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TITLE Stress Control of Seismicity Patterns Observed During Hydraulic Fracturing Experiments at the Fenton Hill Hot Dry Rock Geothermal Energy Site, New Mexico

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STRESS CONTROL OF SEISMICITY PATTERNS OBSERVED DURING HYDRAULIC FRACTURING EXPERIMENTS AT THE FENTON HILL HOT DRY ROCK GEOTHERMAL ENERGY SITE, NEW MEXICO

by

Michael C. Fehler

ABSTRACT

Seismicity accompanying hydraulic injections into granitic rock is often diffuse rather than falling along a single plane. This diffuse zone of seismicity cannot be attributed to systematic errors in locations of the events. It has often been asserted that seismicity occurs along preexisting joints in the rock that are favorably aligned with the stress field so that slip can occur along them when effective stress is reduced by increasing pore fluid pressure. A new scheme for determining orientations and locations of planes along which the microearthquakes occurred was recently developed. The basic assumption of the method, called the three point method, is that many of the events fall along well defined planes; these planes are often difficult to identify visually in the data because planes of many orientations are present. The method has been applied to four hydraulic fracturing experiments conducted at Fenton Hill as part of a hot dry rock geothermal energy project. While multiple planes are found for each experiment; one plane is common to all experiments. The ratio of shear to normal stress along planes of all orientations is calculated using a best estimate of the current stress state at Fenton Hill. The plane common to all experiments has the highest ratio of shear to normal stress acting along it, so it is the plane most likely to slip. The other planes found by the three point method all have orientations with respect to current principal stresses that are favorable for slip to occur along preexisting planes of weakness. These results are consistent with the assertion that the rock contains pre-existing joints which slip when the effective stress is reduced by the increased pore fluid pressure accompanying the hydraulic injection. Microearthquakes occur along those planes that are favorably aligned with respect to the current stress field.

INTRODUCTION

Seismic monitoring of hydraulic fracturing has been carried out at Fenton Hill by the Los Alamos Hot Dry rock group over a period of twelve years (Albright and Hanold, 1976; Albright and Pearson, 1982; Pearson, 1982; Keppler, et al., 1983; House, et al., 1985; Fehler and Bame, 1985). This work has been undertaken with the implicit assumption that the occurrence of seismicity is a direct result of fluid penetration into the rock (Pearson, 1981; Murphy and Fehler, 1986). Since a hot dry rock geothermal system can only be constructed by connecting two wellbores to a fracture system through which water can flow, there has been continued interest by hot dry rock programs in increasing our understanding of the seismicity accompanying hydraulic fracturing so that the induced fracture system can be delineated.

One major conclusion from the seismic studies is that a majority of the seismic events are shear, not tensile, as proven by their well constrained fault plane solutions (Cash, et al. 1983 ; Kaieda, 1984; House, et al., 1985, Fehler, at al. 1987). Some exceptions occur, as have been noted by Bame and Fehler (1986) and Majer and Doe (1986), where long period microearthquakes similar in character to those observed at volcanoes have been observed (Ferrazzini, et al, 1986; Fehler and Chouet, 1982). These long period events have been interpreted as being the seismic signals from tensile fracturing (Bame and Fehler, 1986; Ferrazzini, et al., 1986). Very few long period events accompany the injections and they have been found to occur only during the early stages of the injection when fluid pressures are high enough near the injection point to cause tensile failure. Shear events may occur in close proximity to tensile failure or, alternatively, they may occur at locations where the fluid pressure is not sufficient to cause jacking of the rock but is sufficient to reduce the effective stress to allow shear to occur. Recently, Murphy and Fehler (1986), following on the work of Cundall and Marti (1978), analyzed the seismicity at Fenton Hill and concluded that the seismicity occurs along preexisting surfaces of weakness in the rock, or joints, that are favorably oriented with respect to the in situ stress field to allow shear slip. Murphy and Fehler (1986) argued that water flows along these planes after the shear has occurred since some increase in permeability along the failure plane must accompany the shear slip due to the surface roughness of the joint (Brown, 1987). If this model is correct, it is desirable to determine where these planes exist in the potential hot dry rock reservoir so that preexisting fluid flow paths can be taken advantage of to create a fluid flow/heat extraction loop through the reservoir.

Seismicity observed at Fenton Hill has been observed to be diffuse in nature (House, et al. 1985; House, 1987), occurring throughout a volume rather than along a single plane as might be expected if fluid were confined to a single tensile fracture. The width of the seismic zone cannot be explained by errors in locations (House, 1987). Recently, Fehler, et al. (1987) developed a method, called the three point method, for analyzing sets of seismic locations to determine locations and orientations of discrete planes along which many of the microearthquakes occurred. They applied this method to data accompanying a massive hydraulic fracturing operation carried out at Fenton Hill and found five planes along which slip occurred. Two of the planes determined from the microearthquake locations were parallel to nodal planes of fault plane solutions for many of the microearthquakes. In addition, these planes intersected wellbores in locations where other data indicate the presence of major fracture zones (Fehler, et al., 1987). These correlations between seismically determined planes and other data provide confirmation of the results obtained by the three point method.

Our hypothesis that the planes along which microearthquakes occur are preexisting joints that slip in response to the changes in the effective stress due to increased pore fluid pressure leads to the conclusion that the planes must be oriented so that the shear stress along these planes is large relative to that on planes with other orientations. To investigate the relationship between the planes defined by the three point method and estimates of in situ stress field, we applied the three point method to microearthquake locations accompanying four large hydraulic injections carried out at Fenton Hill. The orientations of planes found by the method will be compared with our best estimate of the stress field at Fenton Hill and it will be shown that the planes defined by the three point method are those with the greatest shear stress acting upon them.

THREE POINT METHOD

The method is described in detail elsewhere (Fehler, et al., 1987) so only a brief synopsis will be given here. The method is an extension to three dimensions of a procedure outlined by Lutz (1986) for finding lineaments in two-dimensional surfical geological data. The method is based on the observation that every combination of three microearthquake locations defines a plane. We begin by calculating the strike and dip of the plane made out of every possible combination of three microearthquake locations within a data set from a single hydraulic fracturing experiment. One intuitive way to find the orientation of any plane along which many microearthquakes occurred would be to separate all of the planes defined by combinations of three locations into bins corresponding to ranges of similar orientations, and to then identify which bin has the largest number of planes. This technique would produce a biased result due to the shape of the region in which the microearthquakes occur. This bias was discussed for a two-dimensional case by Lutz (1986). The bias caused by the shape of the region in which the microearthquakes fall can be eliminated by normalizing the number of combinations in each bin by the number of combinations in each bin found for synthetic sets of location data. These synthetic locations are uniformly but randomly distributed throughout the zone in which the actual microearthquakes were found to occur. In this way, an unbiased estimate of the orientation of planes along which microearthquakes fall is obtained and, by comparison with many sets of synthetic locations, a statistical estimate of the reliability of the result can be made.

Once the orientation of a plane is determined, the absolute location of the plane can be found by counting how many times, T_j, that a particular microearthquake, j, combines with other microearthquakes to form planes with the preferred orientation. The earthquakes that have the largest value of T_j are those that fall along the plane. By plotting the locations of these events, we find the location of the plane defined by the data.

The method can be successively applied to a given dataset to find planes of differing orientations and locations. By removing those earthquakes that were found to define the plane, we eliminate the preference for that orientation in a subsequent application. In this manner further planes can be obtained from the data.

The method has been extensively tested on synthetic data. In a typical test, synthetic locations that fall along a predetermined plane were generated and supplemented with points that fall randomly but uniformly in a zone surrounding the plane. The three point method was applied and the plane located. The points that fell along the plane were subsequently perturbed away from the plane to represent errors in microearthquake locations. The ability of the three point method to locate the plane in the presence of this locational noise was then investigated to determine how much error could be added to the locations that originally fell along the plane before the method was unable to resolve the plane. Figure 1 shows an example of such a test. The test data consist of 200 synthetic locations that fall inside a box of dimensions 200 by 200 by 400 m, with the long axis oriented north-south. Twenty five of the locations were placed along a plane and subsequently perturbed in random directions by an average of 20 m to represent errors in locations. The locations are drawn in vertical cross section oriented perpendicular to the strike of the plane so that the line represents the location of the plane defined by the unperturbed data. The method was successful in determining the location of the plane in these data even though the plane could not be picked out by eye from examination of location plots.

DATA COLLECTION AND ANALYSIS

During hydraulic fracturing experiments, seismic data are collected using both surface and downhole seismic stations. Figure 2 is a map showing the locations of the Fenton Hill site and the seismic stations used to monitor seismicity. Stations PC-1, PC-2, GT-1 and EE-1 comprise the downhole seismic network. The remaining stations shown consist of surface sensors. Due to the presence of approximately 700 m of highly attenuating sediments and tuff at the surface in the vicinity of Fenton Hill, the surface stations record only the largest events. Since signals recorded at these stations consist of frequencies below 100 Hz, we cannot measure arrival times at these stations precisely enough to determine reliable locations from these data. The downhole sensors, while not all located within the Precambrian granitic rock into which we inject water, record frequencies as high as 1 kHz so that arrival times can be determined to within 1 ms. With this precision in arrival times, event locations can be determined to a precision of 20 m. Details are given by House (1987). The surface network is used for environmental monitoring in the event of a large earthquake. Data from these sensors can be analyzed to determine fault plane solutions of the larger (up to M_L=1.0) events.

Data from the seismic sensors are transmitted directly over wires or by radio to a central recording site where both analog and digital recording are carried out. Analog recordings are made for archival purposes. Digital data are acquired by a UNIX based digital data acquisition system. Data are digitized at software selectable rates, typically 500 samples per second for the surface network data, 5000 samples per second for all borehole data and 50000 samples per second for close in borehole data such as that from station EE-1 (Figure 2). The system performs event detection on the data from the downhole stations and stores data from all channels when an event is detected. The system has software selectable pre-event memory so that first arrivals from all stations are stored. The system is capable of storing events at a rate as high as 1 per second.

Data for experiments 2032, 2042 and 2061, discussed below, were collected using our 'old' data acquisition scheme which detected events using a Schmidt trigger operating on data from the sensor in EE-1. This system was capable of storing a limited quantity of data for each event and could store data at a rate of only one event per minute. We are currently reprocessing data from experiment 2032 by redigitizing events from analog tapes to study a larger sample of the events that accompanied this, our largest hydraulic injection to date.

EVENT LOCATIONS

Data from four experiments have been analyzed using the three point method. Table 1 lists relevant information about each experiment. Figures 3-6 show the locations of microseismic events accompanying each injection. During the time that experiments 2032 and 2042 were carried out, wellbores EE-2 and EE-3 existed as shown in Figures 3 and 4. Since no hydraulic connection was made between the two wellbores by these two injections, wellbore EE-3 was subsequently deviated from its original trajectory as shown in Figures 5 and 6. This wellbore is referred to as EE-3a. During this redrilling phase, numerous hydraulic injections were carried out, of which 2061 and 2066 were two. Experiments 2061 and 2066 were carried out deep in the EE-3a wellbore and did not result in hydraulic communication between wellbores EE-3a and EE-2. Two injections, carried out in shallower portions of the EE-3a wellbore, did result in hydraulic communication between the two wellbores. These experiments, called 2052 and 2062, were also accompanied by seismicity. Only four locatable events were recorded during experiment 2052. Many seismic events accompanied experiment 2062 and these data are currently being reanalyzed.

Locations of microearthquakes accompanying the two deepest injections, experiments 2042 and 2061, demonstrate that seismicity grew generally downward from the injection points as shown in Figures 4 and 5. This downward migration of event locations was particularly evident during the later periods of the injections. This downward migration of event locations is consistent with results obtained by the British Hot Dry Rock project as reported by Pine and Batchelor (1984). They interpreted the downward migration of shear type microearthquakes as being due to an increased shear stress acting along preexisting joints caused by differences in the gradients in principal stresses with depth.

Locations of seismicity accompanying experiment 2032, shown in Figure 3, occur in all directions from the injection point and showed no clear migration of event locations with time. Experiment 2066, Figure 6, was carried out in a transitional zone between the deeper region where 2042 and 2061 were carried out and the shallower zone of experiment 2032.

APPLICATION OF THE THREE POINT METHOD

The three point method was applied to locations of microseismic events determined for each of the four experiments listed in Table 1. Each data set was treated independently for two reasons. First, we estimate that the precision in the relative locations of events in a single experiment is 20 m. The relative error is larger when comparing events from different experiments. The larger error in relative event locations between experiments arises because of differences in station locations used to record data for various experiments. The second reason for treating each experiment independently is that the amount of computer time required to analyze one dataset increases dramatically as the number of events analyzed increases.

Table 2 lists the orientations of planes found for each experiment. The orientations are listed in the order in which they were determined by the three point method. In applying the method, events that were found to lie along a plane were removed from the dataset and the method reapplied. In this way multiple planes along which the microearthquakes fall can be determined. Also listed in Table 2 is the depth of the center of each plane. This depth is the average depth of the locations of all the events on the plane. Maps showing locations of some of the planes found for experiment 2032 can be found in Fehler, et al. (1987).

Figure 7 shows a lower hemisphere equal area projection of the poles to the planes found by the three point method. Symbols are used in the figure to indicate the planes as listed in Table 2. The poles define a zone trending WNW to ESE indicating that planes strike predominatly NNE. Planes striking N7°E and dipping 67°E occur in all experiments. This orientation was the first one found for experiment 2061. The azimuth of this plane is slightly different in experiment 2066, N14°E. The location of the plane is different for each experiment indicating that joints of this orientation are pervasive throughout the reservoir.

IN SITU STRESS AT FENTON HILL

Many attempts have been made to infer the state of stress at Fenton Hill. Kelkar, et. al, (1986) analyzed pressure records from hydraulic injections to infer the amplitude of the least compressive stress. They assumed that the orientations of principal stresses are parallel to the P and T axes of a fault plane solution. This assumption has been shown to lead to incorrect results (McKenzie, 1969). Dey (1987) analyzed the orientations of microcracks in core removed from borehole EE-3a to determine orientations of principal stresses. He assumed that the ratio of the in situ stress magnitudes is proportional to the relative abundance of microcracks of each orientation. Dey deduces principal stress amplitudes by assuming that the vertical stress is entirely due to the weight of the overburden. We choose not to use Dey's results because of the difficulties in determining reliable orientations of the core and the assumption that cracks in the core are a direct function of the in situ stress field. Barton and Zoback (written communication) analyzed borehole televiewer data to determine the orientations of wellbore breakouts measured between 3350 and 3550 m in wellbore EE-3a. Using the model of Zoback et al. (1985) to explain the relation of wellbore breakouts to the in situ stress field, they concluded that the least compressive stress is horizontal and oriented N104°E. This result is in agreement with that obtained by a complete analysis of fault plane solutions of many microearthquakes by Burns (personal communication). Burns also found that the vertical stress is the maximum principal stress.

Hydraulic data taken during the phase I hot dry rock experiments, carried out at depths less than 3000 m, indicate that the ratio of effective stresses when pore pressure is only due to the hydrostatic head of water are

$$\sigma_1/\sigma_2 = 2 \qquad \sigma_2/\sigma_3 = 1.5 \qquad (1)$$

where σ_1, σ_2 and σ_3 are the maximum, intermediate and minimum principal stresses respectively (D. Brown, personal communication).

Although these measurements were carried out in a shallower region than that of the current work, indications are that the stress ratios are roughly comparable in the deeper region (H. Murphy, personal communication).

COMPARISON OF IN SITU STRESS FIELD TO ORIENTATION OF PLANES OF SLIP

McKenzie (1969) has shown that knowledge of a single fault plane solution provides little constraint on the orientations of in situ principal stresses. Gephart and Forsyth (1984), Angelier (1979) and others have shown how a suite of differing fault plane solutions can be analyzed to place four constraints on the stress tensor. Unfortunately, knowing the orientation of a plane along which slip occurs places little constraint on the orientations of the principal stresses unless the direction of slip along each plane is known. We can, however, use our best estimates of the in situ stress tensor and infer which planes are most likely to slip.

Using the estimate of principal stress orientations given by the borehole televiewer data, and ratios of magnitudes of these stresses given in Equation 1, we can calculate the ratio of shear stress acting along a given plane to the normal stress acting across the plane. For a given failure criterion, this ratio could be used to determine which planes will slip. In any event, the planes with the largest ratio of shear to normal stress will be those most likely to slip. In Figure 8, poles to planes are plotted in a lower hemisphere equal area projection and contours show regions of equal value of shear to normal stress acting on the plane whose pole is in a given location on the projection. There are two regions where the ratio is highest; one representing planes striking NNE and dipping East and the other striking NNE and dipping West. The poles to planes found by the three point method fall in the regions where slip is most likely to occur. The plane with the largest ratio of shear to normal stress, and hence the one most likely to slip, is nearly parallel to the common plane (N7°E azimuth, dip 67°E) found in all of the experiments. The plane with the largest ratio of shear to normal stress is the plane most likely to slip as well as the plane along which brittle failure would occur should a brittle failure criterion be met. We thus cannot exclude the possibility that the planes with common orientation in all experiments represent new fractures.

CONCLUSIONS

The three point method has been applied to seismic data collected during four hydraulic fracturing experiments carried out at Fenton Hill, New Mexico. A suite of planes along which microearthquakes fall has been found. These planes all strike roughly NNE and dip both E and W. Since planes of many orientations were found, we must conclude that these planes were preexisting joints in the rock that slip when the effective stress is reduced by increased pore pressure. Using best estimates of the in situ effective stress tensor, it is concluded that the planes found by the three point method are those most favorably aligned for shear to occur. The orientation of the seismic plane that occurs in all experiments is the one that is predicted to have the highest ratio of shear to normal stress, which makes it the most likely orientation for shear slip. Presumably joints of orientations other than those found by the three point method exist in the reservoir region but these are oriented such that shear slip is less likely to occur along them so we do not detect them.

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Table 1. Hydraulic Injections

Expt. Number	Date	Depth to top of injection zone*	Wellbore	Volume Injected (m^3)	Average Pumping (m^3/sec)	Number of Micro-earthquakes located **
2032	12/6/83-12/9/83	3463	EE-2	21,600	.10	844
2042	5/15/84-5-19/84	3344	EE-3	7,600	.02	946
2061	6/29/85-7/2/85	3766	EE-3a	5,600	.02	1021
2066	1/30/86-2/1/86	3706	EE-3a	4,400	.02	1962

* Depths are listed as meters below an elevation of 8700 feet above mean sea lever

** Reliable locations

Table 2. FRACTURE PLANES ACCOMPANYING HYDRAULIC INJECTIONS

Experiment	Aximuth	DIP	Number Events	Average Depth of Plane (m)	Symbol in Figure 6
2032	329	74E	130	3383	F
2032	270	27N	35	3738	G
2032	151	67W	50	3165	H
2032	7	67E	81	3548	D
2032	209	30W	28	3594	I
2042	3	40E	387	3728	A
2042	328	27E	131	3513	B
2042	41	47E	58	3511	C
2042	7	67	36	3754	D
2042	353	67E	41	3517	E
2061	7	67E	546	3930	D
2061	241	54W	59	3766	J
2061	10	74E	117	3913	K
2061	202	80W	35	3570	L
2061	4	54E	26	4103	M
2061	212	27W	25	3721	N
2066	160	54W	481	3760	P
2066	14	67E	723	3701	Q
2066	119	54W	87	3683	R
2066	153	87W	69	3680	S

FIGURE CAPTIONS

Figure 1. Vertical cross section showing synthetic locations used to test the three point method. Twenty-five locations were chosen to fall randomly along one plane and 175 locations were chosen to fall randomly throughout a rectangular box of dimensions 400 by 200 by 200 m with the long axis north-south. The locations along the plane were moved in random directions by an average of 20 m to represent errors in microearthquake locations. The plane strikes N60°E and dips 60°E. The view is towards 60°E, parallel to the plane. The points that fall along the plane are connected by a line.

Figure 2. Map showing locations of the seismic monitoring network in the vicinity of the Fenton Hill hot dry rock site. Stations EE-1, PC-1, PC-2 and GT-1 are subsurface stations. The remaining stations are all located on the surface.

Figure 3. Three orthogonal views showing locations of actual events accompanying experiment 2032. Upper left: epicenter plot. Lower left: vertical cross section projected onto an east-west plane. Lower right: vertical cross section projected onto a north-south plane. There is no vertical exaggeration in the figures. The trajectory of wellbore EE-2, the injection wellbore, and EE-3 are shown. The injection interval in wellbore EE-2 is labeled.

Figure 4. Three orthogonal views showing locations of microseismic events accompanying experiment 2042. Views are the same as in Figure 3. Water was injected into wellbore EE-3 in this experiment. The injection interval is labeled in the figure.

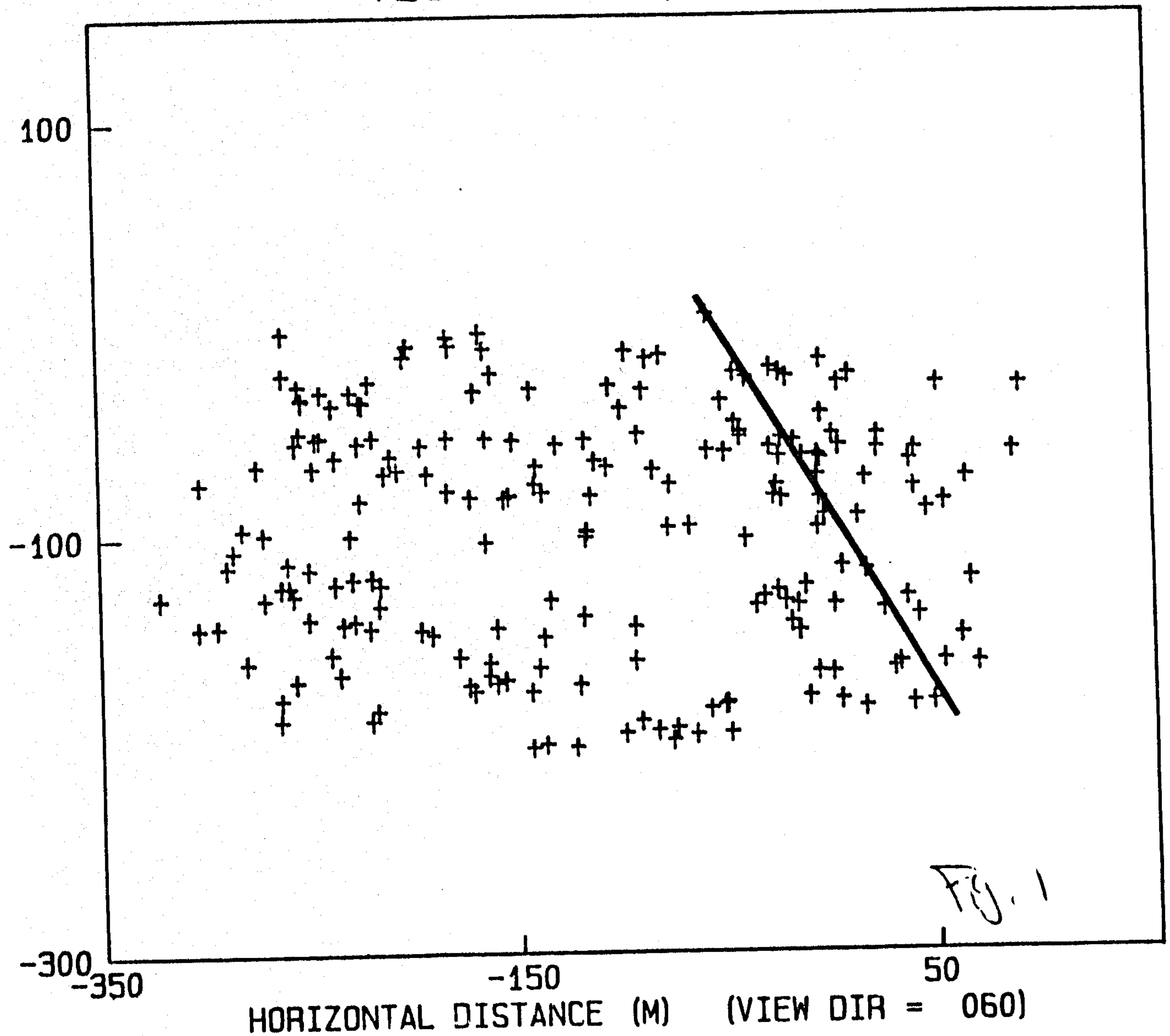
Figure 5. Views showing locations of microseismic events accompanying experiment 2061. Views are the same as in Figure 3. Water was injected into wellbore EE-3a in the interval labeled in the figure.

Figure 6. Views showing locations of microseismic events accompanying experiment 2066. Views are the same as in Figure 3. During this experiment, water was injected into wellbore EE-3a. The injection interval in labeled is the figure.

Figure 7. Lower hemisphere equal area projection showing poles to planes found by application of the three point method to locations accompanying four hydraulic injections. Each pole is plotted with a letter. The letters refer to the planes listed in table 2.

Figure 8. Lower hemisphere equal area projections showing contours of the ratio of shear to normal stress acting on planes. Poles to planes are plotted. Ratios were calculated for effective stress as described in the text.

TEST DATA (20 M ERROR)



Network of Fenton Hill Seismic Stations

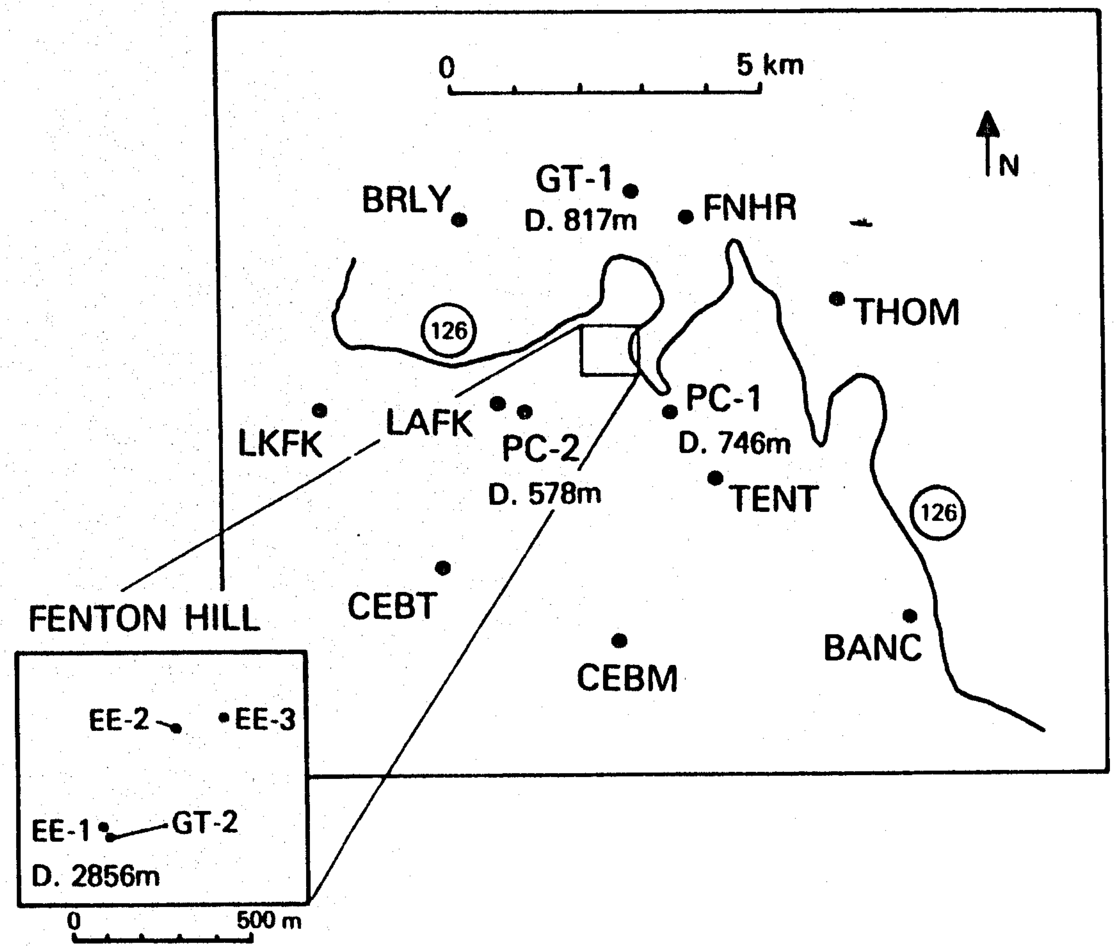
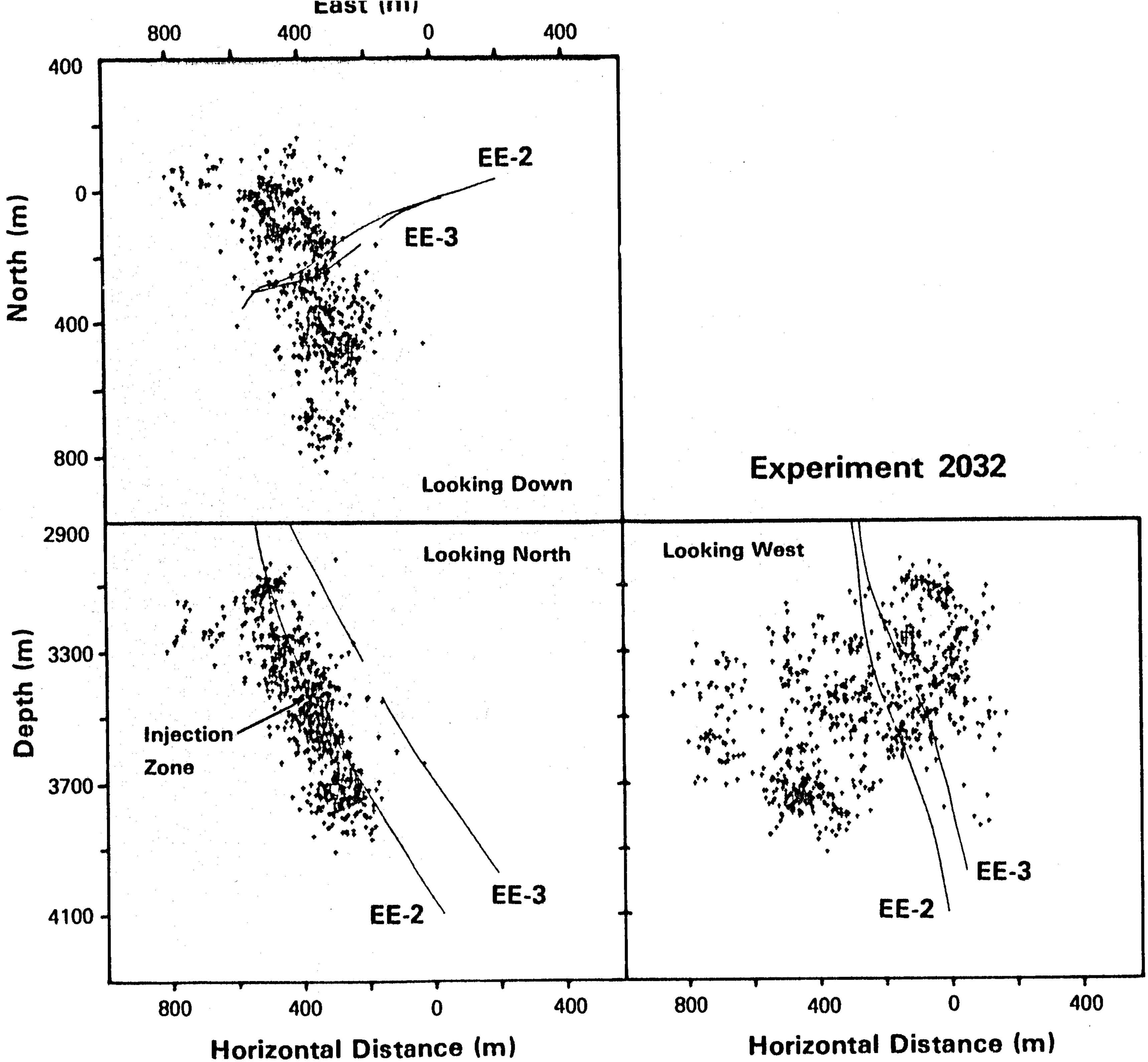
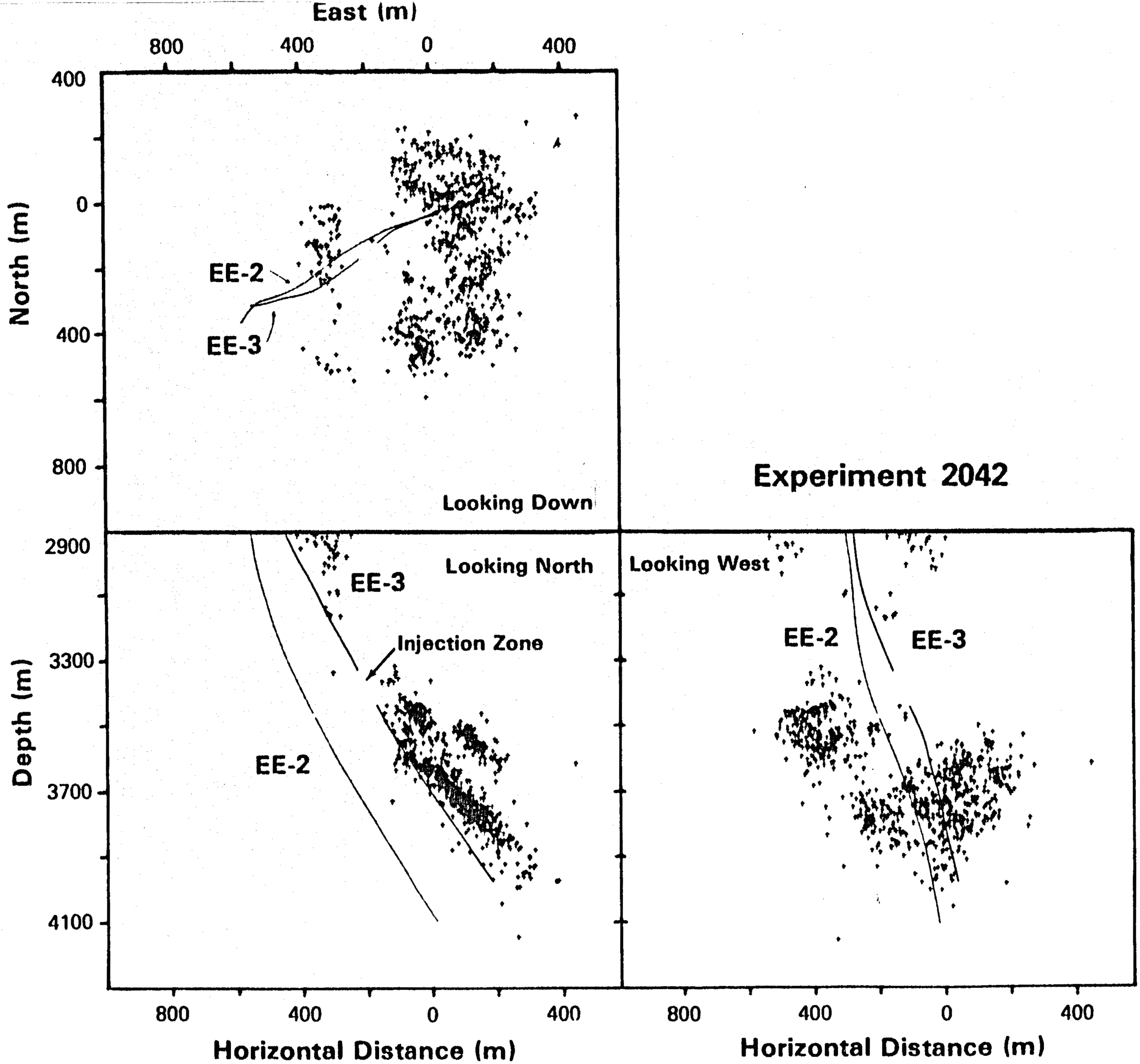
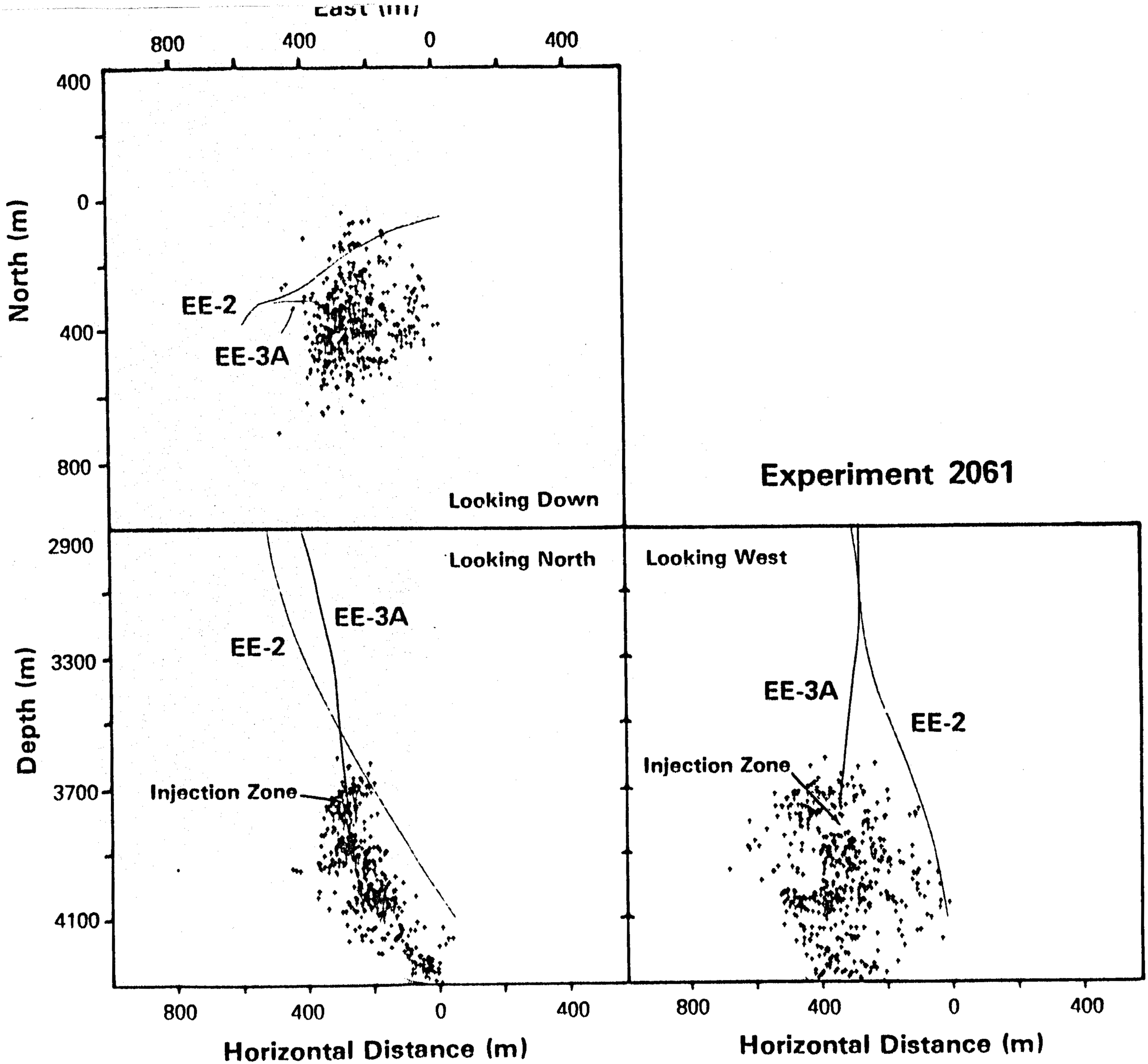


Fig. 2

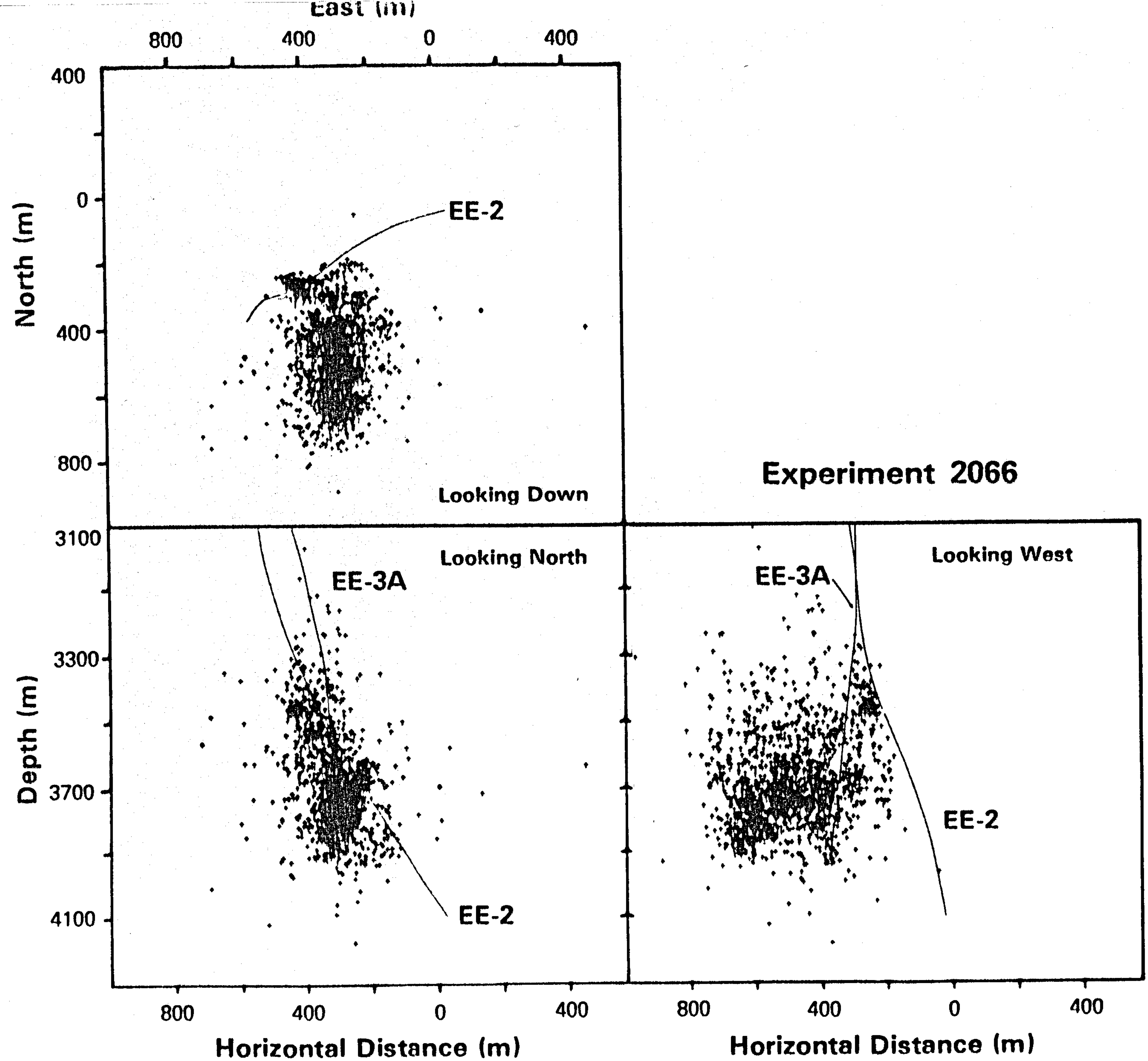

East (m)
800
400
0
400
North (m)
400
0
400
800
EE-2
EE-3
Looking Down
Experiment 2032
Depth (m)
2900
3300
3700
4100
Looking North
Injection
Zone
EE-3
EE-2
800
400
0
400
Horizontal Distance (m)
Looking West
EE-3
EE-2
800
400
0
400
Horizontal Distance (m)

3

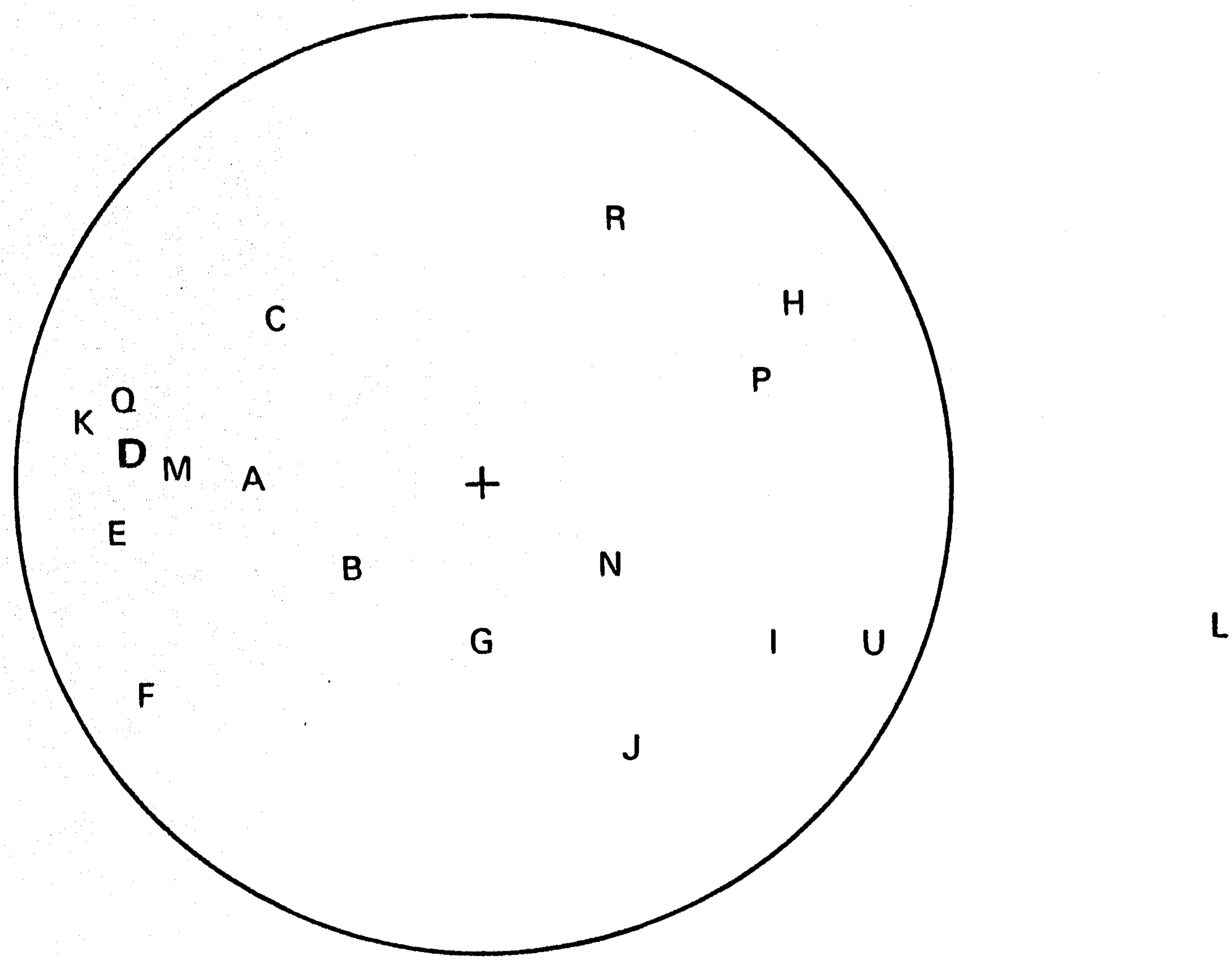

East (m)
800
400
0
400
400
0
400
800
North (m)
EE-2
EE-3
Looking Down
Experiment 2042
2900
3300
3700
4100
Depth (m)
Looking North
EE-3
Injection Zone
EE-2
800
400
0
400
Horizontal Distance (m)
Looking West
EE-2
EE-3
800
400
0
400
Horizontal Distance (m)



Experiment 2061

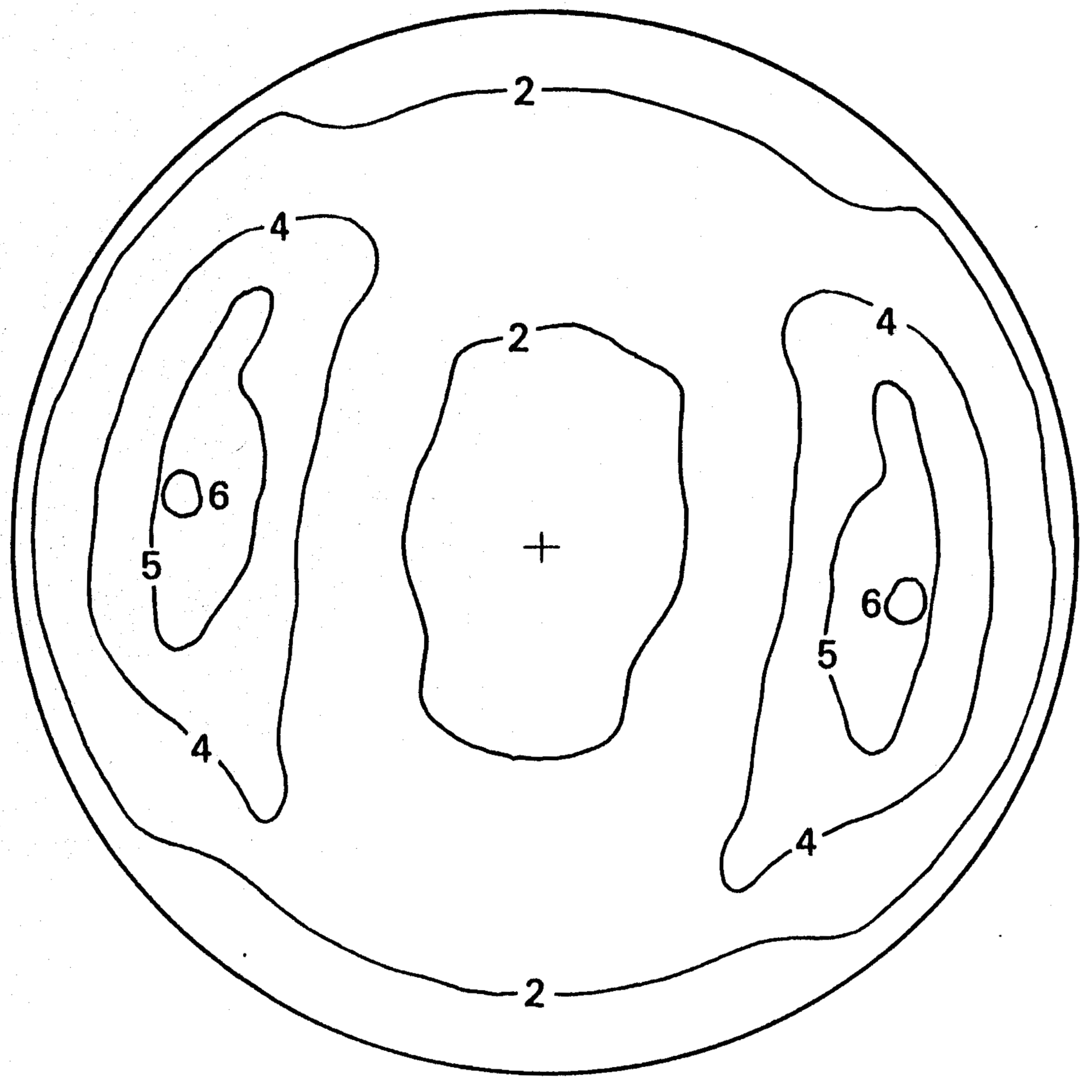

East (m)
800
400
0
400
North (m)
400
0
400
800
EE-2
Looking Down
Experiment 2066
Looking North
EE-3A
EE-2
Depth (m)
3100
3300
3700
4100
Looking West
EE-3A
EE-2
800
400
0
400
Horizontal Distance (m)
800
400
0
400
Horizontal Distance (m)

6



Poles to Planes Found by the Three Point Method

Fig. 7



Ratio of Shear to Normal Stress on Planes
(Poles to Planes Shown)