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THE DETERMINATION OF DIRECTION AND LENGTH OF HYDRAULICALLY INDUCED FRACTURES IN PETROLEUM RESERVOIRS: A FIELD EXPERIMENT

By

L. Z. Shuck
Morgantown Energy Research Center, USBM

ABSTRACT

Hydraulic fracturing of oil and gas bearing sandstone formations to enhance recovery is still being done today without any means of determining the actual types, lengths, or directions of fractures induced away from the wellbore. The mechanics of hydraulic fracturing processes affecting the acoustic mapping of fractures, the associated crack and wave propagation phenomena, monitoring system requirements, an example of a monitoring system used, and field experiments conducted to date by the Morgantown Energy Research Center, U.S. Bureau of Mines are discussed.

Applications of the fracture mapping technique, if proven successful could lead to improved well location design and fracturing treatments for more efficient petroleum and natural gas recovery, solution mining, in situ coal gasification and liquefaction, subsurface waste disposal, oil shale and geothermal energy extraction, and perhaps others.

Preliminary analysis of the data indicates that the fractures propagate in discrete phases or arc lengths during which sufficient acoustic emissions occur to allow the fractures to be mapped, and that the best bandwidth for monitoring the acoustic emission may be the 80 to 500 Hz range.

INTRODUCTION

Hydraulic fracturing of oil and gas bearing formations to increase recovery has been a practice since the late 1940's. Although many schemes of calculating fracture lengths and predicting the directions have been devised, no direct means of measuring the number, types, lengths, directions, or rates of growth of induced fractures exists today. Wellbore post-fracture measurements, including impression packers, are presently the best means of direct measurement of induced fracture orientations. These observations, however, are not necessarily valid a few inches away from the wellbore. Further development of hydraulic fracturing technology depends upon a more immediate means of measuring results. Accurate and immediate measurement of the fracture directions for only a few wells in a new reservoir could allow systematic development for maximum and more economical recovery. Applications of the fracture mapping technique, if proven

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References and illustrations at end of paper.

successful, are numerous, including: petroleum and natural gas recovery, oil shale and geothermal energy recovery, solution mining, in situ gasification and liquefaction, liquid and slurry subsurface waste disposal, and perhaps many others.

During 1970, the Morgantown Energy Research Center initiated a theoretical, experimental, and field oriented research project to investigate the technique of mapping hydraulically induced fractures in space and time through monitoring acoustic emission from stressed rocks. This paper gives an overview of the objectives, disciplines involved, techniques developed, and field experiments conducted to date.

Before a quantity can be accurately measured, a great deal must be known about its nature. This is the essence of much of this research effort. Information about reservoir fracturing mechanisms and processes, the controlling factors, and characteristics of waves propagated under real reservoir conditions is sparse.

Some basic objectives of the research effort have been: (1) to investigate hydraulic fracturing processes and define conditions and intrinsic features affecting wave propagation, (2) to assess the feasibility of determining these intrinsic features through the monitoring of acoustic emission under ideal, or the best possible, field conditions, and (3) assuming feasibility under ideal field conditions, determine the extent to which those conditions can be relaxed, and the corresponding accuracy or resolution with which the fracture growth rates, number, types, directions, and lengths can be determined. This is the ultimate answer desired, since it will govern the economics of the process and its ultimate usefulness to the industry. Answers to these questions should provide potential users with refined information which might not be economically attractive for them to pursue through their own research programs.

Three fundamental approaches to this problem have been attempted at MERC simultaneously: (1) a general-purpose data acquisition system was designed, assembled, and used in field experiments to obtain some basic information, (2) a theoretical, a priori, analysis was initiated to define one or more specific characteristics of the process so that a special-purpose system could be designed to measure them, and (3) some basic experiments to be performed under well-defined and controlled laboratory conditions, were designed to verify certain process characteristics. The general scope of the ongoing research is as follows:

I. Theoretical Considerations

    A. Analysis of actual field hydraulic fracturing processes, boundary and initial conditions, shape and rates of propagating cracks

    B. Wave types and properties such as energy density, acoustic intensity, spectral content, length of pulses, bursts, and wave trains for waves corresponding to different fracture modes

    C. Near and far field transient wave propagation solutions

    D. Medium effects on the propagation of each type wave

    E. Selection of one or more combinations of wave characteristics to be measured for optimizing the determination of specific fracture results

    F. Assessment of the optimum, practical, and minimum requirements for a field data acquisition system

    G. Noise environment characteristics and signal-to-noise ratios

    H. Acoustic source location techniques

    I. Strain energy associated with different fracture modes

II. Monitoring System Design

    A. Number of monitoring stations required and array configuration

    B. Number and type of sensors required at each monitoring station

    C. Sensitivity and frequency response required of each type sensor

    D. Total system design, fabrication, calibration, and evaluation

III. Laboratory Experimentation

    A. Determination of mechanical, physical, and acoustic properties of oriented core from a well in which fracture map experiment is to be conducted

- B. Acoustically map hydraulically induced fracture initiation and growth in laboratory test specimens under structural, geometric, tectonic, and hydraulic similitude conditions.

IV. Field Experimentation

- A. Performance field tests to prove total system source location and result display capability
- B. Pre-fracture testing and site evaluation
- C. Hydraulic fracture experiments in oilwells
- D. Post fracture experiment field testing and evaluation

V. Data Reduction and Analysis

- A. Type of analyses required
- B. Data enhancement techniques such as filtering and correlation
- C. Data conversion system design, fabrication, and evaluation
- D. Real time or on-line analysis system design and evaluation
- E. Visual and acoustic detection and display systems
- F. Post field test analysis system design and evaluation

The monitoring of acoustic emission in stressed materials for the purpose of detecting stress buildup and fracture initiation is now a well known technique. Obert[28] used the technique as early as 1941 to predict rock bursts in mines. Blake,[5] Cook,[8] Duvall,[11] Hardy,[16,17] Knill,[20] Obert et.al.,[29] Oudenhoven[30] and many others have advanced the understanding of acoustic emission as related to rock mechanics problems. Blake et.al.[6] discuss some characteristics of the acoustic emission from rocks. Barron,[4] Harris et.al.[18] have monitored acoustic emission for the purposes of detecting fracture initiation and growth. Leighton, et.al.[24] discuss techniques for locating the noise sources in rocks.

The first known application of seismic techniques to the mapping of hydraulic fractures was by McClain[25,26] in 1969. This work was conducted as part of a program for subsurface disposal of radioactive wastes. Low frequency response surface geophones were used to detect the acoustic emission signals. Results of these fracture mapping tests were very encouraging with several noise source points located in a horizontal plane. From the noise sources located in this experiment the fractures initiated and propagated "horizontally" or radially in a plane perpendicular to the wellbore axis as opposed to vertically or inclined as illustrated later in figures 2-b and 2-c. The probable error was estimated at ± 100 feet since directional velocity corrections were not made and low frequency, 0.5 Hz period, geophones were used.

Recently, numerous researchers have shown interest in determining the direction of induced fractures, through acoustic or seismic monitoring techniques. Senturion Sciences, Inc.[32] holds a patent related to the seismic mapping of hydraulic fractures in reservoirs.

MECHANICS OF HYDRAULIC FRACTURING PROCESSES

The monitoring of acoustic emission associated with hydraulic fracturing processes for the purposes of mapping the induced fractures may be approached in various ways. One approach is simply to monitor the noises generated without regard to the internal mechanics of the fracturing process and then attempt to locate the sources. Such sources would presumably represent a fracture zone. Although this approach is simple, any degree of refinement of the technique is precluded by a thorough understanding of the practical field fracturing processes, the associated fracture mechanics and wave propagation phenomena.

The boundary and initial conditions of a wellbore prior to fracturing may vary considerably depending upon the type well completion. Fully cased, cemented, and perforated tubing type completions represent substantially different conditions at the wellbore wall from those of the open or uncased wellbore type. Since the fractures are expected to follow the paths of minimum energy, which include combinations of the direction of the greatest compressive stress and directions of minimum rock strength, the wellbore conditions such as perforations or notches may not influence fracture growth beyond a few inches or feet from the wellbore. Nevertheless, the initial acoustic emission, flow-related noise level, and injection wellbore monitored transient pressures would be different for cased and uncased wells and would require different interpretations.

The dynamic injection wellbore pressure is an important and useful quantity in analyzing various aspects of the fracturing process. With flow associated pressure drop corrections, it gives the dynamic state of stress along the fracture cavity. Obviously, it is more meaningful in open wellbore completions, especially, if monitored with a pressure transducer in the same wellbore at the fractured formation elevation. A pressure transducer and monitoring scheme suitable for this purpose has been developed at the Morgantown Energy Research Center. Not only are the transient states of stress recorded, but the timing of the transient pressure pulses can be extremely useful in locating the points of interest in the recorded acoustic data. Figure 1 shows an example of a pressure record obtained at the top of the wellbore during an open or uncased well fracture operation. Care must be exercised in the interpretation of these surface pressure curves since transients due to changes in pumping operations and other mechanical disturbances can introduce anomolies and be very misleading. The pressure change between points D E F on the curve in Figure 1 is an example of the pump speed being changed. Monitoring dynamic pressures both at top and bottom of the wellbore will allow elimination of these uncertainties. Such a transient could otherwise be misinterpreted as a fracture extension.

The total acoustic emission is a result of numerous micro and macro processes associated with the fracture events. Low energy microseisms due to dislocation type mechanisms are initiated at low stress levels and coalesce into higher intensity signals as the stress approaches the ultimate strength values of the material. Since this type of acoustic emission is a stress level dependent phenomenon, a knowledge of the stress distribution during various phases of the fracture initiation and growth is important. The pressure increase between points A and B in Figure 1 is where the microseismic emission from a zone or region around the wellbore occurs initially. Theoretical examination of the stress distribution around the wellbore prior to fracture reveals that a zone with a radius of several feet will emit these microseismic signals, which presents no real monitoring problem. Interpretation and monitoring problems arise once fractures are initiated and extended. Most rock noise monitoring schemes for the purpose of source location, assume point sources. This is not the case, in general, for any hydraulic fracturing conditions. Some insight into the nature of the sources can be gained by referring to Figure 2. If the fracture is horizontal as depicted in Figure 2a, the shape of the transient energy emitting zone is similar to an expanding torus, assuming ideal radial growth of the fracture. Tne tip of the crack in this case forms theoretically an expanding circle in the horizontal plane. The vertical fracture tip shown in figure 2c constitutes approximately an expanding ellipse in the vertical plane which may be considered under certain conditions a vertical line source moving out from the wellbore. The shapes of the emitting zones will vary from these basic patterns due to numerous reservoir conditions and inhomogeneities. For vertical fractures, the strengths of the interfaces between shale and sandstone layers will play a significant role, especially if the fractures do not penetrate across the bedding planes as is believed to frequently be the case. Ghosh,[15] Heelan,[19] and Viswanathan[39] have derived expressions for line and cylindrical type sources. The necessity of utilizing near-field solutions, as opposed to far-field, depends upon the required resolution, heights of the zones being fractured, and the relative locations of the sensors. For example, monitoring vertically propagating fractures in a 10-foot thick sandstone at a distance of 1,000 feet would reasonably not require line source interpretation.

When vertical fractures are formed, there are usually at least two such line sources or fractures leaving the wellbore. The microseismic emitting zone is again a distributed source over a radius of several feet from the tip. The stress distribution around the tip which defines the emitting zone is complex. Shuck et.al.[33] investigated this distribution for the static, plane-strain case for vertically initiated fractures under typical reservoir conditions. Barnett, et.al[3] have calculated static stress intensity factors and extension forces associated with slit-cracks. Baker[2] considered the transient problem of the dynamic stresses created by a moving crack at constant velocity in a stretched elastic body.

Fracture propagation characteristics in geological materials are naturally some of the questions that hopefully will be answered by the acoustic monitoring techniques as studied both in the laboratory and the field. At this time, it is believed that the fractures propagate in discrete phases, as in a damped brittle material, and that two or more fractures propagating away from the wellbore in different directions are not likely to extend simultaneously or in synchronization on a millisecond time scale. Likewise, the horizontal fractures are also not expected to grow uniformly in a radial direction, but by discrete arcs or lobes.

The basic manner in which energy is supplied to the tip of a crack during a hydraulic fracturing operation substantiates the discrete fracture propagation theory. Due to the hydraulic flow impedance from a pump at the top of a wellbore, usually through more than 1,000 feet of tubing and through a fracture in porous media to the fracture tip, sufficient energy cannot be supplied to sustain a constant growth rate, except for very short periods. This must be true if the crack velocity were to approach some terminal velocity corresponding to even a small fraction of either the shear or Rayleigh wave velocities in typical sandstones of 8,500 and 7,815 feet per second, respectively. The maximum possible velocity in the fracturing fluid is only approximately 4,860 feet per second, and practically, the actual fluid velocity is less than 100 feet per second during most fracturing operations. With the fluid also flowing into the porous media perpendicular to the fracture direction, the hydraulic fracturing process is an intermittent, quasi-static--transient process of building up the elastic strain energy sufficient to extend the fracture only a small amount at a time. The energy supplied to the cavity during a discrete growth phase is insignificant to that required for even a small fracture extension. The amount of elastic strain energy that can be stored between crack extensions is largely a function of the tensile strength of the sandstone. Crack growth rates or velocities have been investigated for brittle, elastic materials by Craggs,[9] Dulaney,[10] Kuppers,[22] McClintock,[27] and Stroh.[37] Achenbach[1] discusses the problem of rapid extension of cracks.

The growth rate is believed to also vary continuously during a discrete phase since the rate is likely to be a function of initial and instantaneous fracture half-lengths.[10] Since the velocity of the crack tip and kinetic energy release associated with the initial part of a crack extension phase is expected to be the largest, it is hypothesized that the first part of the traveling wave train would have a significantly larger amplitude. Fracture growth in direction and shape is considered by this author to be a dynamic stability problem with the smallest of inhomogeneities or perturbations of the stress field capable of altering the fracture direction and shape prior to, and during an extension or growth phase. Directional stability of an extending fracture in a transversely isotropic layer is governed largely by the difference in principal tectonic stresses within the plane.

Observation of wellbore fluid pressure changes due to discrete extensions is unlikely at the surface after the initial or second extension, because of the normal fluid pumping noise and attenuation of the transients through the fracture cavity and the wellbore tubing.

In addition to the microseismic emission occurring around the crack tip, there are other types or sources of acoustic energy released. The creation of free surfaces and the sudden release of elastic strain energy with a moving crack tip due to tensile or shear fracture modes each generate different types of waves. These irrotational, equivoluminal, Rayleigh, and possibly Love and plastic-acceleration waves are functions of the kinetic, elastic strain and total surface energies, and are directional relative to the crack orientation. Finkel' et.al.,[12] Freund,[13] Gerberick, et.al.,[14] Kostrov,[21] Ravera,[31] and Sih[36] give developments for the stress waves associated with crack formation and propagation. Waves are also likely to propagate due to Coulomb forces acting along fractured planes with relative motion or the impact of faces collapsing together from temporarily propped positions. Teisseyre[38] has considered a related problem of crack formation and energy release along fault planes. These acoustic sources would also be of value in locating the fracture systems. The acoustic energies associated with the moving crack tip, however, are believed to be of sufficient magnitude to be monitored at large distances and are of primary interest in attempting to map the growth of hydraulically induced fractures.

MONITORING SYSTEMS AND SCHEMES

Acoustic emission from stressed materials is monitored for numerous purposes,[18] each requiring special monitoring or processing schemes. Some techniques employ digital counters and correlate rate and/or total accumulation of emitted pulses above a given level with such conditions as predicted failure. Such techniques may not require a recording for further off-line analysis. For the purpose of mapping hydraulic fractures, it is almost essential to have a recording of the data on a medium for additional expedient processing. The signals of interest are usually of small amplitude with unfavorable signal-to-noise ratios, and enhancement techniques of filtering and auto- or cross-correlation are required. The major obstacle to acoustic monitoring of fracture initiation and growth in petroleum reservoirs is the large distances between the fractures being created and the monitoring stations.

Various schemes can be devised to improve the acoustic coupling or general monitoring conditions with the only limitation being economical justification. Some of the schemes considered are illustrated in Figure 3.

Obviously, sensors would ideally be located at different elevations near the fractured zone and as close as possible to the propagating fractures. In some cases it may be possible to enter old wells and lower instruments to the desired elevation. Well casings may also be used as a means of improving the acoustical coupling if transducers are mounted rigidly on top of the casing. Monitoring from the injection wellbore offers some advantages but also introduces several operational complications.

It is desirable to monitor the highest frequency present, that can be detected by the monitoring system, for the purpose of source locations because the accuracy and resolution of the technique are inversely proportional to the highest frequency of the transmitted signals. However, attenuation of acoustic signals through geological materials is usually linearly proportional to frequency. Thus, the high frequency capability needed for monitoring systems is dictated, for a given strength signal, by the distance between the source and monitoring points and the required resolution.

The number of monitoring stations and array configuration are also important considerations. Except for surface positions or specially drilled monitoring holes, the array pattern in petroleum reservoirs is constrained by existing wells in the area. For a three dimensional source location, it is necessary to locate the sensors in different planes at each anticipated fracture zone to provide adequate resolution of the source. Lee[23] presents a related discussion of the optimal distribution of sensors. In monitoring the elusive fractures, it is necessary to have at least 4 sensors in the area of interest. With the options under well fracturing, this means that a minimum of 4 per quadrant surrounding a well is necessary, assuming small signals and that fractures propagate in two opposite directions. Thus, a minimal system would consist of at least 12 sensors in order to separate different fractures propagating within a short time of each other. Also, as pointed out by McClain,[26] if a given source is detected by as many as nine sensors instead of the minimum of four, the location accuracy is theoretically improved by a factor of ten, assuming all the redundant combinations are used to solve for the source and the least square value obtained.

As a first attempt at MERC in monitoring fracture initiation, it was decided to use wide band, high-sensitivity, hydrophone-type transducers which could easily be run into small tubing wellbores. Each hydrophone was designed with a built-in preamplifier and a post amplifier at the surface. The general data acquisition and processing scheme is shown in figure 4. Also, not shown in Figure 4 are selectable filters on each side of the post amplifiers. The 12 hydrophone signals along with the injection well pressure and IRIG-A time code were recorded simultaneously at 120 ips on a 14-channel FM magnetic tape recorder. These signals were also monitored simultaneously by an 18-channel oscillograph. The instrumentation system had a flat frequency response from 10 Hz to 40 kHz, a total system sensitivity of 2×10^{-2} Pa/mv, and a range of approximately 5×10^{-2} to 30. Pa(Newton/meter^2)

Data are reduced by either manual screening or a coincidence detector to select special events, then all channels are sampled simultaneously, usually at either a 10 or 200 kHz rate per channel, digitized, and written on digital magnetic tape for further processing. After conditioning and arrival time separation, the data are entered into the Fortran programs shown in the flow chart of Figure 5 for directional velocity corrections and location of the acoustic sources. The source locations are then plotted as determined sequentially in time and as shown in the simulated fracture location and growth maps of Figures 6 and 7.

The source locating capability of the system was first proven and evaluated through near-surface field testing in April 1972. Since that time two field experiments have been conducted. Both experiments were conducted at the same test site near Bradford, Pa., with the well configuration shown in Figure 8. The monitoring wells and general wellbore monitoring conditions, illustrated in Figure 9 were the same for each test. The 41 wells on the 36 acre test site owned by Minard Run Oil Company, Bradford, Pa., were drilled and developed as a waterflood project in the mid 1950's. The formation of interest, the Bradford Third sandstone, consists of three sand units separated by shale stringers, and has average porosity and permeability of 14 percent and 1-3 md., respectively. Pipes extending from each of the 25 water injection and 16 producer wells to a central location existed so that wellhead pressures could also be easily monitored simultaneously. Numerous tests were conducted as part of this general research program including pressure buildup and decline, short- and long-term interference, chemical tracer, acoustic noise, and directional velocity survey.

The first fracture mapping field test was conducted in July 1973, in well A33 shown in Figure 8. This well had been fractured some 15 or 20 years earlier. Therefore, the test was considered as an effort to map fracture extensions in a previously fractured well. It also served as the first test of the monitoring system under real operating conditions to evaluate such effects as noise introduced by pumps, blenders, and sand-slurry flow.

The second field test was conducted November 6, 1973, in a newly drilled experimental well A33X, located 30 feet due north of A33. The general test procedure was as follows:

1. Insert 12 hydrophones in wells at prescribed depths.
2. Install and calibrate pressure transducers in 40 monitoring well lines.
3. Inject chemical tracers and monitor wells to delineate fracture systems.
4. Evaluate noise level and spectral content in monitoring wells.
5. Monitor pressure time history over 2 to 3 weeks in other 40 wells.
6. Drill new experimental well A33X and obtain three 25' oriented cores.
7. Run temperature, 3-D velocity, guard, gamma ray-neutron, and density logs, and impression packers on A33X prior to fracture.
8. Prepare to fracture four different zones.
9. Control injection flow rates, sand injection period, maximum injection pressure, total fluid injection per stage, backflow time and total time between stages.
10. Monitor instantaneous shut-in pressures.
11. Obtain wellbore fracture pattern by impression packers.
12. Continue monitoring 40 wellhead pressures.
13. Perform complete core analysis including directional mechanical and physical properties.
14. Conduct long- and short-term pressure pulse interference tests in A33X.

RESULTS AND CONCLUSIONS

An overview of a continuing energy-related research project has been presented. To date, the noise environment of the reservoir[35] has been characterized and the directional velocity distribution through the bedding plane[34] has been evaluated. The noise spectrum generated by surface operating equipment and water-sand slurries is being analyzed. Through the discharge of blasting caps at known locations, it has been determined that acoustic sources in this particular reservoir can be located within a radius of 8 to 10 feet.

Qualified statements about the methodical mapping of fractures from these experiments cannot be made at this time due to incomplete data analysis, although it is believed that the numerous signals received will allow the fractures to be mapped. The system designed and used to monitor the fracturing process has proved successful in detecting sources (fig. 10) presently attributed to the fracture initiation and growth. Through analysis of noise data and signals transmitted in this particular reservoir it has been concluded that the broad bandwidth between 80 and 500 Hz and possibly the narrower bandwidth 80 to 150 Hz appear to be the best for fracture monitoring purposes.

Research is continuing with particular emphasis on measuring the acoustic energies and forms associated with different fracture modes.

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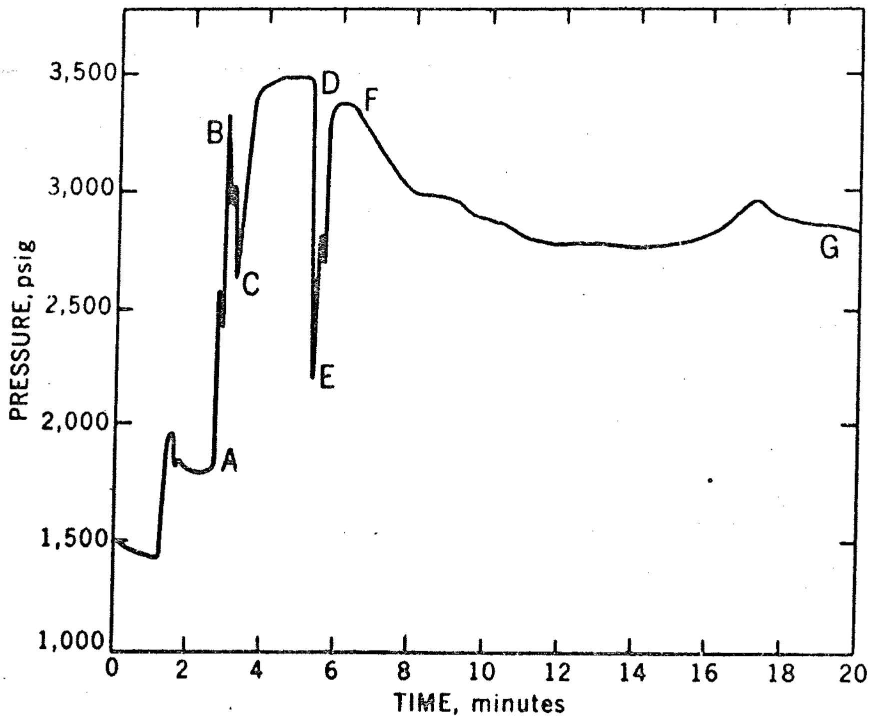


Figure 1. - Example of a Hydraulic Fracture Well Pressure Curve

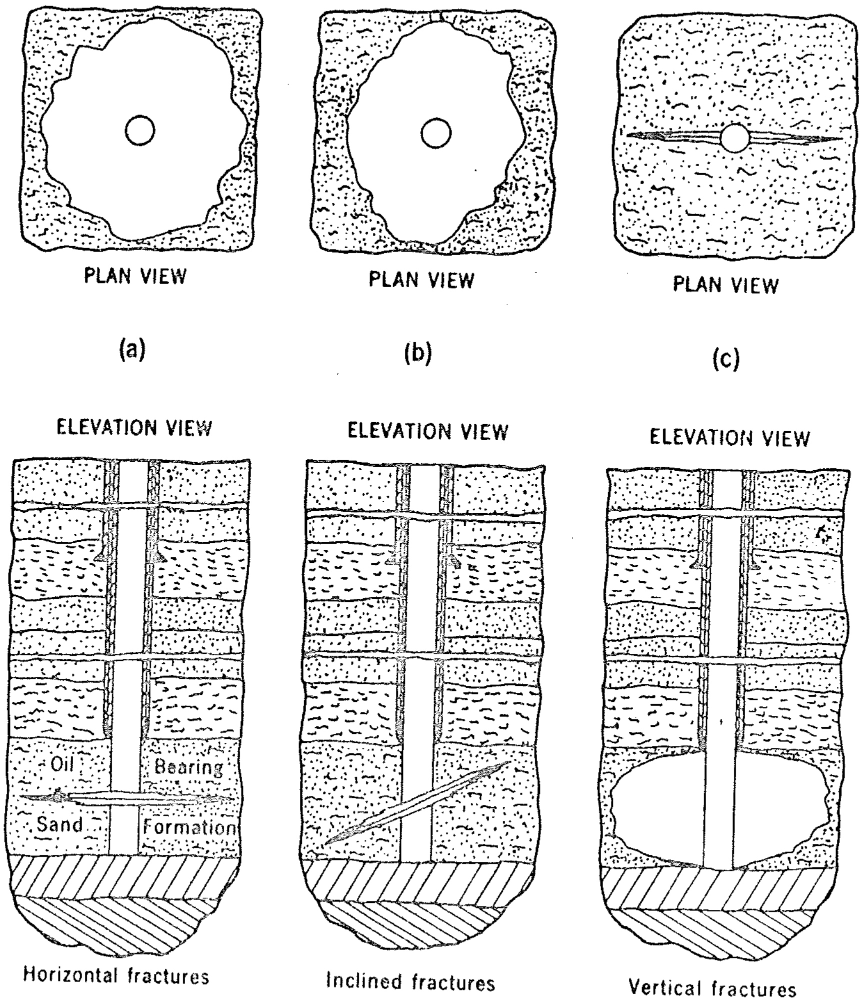


Figure 2. - A Simplified Representation of Different Types of Hydraulically Induced Fractures

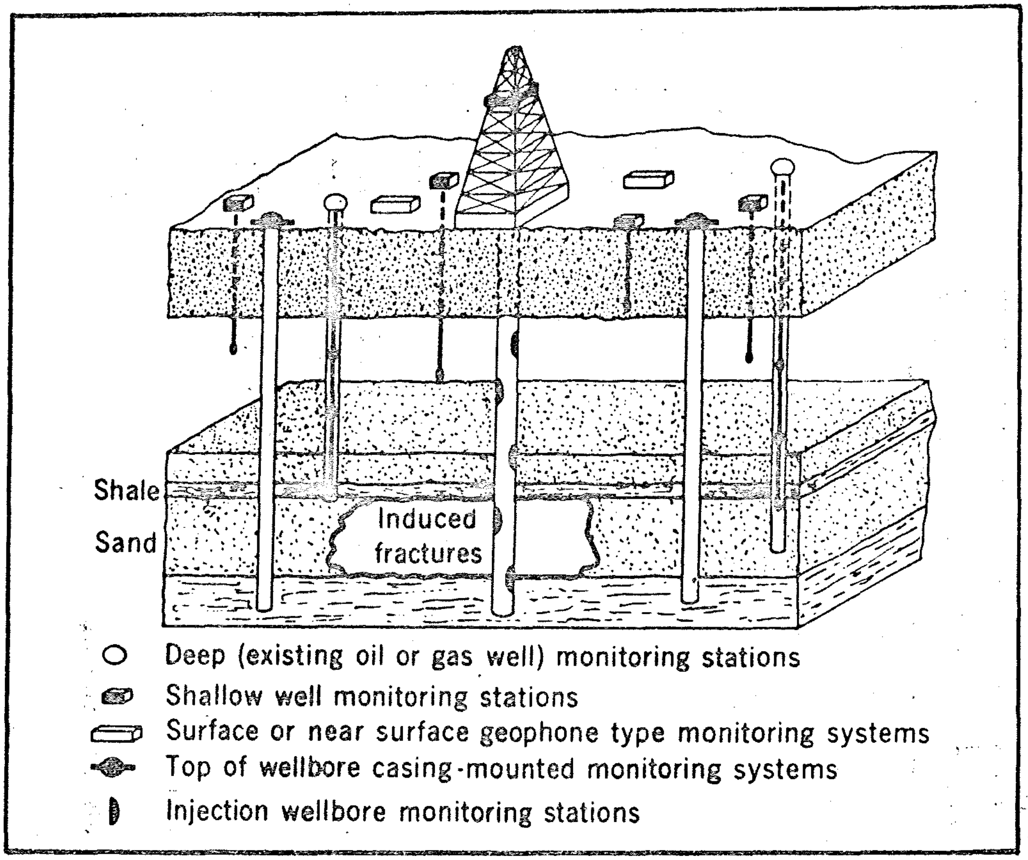


Figure 3. - Schemes for Acoustically Monitoring Hydraulically Induced Fractures

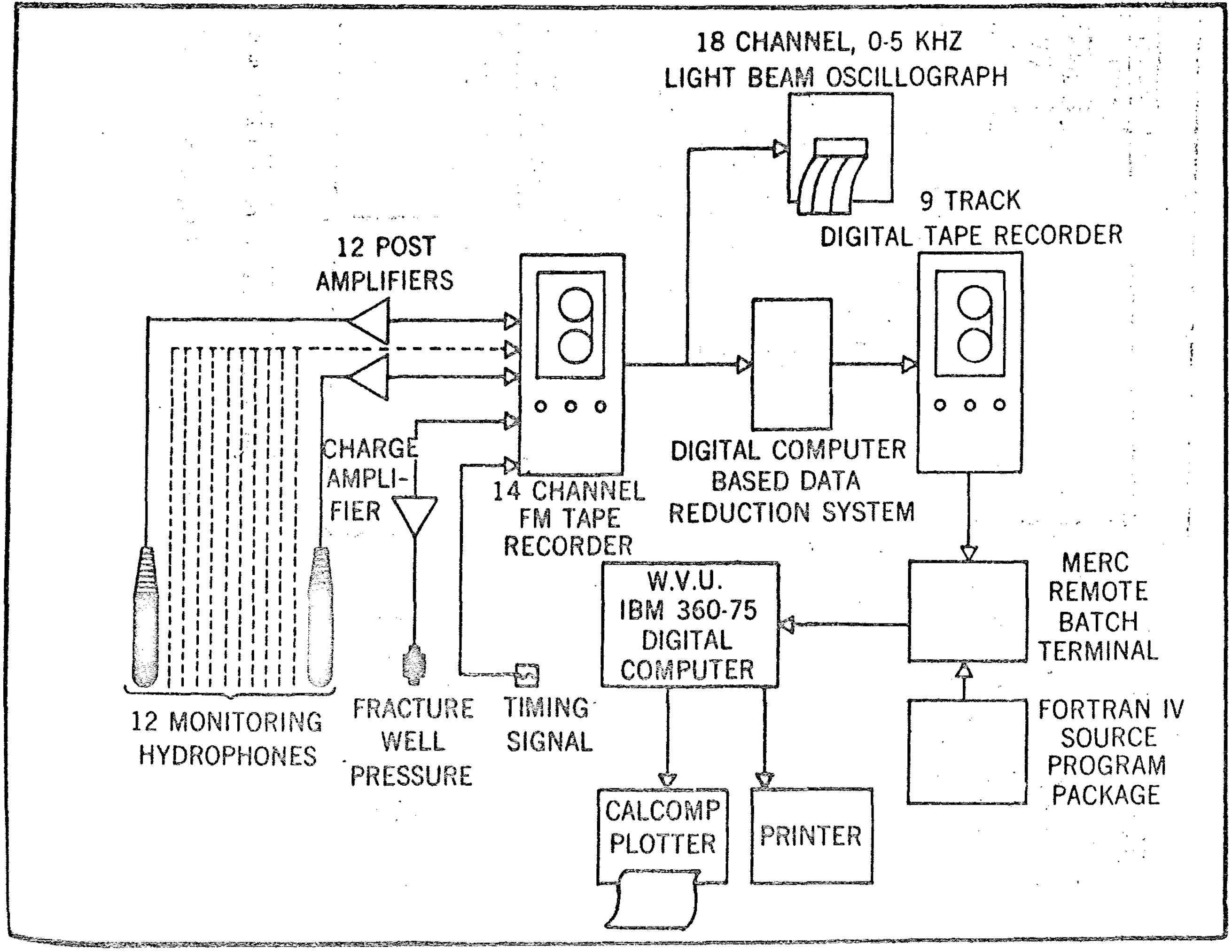


Figure 4. - Data Acquisition Systems

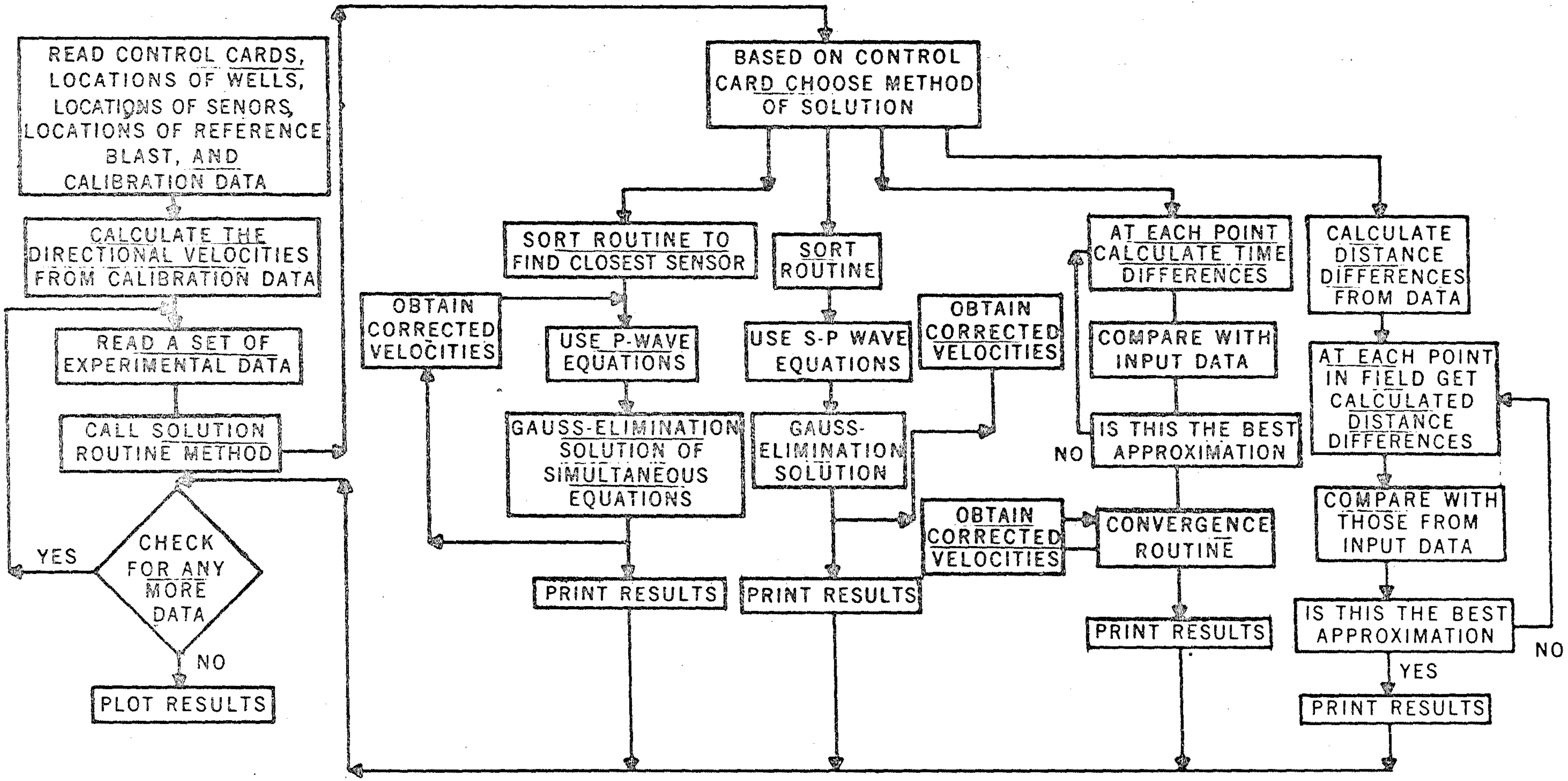
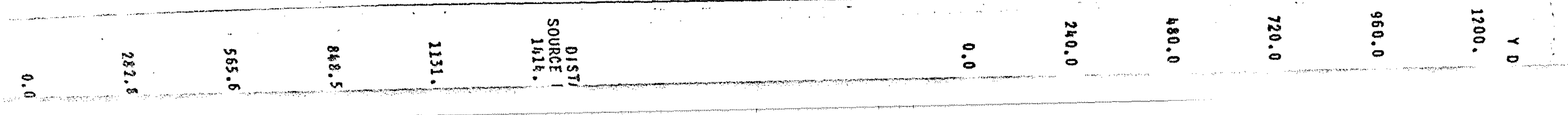


Figure 5. - Flow Chart of Computer Programs for Source Location



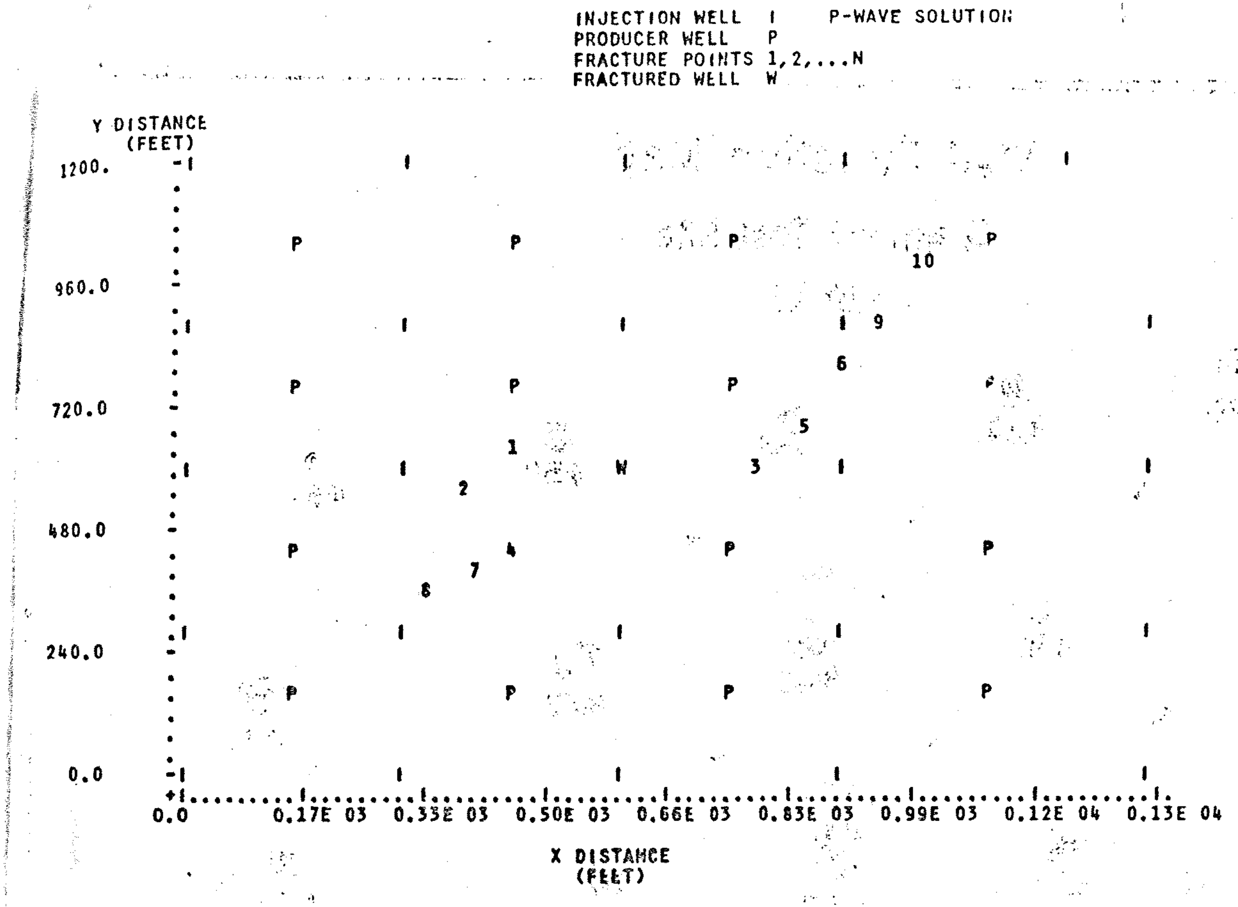


Figure 6. - Computer Plots of Simulated Fracture Growth in Magnitude and Direction

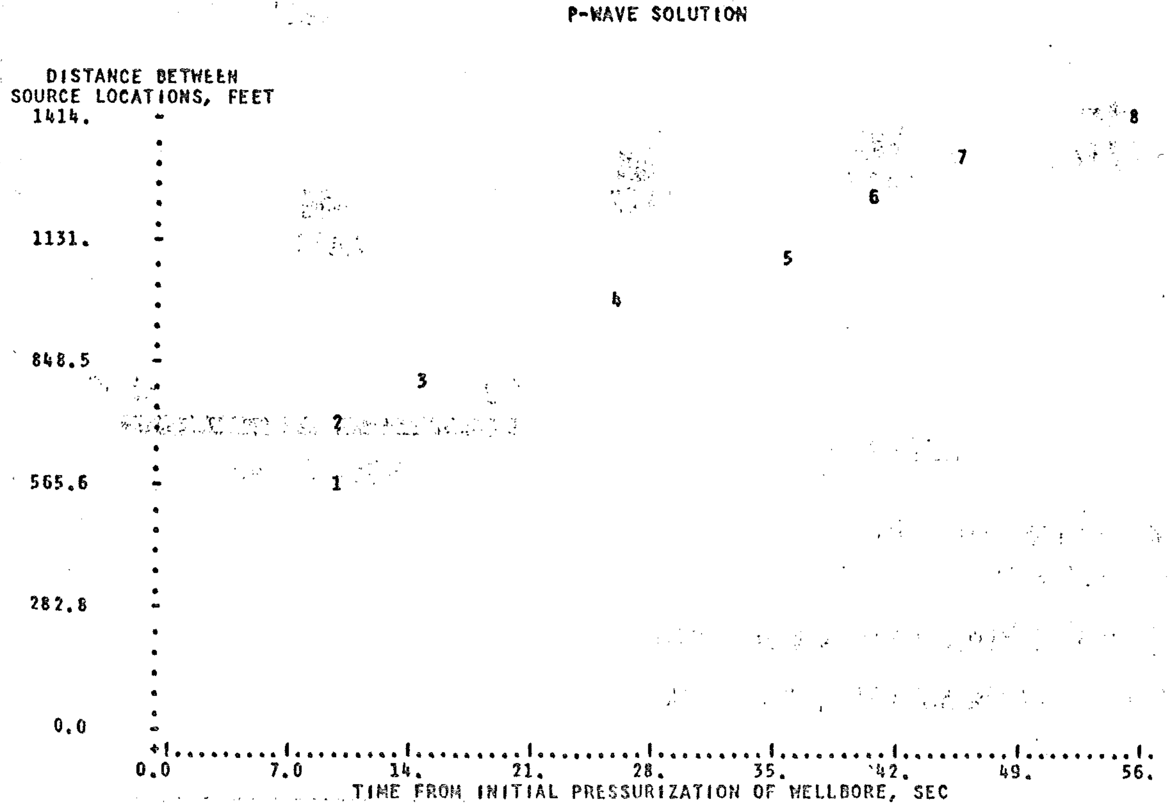


Figure 7. - Computer Plot of Simulated Fracture Growth with Time

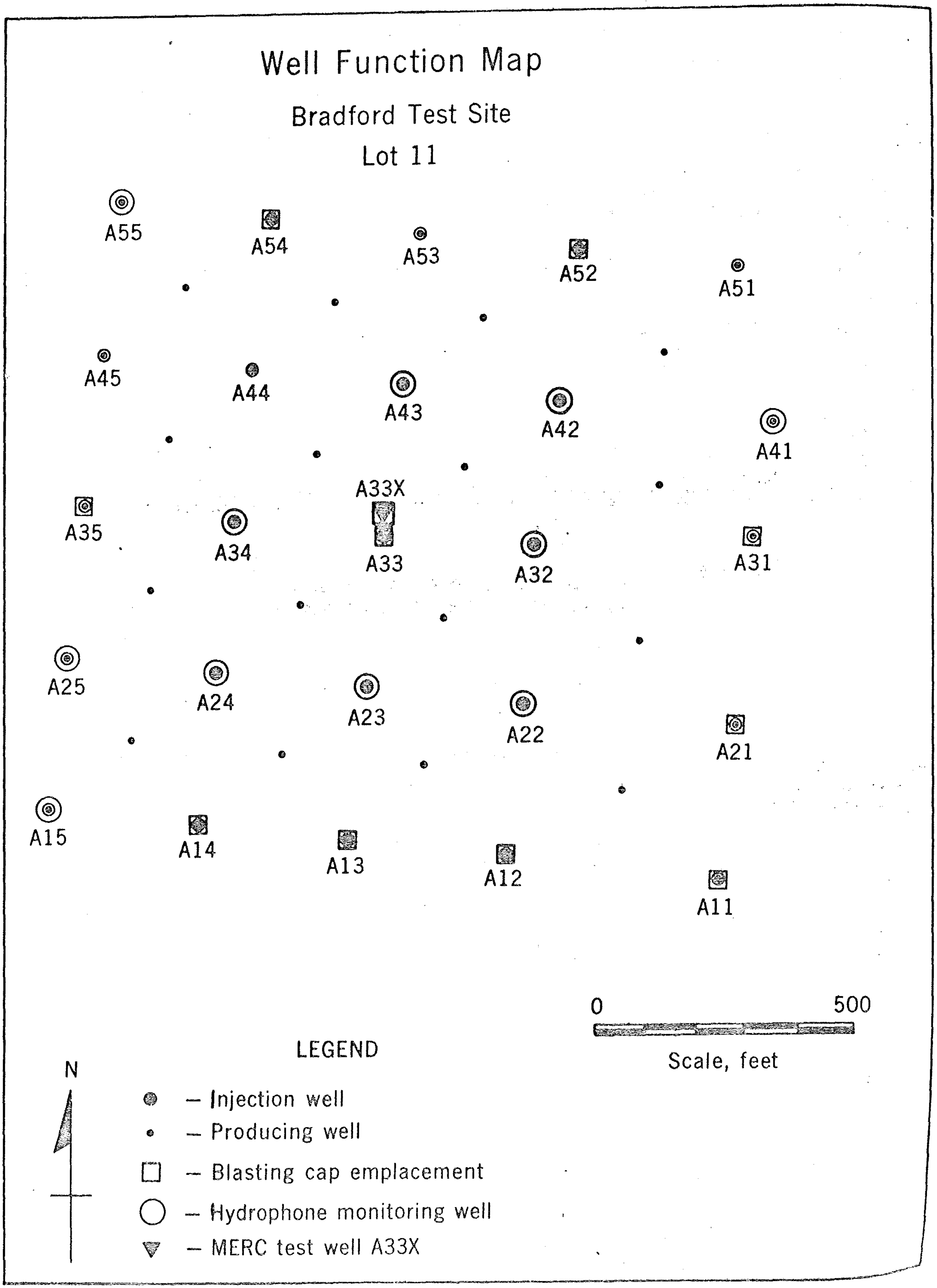


Figure 8. - Well Function Map for the Bradford Test Site

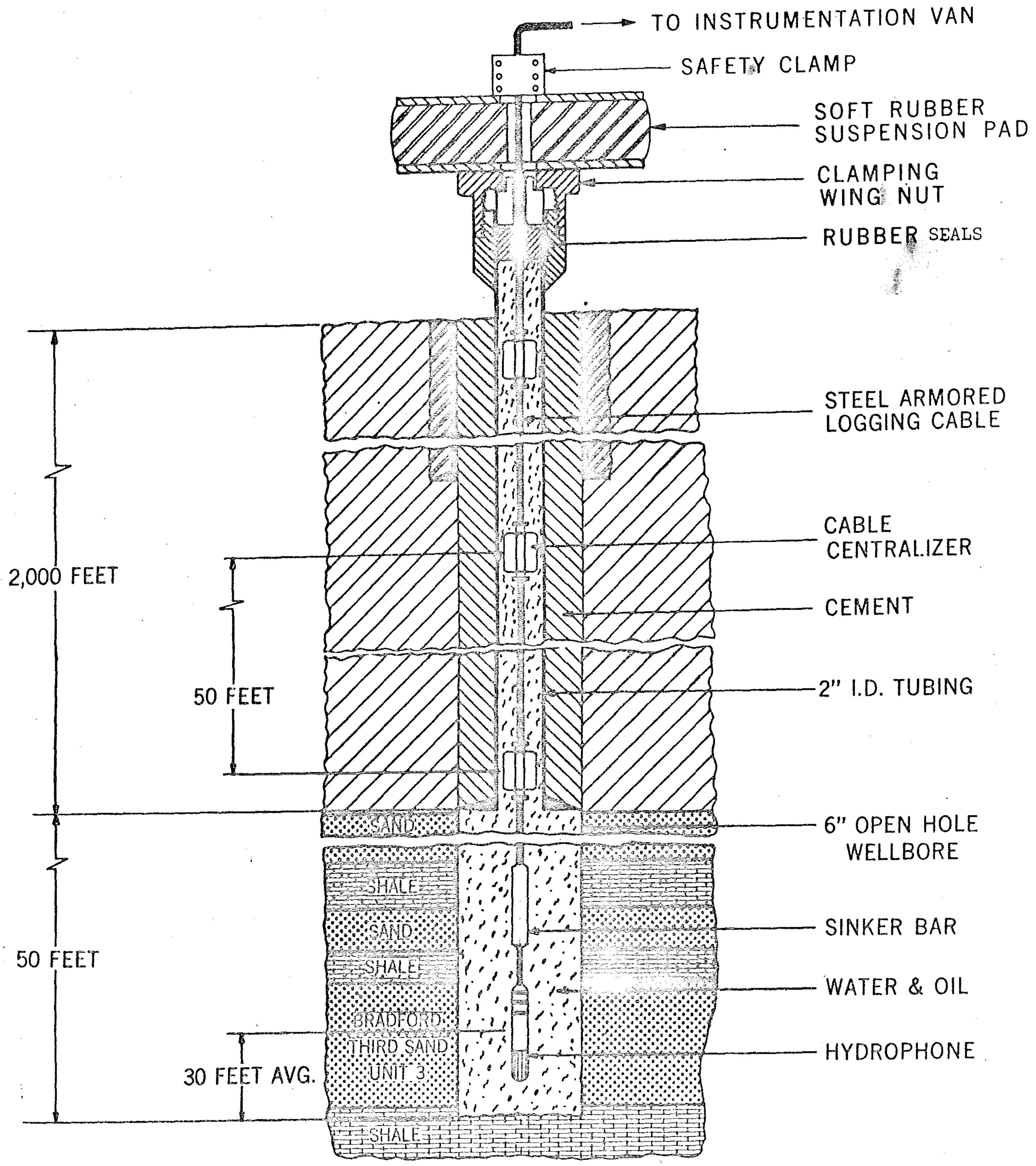


Figure 9. - Wellbore Monitoring Conditions

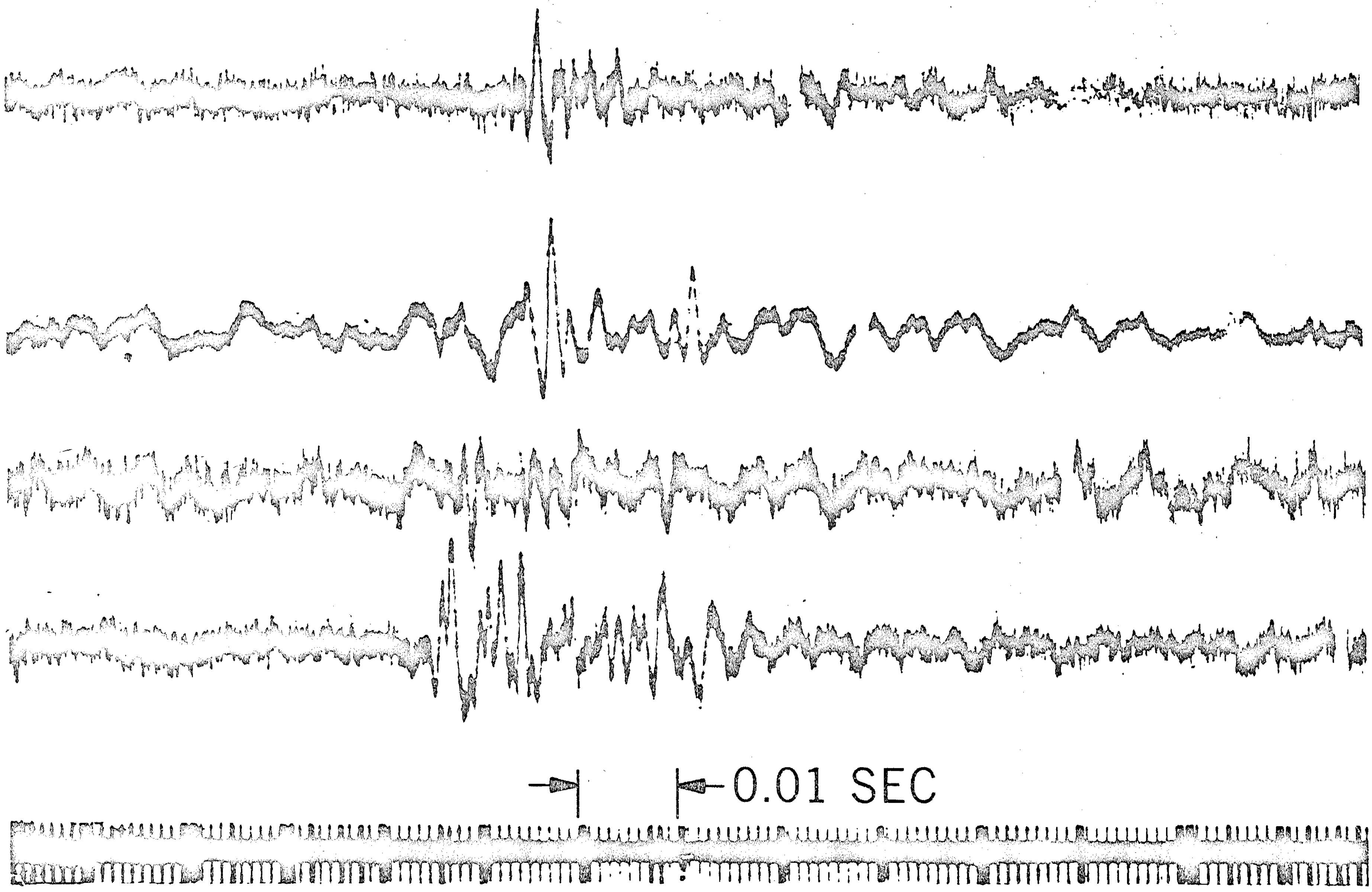


Figure 10. - Oscillograph Record of Acoustic Signals Received During the July, 1973 Hydraulic Fracture Experiment