Memorandum

UNOCAL 76

CONFIDENTIAL

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June 12, 1992

TO: Jens Pedersen

FM: David De Witt

RE: **GEOLOGICAL AND GEOCHEMICAL RESULTS FROM THE GMF 87-13 DEEPENING**

Summary

Rock alteration mineralogy and chemistry of produced reservoir fluids from GMF 87-13 indicate both are in equilibrium with a reservoir rock of intermediate composition and at a temperature of 250 - 280°C. Results from the 1991 temperature surveys show that fluid from the main producing horizon, at 2600' and 487°F, is slightly overpressured with respect to steam saturation. Fluid (static condition) is on the boiling point with depth curve at 2000', but during production (WHP of 235 psig and separator pressure of 70 psig) the boiling point in the wellbore drops to 2300'. The boiling at this point apparently releases CO_2 and most likely, calcite deposition occurs in the wellbore. The well produced 2-phase fluids during testing.

Chemical modelling of the fluids show that calculated alteration mineralogy is consistent with the mineralogy found in thin section. The modelling shows that low TDS (<3000 ppm) reservoir fluids are in chemical equilibrium with a reservoir rock at 250 - 260°C and with a calculated reservoir pH of 6.75. Mineralogy of some of the fractures contain a slightly higher temperature assemblage, possibly as high as 280°C. The occurrence of the higher temperature mineralogy as the latest deposited mineral in the fractures suggest the present geothermal system is young, or the reservoir lithology is vertically impermeable, or both.

Fluid chemistry of the well showed variability during testing, both from year-to-year, and during individual flow tests. This variability is probably the result of several processes: some produced geothermal fluids from GMF 68-8 were used in the drilling of GMF 87-13 during 1989 and dilute well water was used for drilling in 1991. Total produced fluids from the tests were approximately the same volume as lost during drilling.

Oxygen isotopes of eleven selected core samples from 3256' to 5574' show a range of values from 0.6‰ to -1.6‰ (unaltered rock is 6.5‰). This large depletion is consistent with the observed alteration and suggests a large water-to-rock ratio is responsible for the alteration.

CA-GMT-

07.25.2

Memorandum

UNOCAL 76

June 15, 1992

To: R. F. Dondanville

Fr: J. R. Pedersen J.R Pedersen

Please find attached a memo by Dave De Witt documenting the geological and geochemical results from the deepening of well GMFU 87-13 at Glass Mountain. The length of the flow tests preclude any definitive stable sampling of reservoir fluids but Dave carefully documents and discusses what was done so that when we go back we will have a base from which to proceed.

Distribution of the memo is to:

R. F. Dondanville (via this memo)
J. R. Pedersen
Central Files (UCA07.2502)

FORM 1-0C02 (REV. 11-85) PRINTED IN U S A

Recommendations

A long-term flow test of the GMF 87-13 well is recommended at the earliest possible date so that stabilized chemical composition, reservoir parameters and potential scaling effects can be determined. These parameters can then be used to help calculate the economics of the Glass Mountain Project.

Introduction

This memorandum summarizes our geological and geochemical findings from the deepening (from 3010' to 5935') of the GMF 87-13 well in the Glass Mountain Unit Area. These results, particularly the fluid chemistry results, should be used with care since the fluid chemistry is quite variable as the result of insufficient flow testing time (Table 1). The flow tests totaled 11.5 hrs in 1989 and 14.5 hrs in 1991. The data collected in the 1989 flow tests was used for comparison.

Data for the evaluation came from several different sources: fluid and gas samples collected during the flow tests, XRD analysis of selected cores and cuttings, thin sections cut from the same cores and cuttings, and temperature/pressure profiles of the well taken before, during, and after the flow tests. There is sufficient variation in all the data so that it would be difficult to come to well-constrained conclusions; rather, trends from the data were combined to form the interpretation.

Rock Chemistry and Alteration Mineralogy

A combined thin section and XRD mineralogical study of core taken from GMF 87-13 Deepening shows that propylitic alteration described by Lutz (1990) from 1200' to 2600', continues to the bottom of the hole (T.D. - 5935'). Variations in the intensity of the alteration appear to be related to the original permeability of the host rock. Dense andesite lava flows are noticeably less altered than flow breccias; however, the temperature indicated by the alteration assemblages are the same for both rock types.

The cored portion of the hole (3010' to 5935') shows that the predominate rock type is an andesitic/basaltic andesite flow rock, ranging from dense flows to highly vesicular flows, interbedded with andesitic flow breccias. The proportion of flow breccias decreases with depth, particularly below 4000'.

The measured reservoir temperatures of the well (250 - 280°C) are consistent with temperatures inferred from the alteration mineralogy (250 - 300°C) and the NKC and SiO_2 geothermometers. A similar temperature was also estimated from filling temperatures

Table 1: Flash corrected fluid chemistry from GMF87-13 (1989 and 1991)

vDate	sample#	Li	Na	K	Ca	Mg	Fe	SiO2	B	As	SO4	HCO3	F	Cl
GMF87-13														
10/30/89	1330	2.18	616.	89.9	10.7	-	0.07	551.	10.39	3.04	111.4	127.9	1.	881.
10/30/89	1340	2.96	652.	103.9	9.69	0.1	-	622.	11.49	-	78.	105.3	-	969.9
10/30/89	1350	2.98	658.9	103.9	10.3	0.1	-	619.99	11.89	-	76.	97.8	-	960.9
11/04/89	1360	3.12	704.9	105.	8.19	-	-	607.	12.1	-	51.9	87.9	1.2	1142.
11/05/89	1370	2.93	610.3	104.5	5.39	-	0.19	566.77	11.08	3.55	63.6	49.9	0.99	958.9
11/06/89	1380	2.8	584.	99.	6.9	-	-	556.99	10.69	-	45.8	64.8	0.99	940.
11/06/89	1390	2.78	579.9	97.9	6.59	-	0.07	550.	10.79	0.81	44.5	69.4	0.89	926.
11/06/89	1400	-	611.	99.9	6.69	-	0.08	552.99	12.49	3.74	40.1	43.5	0.8	918.9
11/06/89	1410	18.73	500.	69.9	5.8	-	0.17	482.	8.89	1.69	41.9	-	-	830.
11/06/89	1420	2.85	591.9	100.9	6.8	-	-	555.99	11.1	-	44.5	62.5	0.89	955.
11/06/89	1430	3.05	632.	107.7	7.92	0.12	0.06	582.28	11.99	-	46.9	49.	0.91	1021.2
GMF87-13DPN														
10/12/91	6510	2.3	520.7	83.5	2.07	0.22	1.1	513.69	9.5	2.51	70.8	121.2	0.73	782.3
10/12/91	6520	2.31	516.9	84.4	0.94	0.	0.38	509.5	9.72	2.69	65.2	36.4	0.72	805.
* 10/12/91	6530	0.05	16.4	2.3	0.57	0.	0.23	13.38	0.05	0.	4.8	215.9	0.07	2.2
10/12/91	6540	2.42	522.	85.7	2.09	0.	0.51	488.71	10.12	2.75	57.8	93.3	0.71	875.
10/12/91	6550	2.73	528.5	82.8	2.15	-	0.21	423.35	8.93	-	55.8	76.8	0.75	866.3
10/12/91	6560	2.47	533.9	86.5	2.13	0.	0.15	496.5	10.34	2.91	54.3	76.8	0.74	879.9
* 10/12/91	6570	0.05	14.1	2.	0.58	0.	0.15	11.46	0.46	0.	7.1	207.9	0.04	1.6
10/13/91	6580	2.43	527.7	85.2	3.02	0.	0.22	486.78	10.08	2.73	56.4	83.1	0.68	879.9
10/13/91	6590	2.52	542.8	87.7	3.05	0.	0.23	503.22	10.57	2.85	53.1	33.	0.71	900.9
* 10/13/91	6600	0.03	9.7	1.3	0.62	0.	0.09	7.81	0.38	0.	4.5	179.8	0.01	1.9
10/13/91	6610	2.81	538.6	85.5	2.63	-	0.3	462.84	9.06	-	51.6	34.2	0.69	905.7
10/13/91	6620	2.64	564.7	93.	2.85	0.	0.09	522.89	10.93	3.17	52.4	63.6	0.69	945.
10/13/91	6630	2.08	425.5	73.8	4.17	-	0.34	425.58	9.63	0.57	44.1	26.4	0.71	1043.8
10/13/91	6640	2.53	542.4	90.7	2.78	0.	0.16	503.03	10.69	3.02	50.	34.2	0.71	924.
+10/12/91	6531	-	-	-	-	-	-	-	-	-	-	-	-	815.
+10/12/91	6551	-	-	-	-	-	-	-	-	-	-	-	-	866.8
+10/12/91	6571	-	-	-	-	-	-	-	-	-	-	-	-	875.1
+10/13/91	6601	-	-	-	-	-	-	-	-	-	-	-	-	895.5
+10/13/91	6650	-	-	-	-	-	-	-	-	-	-	-	-	918.8
+10/12/91	6660	-	-	-	-	-	-	-	-	-	-	-	-	896.5
+10/13/91	6670	-	-	-	-	-	-	-	-	-	-	-	-	895.5

* - denotes steam sample
\+ - chloride analysis only

of fluid inclusions found in quartz from 5574' (Hulen, UURI). The well produces from the 2600'- 2700' interval and possibly several small entries near the 4000' depth (the TPS is not definitive due to the low flow rate).

Six core samples from the deepened section of hole (3010' to 5935') were sent to UURI for XRD analysis and thin sections. The results of the XRD were compared with those of the upper portion of the hole. Note that cuttings were used for the XRD and thin sections for the interval 160' to 2600'. Between 2600 and 3010', no samples were collected because of lost circulation.

In general terms, the following trends were noted:

1. Epidote, chlorite and smectite clays are nearly ubiquitous throughout the drill hole below 1000'. The intensity of the alteration, however, changes markedly. Alteration becomes pervasive below 2000', except where the original formation was so impermeable that minimal alteration occurred.

2. Calcite is the predominate vein and amygdaloidal filling mineral at 1000'. It becomes less prominent with depth, but persists to the bottom of the hole. A graphical representation of the calcite content indicates that calcite content decreases in the production zones and at depth (Figure 1). Coincident with the calcite decrease is the increase in epidote content, particularly near the known production horizons. This relationship suggests that epidote may be forming at the expense of calcite in the major production zones.

3. XRD data of the clay separates (< 5μ fraction) from each sample show a clay mineralogy change with depth (Figure 2). Smectites are the predominate clay phase at depths of less than 1000'; below that depth and continuing to the bottom of the hole are mixtures of smectite, illite and chlorite. With increasing depth, smectite decreases in content, while illite becomes more prominent. Chlorite is most abundant where fluid entries are found. In the lower section of the hole, chlorite appears to be formed at the expense of illite/smectite.

4. The XRD analysis shows a positive correlation between known productive zones and unidentified titanium phases (sphene or rutile or leucoxene) (Figure 3). The weight percent of the titanium phases appears to increase at the known production horizons, but this correlation may not be entirely correct. The apparent increase in titanium bearing phases may partially be the mineralogical change from ilmenite/rutile

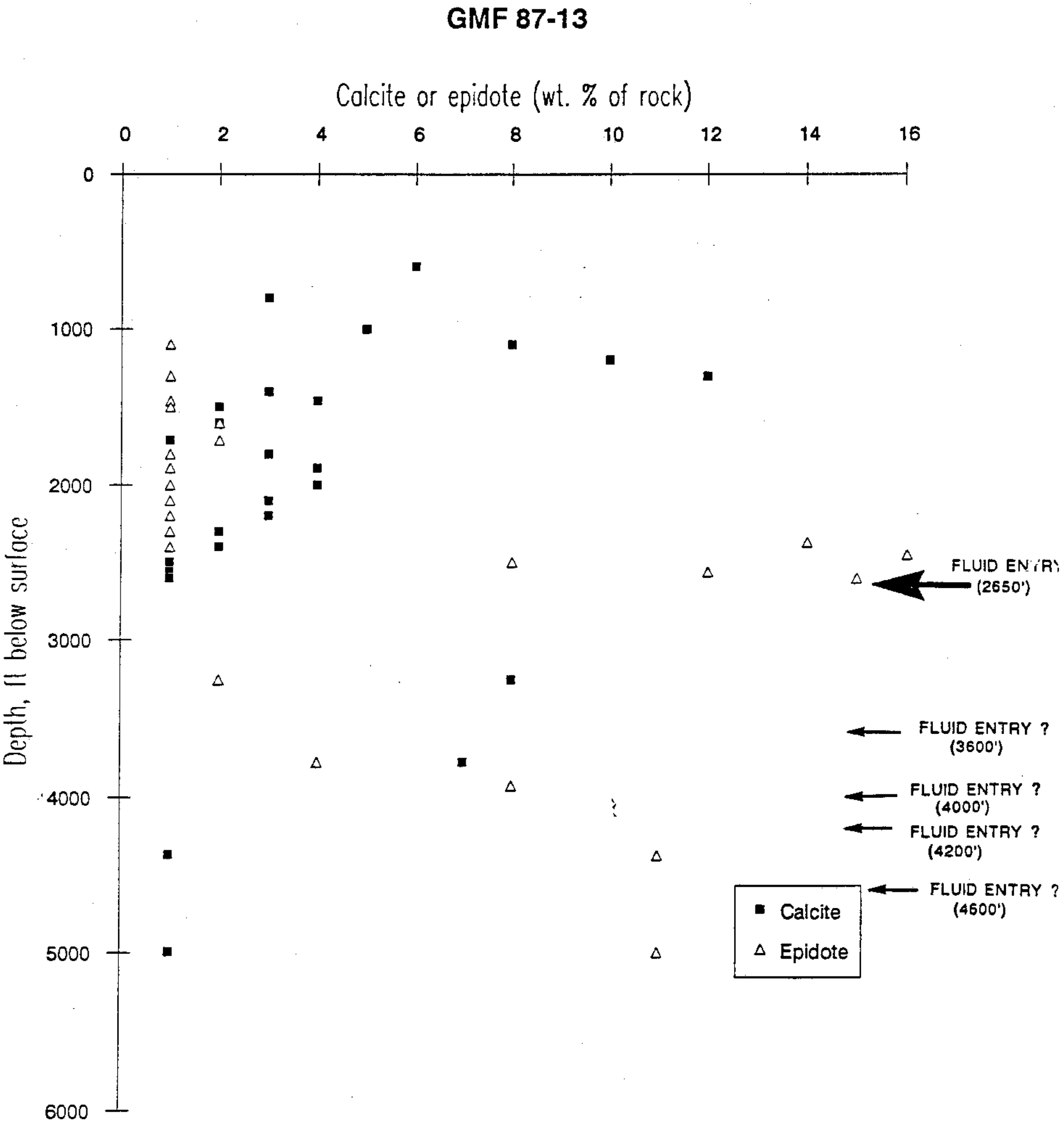

GMF 87-13
Calcite or epidote (wt. % of rock)
0
2
4
6
8
10
12
14
16
Depth, ft below surface
0
1000
2000
3000
4000
5000
6000
FLUID ENTRY
(2650')
FLUID ENTRY ?
(3600')
FLUID ENTRY ?
(4000')
FLUID ENTRY ?
(4200')
FLUID ENTRY ?
(4600')
■ Calcite
△ Epidote

Figure 1

GMF 87-13

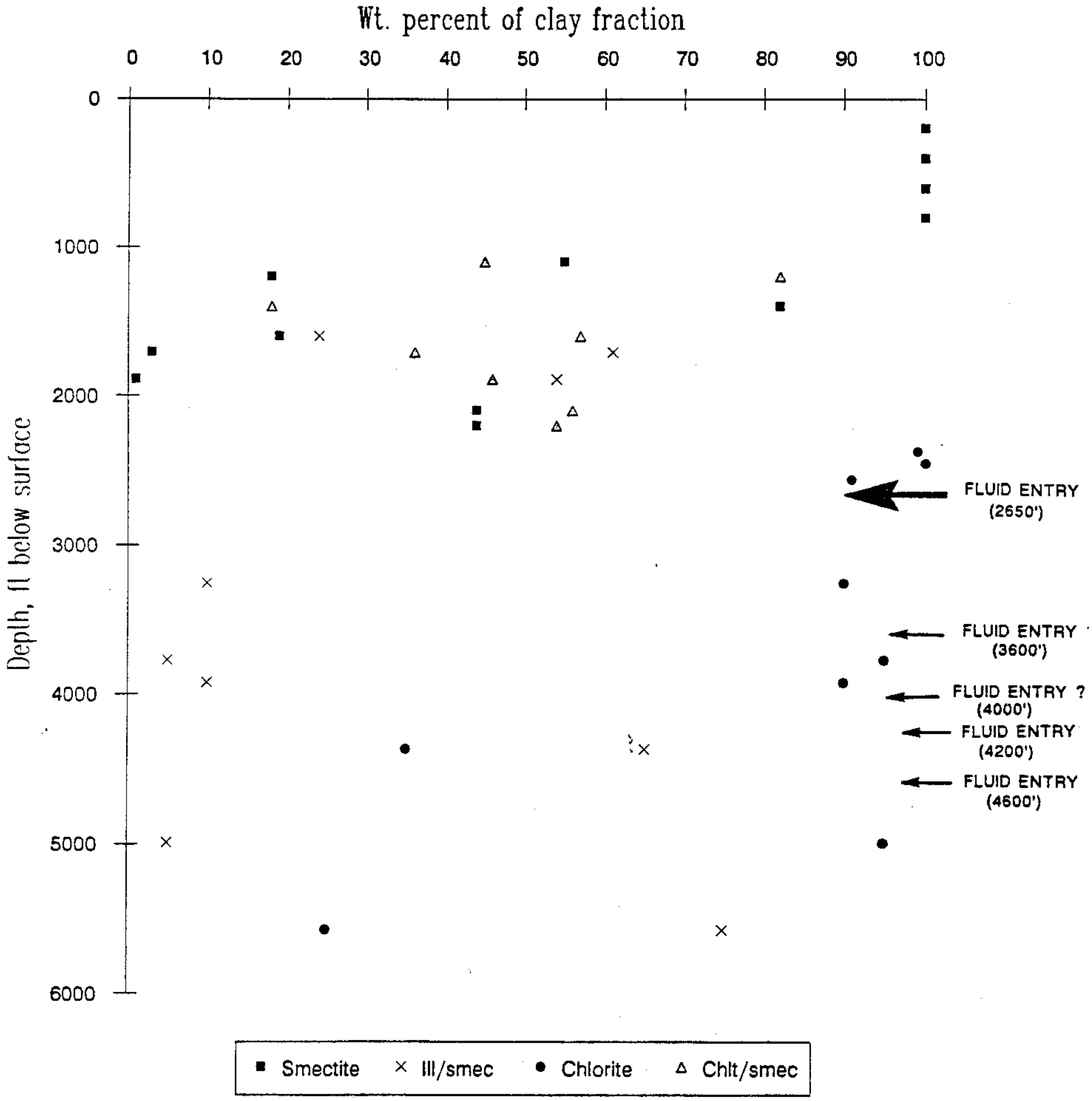


Figure 2

D.B.D. 6/92

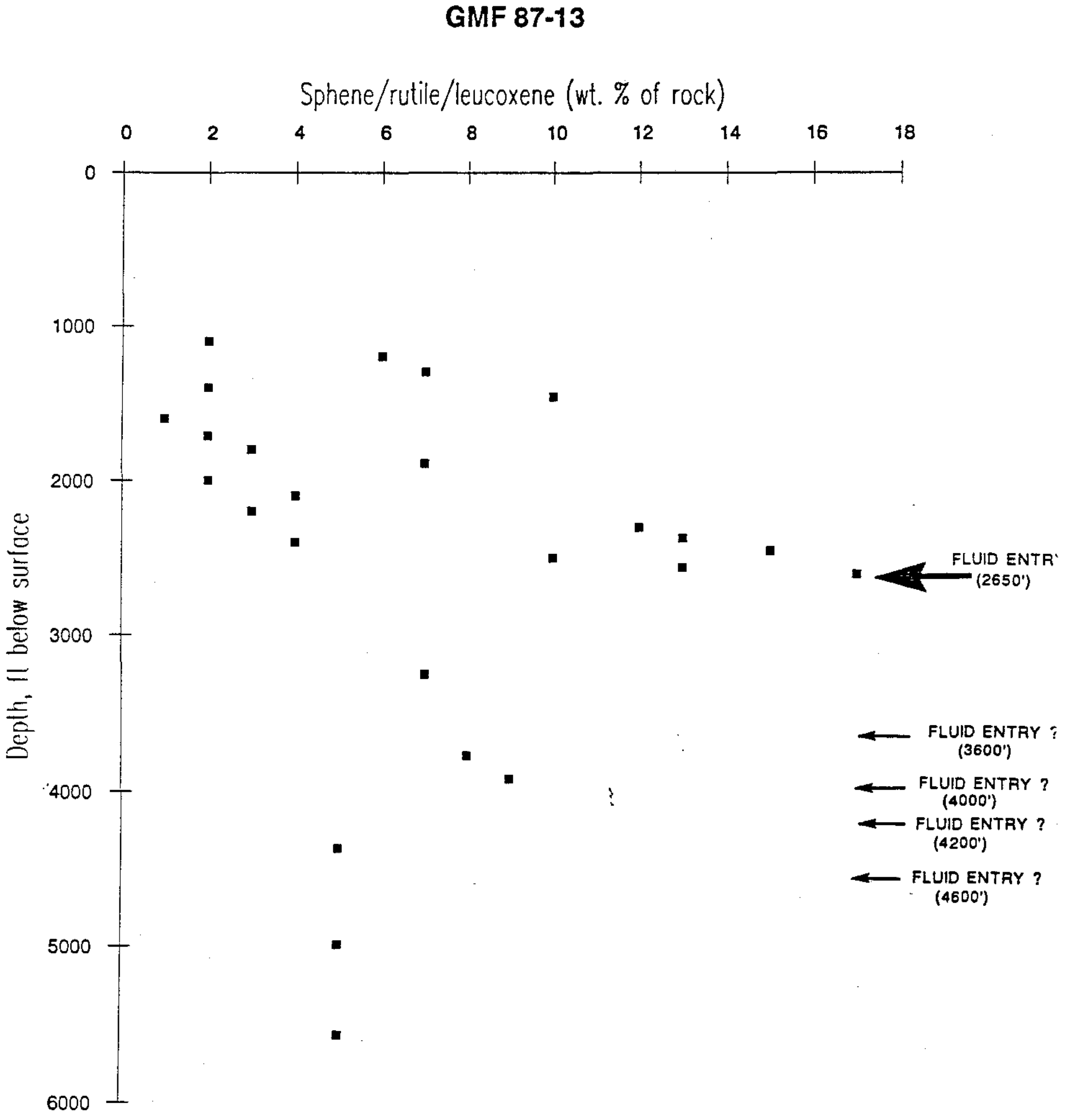

GMF 87-13
Sphene/rutile/leucoxene (wt. % of rock)
0
2
4
6
8
10
12
14
16
18
0
1000
2000
3000
4000
5000
6000
Depth, ft below surface
FLUID ENTR
(2650')
FLUID ENTRY ?
(3600')
FLUID ENTRY ?
(4000')
FLUID ENTRY ?
(4200')
FLUID ENTRY ?
(4600')

Figure 3

(originally in the andesite) to sphene (hydrothermal alteration) to leucoxene (hydration due to young geothermal fluids in specific production horizons). All whole-rock analysis of andesites and basalts in the Medicine Lake region have normal TiO_2 contents of 1.5% or less. If all the TiO_2 were concentrated in rutile (TiO_2), the rock would have a rutile weight percent of about 1.5%. If the TiO_2 were in the form of sphene ($CaTiSiO_5$), the rock would have a (titanium) mineral weight percent of about 6%. Leucoxene is an amorphous titanium oxide which can contain small amounts of water (Heinrich, 1965) so that its titanium content can be variable. It also has X-ray lines which are the same as rutile (from which it can be formed), making identification difficult. Since it is not possible to differentiate between several of the titanium phases, it is not possible to define the exact percentage of each phase; however, the increase in the total content far exceeds any change which could be attributed to different titanium phases. It should be noted that titanium content determinations are notoriously difficult since their x-ray lines have interference with those of feldspars.

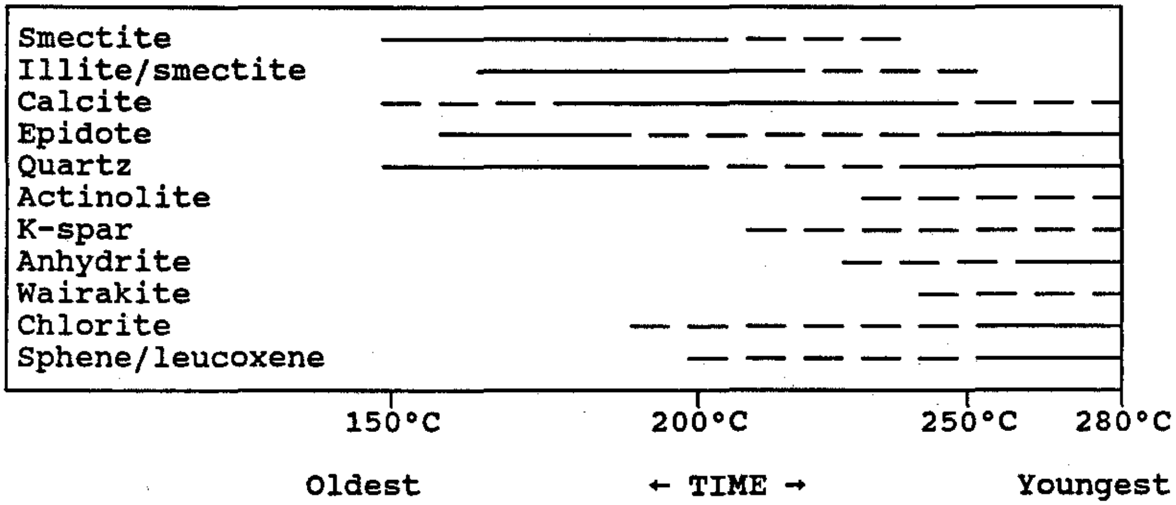
Hulen (pers. comm.) has shown that increases in the titanium content of reservoir rocks (hydrothermal sphene) is found in some of the producing fractures of the VC-2B core hole in the Valles Caldera, New Mexico. Whether the Glass Mountain system can produce the large amount of Ti-bearing minerals found in thin section has not been determined.

5. The effects of geothermal alteration are not well seen in the changes of bulk quartz and K-spar content using XRD. A sharp increase in both the quartz and K-spar content occurs between 1500 and 2000', but this is related to a rock type change (andesite to dacite/rhyolite) rather than an alteration feature. Thin section petrography, on the other hand, has identified the presence of late-stage feldspar and quartz veining in lower portions of the hole.

6. The high temperature geothermal alteration mineral, actinolite, is found in thin section in limited amounts (generally less than 1%). Its importance lies in the fact that actinolite normally forms at temperatures of 250 - 300°C and is most concentrated near production zones. Of additional interest is the occurrence of wairakite, an alteration mineral that normally has formation temperatures in excess of 200°C.

7. Anhydrite is found as a late-stage mineral throughout the well, but is more abundant in the lower portion of the well.

8. A schematic paragenetic sequence of alteration minerals, based upon cross-cutting relationships seen in thin section, would be as follows:



An important feature of this paragenitic sequence is that it correlates with an increase in temperature. The best examples of the high temperature minerals (250 - 280°C) are found in fractures and open space fillings as the youngest formed minerals. This indicates there is a "transient" nature to the alteration mineralogy whereby the most permeable zones are the first to alter (due to good permeability) and that it will take more time and fluid to alter the remainder of the less permeable rock. It further implies that the system has not cooled down and that matrix (isotropic) permeability is low.

Geochemical Modelling

As a check on alteration mineral paragenesis, the chemical and gas analysis were input into the CHILLER geochemical modelling program. This was done to: 1. determine if the reservoir fluids were in equilibrium with the reservoir rock and 2. establish if the current equilibrium mineral assemblage indicate a high temperature (possibly a prograde system) or if the system is cooling.

The results of the modelling (Molling, pers. comm.) indicate that the geothermal fluid is in equilibrium with the reservoir rock at a temperature of 250 - 260°C and a pH of 6.75. Table 2 and Appendix I list the mineralogy that is stable and oversaturated at specific temperatures. The stable mineralogy, at this temperature and fluid composition, consists of quartz, muscovite (sericite), plagioclase, calcite and epidote. These fluids are nearly saturated in dolomite and anhydrite and are over-saturated in actinolite and hematite. The solubility calculations of these minerals are very sensitive to changes in Fe, $Al_{(total)}$ and NH_4 (a pH buffer) content; species that are difficult to analyze. For this reason, it would not be unreasonable to see epidote in these rocks at temperatures below those predicted. Note that even though a mineral is oversaturated, it may not be deposited (or is slowly deposited) because of kinetic effects on deposition.

Table 2. Calculated mineral stability from GMF 87-13 (Molling, pers. comm)

Equilibrium	Supersaturated
T = 260°C	
calcite	actinolite
muscovite	hematite
quartz	
plagioclase	
T = 280°C	
k-spar	actinolite
albite	calcite
epidote	hematite
anhydrite	

An important point to remember is that the majority of fluid is being produced from the 2600' entry and the calculations are based upon this fluid. Fluids and fluid/mineral equilibria from deeper and hotter entries (280°C) are not represented and the lower portion of the hole was not modelled; however, it would be reasonable to assume that the mineralogy and fluids would be very similar.

Temperature and Pressure Surveys

Temperature and pressure surveys taken before, during and after the flow test show several features (Figures 4 and 5). Although a TPS survey was conducted, it was made during the injection portion of the test. Interpretations of possible deeper entries were made from the TPS data combined with a static temperature survey immediately after the flow test (Figure 5, 10-13-91). It is quite clear that the major producing entry is found at 2600', but there are possible entries at 3600', 4000', 4200' and 4600'. It is estimated (Birdzell, 1992) that the lower portion of the hole (greater than 2600') contributes only 7% of the mass flow of the well.

[illegible] 53.5

GLASS MOUNTAIN 87-13

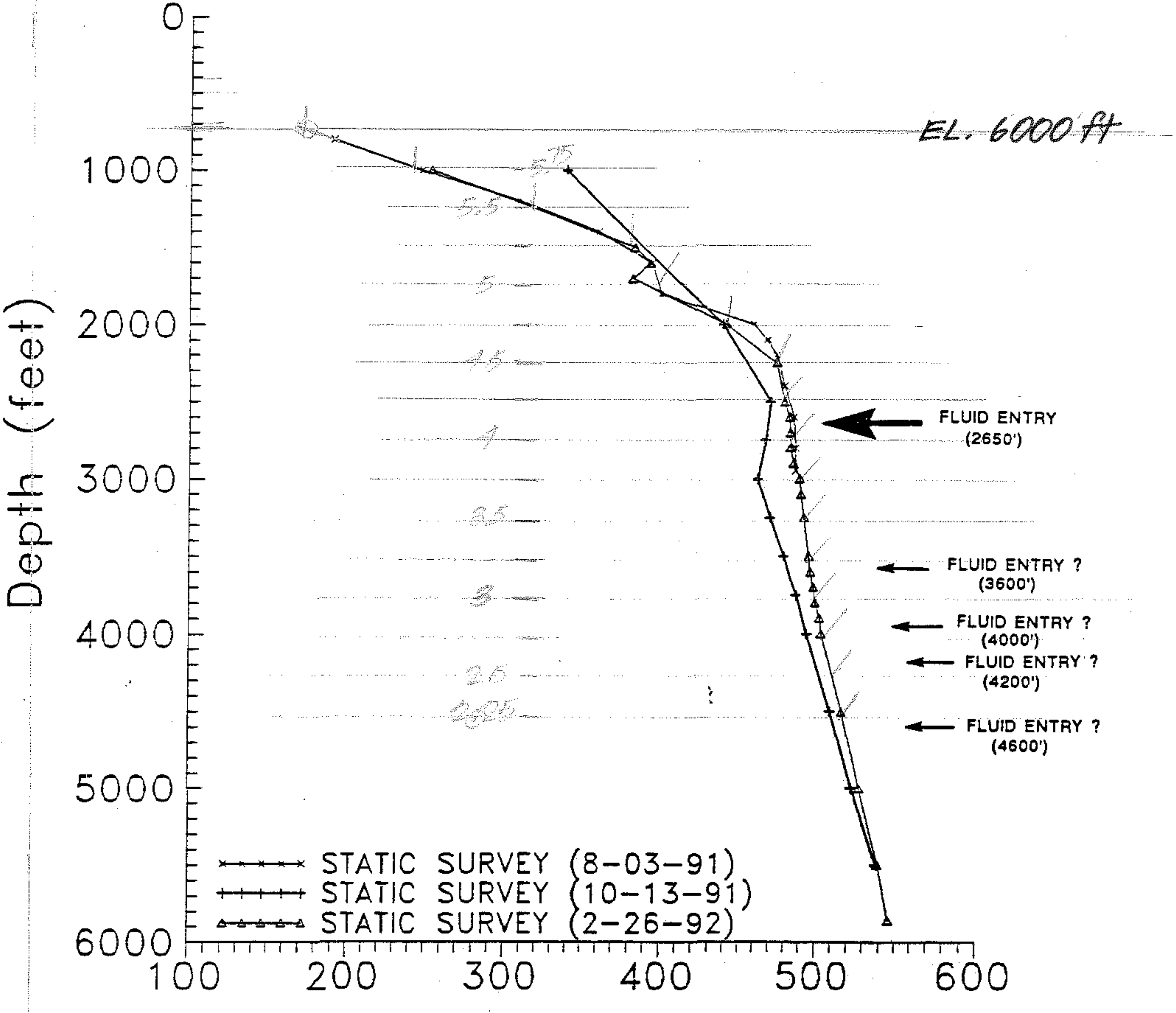


Figure 4

D.B.D. 6/92

92/X
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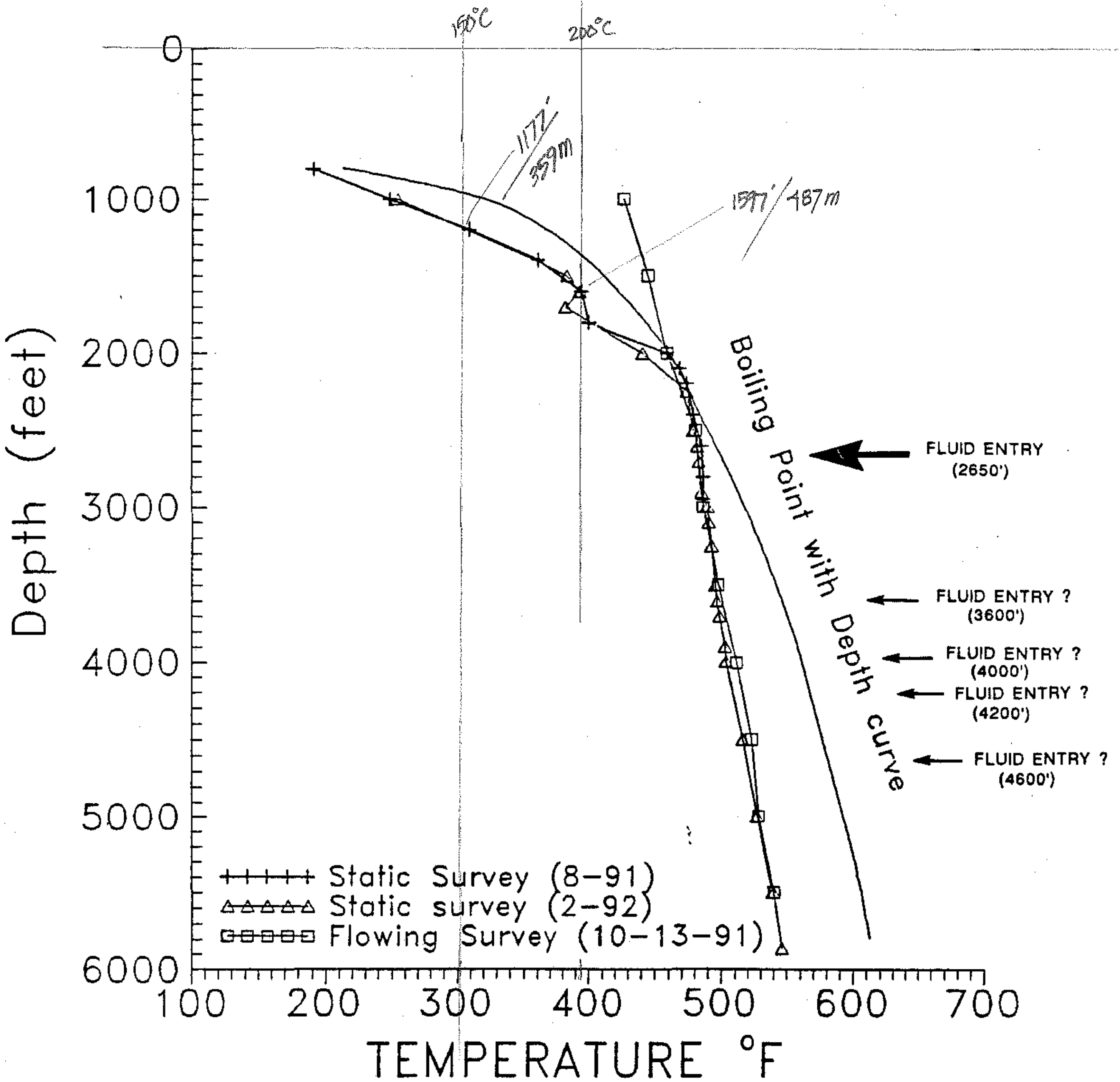
GLASS MOUNTAIN 87-13



53.5/105 X/92

Figure 5

D.B.D. 6/92

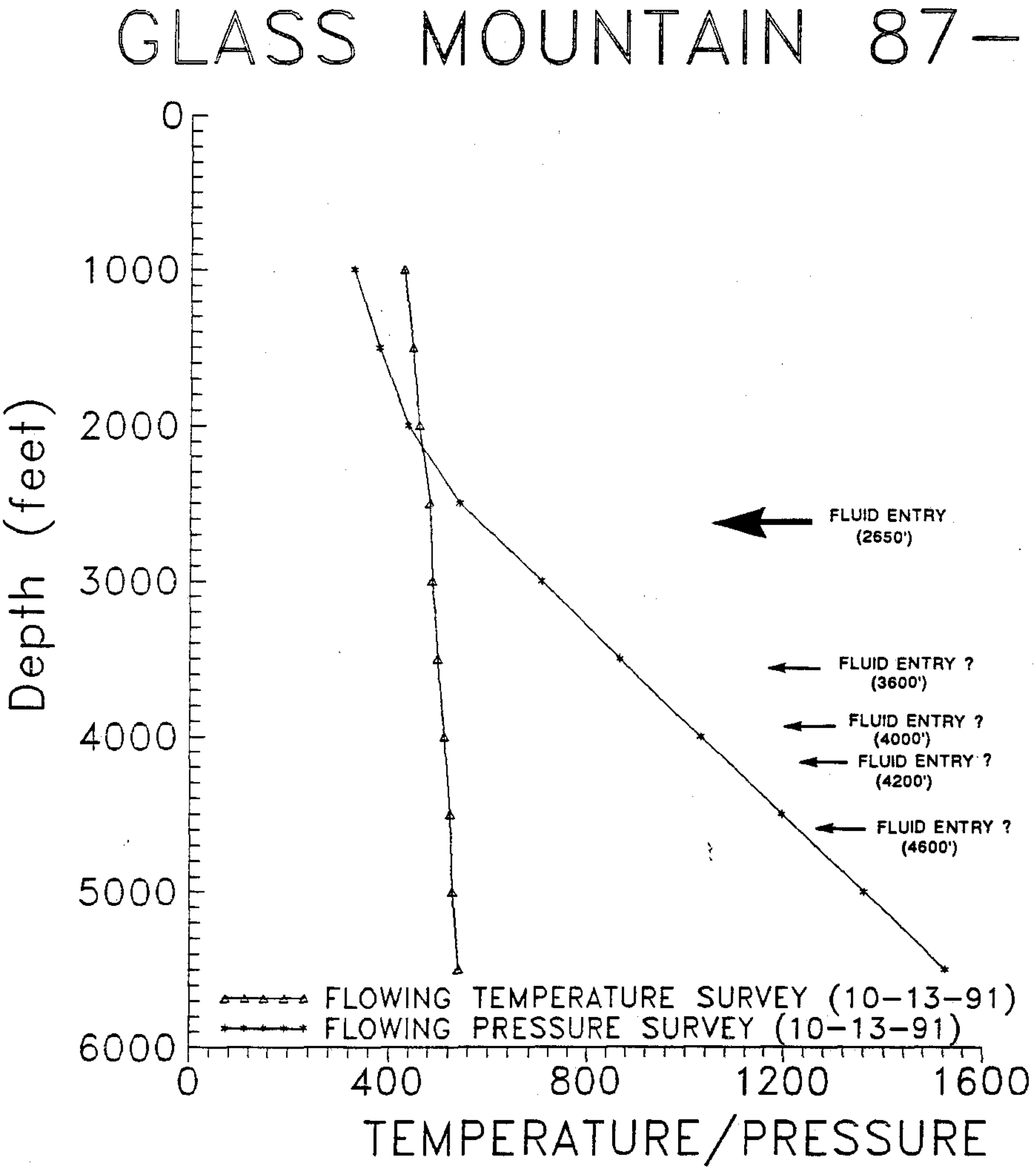

GLASS MOUNTAIN 87-13
Depth (feet)
0
1000
2000
3000
4000
5000
6000
FLUID ENTRY (2650')
FLUID ENTRY ? (3600')
FLUID ENTRY ? (4000')
FLUID ENTRY ? (4200')
FLUID ENTRY ? (4600')
FLOWING TEMPERATURE SURVEY (10-13-91)
FLOWING PRESSURE SURVEY (10-13-91)
0
400
800
1200
1600
TEMPERATURE/PRESSURE

Figure 6

When static well temperatures are plotted against the boiling point with depth curve (adjusted to the top of the water level), the well temperatures fall along the curve from 1900' to 2300'(Figure 5); below this depth, the well becomes progressively overpressured to the bottom of the hole.

Examination of the flowing pressure gradient survey (Figure 6) shows that the well begins to boil at 2300' and remains 2-phase to the surface. It is apparent that hot liquid (475°F) enters the wellbore at 2600', flows upward to 2300' where it begins to boil and then flows 2-phase to the surface (WHP = 235 psig, Sep. = 70 psig).

It should be noted that the latest static temperature (on 2-92) showed a significantly cooler upper profile, suggesting a possible casing problem at 1700'.

Fluid and Gas Chemistry

Evaluation of the fluid and gas chemical data from the 1989 and 1991 flow tests left many questions unanswered. Due to inadequate duration of the flow tests and a large number of sampling regimens for the produced fluids, there is a significant variability in the chemical composition of the produced fluid (Figure 8). Even with the variability, several trends stand out:

1. The TDS content of the fluid from the 1989 flow tests is consistently higher than that produced in the 1991 flow tests by nearly 10%. Variations of this magnitude would most likely result from dilution of the geothermal fluid by the drilling fluid used in the deepening process of GMF 87-13, by boiling and steam separation in the 1989 test or resulting from the use of produced brine (GMF 68-8) for drilling in 1989. Cation geothermometry does not change appreciably but the silica values decrease slightly, suggesting that dilution of the reservoir was the main process for changing fluid chemistry.

2. While most of the cation values did not change much, the amount of calcium was reduced by 30 to 60% when compared to the previous flow tests. The 1989 flow tests used a mini-separator at 200 psig, while the 1991 flow test used the test separator at 70 psig. This difference could allow calcite precipitation in the wellbore in 1991, and reduce the amount of calcium in the produced fluid.

3. Several cations show an increase in TDS content over the period of the flow test (Figure 7). This change suggests that the proportion of pristine (undiluted) geothermal fluids is becoming greater as production continues but that undiluted reservoir fluids are not yet being produced.

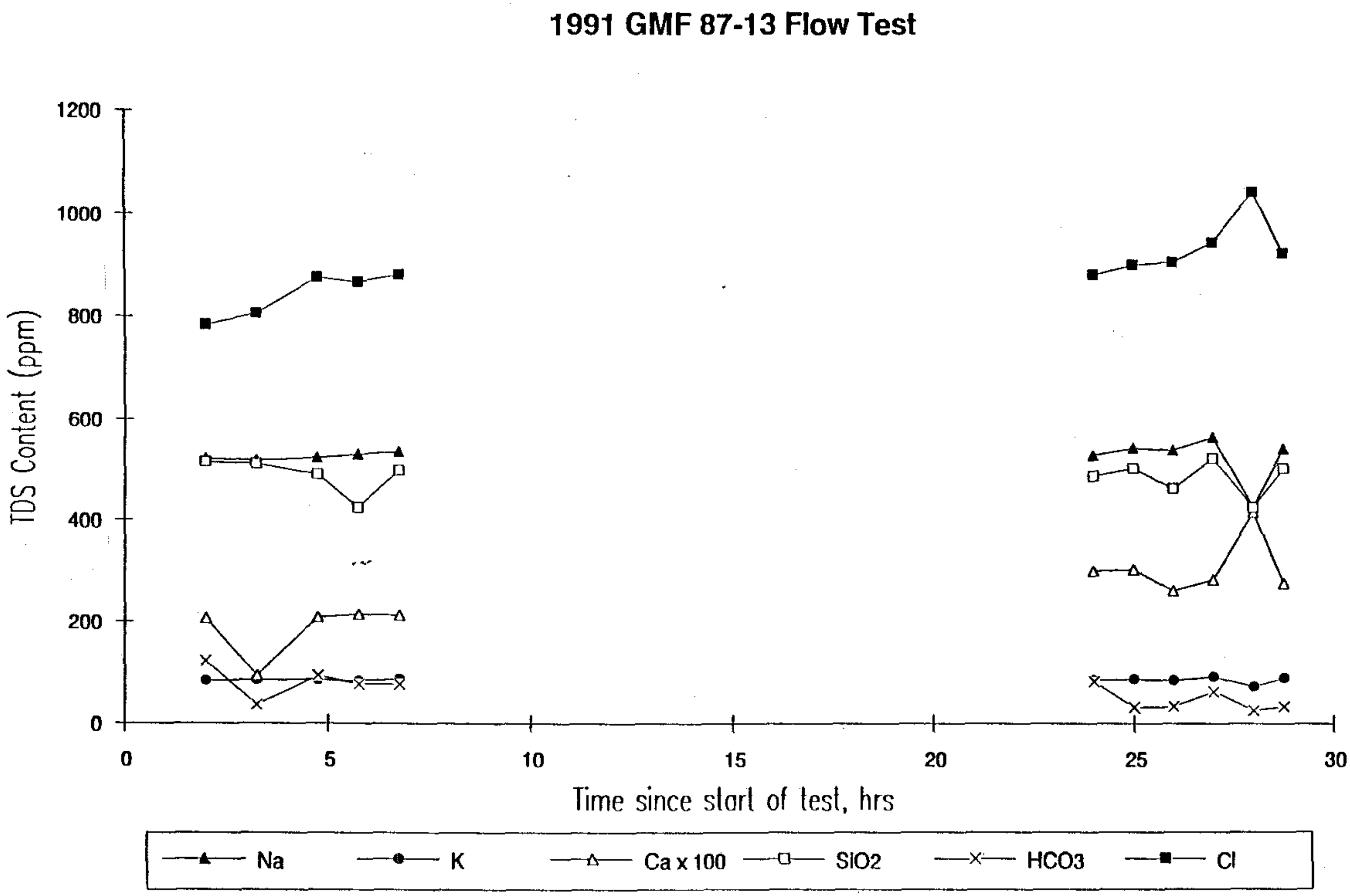

1991 GMF 87-13 Flow Test
TDS Content (ppm)
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30
Time since start of test, hrs
Na
K
Ca x 100
SiO2
HCO3
Cl

Figure 7

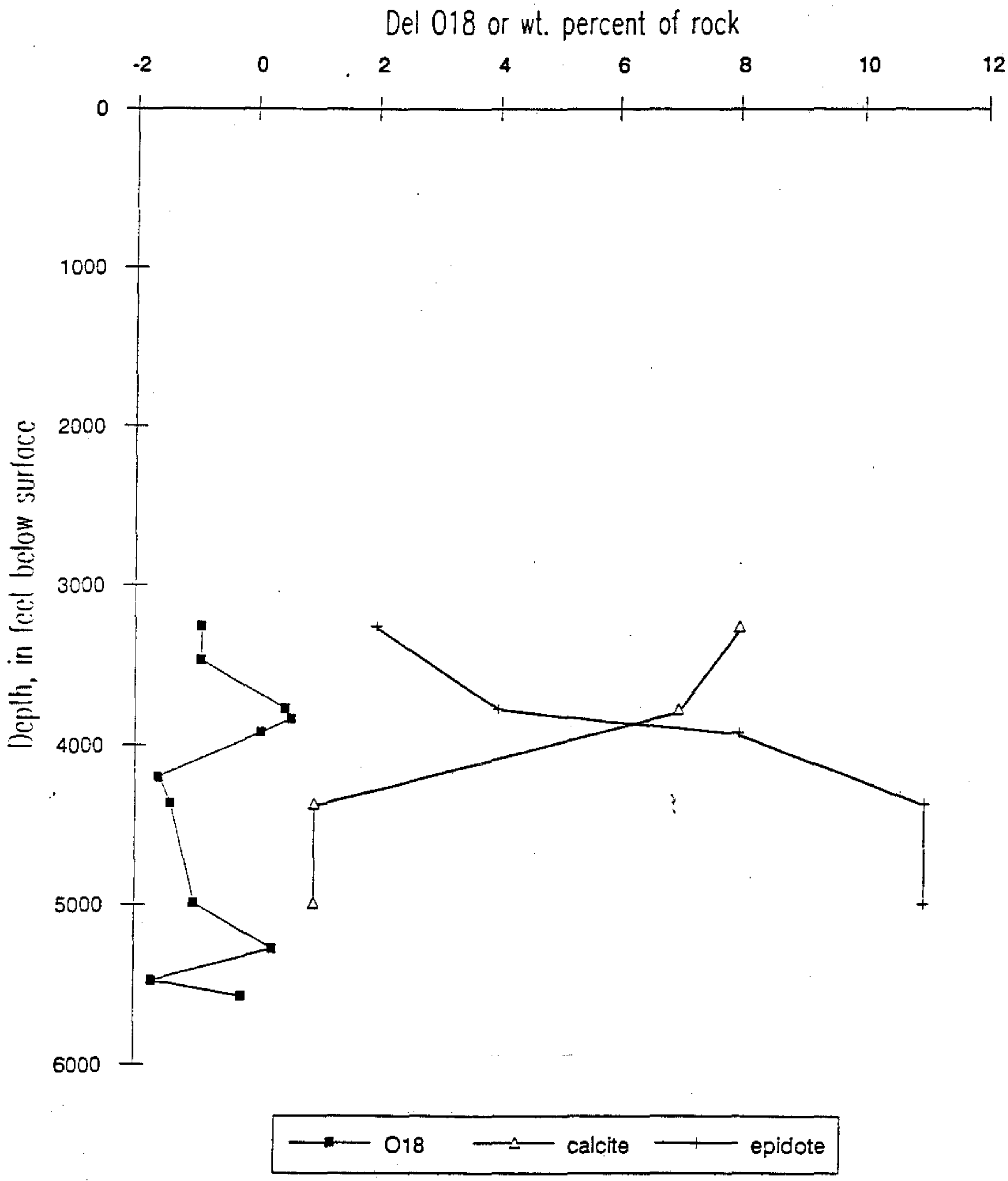
Oxygen Isotopes

Eleven selected core samples (3256' to 5574') were analyzed for their oxygen isotope content. Their values ranged from 0.6‰ to -1.7‰, a significant depletion from unaltered rock (6.5‰), but similar to those found in GMF 68-8 and GMF 31-17. Of particular interest is the difference in oxygen isotope content between the highly altered andesitic flow breccias and the less permeable andesitic lava flows (Table 3). These "tighter" units appear to be 1-2‰ heavier than the more altered rocks, indicating the water-rock ratio for the lava flows is considerably less than the more altered rocks. Simplified calculations (at 260°C) show that the water/rock ratio is about 1.7:1 for the lavas and 3.8:1 for the more permeable flow breccias.

Comparison of oxygen isotopes and calcite/epidote content of the rock (Figure 8) shows that the more depleted the rock, the higher the epidote content. This is consistent with having large water-rock ratios (i.e., high permeability) and the formation of epidote at the expense of calcite as the current alteration process.

TABLE 3. Oxygen-18 and lithology for GMFU 87-13

Depth, feet	Lithology	^{18}O, ‰
3256	Altered andesitic lava	-0.9
3468	Fractured and altered andesitic lava	-0.9
3774	Fg, aphanetic andesitic lava	0.5
3836	Equigranular andesitic lava	0.6
3923	Altered andesitic flow breccia	0.1
4202	Altered andesitic flow breccia	-1.6
4367	Highly altered andesitc flow breccia	-1.4
4993	Fractured andesitc lava	-1.0
5281	Equigranular andesitc lava	0.3
5478	Fractured and altered andesite lava	-1.7
5578	Oxidized andesitic flow breccia	-0.2



GMF 87-13 Oxygen isotopes/mineral content

Figure 8

References

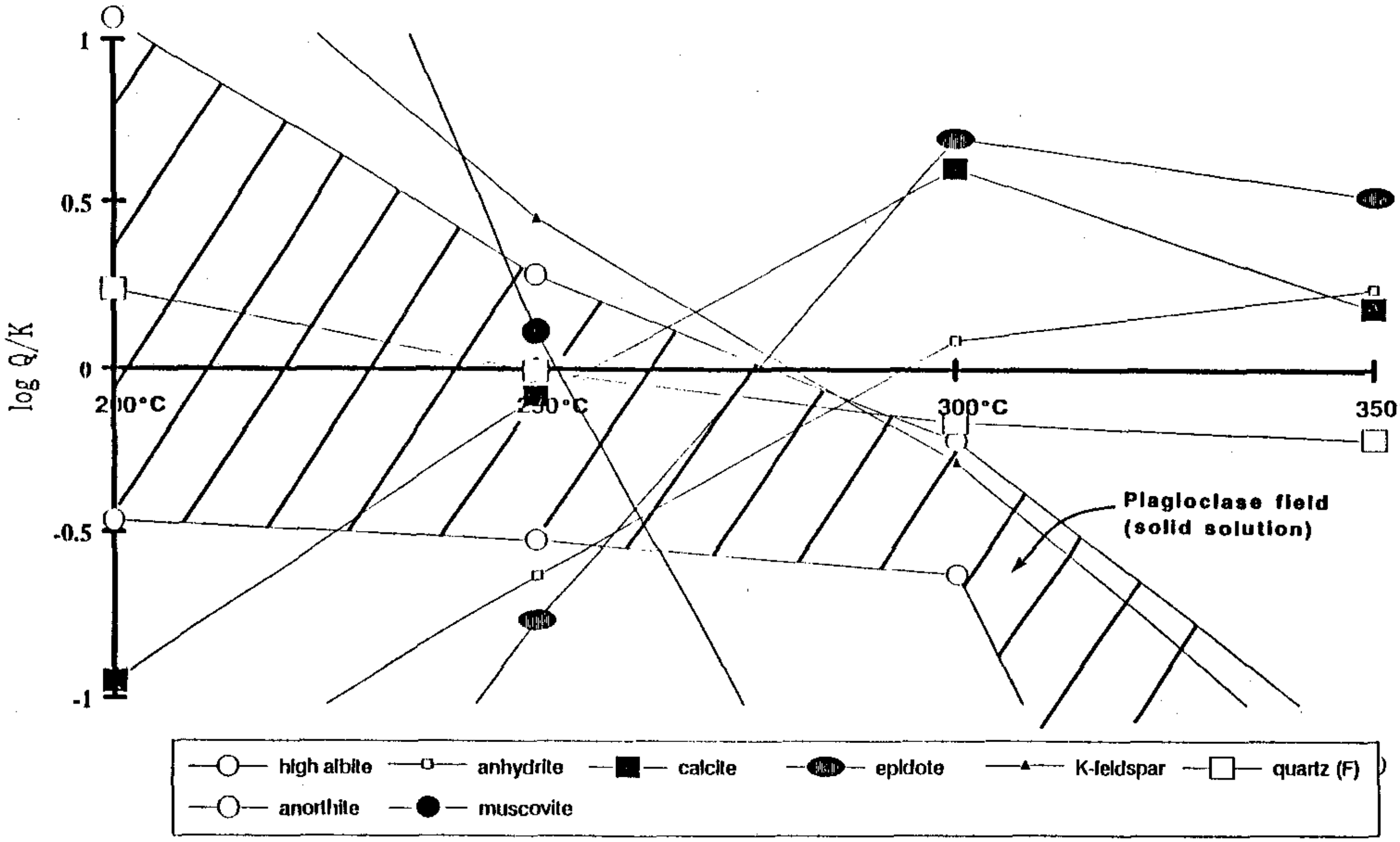
Birdzell, Jeff C., 1992, 1992 Glass Mountain Well Test Activities, Unocal Geothermal internal report, 9 p. and appendicies.

Hulen, Jeff B., 1992, Letter to David De Witt, April, 1992, on the results of x-ray diffraction studies on 6 core samples from GMF 87-13, UURI, 1 p.

Lutz, Susan Juch, 1990, Letter to Randolph Thompson, dated April 9, 1992, results of x-ray diffraction on GMF 87-13 cuttings, UURI, 9 p.

APPENDIX I

GMF 87-13 Fluid-Mineral Equilibria



Appendix I is a "mineral stability diagram" which plots temperature on the horizontal axis and a saturation index defined as log Q/K on the vertical axis. Log Q/K is a measure of the saturation state of a particular mineral in a fluid (in this case, a produced geothermal fluid) at a specified temperature. Log Q/K = 0 indicates the mineral is in equilibrium with the fluid, log Q/K >0 indicates a mineral that is supersaturated with respect to the fluid; conversely, log Q/K < 0 means the mineral is undersaturated with respect to the fluid.