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Passive Seismic Monitoring of Hydraulic Fracture Experiments at the Multiwell Experiment Site

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PASSIVE SEISMIC MONITORING OF HYDRAULIC FRACTURE
EXPERIMENTS AT THE MULTIWELL EXPERIMENT SITE

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ABSTRACT

Redesign of hardware, software, and data-reduction techniques associated with the Sandia National Laboratories' Borehole Seismic System (BSS) have made possible better estimates of hydraulic fracture geometry at the Multiwell Experiment (MWX) site. The redesigned system now incorporates four geophones per axis and provides up to 112 dB of downhole gain, for 100 times the sensitivity of the original system. Improved signal-to-noise ratios, extended frequency response and increased digitization rates have made possible the acquisition and processing of data which were previously inaccessible. A maximum likelihood event location scheme, which incorporates an algorithm based on the use of spherical statistics, is used to compute the location of microseismic events and error estimates for these locations. Accuracy estimates for the redesigned system, based on the ability to locate perforation shots, indicates a 25 ft (7.6 m) uncertainty in the location of individual microseismic events using data from two BSS receivers. This resulted in a high level of confidence in determination of the azimuth of the November 1, 1986, hydraulic fracture in the Fluvial B sandstone. A reasonable determination of the azimuth, propped wing length and height for the September 23, 1987, hydraulic fracture in the Fluvial E sandstone was possible using data from only one BSS receiver.

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1.0 INTRODUCTION

The Multiwell Experiment was conceived to provide a systematic approach to the uncertainties of production in the lenticular tight gas resource.¹ Objectives of this field laboratory are to characterize lenticular tight gas reservoirs and to evaluate technology for their production, including hydraulic fracturing. A series of stimulation experiments has been conducted to provide the data necessary to meet these objectives. Prototypes of the Borehole Seismic System (BSS) have been fielded in these stimulations. Analysis of microseismic event data taken during the Phase I stimulation experiment in the Paludal zone, completed in December 1983, yielded a fracture azimuth, wing length and height which were in close agreement with other data and theoretical calculations.² Attempts to apply the same methods to the Phase II stimulation experiment in the Paludal zone yielded ambiguous results, primarily due to poor signal-to-noise ratios.³ Upgrades of the BSS and the associated data reduction methods have improved signal-to-noise ratios and made possible the analysis of complex waveforms which result from microseismic events in this highly anisotropic geological formation. Evolving versions of this system were fielded during the August 1, 1985 stimulation experiment in the Coastal interval,⁴ during the November 1, 1986 stimulation experiment in the Fluvial B sandstone,⁵ during minifrac in the Fluvial C sandstone on April 30 and May 12, 1987⁶ and during the stimulation experiment in the Fluvial E sandstone on September 23, 1987.⁶

1.1 PASSIVE SEISMIC FRACTURE LOCATION

Acoustic emissions resulting from a hydraulic fracture are thought to be caused by shear failures induced by the open, pressurized fracture and the localized high pore pressure zone surrounding the fracture.⁷ Although these acoustic emissions are not thought to be caused by tensile failure as the hydraulic fracture propagates through the gas reservoir, they should occur in a tight band near the hydraulic fracture face.⁸ Thus, it should be possible to use their location to infer the fracture azimuth, wing length and height. The purpose of the BSS is to determine the fracture azimuth, wing length and height by detecting and locating these microseismic events.

The method of microseismic event location depends on detection of the primary wave (P-wave) arrival and the secondary wave (S-wave) arrival to compute the distance from the BSS receiver to the microseismic event. The direction from which the P-wave arrives is determined from phase information contained in the triaxial geophone data.⁹ This method depends on the fact that, in a homogeneous isotropic elastic medium, the P-wave is polarized in the direction of propagation, so that a three-dimensional vector with components proportional to the output of the three geophone axes points either towards or away from the source. This is combined with two properties of the S-wave: 1) the fact that the S-wave is polarized orthogonal to the P-wave, so that the S-wave arrival can be detected, and 2) the fact that the S-wave travels at a slower speed than the P-wave, so that distance to the source should be proportional to the difference in arrival times between the P-wave and the S-wave.

2.0 INSTRUMENTATION UPGRADES

The original BSS¹⁰ was fielded in experiments conducted by Sandia National Laboratories at the Department of Energy Bayou Choctaw petroleum storage facility in 1981 and 1982.¹¹ In this fielding the dominant frequency of the signal recorded on the horizontal geophone aligned perpendicular to the clamp arm was about 200 Hz, much lower than the dominant frequency recorded on the horizontal geophone aligned parallel to the clamp arm plane and the frequency recorded on the vertically aligned geophone. This resulted in discrepancies in azimuth ranging from 32° to 69° for detonator tests at known positions. Detailed calibration of the BSS and review of all available geophysical data indicated that the problem probably resulted from a resonance associated with the 17.25 inch (438 mm) clamp arm. A compound beam analysis of the clamp arm gave resonant frequencies in the vertical direction and the direction parallel to the clamp arm which were above the frequency range of the data. The resonant frequency predicted for the direction perpendicular to the clamp arm plane was 195 Hz,¹¹ almost identical to the dominant frequency of the data for that geophone.

The clamp arm length was reduced to 6.75 inches (171 mm), which moved the predicted resonance frequency beyond 1.2 kHz. This also increased the maximum force exerted by the clamp arm on the wall of a 7 inch (178 mm) casing to 220 lb (100 kg), much closer to the 260 lb (120 kg) weight of the BSS receiver but still requiring a sharp point to hold the receiver in place. Clearly more force is necessary for good coupling. In addition, the horizontal geophones were placed at a 45° angle with the plane of the clamp arm, to distribute the clamp arm force equally to both horizontal geophones.¹²

This configuration was fielded during the Phase I stimulation experiment in the Paludal zone completed in December 1983, and yielded a fracture azimuth, height and wing length which were in close agreement with other data and calculations.² Attempts to apply these same methods to the Phase II stimulation experiment in the Paludal zone did not result in enough microseismic event locations for estimation of fracture properties, primarily due to poor signal-to-noise ratios.³

2.1 INITIAL UPGRADE

The initial BSS upgrade was based on the data sets produced during the stimulation experiments in the Paludal zone. Analyses of these data indicated that a minimum peak level of 0.05 V at the computer interface was necessary for an acceptable modulation index on the frequency modulation (FM) data transmission system. Signals below this level contained too much electronic noise for successful analysis. More than 80 percent of the Phase I data set and all but 12 events in the Phase II data set were below the 0.05 V level and, therefore, unusable. Figure 1 shows the three components of one of the strongest events recorded during the Phase II stimulation, together with horizontal and vertical hodograms of the first arrival of the P-wave. The two vertical lines indicate the interval used to produce the hodograms. It is clear that the signal-to-noise ratio is less than two to one, that the direction of polarization is poorly defined and that the arrival of the P-wave is impossible to determine from the time history. In fact, the P-wave arrival was very difficult to determine even from the hodogram.

The computer interface voltage of most of the events detected in the Paludal stimulation experiments was below the 0.05 V minimum level necessary for successful analysis. The design level at the computer interface was 5 V peak, 40 dB above this level. Events which produced this 0.05 V minimum level were taken as reference events which should be moved to the center of the data range. In the original BSS, the downhole electronic gain was 80 dB, with 6 dB added at the surface FM discriminator for a total system gain of 86 dB. This means that the output of the geophone array was only 2.5 μ V for these reference events. To produce 2.5 V at the computer interface, to move the reference level from the bottom of the design range to the center, would require a BSS gain of one million (120 dB).

Figure 1. Microseismic event detected during the 1984 stimulation of the Paludal Zone at the MWX site.

Figure 2. Microseismic event detected during the 1986 stimulation of the Fluvial B sandstone at the MWX site.

The design approach was twofold: increase the output of the geophone array, and add higher gain channels to the BSS electronics. The geophone array was redesigned to include three geophones per axis producing three times the sensitivity, a gain of 9.5 dB. New channels, with 100 dB gain, boosted the $7.5 \mu\text{V}$ ($2.5 \mu\text{V}/\text{geophone}$) output of the new geophone array for a reference event to 0.75 V at the FM subcarrier oscillator inputs, 30 percent of the subcarrier full scale input peak level of 2.5 V. An additional 6 dB of gain was achieved in the surface FM discriminator for a total system gain of 115.5 dB above the output of a single geophone. The low gain channels, 20 dB below the high gain channels, were retained for strong microseismic events which might saturate the high gain channels. Since the dynamic range of the FM system is at least 40 dB, this gives the system a dynamic range of at least 60 dB using both the high and low gain channels.

The BSS was upgraded to include several diagnostic capabilities. The new geophone array contained vertical and horizontal exciters which could be activated from the surface to confirm functional operation of the entire system. Calibration and balancing of the data channels are achieved through the wireline using surface instrumentation. Voltage to the electronics, the BSS receiver temperature, the position of the clamp arm and the force which it exerted on the well casing are displayed on surface instrumentation while the BSS receiver is in place downhole.

The upgraded BSS receiver is 15 inches (380 mm) longer than the original for a total length of almost 12 ft (3.7 m), and 20 lb (9 kg) heavier for a total weight of 280 lb (127 kg). The clamp arm mechanism and drive account for two thirds of the total length and weight.

2.2 SECOND UPGRADE

Analysis of the Coastal data set revealed that the low pass filters must be set no lower than 1 kHz in order to maintain phase parity.⁴ With the maximum sample rate of the PDP-11/34 based analog-to-digital (A/D) system, this would have resulted in unacceptable aliasing. In addition, during analysis of the Coastal data set the arrival of the P-wave had been missed because of the low sample rate of the PDP-11/34 based A/D system.⁴ This resulted in incorrect direction and distance

estimates. A new A/D conversion method based on a Phoenix Data IDAS 8 channel A/D converter with vector sample and hold was implemented. The IDAS was coupled to an IBM-PC through an event detector which triggered the computer to store data when any one of the six channels exceeded a preset voltage. This system was capable of simultaneously digitizing all six channels at a rate of 13.3 kHz per channel, as compared to a maximum rate of 2.3 kHz per channel for the PDP-11/34 based system. For the Fluvial data sets, a digitization rate of 10 kHz per channel was used. Figure 2 shows time histories of three data traces from the high gain channels for the first 25 ms of a typical event recorded during the Fluvial B stimulation experiment, together with horizontal and vertical hodograms of the first 1.5 ms of the P-wave. Note the improved signal-to-noise ratio and the improvement in resolution of the hodograms as compared to Figure 1.

Low frequency seismic noise at the MWX site requires the use of high pass filter settings of 70 Hz to 200 Hz depending on local conditions. This results in impulse distortion of the first three half cycles of the P-wave arrival. The attenuation of the first three half cycles evident in Figure 2 is the result of a high pass filter setting of 80 Hz. By using flat phase filters, phase and amplitude balance can be maintained between channels in spite of this attenuation.⁴ This makes it possible to determine the correct polarization direction, but makes good signal-to-noise ratios even more important, because the amplitude of the P-wave arrival is attenuated by the high pass filters.

2.3 THIRD UPGRADE

During the Coastal and Fluvial B stimulation experiments, the high gain channels were never saturated and the low gain channels did not produce any usable signals. In an effort to increase the range at which microseismic events can be detected, the gain of all channels was increased. The new low gain channels were given 100 dB of gain, exactly the same value previously used for the high gain channels. The new high gain channels were given 112 dB of gain, resulting in a factor of four between the high and low gain channels. This 12 dB separation between high and low gain channels does not optimize the dynamic range.

However, the 52 dB dynamic range resulting from using both sets of channels seems adequate for all of the data recorded at the MWX site.

A few small, but significant, changes were made to the clamp arm mechanism. Tolerances were tightened and the single sharp point of contact with the casing was replaced with two sharp points of contact separated by 3/4 inch (19 mm) in a horizontal line. The clamp arm was shortened to 6 inches (150 mm) which increased the maximum force exerted on a 7 inch casing to 300 lb (136 kg), slightly greater than the 280 lb (127 kg) weight of the upgraded BSS receiver.

2.4 FINAL UPGRADE

Careful analysis of the data set produced during the August 1, 1985, stimulation experiment in the Coastal interval lead to the conclusion that frequency content up to 1 kHz must be included for successful analysis.⁴ Subsequent data sets, particularly the Fluvial B data set, confirmed this conclusion. Since the Mark Products L-25 geophones used in the BSS receivers have non-linear response above 400 Hz, Figure 3, obtaining accurate data to 1 kHz required the redesign of the geophone array using geophones with higher frequency capability. In addition, differences in the frequency content between vertical and horizontal components, Figure 2, made determination of elevation more difficult than determination of azimuth. While this was possibly due to properties of the clamp arm and/or well casing, differences between the horizontal and vertical geophones could be eliminated as a possible source of this difference by using identical geophones on all axes. Both of these objectives were accomplished by using Geo Space GS-14-L9 geophones which have a flat frequency response from 28 Hz to 2 kHz and can be placed at any angle with the vertical.

In order to produce the most uniform response from all axes, it was decided to use four axes arranged so that all axes make the same angle with the horizontal plane and with the plane of the clamp arm, analogous to the earlier decision to mount the horizontal geophones at 45° with the clamp arm plane. This also provides redundancy, since any three of

Figure 3. Amplitude calibration for three Mark Products L-25 Geophones using the amplitude at 100 Hz as a reference level.

the axes can be used to construct a full triaxial data set. This redundancy can be used in two ways: 1) to check channel balance by comparing triaxial data constructed using all four axes with the four possible ways of constructing triaxial data using three of the axes at a time, and 2) to allow continued operation in the event of failure of a single channel. With this geometry and the smaller size of the Geo Space GS-14-L9 geophones it would be possible to use 10 geophones per axis in less space than was required for three of the larger geophones. It was decided to use four geophones per axis to produce about the same sensitivity as the old three geophone per axis array.

The new geophone array contains a vertical exciter and horizontal exciters oriented parallel and perpendicular to the plane of the clamp arm. These exciters can be individually activated from the surface to confirm operation of the entire system and to analyze the resonance properties of the BSS receiver while clamped in the well casing or hanging from the wireline.

During stimulation experiments in the Fluvial B and minifrac in the Fluvial C, problems with the software for the Phoenix Data IDAS A/D converter limited data acquisition to six channels, required up to 50 seconds to write an event to disk and required typing a new file name and manually restarting the system after each event. This resulted in missing many events and rendered the system incapable of digitizing eight channels from two of the new four axes BSS receivers. The Phoenix Data IDAS A/D converter was replaced with a Metrabyte DASH 16F data acquisition plug-in board for the IBM-XT. This board is capable of 12 bit digitization of up to 16 channels (both high and low gain from two of the new four axes BSS receivers) at a rate of 6.25 kHz per channel. The computer interface design level was increased to 10 V by increasing the gain in the surface FM discriminator 12 dB. The Metrabyte board was coupled to the analog channels through an event detector which triggers the IBM-XT computer to store data when any one of a preselected set of four of the 16 channels exceeds a dial set voltage which can be reset independently for each channel at any time during data acquisition. The new system is capable of digitizing eight channels at a rate of 12.5 kHz per channel and can write an event to disk in less than two seconds.

For the Fluvial E stimulation experiment a digitization rate of 10 kHz per channel on the eight low gain channels was used, with a separate A/D playback from the analog tape required for the high gain channels. Since the Metrabyte board does not have vector sample and hold, linear interpolation is applied to center the four channels from each BSS receiver at a common time. Figure 4(a) shows time histories of the four data traces from the low gain channels for the first 25 ms of a typical microseismic event recorded during the Fluvial E stimulation experiment. Figure 4(b) shows the resulting horizontal and vertical time histories, together with horizontal and vertical hodograms of the first 2.4 ms of the P-wave. Note the good signal-to-noise ratio, in spite of obvious attenuation of the first three half cycles resulting from a 160 Hz setting of the high pass filters. Also note the clear direction of polarization of the hodograms.

Figure 4(a). Four axes geophone data for a typical microseismic event.

Figure 4(b). Tri-axial data and hodograms for this microseismic event.

3.0 EVENT LOCATION

3.1 SINGLE-RECEIVER EVENT LOCATION

If, in a homogenous isotropic elastic medium, the P- and S-wave arrival times, t_p and t_s can be determined, then the distance D to a seismic source can be calculated by

$$D = F_v (t_s - t_p). \quad (1)$$

The "velocity factor",

$$F_v = v_s v_p / (v_p - v_s), \quad (2)$$

can be determined empirically from seismic sources at known distances, without knowledge of the P-wave velocity, v_p , the S-wave velocity, v_s , or the time of the seismic source.

Since the P-wave travels faster than all other waves and, in a homogeneous isotropic medium, is polarized parallel to the direction of travel, it is possible to determine the direction from which it arrives at a triaxial geophone of known orientation by analysis of the three components of the first arrival of the signal.⁹ However, analysis of the triaxial geophone data can only determine this direction with a 180° ambiguity, i.e., it cannot distinguish between a compressional first arrival from a given direction and a dilatational first arrival from the opposite direction.

For data from the BSS, determination of the direction of P-wave arrival is done in two steps. First, the horizontal components are analyzed by using spherical statistics to determine the azimuth of the direction of arrival.¹³ The same method is then applied to the horizontal component in the vertical plane determined by that azimuth and the vertical component, in order to determine the elevation. The resulting azimuth and elevation are indicated by the straight lines drawn on the hodograms in Figures 1, 2 and 4. In addition to the azimuth and elevation, spherical statistics yields an estimate of the probable error in the form of standard deviations for both the azimuth

and elevation.¹³ Resolution of the 180° ambiguity is handled by the analyst based on knowledge of the probable location of the source or, when possible, by comparison of data from two BSS receivers.

3.2 TWO-RECEIVER EVENT LOCATION

Given the azimuth, elevation, and distance to an event determined by several BSS receivers, it is desirable to refer the single-receiver locations and their error measures to a common coordinate system and determine a most probable single location and an error measure for that location. This can be done by assuming a triangular probability distribution about each location based on the mean, mode, and standard deviation for the azimuth, elevation, and distance, and solving for the position which minimizes the error measure.¹³ For a rectangular coordinate system, the error measure is expressed as a standard deviation for each of the coordinate axes and can be thought of as an ellipsoid with axes parallel to the coordinate axes. The minimum error position is the position which minimizes the volume of this error ellipsoid.

Figure 5 illustrates the method as applied to a single microseismic event from the stimulation in the Fluvial B sandstone. In Figure 5(a), the 5800 ft (1770 m) depth horizontal positions of the three wells are plotted in a rectangular coordinates system with origin at the stimulation well, MWX-1. The horizontal locations determined from BSS data taken in wells MWX-2 and MWX-3 are given by the triangle symbols nearest to the respective observation wells. The ellipse drawn about each of these two locations represents the horizontal projection of the error ellipsoid for that location. The third triangle symbol and the ellipse drawn about it represent the two-receiver minimum error horizontal location and the horizontal projection of the minimum error ellipsoid. Note that the ellipse about the minimum error position is smaller than the ellipse about either single-receiver location. The line through MWX-1 is given by the spherical average of the three angles determined by these three locations and is at an azimuth of N70°W. Figure 5(b) gives the projection of these same three points into the vertical plane determined by this line. In Figure 5(b) the positions of

the bottoms of the BSS receivers in MWX-2 and MWX-3 are indicated by the square symbols on the projections of the well bores onto this plane. The square symbol on the projection of well MWX-1 indicates the center of the perforation zone. Depth is measured from the surface at well MWX-1 and the top and bottom of the Fluvial B sandstone are indicated by horizontal lines. The lower triangle symbol corresponds to the location determined from MWX-2 and the ellipse about it to the projection of the error ellipsoid for that location onto the vertical plane. The upper triangle symbol and ellipse correspond to the location determined from MWX-3, with the third triangle symbol and ellipse corresponding to the minimum error location and ellipsoid.

Figure 5(a). Horizontal projection of microseismic event location.

Figure 5(b). Vertical projection of microseismic event location.

4.0 DETERMINATION OF THE VELOCITY FACTOR

Before the distance to a source can be determined, the velocity factor, F_v , must be established. At the MWX site this was accomplished by analysis of data from perforation shots at known locations in the other two wells. The velocity factor, F_v , is calculated from the known distance and the P- and S-wave arrival times using Equation 1.

4.1 VELOCITY FACTOR DETERMINATION FOR THE FLUVIAL B STIMULATION

To determine F_v for the Fluvial B stimulation, 20 ten-gram perforation shots were fired at an average depth of 5831 ft (1777 m) in well MWX-3 with a BSS receiver in place at a depth of 5744 ft (1751 m) in well MWX-2. The velocity factor, F_v , was calculated for each shot from the known distance and the P- and S-wave arrival times. Without moving the BSS receiver in well MWX-2, a second BSS receiver was placed in well MWX-3 at a depth of 5731 ft (1747 m), and 13 ten-gram perforation shots were fired at an average depth of 5835 ft (1778 m) in well MWX-1. Velocity factors proved to be different for all three paths, Table 1.

TABLE 1
VELOCITY FACTORS FOR THE FLUVIAL B STIMULATION

Observation Well	Perforation Well	Velocity Factor ft/ms (m/s)	Standard Deviation ft/ms (m/s)	Path Length ft (m)	Path Azimuth
MWX-2	MWX-3	17.5 (5330)	0.8 (240)	224 (68)	N2.2°W
MWX-2	MWX-1	15.5 (4720)	1.2 (370)	150 (46)	N63.2°E
MWX-3	MWX-1	18.4 (5610)	1.2 (370)	217 (66)	N36.8°W

Since the MWX site is inhomogeneous and anisotropic, it is reasonable to assume that the different values of F_v for the three paths are a result of a variation in v_s , and perhaps v_p , with direction. In order to be able to use Equation 1 to compute the distance to a microseismic event, it is reasonable to compute F_v as a function of azimuth in a manner which agrees with the measured values. Since we have measured values for three azimuths, a three parameter model is required. A model which gives a minimum value for F_v at a critical

azimuth α and a maximum value perpendicular to that azimuth was chosen in the form:

$$F_v(\theta) = v_1[1 - v_2\cos(2\theta - 2\alpha)] \quad (3)$$

The values of F_v for the three azimuths measured dictate the following values for the three parameters in Equation 3:

$$\alpha = N54.4^\circ E$$

$$v_1 = 16.9 \text{ ft/ms (5150 m/s)}$$

$$v_2 = 0.088$$

This gives values of F_v in a range from 15.4 ft/ms (4690 m/s) to 18.4 ft/ms (5610 m/s). The critical angle α does not seem to have any obvious physical significance.

4.2 VELOCITY FACTOR DETERMINATION FOR THE FLUVIAL C MINIFRACS

Prior to the minifracs in the Fluvial C sandstone, a series of 18 ten-gram perforation shots was fired at an average depth of 5730 ft (1746 m) in well MWX-1 with a BSS receiver in place at a depth of 5728 ft (1745 m) in well MWX-3. A second series of 10 ten-gram perforation shots was fired at an average depth of 5732 ft (1747 m) in well MWX-2. Since both series were at approximately the same depth as the BSS receiver, horizontally polarized P-waves were detected. The wave form was very complex and no horizontally polarized component of the S-waves could be detected. Vertically polarized S-wave arrivals were clear, so these were used to compute the velocity factor. Velocity factors for both paths proved to be close enough together to consider all 28 values to be one data set, Table 2. Averaging all values for both paths gives a velocity factor of 23.7 ft/ms (7224 m/s), with a standard deviation of 1.2 ft/ms (366 m/s).

TABLE 2
VELOCITY FACTORS FOR THE FLUVIAL C MINIFRACS

Perforation Well	Velocity Factor ft/ms (m/s)	Standard Deviation ft/ms (m/s)	Path Length ft (m)
MWX-1	24.0 (7315)	1.3 (396)	206 (63)
MWX-2	23.1 (7041)	0.3 (91)	190 (58)

4.3 VELOCITY FACTOR DETERMINATION FOR THE FLUVIAL E STIMULATION

Prior to the Fluvial E stimulation, 17 ten-gram perforation shots were fired at an average depth of 5555 ft (1693 m) in well MWX-3 with a BSS receiver in place at a depth of 5480 ft (1670 m) in well MWX-2. Without moving the BSS receiver in well MWX-2, a second BSS receiver was placed in well MWX-3 at a depth of 5450 ft (1661 m), and 14 ten-gram perforation shots were fired at an average depth of 5555 ft (1670 m) in well MWX-1. Velocity factors proved to be the same for all three paths, Table 3, so all three data sets were combined to give an average value of 19.8 ft/ms (6035 m/s).

TABLE 3
VELOCITY FACTORS FOR THE FLUVIAL E STIMULATION

Observation Well	Perforation Well	Velocity Factor ft/ms (m/s)	Standard Deviation ft/ms (m/s)	Path Length ft (m)
MWX-2	MWX-3	19.8 (6035)	1.3 (396)	219 (67)
MWX-2	MWX-1	20.4 (6218)	2.7 (823)	146 (45)
MWX-3	MWX-1	19.2 (5852)	3.3 (1006)	218 (66)

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5.0 ORIENTATION OF THE BSS RECEIVERS

If it is assumed that the direction of polarization of the P-wave is the direction towards the source, as it would be in a homogeneous isotropic elastic medium, then the orientation of the geophone axes can be determined from the same perforation shots used to determine the velocity factor. Since the wells at the MWX site are very nearly vertical, the orientation of the vertical axis is known. This allows the elevation calculated from perforation shot data to be compared to the known elevation to the center of the perforation gun, as a check on the assumption that the direction of arrival is the same as the direction to the source. It is unreasonable to assume that a correct orientation has been obtained if large errors in elevation result. In addition it is desirable to check the orientation obtained from any source against another source at a different azimuth. Orientations are measured from the y-geophone axis to north as shown in Figure 5(a).

5.1 ORIENTATION FOR THE FLUVIAL B STIMULATION EXPERIMENT

Table 4 gives the elevation errors and orientations determined for all three paths using data from the same perforation shots in wells MWX-1 and MWX-3 used to determine the velocity factors in Table 1. Average elevation errors vary from -4.2° to 4.2° , indicating a scatter about zero slightly larger than the 2.9° to 3.7° standard deviations of the three data sets. Before the final observation depths were chosen, several positions were rejected in both wells because of large errors in elevation on previous perforation shot series. The reasons for unsatisfactory results at rejected positions is not clear. It is possible that the quality of the casing cement bond is the dominate factor, or inhomogeneities in the formation could be causing the first arrival to be along a path different from the straight line path to the source.

The orientations obtained from both sets of perforation shots are given in Table 4. The 13 perforation shots in well MWX-1 confirm the orientation of the BSS receiver in well MWX-2 obtained from the 20

perforation shots in well MWX-3 to within a fraction of the 3.0° and 3.6° standard deviations of the two data sets. Thus, the assumption that the direction of P-wave polarization is the same as the direction towards the seismic source should be accurate to within 4° in both azimuth and elevation, even though the formation is neither homogeneous nor isotropic. Before the final observation depth in well MWX-2 was chosen, several positions were rejected because of large differences in orientation obtained from perforation shots in wells MWX-1 and MWX-3. Most positions rejected because of large orientation discrepancies also exhibited large elevation errors. Previous perforation shot series in wells MWX-1 and MWX-2 were used to pick the final observation depth in well MWX-3 based on confirmation of orientation. However, it was impossible to confirm the the final orientation of the BSS receiver in well MWX-3 due to the presence of the BSS receiver in well MWX-2.

TABLE 4
ORIENTATION FOR THE FLUVIAL B STIMULATION

Observation Well	Perforation Well	Receiver Orientation	Standard Deviation	Elevation Error	Standard Deviation
MWX-2	MWX-3	29.9°	3.6°	4.2°	2.9°
MWX-2	MWX-1	30.8°	3.0°	-3.6°	3.2°
MWX-3	MWX-1	-73.3°	2.4°	-4.2°	3.7°

5.2 ORIENTATION FOR THE FLUVIAL C MINIFRACS

Elevation errors and orientations obtained from the 18 perforation shots in well MWX-1 and the 10 perforation shots in well MWX-2 used to determine F_v for the Fluvial C minifrac are given in Table 5. The MWX-1 data set indicates a small scatter about the correct elevation, while the MWX-2 data set has such a small scatter that the even the 3.8° average error can be interpreted as a slight upward bias. Orientation based on perforation shots in well MWX-1 differs from orientation based on perforation shots in well MWX-2 by 9.6° , approximately four times the standard deviation of either data set. This indicates that there is probably a violation of the assumption that the direction of P-wave polarization is the same as the direction to the source. Since we wanted to leave the BSS receiver in the Fluvial C sandstone, this

problem was ignored, as were good statistical procedures, and all 28 values from the two data sets were combined to give an average orientation of -78.2° , with a standard deviation of 5.2° .

TABLE 5
ORIENTATION FOR THE FLUVIAL C MINIFRACS

Perforation Well	Receiver Orientation	Standard Deviation	Elevation Error	Standard Deviation
MWX-1	-81.6°	2.5°	2.5°	3.7°
MWX-2	-72.0°	2.1°	3.8°	0.7°

5.3 ORIENTATION FOR THE FLUVIAL E STIMULATION EXPERIMENT

Table 6 gives the elevation errors and orientations determined for all three paths using data from the same perforation shot in wells MWX-1 and MWX-3 used to determine the velocity factors in Table 3. The average elevation error for perforation shots in well MWX-3 was 2.9° with a standard deviation of 13.3° , indicating a rather large scatter about the correct value. Using data from well MWX-2, perforation shots in well MWX-1 resulted in an average elevation error of 0.0° with a standard deviation of 2.7° . Based on data from well MWX-3, these same perforation shots resulted in an average elevation error of 16.7° with a standard deviation of 11.0° , indicating both a large scatter and a strong upward bias. Previous perforation shot series in wells MWX-1 and MWX-2 with a BSS receiver at a depth of 5480 ft (1670 m) in well MWX-3 yielded much better results. However, excessive background noise resulting from a leaking bridge plug required that the BSS receiver in well MWX-3 be moved up 30 ft (9 m), to reduce the noise to an acceptable level.

The orientations obtained from both sets of perforation shots are given in Table 6. The perforation shots in well MWX-1 confirm the orientation of the BSS receiver in well MWX-2 obtained from the perforation shots in well MWX-3 to within a fraction of the 3.4° and 4.6° standard deviations of the two data sets. Thus, the assumption that the direction of P-wave polarization is the same as the direction

towards the seismic source is reasonable for the BSS receiver in well MWX-2. Previous perforation shot series in wells MWX-1 and MWX-2 confirmed the orientation of a BSS receiver in well MWX-3 at a depth of 5480 ft (1679 m). However, it was impossible to check the the orientation of the BSS receiver at the final depth of 5450 ft (1661 m) in well MWX-3 due to the presence of the BSS receiver in well MWX-2. In view of the absence of confirmation of orientation at the final depth and the large elevation errors from perforation shots, the orientation of the BSS receiver in well MWX-3 is questionable.

TABLE 6
ORIENTATION FOR THE FLUVIAL E STIMULATION

Observation Well	Perforation Well	Receiver Orientation	Standard Deviation	Elevation Error	Standard Deviation
MWX-2	MWX-3	48.0°	3.4°	2.9°	13.3°
MWX-2	MWX-1	49.0°	4.6°	0.0°	2.7°
MWX-3	MWX-1	-1.6°	3.9°	16.7°	11.0°

6.0 LOCATION OF PERFORATION SHOTS

In order to illustrate the accuracy which can be expected from the method, data from the perforation shots used for velocity factor determination and receiver orientation were analyzed as if they were microseismic events of unknown location.

6.1 LOCATION OF FLUVIAL B PERFORATION SHOTS

Analysis of the 13 Fluvial B perforation shots in well MWX-1 using data from both observation wells resulted in locations which have horizontal components that fall within a circle of radius 25 ft (7.6 m) about well MWX-1, as indicated by the triangle symbols in Figure 6(a). Figure 6(b) indicates that these locations are biased to lie above the center of the perforation gun and lie inside an ellipsoid of revolution about a vertical major axis extending 30 ft (9.1 m) above the center of the perforation gun with horizontal radius 25 ft (7.6 m). This is a considerably smaller error ellipsoid than results from analysis of data from either observation well alone. This error ellipsoid will be used as a standard against which to judge the single-receiver perforation locations for the Fluvial C and Fluvial E.

6.2 LOCATION OF FLUVIAL C PERFORATION SHOTS

Locations determined for Fluvial C perforation shots in both wells are shown in Figure 7. A few of these locations have horizontal components falling outside of circles of radius 25 ft (7.6 m) about the perforation wells, as indicated by the triangle symbols in Figure 7(a). This is clearly a result of using the average orientation value, and affects perforation shots in well MWX-2 to a greater extent than perforation shots in well MWX-1, only because more perforation shots were recorded in well MWX-1. Figure 7(b) indicates that all of the projections on the north-south plane lie inside circles of 25 ft (7.6 m) radius located at the center of the perforation guns; the center of the BSS receiver is indicated by the square symbol on the projection of well MWX-3. Thus, it appears that locations resulting from data from the single BSS receiver will be less accurate than locations resulting from

the two-receiver analysis of the Fluvial B data, mainly because of questionable orientation.

6.3 LOCATION OF FLUVIAL E PERFORATION SHOTS

Data from Fluvial E perforation shots in well MWX-1 were analyzed as if they were microseismic events of unknown location. The locations resulting from analysis of the MWX-3 data were inaccurate, as would be expected from the large elevation errors. The locations determined from well MWX-2 were more accurate. These locations, together with locations determined for the perforation shots in well MWX-3 are given by the triangle symbols in Figure 8. Some of these locations have horizontal components which fall outside of circles of radius 25 ft (7.6 m) about the perforation wells, as indicated by the triangle symbols in Figure 8(a). Figure 8(b) indicates that many of these locations lie outside of ellipsoids of revolution with horizontal major axes of 25 ft (7.6 m) and a vertical major axis of 30 ft (9.1 m) centered at the center of the perforation guns. Thus, it appears that locations resulting from data in well MWX-3 will be inaccurate and that locations determined using data from well MWX-2 alone will be less accurate than locations resulting from the two-receiver analysis of the Fluvial B data.

Figure 6(a). Horizontal projection of perforation shot locations for the Fluvial B sandstone at the MWX site.

Figure 6(b). Vertical projection of perforation shot locations for the Fluvial B sandstone at the MWX site.

Figure 7(a). Horizontal projection of perforation shot locations for the Fluvial C sandstone at the MWX site.

Figure 7(b). Vertical projection of perforation shot locations for the Fluvial C sandstone at the MWX site.

Figure 8(a). Horizontal projection of perforation shot locations for the Fluvial E sandstone at the MWX site.

Figure 8(b). Vertical projection of perforation shot locations for the Fluvial E sandstone at the MWX site.

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7.0 FRACTURE LOCATION IN THE FLUVIAL INTERVAL

Prior to the stimulation experiment in the Fluvial B sandstone an extensive series of perforation shots was used to locate the best depth for placement of the BSS receivers in both wells. The selection of receiver depth in each well was based on elevation errors and agreement in orientation between perforation shots in the other two wells. Perhaps as a result of this, data from two properly oriented BSS receivers were available for analysis of the stimulation experiment in the Fluvial B sandstone.

Well MWX-2 was being used for stress tests during the minifrac in the Fluvial C sandstone, so it was only possible to collect data from one BSS receiver. However, it was possible to place that receiver in the Fluvial C sandstone. This was felt to be a great advantage, since it avoided many of the problems thought to be associated with vertical layering. Perforation shots recorded from this position did result in acceptably small elevation errors. However, confirmation of orientation was off by almost 10° , shedding doubt on the advantage of placing the BSS receiver in the target sandstone.

Based on experience gained in the extensive perforation shot series prior to the stimulation experiment in the Fluvial B sandstone, both receivers were placed at the 5480 ft (1670 m) depth for the stimulation experiment in the Fluvial E sandstone. Perforation shots confirmed these to be good locations. Prior to the first minifrac, the bridge plug in well MWX-3 developed a small leak which produced unacceptable noise levels at this position. In the short time available it was impossible to find another good location and confirm receiver orientation, so the BSS receiver in well MWX-3 was moved up 30 ft (9 m), enough to reduce the noise to an acceptable level. Perforation shots with the BSS receiver in this position resulted in large elevation errors casting doubt on the orientation obtained for the BSS receiver in well MWX-3.

7.1 FLUVIAL B FRACTURE LOCATION

Over 1000 microseismic events were recorded on analog tape during the stimulation experiment in the Fluvial B sandstone on November 1, 1986. The treatment consisted of 22,000 gal (83.3 m³) of 75 quality nitrogen foam, and 32,500 lbs (14,750 kg) of intermediate strength proppant, pumped at 10 bpm (1.6 m³/min). The zone was the 23 ft (7.0 m) thick Fluvial B sandstone at a depth of 5822-5845 ft (1775-1782 m).

Problems with the IDAS software prevented digitization of all but about 160 of these events. The location of most of the events digitized during pump in could not be determined due to high noise levels, probably resulting from flow of the frac fluid through the formation. Most events digitized during shut in and flow back had very good signal-to-noise ratios and could be located from both wells. However, some of these events resulted in two single-receiver locations which were so far apart that it seemed unreasonable to believe the resulting two-receiver location. Still others resulted in locations that were not consistent with the differences in P-wave arrival times at the two BSS receivers.

Figure 9 shows the locations given to 29 microseismic events which were located from both BSS receivers. These locations indicate a fracture azimuth of N68°W, Figure 9(a). It is interesting to note that all of these locations lie between parallel lines 25 ft (7.6 m) on either side of this line, consistent with the scatter in locations determined for the perforation shots in well MWX-1. This indicates that a fairly high level of confidence can be associated with the N68°W fracture azimuth determined from these locations, in spite of the fact that spherical statistics on the set of angles measured from well MWX-1 to event locations yields a 21.3° standard deviation. The N68°W azimuth is in excellent agreement with previous measurements at this site.¹⁴

Projections of these locations onto the vertical plane through well MWX-1 at N68°W are shown in Figure 9(b). Most of these locations lie above the Fluvial B sandstone. It is clear from Figure 9(b) that scatter in the vertical direction has a more serious detrimental effect

Figure 9(a). Horizontal projection of microseismic event locations for the stimulation experiment in the Fluvial B sandstone.

Figure 9(b). Vertical projection of microseismic event locations for the stimulation experiment in the Fluvial B sandstone.

on determination of fracture height than scatter in the horizontal direction has on determination of fracture azimuth. It is known from radioactive tracers in the proppant that the fracture broke out of the top of the Fluvial B sandstone by at least 10 ft (3 m) at well MWX-1. This, together with the upward bias and 30 ft (9 m) uncertainty in determination of the vertical location of the perforation shots in well MWX-1, would lead us to expect microseismic event locations associated with the top of the fracture at depths up to 5780 ft (1760 m). All but two events lie below this level. However, it is obvious that the bottom of the fracture cannot be determined from these locations.

Most of the events shown in Figure 9 occurred during flow back. In an earlier minifrac in this same formation no locatable events were detected during flow back. This leads us to conjecture that these events are related to the proppant. If this is true, then it may be possible to use events recorded during flow back to map the propped fracture length and height, and in fact Figure 9 may represent only the propped portion of the west wing of the fracture.

7.1.1 DIFFERENCES BETWEEN FLUVIAL B DATA FROM THE TWO OBSERVATION WELLS

Certain systematic differences between data from the two observation wells became obvious after a thorough analysis of the data from the Fluvial B stimulation experiment. Definite causes for these differences have not been established, but it is tempting to speculate.

There seems to be a difference in signal strength between data from the BSS receivers in wells MWX-2 and MWX-3. For events located at equal distances from both observation wells, signal strength for the BSS receiver in well MWX-2 was approximately three times that for the BSS receiver in well MWX-3. It has been suggested that the difference in signal strength between the two wells is a result of differences in the formations in which the two BSS receivers were placed or differences in the quality of the well casing cement bonds at the receiver locations. At this time such suggestions must be regarded as speculation.

Figure 10 shows 73 locations given microseismic events based on data from well MWX-2. Some of these events occurred during pump in and have very large error ellipsoids. Less than 40 percent of these 73 events resulted in acceptable two-receiver locations for reasons mentioned above. In spite of the problems with this data set, Figure 10 can be used to illustrate several points.

Figure 10 shows several events on the east wing of the fracture at distances of up to 130 ft (40 m) from the stimulation well. This confirms the existence of an east wing of the fracture. For all but one of these events, the signal strength from the BSS receiver in MWX-3 was too weak to give a consistent two-receiver location. This is probably related to the above mentioned difference in signal strength between wells MWX-2 and MWX-3. The single event on the east wing of the fracture in Figure 9 is more than 300 ft (90 m) from the BSS receiver in well MWX-3. Beyond this range, data from well MWX-3 produced no analyzable events which were in close enough agreement with positions determined from well MWX-2 to result in acceptable two-receiver locations.

Figure 10(a) indicates a fracture azimuth of N80°W, 12° different from Figure 9(a). The cause of this difference is illustrated by the single event shown in Figure 5. In Figure 5(a), the single-receiver locations are 10° above and below the N70°W azimuth of the two-receiver location, causing both of the single-receiver azimuths to differ from the two-receiver azimuth by 10°. This is typical of most of the 29 locations in Figure 9. It seems reasonable to assume that this pattern is caused by the inhomogeneous anisotropic nature of the MWX site. Whether it results from violation of the assumption that the direction of polarization is the direction to the source or problems with the velocity model remains to be determined. It is clear, however, that errors in azimuth could result from dependence on data from only one observation well.

Figure 10(a). Horizontal projection of Fluvial B microseismic event locations determine from Well MWX-2 data.

Figure 10(b). Vertical projection of Fluvial B microseismic event locations determined from Well MWX-2 data.

7.2 FLUVIAL C FRACTURE LOCATION

Over 1000 microseismic events were recorded on analog tape during each of the two minifrac in the Fluvial C sandstone which were conducted on April 30 and May 12, 1987. The April 30 treatment consisted of 6,300 gal (24 m³) of 75 quality nitrogen foam pumped at a rate of 10 bpm (1.6 m³/min). The May 12 treatment consisted of 15,000 gal (57 m³) of 75 quality nitrogen foam and 5,000 lbs (2,273 kg) of 100 mesh sand pumped at 9.2 bpm (1.5 m³/min). The target zone was the 22 ft (6.7 m) thick fluvial B sandstone at a depth range of 5714-5736 ft (1742-1748 m).

Problems with the IDAS software prevented digitization of all but about 150 of these events for each minifrac. Since there seemed to be no difference between the two data sets, they were combined. Figure 11 is based on 53 microseismic events located using data from both data sets. Flow noise prevented the analysis of most signals digitized during the pump in phases. Most locatable events occurred during the shut in phases, with very little activity during either flow back phase. The absence of significant seismic activity during flow back confirms the conjecture that there is a relationship between events occurring during flow back and the presences of proppant in the frac fluid.

Figure 11(a) indicates an azimuth of N63°W. The standard deviation resulting from spherical statistics on the set of angles measured from well MWX-1 to microseismic event locations is 23.7°. It would seem reasonable to assume that the N63°W azimuth could be off by as much as 20°. Figure 11(b) shows a west wing of at least 250 ft (76 m) and a less well defined east wing of 200 ft (61 m). Height appears to be 100 ft (30 m) with a fairly well defined bottom at 5800 ft (1758 m) and a less well defined top at about 5700 ft (1737 m).

Figure 11(a). Horizontal projection of microseismic event locations for minifrac in the Fluvial C sandstone.

Figure 11(b). Vertical projection of microseismic event locations for minifrac in the Fluvial C sandstone.

7.3 FLUVIAL E FRACTURE LOCATION

Over 2000 microseismic events were recorded on analog tape during the stimulation experiment in the Fluvial E sandstone on September 23, 1987. The treatment consisted of 42,000 gal (160 m³) of 75 quality nitrogen foam and 20 lb/1000 gal (2.4 kg/m³) of Xanthan gum gel, with 72,000 lb (19,000 kg) of 20-40 mesh proppant (Proflow) and 10,000 lb (4,500 kg) of 100 mesh sand, pumped at 23 bpm (3.7 m³/min). The zone was the 24 ft (7.3 m) to 35 ft (10.7 m) thick Fluvial E sandstone at a depth of 5535-5565 ft (1687-1696 m) in well MWX-1.

Activity was intense during the one hour and 15 min of the pump in phase. However, only four microseismic events could be located from the 140 signals detected at a trigger level of 4.5 V (full scale is 10 V), because of the high level of background noise. This high background noise level is probably the result of fluid moving through the formation as well as from the pumping equipment itself.

During the shut in phase, background noise was not a problem, and 72 microseismic events were located from 340 signals which were digitized at a trigger level of 3 V. Many of the unanalyzable signals seemed to be associated with vertical oscillations, possibly resulting from tube waves in the fluid filled portion of the casing below the bridge plug.

Background noise increased only slightly during the flow back phase, but activity was so intense that it was necessary to increase the trigger level to 5 V for the first hour, in order to avoid rapid saturation of available disk space. Over 800 signals which exceeded the 3 V level were recorded on analog tape during the first hour of the flow back phase, including 180 which exceeded the 5 V level and were digitized. After the first hour of the flow back phase, the trigger level was reduced to 3 V and only 40 signals were digitized during the next hour. From these 220 signals, 84 microseismic events were located. Again, vertical oscillations seem to dominate the unanalyzable signals.

In earlier minifrac in this same formation, very little seismic activity was detected during flow back. Thus, the dramatic contrast

Figure 12(a). Horizontal projection of microseismic event locations for the stimulation experiment in the Fluvial E sandstone.

Figure 12(b). Vertical projection of microseismic event locations for the stimulation experiment in the Fluvial E sandstone.

between seismic activity during flow back with and without proppant, noted during the Fluvial B stimulation experiments, is confirmed by the Fluvial E stimulation experiments.

All of these signals were also recorded in well MWX-3. However, almost all azimuths derived from well MWX-3 data were within eight degrees of the average perforation shot azimuth. Since the scatter in perforation shot azimuths was almost eight degrees, and confirmation of orientation had not been possible for the final receiver position, it seems reasonable to assume that orientation of the receiver in well MWX-3 is unknown. For the 160 microseismic events located, it was possible to confirm that positions derived from MWX-2 data are consistent with P-wave arrival times in well MWX-3. This was done by using differences between P-wave arrival times in wells MWX-2 and MWX-3, together with differences in distances, to compute a reasonable P-wave velocity for the two paths. This P-wave velocity and the separation between the P-wave arrival and the S-wave arrival can then be used to compute the corresponding S-wave velocity. As an example, consider the event shown in Figure 4. This event is located 305 ft (93 m) from well MWX-2 and 376 ft (115 m) from well MWX-3. The difference in times of arrival for the P-wave at the two wells is 6.1 ms. This results in a P-wave velocity of 11.6 ft/ms (3548 m/s) and gives an S-wave velocity of 7.3 ft/ms (2225 m/s), both considered reasonable for this formation.

Figure 12 is based on 160 microseismic events located using data from well MWX-2. It is the result of analysis of the 700 signals digitized from the low gain channels during the stimulation experiment. Figure 12 shows symmetric wings of 250 ft (76 m) length. Vertical positions indicate a fairly well defined top and bottom, giving a frac height of about 120 ft (37 m). The N60°W azimuth is about 10° from what was expected (N70°W). The standard deviation resulting from statistics on the set of angles measured from well MWX-1 to microseismic event locations is 14.9°. The locations resulting from analysis of well MWX-2 data in the Fluvial B yielded an azimuth that was 12° different from the azimuth determined from locations based on analysis of data in both wells. For these reasons it would seem reasonable to assume that the N60°W azimuth shown in Figure 12(a) could easily be off by 10°.

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8.0 EVALUATION AND RECOMMENDATIONS

Perhaps the thing most obvious from the material presented above is: Hydraulic fracture stimulations create enough microseismic events for determination of fracture azimuth, height and wing length by passive seismic monitoring using the BSS. At the MWX site, receivers in two closely spaced offset wells were sufficient to determine the azimuth, near-wellbore height and possibly the propped fracture length. Since even two closely spaced offset wells are not usually available, testing the range of the BSS is certainly necessary if it is to be developed into a practical method of hydraulic fracture mapping.

Most of the improvements in BSS design discussed above have concentrated on the electronics necessary to bring geophone signals to the surface and digitize them with high enough resolution and signal-to-noise ratios for analysis. The current electronics are probably adequate for a practical system, and should be easy to fine tune to field conditions different from the MWX site. Gain can easily be increased or decreased to adjust the system to background noise levels and signal strengths. The dynamic range of the BSS can be increased by separating the gain of the high and low gain channels by more than the current 12 dB.

Because the seismic monitoring task at the MWX site was planned as a test of principle through application, rather than as a development project, many potential problems with the BSS which have been observed during the last two years have not been systematically investigated. We would like to use the remainder of this section to discuss the things we have done to understand and alleviate some of these problems, and to suggest research which would be advisable before development of the BSS into a practical field receiver should be considered.

8.1 MECHANICAL PROPERTIES OF THE BSS RECEIVER AND GEOPHONES

Some effort has gone into understanding the vibrational modes of the BSS receiver and their possible effects on the output of the geophones.

As mentioned in section 2.0, a resonance associated with the long clamp arm of the original design dominated data taken during the Strategic Petroleum Reserve acoustical emissions experiment at Bayou Choctaw,¹¹ emphasizing the importance of the vibrational modes of the BSS receiver. With a shorter clamp arm and horizontal geophones oriented at 45° with the plane of the clamp arm, data from the Phase I stimulation experiment in the Paludal zone yielded a fracture azimuth, height and wing length in close agreement with data from other sources and with theoretical calculations.² However, these data were at a single frequency, independent of distance and source, indicating possible resonance problems.

Data recorded with the upgraded BSS during the Coastal stimulation experiment exhibited more complex wave forms, but were still dominated by a single frequency. Figure 13 gives the energy spectral density of a horizontal component of a perforation shot, the spectral amplitude of a horizontal component of the flow noise during pump in and the summed spectral content of the horizontal components of 30 microseisms recorded during the Coastal stimulation experiment. The dominant frequency is between 360 Hz and 390 Hz for all three sources, with only the microseismic events exhibiting significant energy at other frequencies. The vertical components for all three sources were also dominated by a single frequency, but at about 250 Hz.

After minor modifications to the clamp arm, data from the Fluvial C minifrac appeared as though most events consisted of a signal of broad frequency content followed by a lower frequency signal which persisted for more than 100 ms. Figure 14(a) shows the horizontal component of an event for which this behavior was particularly obvious. The higher frequency content of the first 85 ms is followed by a slowly decaying signal of lower frequency. The amplitude spectrum of the first 85 ms of this event, Figure 14(b), shows a dominant frequency of 470 Hz with significant content both above and below that frequency. Peaks are obvious at 140 Hz and 280 Hz in the amplitude spectrum of the remaining 115 ms of this event, given in figure 14(c). While the BSS receiver was still clamped in the Fluvial C sandstone, the horizontal exciter was

Figure 13(a). Energy spectral density for a tubing shot from the Coastal zone stimulation experiment at the MWX site.

Figure 13(b). Spectral amplitude of flow noise during pump in for the Coastal zone stimulation experiment at the MWX site.

Figure 13(c). Summed spectral content of 30 events recorded during the Coastal zone stimulation experiment at the MWX site.

Figure 14(a). Horizontal geophone data for a Fluvial C minifrac event.

Figure 14(b). Amplitude spectrum of the first 85 ms of Figure 14(a).

Figure 14(c). Amplitude spectrum of the last 115 ms of Figure 14(a).

Figure 15(a). Vertical geophone data for a Fluvial C minifrac event.

Figure 15(b). Amplitude spectrum of the first 60 ms of Figure 15(a).

Figure 15(c). Amplitude spectrum of the last 140 ms of Figure 15(a).

sweep through a frequency range of 100 Hz to 1 kHz. This indicated resonances at 140 Hz and 280 Hz. Short bursts applied to the horizontal exciter at these frequencies produced ringing which decayed by only 12 dB after 150 ms.

Data from the vertical axis exhibited even more dramatic behavior. The vertical time history for the same event is shown in Figure 15(a). Note the dramatic change in frequency content at 65 ms, with an increase in amplitude. The amplitude spectrum of the first 60 ms, Figure 15(b), shows a broad frequency content. The amplitude spectrum of the remaining 140 ms, Figure 15(c), shows a dominant frequency of 285 Hz. Sweeping the vertical exciter through a 100 Hz to 1 kHz frequency range, while the BSS receiver remained clamped in this position, revealed a resonance at 285 Hz. A short burst applied to the vertical exciter at 285 Hz produced ringing which attenuated very little during the first 150 ms after the driving signal was turned off.

Motivated by these results, it was decided to try to eliminate the geophones themselves as the cause of these apparent resonance and damping problems. We were aware that properties of the clamp arm, the length and weight of the BSS receivers and properties of the well bore casing were also likely causes, but we had neither the time nor funds to pursue these possibilities. We already knew that the Mark Products L-25 geophones should be replaced because of their nonlinear response above 400 Hz, Figure 3. It required only a small additional effort to make the new geophone array as uniform as possible in both its directional and frequency response.

To this end we chose Geo Space GS-14-L9 geophones which not only provide a 28 Hz to 2 kHz frequency range, but can be mounted at any angle with the vertical. This allowed us to use identical geophones on all axes to eliminate the type of physical differences known to exist between the Mark Products L-25 horizontal and vertical geophones. In order to minimize directional differences, we used four axes, oriented in such a manner that all axes make the same angle with both the plane of the clamp arm and the horizontal plane, a three-dimensional analogy of the earlier decision to mount the horizontal geophones at 45° to the

plane of the clamp arm. Four Geo Space GS-14-L9 geophones per axes were used to give about the same sensitivity as three of the Mark Products L-25 geophones. Great care was taken to match the mounted response of all 16 geophones in each BSS receiver over a 100 Hz to 1 kHz range by using the the vertical exciter geophone as a signal source. This process required almost six weeks and resulted in the rejection of over 60% of the geophones tested, but produced two four axes arrays which had perfectly balanced response to the vertical exciter over the frequency range of 100 Hz to 1 kHz in the laboratory. However, perfect balance was maintained only over the frequency range of 300 Hz to 500 Hz when the same tests were performed with a BSS receiver clamped in well MWX-2 in the position used for the Fluvial E stimulation experiment. Tests using the horizontal exciters confirmed balance between all axes when the BSS receiver was hanging from the wireline, but produced biased response at all frequencies with the BSS receiver clamped in well MWX-2 in the position used for the Fluvial E stimulation experiment. These tests firmly establish that clamp arm and well casing properties cannot be ignored.

Data from the BSS receiver located in well MWX-2 during the Fluvial E stimulation exhibited a broadband frequency spectrum and differences between the amplitude spectra of perforation shots, background noise and microseismic events were obvious. Events located nearer to well MWX-2 showed much greater high frequency content than events at greater ranges. Figure 16(a) shows the amplitude spectrum of the vertical component of a microseismic event located 200 ft (60 m) from well MWX-2, and Figure 16(b) shows the amplitude spectrum of an event located 300 ft (90 m) from well MWX-2. Note that the dominant frequency of the nearer event is 370 Hz with significant content above 400 Hz, while the event at greater range has a dominant frequency of 190 Hz with very little content above 400 Hz.

The Fluvial E data set from well MWX-2 is a significant improvement over previous data sets. However, the fact that the geophones responded correctly to tests using both the vertical and horizontal exciter geophones when the BSS receiver was hanging from the wire line, but failed these same tests when the BSS receiver was clamped in well MWX-2

Figure 16(a). Amplitude spectrum of the vertical component of an event located 200 ft (60 m) from well MWX-2 during the Fluvial E stimulation experiment at the MWX site.

Figure 16(b). Amplitude spectrum of the vertical component of an event located 300 ft (90 m) from well MWX-2 during the Fluvial E stimulation experiment at the MWX site.

at the position used to collect the Fluvial E data set, indicates that the response of the clamp arm and/or well casing must be coloring the data. It seems unreasonable to assume that a clamp arm with a maximum force of 300 lb (136 kg) is sufficient to secure the 12 ft (3.7 m) long, 280 lb (127 kg) BSS receiver rigidly to the well casing.

Vibrational modes of the BSS receiver should be studied by finite element analysis and tests under controlled conditions. It seems possible that the rigidity with which the clamp arm mechanism can secure the BSS receiver to the well casing could be significantly improved by such simple things as increasing the force exerted by the clamp arm and assuring wide spaced contact points opposite the clamp arm at both the top and bottom of the BSS receiver.¹⁵ If these studies were to show that simple modifications of the current clamp arm system are not sufficient to produce a uniform response, it should be possible to develop a short light geophone or accelerometer array which could be clamped to the well casing with a force many times its own weight.

A finite element analysis of the current BSS receiver and the effects of potential modifications could be performed with existing software and only a modest amount of manpower and computer time. However, it would be necessary to test the current BSS receivers and any proposed improvements under controlled field conditions in order to guide the analysis and confirm the results.

8.2 EFFECTS OF THE WELL CASING

Perforation shot data recorded at some positions in the observation wells resulted in large elevation errors and orientation conflicts. This was most dramatically illustrated by the choice of a particularly bad location in well MWX-3 during the Fluvial E stimulation experiment. Not only were large elevation errors observed during the perforation shot series, but the direction of P-wave polarization seemed to be unrelated to microseismic event location during the stimulation experiment itself. The most likely cause of this is the poor quality of the casing cement bond at this location. It is important to include

the effects of the well casing and the quality of the casing cement bond in the finite element analysis and controlled field tests proposed in section 8.1. This should include some tests in uncased wells.

8.3 ANALYSIS METHODS

The method of analysis used for all of the data sets discussed above involved the use of interactive graphics to aid the analyst in deciding which signals represent microseismic activity associated with the hydraulic fracture, in picking P- and S-wave arrivals and in determining the number of sample points to use for the spherical statistical determination of microseismic event locations. This is a time consuming process which must be automated before the method is to be considered practical. It should be possible to develop an expert system, based on the experience gained in the analysis of the Fluvial data sets, which would automatically perform the same tasks which are used by the analyst to make these decisions. The most difficult part of this would be picking the S-wave arrivals, since the S-wave usually arrives within the P-wave coda and is further masked by reflected and refracted P-waves and perhaps vibrational modes within the BSS receiver and well casing. Development of such an expert system could be accomplished on a personal computer and tested on existing data sets with only a small manpower commitment.

Automating the analysis would allow the processing of more data and should allow a larger number of event locations to be determined; the number of location in Figure 12 was limited by the analyst's time, not the availability of data. In addition, automation would avoid prejudice on the part of the analyst, which could bias the results. The current analysis techniques and hardware are slow and frustrating. With automated data processing much of the frustration associated with the slowness would be removed, since the analysis program could run unattended. This would also produce results faster than the current method which usually takes at least a month.

If a larger faster computer with at least two central processing units (CPUs) were available, the analysis task could be accomplished in parallel with data acquisition. Without a large number of CPUs, it would be impossible to design an expert system which could keep up with data acquisition during the most active part of the stimulation experiment, when microseismic events would be recorded faster than the 30 per minute maximum rate of the current system. However, even with only two CPUs, the analysis program could probably catch up with the data acquisition program during less active parts of the experiment and produce a complete fracture map shortly after activity returned to normal levels. This would require a capital expenditure, but could be tested without further field activity by playing back the analog records of existing data sets.

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9.0 SUMMARY AND CONCLUSIONS

In spite of the inhomogeneous anisotropic conditions existing at the MWX site, it has been possible to orient BSS receivers in both observation wells by assuming that the direction of primary wave polarization is the direction to the seismic source, with only small errors in elevation and an even smaller scatter in azimuth. During the stimulation experiment in the Fluvial B sandstone, this resulted in the ability to locate perforation shots at a known depth in well MWX-1 to within 25 ft (7.6 m) in the horizontal and 30 ft (9.1 m) in the vertical by using data from both observation wells.

Placing the BSS receiver in the target sand during the two minifrac in the Fluvial C sandstone did not seem to result in improved signals. Analysis of perforation shots in wells MWX-1 and MWX-2 in the Fluvial C sandstone indicated that orientation of the single BSS receiver in well MWX-3, centered in the the Fluvial C sandstone, was off by at least 9.6° .

During the stimulation experiment in the Fluvial E sandstone, it was possible to orient the BSS receiver in well MWX-2 from perforation shots in well MWX-1 with very small errors in elevation and small scatter in azimuth. This orientation was confirmed by perforation shots in well MWX-3. However, the perforation shots in well MWX-1 yielded large errors in elevation when analyzed from data collected in well MWX-3, casting serious doubt on the orientation of the BSS receiver in well MWX-3. Using only data from well MWX-2 resulted in the ability to locate perforation shots somewhat less accurately than was possible in the Fluvial B by using data from both observation wells.

Data collected in both observation wells during the stimulation experiment in the Fluvial B sandstone, indicate a fracture azimuth of $N68^\circ W$ with a fairly high level of confidence. However, fracture height could not be established due to the almost total absence of microseismic events located near the bottom of the fracture. Systematic differences between the data from the two observation wells indicate that dependence on data from one observation well could result in errors in fracture azimuth for inhomogeneous anisotropic geologies such as the MWX site.

Analysis of data recorded in well MWX-3 during the two minifrac in the Fluvial C sandstone indicates a fracture azimuth of N63°W, a fracture height of 100 ft (30 m) and asymmetric wings of at least 250 ft (76 m) to the west and 200 ft (61 m) to the east. Analysis of data from well MWX-2 collected during the Fluvial E stimulation indicates a fracture azimuth of N60°W, a fracture height of 120 ft (37 m) and symmetric wings of 250 ft (76 m).

Improvements in the BSS electronics and the geophone array have resulted in a practical method of fracture mapping from two closely spaced observation wells. Extension of this to a more accurate method for fracture mapping will require a better understanding of the mechanical properties of the BSS receiver and how it is coupled to the formation through the well casing. Automation of data analysis methods will be necessary before seismic determination of fracture properties can be considered to be practical.

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