Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

memorandum

TO: MARP Committee

FROM: Michael C. Fehler *mf*

SYMBOL: ESS-4/84/279

SUBJECT: MARP REPORT

DATE: July 26, 1984

MAIL STOP/TELEPHONE: J979/7-1925

This report is written using notes provided by Kei Aki, my own notes taken during the panel discussion, the notes taken by Francis Appert during the panel discussion, and my own recollection of the mood of the committee.

Five specific issues were selected for discussion. For each issue there was extensive discussion among panel members and Los Alamos investigators. The culmination of the discussion of each issue was a set of recommendations by the committee on how to address the issue. The five issues raised were:

- 1) Determining the best method to locate microseismic events induced by hydraulic fracturing.
- 2) What is the seismic source for the microearthquakes? Are they seismic shear events, seismic tensile events, compensated linear vector dipole events, or aseismic shear, tensile events?
- 3) Does injected water create a single tensile fracture or multiple fractures?
- 4) What determines the orientation of the fractures?
- 5) What should be chosen as the target for the next redrilling campaign?

Discussion of Issue Number 1 - Mapping Methods: The methods that are currently in use to locate microearthquakes caused by hydraulic fracturing at Fenton Hill are the hodogram method and the travel time method, which is used on data collected by both the Precambrian and surface networks. The hodogram method uses the difference between S and P wave travel times to obtain the distance to a station and the particle motion in three dimensions to determine the direction to the event. A multiple station hodogram technique has been attempted, but, so far, only the travel times to the second station have been used. The committee felt that the travel time method is superior to the hodogram technique for locating earthquakes because there is less uncertainty in the travel time method; it is less effected by rock heterogeneity and instrumentation coupling problems. The networks also provide data for determining fault plane solutions and seismic structure of the reservoir. One recommendation to improve the travel time determined microearthquake locations was to install a vertical array of multiple geophone tools in one or more boreholes to improve signal to noise as well as to measure phase velocity and thus determine direction of approach of the waves from the microearthquakes. Another Precambrian network station located to the west of Fenton Hill was recommended to help remove the perceived poor east-west control on epicenter determination. The committee recommended that the trade off between adding new stations at the surface and drilling a hole for another Precambrian network station be studied by calculating the covariance matrix for various array geometries. In this way the cost-benefit ratio can be estimated and the best combination of new stations chosen. More surface stations may help improve the determination of locations of microearthquakes and aid in better constraining fault plane solutions. The possible bias in event selection using the current Biomation digitizing scheme should be removed. Travel time corrections to both the Precambrian and Surface network stations should be determined by using large calibration shots placed in the wellbore. Simultaneous inversion for earthquake locations was recommended as a way to improve the reliability of the determined locations. It is not reasonable to attempt to determine locations to an

accuracy of better than 10 m since that is the source radius of typical microearthquakes occurring at Fenton Hill.

The committee realized that the hodogram method for locating microearthquakes is an integral part of the Hot Dry Rock project and that it may be the only means by which locations can be determined when a commercial reservoir is being created at some location other than Fenton Hill. At such locations it is quite likely that only one well would be available for seismic monitoring, so only the hodogram method could be used. Several recommendations were made for improving upon the hodogram method. One suggestion was that the stability of the particle motion could be improved and the length of time from which particle motion could be determined could be increased if data were filtered with a low pass filter prior to determining particle motion. Better understanding of the geophone coupling problem is essential in order to increase confidence in the hodogram determined locations. Experiments using explosives and/or air guns should be carried out in order to study the coupling problem. Improvements in tool design may help to improve the geophone coupling. S wave particle motion may be used as an additional constraint in the hodogram method and its use should be explored. A more systematic method should be developed to incorporate the hodogram and travel time methods into one simultaneous inversion to determine the location that is most consistent with all available data.

Discussion of Issue Number 2 - Seismic Source: It is clear from the fault plane solutions of events that shear events are occurring. All of the events share a nearly common tension axis which is roughly perpendicular to the plane of the seismic cluster. One major question is whether or not all events are shear or whether tensile fracturing or events with compensated linear vector dipole mechanism, as seen at Mammoth Lakes and attributed to magma intrusion, are occurring. Ernie Majer reported clear observations of tensile events during the early

phase of some hydraulic fracturing tests that he has monitored. Comparing estimates of the seismic source area, which is the area of the largest plane onto which all events may be projected, with the injected water volume leads to an estimate of the crack opening of 20 to 50 mm. Comparing estimates of the seismic source area with the total seismic moment of all events gives an estimate of the average shear slip along the fault plane to be 0.3 mm, which is 1% of the crack opening. One conclusion that was supported by many committee members is that the seismic events are caused by shear slip on a pre-existing fault plane due to the increase of pore pressure transmitted through tensile cracks that opened aseismically. The tectonic stress that controls the orientation of the tensile crack and the orientation of the seismic plane also controls the tension axis of the shear events. The shear events accomodate only a minor portion (1%) of the volume of injected water. The tensile fracturing dominates. Shear events are important because they provide the most direct observation of where the tensile fracture has propagated. A suggestion was made to study the spatial and temporal relationship between the events in an attempt to better understand what causes them to occur. The committee recommended that seismic data collected during the early phases of fracturing experiments be studied carefully for the occurrence of long period type seismic events or tremor which may indicate tensile fracturing that preceeds shear failure. Since seismic monitoring capability at Fenton Hill is greatly improved over what it was when fracturing experiments began, it would be most useful to conduct a careful monitoring campaign of a hydraulic fracturing experiment in virgin rock. Bob Pine made a strong recommendation that more reservoir engineering studies be carried out to complement the seismic analysis.

Discussion of Issue Number 3 - Single or Multiple Fractures: The most striking observation about the locations of microseismic events is that a nearly planar seismic zone appears, using Precambrian mapped events,

during experiment 2042. The 2032 seismic zone is also nearly planar. In order to further investigate these zones and as an aid in choosing a redrilling target, the committee recommended that active cross-hole experiments be carried out. Since it may not be possible to carry out cross-hole experiments, a minimum experiment should be to conduct a single well experiment where full waveforms are recorded. Full waveforms may contain reflections which can be used to infer where an open fracture exists and what are the characteristics of the fracture. A cross wellbore experiment could be used to create a tomographic image of the reservoir as well as to study scattering and conversions due to fractures. Simultaneous determination of earthquake epicenters and reservoir velocity structure should be attempted to find reservoir velocity structure to detect fracture inflation and long period seismic measurements to measure tremor should be investigated.

Discussion of Issue Number 4 - Orientation of Fractures: The seismic zones created during experiments 2032 and 2042 are roughly parallel and are nearly parallel to the injection wells. The fractures trend roughly north-south and dip to the east. The fractures created in the phase I system, which is shallower than the current system, were believed to trend roughly north-south and be vertical. These trends in the seismic pattern are consistent with the possibility that the fracture orientation is controlled by the orientation of cooling joints due to the magma body that underlays the Valles Caldera. These joints should be vertical at the surface and dip in towards the Caldera. In order to better understand this hypothesis, a more quantitative understanding of the regional tectonic setting at Fenton Hill is needed. As an aid to obtaining a better tectonic model more focal mechanisms of regional events and those induced by hydraulic fracturing should be made. A dense seismic network should be installed in the Valles Caldera and vicinity in order to collect arrival time data for use in a three dimensional

study of the velocity structure below the Caldera.

Discussion of Issue Number 5 - Drilling Target: It has already been noted that the large fractures created during experiments 2032 and 2042 are roughly parallel to the holes EE-2 and EE-3, respectively. In order to intersect these fractures, it is necessary to have a well which is not parallel to the existing wells. The committee felt that many points in the seismically active region should be probed during redrilling. A number of redrilling paths were discussed and the only path with strong committee support (3 members in favor, 3 neutral) was a vertical hole beginning from the surface and intersecting the plane of seismicity generated during experiment 2042. If possible, the hole should also intersect the 2032 seismic source region.

MCF:nr

Xc: John Whetten, D446

Don Brown, J979

ESS-4 File

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Cambridge, Massachusetts 02139

DEPARTMENT OF EARTH, ATMOSPHERIC, AND PLANETARY SCIENCES
(617) 253-3381 Telex: 92 1473

*From Gay through
Mile*

July 17, 1984

Dr. Gregory J. Nunz
HDR Project Manager
Planning and Administration
Los Alamos National Laboratory
Los Alamos NM 87545

Dear Greg:

Thank you for your kind letter about my contribution to the HDR Microseismic Analysis Review Panel session at Los Alamos. I really enjoyed participating in the discussions which were scientifically stimulating and productive.

I was very pleased to hear the presentation by the LANL staff who applied most applicable up-to-date seismological methods to the Fenton Hill microseismicity in an extensive and thorough manner so that several significant conclusions can be drawn from the analysis of data. I think this is a model case in which scientists and engineers are communicating and cooperating with promising products useful to society.

The most important question the panel addressed was "What are those microseismic events?" The panel agreed on the following observations: 1) they are shear events because they showed clear double couple fault plane solutions; 2) they share a common tensional axis which is normal to the plane of seismic hypocenters; and 3) their cumulative moment amounted to negligible total shear slip as compared to the total tensile opening estimated from the injected fluid.

From these observations, we concluded that the tensile openings which accommodated the fluid flow were largely aseismic. This conclusion was supported by the remarkable observation reported by Bob Pine that the pumping of viscous fluid did not generate microseismicity, but that of water did.

My personal view of the microseismic events, then, is as follows: they are shear events on pre-existing joints due to pre-existing tectonic stress stimulated by the decrease in the effective stress due to the increase in the pore pressure transmitted through the aseismically opened tensile crack. normal

There were a couple of mild dissenters among the panelists about this somewhat over-simplified view, not from the seismological but from the hydrological viewpoints.

The next question was the geometrical properties of this aseismically opened tensile crack. Is it a single large smooth crack or multiple small cracks connected by joints? Hugh Murphy presented cartoons of two such crack-systems in the introduction to the LANL presentation.

I strongly felt that active experiments such as the shear-shadowing or dual-hole experiments conducted during the Phase I (GT-2, EE-1) experiment would be useful for delineating the geometry of the crack system.

Another important question raised in the panel discussion is "What determines the orientation of the tensile crack?" The apparent agreement of the inferred tension axis with that of the cooling joints for the hypothesized magma chamber under the Jamez caldera justifies a major effort on an extensive seismological study of the detailed 3-D structure of the Jamez caldera including the deeper background structure of the Jamez lineament as well as the Rio Grande rift. Various tomographic techniques are available using both natural (local earthquake and teleseismic) and artificial sources. In particular, seismic experiments with receivers at the bottom of EE-2 and EE-3 and seismic sources at the caldera rim across the caldera from Fenton Hill may provide crucial evidence for the existence of a magma chamber.

Active sources such as explosives set up around the entire caldera rim would generate very important seismic data. I would be very interested in participating in such experiments.

Such active experiments, if carried out under both pressurized and unpressurized conditions of the injection well, may also resolve the question about the geometry of the tensile crack system raised earlier. In any case, the next step in HDR research at the Fenton Hill is to define the aseismically-opened tensile crack system, using some active seismic experiments.

Sincerely,

Keiiti Aki

cc: Dr. J.E. Rannels

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James E. Rannels
Geothermal and Hydropower
Technologies Division
Conservation and Renewable Energy
Department of Energy
Washington, D.C. 20585

Dear Mr. Rannels:

Enclosed is a preliminary summary of some ideas and recommendations for HDR seismology. Please excuse the computer printout, due to our reduced staff during summer vacation.

I hope that I will be able to visit Los Alamos again for about 4 weeks next year to realize some of the recommendations together with H. Keppler and to discuss the results of my theoretical investigations of wave radiation and waveform inversion with the HDR staff at Los Alamos.

Sincerely,

Dieter Seidl

(Dr. Dieter Seidl)

HOT-DRY-ROCK SEISMOLOGY

Current seismological research activities on the hydraulic fracturing experiments at Falkenberg (FRG, Bavaria) and some recommendations for HDR seismology at Fenton Hill in connection with the Microseismic Analysis Review Panel, held at Los Alamos from June 25 through June 27, 1984.

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1. SEISMOLOGY, DATA ACQUISITION AND PROCESSING
 - 1.1 Seismometer on-site calibration

A calibration test should be performed during a fracturing experiment to check the constancy of the geophone transfer functions. The quickest method is the measurement of the impulse response injecting a short current impulse through an auxiliary coil or a balanced impedance bridge.
 - 1.2 Borehole coupling

Systematic experiments performed by G. Leydecker at Falkenberg have demonstrated the significance of borehole coupling for hodogram location and waveform inversion. In general, for a 3-component geophone, borehole coupling can be described in frequency domain by three complex transfer functions depending on frequency, azimuth and angle of incidence. The functions can be determined by recording the signals of detonators fired in a distant

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borehole in different depths with a geophone tool at various orientations and correcting for the medium and geophone transfer functions.

1.3 Digital data acquisition and processing

1.3.1 Spectral analysis of hydraulic noise

In the case of volcanic tremors much information about the number and the type of sources can be derived from the tremor power spectra estimated for different time-window lengths. Perhaps some kind of stochastic hydraulic tremors also exists resulting from the superposition of many weak signals caused by a more or less continuous series of small-scale shear and tensile cracks between the observed larger episodic microearthquakes.

Problems:

- Estimation of noise power spectra for the unpressurized case.
- Continuous digital recording of the hydraulic noise and the events (especially during the initial stage of pressurization)
- Estimation of hydraulic noise spectra for different time-window lengths. The short-time spectra can be estimated using adaptive spectral analysis methods (for example maximum entropy spectral analysis).

1.3.2 Restoration of microearthquake seismograms

Determination of true ground velocity $v(t)$ and ground displacement $u(t)$ for the estimation of pulse energy $e = \int v(t) dt \sim E_0$ (E_0 radiated energy) and pulse moment $m = \int u(t) dt \sim M_0$ (M_0 scalar moment) for P- and S-wavelets.

2. KINEMATIC LOCATION TECHNIQUES

2.1 Improvement of hodogram method

At the Microseismic Analysis Review Panel a very sophisticated version of the numerical algorithm of the hodogram method and its implementation in an interactive analysis program was presented. The following extensions are recommended to increase the location accuracy and to estimate the location error:

2.1.1 Data prefiltering

Using a Butterworth low-pass filter (rejection of high-frequency scattered energy) and a REMODE polarization filter (enhancement of linearly polarized P- or SV-wave energy) see for example: E.R. KANASEW, Time Sequence Analysis in Geophysics, The University of Alberta Press, 1981) the time window length for hodogram analysis can be extended. In this way a segment of the P-wave group with higher signal-to-ratio can be analyzed, probably resulting in a more stable polarization vector. In addition, the time duration of the P- and S-wave group can be estimated (for spectral analysis, time-domain scalar moment and energy determination).

2.1.2 Error analysis

The errors of the hodogram location technique due to the orientation and the transfer functions of the three geophone components as well as due to geophone-borehole coupling can be estimated best by numerical simulation. The synthetic seismograms of a 3-component geophone tool with variable orientation, transfer and coupling functions are computed for an input pulse $u(t) * \vec{n}$ ($\vec{n}$ polarization vector), superimposed with synthetic noise and analysed using the hodogram method. From the partial derivatives of the polarization direction with respect to various parameters (angles of orientation, geophone parameters: free periods, damping factors, generator constants; coupling parameters) some basic questions can be answered about the part of the location error which can be technically controlled to some degree:

- How accurately must the geophone tool be oriented and calibrated for a desired directional resolution or location accuracy?
- Is it necessary to correct for the different transfer functions of the horizontal and vertical geophones?
- What are the limits of the location accuracy for a given

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- source-geophone configuration due to technical limitations in orientation and calibration?
- d. What is the error due to a complex borehole-coupling transfer function as was observed in systematic coupling experiments at Falkenberg (G.Leydecker, personal communication)?
- e. Can the systematic pattern of location shift vectors between hodogram and arrival time locations observed at Fenton Hill be explained by a Falkenberg-like borehole coupling function?

2.1.3 Geophone-borehole coupling equalization

If it is not possible to match the transfer functions of the 3-component geophone tool within the limits derived by the error analysis in 2.1.2 and/or if the borehole coupling cannot be neglected a correction for the geophone-borehole coupling over-all transfer function $T=CTZ(f), TN(f), TE(f)$ must be performed. Probably T has the form $T=(AZ, AN, AE)*F(f)$ and the hodogram correction is simply a division. If the frequency dependent part of T is not the same for the three geophones, a recursive time-domain equalization for the hodogram method and a frequency-domain FFT-method for the waveform inversion is recommended.

2.1.4 Remarks

- a. Can the S-polarization be used as an additional constraint for the hodogram method (applying a RENODE polarization filter)?
- b. Plot of Wadati-diagrams for successive time intervals can be used to check the constancy of the VP/VS-ratio during a pumping experiment.

3. WAVE RADIATION AND WAVEFORM INVERSION

3.1 Wave radiation from shear and tensile cracks

- 3.1.1 Computation of radiation patterns and theoretical seismograms for shear and tensile crack models
- 3.1.2 Computation of radiated energy and seismic efficiency for shear and tensile cracks with given moment tensors
- 3.1.3 Definition of crack-magnitudes using the P- and S-pulse energies
- 3.1.4 Theoretical relationships between rise time, rupture time, energy and scalar moment for different models of shear and tensile cracks

3.2 Waveform inversion

Development of algorithms and programs for the estimation of source parameters by the inversion of waveform data from a single 3-component geophone and a vertical geophone array, respectively. Problems:

- a. Estimation of pulse moment, pulse energy and corner frequency.
- b. Recovery of the moment tensor from waveform data.
- c. Estimation of scalar moment and radiated energy from pulse moment and pulse energy of P- and S-wave groups, respectively.
- d. Estimation of source dimensions from corner frequencies.
- e. Estimation of crack magnitudes.
- f. Interpretation of the empirical relationships involving scalar moment, radiated energy, crack magnitude and source dimension on the basis of the theoretical results from 3.1.4.

4. STATISTICAL ANALYSIS OF SEISMIC CLOUDS

4.1 Poisson test

Are the microearthquakes observed in a fracturing experiment statistically independent or does a compound probability caused by a migrating stress field exist? A simple Poisson test for the time intervals between the events may answer this question and provide important constraints for dynamic models of the crack system.

c. Can the systematic differences between the hodogram and arrival time locations observed at Fenton Hill be explained by a Falkenberg-like borehole coupling function?

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If it is not possible to match the transfer functions of the 3-component geophone tool within the limits derived by the error analysis in 2.1.2 and/or if the borehole coupling cannot be neglected a correction for the geophone-borehole coupling over-all transfer function $T = (T_Z(f), T_N(f), T_E(f))$ must be performed. Probably T has the form $T = (A_Z, A_N, A_E) \cdot F(f)$ and the hodogram correction is simply a division. If the frequency dependent part of T is not the same for the three geophones, a recursive time-domain equalization for the hodogram method and a frequency-domain FFT-method for the waveform inversion is recommended.

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- a. Can the S-polarization be used as an additional constraint for the hodogram method (applying a RENODE polarization filter)?
- b. Plot of Wadati-diagrams for successive time intervals can be used to check the constancy of the VP/VS-ratio during a pumping pumping experiment.

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4. STATISTICAL ANALYSIS OF SEISMIC CLOUDS

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4.2 Cluster analysis

Clustering in space and time is a common phenomenon in ensembles

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of statistically independent events because the Poisson probability increases with decreasing interval lengths. Cluster analysis provides a method to separate statistical from structural clusters. Application of cluster analysis to microseismic clouds may be useful if the location accuracy can be increased to about $\pm 20\text{m}$ and the hypocenters are weighted according to the location errors.

4.3 Pattern recognition

Pattern recognition can be used to classify the microearthquake waveforms into several classes. This may be of interest for interactive or fully automatic processing of selected classes of waveforms extracted from the large volume of seismic data by their characteristic pattern features.

CAMBORNE SCHOOL OF MINES
GEO THERMAL ENERGY PROJECT

Rosemanowes Quarry, Herniss, Penryn, Cornwall TR10 9DU
Telephone: Stithians (0209) 860141
Telex 45591 HOTROK G

23 July 1984

Dr Hugh Murphy
Los Alamos National Laboratory
Mail Stop J979
Los Alamos
New Mexico 87545

Dear Hugh

REVIEW OF MARP MEETING

Thank you for the copies of papers you sent on 3 July. I have reviewed these and the memo on test 2032 and along with my notes from the MARP meeting have produced an internal memo comparing the results of LANL test 2032 and our own 2046.

I enclose a copy of the memo, which can be regarded as a preliminary version of my minority report on the MARP. I propose to send you a proper version when I have reviewed Professor Aki's majority report.

Regards

R J PINE
Geotechnical Consultant

RJP/SMB/317/03/00

Enc

cc. Dr Gregory J Nunz (LANL HDR Project Manager)
(Thanks for your letter of 6 July).

Mr James E Rannels (US DOE, Washington)
(Thanks for your letter of 9 July).

NOTES TO ACCOMPANY MEMO OF 10 JULY 1984 - COMPARISON OF RT2046 AND LANL TEST 2032.

I have now read the Aarnodt and Kuriyagawa paper in detail and I am fairly happy with the approach. It certainly seems to work in practice.

I have continued to model the RT2046 injections with FRIP. With the ambient in situ stress and jointing conditions as we believe them to be, using water as the injection fluid (low viscosity) I have not yet seen any jacking dilations, but some very significant shear displacements.

As we have noted before this is partly due to the relative freedom of blocks to move in the regular joint network. To partly overcome this I have used some glued joint patterns, which do restrict shearing and allow pressures to build. I haven't yet got to the stage where the pressures are sufficient to cause straightforward jacking. However large secondary joint dilations (> 1 mm) have occurred similar to those seen by HDM (Ref 1) and RJP (Ref 2).

In the glued joint model with a fracture 80 m long attached to the well, relative shear displacements of > 10 mm have occurred.

This modelling is still rather preliminary. I need to vary quite a few parameters yet before coming to any firm conclusions.

RJP
23 July 1984

REFERENCES

- 1 MURPHY H D. "Modelling hydraulic fracturing in jointed rock; preliminary FRIP results". CSM internal memo ref 13/04/01, Dec 1982, 34 pp.
- 2 PINE R J. "Pressure transient analysis for large scale hydraulic injections in the Carnmenellis Granite, England". Proc. 9th Workshop, Geoth. Res. Eng., Stanford Univ. Dec 1983. 9 pp.

INTERNAL MEMORANDUM

From R J Pine
To ASB, PL, KK
Date 10 July 1984

RJP/SMB/317/03/00

COMPARISON OF RT2046 AND LANL TEST 2032

SUMMARY

There are several similarities between the hydraulic and microseismic results of the major injections at Rosemanowes (test RT2046) and Fenton Hill (test 2032).

In both cases it is necessary to postulate jacking dilations in order to accommodate the initially high flow rates and the observed pressure time behaviour. Such dilations require higher fluid pressures than the accompanying shears detected by the microseismic networks. It is therefore inferred that the dilated planes were contained within the microseismic envelopes.

When the fluid pressures decrease due to venting or diffusion the dilations will tend to decrease. The residual apertures will depend on the degree of mismatch (by shear) or debris blocking (jacking only).

There have been no satisfactory measurements direct, or indirect of the residual apertures. By inference the transient tests following RT2046 indicated significant fracture extent near the wellbore, as did the efficient venting of LANL test 2032.

The best targets for future drilling appear to be towards the edges of the microseismic clouds developed during the first 2-3 days of RT2046 and LANL 2032. In the latter case the microseismic cloud resulting from injection 2042 into hole EE3 might also be a target, but this has not been considered here due to lack of available hydraulic data.

1 INTRODUCTION

Following my attendance at the LANL MARP on June 25-27. I had a brief discussion with Hugh Murphy where we agreed that the hydraulic data for their tests 2032 and 2042 needed to be looked at carefully to assist with defining their redrilling target(s). (This followed on from 3 days devoted almost exclusively to microseismic interpretations of the same tests).

He gave me a copy of his memo of 26 March 1984 "Experiment 2032 report" (Ref 1). While reviewing it, I was struck by some similarities between test 2032 and our own RT2046. In this memo I attempt to show the similarities and differences between the tests and discuss the implications of the results with regard to possible drilling targets. Some suggestions for further tests are made. Some of the ideas are certainly not new but worth exhuming!

Incidentally, since we have shown that very little change in our system impedance occurred subsequent to the first steady state test after RT2046, this emphasises the importance of trying to understand the net effect of this type of (high flowrate, large volume) injection test.

2 BASIC TEST FIGURES

The test data are compared in Table 1.

In both cases the main tests had been preceded by preliminary tests. For the CSM tests, previous injections into hole RH12 had totalled about 2000 m³. At LANL, previous injections into hole EE2 through the same open hole interval as for test 2032 totalled about 4000 m³ (1 070 000 US gallons).

The pressure and flow rate vs time data for the two main tests are shown in Figs 1 and 2.

TABLE 1 - COMPARISON OF BASIC TEST DATA

Item	RT2046	LANL 2032
Injection hole	RH12	EE2
Mean vertical depth of injection zone (m)	1750	3540
Open hole length (m)	357	20 (but sanded up hole below)
Sustained peak injection rate (l/s)	90	105 (40 bbl/min)
Duration of peak rate (hrs)	38	56
Volume injected at peak rate (m ³)	12 300	21 200
Total volume for complete test (m ³)	18 500	22 000
Mean wellhead pressure (MPa) during peak flow rate	13.5	48.3
Mean downhole pressure (MPa)	31	80 (Note friction loss significant)

3 MICROSEISMIC DATA

It can be seen from Fig 1 that events were detected almost immediately at the beginning of RT2046. I do not have an equivalent plot for LANL 2032 but it was stated at the MARP that events were not detected for 8 hours. Because of the distinctions between detection and location I'm not sure if the event rates were comparable. Certainly we are talking of total locations of many hundreds in both cases. Microseismic details for the LANL tests 2032 and 2042 were summarised in my trip report for the MARP meeting (Ref 2).

The locations for events during the complete RT2046 injections are shown in Figs 3 and 4. Similar data for the LANL 2032 are shown in figures

5-7. In both cases the stimulated region appears volumetric rather than planar. Comparative volumes and areas for 90% of locations are approximately as follows:

TABLE 2 - COMPARISON OF SEISMIC VOLUMES AND AREAS

ITEM	RT 2046	LANL 2032
Minimum dimension, a (m)	200-300 (Fig 3)	300-400 (Fig 6)
Maximum dimension, b (m)	500-700 (Fig 4)	900-1000 (Fig 7)
Intermediate dimension, c (m)	400-500 (figs 3 & 4)	700-800 (Fig 6)
Maximum elliptical area $\pi bc/4$ (m ²)	200 000 (fig 4)	550 000
Maximum ellipsoidal volume, $\pi abc/6$ (m ³)	35 million	130 million

It is interesting to note that the much smaller open hole length for LANL 2032 did not result in any more focussed microseismics than in RT 2046. This tends to suggest that once the water gets a small distance away from the borehole, the natural rock structure takes over and the open hole length of the injection well is therefore irrelevant (within limits). However, there may be other unfathomable factors at work here (accuracy of seismic locations?).

The growth in size of the RT 2046 microseismic envelope was progressive but with more rapid growth in dimensions earlier on. However the volumetric growth was approximately linear. After 8 hours, events had occurred within about half of the ultimate envelope (Fig 8). Similar results were experienced with LANL 2032 (Ref 2). In both cases it could be inferred that the preceeding injections had pre-stimulated a significant volume. In the LANL case this was to the extent of suppressing events for several hours.

During all the LANL and CSM injections only microseismic events with a shear source mechanism were located. In both cases fault plane solutions were derived which were consistent with shear mechanisms.

4 HYDRAULIC DATA

4.1 Steady pressure and flow conditions (both tests)

The most striking aspect of the hydraulic data in both cases is that very steady wellhead pressures (and therefore downhole pressures) were achieved early on and maintained for long periods.

In Ref 1, HDM et al show fairly convincingly that their steady downhole pressure relates to the concept of a classic hydraulic fracture behaviour, without consideration of leak off (ie all injected fluid goes into normal fractures dilation (or jacking)). We have previously discussed this in relation to pressure flow relationships in RH12 which were sympathetic with jacking at or near σ min (Ref 3).

It can be seen in Figs 9 and 10 that the p vs q relationship for both the CSM and LANL data are similar and imply lift-off type conditions near the maximum in-situ stress value.

The only other simple form of behaviour that gives near constant p and q values is long term spherical diffusion. In this case the steady state condition is given by:

$$\Delta p = \frac{\mu q}{4\pi k a} \quad - (1)$$

which can be rearranged to give

$$k a = \frac{\mu q}{4\pi \Delta p} \quad - (2)$$

Where k = permeability (m^2)
 a = Source radius (m) (k is infinite where radius $< a$)
 μ = Viscosity (Pa sec)
 q = flow rate (m^3/sec)
 Δp = fluid overpressure above hydrostatic (Pa)

For the short timescales involved I assumed that a could be no greater than 100 m. I used μ of 0.5 E-3 and 0.3 E-3 Pa sec and Δp of 14 and 45 MPa for RT2046 and LANL 2032 respectively. The required far field k values were 2.6 and 0.5 md respectively which are far too high. We can conclude that at early time jacking predominates over diffusion.

There are other alternatives for approximately constant pressure and flow conditions including combinations of jacking with leak off, and progressive FRIP type volumetric/areal fracture stimulation. The former still implies the need for large areas of stimulated fracture. The latter is an alternative form of spherical diffusion and still requires untenably high far field k values to match the measured data.

4.2 Fluid balance

4.2.1 LANL 2032

The end of LANL test 2032 injections was caused by the flange failure, and venting occurred immediately. Within 3 days some 54% of the injected fluid had been vented, according to Bob Potter's figures in Ref 1. It is not clear what the ultimate vented recovery would be, but I estimate that 70% or so would be reasonable.

It is evident that at least 50% of the injected water was in good communication with the well at the time of venting, implying storage within fractures of reasonably large apertures. Assuming that fluid had to travel back a mean distance of 500 m under a mean pressure drop of 20 MPa at a mean flow rate of 40 l/sec, under a predominantly laminar flow regime leads to a value for the product w^3l of 3.6 E-6 m^4 . Here w is the average joint aperture and l is the total length of joint normal to the direction of flow. For $l = 1000$ m, w is about 1.5 mm; for $l = 10\,000$ m (multiple planes) w is about 0.7 mm. This is admittedly pretty

gross arm waving and a further complication, of course, is that the aperture is probably decreasing with the depressurisation. However, our old friend the 1 mm size aperture appears yet again.

If 70% of the fluid is recovered what has happened to the 30% left in-situ? There are at least two possibilities:

- i The fluid has been absorbed by essentially 1-D diffusion away from the stimulated joint planes.
- ii The stimulated joints have re-closed as far as they can and are now propped open by debris or shear mismatch and contain the balance.

There could also be some aseismic diffusion from the edges (within the plane of the stimulated joints) and a combination of i and ii.

For a constant pressure planar (1-D) diffusion

$$Q = 4\Delta p A \sqrt{\frac{k\beta t}{\mu\pi}} \quad - (3)$$

Where Q = total flow (m^3)
 A = area of source plane (one side) (m^2)
 β = rock mass compressibility (Pa^{-1})
 t = time for Q to occur (secs)

Other terms are as defined above.

Equation 3 can be rearranged to give:

$$k = \left(\frac{Q}{4\Delta p A} \right)^2 \frac{\mu\pi}{\beta t} \quad - (4)$$

Assuming an average Δp of 20 MPa (declines from about 40 MPa), Q of 6000 m^3 , β of $2.5E-11 Pa^{-1}$, A of 550 000 m^2 , and t of 3 days leads to a required value for k of about $3\mu d$. The value of A was taken from Table 2. If a few multiple planes are present then permeabilities of the order $1\mu d$ are required. I believe that values of the order $1\mu d$ are not unrealistic for the Fenton Hill host rock using the above β value.

(Ref 4 p.40). It appears that planar diffusion is capable of absorbing a large portion of the net injection.

If multiple planes are involved, the fluid is ultimately taken up in a volumetric manner. Using the microseismic volume in Table 2 as a guide, the required porosity is 6000/130 million = 4.5 E-5. In Ref 2 a value of 2E-4 was derived for the 20 000 m³ total injection and the correlation between seismic volume and injected volume was approximately linear.

Although these values of porosity are apparently small, they are still large if attributed to storage within joints. For three sets of equally spaced orthogonal joints the following combinations of spacing, aperture and permeability are implied for the storage of the 6000 m³:

TABLE 3 - Combination of joint spacings and apertures for 4.5 E-5 porosity

Spacings, S (m)	Apertures, w (μm)	Mass permeability, k (md)
0.1	1.5	0.0056
1	15	0.56
10	150	56
20	300	225

The permeabilities were calculated from the laminar flow, aperture cubed rule:

$$k = \frac{2w^3}{12S} \quad - (5)$$

(two joint sets per principal flow direction)

I suspect that the spacings of joints capable of accepting any fluid are towards the higher end of the above range where the implied permeabilities appear far too large.

For a single set of parallel planes with the same joint spacings, the apertures must be a factor of 3 higher leading to even larger implied k values (by a factor of 13.5). This model could apply for the case where the residual 30% is contained in partially reclosed joints.

Because there was no satisfactory connection and circulation these implied permeabilities are difficult to prove or disprove. The available pressure transient data relates to the very active injection period when joint dilation was occurring and when 'permeability' cannot really be assessed separately. By definition the constant pressure-constant flow rate period is not an analysable transient.

4.2.2 RT2046

Similar arguments can be employed to consider the possible effects of the RT2046 injection. Since no venting tests were conducted immediately following this test the primary fracture volume connected to RH12 is less easy to estimate.

However, it has been shown that the system impedance between RH12 and RH11 remained essentially constant for all steady state tests run after RT2046. It is perhaps reasonable to assume that the primary fracture extent of RH12 was similar during RT2046 and the later venting of RH12 during RT2056. In RT2056 a volume of 3750 m³ was vented over 3 days, starting at a wellhead pressure of only 8.2 MPa, declining to 3.3 MPa. The pressure at RH12 during RT2046 was typically about 13.5 MPa, and the minimum earth stress 8-10 MPa above hydrostatic.

The figure of 3750 m³ is probably an underestimate of the primary fracture volume at 13.5 MPa but a reasonable estimate near the minimum earth stress. Again this might be brought up to 5000 m³ or more for the volume to follow after the initial 3750 m³. On the other hand the very large 'diffusive' system attached to RH12 by this time could have exaggerated the primary volume available.

For the purpose of this exercise, if we take an initial RT2046 injection volume of 12 300 m³ (at high flow rate) and a vented volume of 5000 m³ with a seismic area (RT2046) of 200 000 m² we are looking at a scaled down version of LANL 2032 with implied combined fracture apertures of about 60 mm (initially) and 30 mm or less after venting.

Exactly the same arguments apply as in LANL 2032 regarding initial acceptance of water (there must have been some normal joint opening or rock fracture), and the later uncertainty regarding residual joint apertures (self propped volume vs diffusive loss and absorption).

The continuing downward growth of the microseismic zone after RT2046 can be explained by the shearing process operating at fluid pressures of less than that required for jacking (Ref 5).

With the eventually large microseismic envelope and apparently higher far field permeability at Rosemanowes compared with Fenton Hill, there is clearly plenty of scope for absorption of most of the injected fluid, leaving only small accessible volumes within the stimulated joints. However, there may also be more scope for shear displacement during jacking due to the particular combination of in-situ stress and jointing at Rosemanowes (which also gave rise to the downward shear growth).

4.3 Transient test analysis

The main results of the pressure transient analyses reported for LANL 2032 were:

- i Product A $\sqrt{k}$ initially about 31 E-6 m^3 (β assumed to be about 2.5 E-11 Pa^{-1}).
- ii Initial slope of Δp vs Δt consistent with pressurisation of frac string alone ie no significant fracture volume seen. This is reasonable considering the small open hole length. Note that the compressibility of the drillpipe was ignored but this only makes about 10% difference.

(However I'm not entirely convinced that the analyses are correct since the same data appears to have been used from the first 2 minutes of the test to produce both results!; Ref 1 Figs P6 and P4)

- iii Shut-in tests used to determine ISIP. Again I'm not clear how this was done. We need the Aamodt and Kuriyagawa reference quoted in Ref 1. The ISIP's appeared to give reasonable agreement with refrac type fracture opening pressures.

For the early RT2046 pressure transient between Δp of about 1.5 MPa and 6.0 MPa and t up to 5 minutes we also have approximately straight lines for p vs t and p vs $\sqrt{t}$. (See Figs 11 & 12). In the first case the implied elastic volume is about 3000 m³ which is clearly too high unless significant rock compression is occurring. This is unlikely at pressures less than σ_h and I am unable to explain the high compressibility (air in the system?).

The p vs $\sqrt{t}$ line gives an $A\sqrt{k\beta}$ product of $0.7 \text{ E-9 m}^3 \text{ Pa}^{\frac{1}{2}}$. For β of 1E-11 Pa^{-1} (from recent test RT3001) $A\sqrt{k}$ is 2.2 E-4 m^3 . For a permeability k , normal to the implied joint of 10 μd this gives a total joint area (both wings) of about 70 000 m². If full height, this gives a uniform fracture penetration of about 100 m. I'm not sure I believe all this. Note that we had barely started RT2046 at this stage. We did however see comparable $A\sqrt{k\beta}$ values during the earlier tests on RH12.

The pressure time data for the first 3 hours of RT2046 was amenable to log-log and semi-log analysis as radial flow with k of about 6md and of -3.5 (for β of 1E-11 Pa^{-1}). The 6md figure must be exaggerated by the active dilation which conspires to give a pseudo-radial behaviour.

Later pressure transients during RT2046 and subsequent tests gave k values of typically 3-6 md, s values of -3.5 to -6.4, fracture half lengths of up to 130 m and $A\sqrt{k\beta}$ of typically $30 \text{ E-9 m}^3 \text{ Pa}^{\frac{1}{2}}$. The $A\sqrt{k\beta}$ values were obtained during shut-ins and were probably the most reliable guide to primary fracture extent. They are at least 30 times higher than pre-RT2046 values. Estimation of A is difficult because both k and β have probably been modified (increased) by the vigorous injection. It is safe to assume that A has also increased!

My conclusion regarding the RT2046 and LANL 2032 transient test results is that they are not much use in absolute terms because of the joint modifications due to the high pressure and flow rates. They may be of some use in comparisons with other tests on the same well. The implied fracture extent from the transient analysis of RT2046 is less than implied by the microseismic mapping. This could be expected for finite conductivity fractures.

5 CONCLUSIONS

The conclusions can be considered in terms of a hypothetical model applicable to both RT2046 and LANL 2032. The main features of the model are:

- i Most of the high flow rate - high pressure injection goes initially into creating large jacked open plane(s). These may be new fractures or existing joints (no direct evidence either way). The total width of apertures within these planes is of the order 50 mm if they extend throughout the full microseismic volumes, as a single set.
- ii It is unlikely that such planes extend beyond the limits of microseismic cloud since they probably require, higher fluid pressures than necessary to trigger shear events.
- iii It is possible that there is aseismic leakage (at lower fluid pressures) beyond the limits of the envelope within 'pipe' like rather than planar channels. Against this argument is the apparently very low overall permeability of the host rock and the high pressures required to initiate significant flows.
- iv During venting of LANL 2032 about 70% of fluid could return significantly reducing the plane apertures. For host rock permeability of less than $5 \mu d$ it is possible for all the remaining 30% to be absorbed in a few days, resulting in zero net apertures.
- v Similar processes are apparent in RT2046. Because of apparently higher in-situ shear stress and higher far field permeability there is scope for both more residual aperture and more diffusion. A smaller fraction of the injected fluid volume might be expected on immediate venting than in the case of LANL 2032.
- vi It is possible that the absorption is a volumetric process, in that diffusion may occur from several planes throughout the microseismic envelope. However there are problems here with

accounting for the porosity required on the basis of dilated joints at 'reasonable' spacings. To overcome this problem absorption into the rock fabric and/or diffusion beyond the limits of the envelope must be considered.

- vii Upon depressurisation (fluid pressures below minimum in-situ stress magnitude) joints are partly dilated in the short term and more closed in the long term. The degree of residual dilation after reclosure depends on the mismatch of the plane surfaces. If purely tensile rock fracturing occurred in the plane of σ_H there is no theoretical shear displacement. Residual dilation then depends on surface damage. Indirect evidence from the RH11 viscous frac at Rosemanowes indicates that the residual apertures were probably small (no significant difference in hydraulic behaviour before and after the frac).

If stimulation of natural joint(s) occurred then some degree of shear mismatch might be expected due to non alignment of joint planes with principal stress directions. The direct (microseismic) evidence suggests that shear displacements were very small resulting in almost negligible mismatch and residual dilation. Taking a more optimistic view, if natural joints had been dilated by as much as 1 mm or so over distances of several tens of metres, then some significant aseismic shear movement and consequent mismatch seems possible. Some numerical (FRIP type) modelling would be useful in this regard.

- viii Finally, the residual situation after both tests may consist of a joint or fracture plane or several such interconnecting planes. The LANL 2032 and early RT2046 microseismic clouds could therefore contain drilling targets for the next phase of operations. However, the degree of enhanced permeability to be expected in the clouds remains uncertain, and is probably not as large as simple calculations based on injected volumes and seismic areas would indicate.

RJP

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FIGURE 1 HYDRAULIC AND SEISMIC EVENT RATE DATA
RT2046 04/11/82 10:00 - 09/11/82 09:40

Solid line denotes RH12 data
Dashed line denotes RH11 data

5 Day plot

Figure 2 Pressure and flow rate history for MHF. Pressure and flow rate measured at frac string surface.

PLAN VIEW
(VIEW 1)

SCALE 1:10000

OBLIQUE VIEW
(VIEW 2)

SCALE 1:10000

**FIGURE 3: PLAN AND OBLIQUE VIEWS OF MICROSEISMIC EVENTS
LOCATED DURING RT 2046**

SECTION X-X
(VIEW 3)

SCALE 1:10000

SECTION Y-Y
(VIEW 4)

SCALE 1:10000

FIGURE 4 VERTICAL SECTION VIEWS OF MICROSEISMIC EVENTS
LOCATED DURING RT 2046

93 DEC 06, 18:48 - 84 MAY 19, 03:53 MT

Expt. 2042: Seismic source locations, Prog. PPH/E4T, Data: D32/L42/ABC

o Precambrian * Partial double tool Hodogian
 + Single tool Hodogian
 Lighter symbols RTet 203C
 Darker symbols Tet 2021

Figure 5

Figure 6

Figure 7

PLAN VIEW
(VIEW 1)

SCALE 1:10000

SECTION X-X
(VIEW 3)

SCALE 1:10000

FIGURE 8

PLAN AND VERTICAL SECTION OF MICROSEISMIC EVENTS
LOCATED DURING RT 2046 (4-8 HRS)

FIGURE 9 RH12 FLOWRATE vs PRESSURE

* Laminar?

Figure 10. Fracturing Pressure vs Injection Rate - Turbulent Flow Interpretation.

FIGURE II RT2046: EARLY TIME P v T PLOT

FIGURE 12 RT2046: EARLY TIME SQUARE ROOT PLOT