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OFFICE MEMORANDUM

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FROM Randy Laney/A. W. Laughlin

SUBJECT GEOLOGY OF THE PHASE II SYSTEM

SYMBOL G-4

MAIL STOP 983

Attached is a report on the analysis of EE-2 cuttings and thin sections, geologic characterization of the Phase II system, comparison with Phase I, and geologic speculations and recommendations concerning Phase II. The EE-2 litholog has been included in the pocket.

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Introduction

Cuttings analysis has been completed for the lower portion of the EE-2 wellbore and a preliminary geologic evaluation of the reservoir rock for the Phase II system can now be made. As opposed to the single lithology Phase I reservoir (GT-2, EE-1), the much more extensive Phase II reservoir (EE-2, EE-3) encompasses a wide variety of rock types. The different rock types in this reservoir imply variable petro-physical properties including thermal conductivity, permeability, porosity, heat capacity, and density. As these properties effectively control factors such as the rate of thermal drawdown and recovery of the HDR geothermal reservoir, it is evident that the Phase II system will involve additional complexities not encountered in Phase I.

On the other hand, due to the contrasting nature of the two reservoirs, the HDR concept can now be tested in two essentially different environments. The Phase I reservoir was developed in a relatively homogeneous rock type; Phase II encompasses both igneous and metamorphic rock types with a wide range of compositions (locally the metamorphic rocks could be folded and several large faults, and possibly numerous minor ones, cut through this deeper reservoir).

EE-2 Cuttings

Rock cuttings and core retrieved during the drilling of exploratory and development wells in a HDR prospect area represent the most important geologic element for the analysis and evaluation of the HDR site. Although coring produces the most reliable data concerning the rock of the reservoir, economic factors severely limit the amount of material that can be cored. In the case of EE-2, the six cores that were retrieved represent only one-half of one percent of the entire reservoir rock. In contrast, cuttings represent a near continuous record of the rock penetrated. Thus the two types of material are complimentary and indispensable.

Although rock cuttings are extremely valuable geologic material, cuttings analysis is fraught with many problems. Certain biases occur during both sampling and recovery and in the analytical phase. For example, rock cuttings become mixed (to an unknown degree) on the way to the surface. For lithologic units of limited vertical extent (0.3 to 1.5 m thickness), this mixing can cause these thin units to effectively "disappear" or blend into the surrounding rock cuttings so that the thin units are not recognized in the cuttings analysis. This has happened in the case of GT-2 and EE-1 where the identity of thin amphibolitic and biotite schist units is masked in the cuttings but the same units are quite apparent on the spectral gamma logs (West and Laughlin, 1976). This is also probably the case in EE-2 where cuttings from relatively thin units have been mixed with rock cuttings from surrounding, more massive units. The mixing process probably becomes more effective, and thus more detrimental to the geologic evaluation, with increasing borehole depth. For geothermal wells with a depth on the order of 4600 m (15,000 ft), units of 3 to 5 m thickness may be missed. In this case, geophysical logging of the borehole is a necessity to better define lithologic boundaries and thicknesses.

Another problem that must be dealt with is analytical bias that occurs when trying to assign a rock type to a cuttings sample. It has been our experience (Laughlin and Eddy, 1977; present work) that minerals such as the feldspars tend to be more finely ground, under the action of tungsten carbide button inserts, than minerals such as quartz and biotite. As grain size is reduced to less than 320 mesh, this "rock flour" tends to be washed away and lost during the sample collection phase. Also during visual examination of the cuttings, it seems the human eye is more aware of the larger grains in the sample and less aware of the very minute grains, even though these smaller grains may be volumetrically more significant. Thus in both sampling and analyzing the cuttings, the volume percent of feldspars will tend to be underestimated and biotite and quartz overestimated. If these factors are not corrected for, erroneous lithologies can easily be assigned to the lithologic column.

We have tried to avoid introducing any unnecessary biases during this study by limiting our cuttings analysis to a certain size fraction of the cuttings material. To aid in the identification, we also ground solid core material to simulate recovered cuttings. We then used these "simulated cuttings" as standards of comparison. The method used will be detailed elsewhere. Overall, we feel we have come up with a satisfactory method for dealing with the EE-2 cuttings.

In brief, rock cuttings from EE-2 were collected by drill site personnel at approximately 3.1 m (10 ft) intervals over the entire wellbore. Individual samples were separately bagged and sent to TA-33 for analysis. Approximately 30 g splits were taken from each sample sack and bottled. The bottled portion was labeled as to the depth interval and the bottle became a permanent part of the cuttings library. The remainder of the sample sack was put into storage. A quick visual and binocular check of the bottled sample was then made for sample color and gross mineralogy. This information was noted on identification sheets which were used to define lithology breaks (i.e., changes in sample color and mineralogy). Representative samples were then taken from each lithologic unit, sieved, and the -60 to +230 fraction examined closely and/or point counted (approximately 200-300 points). If need be, the fraction was compared to previously hand-ground core material. It was usually then possible to assign a rock type to the cuttings sample.

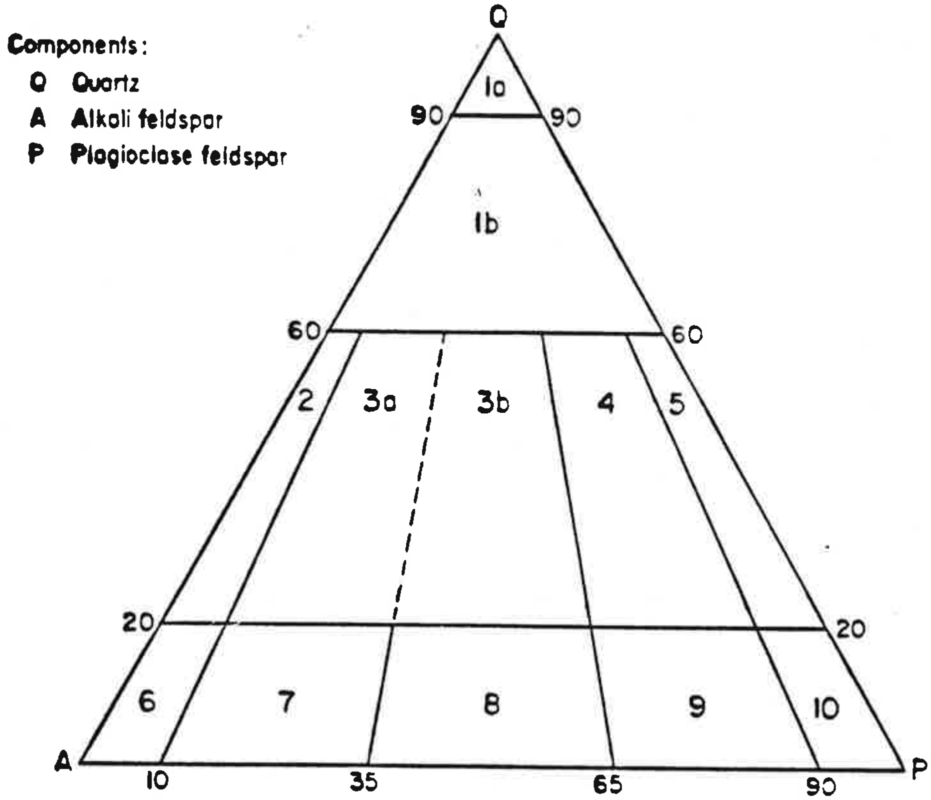
The EE-2 Litholog

The method outlined above was used to construct the lithologic column included in this report as Sheets 1 and 2 (in pocket). Since previous studies (West et al., 1975; Laughlin and Eddy, 1977) had dealt with the geologic characteristics of the Precambrian rocks encountered by GT-2 and EE-1, this study concentrated on the material collected from 2926 to 4660 m (9600 to 15290 ft, along wellbore) in EE-2.

In this report, rock-type nomenclature will adhere to the system proposed by the IUGS Subcommission on the Systematics of Igneous Rocks (Streckeisen, 1973) and followed by Laughlin and Eddy (1977) in their report on GT-2 and EE-1. Figure 1 reproduces the triangular diagram that is used to classify felsic and intermediate plutonic rocks. The apices "Q", "A", and "P" represent, respectively, the modal volume percentages of quartz, alkali feldspar and plagioclase. These percentages are derived from modal analysis (point counting) of thin sections of rocks. The three percentages are recalculated so that Q + A + P = 100.

The first column of the litholog, "Miscellaneous Data and Comments" is self-explanatory. Pertinent data from core recoveries and junk basket recoveries have been included. Ambient temperatures listed for the general vicinity of where core was recovered are taken from a LASL temperature survey completed on August 12, 1980, approximately 94 days after drilling was halted on EE-2. The temperatures listed should be approaching equilibrium values. The statements, "X-ray or chemical data are available" refer to data listed in an Office Memorandum issued by us on August 21, 1980.

The next column, "Drill Cuttings Descriptions" is the lithologic column for the lower section of EE-2. Felsic and intermediate rock types listed follow the IUGS classification system. All lithologic boundaries are indicated by dashed lines, reflecting our uncertainty about these boundaries since they are based solely on cuttings analysis. Successful geophysical logging of EE-2 may allow us to give more definite boundaries to distinct lithologic units.



Key:
- 1a - Quartzolite (silexite)
- 1b - Quartz-rich granitoids
- 2 - Alkali-feldspar granite
- 3a - Syenogranite } Granites
- 3b - Monzogranite } Granites
- 4 - Granodiorite
- 5 - Tonalite
- 6 - Alkali-feldspar syenite
- 7 - Syenite
- 8 - Monzonite
- 9 - Monzodiorite and monzogabbro
- 10 - Anorthosite, gabbro, and diorite

Fig. 1 IUGS diagram for felsic and intermediate plutonic rock nomenclature.

The samples from EE-2 have not been lagged; we have used the depth interval on the sample sack as representing the depth at which the material in the sack was derived. Obviously this can not be the case because a certain amount of time is required for cuttings to travel from the drill bit to the surface. This time interval depends on factors such as variable drilling fluid pump pressures, etc. Therefore, we have left any "lagging" to the discretion of the interested reader. As a general guide however, at approximately 3048 m (10000') cuttings would come to the surface 1.0 to 2.0 hours after drilling commenced, and at around 4267 m (14000') cuttings would return 1.5 to 2.5 hours after the start of drilling. Therefore, given an "average" penetration rate of 4.57 m/hr (15 ft/hour) cuttings will lag behind the actual drilling point by about 4.6 to 12.2 m (15 to 40 ft). Therefore, it is permissible to move any lithologic boundary or unit "up the hole" by a maximum of approximately 12.2 m (40 ft).

We have used a "breccia pattern" to represent the presence of altered material in a sample sack (see our memorandum dated August 21, 1980). The width of the pattern represents the approximate percentage of altered material in the sample. If the sample was 100% altered (full width pattern) we have designated these areas as "fault zones", for want of a better description.

The next column, "Drilling rate" gives the penetration rate in ft/hr for the bottom hole assembly, averaged over every 3.1 m (10 ft) interval. This data is compiled from the drilling recorder charts (Geolographs). Over the interval 2926.1 to 4654.3 m (9600 to 15270 ft) penetration rate varied from a low of 4.4 ft/hr up to 42.9 ft/hr. The average drilling rate was 14.53 ft/hr over 1728.2 m (5670 ft) of Precambrian crystalline rock.

This column also indicates bit type and when bit changes were made. We have included this information to assess whether the condition of the bit or lithology influenced the penetration rate. Generally bit changes were made when the drill string began to "torque up" (rpm decrease and a decrease in drilling rate) indicating the cutting elements of the rock bit had worn out or broke off. The symbol "RR" stands for re-run, indicating use of a previously run bit.

The next two columns give drilling depths measured from the Kelly bushing and calculated true vertical depths. The scale for the true vertical depth column is not linear because we are dealing with a deviated hole. Directional drilling to steadily build up the angle of the borehole was commenced at approximately 2286 m (7500 ft). From a true vertical depth of approximately 3353 m (11000 ft) to total depth, the EE-2 wellbore is deviated approximately 35° from the vertical.

<u>Precambrian Rock Types at Fenton Hill</u>

With the completion of EE-2, we are now at a point where it is possible to make a preliminary geologic assessment of the Phase II reservoir and how it compares with Phase I. In the following discussion we have defined the Phase I reservoir (following Murphy et al., 1980) as that volume of rock occurring between approximately 2621 m (8600 ft) and 2957 m (9700 ft) below the ground surface at Fenton Hill. This HDR reservoir was produced by hydraulic fractures created between the EE-1 and GT-2 boreholes.

The Phase II HDR reservoir will be created by a series of parallel, hydraulic fractures between the EE-2 and EE-3 wellbores. We have tentatively defined Phase II as that volume of rock occurring between a true vertical depth of 3200 m (10500 ft) and 4389 m (14400 ft) below the ground surface at Fenton Hill. Equivalently, the Phase II system will encompass those rock types occurring from 3231 m (10600 ft) to 4460 m (15290 ft) along the EE-2 wellbore. This is based on the premise that a series of fractures approximately 305 to 370 m in diameter (1000-1200 ft) will be created between EE-2 and EE-3, with the uppermost fracture initiated some 60-90 m below the casing point of EE-2. Even if the final hydraulic fracturing pattern is somewhat different from our tentative estimates, the conclusions of this study will not vary significantly.

We have assembled pertinent chemical and mineralogic data available to date on the Precambrian rocks of Fenton Hill (Table 1). These data all refer to rock cored in GT-2 and EE-2 except for the altered material of EE-2. Altered cuttings were used to obtain these two analyses. We have presented the data as volume percentages because according to Sibbitt et al. (1979), these numbers in large part determine the thermal conductivity values of the various rock types. As can be seen, the Precambrian rocks at Fenton Hill are quite variable in composition. For example, the volume percent mafic minerals varies by a factor of 15 comparing the granitic rocks to the mafic rocks.

Figure 2 graphically illustrates the variation in rock types with depth. The QAP triangle "GT-2, 2400-8500 ft" illustrates the variable mineralogy of the Precambrian metamorphic complex at that depth interval. The <u>bulk</u> of the rock types lie within the monzogranite field (field 3b of Fig. 1).

The next QAP diagram labeled "Phase I" represents the rock types encountered in the Phase I reservoir. From cuttings analysis and spectral gamma logging, it is estimated that 90% of the reservoir rock is homogeneous, intrusive igneous granodioritic rock, the remaining 10% is composed of granodiorite gneiss.

Preliminary data on the rocks of EE-2 are plotted on the third QAP triangle. As can be seen, the Phase II reservoir apparently encompasses a wide variety of rock types. Figure 3 compares the Phase I and the proposed Phase II systems.

We have arrived at a preliminary estimate of the percentages of the various rock types in Phase II (Table 2). This information was derived from the EE-2 litholog. Although firm values for these numbers must await

	SYENOGRANITIC TO MONZONOGRANITIC	GRANODIORITIC		GRANODIORITIC (INTRUSIVE)		TONALITIC		[2]MAFIC - RICH ROCKS		ALTERED ZONES
	GT-2	GT-2	EE-2	GT-2	EE-2	GT-2	EE-2	GT-2	EE-2	EE-2
Weight % SiO_2	$\bar{x}$ = 75.0 S_x = 1.1 (10)	$\bar{x}$ = 68.7 S_x = 2.5 (7)	$\bar{x}$ = 66.6 S_x = 0.1 (2)	$\bar{x}$ = 64.3 S_x = 1.4 (6)	$\bar{x}$ = 68.1 S_x = 2.8 (5)	$\bar{x}$ = 68.3 S_x = 3.0 (3)	$\bar{x}$ = 63.3 S_x = 5.4 (2)	$\bar{x}$ = 55.1 S_x = 0.0 (2)	$\bar{x}$ = 59.7 S_x = 0.3 (2)	$\bar{x}$ = 52.3 S_x = 6.2 (2)
Volume % Quartz	$\bar{x}$ = 35.6 S_x = 5.3 (15)	$\bar{x}$ = 33.7 S_x = 6.1 (15)	$\bar{x}$ = 33.2 S_x = 4.0 (4)	$\bar{x}$ = 25.7 S_x = 3.1 (3)	$\bar{x}$ = 26.1 S_x = 4.4 (8)	$\bar{x}$ = 28.0 S_x = 6.5 (4)	$\bar{x}$ = 22.7 S_x = 5.6 (5)	$\bar{x}$ = 10.0 S_x = 6.1 (3)	$\bar{x}$ = 9.2 S_x = 2.1 (3)	? $\lesssim$ 10.0
Volume % Quartz + K-spar	$\bar{x}$ = 69.0 S_x = 5.8 (15)	$\bar{x}$ = 45.4 S_x = 7.1 (15)	$\bar{x}$ = 44.5 S_x = 5.5 (4)	$\bar{x}$ = 44.3 S_x = 5.1 (3)	$\bar{x}$ = 48.6 S_x = 12.5 (8)	$\bar{x}$ = 28.4 S_x = 6.6 (4)	$\bar{x}$ = 22.8 S_x = 5.8 (5)	$\bar{x}$ = 10.3 S_x = 5.8 (3)	$\bar{x}$ = 12.3 S_x = 1.7 (3)	? Variable, low
[1]Volume % Mafics	$\bar{x}$ = 4.3 S_x = 2.1 (15)	$\bar{x}$ = 13.7 S_x = 6.0 (15)	$\bar{x}$ = 24.6 S_x = 5.3 (4)	$\bar{x}$ = 19.5 S_x = 2.1 (3)	$\bar{x}$ = 19.0 S_x = 7.1 (8)	$\bar{x}$ = 21.0 S_x = 5.1 (4)	$\bar{x}$ = 38.2 S_x = 10.3 (5)	$\bar{x}$ = 45.9 S_x = 4.9 (3)	$\bar{x}$ = 64.7 S_x = 6.0 (3)	? Dominated by clay type minerals

[1]Includes biotite, muscovite chlorite, amphibole, opaques, epidote, apatite, sphene, zircon, and allanite.

[2]Includes metavolcanic rocks, biotite-chlorite schists and amphibolites.

Table 1. Chemical and mineralogic characteristics of the Precambrian rocks encountered at Fenton Hill. The symbol "$\bar{x}$" is the mean, "S_x" is the standard deviation, and "( )" is the number of analyses used in the tabulation.

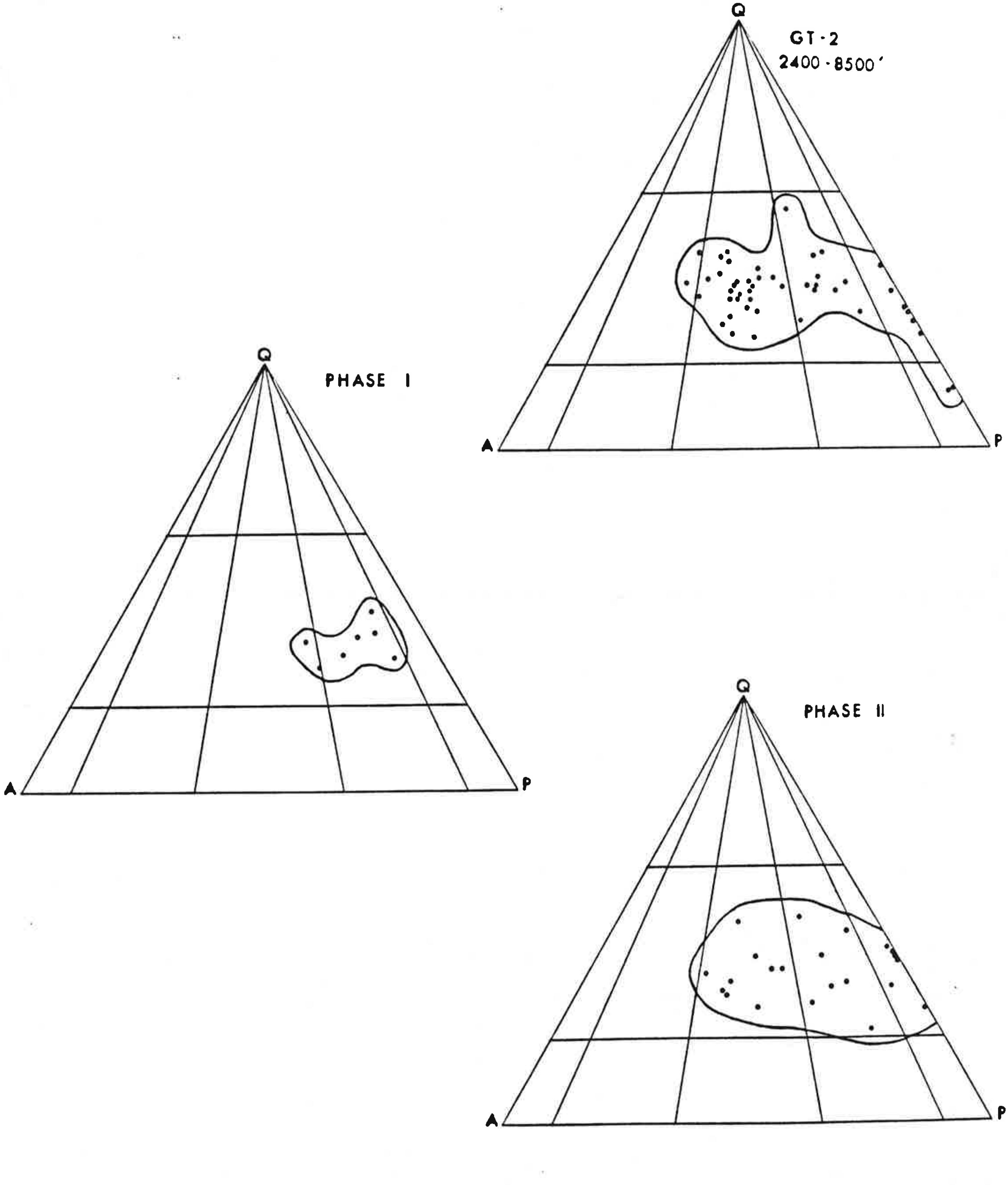


Fig. 2 QAP diagrams for the Precambrian section at Fenton Hill.

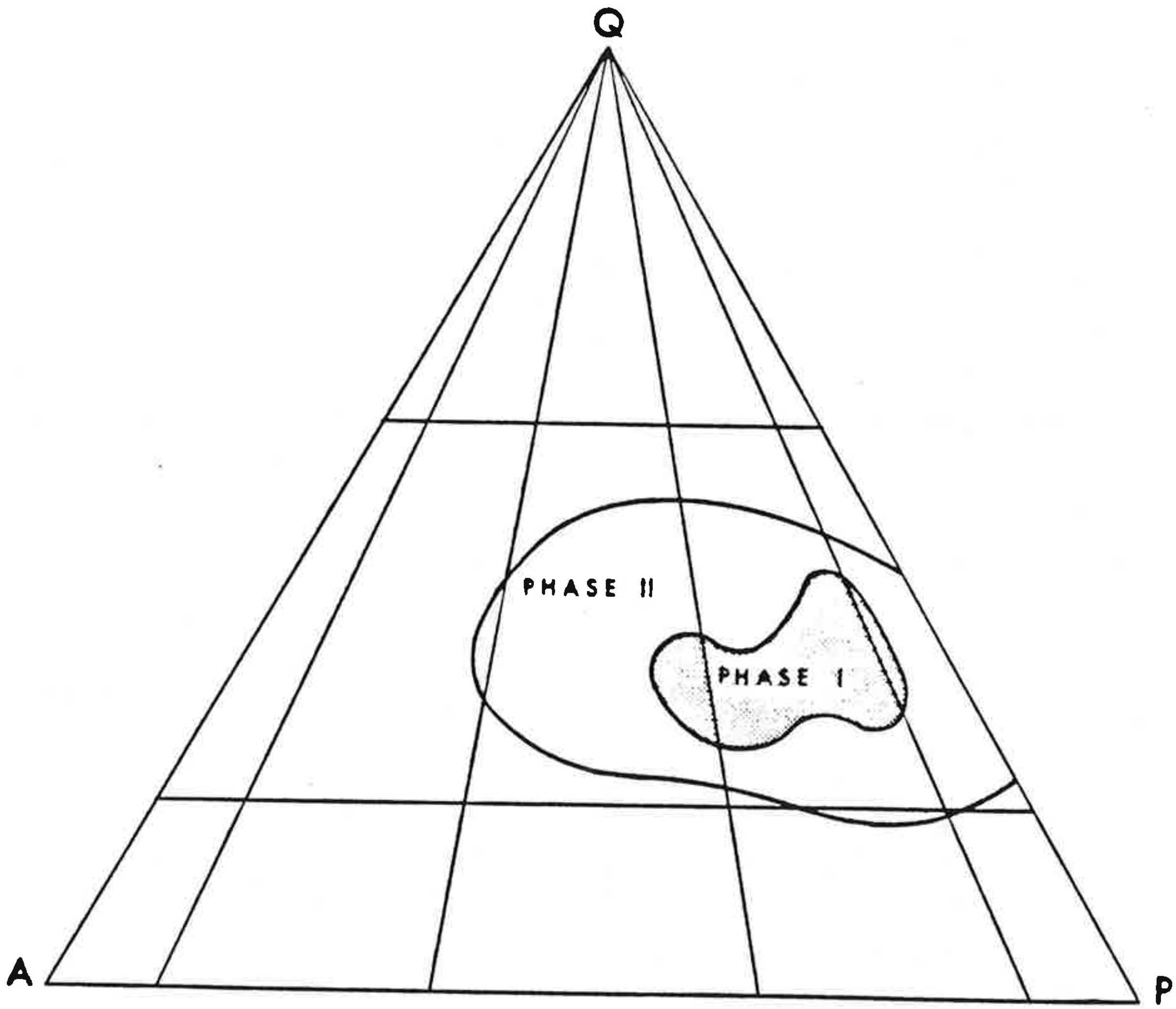


Fig. 3 QAP diagram comparing rock types for the Phase I and Phase II reservoirs.

ROCK TYPE	PHASE I RESERVOIR GT-2, EE-1 (8600' - 9700')	PHASE II RESERVOIR EE-2, EE-3 (Tentatively 10500' to 14400 TVD or 4700' along the EE-2 deviated borehole)
Syenogranitic to Monzogranitic	---	8.0%
Granodioritic	10.0%	49.0%
Granodioritic (intrusive)	90.0%	8.0%
Tonalitic	---	15.0%
Mafic-Rich Rocks	---	14.0%
tered Zones	---	6.0%
Summary	100% Granodioritic	57% Granodioritic 35% Tonalitic to Mafic (includes altered rock) 8% Granitic

Table 2. Comparison of the compositions of the Phase I and Phase II reservoirs.

completion of EE-3 (and hopefully successful geophysical logging of EE-2), they can be used for a preliminary assessment. As can be seen, Phase I was developed in predominately Precambrian intrusive, igneous rock. On the other hand, it appears Phase II will be developed in rock of the Precambrian metamorphic complex (Fig. 4).

The manner in which this highly variable metamorphic rock complex will respond to processes such as hydraulic fracturing and heat extraction can only be speculated upon at the present time. Because the thermal capacity, the lifetime, and other characteristics of HDR reservoirs are in part determined by the mineralogy of the reservoir, Table 3 may be of interest. This table compares Phase I and Phase II compositions and shows the wide range of mineralogic values expected in the Phase II reservoir rock.

We have gone one step further and calculated possible volume compositions of six different "mini-reservoirs" in Phase II (Table 4). We have assumed that vertical hydraulic fractures will connect the EE-2 and EE-3 wellbores, and these fractures will have inlet-to-outlet spacings of approximately 335 m (1100 ft). We have also assumed that the fractures will be roughly circular in shape and that water will circulate over an area with the diameter of the inlet-to-outlet spacing (potential flow theory, see Murphy et al., 1980). As can be seen, each proposed fractured region (mini-reservoir) differs mineralogically from its neighbors, and all six "mini-reservoirs" differ (in some cases significantly) from Phase I.

Discussion

Although the highly variable nature of the proposed Phase II reservoir may present additional complexities, both in completion and in subsequent modelling of its characteristics, it will have one large benefit for the HDR program.