SESSION 8

HOT DRY ROCK UPDATE

In 1970, Los Alamos began an informal study of the possible usefulness of hot dry rock (HDR) energy systems based on circulation of water through hydraulic fractures connecting two wellbores drilled into hot crustal rock of low initial permeability and free-water content. In 1973 this was established as a formal HDR Program. It has since been sponsored by DOE and its predecessor agencies, with supplementary support since 1980 by agencies of the governments of West Germany and Japan. In the meantime, complementary HDR projects have been initiated in Germany, Japan, the United Kingdom, Sweden, France, and the Soviet Union, and several other countries have undertaken HDR resource evaluations and theoretical background studies. The HDR Program is now truly international, although the broadest and most advanced effort is still at Los Alamos.

By 1977, Los Alamos had completed the pioneering Phase I ("Research") HDR system at Fenton Hill, about 20 miles west of the Laboratory. This was a recirculating pressurized-water heat-extraction loop, recovering thermal energy from a granodiorite intrusive at a depth around 8500 ft -- where the initial rock temperature was about 185°C. The system was operated successfully and without significant problems for a total period of more than a year, producing heat at rates up to 5 MW(t). In general, the heat was rejected to the atmosphere through air-cooled heat exchangers, although for short periods some of it was used to operate a 60 kVA experimental binary cycle electrical power plant.

The Phase I system has demonstrated the technical feasibility of creating and operating HDR systems and using them to generate electricity. If it had been located in a populated area, it could have heated several hundred homes. However, it did not produce heat at the temperature or rate required for efficient, large-scale generation of electricity. To more nearly approach the requirements of a commercial power plant, a deeper, larger Phase II ("Engineering") system is now being developed at Fenton Hill.

In constructing the Phase I system, a slightly inclined injection well was drilled into the hot rock, a large hydraulic fracture was made from it, and a production well was directionally drilled to intersect that fracture. Several hydraulic-fracturing operations and two redrillings of the production well were required to complete a loop with usefully low flow impedance, and modeling of system behavior indicated that heat extraction occurred primarily in that part of the fracture best represented by a circular area between the fluid entrance and exit locations. The hydraulic fractures produced were substantially vertical with an approximately north-northwest azimuthal orientation.

In designing the Phase II system, it was assumed that the hydraulic fractures would also be vertical and similarly oriented, and that the effective heat-transfer surface would be similarly confined between the injection and production wells. Since it was considered too risky to increase the separation between fluid entry and exit points to a distance much greater than that through which water had been successfully circulated in the Phase I fracture system, this required creation of a number of relatively small hydraulic fractures instead of a single very large one. And since the fractures were expected to be vertical, a sufficient horizontal separation was required to prevent premature thermal interaction between adjacent fractures as they were cooled by fluid circulated through them. Further, because of the difficulties anticipated in directionally drilling the second hole through a succession of fractures that were displaced from each other both horizontally and vertically, it was decided this time to drill the two holes first and then drive the fractures from one to the other.

Accordingly, the two wells of the Phase II system were designed with their lower 3000 ft inclined at 35° to the vertical, to provide a horizontal distance of about 1000 ft within which up to a dozen or more thermally isolated, parallel, vertical fractures could be created. The wells were to be directed toward the east-northeast so that, in plan view, they would be normal to the expected strike of the fractures. And the production well, in its inclined section was to be about 1200 ft above the injection well.

Well EE-2, the injection well of the Phase II system, was completed as planned in 1980 at a vertical depth of 14,400 ft, where the rock temperature was about 325°C. Well EE-3, the production well, was completed in 1981 at a vertical depth of 13,050 ft, and in its inclined section was about 1250 ft above EE-2. This was a pioneering effort in precisely controlled directional drilling of deviated holes in very hot, hard, abrasive crystalline rock. Many innovations were required in equipment, techniques, and instrumentation, and a number of failures were experienced -- including a casing collapse in EE-2 and a stuck drilling assembly that required sidetracking of EE-3. These failures were costly in time and money, but the final per-foot costs of these wells were not inconsistent with those of conventional geothermal wells extrapolated to similar depths, or of vertical wells drilled in sedimentary formations in geopressured geothermal areas.

About 3000 ft at the bottom of the inclined section of each well were left uncased. When the two wells were pressure-tested early in 1982, EE-2 was found to be very tight at pumping pressures up to 2070 psi, but a fracture zone just below the casing shoe in EE-3 opened at 1480 psi and thereafter accepted water readily at wellhead pressures above 1400 psi.

Hydraulic-fracturing attempts began in the spring of 1982 in the uncased bottom section of well EE-2. To assist in initiating fractures, a notch was cut in the borehole wall about 160 ft off bottom, using a Hydrojet tool, but there is no evidence that it actually affected subsequent fracturing behavior. After two unsuccessful attempts to fracture through inflatable packers (both terminated by packer failures), a liner was cemented in place, about 450 ft off bottom. It was equipped at its upper end with a polished-bore receptacle (PBR) into which a seal assembly could be inserted at the end of drill pipe or a fracturing string leading to the wellhead. Pumping water through this, formation breakdown was observed at a wellhead pressure of 4800 psi. In three pumping operations -- two of which were terminated by equipment failures -- a total of 2.33 million gallons of water were injected into the openhole section. Fractures were extended radially for large distances from the wellbore, but unexpectedly the fracture system was inclined at about 45° -- upward toward the east (i.e., toward the Valles Caldera) -- and passed beneath the bottom of well EE-3.

Another unexpected effect of the fracturing operations was that they initiated evolution of large volumes of gas -- chiefly CO_2 but with a sufficient content of H_2S (of the order of 50 to 60 PPM) to cause serious stress-corrosion-cracking problems with tubular goods in subsequent operations.

Since it appeared unlikely that further pumping into the fracture zone at the bottom of EE-2 would result in a connection to EE-3, we decided to fracture from a higher point in that well -- where an inclined fracture would be more likely to intersect the other well. A sand and gel plug was therefore emplaced in EE-2, reaching upward to a point about 350 ft below the bottom of the casing. Because the casing had been damaged by drilling through it, it was considered unsafe to pressurize it to above about 2000 psi. Therefore, after several attempts, a casing packer was set within and near the bottom of the casing, connected to the surface by drill pipe or a frac string, and the open-hole section between the sand and the casing was pressurized by pumping water through it instead of directly through the casing.

In the first attempt to hydraulically fracture this zone, in the summer of 1982, 239,000 gal of water were injected, and temperature logging indicated that three fractures about 100 ft apart had been produced. Pumping was terminated by drill-pipe failure, attributed to stress-corrosion cracking. A subsequent pump was terminated by a frac-string failure after only 11,300 gallons of additional water had been injected. Finally on October 7, 844,000 gallons were injected before failure of a coupling terminated the experiment. Although a total of 1.09 million gallons of water had been injected into the upper fracture zone of EE-2, no connection with EE-3 was achieved. However, the series of equipment failures convinced us that no further fluid injections should be attempted until tubular goods more resistant to the downhole environment had been obtained.

Seismic mapping of the acoustic signals generated by these fracturing operations indicated growth of a system of fractures occupying a roughly ellipsoidal volume whose major axis was directed somewhat to the north of well EE-3. It appears that the fractures grew fairly symmetrically around the injection zone until they reached natural boundaries above them and to the south, after which their growth was almost entirely downward and toward the north.

While we were awaiting delivery of a new frac string for EE-2, it appeared useful to investigate the fracturing behavior and the existing fractures in the other well, using rented drill pipe. A major difficulty was foreseen in that, to accommodate thermal expansion when hot water flowed through it during production, the EE-3 casing had been pretensioned to about 80% of its yield strength. It was evident that, if cool water were pumped through it, thermal contraction would probably pull the casing apart. However, modeling of the system indicated that if the water were preheated to about 70°C or more, the risk to the casing would be small.

In the absence of a large and quite elaborate preheating system, a very large injection of water at such temperatures could not be managed. However, the "hot oilers" available from oil-field service companies could be used for volumes up to about 200,000 gallons. An injection of that size could not be expected to extend fractures to a connection with EE-2, but it would produce additional information about the fracturing behavior of the reservoir rock, provide an opportunity for improving our fracture-mapping capabilities, and present a target larger than a wellbore for intersection by fractures extended from EE-2 when pumping in that well could be resumed. Accordingly, the drilling rig was skidded to EE-3 for a limited set of experiments there.

To confine the region being pressurized in EE-3 to a zone likely to be intersected by fractures subsequently extended from EE-2, the well was sanded up to within about 1600 ft of the casing shoe.

Since it was feared that the fracture zone just below the casing might be a fault or might connect with the old Phase I fracture system, an attempt was made to seal it with lost-circulation materials. This was temporarily successful, but the seal soon washed out. Therefore it was bypassed by emplacing an inflatable packer, at the end of drill pipe, at a point about 800 ft below the casing shoe, and pumping preheated water through it into the open-hole section. However, the packer failed at a pumping pressure of 2050 psi, with no indication of formation breakdown.

Since a cemented-in liner and PBR had been used successfully in EE-2, a similar assembly was emplaced in EE-3. The bottom of the assembly was about

1000 ft below the casing shoe, and there were about 380 ft of openhole between it and the top of the sand plug. On December 14, 1982, 151,200 gallons of hot water were pumped into this interval before another drill-pipe failure terminated the experiment. No distinct formation breakdown occurred. The fractures produced formed a northerly trending system whose growth upward and to the south terminated at the same boundaries that previously had halted the growth of fractures extended from the upper zone of the other well. The median plane of this new fracture system is about 600 ft east of the median plane of the fracture system made from EE-2.

Further pumping was postponed until a new 4.5-in L-80 frac string was delivered. When it arrived, the old N-80 frac string and seal assembly were pulled out of the hole. However, when a small mill was run in to clean out the liner, an obstruction was encountered that was later found to be a buckle in the uncemented upper part of the liner. This led to a very difficult fishing job that lasted from May 5 to June 18, 1983, and left the threaded box end of the liner stub looking up. Twenty joints of the new L-80 pipe, terminating in a PBR, were successfully screwed into it.

It had been proposed that if the upper part of the annulus between the frac-string and the casing were filled with nitrogen instead of water, heat transfer would be sufficiently reduced so that cool water could safely be pumped down the frac string. The seal assembly, which had been inserted into the PBR at the end of the L-80 frac string, was pulled out of the PBR to permit the water in the top 5900 ft of the annulus to be displaced with nitrogen. The seal was reinserted, and cool water was pumped down at 1 BPM and about 5000 psi wellhead pressure. This was slowly increased to 8 BPM at 5500 to 5600 psi. After two hours of pumping a pressure rise in the annulus indicated leakage from the frac string into the annulus, and the experiment was terminated. Its results were disappointing. Temperature records showed that the nitrogen blanket was not a good enough thermal insulator to permit pumping large volumes of unheated water.

This time the failure was at the threaded connection between the new L-80 pipe and the old N-80 liner. Subsequent examinations indicated that it resulted jointly from a poorly made up connection -- due to extraneous chips of steel in the threads -- and excessive downward force used to drive the seal assembly into the PBR.

Again, a difficult fishing job was required which lasted from June 25 to July 5, and left a short cut-off liner stub sticking up above good cement. Since a threaded connection to it was impossible, we decided to procure a special high-temperature casing patching to make a connection that had a reasonable chance of withstanding fracturing pressures. This has since been designed and built.

In the meantime the liner was plugged and a temporary casing patch, at the end of the frac string, attached to it. Sepiolite mud was emplaced in the annulus to reduce fluid loss into the fracture zone below the casing, and corrosion inhibitors were added to protect the casing.

On August 18, 1983, a small pumping experiment was run with unheated water to investigate fluid acceptance by that fracture zone. Essentially no water entered it until wellhead pressure reached about 1500 psi, compared with an opening pressure of 1400 psi in a previous experiment. (Presumably this was because of the presence of the sepiolite mud.) Fluid acceptance increased with pumping pressure until, at 2350 psi, the fracture accepted the full flow (34 GPM) of the small injection pump being used. Unexpectedly, increasing the flow by 9 GPM by bringing a second pump on line caused no further increase in injection pressure. When the well was shut-in, after injection of 1776 gallons of water, wellhead pressure dropped to 945 psi in 1.25 hr. The well was then vented and returned something less than 40 gallons before pressure dropped to hydrostatic.

To investigate this behavior further and to study fracturing behavior in this part of the reservoir, a larger pumping test was run on September 27 and 28, 1983. In this experiment, 197,000 gallons of preheated water were pumped into the annulus between the frac string and the EE-3 casing. This time there was essentially no flow into the fracture zone below the casing until a wellhead pressure of about 2500 psi was reached, again presumably because of fracture-sealing by the mud. Then a breakdown occurred and pressure dropped quickly to about 2000 psi, after which it declined slowly to an essentially constant value of 1900 psi. Preliminary seismic source-location maps indicate that the mud acted as a diverting agent. Until near the end of the experiment there apparently was no significant extension of preexisting fractures. Instead new fractures formed that spread northward across the boundary that, in a previous experiment, had apparently been an effective crack stopper. Fracture extension was largely horizontal, and it is not known whether a large fluid injection would cause the fractures to extend downward toward the other boundary that constrained upward growth of fractures made from the two wells. Because of the difficulty of preheating a large volume of water and lack of confidence in the ability of a casing patch to survive fracturing pressures, no large pump into either of the EE-3 fracture zones is planned at this time. However, this remains as one of the possibilities for the future in case a connection is not completed by a large pump into EE-2, and the apparent effectiveness of the sepiolite mud as a diverting agent also broadens the scope of contingency planning.

The present plan is to install the new casing patch and frac string in EE-3 to permit corrosion protection of the casing, act as a production string if a connection is made by pumping into EE-2, and provide for further pumping into the lower fracture zone in EE-3 if it is not. (Injection into the upper fracture zone in EE-3 will still be possible by pumping into the annulus between the frac string and the casing.) Then the drilling rig will be skidded back to EE-2, a new 5.5-in C-90 work string installed there, and a fluid injection of 4 to 6 million gallons made into the existing fracture system in the upper part of the uncased section of that well. If this results in a hydraulic connection to EE-3, the surface system will be completed and recirculating flow experiments initiated. If it does not, several courses of action are open for the next attempt, the choice among them depending primarily upon the geometry of the fracture system that exists at the end of this "massive hydraulic fracturing" experiment.

Fracture mapping is still done primarily by analysis of acoustic signals received by a downhole three-axis geophone system, using S-P delay time to measure distance to the signal source and the hodogram method to determine the direction from which the signal came. However, energy release from fracturing in the Phase II system is great enough so that some of the acoustic signals can be recorded at the surface (which was not the case in development of the Phase I system). Therefore an array of sensitive surface seismometers is now used during fracturing operations to confirm the general location of the microseismic signals and make possible fault-plane solutions as an indication of _in situ_ stress conditions. Further, acoustic signals from the last fracturing experiment were clearly recorded by a geophone emplaced in the Precambrian crystalline rock at the bottom of exploratory well GT-1, about 1.5 miles north of Fenton Hill. The first steps have therefore been taken to develop a "Precambrian seismic net" of geophones emplaced in the basement rock in deep holes surrounding Fenton Hill. P-wave arrival times at the various stations in this net should permit significant improvements in the accuracy with which acoustic sources can be mapped.

Los Alamos instrumentation and personnel have supported geothermal well-stimulation experiments at the Baca Location, the Geysers, and Beowawe, and done vertical seismic profiling in the Imperial Valley, and industry is beginning to use our acoustic-mapping techniques. However, we are continuing to improve our instrumentation and methods. One recent improvement is development of an on-line system that permits prompt mapping of source locations while hydraulic-fracturing experiments are in progress. Another is use of a new type of vertical geophone in the downhole instrument package which is insensitive to inclination and whose response to an acoustic signal is a good and consistent match to that of the horizontal geophones. A third is an increase by a factor of about four in the time to which the geophone package can safely be exposed to a very hot downhole environment, accomplished primarily by using small heat pipes to accelerate heat transfer from source to sink.

A related development is an acoustic transceiver now used for investigation of rock structure between wellbores and potentially useful (by acoustic reflection) for investigations of structure from a single well. It incorporates a magnetostrictive driver that transmits a relatively low-frequency acoustic signal into the rock and a receiver that can be emplaced in a different well or at a different level in the same well.

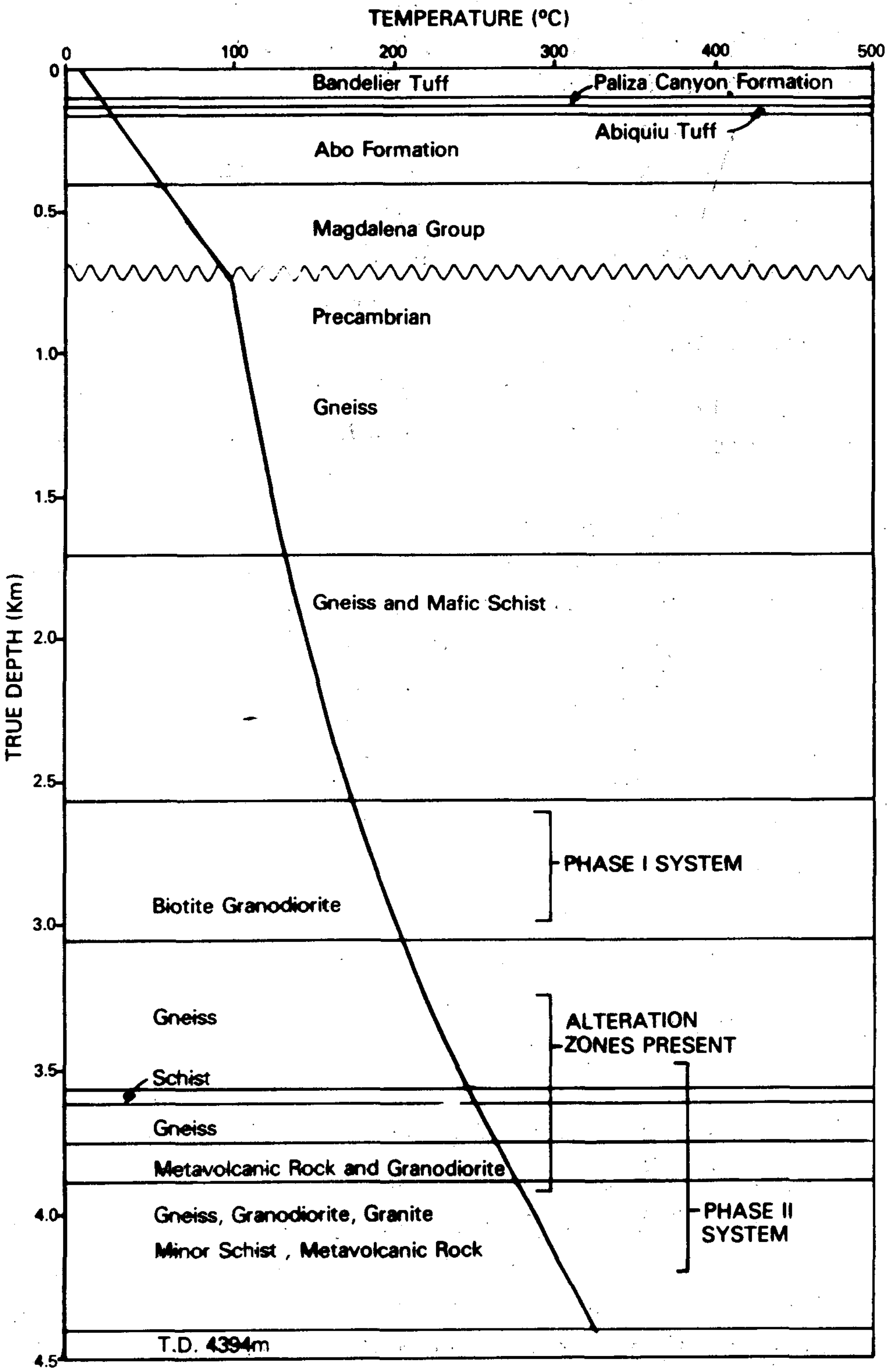
The requirement for logging through a frac string instead of larger-diameter well casing has made necessary development of a new family of "slim-line" downhole instruments. The first of these, which was used to calibrate seismic-detection instruments in advance of the recent fracturing experiment in EE-3, is a slim-line detonator tool.

Another new family of downhole tools now being developed is a set of explosive devices to be used not only for seismic calibration but also for such purposes as initiating or reducing the flow impedance of fractures, perforating casing, and cutting off pipe. The behavior of previous explosive tools has been erratic because of the effect of temperature on the initiator and the downhole electronic package required to fire it. A new type of exploding-wire initiator is now being developed which is insensitive to temperature and requires no downhole electronics.

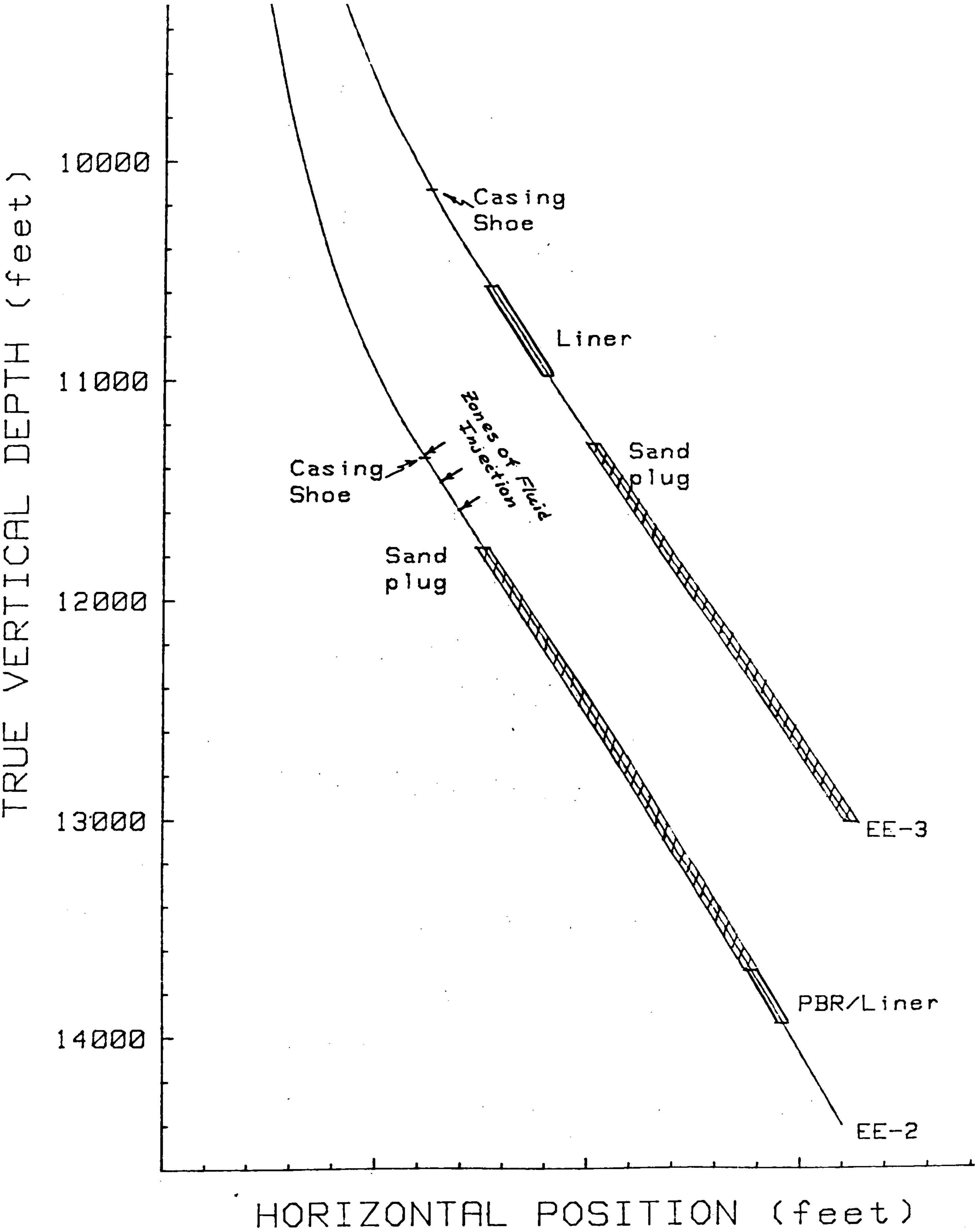
Several other instrument developments are in progress, including an investigation of methods of evaluating in situ stresses by means of very sensitive measurements of the deformation of a borehole as it is pressurized, and a cooperative program with Sandia to improve the high-temperature borehole televiewer. Geochemical studies are also continuing, emphasizing both the rock-water interactions to be expected in the very hot Phase II system and the possibility of using reactive tracers to measure thermal drawdown in the fracture system before there is a significant change in fluid temperature at the outlet from it. And modeling studies continue, both to interpret and understand the results of Fenton Hill experiments and to permit improved prediction of fracturing behavior and of heat and mass transport in a fractured geothermal reservoir.

Much remains to be learned, but good progress is being made in understanding the very complex environment encountered in the Phase II thermal reservoir, in developing methods for creating a heat-extraction loop to produce thermal energy from it, and in broadening and improving the supporting technologies required for efficient development and operation of HDR systems at Fenton Hill and wherever else that may eventually be useful.

GEOLOGIC CROSS SECTION, FENTON HILL
HDR SITE NEW MEXICO



GRADIENT SHOWN IS DERIVED FROM MEASUREMENTS IN GT-2, EE-1 AND EE-2


TRUE VERTICAL DEPTH (feet)
10000
11000
12000
13000
14000
HORIZONTAL POSITION (feet)
Casing Shoe
Liner
Sand plug
EE-3
Zones of Fluid Injection
Casing Shoe
Sand plug
PBR/Liner
EE-2

RECENT HDR ACTIVITIES

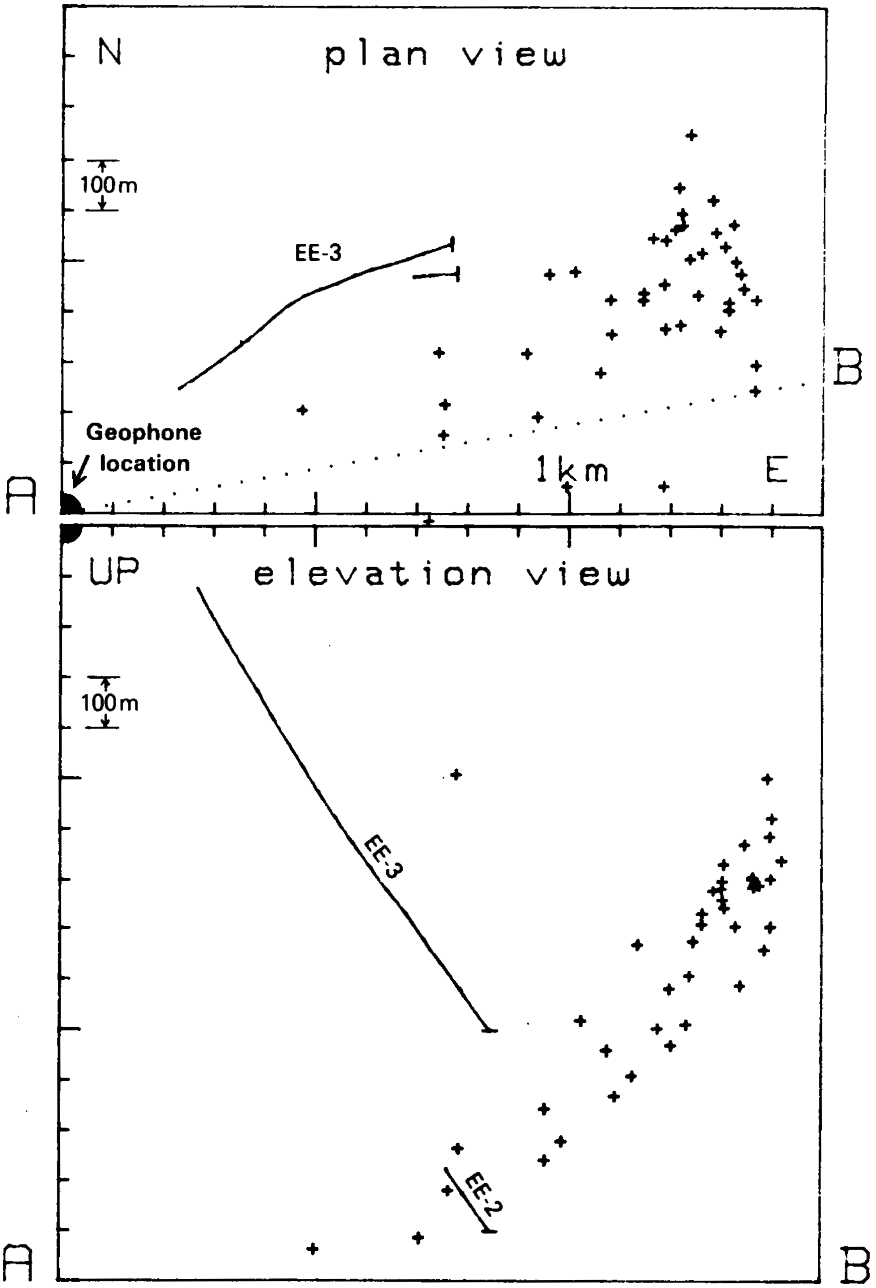
1982

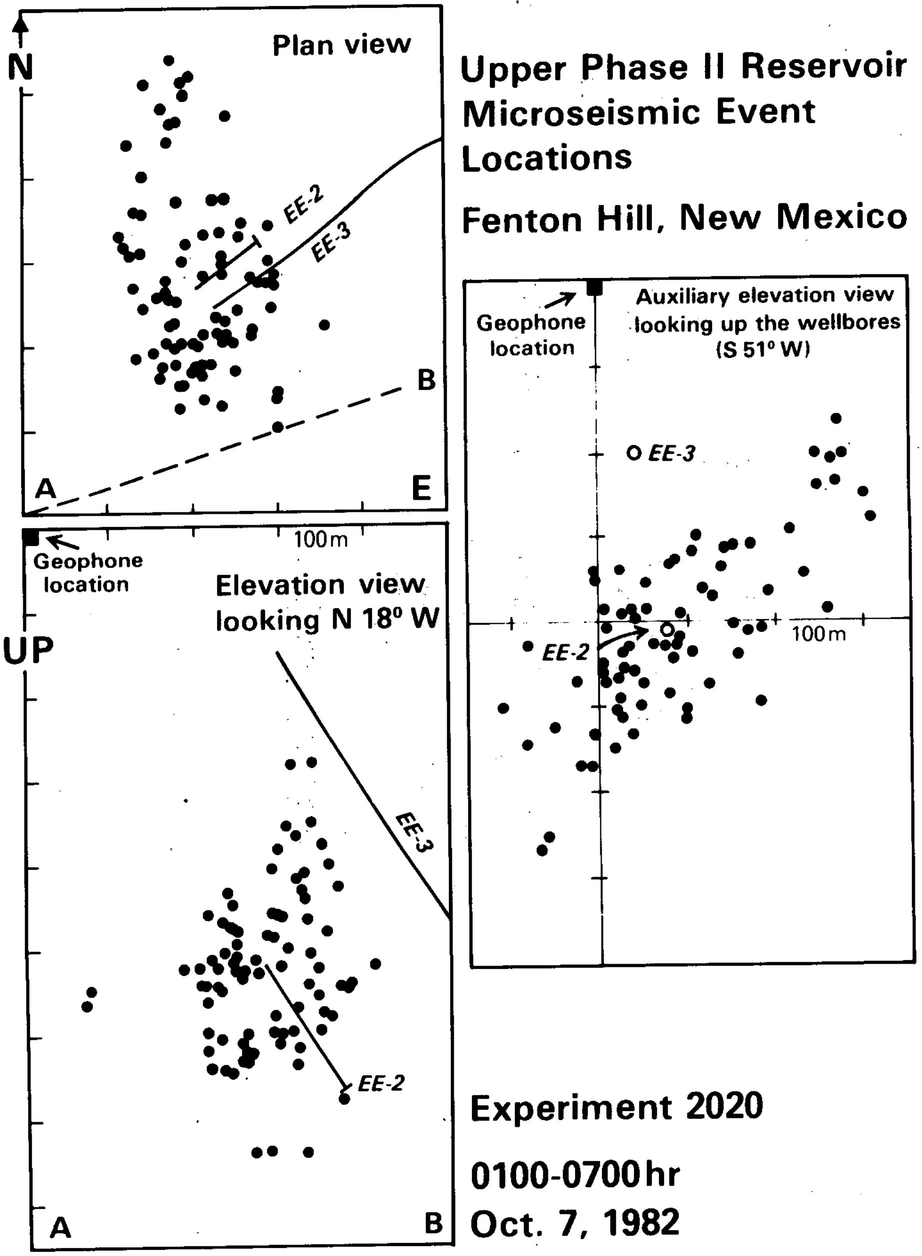
October 6 & 7	EXPERIMENT 2020: 844,000 gallons into EE-2; experiment terminated by numerous failures in "old" P-110 frac string.
October 21	Specifications for L-80 4-1/2-in. frac string submitted to purchasing.
November 8	EXPERIMENT 2023: Flow test of the near-vertical joints just below the EE-3 casing shoe (TVD ~10,150 ft to fracture entrance).
December 13	EXPERIMENT 2025: 153,000 gallons of heated water injected into EE-3 below scab liner; experiment terminated due to an axial split in S-135 drill pipe.

1983

January 24	Order placed for new L-80 VAM-collared frac string (4-1/2-inch).
February 22 & 28	EE-2 Pressurization/Water-Loss Tests (less than 0.5 gpm loss rate at 1550 psi)
April 22	Order placed for 5-1/2-in. Hydrill C-90 frac string.
May 6	L-80 4-1/2-in. frac string delivered to Fenton Hill.
May 13	EXPERIMENT 2029: Preliminary test of the Precambrian net.
June 22	EXPERIMENTS 2026 AND 2028: EE-3 fracture entrances identified; nitrogen blanket evaluated.
July 8	Rig Furloughed for 10 to 12 weeks to allow sufficient time to design and fabricate a suitable overshot liner patch for EE-3.
September 27 & 28	EXPERIMENT 2033: 197,000 gallons of heated water injected into the set of near-vertical joints just below the EE-3 casing shoe.

EXP. 2016: JUN 20, 12:30 - 13:30 MDT





Upper Phase II Reservoir Microseismic Event Locations

Fenton Hill, New Mexico

Plan view

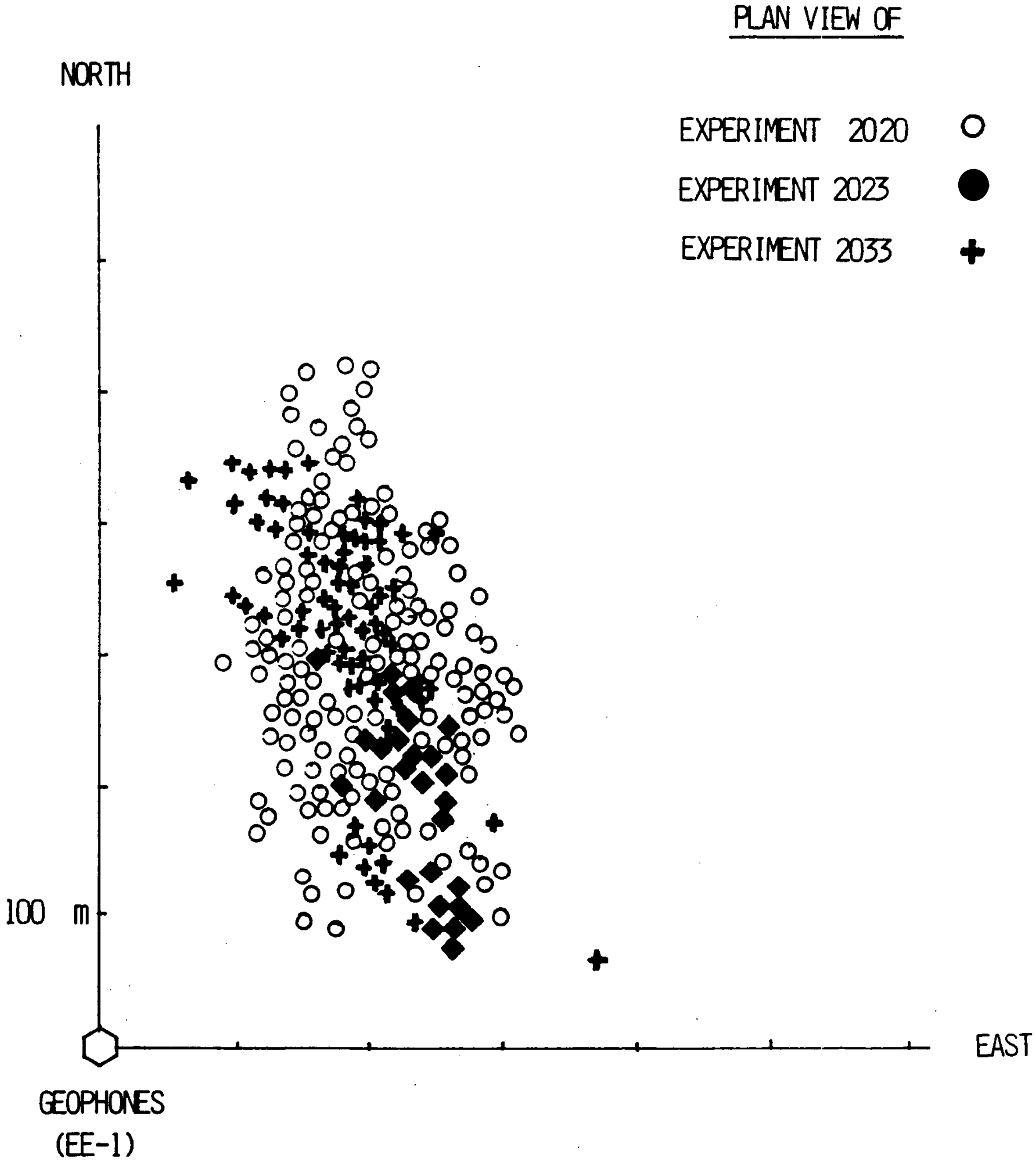
Elevation view looking N 18° W

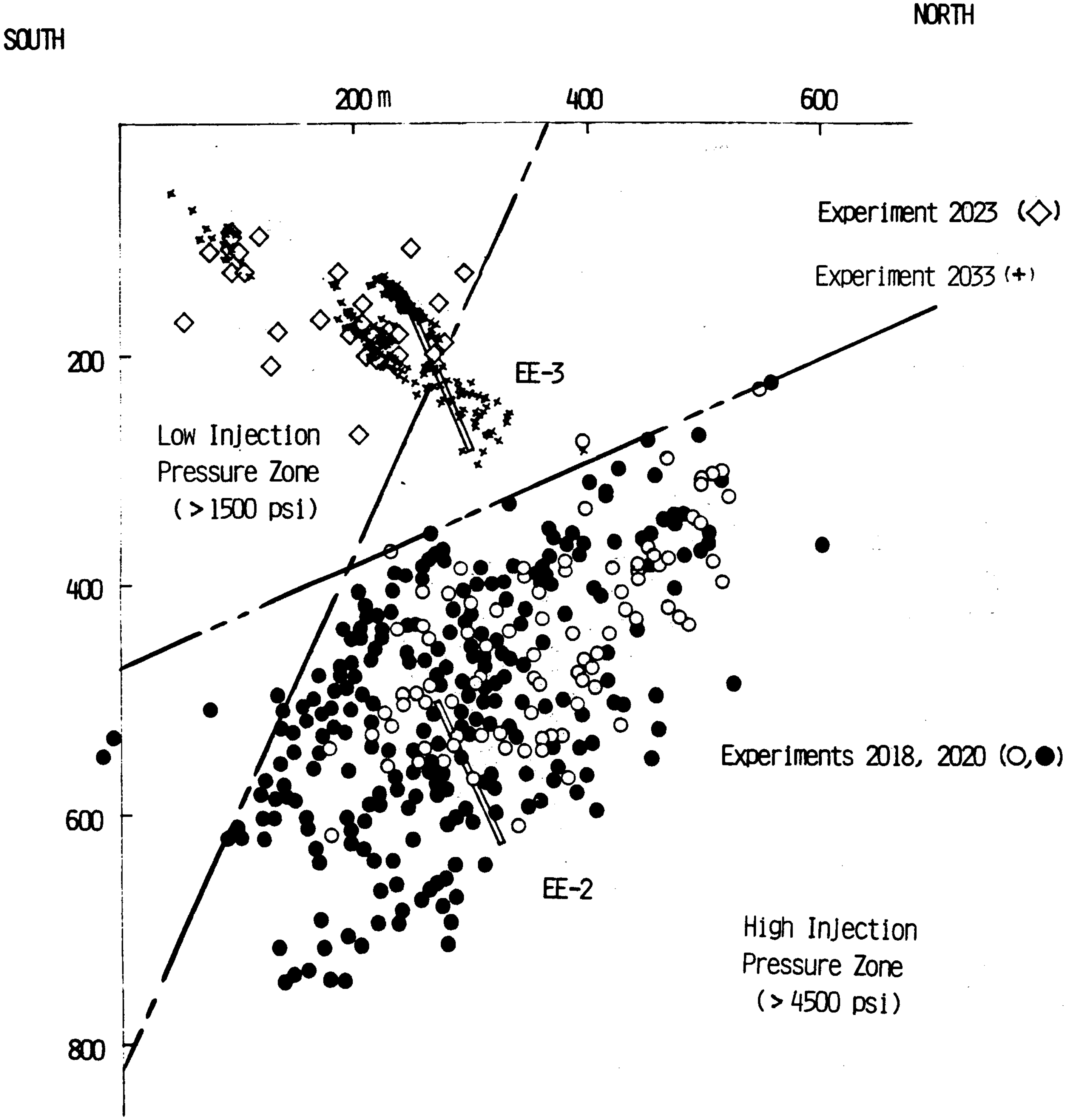
Auxiliary elevation view looking up the wellbores (S 51° W)

Experiment 2020

0100-0700hr

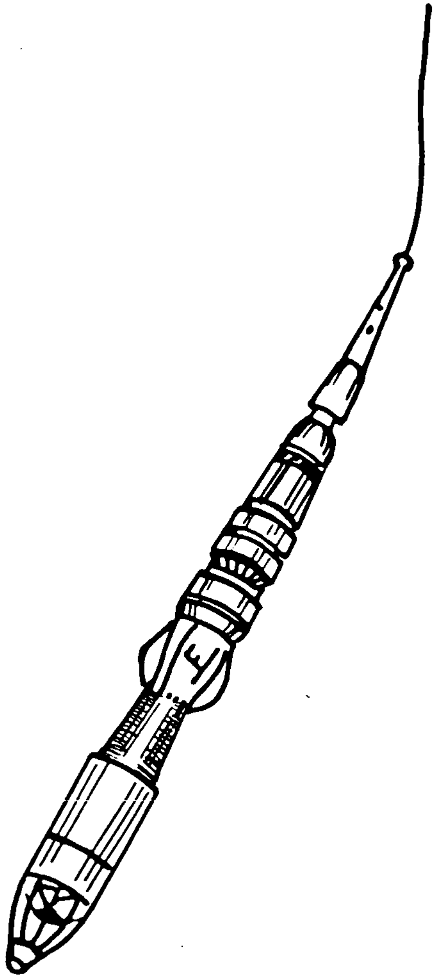
Oct. 7, 1982


PLAN VIEW OF
EXPERIMENT 2020 ○
EXPERIMENT 2023 ●
EXPERIMENT 2033 ✚
NORTH
100 m
EAST
GEOPHONES
(EE-1)



Events Projected Onto Plane Y = -225
(Approximate Symmetry Plane of
Experiments 2018, 2020 and 2023)

DOWNHOLE INSTRUMENTATION
EXISTING SONDES
(275°C - 300°C)

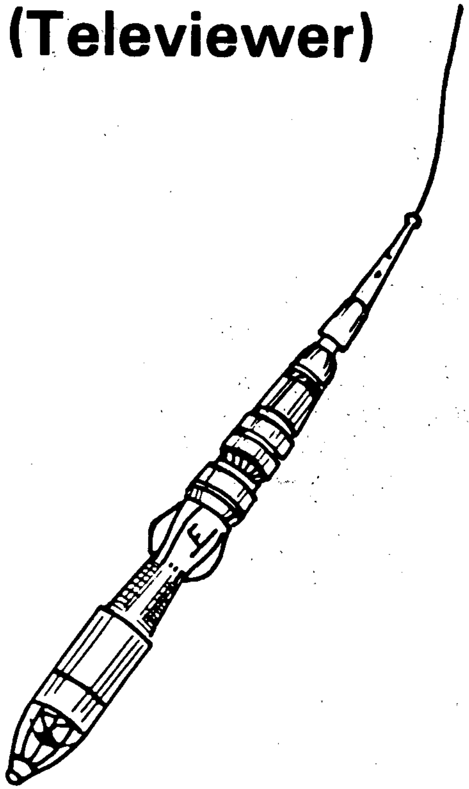


- Temperature Probe
- Caliper and Contour Probe
- Fluid Velocity Probe (Spinner)
- Gamma Ray Injector - Detector
- Geophone Acoustic Detector
- Accelerometer Acoustic Detector
- Acoustic Detonator Source
- Crosswell Acoustic Transceiver
- Borehole Fluid Sampler
- Borehole Dye Tracer Injector

DOWNHOLE INSTRUMENTATION SONDES UNDER DEVELOPMENT

275°C - 300°C

- Borehole Acoustic Survey System (Televiewer)
- Drill Pipe Severing Sonde
- Tri-Axial Fluxgate Magnetometer
- Explosive Fracture Initiation Sonde
- Shaped Charge Explosive Sonde
- Borehole Deformation Gage



HIGH TEMPERATURE COMPONENT DEVELOPMENT

DESCRIPTION	*MANUFACTURER*	*TYPE*	*TEMP★ RATING (C°)*
ARMORED CABLE	Rochester Corp.	TFE	350
CABLEHEAD	LANL	800-2	320
DEWARS	Vaccum Barrier	B13254-A	320
HEAT PIPES	LANL		320
CONNECTORS	ITT Cannon	Ca3101-HR	320
CONNECTORS	Reynolds	178-7440	350
DC MOTORS	AEI	17D62	300

★ *TEMPERATURE LISTED IN COLUMN IS MAXIMUM OPERATIONAL TEMPERATURE USED OR TESTED BY LANL TO DATE.*

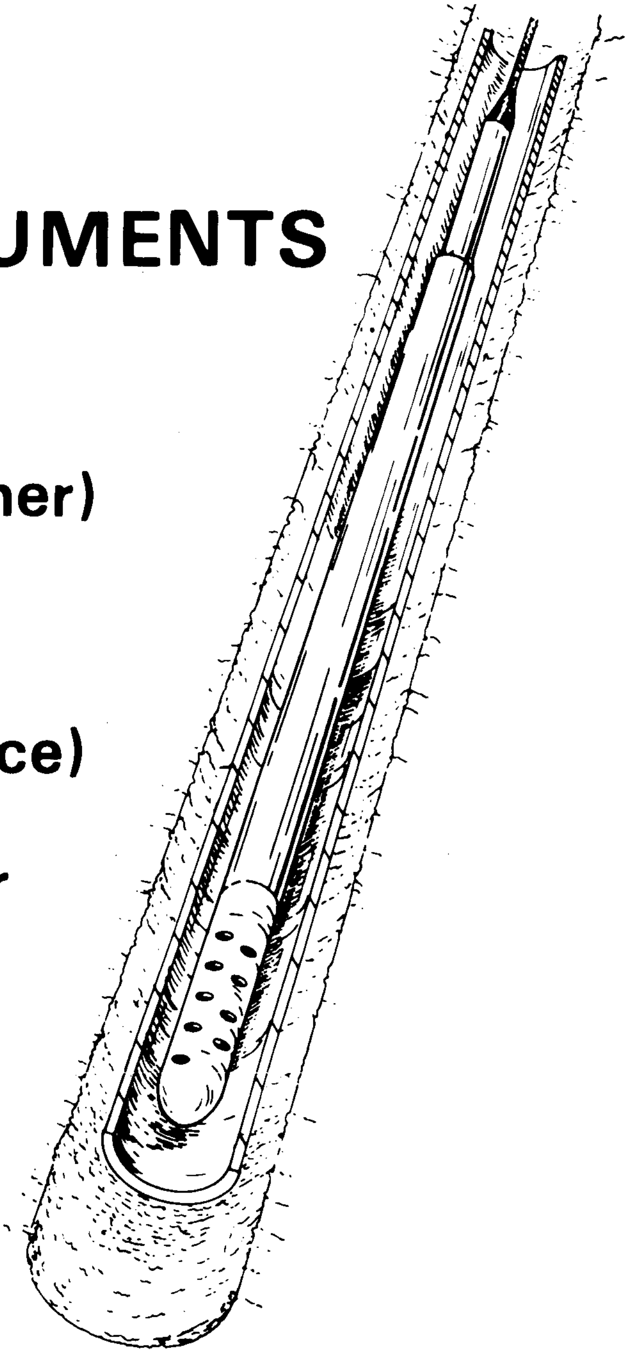
(continued)

DESCRIPTION	*MANUFACTURER*	*TYPE*	*TEMP ★ RATING (C°)*
GEOPHONES	Mark Products	L-15-A	280
PRESSURE TRANSDUCERS	Bell & Howell	CEC-1000-04	250
POTENTIOMETERS	TIC	PS-091-100	300
DETONATORS	Reynolds	HNS-EBW	250
O' RINGS	L'Garde	Y26-EPDM	320
THERMALLY STABLE EXPLOSIVES	LANL/Airforce	AFX-521	340

★ *TEMPERATURE LISTED IN COLUMN IS MAXIMUM OPERATIONAL TEMPERATURE USED OR TESTED BY LANL TO DATE.*

DOWNHOLE SLIMLINE INSTRUMENTS

300° C



- Fluid Velocity Probe (Spinner)
- Temperature Probe
- Detonator (Acoustic Source)
- Triaxial Geophone Detector
- Gamma Detector

TECHNOLOGY TRANSFER

FLUID SAMPLES——————Occanic Rift, East Pacific Rise

NSF ALVIN SUBMARINE

CROSSWELL ACOUSTIC IMAGING——————Rifle, Co.

DOE WESTERN GAS SANDS

MICROSEISMIC MAPPING——————Baca Location, N.M.

DOE UNION GEOTHERMAL

TEMPERATURE/FLUID VELOCITY——————Ontario, Oregon

DOE ORE-IDA FOOD CO.

FLUID SAMPLES/TEMPERATURE/
FLUID VELOCITY ——————Thompson's Rigde, N.M.

GEOTHERMAL RESOURCES INC.

VSP/TEMPERATURE/FLUID SAMPLES—————— Brawley, Calif.

PHILLIPS PETROLEUM

MICROSEISMIC/TEMPERATURE/FLUID
SAMPLES——————Boewawe, Nevada

DOE REPUBLIC GEOTHERMAL