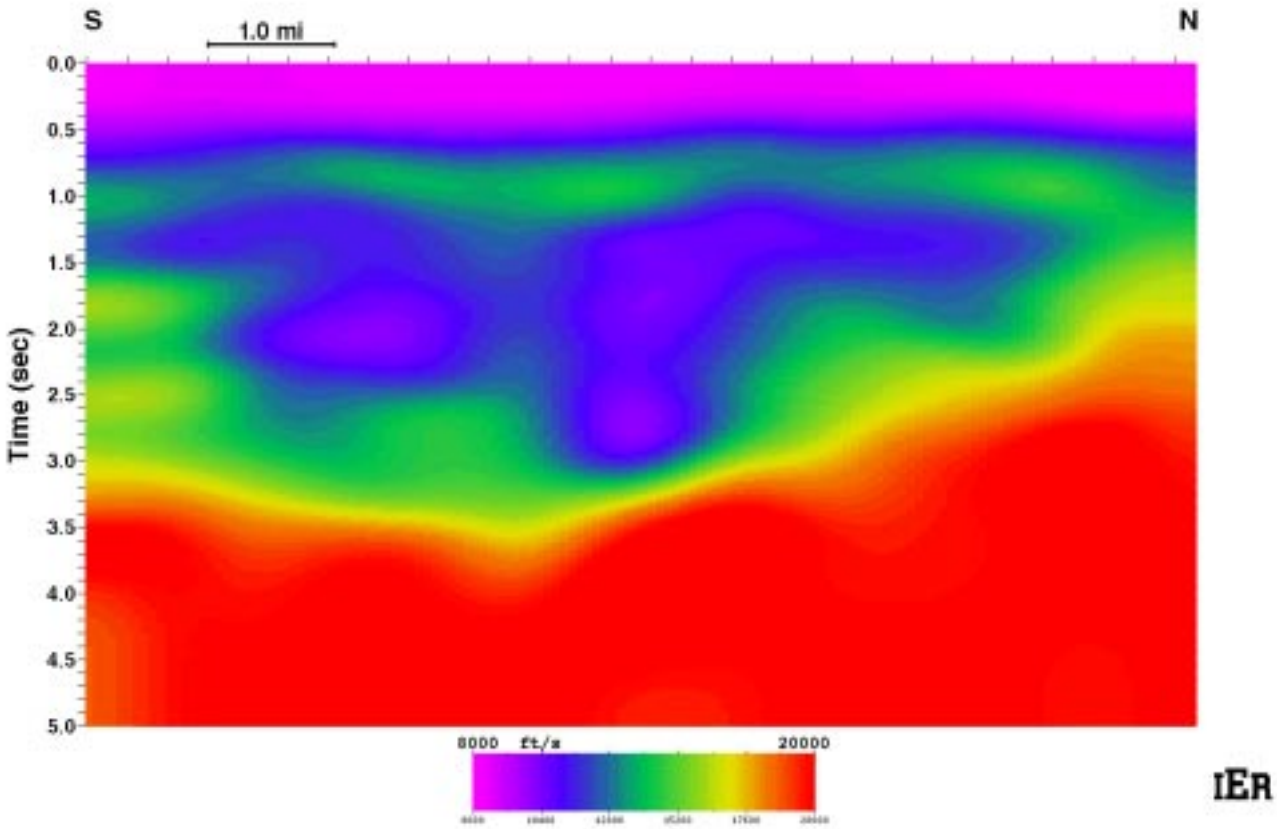


Figure 4. 2-D seismic interval velocity profile from a seismic line from the area north of the Riverton Dome area. Top of the regional pressure surface boundary is at the color change from green to blue at approximately 1.0 sec TWTT.

input into the ProMAX velocity analysis program.

In more detail, the Riverton Dome 3-D survey consists of 382 end lines and 577 cross lines. The end lines typically are separated by 100 ft and the cross lines are separated by 110 ft. For the purposes of this study, the velocity analysis was done on every tenth end line (i.e., 1000 ft intervals) and at every ninth cross line (i.e., 990 ft). The vertical sampling for the velocity study was done at 100 ms intervals. In contrast, commercial processing for velocity constructions typically utilize a grid of every 25th end line (i.e., every 2500 ft) and a sample point at every 50th cross line (5500 ft). Thus, the sampling grid utilized in this study (i.e., 60 points per end line) was considerably closer than in typical commercial processing (i.e., 10 to 11 samples per end line).

Thus far in the study, the two tasks accomplished include (1) the evaluation and construction of the velocity field in the Riverton Dome area according to the sampling strategy outlined above, and (2) isolation of anomalously slow velocity domains. Task 2 was accomplished by subtracting the normal regional velocity-depth gradient from the observed velocity-depth profile at 1620 sample points (i.e., CDP's; see Figure 6) in the Riverton Dome 3-D survey. A typical normal velocity-depth gradient for the study area was determined by modelling the compaction trend-sonic velocity-depth profile relationships from nearby well logs from within or from nearby well logs in the study area (Figure 3). In summary, the anomalous velocity profiles (Figures 7A - 7C) and volume (Figure 8) are the result of removing the typical regional normal velocity-depth profile from the observed velocity-depth gradients at each of the 1620 sample points. As noted in Figures 7A through 7C, the match with depth (or time) between anomalous seismic interval velocity and anomalous sonic velocity are not exact. The velocity-time gradients shown in Figures 7A - 7C are from

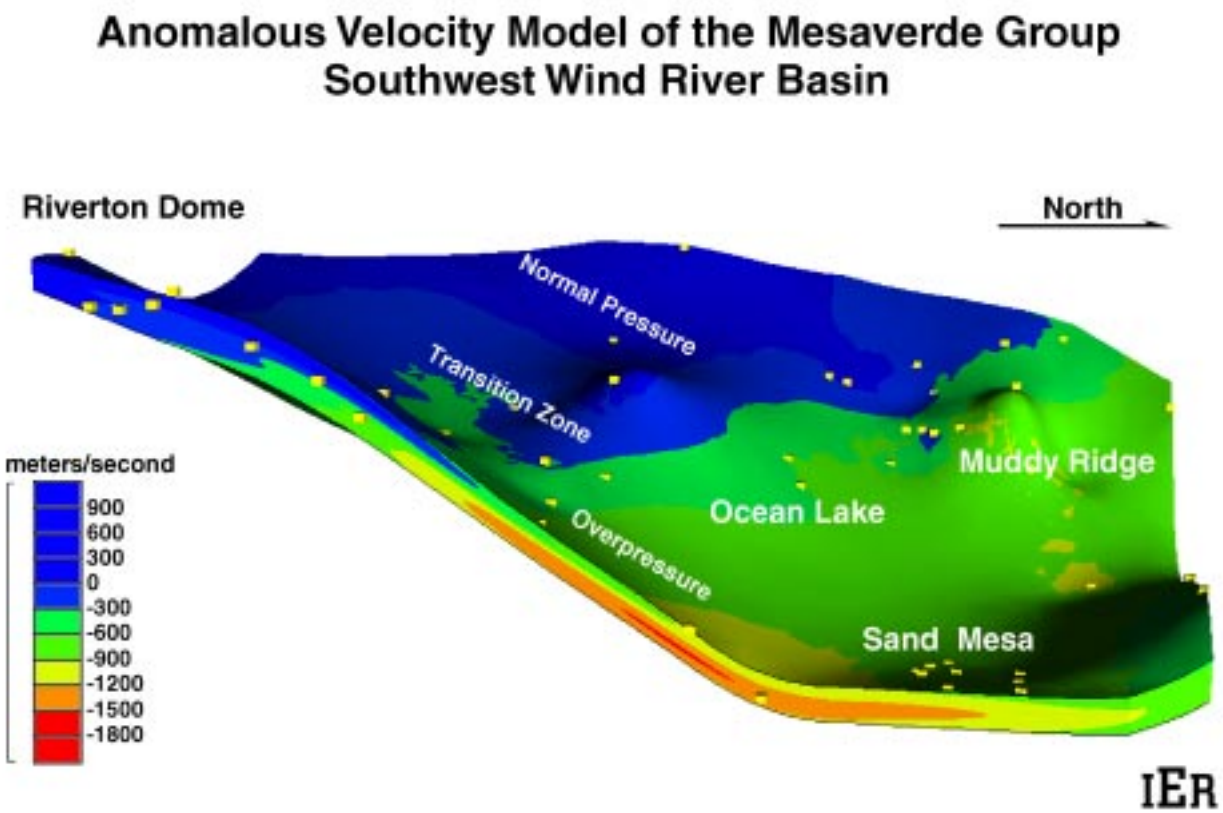


Figure 5. Three-dimensional anomalous sonic velocity model for the Mesaverde Group stratigraphic unit in the southwestern portion of the Wind River Basin, Wyoming. Model illustrates normal, transitional and anomalously pressured domains within the Mesaverde and locations of hydrocarbon fields. Yellow data are the well control for the figure.

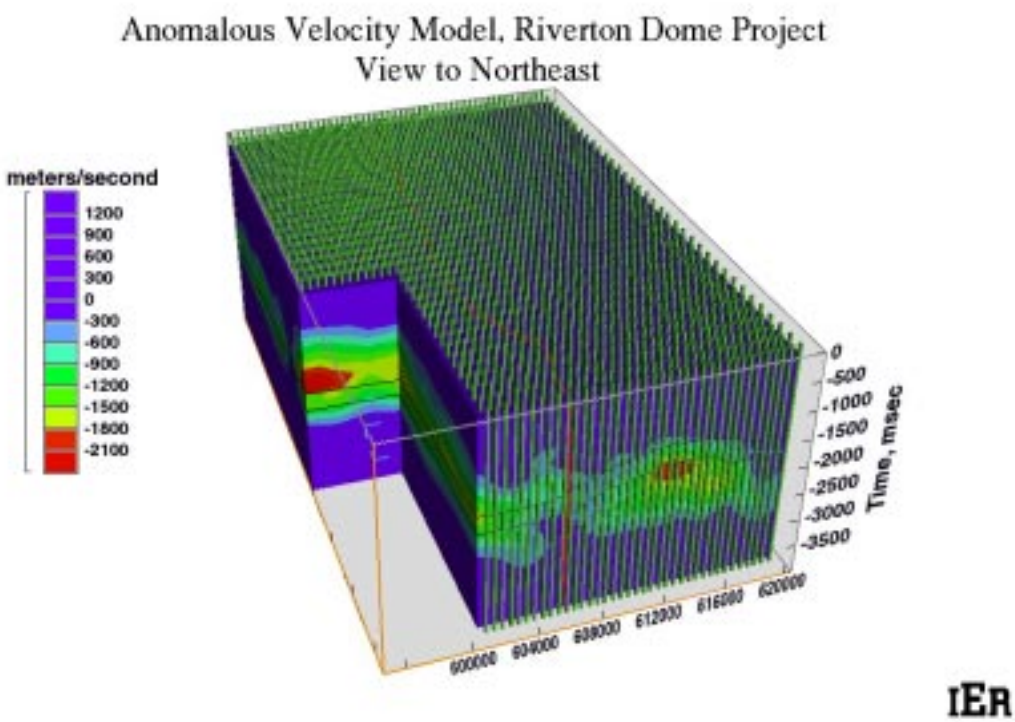
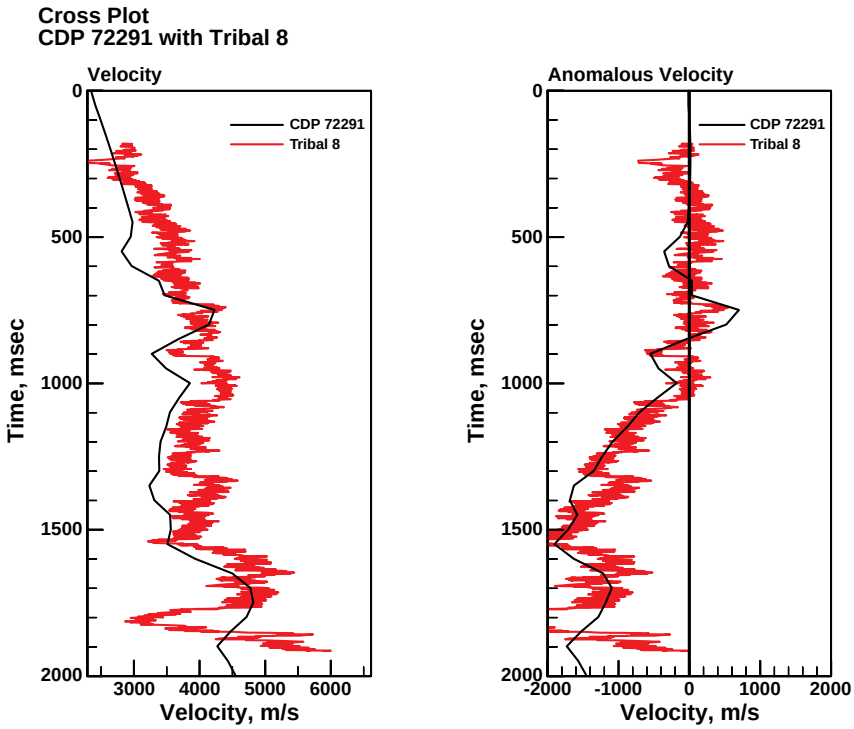


Figure 6. Anomalous seismic interval velocity volume derived from the Riverton Dome 3-D seismic survey. Figure shows location of 1620 CDP's used in this study; for each of the CDP's a velocity-depth (i.e., time) profile was constructed.

A.



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Figures 7A-C. Sonic and seismic interval velocity-depth profiles from coincident well logs and seismic line CDP's on the right side of the diagram (i.e., anomalous velocity profile) the typical velocity-depth gradient has been removed from both the sonic and seismic velocity profiles allowing for the isolation of anomalously slow velocity domains.

B.

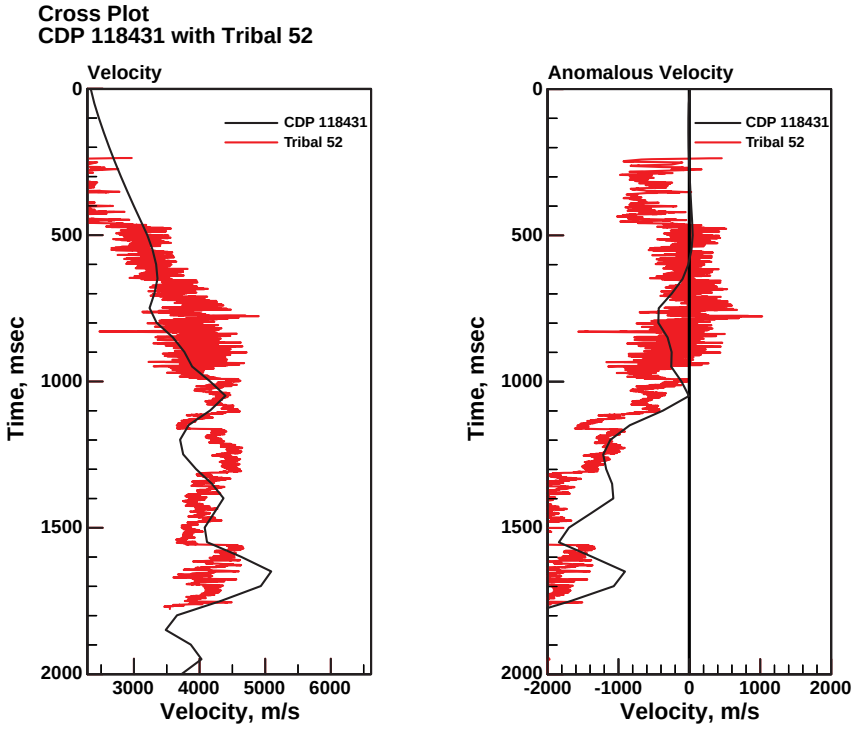

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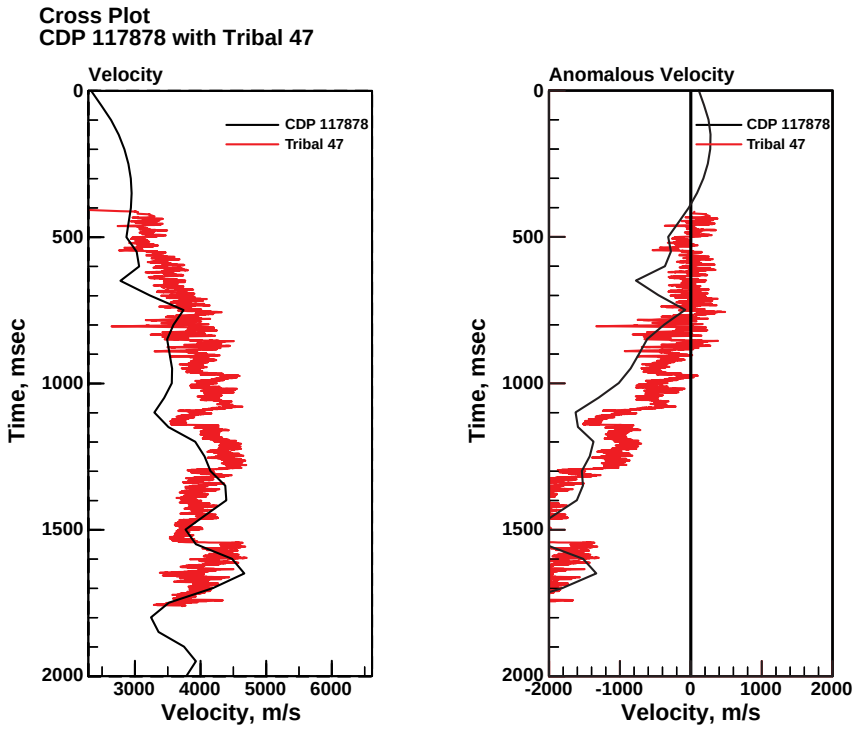
Figure 7B.



C.

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Figure 7C.

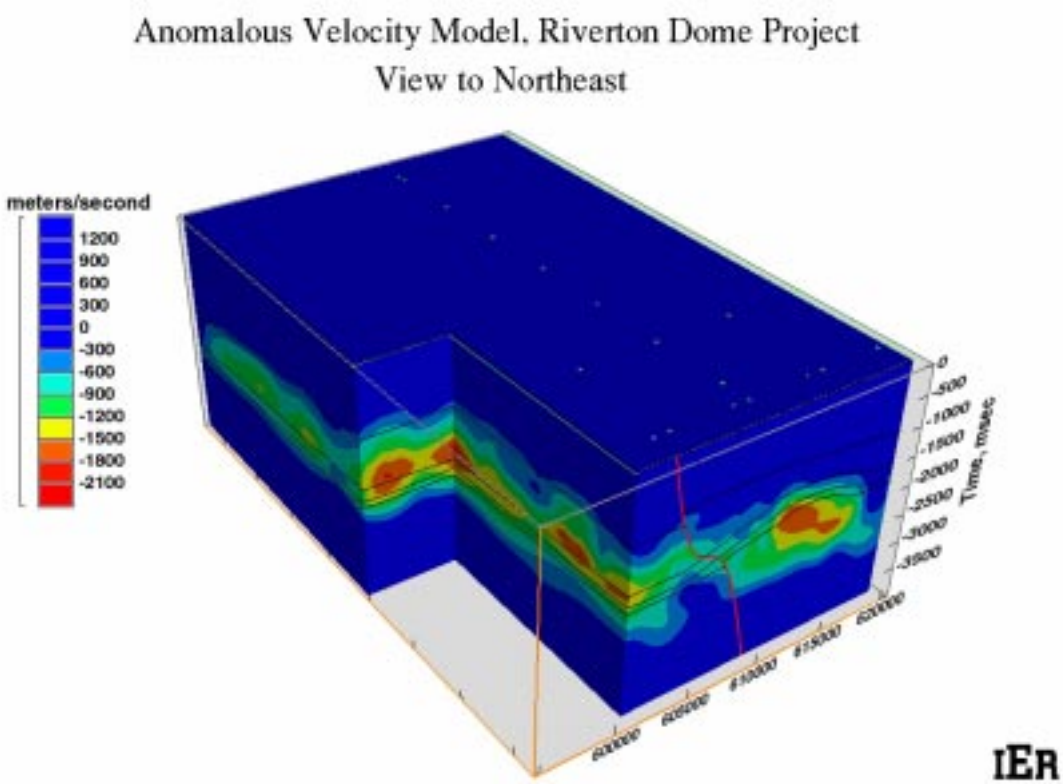

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Figure 8. Anomalous seismic interval velocity volume for the Riverton Dome, 3-D seismic survey. That portion of the volume shown in dark blue consists of rocks with a fluid system following a hydrostatic gradient and a normal or typical velocity-depth gradient. In contrast, those rocks shown in light blue, green, yellow and orange have fluid systems that are anomalously pressured and that are characterized by anomalously slow seismic velocities (i.e., fall below the typical regional velocity-depth gradient).

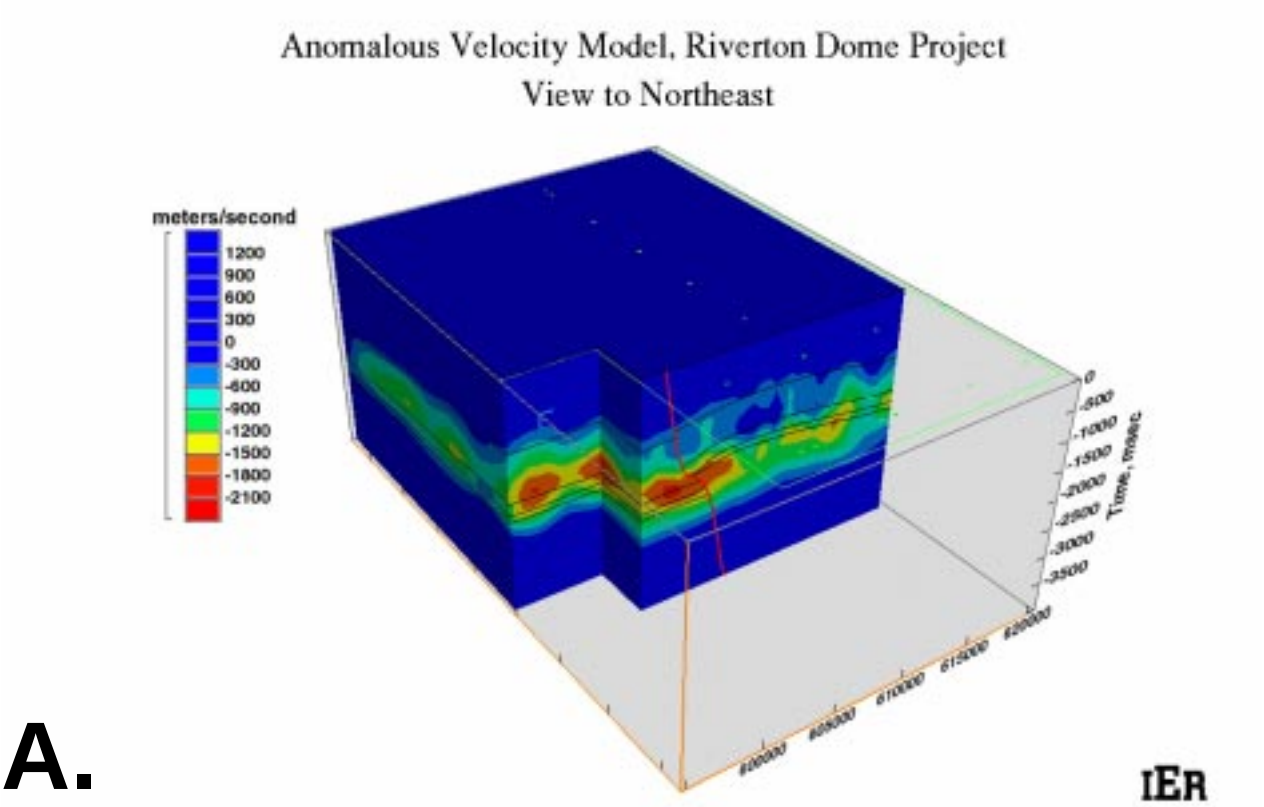


Figure 9A. East-west section through the anomalous velocity volume illustrated in Figure 8; the cross section is viewed from the southwest to northeast. Diagram demonstrates the intense velocity anomaly adjacent to the North-South fault running through the 3-D seismic survey area. Also note the topographic relief on the regional velocity inversion surfaces (i.e., color change from dark to light blue).

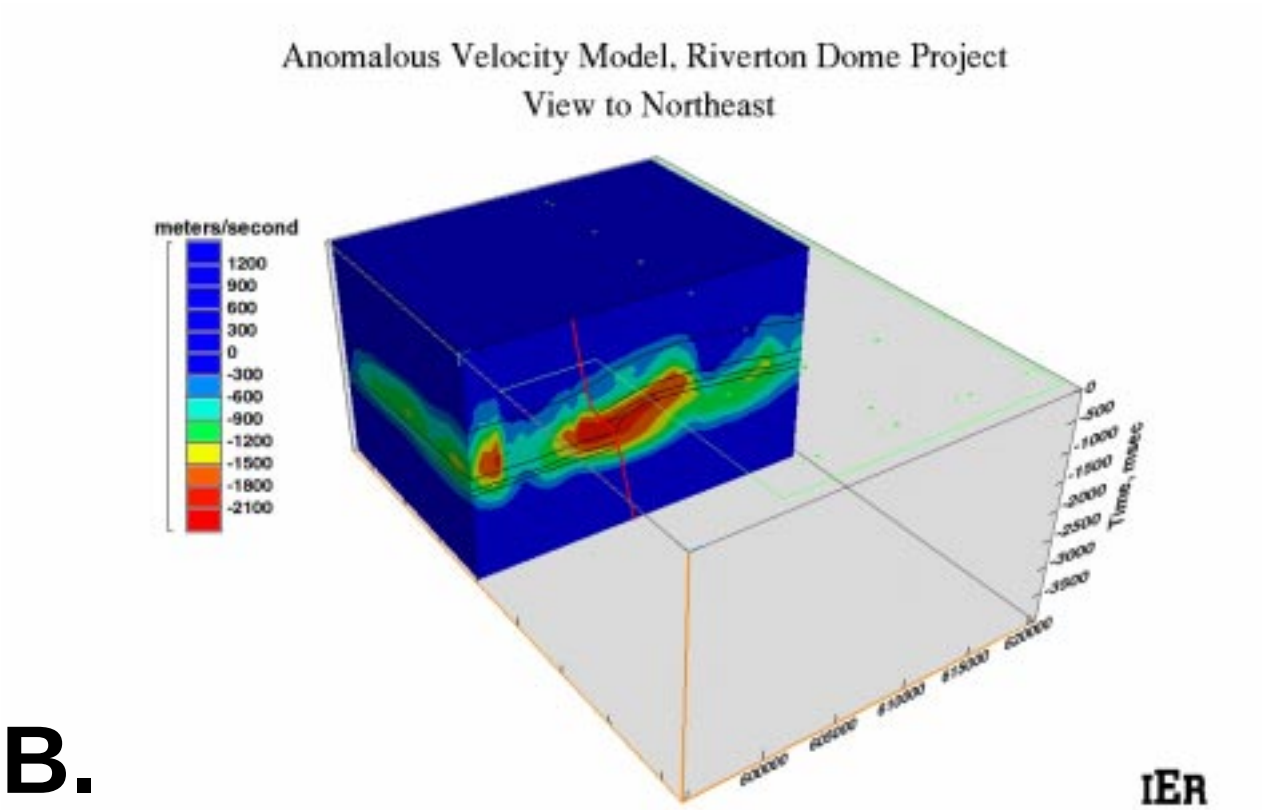


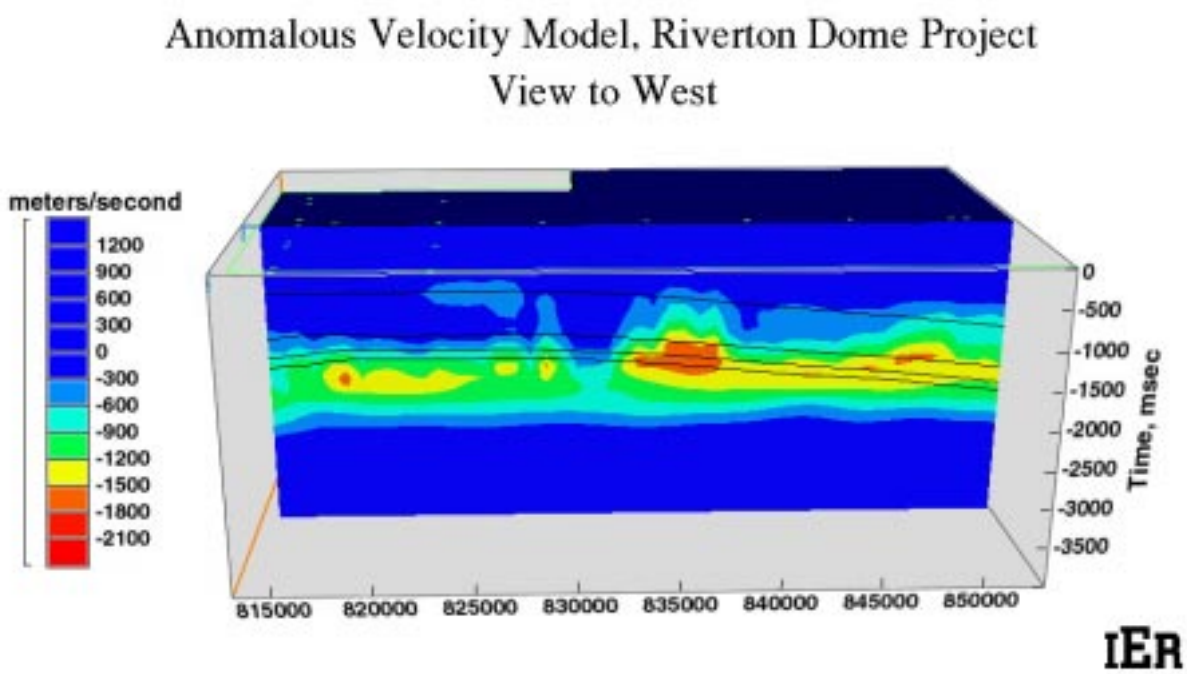
Figure 9B. Same as Figure 9A, only the east-west cross section is farther to the north.

wells that deviate from vertical, so it is impossible to match exactly the geographic position of a well with a CDP from the seismic survey. The comparisons shown in Figures 7A - 7C are from geographic overlapping CDPs (seismic velocity) and well locations (sonic velocity). Therefore, most of the differences noted in Figures 7A - 7C when comparing the seismic and sonic velocities can be attributed to uncertainties resulting from the deviation of the drilled wells. Any velocity domain falling below the typical regional velocity-depth profile is considered to be anomalously slow and is assigned a negative sign to signify that it is anomalously slow.

PRELIMINARY RESULTS

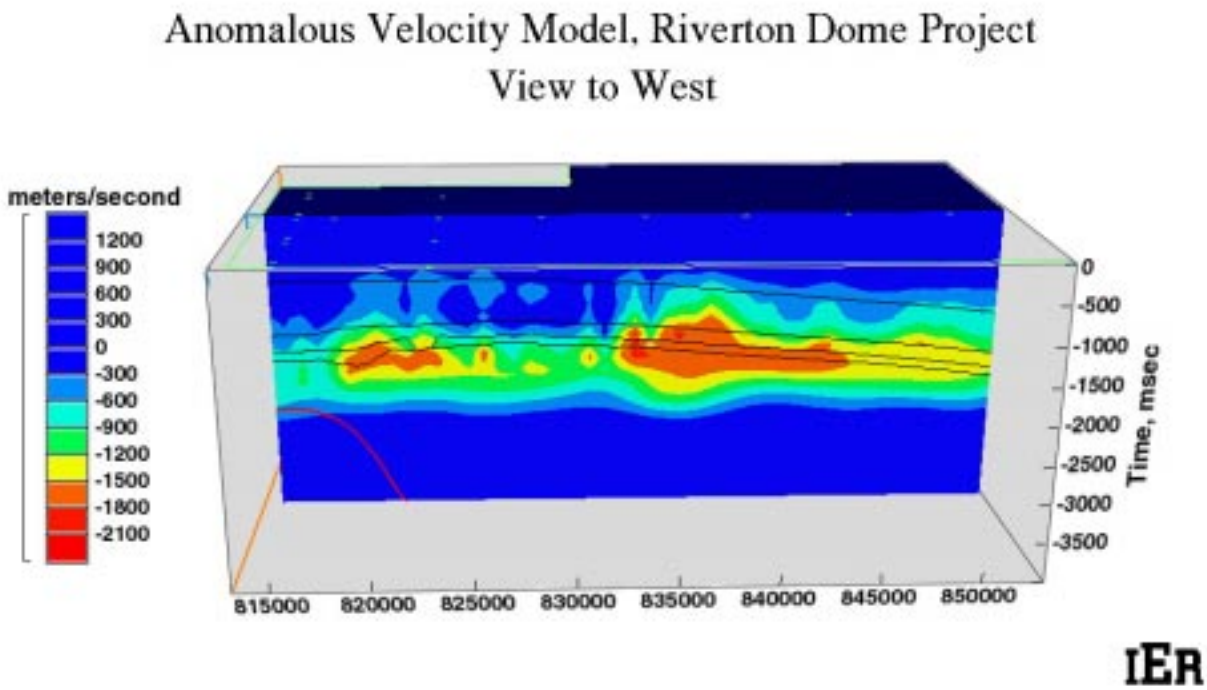
Using the procedures outlined above, it is possible in the Riverton Dome 3-D seismic survey area to detect and to delineate anomalously slow velocity domains in 3-D visualizations, as well as the regional pressure surface boundary/velocity inversion surface (see Figures 9A,B). Figures 9A and 9B are east-west cross sections through the anomalous velocity volume (Figure 8) in the study area viewed from the southwest to northeast. The red line shown in Figures 9A and 9B is a significant N-S fault in the Riverton Dome area; the position of the fault was determined from geological data provided to IER by Snyder Oil Company. Clearly illustrated in Figures 9A and 9B is the top of anomalous pressure (uppermost velocity inversion surface shown in the figures as a color change from dark to light blue) and domains of intense anomalously slow velocities (red color).

Figures 10 A-C are a series of north-south cross sections viewed from east to west through the anomalous velocity volume (Figure 8). Again the regional velocity inversion surface (i.e., pressure surface boundary) is clearly delineated, as are the intense velocity anomalies beneath the inversion surface. Note the significant topographic relief characterizing the regional velocity inversion surface (see especially Figures 10A - 10C). The topographic highs on the velocity inversion surface (Figures 10A - 10C) represent areas where



A.

Figure 10A. North-south cross section, view from east to west, through the anomalous velocity volume shown in Figure 8.



B.

Figure 10B. North-south cross section, view from east to west, through the anomalous velocity volume shown in Figure 8. Figure 10B is farther west than Figure 10A.

gas is penetrating up into the overlying stratigraphic section.

Figure 10C is a cross section cut very close to the place of the north-south fault mentioned previously. Based on the relationship between the fault plane and the velocity anomalies, it is concluded that the north-south fault plane is a controlling factor with regard to the distribution of anomalous velocity domains within the Riverton Dome velocity volume.

Also, it is possible to study the configuration of the regional velocity inversion surface by stripping away all of the overlying section to view the surface in three dimension (Figure 11A). The volume shown in Figure 11A represents not only the uppermost surface of the anomalous velocity volume, but also the whole anomalous velocity volume (both top and bottom). In Figure 11B, all anomalous velocity layers down to 1500 ms (anomalously slow) have been stripped off of the anomalous velocity volume; therefore Figure 11B is a representation of the most intense anomalously slow velocities in the anomalous velocity volume. As a consequence, of the operations illustrated in Figures 9, 10, and 11, it is possible to more fully define in detail the distribution and configurations of all anomalous velocity domains in the Riverton Dome 3-D seismic survey.

Velocity Anomalies

In Figures 12A and 12B, the stratigraphic section above the Cody Formation has been removed from the anomalous velocity volume. Therefore, the viewer is looking at the velocity character of the anomalous velocity at the top of the Cody Formation in both inclined (Figure 12A) and map views (Figure 12B). From Figures 12A and 12B it is apparent that in the southern half of the study area, the Cody is characterized by normal seismic interval velocity, and presumably normal pressures; whereas in the northern half of the area, the Cody is characterized by anomalously slow seismic interval velocities, and presumably anomalous pressures.

Figures 13A and 13B are similar constructions

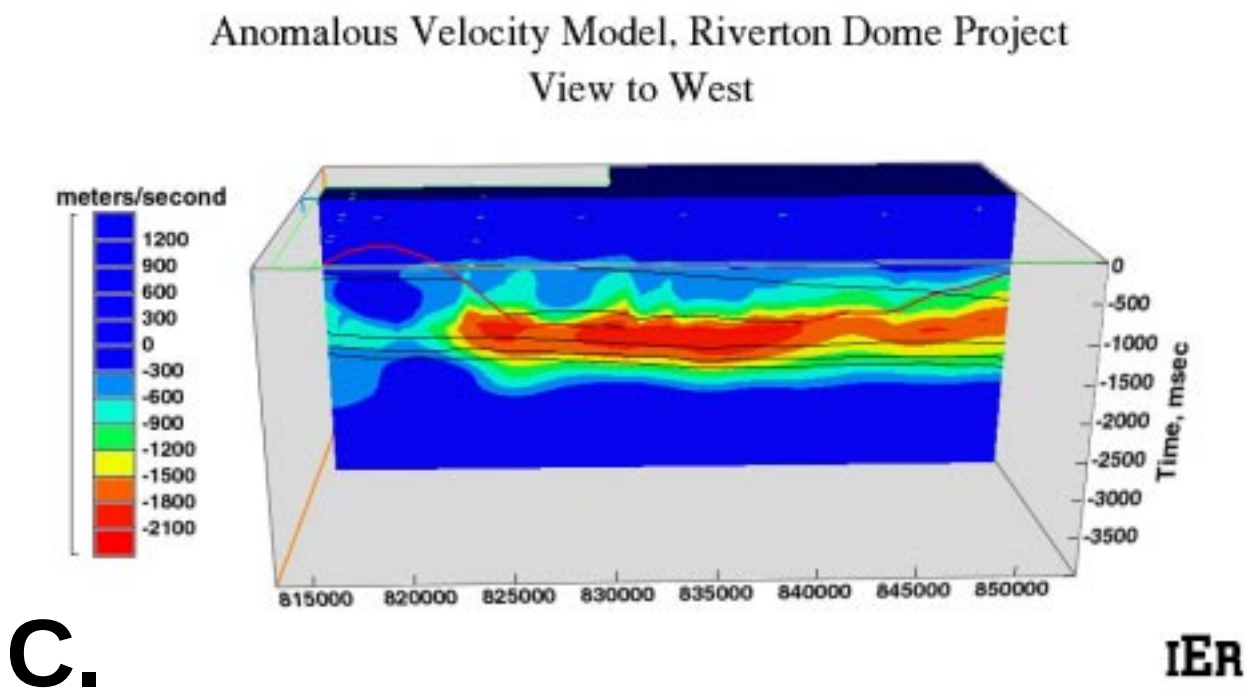


Figure 10C. North-south cross section through the anomalous velocity volume (Figure 8) approximately parallel to the fault plane of the major North-South fault that is located down dip and west of the major structural closure in the area (i.e., doubly plunging north-south anticline).

for the top of the Frontier Formation. It is clear from Figures 13A and 13B that there is a significant domain adjacent to the north-south fault that is anomalously slow. This particular velocity anomaly is observed in 10% or 160 of the 1620 CDP's shown in Figure 6. From Figure 9A it is concluded that this anomaly extends down into the main portion of the Frontier Formation.

East of the anomaly along the fault at the crest of the structure there is normally pressured hydrocarbon production in the Frontier Formation (see location of the Tribal 8 well on Figure 14B). Figures 14A and 14B clearly illustrate that at the crest of the structure east of the fault, a portion of the Frontier Formation is characterized by normal velocity (i.e., velocity values falling on the typical regional velocity-depth gradient). In both Figures 14A and 14B, the rocks within that part of the Frontier Formation characterized by normal velocity have been removed. Clearly, the removal of the rocks creates a canyon or topographic low on the Frontier anomalous velocity volume at the crest of the structure and trending from south to north. Production histories demonstrate that the Frontier rocks that were removed (thereby creating the topographic low; Figure 14B) are normally pressured. From the geometry of the topographic low, it is speculated that the low represents a north-south channel-like sandstone within the Frontier Formation that is draped over the structure (i.e., north-south anticline plunging to the north). This "channel" sandstone is probably connected to the Frontier outcrop that occurs to the south of the Riverton Dome area. This scenario would explain how the Frontier Formation could be normally pressured (i.e., fluid system follows a hydrostatic gradient) at the crest of the structure, but with anomalously pressured rocks downdip to the west in the vicinity of the north-south fault. The sandstones within the channel probably are recharged by meteoric water from the south with hydrocarbons collecting at the crest of the structure due to a strong water drive. In strong contrast, the Frontier Formation down dip to the west is isolated from the outcrop and is being charged with hydrocarbons migrating up along the north-south fault.

Figures 15A and 15B represent inclined and map views of the Muddy Formation. The spatial

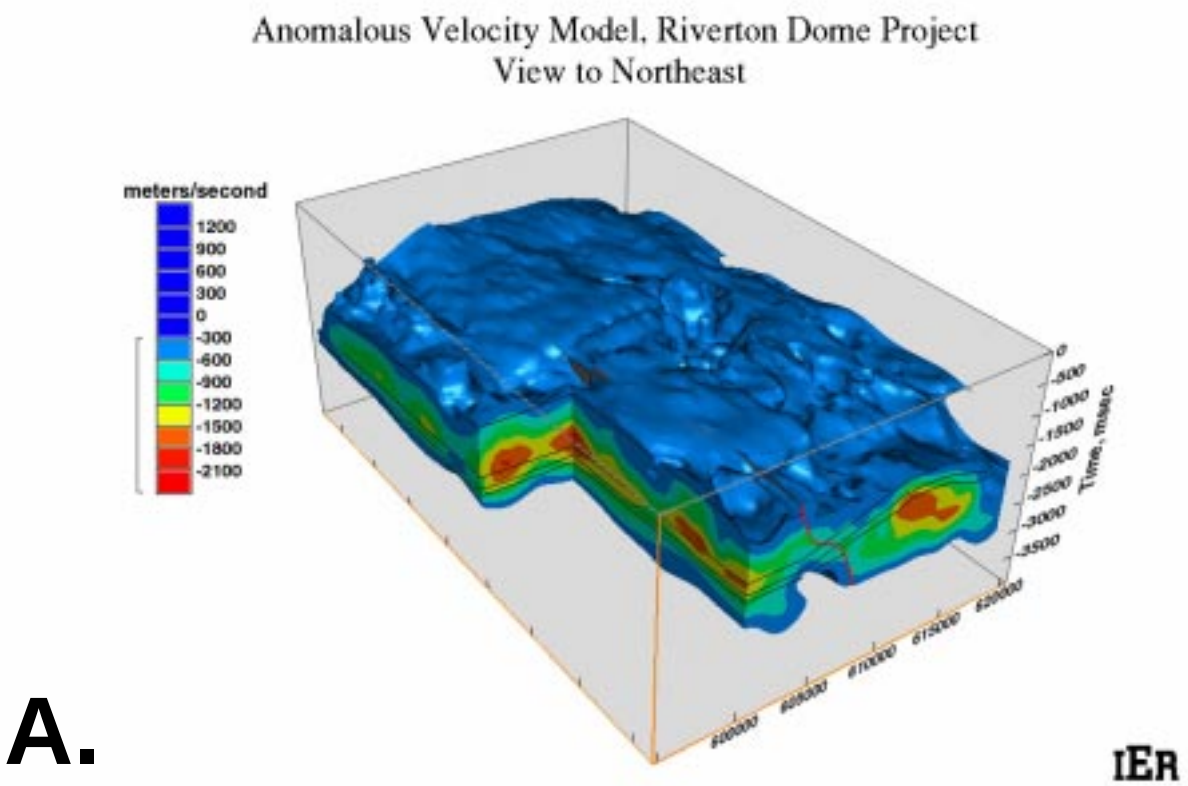


Figure 11A. Anomalous velocity volume where all the stratigraphic units above the top of the regional velocity surface (i.e., pressure surface boundary) have been removed. In addition the rocks with normal velocity characteristics below the anomalous velocity volume also have been removed.

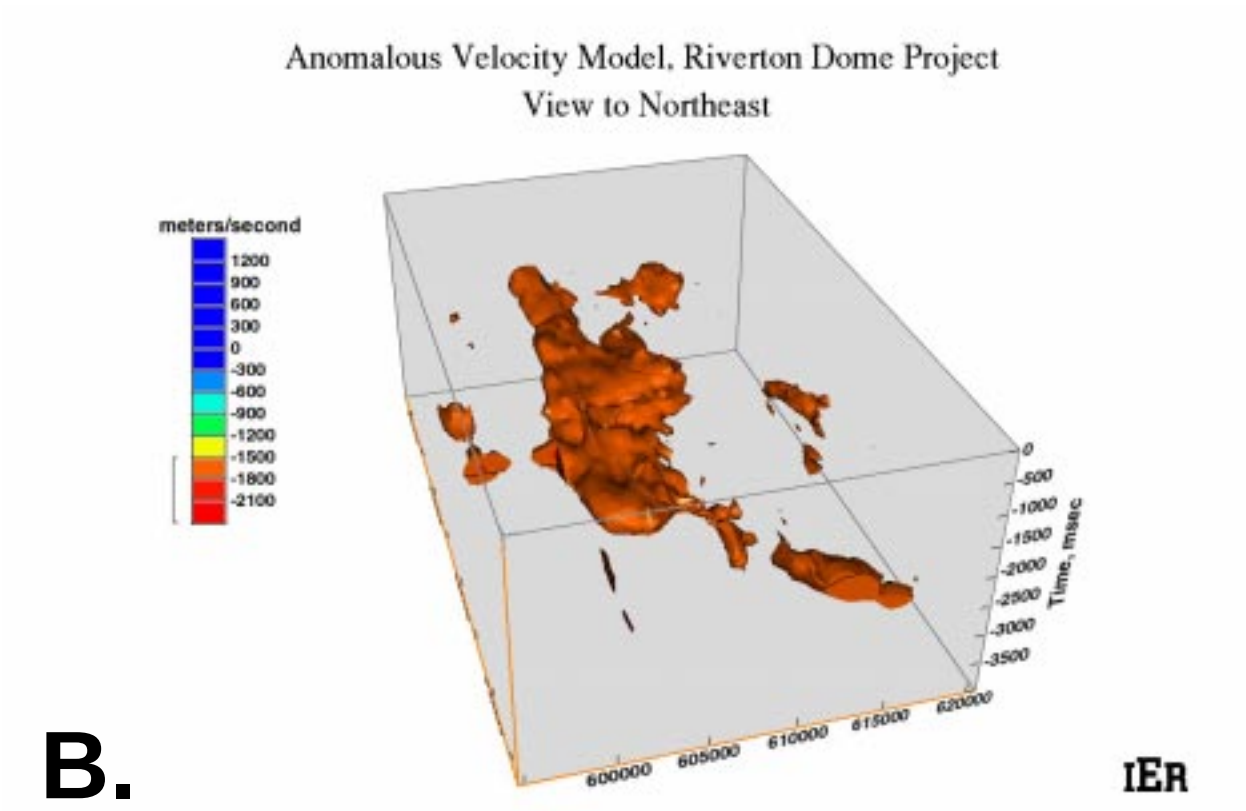


Figure 11B. Isolated anomalous velocity volume showing only rocks characterized by velocities at least 1500 ms slower than the regional velocity-depth gradient (i.e., intense anomalously slow velocities).

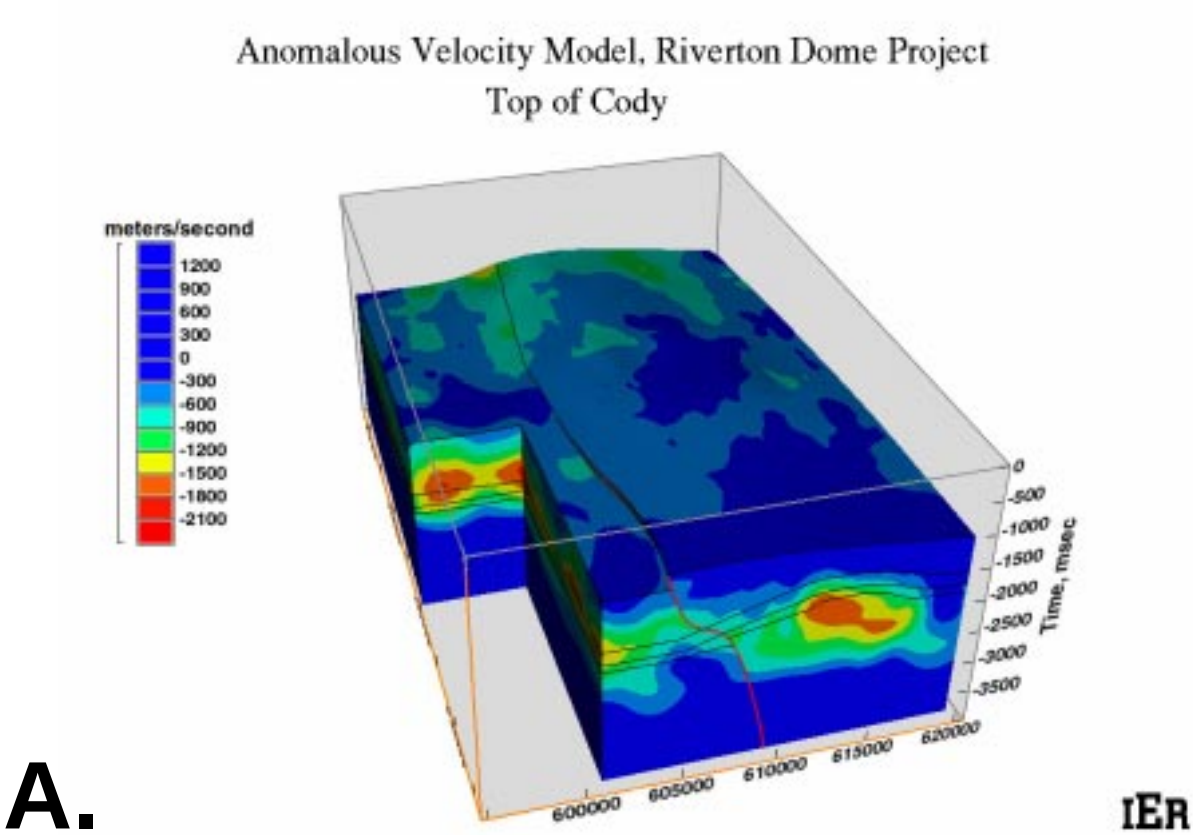


Figure 12A. Anomalous velocity volume in which all the stratigraphic units above the top of the Cody Formation have been removed. The top of the volume in this figure is the top of the Cody Formation.

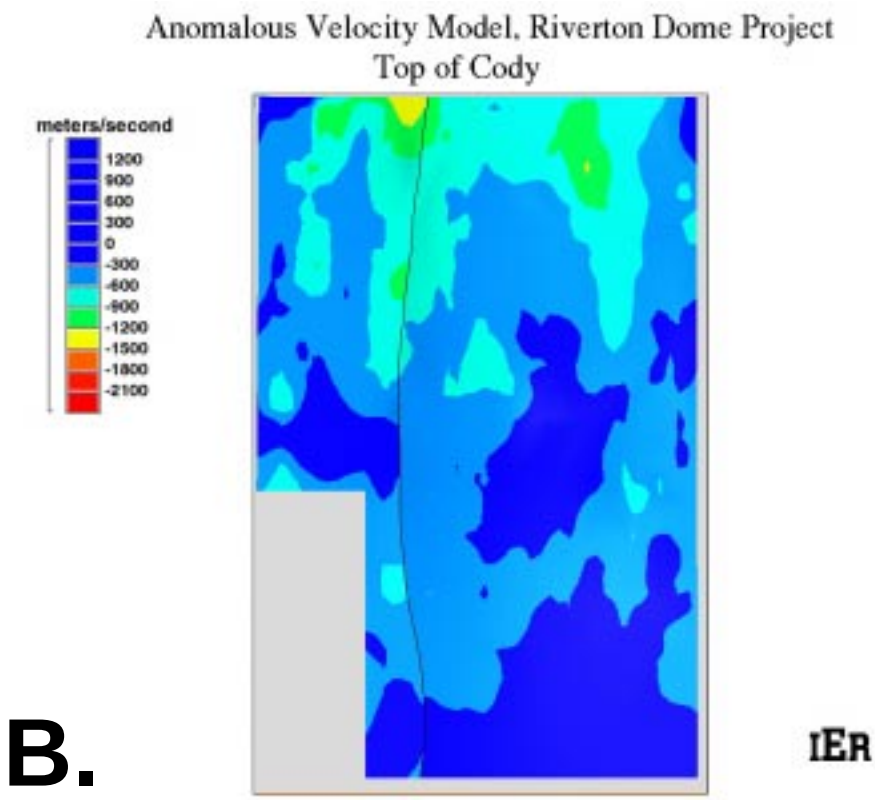


Figure 12B. Map view of the top of the Cody Formation showing the anomalous velocity distribution at the top surface of the Cody Formation.

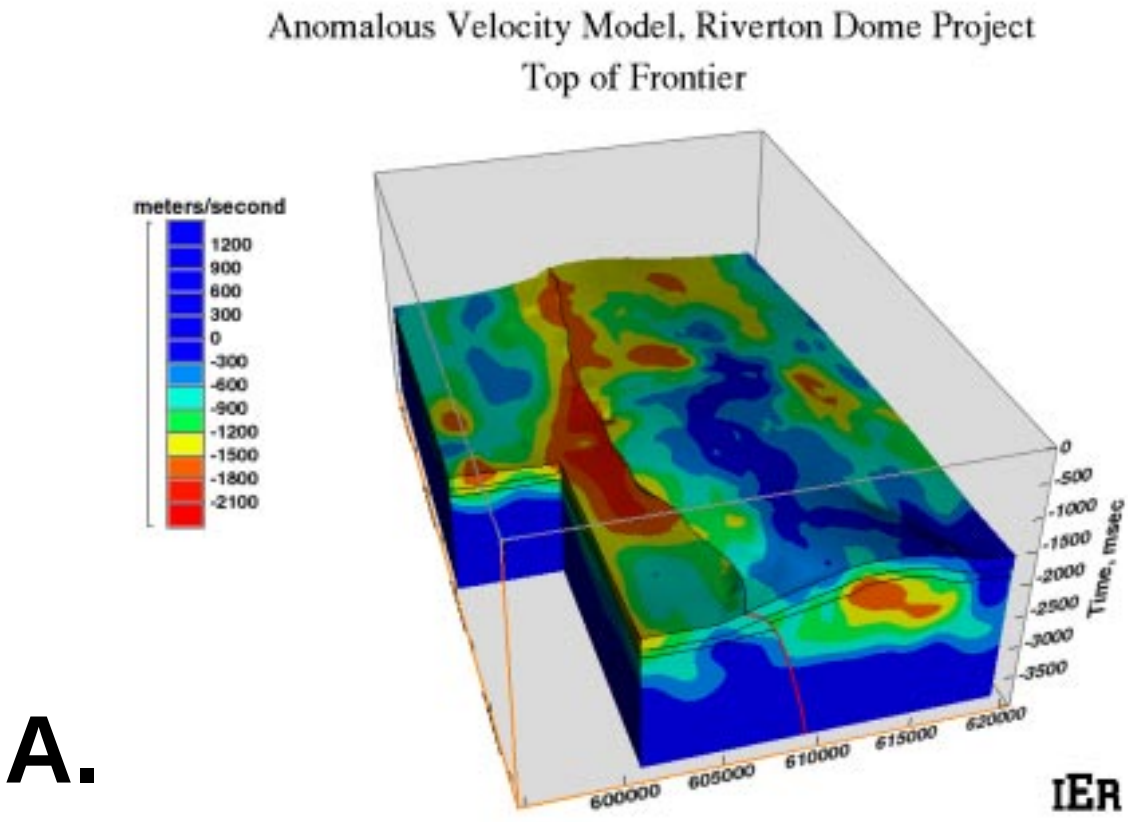


Figure 13A. Anomalous velocity volume in which all the stratigraphic units above the top of the Frontier Formation have been removed. The top of the volume in this figure is the top of the Frontier Formation.

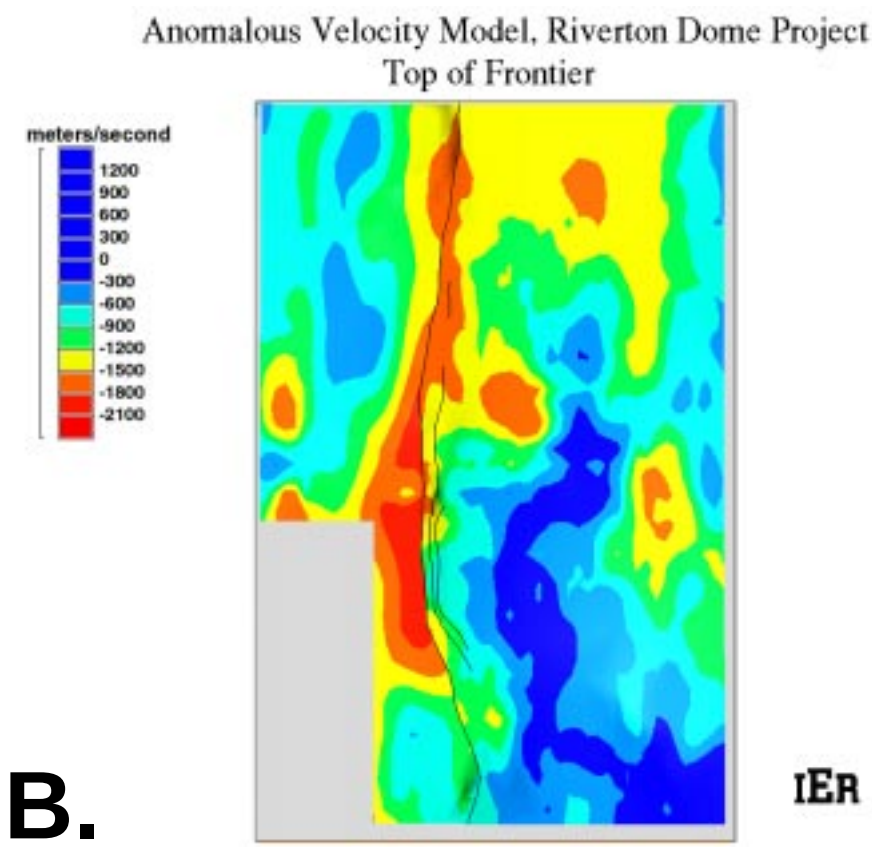
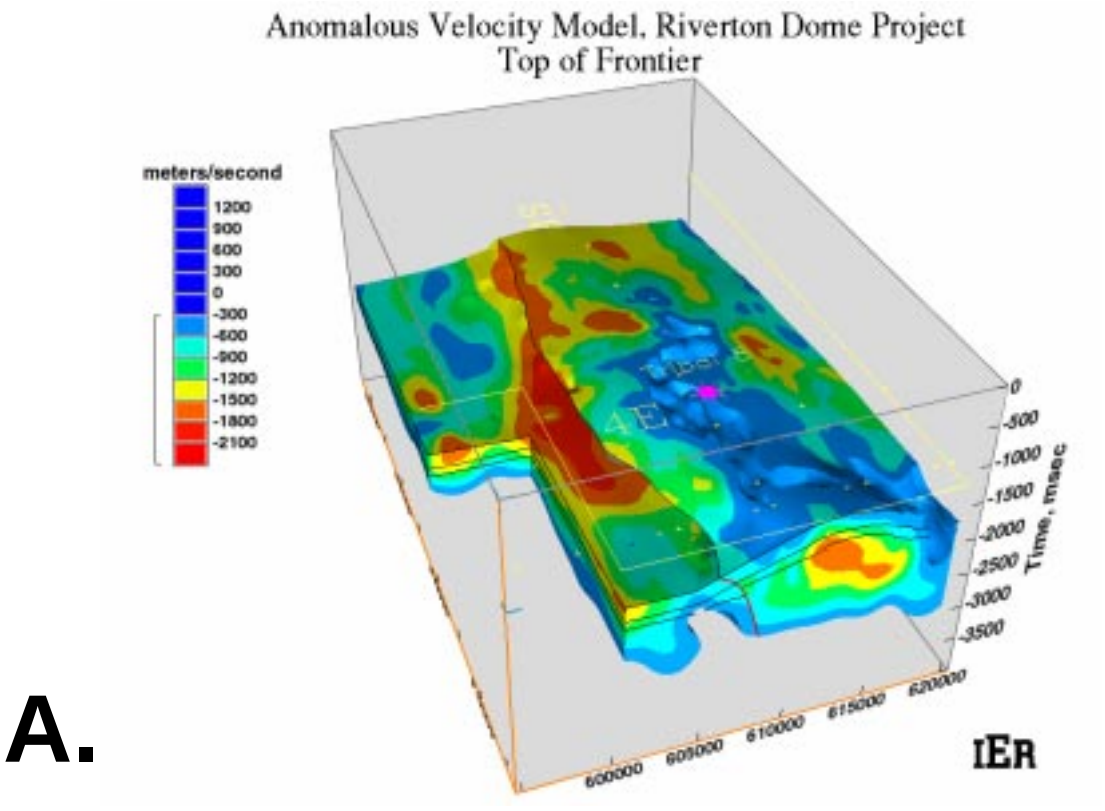
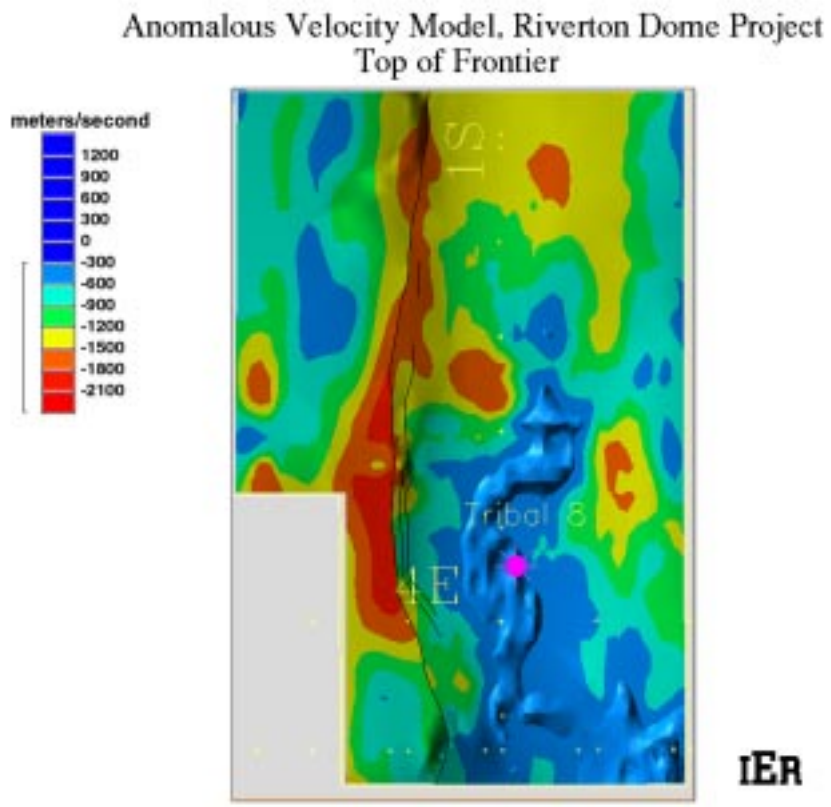


Figure 13B. Map view of the top of the Frontier Formation showing the anomalous velocity distribution at the top surface of the Frontier Formation.

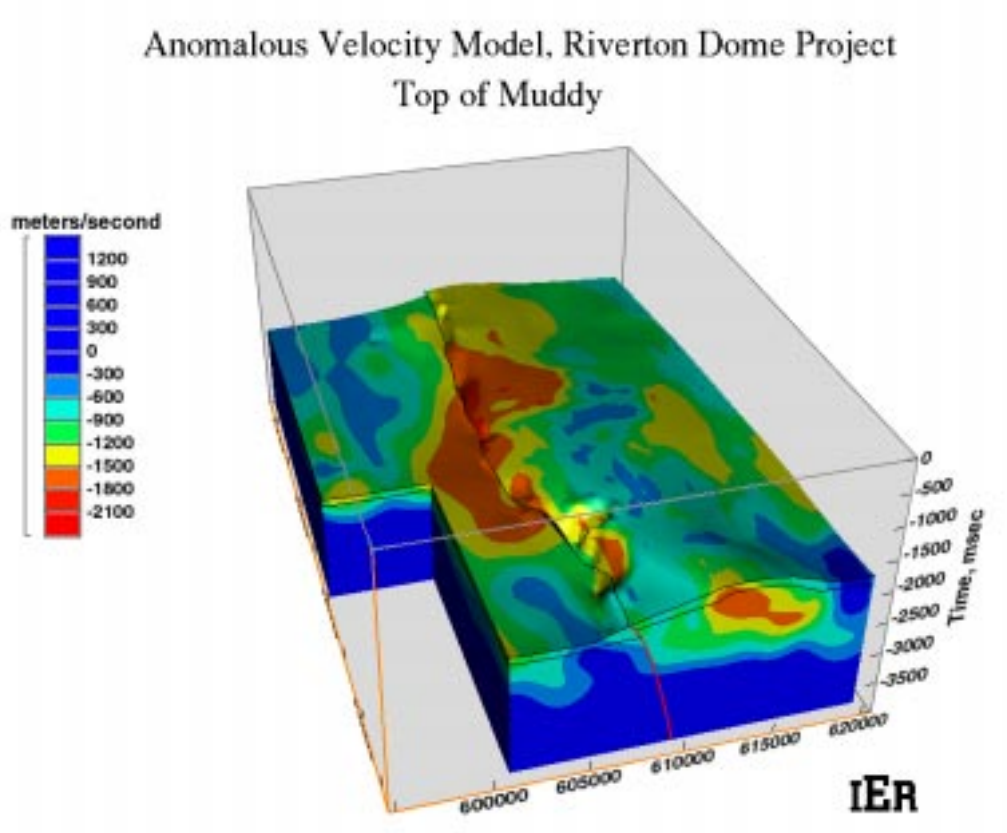


A.



B.

Figures 14A,B. Same as Figures 13A and 13B only all Frontier rocks characterized by normal velocities (i.e., probably normally pressured) have been removed. The Tribal 8 well is shown (pink dot) because it is producing normally pressured hydrocarbons from the Frontier Formation at the top of the structural closure.



A.

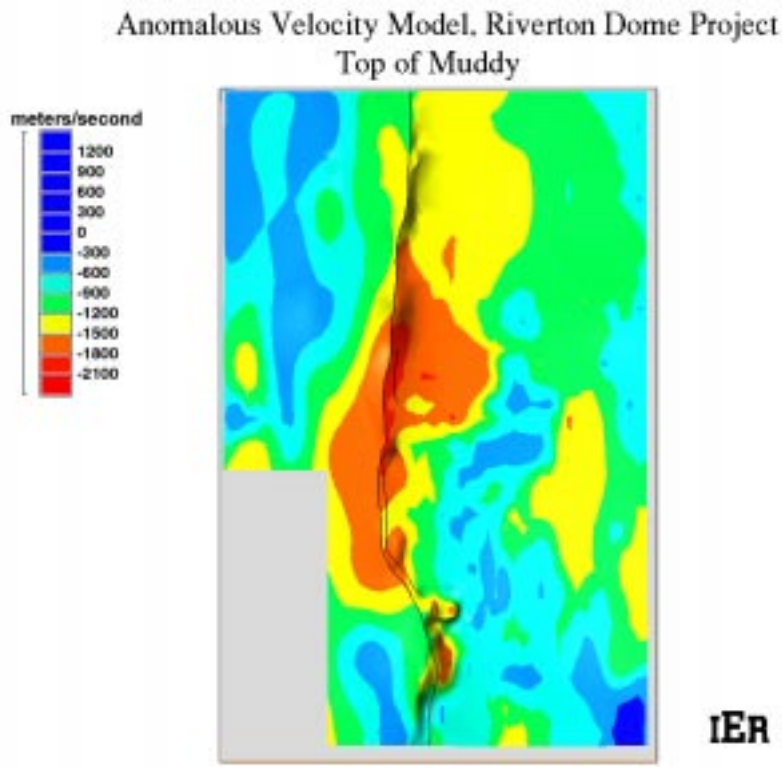
Figure 15A. Anomalous velocity volume in which all the stratigraphic units above the top of the Muddy Formation have been removed. The top of the volume in this figure is the top of the Muddy Formation.

pattern of the anomalous velocities is similar to the pattern observed for the Frontier Formation. At the crest of the structure at the south end of the survey area, there is a significant velocity anomaly in the Muddy Formation (Figures 15A,B). The most intense and volumetrically important velocity anomaly in the Muddy Formation, like in the Frontier Formation, occurs along both sides of the north-south fault (Figures 15A,B). In summary, this velocity anomaly occurs on both the up and down thrown sides of the fault (Figures 9A,B); with the fault clearly controlling the distribution of the velocity anomaly, and presumably the gas saturated, anomalously pressured rocks within the Muddy Formation.

Figures 16A,B are similar velocity reconstructions for the Nugget Formation. Although the configuration of the Nugget Formation velocity anomaly is similar to that of both the Frontier and Muddy formations, there is one important difference; the most intense Nugget velocity anomalies are confined to the eastern side of the north-south fault (Figures 16A,B). The intense velocity anomalies within the Nugget Formation are very important, for the Nugget is typically a porous sandstone, whereas the sandstones in the Frontier and Muddy formations commonly are relatively tight. So the velocity anomalies within the Nugget may represent significant gas accumulations in a porous sandstone reservoir. Elsewhere in the general area, the Nugget commonly is water-filled. Again it should be noted that the most intense velocity anomaly occurs along the north-south fault and downdip from the crest of the structural closure.

INTERPRETATION

The velocity anomalies demonstrated in Figures 13 through 16 can be isolated and visualized in three dimensions using the IER technology (Figures 11A,B). The importance of this operation is that the volume shown in Figure 11B is gas saturated and anomalously pressured. Core observations in the area show that the Cody, Frontier, Muddy, and Nugget formations are not



B.

Figure 15B. Map view of the top of the Muddy formation showing the anomalous velocity distribution at the top surface of the Muddy Formation.

undercompacted. Therefore, the best explanation for the intensely slow velocities shown in Figure 11B is that the fluid system within the volume contain significant free gas in the fluid phase (Surdam et al., 1997). As a result the anomalous velocity volume shown in Figure 11B is an important lead as to where to explore for anomalously pressured gas accumulations in the Riverton Dome area. This exploration lead will evolve into a serious gas prospect if it can be shown that potential reservoir units with commercial porosity/permeability intersect the anomalous velocity volume shown in Figure 11B.

VALIDATION OF IER EXPLORATION TECHNOLOGY

During the time that the velocity field evaluation was progressing at IER, six Muddy Formation tests were completed by Santa Fe Snyder Oil Company. From the perspective of the IER researchers, these were blind tests of the exploration strategy. The test well results were made known to IER only after the final results of the Riverton Dome velocity evaluation were presented to Santa Fe Snyder Oil Company by IER in Laramie, Wyoming on January 27, 1999. The range of initial gas production of the six wells was < one to four mmcf/day. Figure 17A is a map view of the anomalous velocity values at the top of the Muddy Formation. In Figure 17A, all anomalous velocity layers < 1200 ms slower than the regional velocity-depth (or time) gradient have been removed from the anomalous velocity volume. Thus, the anomalous velocity remnant shown in Figure 17A includes all rocks within the Muddy Formation that have anomalous velocities more than 1200 ms slower than the regional velocity-depth gradient. Also plotted on the anomalous velocity diagram (Figure 17A) are the positions of the six test wells and their characteristic initial production (IP) values in mmcf/day. Figure 17B is an enlarged display of the area of interest within the Riverton Dome survey area showing in detail the relationship between the anomalous velocity domain within the Muddy Formation and the IP values for

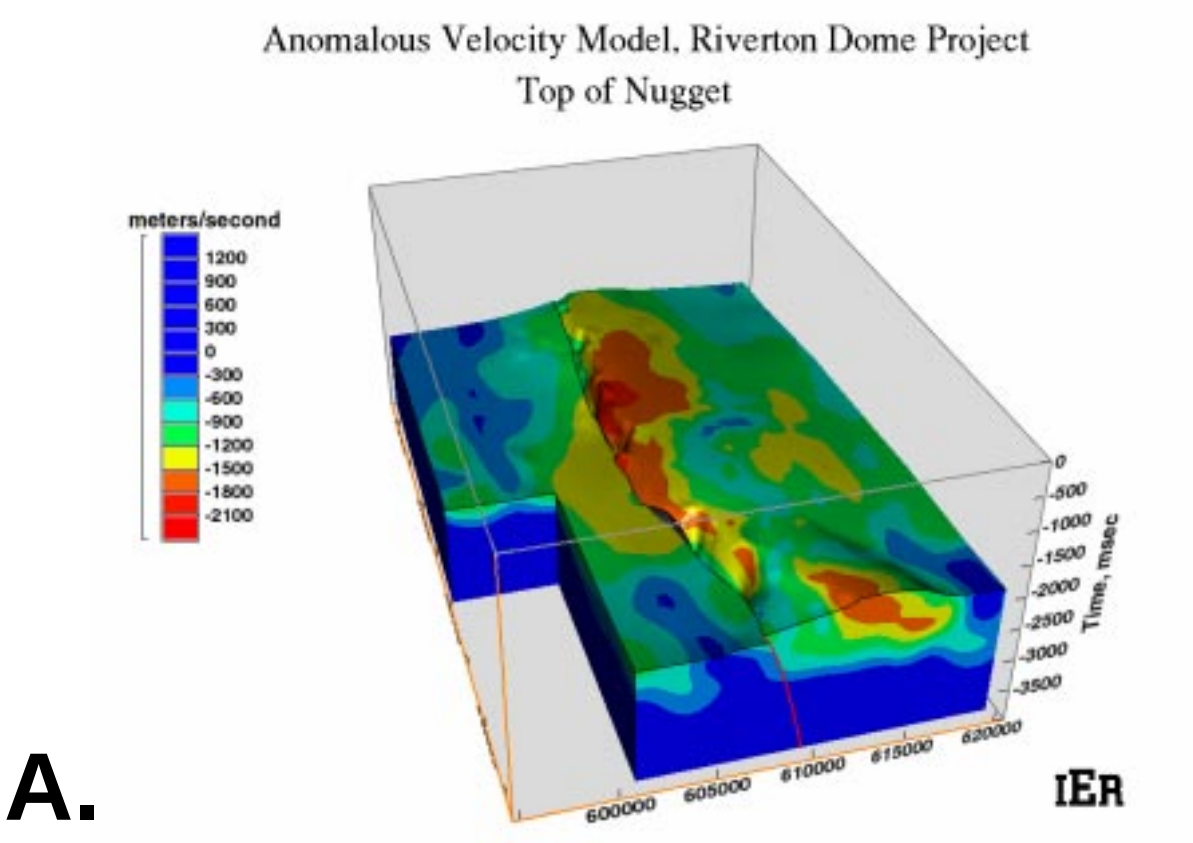


Figure 16A. Anomalous velocity volume in which all the stratigraphic units above the top of the Nugget Formation have been removed. The top of the volume in this figure is the top of the Nugget Formation.

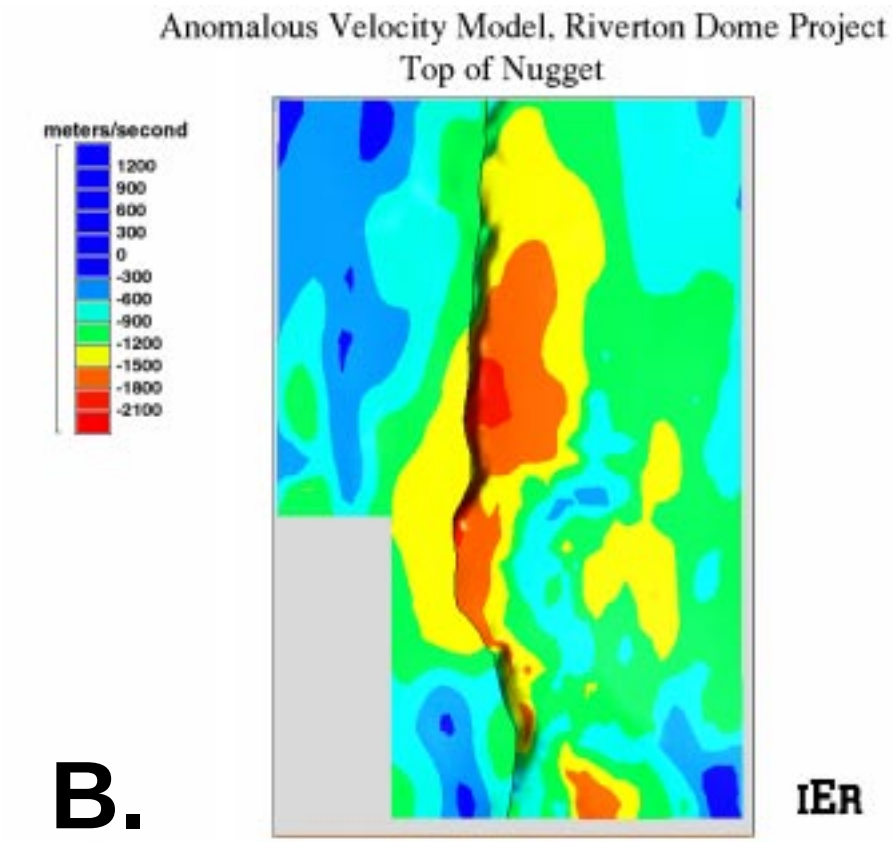
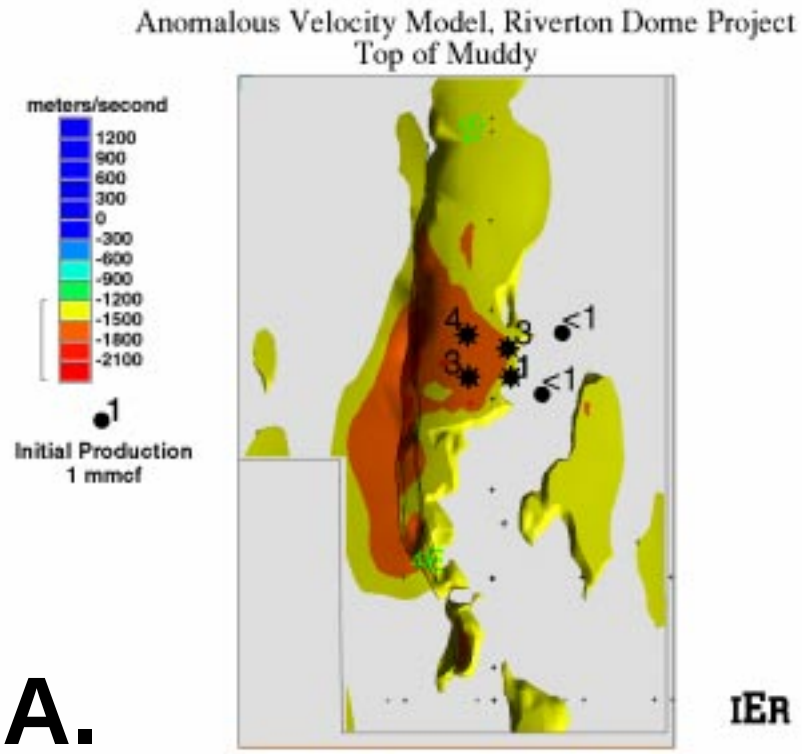
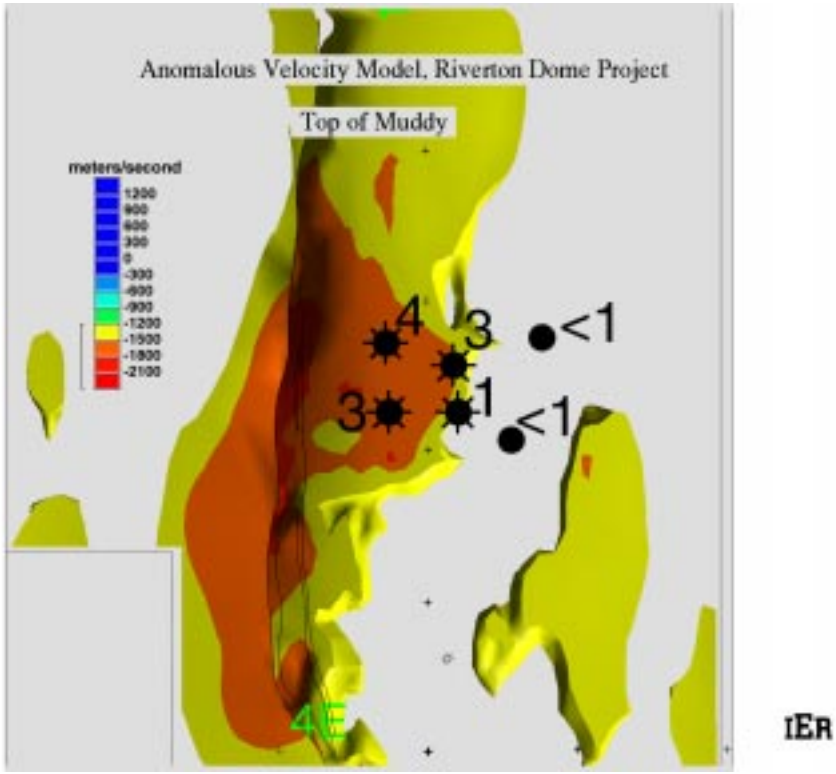


Figure 16B. Map view of the top of the Nugget Formation showing the anomalous velocity distribution at the top surface of the Nugget Formation.



A.

Figure 17A. Map view at the top of a targeted reservoir interval (i.e., Muddy Formation); map is derived from a 3-D anomalous velocity volume constructed from a 3-D seismic survey in the Wind River Basin. In a blind test five recent Muddy Formation wells are plotted on the anomalous velocity surface at the top of the Muddy Formation. The wells within the velocity anomaly (i.e., > 1500 meters/sec below the regional velocity-depth gradient) had initial production values of two to four mmcf/day; the well at the edge of the velocity anomaly (i.e., < 1200 meters/sec below regional gradient) had initial production of one mmcf/day; whereas the well drilled outside the velocity anomaly had initial production of < mmcf/day and presently is shut in.



B.

Figure 17B. Enlarged diagram showing the details of the area of interest in Figure 18A.

the six recent test wells. Wells completed in the Muddy Formation and in those rocks characterized by anomalous velocity values 1500 ms slower than the regional velocity-depth gradient (i.e., three wells) have IP values ranging from three to four mmcf/day. The one well at the edge of the velocity anomaly (i.e., anomalous velocity value of < 1200 ms below, or slower than the regional velocity-depth gradient) had an IP value of one mmcf/day. The two wells drilled into Muddy Formation rocks with a maximum anomalous velocity value of < 1200 ms have IPs of < one mmcf/day and at last notice were shut in. In fact, judging from Figure 15B, the Muddy Formation in the vicinity of the < one mmcf/day wells may have anomalous velocity values of only 300 to 600 ms (slow). The uncertainties associated with the velocity selections and resultant anomalous velocity values derived in this study are on the order of no more than 600 ms, and perhaps as low as 300 ms. It is concluded, with respect to the six recent Muddy test wells, that the IER exploration strategy for detecting and delineating commercial anomalously pressured gas accumulations is valid within the Riverton Dome 3-D seismic survey area, and can be utilized to significantly reduce exploration risk and increase profitability of so-called deep basin accumulations.

CONCLUSIONS

The Ideal Test of the IER Exploration Technology

Armed with the new conceptual model and resultant exploration paradigm, plus the detection and delineation techniques discussed in this report, it should be possible to greatly reduce exploration risk in the Riverton Dome area and in other Rocky Mountain Laramide Basins. The ultimate value of the new technology will be determined by the degree to which it is able to predict in a forward fashion the distribution of basin-center gas accumulation. As such, the following final test is suggested. A careful review of all the results from this study suggest that a prime location exists in the Riverton Dome survey area where the new concept, IER exploration paradigm, technology, and detection techniques can be tested in three formations by a single well. The location is shown by a black dot on Figures 18A (i.e., Frontier anoma-

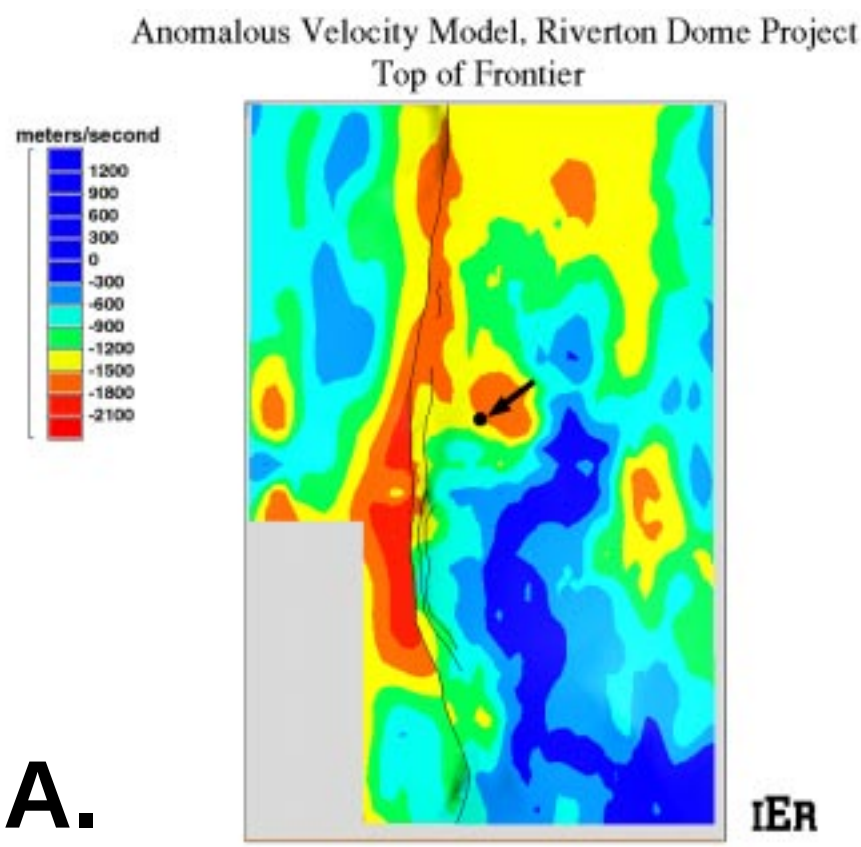


Figure 18A. Anomalous velocity map of top of Frontier Formation (Figure 13B) with the location of the proposed test well shown with a black dot (CDP 124896 in the Riverton Dome 3-D seismic survey area).

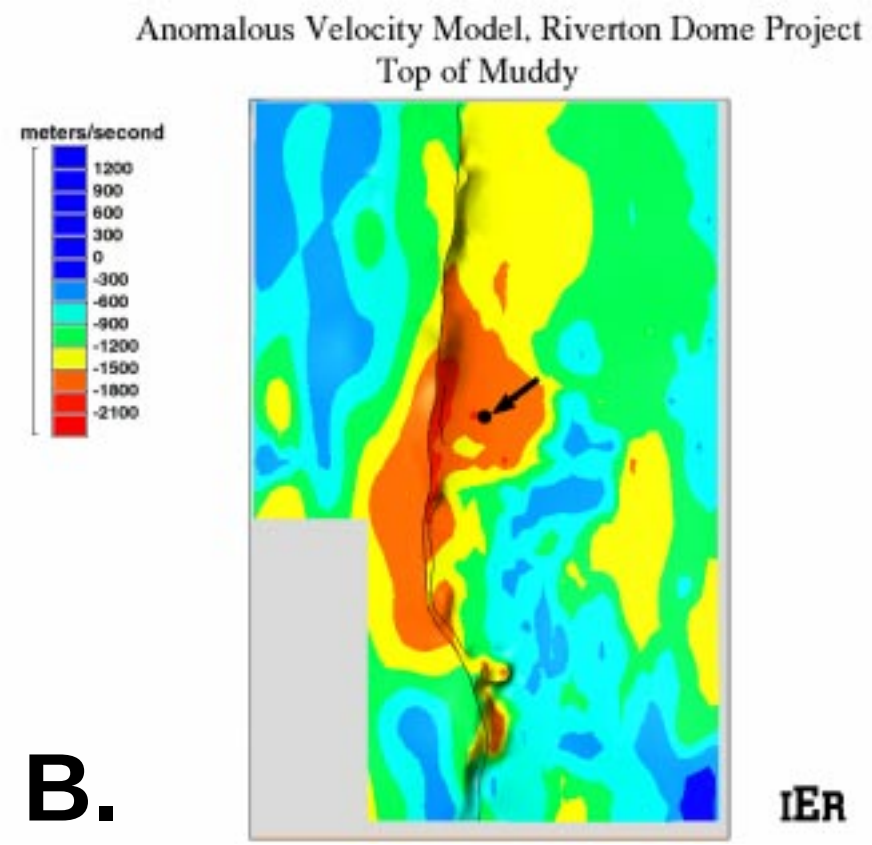


Figure 18B. Same as Figure 18A only map is of the anomalous velocity distribution on the top of the Muddy Formation.

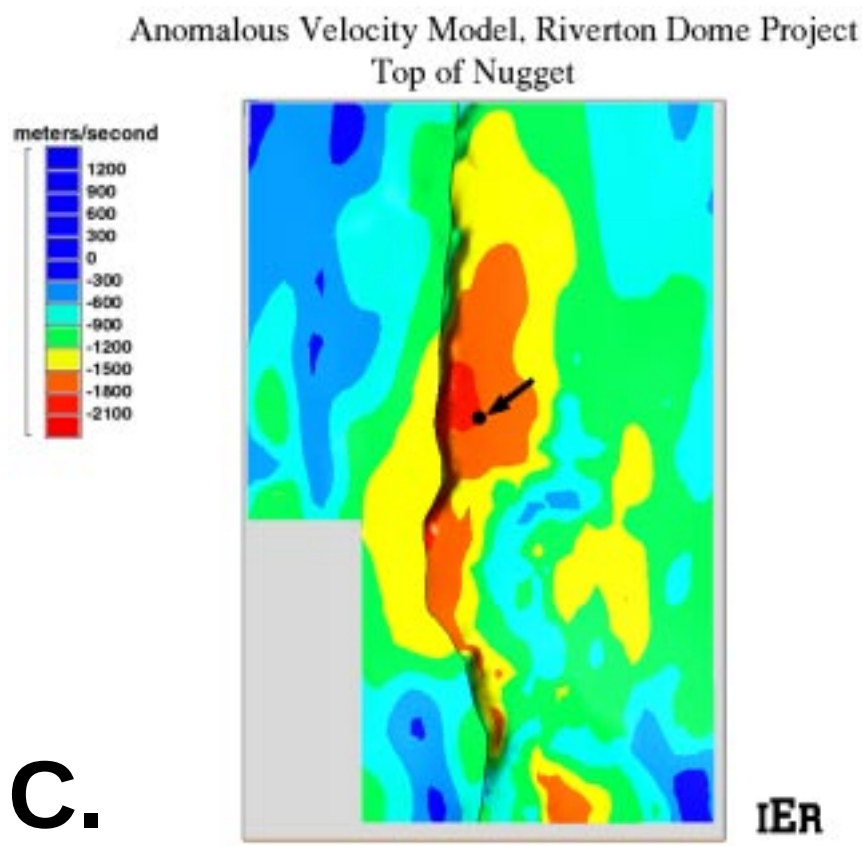


Figure 18C. Same as Figure 18A and 18B only map is of the anomalous velocity distribution on the top of the Nugget Formation.

lous velocity map), 18B (i.e., Muddy anomalous velocity map), and 18C (i.e., Nugget anomalous velocity map). In each case, the drill site (the black dot) is located over an intense velocity anomaly in each of the respective formations. The drill site is located at CDP 124896 of the Riverton Dome 3-D seismic survey. Figure 19 is an interval velocity and anomalous velocity profile for the drill site (at CDP 124896). The anomalous velocity increases from -1100 ms to -1800 ms in the Frontier Formation; the anomalous velocity increases from -1800 ms to -1900 ms in the Muddy; and reaches -1900 ms in the upper portion of the Nugget Sandstone. These are truly significant anomalously slow velocities in each of the target reservoir intervals, and demonstrate that all three formations can be tested in a single well.

To further illustrate the velocity characteristics of the suggested drill site (i.e., CDP 124896), north-south and east-west anomalous velocity profiles that intersect at the drill site have been constructed [Figure 20A (north-south profile) and Figure 20B (east-west profile)]. Both Figures 20A and 20B illustrate that the Frontier, Muddy, and Nugget potential reservoir intervals are characterized by intensely slow velocities beneath the drill site location. It is also important to note that the regional velocity inversion surface is characterized by a very significant topographic high, suggesting that at this location gas is migrating further up into the section than in most other parts of the survey area.

Thus, it is concluded that a well drilled at CDP 124896 in the Riverton Dome 3-D seismic survey is not only an ideal test of the IER exploration technology, but also the highest priority drill site for so-called basin center gas accumulations within the survey area.

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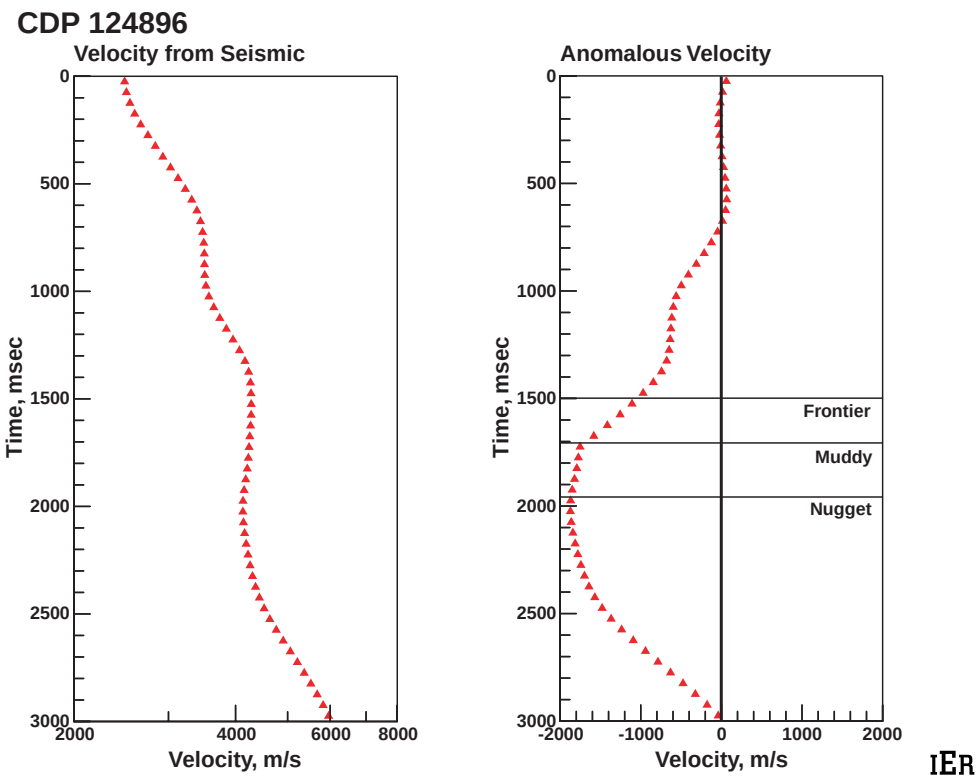

Figure 19. On the right the seismic interval velocity profile at CDP 124896, and on the left the anomalous velocity profile at CDP 124896.

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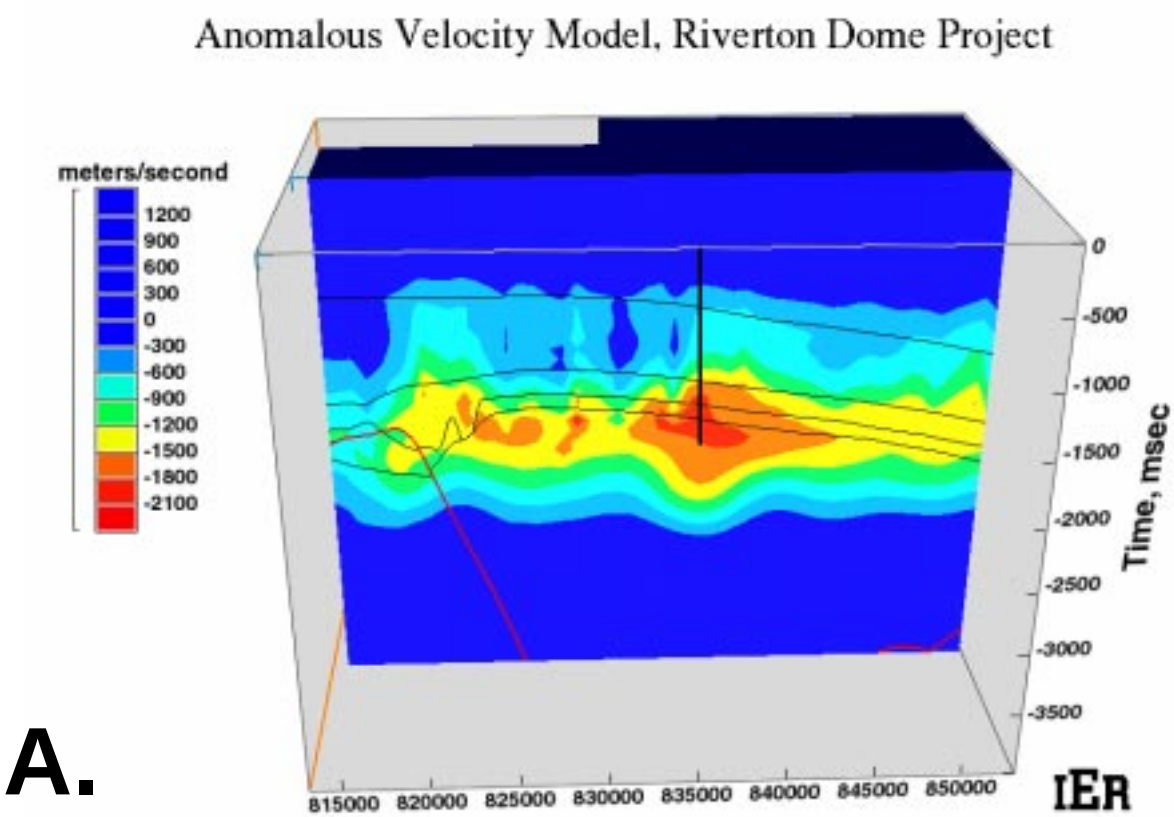
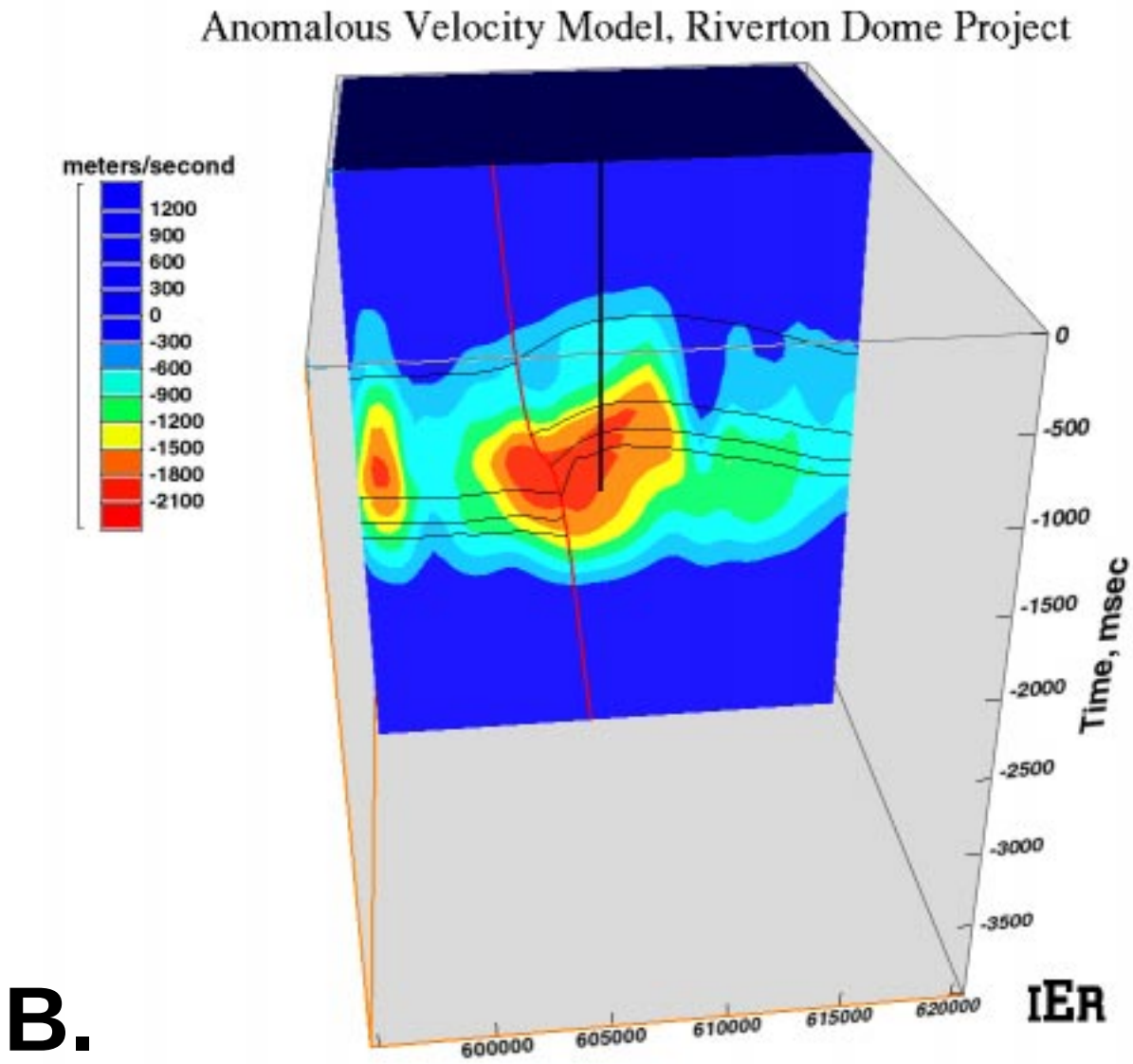


A.

Figure 20A. North-south anomalous velocity cross section through the proposed drill site (i.e., CDP 124896). The black vertical line indicates location of proposed well on the cross section. Note that the Frontier, Muddy, and Nugget Formations all are characterized by anomalous velocities at least 1500 ms slower than the regional velocity depth gradient.



B.

Figure 20B. East-west anomalous velocity cross section through the proposed drill site (i.e., 124896). The black vertical line indicates location of the proposed well on the cross section (same location as in Figure 20A). Again note that the Frontier, Muddy and Nugget Formations are all characterized by intense velocity anomalies. For a more exact measure of the intensities of the anomalous velocities see Figure 19.