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EVIDENCE FOR THE EXISTENCE OF A STABLE, HIGHLY FLUID-PRESSURIZED REGION OF DEEP, JOINTED CRYSTALLINE ROCK FROM FENTON HILL HOT DRY ROCK TEST DATA

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ABSTRACT

Large volumes of naturally jointed Precambrian crystalline rock can be stably maintained at pressures considerably above the least principal earth stress in the surrounding rock mass. At Los Alamos National Laboratory's Fenton Hill hot dry rock (HDR) geothermal test site, tests carried out for a cumulative period of 11 months in the deeper and larger of the two HDR reservoirs showed no evidence of fracture extension at the boundaries of the pressure-stimulated region. These results were obtained while maintaining a very high reservoir inlet circulating pressure of 27.3 MPa (3960 psi) above hydrostatic, considerably in excess of the least principal earth stress in the surrounding rock mass of about 10 MPa above hydrostatic at a depth of 3500 m.

We review and summarize information concerning the earth stresses at depth and the test data relative to the containment of pressurized fluid, particularly the data showing the *declining* rate of water loss and the *absence* of microseismicity—the two principal indicators of a stable, pressurized reservoir region. We then provide a coherent and concise evaluation of this and other evidence supporting our assertion that one can indeed maintain large volumes of jointed rock at pressures considerably in excess of the least principal earth stress. In addition, a discussion is presented concerning the initial state of stress at depth beneath Fenton Hill and then possible changes to the stress state resulting from the very large volumes of injected high-pressure water and the accompanying shear displacements—and shear dilation—associated with these pressurizations.

INTRODUCTION

Recently, the Laboratory has embarked on a "Cradle-to-Grave" Carbon Management research program to investigate a number of methods for reducing or eliminating the carbon dioxide emissions from fossil-fueled power plants. This multi-pronged effort is considering either upstream carbon separation prior to combustion or carbon dioxide separation from the power plant effluent stream, and then long-term storage. As one part of the Laboratory's overall strategy, the sequestering of carbon dioxide by deep earth injection is being investigated. It is to this end that the data obtained at Fenton Hill is being reviewed, since this testing represents the most significant data set presently available relating to the deep earth storage of high-pressure fluids.

From 1972 through 1995, researchers at Los Alamos National Laboratory were engaged in developing the technology for creating fully engineered geothermal reservoirs in hot, impermeable, crystalline rock. The two separate hot dry rock (HDR) reservoirs that were repeatedly tested since the late 1970's were formed by hydraulic fracturing techniques, and subsequently circulated with water—at very high pressures—to mine heat from the hot rock. The results from this testing have indicated that it is practical and economical to operate commercial-scale HDR heat mining facilities to produce thermal power on a sustained basis—with little or no environmental impact.

However, our colleagues in the international rock mechanics community view with incredulity the fact that we have been able to maintain, for months at a time, a highly fluid-pressurized region of deep, jointed, crystalline rock at pressures up to 17 MPa above the least principal earth stress in the surrounding rock mass—without significant fluid leak-off due to continuing fracturing or joint dilation at the boundaries of the HDR reservoir. Based principally on three years of well-documented testing of the deeper Phase II reservoir at the Laboratory's now decommissioned Fenton Hill HDR test site (from 1992 through 1995), it is absolutely clear that we had routinely maintained mean reservoir pressures of at least 24 MPa above hydrostatic without any observable reservoir growth due to renewed fracture extension. This profound observation, though not yet well understood, may eventually provide significant insight into the mechanisms controlling the movement of fluids deep in the earth's crust.

In this paper, we address the two basic issues discussed above, particularly as these concern the Phase II reservoir region:

1. What evidence do we have that this region was actually pressurized to a level well above the existing least principal earth stress?
2. How did we determine that the region was indeed stable?

THE PHYSIOGRAPHIC AND STRUCTURAL SETTING OF FENTON HILL HDR TEST SITE

The Fenton Hill Test Site is located on the western flank of the Valles Caldera, in north-central New Mexico. The site is situated on a deeply incised apron of ash-fall tuff (referred to as Fenton Hill in the area), approximately 2.9 km west of the caldera ring-fault structure. Figure 1 shows a portion of the geological map of the Jemez Mountains of New Mexico prepared by Smith et al. (1970), showing the Fenton Hill area and a portion of the Valles Caldera to the east. The curved trace of the caldera ring fault (concave to the east) is depicted by the series of large black dots in the right-hand portion of this figure. Of particular note is the short (about 1.5 km long) normal fault mapped just to the east of the Fenton Hill site (the curved, north-trending, solid dark line), with the downthrown block to the east. It is inferred that this small normal fault is related to the adjacent ring-fault structure, and is indicative of the contemporary state of stress at depth beneath Fenton Hill—extensional, with a horizontal least principal earth stress oriented roughly ENE, and a vertical maximum principal stress.

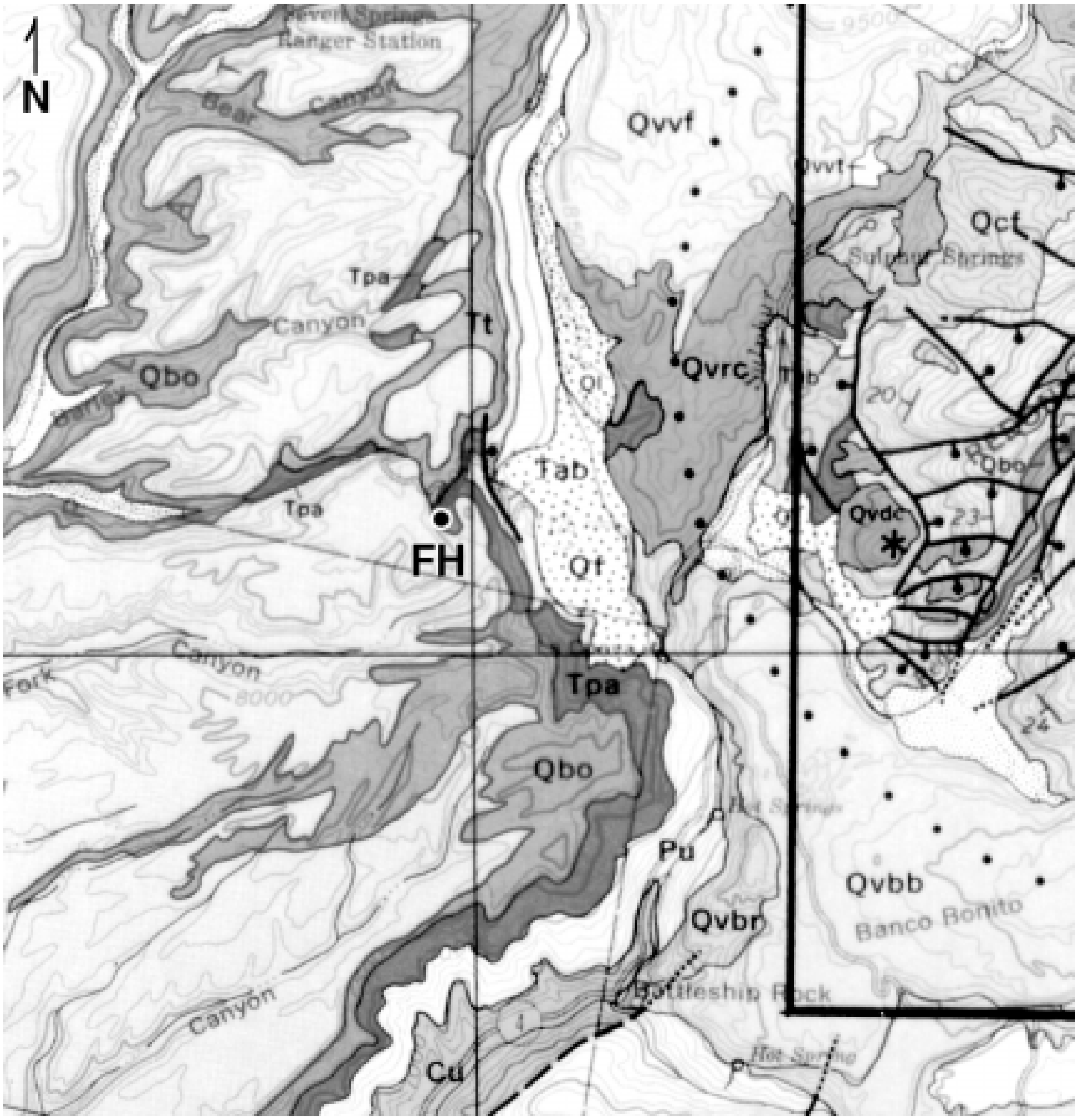

Fig. 1: The geological and structural setting for the Fenton Hill HDR Test Site, located to the west of the Valles Caldera in north-central New Mexico

This site was selected for HDR testing early in 1973 based on a number of factors, the most important of which were:

- An elevated heat flow due to its proximity to the caldera,
- The absence of major faulting in the immediate area. (The site is situated within a large fault block, with the principal bounding faults trending roughly north-south) and,
- An uncomplicated geological setting, with the crystalline basement at a relatively shallow depth of 730 m.

DETERMINING THE STABILITY OF A PRESSURE-DILATED VOLUME OF JOINTED CRYSTALLINE ROCK

The stability of a fluid-pressurized volume of naturally jointed basement rock is determined in two ways:

- An analysis of the temporal variation of the rate of fluid leakoff as measured by the amount of injected fluid needed to maintain a given level of pressurization and,
- The presence or absence of microseismic activity, which is normally associated with continued (or renewed) joint extension at the boundaries of the stimulated reservoir region.

In principal, each of these two types of reservoir monitoring is easy to perform. In practice, however, the extended period of time required to acquire sufficient and reliable data may present problems. For instance, if the region is essentially “aseismic,” but pressure levels and gradients are being continually changed during operation (such as occurs when equipment change-out is required or when pumps fail), the seismic monitoring my represent a Herculean task of listening for a “something” among a whole lot of “nothing” but noise. Similarly, the continued monitoring of reservoir pressure may necessarily have to extend over many months while the initial period of transient fluid storage is first satisfied and then a more diffusion-like behavior from the boundaries of the reservoir region is established.

SEISMICITY DURING SIX YEARS OF PHASE II RESERVOIR TESTING

During the entire sequence of pressure and flow tests of the Phase II reservoir, extending from 1989 through 1995, there was only one period when any seismicity was detected—49 events between late December 1992 and early May 1993. Figure 2 shows a composite plot of the histogram of located seismic events along with the surface injection and production pressure profiles during this time (Fairbanks and DuTeau, 1993).

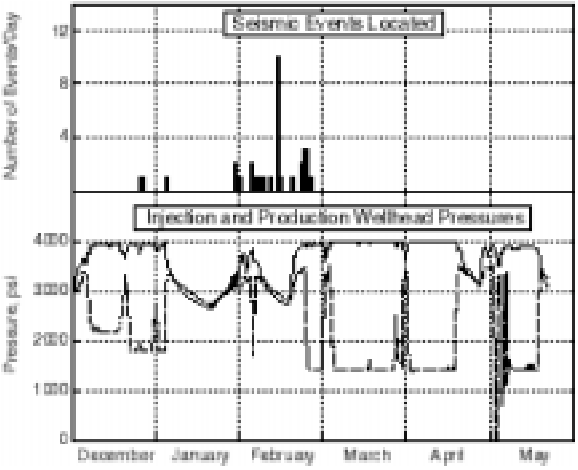

Fig. 2: A histogram of the located microseismic events along with the surface injection and production pressure profiles during the only period of seismic activity in 1993.

As can be seen, the majority of these events were concentrated between late January and late February, 1993, and were associated with by far the longest period of high-pressure production-well shut-in that occurred during this entire 6-year sequence of tests. During this time, the pressure acting along that portion of the boundary of the fractured reservoir to the north of the production well was first pressurized (without circulating) from 2700 psi to 3300 psi, and then allowed to slowly decay back to 2800 psi—the highest sustained pressure along the northern boundary of the reservoir ever achieved. Otherwise, reservoir flow testing at *injection* pressures maintained at 27.3 MPa (3960 psi) above hydrostatic were all aseismic.

Figure 3 shows a plan view of the Phase II reservoir, as delineated by the recorded microseismicity during its initial formation in 1983 and its subsequent extension to the south in 1986. During an aggregate of 11 months of closed-loop flow testing between 1992 and 1993, the injection pressure was maintained at 3960 psi by a closed-loop flow-control system. Following the initial period of pressurized fluid storage within the fractured reservoir, an essentially no-flow boundary would have developed around the periphery of the reservoir region; this approximate boundary to the fractured reservoir region is indicated by the dashed line in Figure 3. In this situation, the large southern portion of the reservoir would have been essentially isobaric at close to 3900 psi, while the pressure around the smaller northern boundary of the reservoir (to the north of the production well as shown in Figure 3)

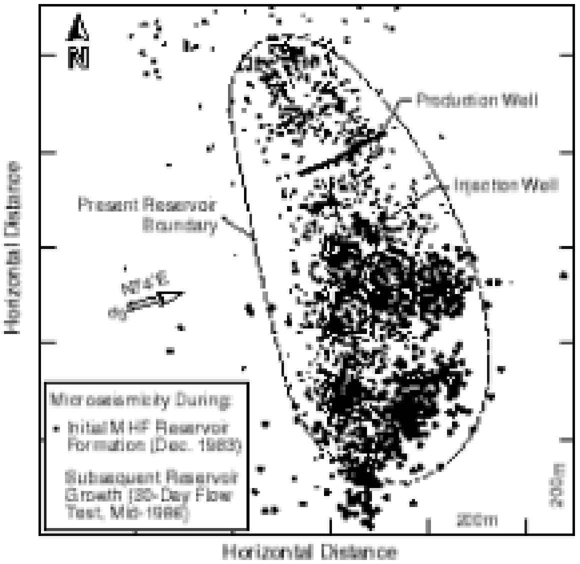

Fig. 3: Plan view of the Phase II reservoir as delineated by the recorded microseismicity during its initial formation in 1983 and its subsequent extension to the south in 1986.

would have been controlled by the pressure being maintained at the production well—typically 1400 psi. Therefore, during the latter stages of testing in mid 1993, the majority of the small 7.3 gpm water loss to the far field (see Table I) would have occurred through the 1400-m-long reservoir periphery south of the injection well, supporting the assertion that this large region was essentially isobaric. This southern extension of the reservoir has often been referred to as a near-static "backwater" region which contributed almost nothing to the reservoir thermal power produced by the fluid flowing more-or-less directly from the injection well north to the production well.

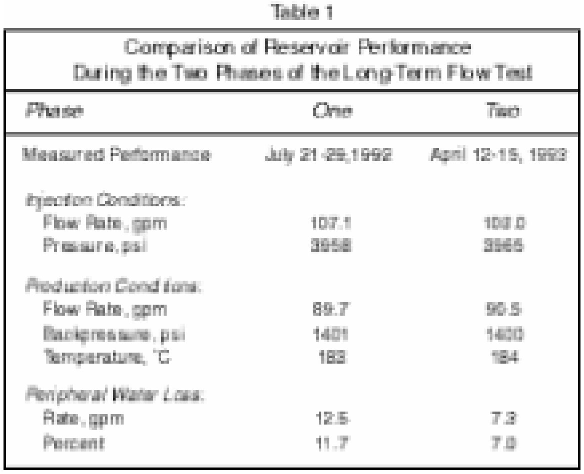

Table 1

Comparison of Reservoir Performance During the Two Phases of the Long-Term Flow Test

Phase	*One*	*Two*
Measured Performance	July 21-29,1992	April 12-15, 1993
Injection Conditions:		
Flow Rate, gpm	107.1	102.0
Pressure, psi	3958	3966
Production Conditions:		
Flow Rate, gpm	89.7	90.5
Backpressure, psi	1401	1400
Temperature, °C	183	184
Peripheral Water Loss:		
Rate, gpm	12.5	7.3
Percent	11.7	7.0

A CHRONOLOGY OF MEASURED RESERVOIR WATER LOSS RATES BETWEEN 1989 AND 1993

Figure 4 presents a plot of the variation in the measured rate of reservoir water loss during a 17-month-long period of static (i.e., non-circulating) reservoir pressurization at 15 MPa (2180 psi) above hydrostatic (Brown, 1995). This static pressure testing of the Phase II reservoir region occurred prior to beginning the Long-Term Flow Test (LTFT) in mid-1992. As shown, the rate of water loss continually decreased to a very low level of just over 2 gpm by the end of this period of pressurization in October 1990.

During this time, however, based on the "conventional wisdom" in the oil industry and elsewhere, the reservoir *should* have been growing due to continued "fracturing"—i.e., joint dilation—at the boundaries since the maintained static pressure of 15 MPa was 5 MPa *above* the least principal earth stress at the mean reservoir depth of 3460 m (as discussed in the next section).

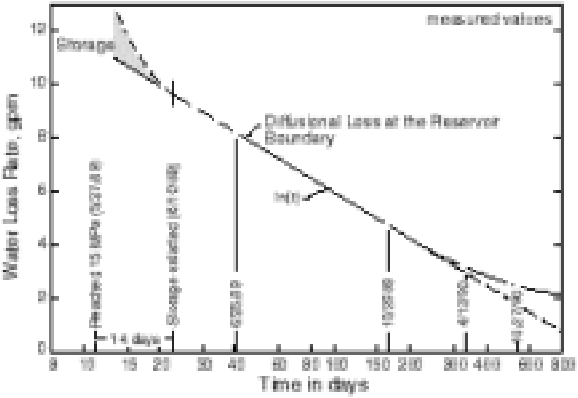

Fig. 4: Variation in the measured rate of reservoir water loss during 17 months of static (i.e., non-circulating) reservoir pressurization at 15 MPa (2180 psi) above hydrostatic.

Figure 5 shows the rate of water loss during the first and second phases of the LTFT in 1992 and 1993. The extreme variation in the actual measured data is a direct consequence of the repeated pump shut-downs (planned and otherwise) during the cumulative 11 months of flow testing. The dark curve is our best

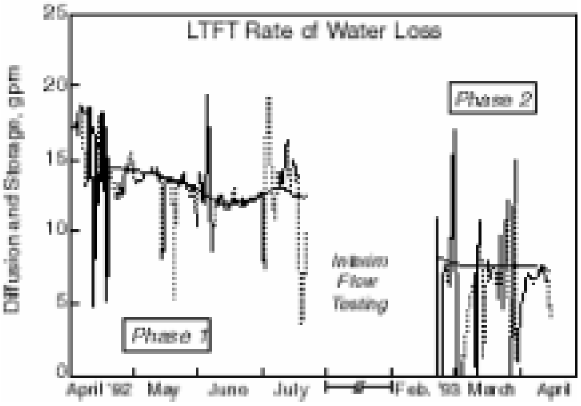

Fig. 5: Rate of water loss during the first and second phases of the LTFT in 1992 and 1993.

effort at "smoothing" the data to capture the true trend in the rate of water-loss during the LTFT. (This is a very noisy plot because it represents the *difference* in two much larger numbers—the rate of injected flow minus the rate of produced flow.) However, one observation is paramount: The rate of water loss steadily declined over this one-year period of time, strongly suggesting that the Phase II reservoir was stable and not growing, even at the very high injection pressure of 27.3 MPa—17.3 MPa above the least principal earth stress. As an aside, the only recorded period of reservoir seismic activity, as discussed previously, was near the end of "Interim Flow Testing" between the two phases of the LTFT, when high reservoir pressure levels were being reestablished.

Table I (above) presents the water loss data for the LTFT in a somewhat different form than that given in Figure 5. As listed in Table I, the water loss data for the LTFT were averaged for the last 8 days of Phase 1 and the last 3 days of Phase 2. In this presentation, it is seen that the reservoir water loss declined from 12.5 gpm at the end of Phase 1 to 7.3 gpm at the end of Phase 2. In summary, the data from the LTFT show that the rate of water loss declined during testing under "steady-state" conditions, and suggest that the rate of water loss would have continued to decline with further testing.

This temporal variation in the rate of water loss during the LTFT is in stark contrast to that observed during the initial flow testing of the Phase II reservoir in 1986 (Dash et al, 1986). During the last half of this brief 30-day flow test, at an injection pressure of about 31.2 MPa (4500 psi), the rate of water loss appeared to level off at about 28% of the injected flow rate, indicative of pronounced reservoir growth. This growth was accompanied by high levels of seismic activity as evidenced by the large number of microseismic events represented by the large dots in Figure 3. As subsequently determined (Brown and Fehler, 1990), the majority of this apparent water loss was not actually being lost from the boundaries of the reservoir, but was instead going into continuing fluid storage within the newly fractured (i.e., joint-dilated) and extending reservoir region to the south of the injection well.

THE STATE OF STRESS IN THE PHASE II RESERVOIR

Information concerning the state of stress in the Phase II reservoir region at Fenton Hill has already been discussed to some extent above in the section titled "The Physiographic and Structural Setting of the Fenton Hill HDR Test Site." Additional information is provided in Brown (1989), Fehler (1991), and Phillips et al. (1997). The consensus from these three references is that in this extensional, normal-faulting region, the maximum principal stress is vertical and equal to the weight of the overburden, and the least principal stress is horizontal. The orientation of the least principal stress is shown in Figure 2 as reported by Phillips et al. (1997) [corrected from the direction shown in Brown (1995).] As shown in this figure, the indicated direction of the least principal stress now correlates very well with the roughly north-south trend of the seismically determined Phase II reservoir region—a very good corroboration of this stress direction.

Finally, the magnitude of the minimum earth stress at the depth of the Phase II reservoir at Fenton Hill (3460 m) must be addressed. For the present discussion, the main issue is the boundary stress situation that actively precludes fracture extension, even in the presence of a very significant pressure gradient from the very high internal pressure of near 27 MPa, to the far field with a subhydrostatic pore pressure (measured as 5.5 MPa subhydrostatic at shallower depths) and a minimum earth stress of about 10 MPa. This is the critical issue as regards reservoir stability, because it is this anomalous stability which needs to be understood.

As pointed out in Brown (1989), the minimum earth stress is a very elusive quantity to determine when one is pressurizing a highly jointed rockmass such as that existing in the deep Precambrian environment at Fenton Hill. The determination of the minimum earth stress using the hydraulic fracturing stress measurement technique can result in serious errors (on the high side) when there are several pre-existing joint sets and the most-favorably-oriented joints (those with the minimum closure stress) are not continuous. Fluid trapped in these open, but non-continuous, joints would only be accessible to the borehole through highly impeded, but continuous, manifolding joints with higher opening pressures.

Figure 6 illustrates a manifestation of this phenomenon. Following a major hydraulic fracturing test that preceded the massive hydraulic fracturing (MHF) test in December 1983 (referred to in Figure 2), the reservoir was vented for a period of three months and then shut in for the next 3 months (from early July through late September 1983). During this time, the fluid stored within the reservoir self-pumped the wellbore to a pressure of almost 9 MPa. If the pressure buildup curve shown in Figure 6 were to be extrapolated to infinite time using the so-called Muskat (1937) technique, this shut-in pressure would have reached about 10 MPa, very close to the measured minimum earth stress in the overlying Phase I reservoir (Dash and Murphy, 1988). The strong inference is that there must have been a large and pervasive source of "locked-in" fluid, at a pressure level of about 10 MPa, existing within the Phase II reservoir region almost a year after the 2-day injection test referred to as Experiment 2020. This would indicate that 10 MPa is very close to the minimum earth stress in the Phase II reservoir as well.

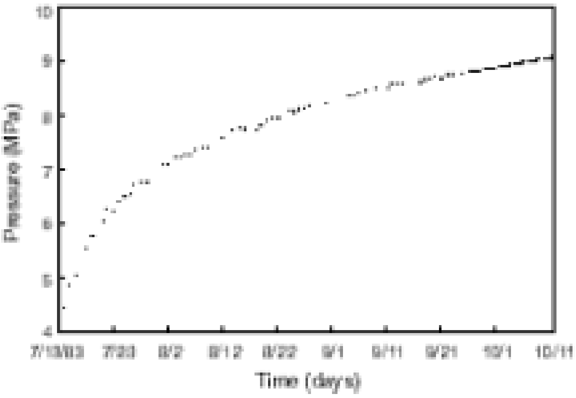

Fig. 6: Phase II reservoir pressure build-up following Experiment 2020 (performed in October 1982).

Obviously, the measurement of the least principal earth stress *within* the reservoir would be distorted by the actual pressurization and accompanying shear dilation that would inevitably occur within such a confined region of the earth. House and Jenson (1987) have suggested, from fault plane solutions determined from the most significant microearthquakes that were recorded on the surface seismic network during the MHF test, that the stress regime *within* the fractured reservoir was considerably modified as a result of the pressurization itself.

FUTURE WORK

The uncertainties in the HDR reservoir boundary stress situation discussed above would suggest that a modeling effort in association with further study of the seismic data obtained during the formation of the initial deep HDR reservoir at Fenton Hill in late 1983 could shed light on the principal unresolved issue in this study—how can a highly fluid-pressurized region of the earth exist stably at such an elevated pressure?

CONCLUSIONS

Experimental results obtained during 6 years of pressure and flow testing of an HDR reservoir formed within a large region of deep Precambrian basement rock suggest that such regions of pressurized and fractured rock could be created in other geologic settings where tight, jointed crystalline rock exists at depth.

The evidence presented for the existence of a *stable* but highly fluid-pressurized region of jointed rock at a depth of 3.6 km beneath the Fenton Hill HDR test site is substantial. The data strongly suggest that such a region can be maintained in a stable condition; that is, without any growth by fracture extension at the margins of the fractured and pressurized region. However, the mechanics of the joint-terminated reservoir boundary region which allows such a stable containment under very large pressure gradients is not yet understood.

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