INTRODUCTION

A number of studies involving water chemistry were conducted to support the development of the Raft River geothermal field. Geothermal waters frequently have high levels of dissolved solids (Ellis and Mahon, 1977), which require characterization to anticipate potential problems associated with utilization of the resource. These problems range from corrosion and scaling to environmental concerns about disposal of geothermal fluids.

Because of the relatively high dissolved solids content of water from the Raft River KGRA, subsurface reinjection of the spent geothermal waters is required by the Idaho Department of Water Resources. Most of the geochemical studies involve potential problems arising from this reinjection requirement. Corrosion and scaling problems in the plant are being investigated by the Conversion Technology Group.

The most important reinjection concern is the effect that injection of cooled waters will have on the geothermal resource. The effects of reinjection of geothermal waters on the quality of ground waters in the valley is also of concern. Salt buildup in soils is a critical problem where agriculture is supported by irrigation in semi-arid areas (El - Ashry, 1980). Large increases in dissolved solids of shallow ground waters in the Raft River Valley from reinjection could interfere with the farming economy of the area. Additional reinjection problems can occur from plugging of injection wells. In geothermal systems this can come from suspended solids or from chemical precipitates.

To define the hydrologic system of the Raft River KGRA, a conceptual model of the field was developed. This model shows sources of water and heat to the aquifer and directions of flow. This model can be used to evaluate the locations of the injection wells at Raft River. Additional studies described here include studies about the reinjectability of the fluids. This includes quantity and size distribution of suspended solids, and the formation of chemical precipitates from waters during mixing.

Finally, a chemical logging technique is described that was developed during drilling at the Raft River KGRA. This logging technique can be used to locate geothermal aquifers while drilling is in progress. The technique is capable of anticipating hot aquifers before they are penetrated by the drill string. This would permit casing to be run before high pressure aquifers were intercepted that would require killing or cementing the well.

WELL CHEMISTRY

As each of the geothermal wells was completed, it was developed and tested for yield. Water samples were collected for chemical analysis at this time. Additional samples were collected from the wells during pump tests, or during production runs. Seven monitor wells were drilled to follow water level and chemical changes in shallow ground water in the vicinity of the KGRA. In addition to these wells drilled in conjunction with the Raft River site, analyses have been made on domestic and irrigation wells in the area. Chemical analyses from these groups of wells have been compiled into a computerized data base to permit easy access to the data.

Discussion of well chemistry in this section is limited to the seven deep geothermal wells. The chemistry of the monitor well network is covered by Spencer and Callan (1980), and of the general shallow ground water by Walker, and others (1970).

Table __ shows a selected analysis from each of the wells used in the development of the geochemical model in the next section. The analyses in this table are averages of the most consistent chemical analyses from each of the wells, and were selected on the basis of yielding results close to electrical neutrality. For the seven geothermal wells, the seven monitor wells, and the three U.S. Geological Survey wells, the temperature is the bottom hole temperature obtained from geophysical logs. Other temperatures are as measured in the water during sampling. The silica and Na-K-Ca temperatures were calculated for wells that had warm water temperatures using the equations given by Fournier (1977).

All the deep geothermal wells are sodium chloride type waters, based on the predominant cation and anion in terms of milliequivalents per liter (meg/L). The sodium ranges from 83 to 91 percent of the cations, and chlonde from 92 to 99 percent of the anions. The waters are all low in alkalinity, ranging from 26 to 60 mg/L as $CaCO_3$ (32 to 73 mg/L as HC_3^-). There is a great deal of variation in the total amount of dissolved solids among the wells.

Wells RRGE-1, RRGE-2, and RRGP-5 are towards the northwest side of the KGRA, and were located to intercept the Bridge Fault at depths where hot water was anticipated. These wells are similar in dissolved solids content, temperature, and chemical character. Contents of dissolved chemical species are relatively low, with specific conductivities ranging from 2500 - 2800 μmhos. These wells also have the highest fluoride contents, with greater than 7 mg/L in all three.

Wells RRGI-6 and RRGI-7, injection wells, are located to the southwest, and were completed at more shallow depths than the production wells so as not to interfere with the geothermal resource. These wells have very high dissolved solids contents, most of which is sodium and chlonde, and are relatively low in fluoride, having 5.7 and 4.9 mg/L for RRGI-6 and RRGI-7 respectively. The temperature of these wells is also much lower than the others, being almost half that of the maximum measured in RRGE-3.

Wells RRGE-3 and RRGP-4 are intermediate in location and dissolved solids between the wells along the Bridge Fault, and those in the central-valley area. Well RRGE-3 has the hottest downhole temperature at 149°.

Calculated temperatures from geochemical thermometers give temperatures that fall within a fairly narrow range, and are close to temperatures measured in the geothermal wells. Calculated Silica temperatures indicate that the maximum temperatures in the reservoir may be from 10 to 20°C warmer than so far encountered in wells. Temperatures calculated from the Na-K-Ca geothermometer genrally give temperatures from 30 to 40°C warmer than measured in wells. The general agreement between measured and calculated temperatures indicates that the wells are probably tapping about the hottest water available.

Well	RRGE-1	RRGE-2	RRGE-3	RRGP-4	RRGP-5	RRGI-6	RRGI-7
TD Well Depth (m)	1521	1994	1789	1654	1497	1176	1185
Casing Depth ① (m)	1105	1289	1293	1054	1039	509	623
T(°C)	141	144	149	142	135	71	78
SpC (µmhos)	2800	2500	8000	4050	2700	10800	12000
pH (units)	7.3	7.1	6.9	7.2	7.5	7.2	–
Ca^{2+}	56	42	224	86	41	171	350
Mg^{2+}	0.6	0.1	0.5	–	0.1	1.4	1.5
Sr^{2+}	1.4	1.2	5.2	6.4	1.2	8.0	–
Na^+	455	441	1194	753	484	2200	2200
K^+	34	38	105	–	31	32	–
Li^+	1.6	1.1	3.1	3.1	1.6	5.1	–
HCO_3^-	41	41	44	42	35	73	32
SO_4^{2-}	36	53	60	–	40	60	64
Cl^-	776	708	2260	1400	800	3640	4000
F^-	7.9	8.7	4.9	6.3	7.2	5.7	4.9
SiO_2	121	131	158	104	133	94	83
T(°C) calc. rom SiO_2	148	153	164	136	154	134	127
(°C) calc. om Na-K-Ca	173	183	187	—	169	114	—

① Depth to bottom of casing or to first perforations

Well ID	MW-1	MW-2	MW-3	MW-4	MW-5	MW-6	MW-7
Well Depth (m)	399	174	153	305	152	305	152
Casing Depth (m)	369	154	140	225	124	274	140
T(°C)	74	106	71	98	29	44	35
SpC (µmhos)	11400	4400	6200	7800	2200	7600	2300
pH (units)	7.6	7.4	7.5	7.7	7.6	7.3	7.6
Ca^{2+}	215	125	155	160	107	207	95
Mg^{2+}	0.4	0.5	6.3	0.6	25	2.4	20
Sr^{2+}	6.3	3.6	1.9	1.4	0.9	1.4	0.9
Na^+	2220	1000	1400	1520	280	1570	333
K^+	30	25	65	31	14	56	14
Li^+	3.7	2.5	3.0	3.7	0.3	3.1	0.6
HCO_3^-	25	26	47	27	120	50	125
SO_4^{2-}	66	57	60	53	27	73	33
Cl^-	3680	1740	2460	2610	610	2770	650
F^-	3.4	5.4	5.4	5.6	0.6	4.9	1.1
SiO_2	80	87	60	67	34	85	40
T(°C) calc. from SiO_2	125	130	111	116	—	—	—
T(°C) calc. from Na-K-Ca	110	128	160	123	—	—	—

Well • ID	BLM ②	CROOK ③	USGS-1	USGS-2	USGS-3	15S-26E 23ABD1	15S-26E 23DDD1
Well Depth (m)	126	165	336	243	434	110	78
Casing Depth (m)	—	—	—	64	60	—	—
T (°C)	93	97	28	55	89	29	42
SpC (Mmhos)	3000	5800	7400	1960	5900	4500	3900
pH (units)	7.4	7.7	7.8	7.7	7.7	7.6	7.1
Ca^{2+}	44	130	230	51	57	97	104
Mg^{2+}	0.7	0.8	2.5	4.0	0.5	5.0	8.0
Sr^{2+}	1.5	2.8	1.7	0.3	2.0	—	—
Na^{+}	577	1020	1500	370	1270	766	644
K^{+}	21	32	200	34	14	20	18
Li^{+}	1.4	2.6	0.9	6.6	1.7	1.9	1.1
HCO_3^-	49	34	100	216	77	155	168
SO_4^{2-}	65	56	45	55	54	96	57
Cl^-	890	1750	2800	520	2040	1270	1100
F^-	7.6	6.2	3.2	2.5	4.8	5.1	4.5
SiO_2	74	86	85	88	54	61	58
T(°C) calc. from SiO_2	120	127	—	130	105	—	—
T(°C) calc. from Na-K-Ca	144	138	—	182	103	—	—

② This well was drilled in the 1920's, and is called the Bridge well by the USGS, a well was drilled nearby in 1974 and is called the BLM offset

③ This well was previously owned by Crank, and is refered to by that name in earlier publications

Well ID	15S-26E 24BAD1	15S-26E 24BCB1	15S-26E 24CAD1	15S-26E 24DCC1	15S-26E 26CAB1	15S-26E 27DCC1	15S-27E 19CCC1
Well Depth (m)	80	69	—	—	—	66	124
Casing Depth (m)	—	—	—	—	—	—	—
T(°C)	27	24	28	32	24	16	19
SpC (Mimhos)	2500	2400	2200	3300	3800	1400	2870
pH (units)	7.2	7.4	7.3	7.5	7.9	7.7	7.1
Ca^{2+}	106	60	121	160	57	59	130
Mg^{2+}	15	8.0	17	25	5.0	12	20
Sr^{2+}	—	—	—	—	—	—	—
Na^+	370	420	294	430	695	230	402
K^+	13	11	13	17	13	9	20
Li^+	0.8	0.9	0.6	0.8	1.5	0.3	0.8
HCO_3^-	200	200	216	150	125	250	235
SO_4^{2-}	61	62	69	76	58	62	75
Cl^-	640	610	535	910	1080	315	750
F^-	2.0	5.5	1.6	2.5	5.5	2.5	2.3
SiO_2	53	55	44	59	59	53	58
T(°C) calc. from SiO_2	—	—	—	—	—	—	—
T(°C) calc. from Na-K-Ca	—	—	—	—	—	—	—

GEOCHEMISTRY OF GROUND WATER

The chemical composition of a ground water is related to the hydrology of the ground-water system. Waters from different source areas, variations in lithology along flow paths, and in geothermal reservoirs, variations in temperature history, produce differences in chemical compositions. By using the chemistry as a tracer for waters, the sources and flow paths may be discernible. A conceptual model of the flow system can be developed from this information.

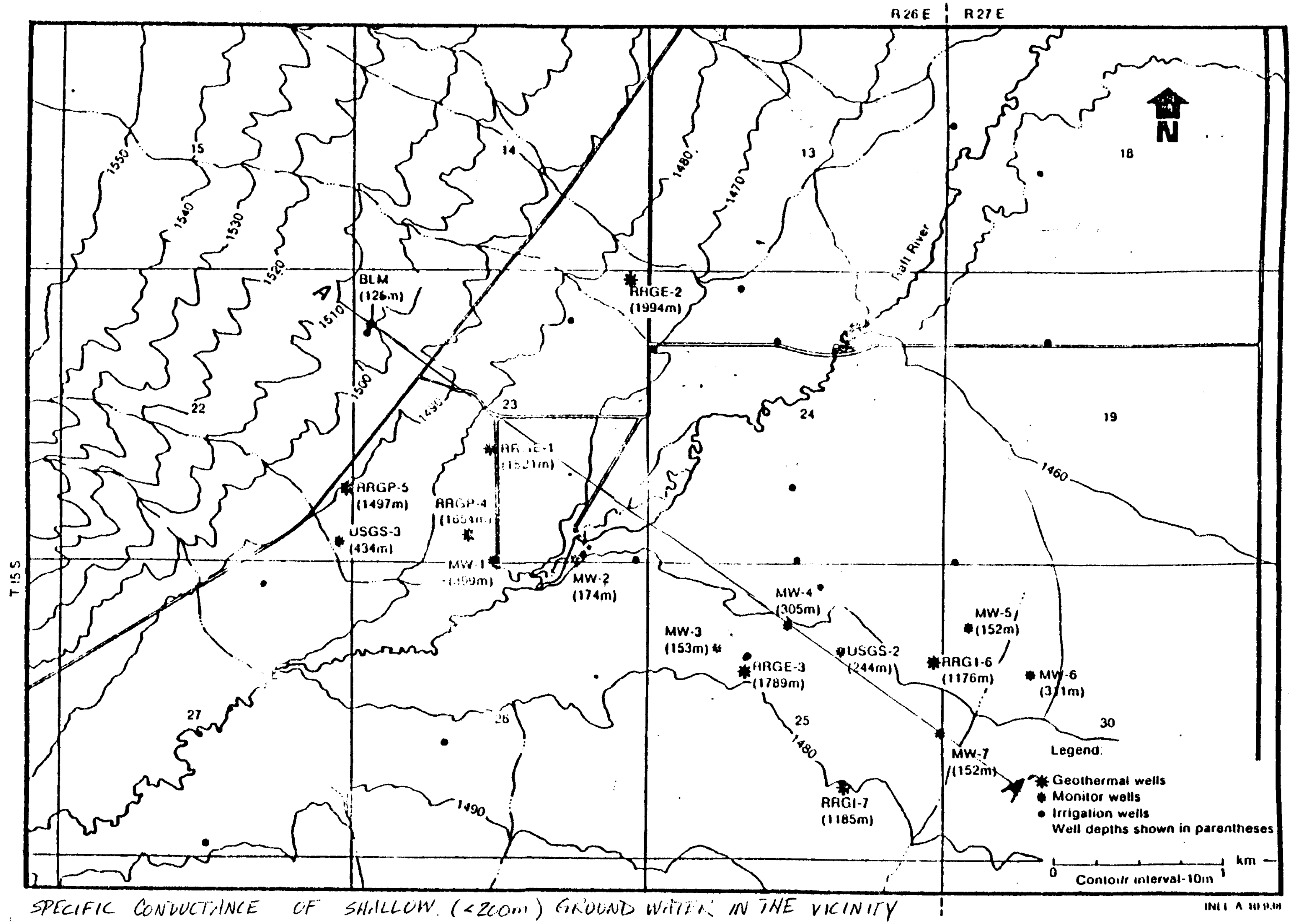
Because of the need to predict the effects of withdrawal and injection of geothermal fluids on the chemical quality of aquifers near the Raft River KGRA, the chemical data was used to develop a conceptual model of the area.

Distribution of Chemical Species

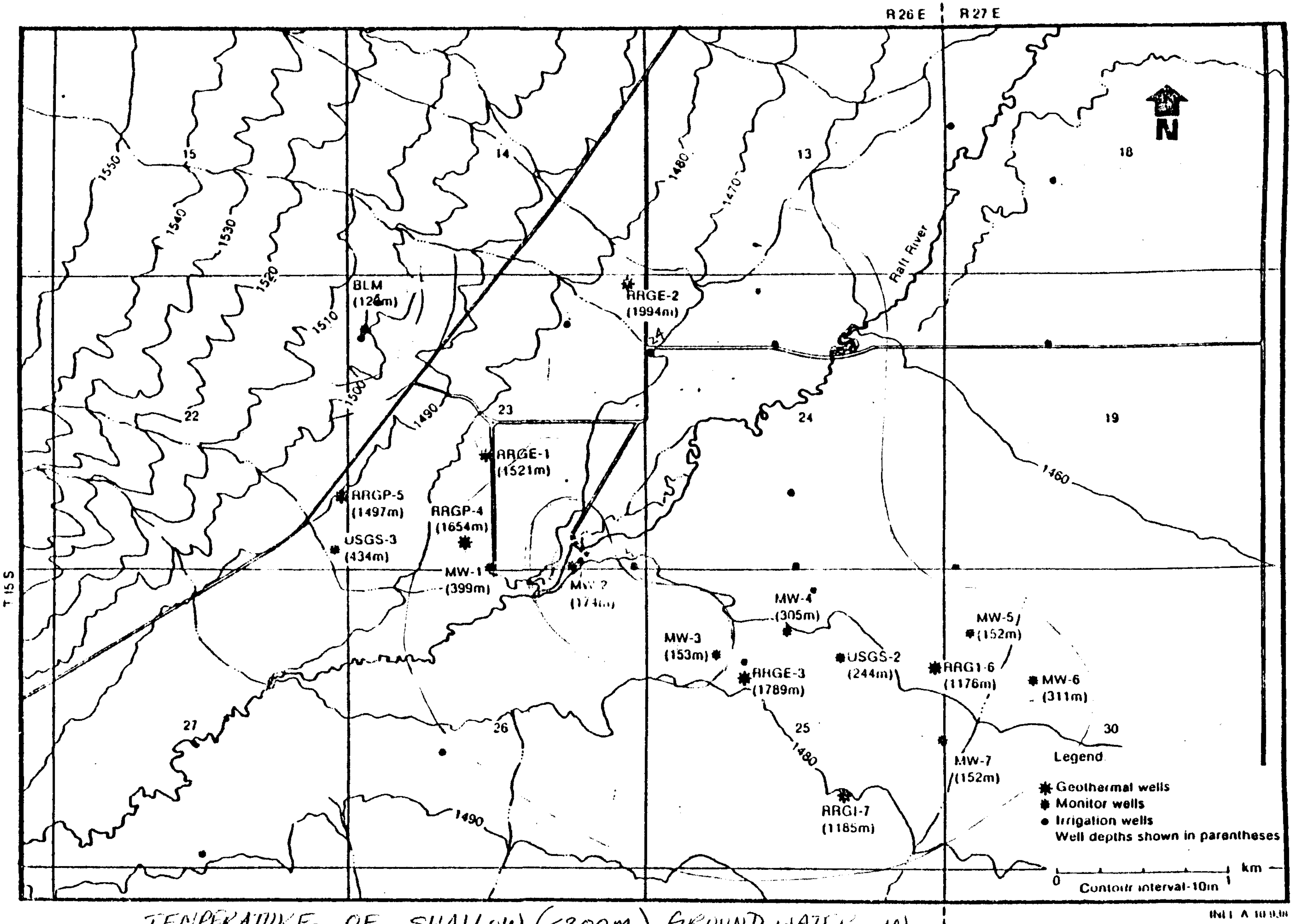
The spatial distribution of chemical species is illustrated by contouring data collected from wells. Contouring requires subjective interpretation of data, and other interpretations than those presented are possible. There is adequate control in shallow ground water around the Raft River KGRA for the preparation of map views of the shallow ground water. Most of the data from the deeper zones falls in a narrow band along a northwest-southeast line between the BLM well and monitor well #7 (MW-7) (Figure __). While this does not give adequate horizontal control for contouring, it is amenable to display in cross-section format. There is a lack of information about deep formation waters in the middle of the cross section (between RRGP-4 and RRGE-3), so the data from RRGE-3 have been weighted heavily in the contouring.

Map View

Figure __ shows the areal distribution in spl of shallow ground water (depth <200m) in the vicinity of the Raft River KGRA. Background conductance levels are less than 2000 μmhos, with some wells having conductivities as low as 1000 μmhos. Specific conductivities of ground water are higher over the geothermal resource, reaching a maximum of about 6000 μmhos southwest of the river. This same area also exhibits the highest temperatures for shallow ground water (Figure __).



SPECIFIC CONDUCTANCE OF SHALLOW (<200m) GROUND WATER IN THE VICINITY OF THE RAFT RIVER KGRA



TEMPERATURE OF SHALLOW (<200M) GROUND WATER IN
THE VICINITY OF THE RAFT RIVER KGRA.

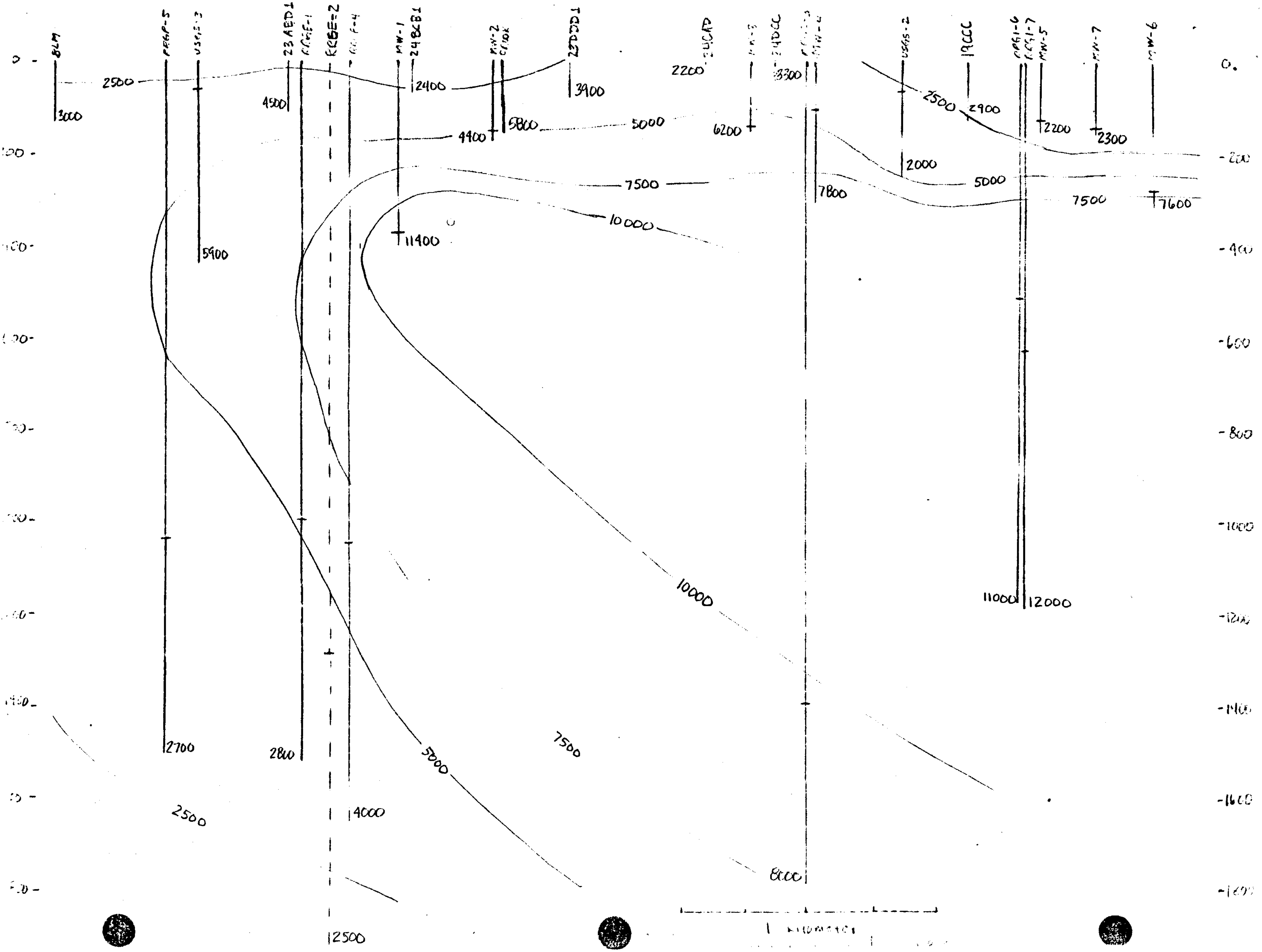
The BLM well, to the northwest, is also quite warm, but appears isolated from the warm waters near the center of the area by cooler waters. This zone of high conductivity and temperature in the ground water indicates a plume of geothermal water rising above the hot zone and mixing with shallow ground waters.

Cross Sections

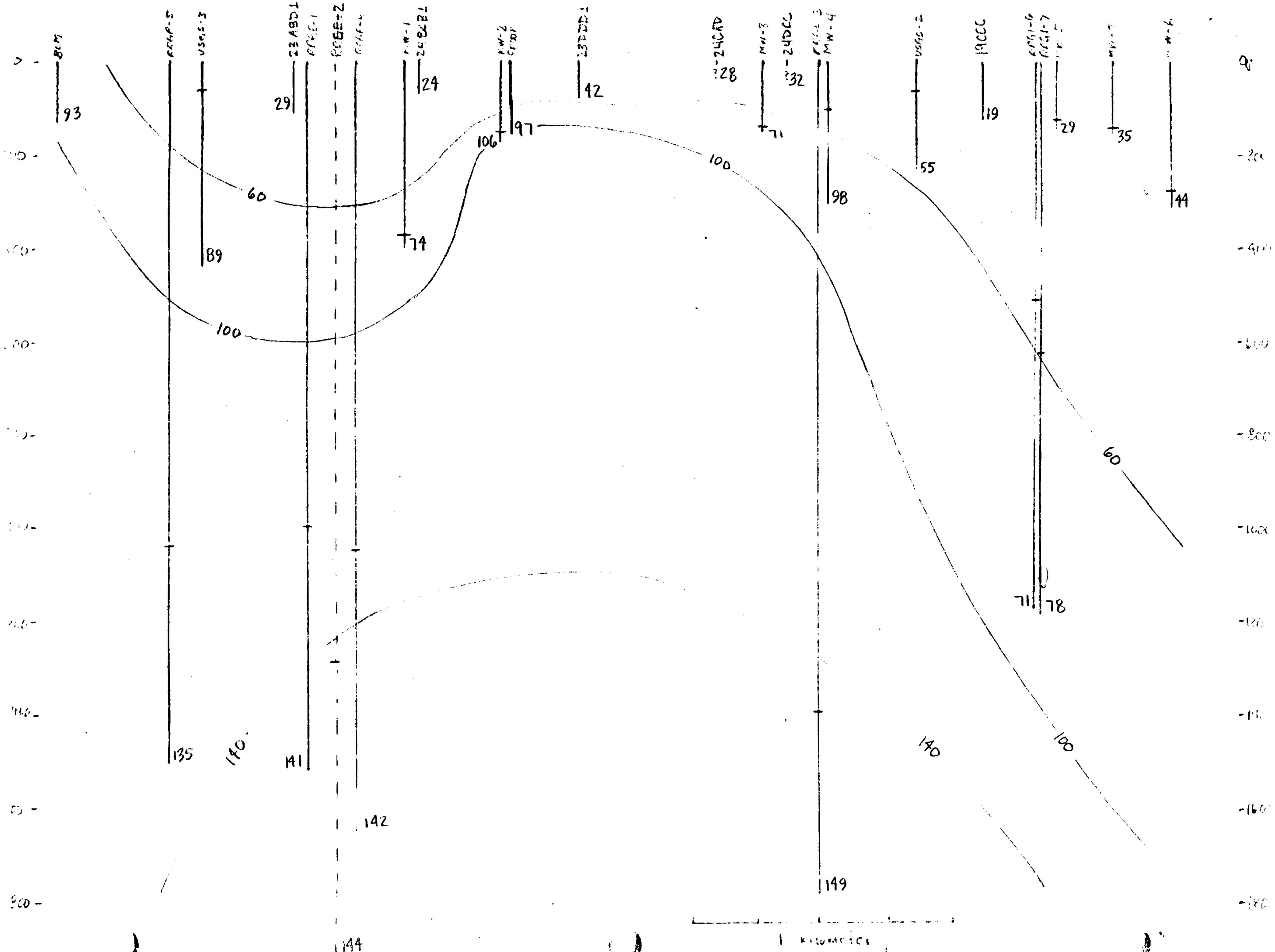
A cross section through the Raft River KGRA (location shown as A-A' in Figure __) shows variations in chemistry and temperature with depth. Wells projected onto the cross section produce some variations due to lateral variations in chemistry. Well RRGE-2 is dashed in the cross section because of its distance from the cross section. It was included to add additional information at depth.

Chemical and temperature cross sections generally show one of two patterns. One type of pattern is exhibited by spl (Figure __), with a plume of high conductivity waters moving in from the southeast through wells RRGI-6 and RRGI-7. This plume moves upwards to near the surface at MW-1. A second pattern is shown by temperature measurements. These temperatures are from downhole temperature logs for the geothermal wells and monitor wells, and from measured water temperatures for the other wells. Temperature contours show a different pattern, with contours dipping steeply to the southeast and approaching the surface near the Crook and BLM wells.

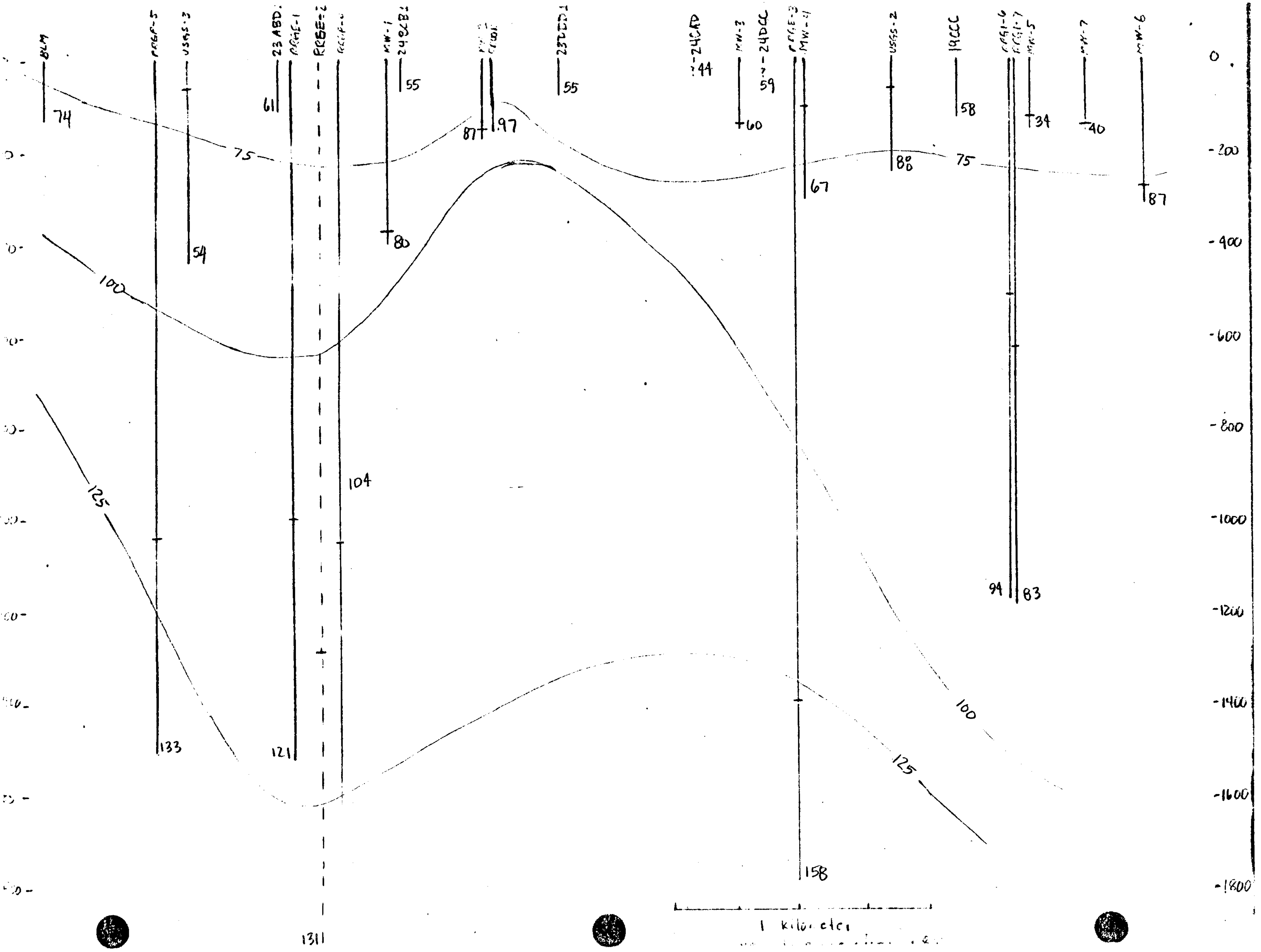
Other chemical species tend to show one of these two patterns. Silica, (Figure __) which is controlled by the temperature effects on the solubility of quartz, closely follows the appearance of the temperature cross section. The dissolved species closely follow the appearance of the conductive cross section. Calcium, for example, also shows the plume of high concentrations moving in from the southeast. Fluoride shows a unique distribution in cross section. While a plume from the southeast is still present, concentrations of fluoride in this plume are lower than in immediately surrounding areas. The highest fluoride concentrations occur in deep geothermal waters to the northwest.



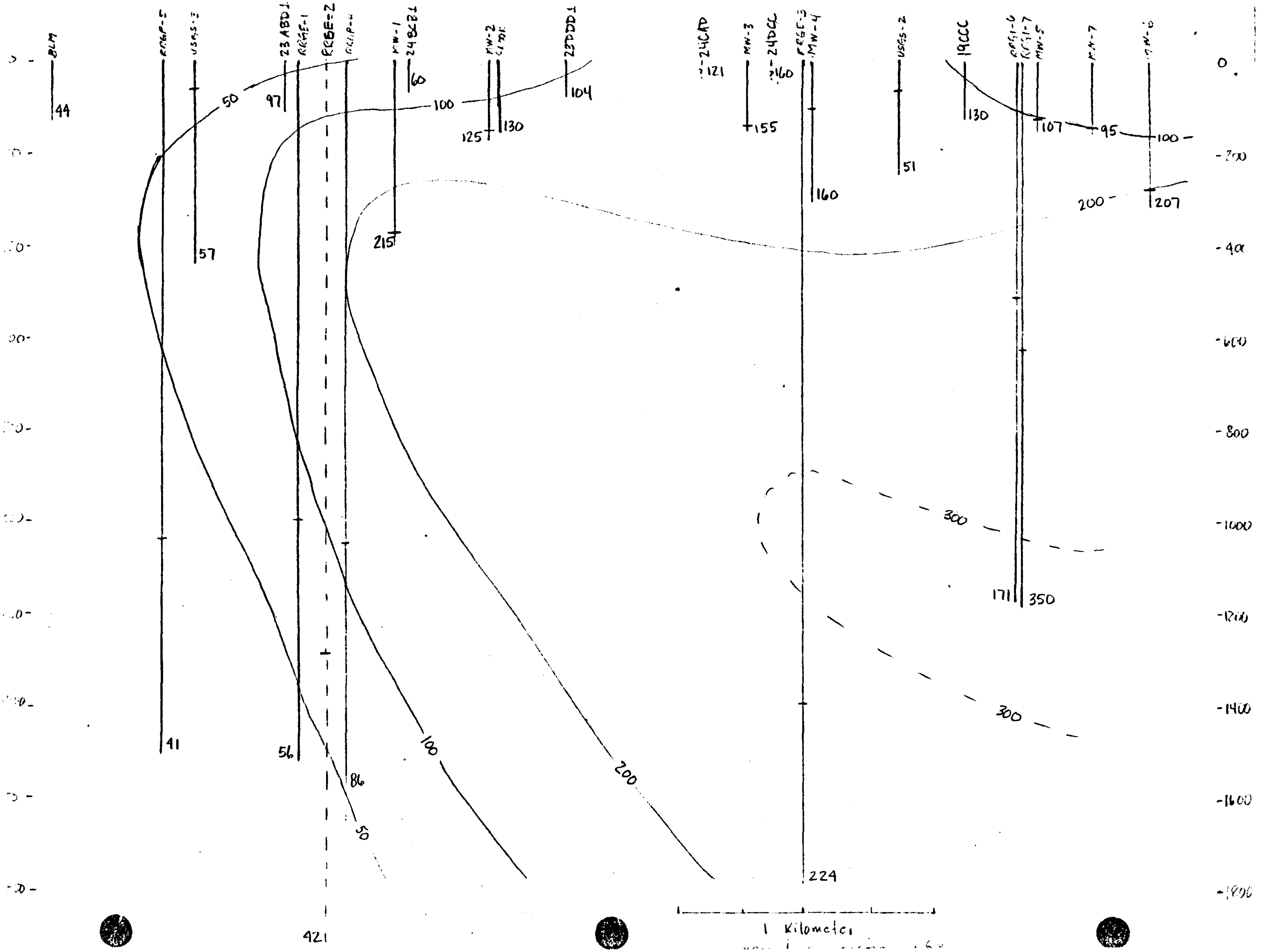
CONDUCTANCE, in micromhos



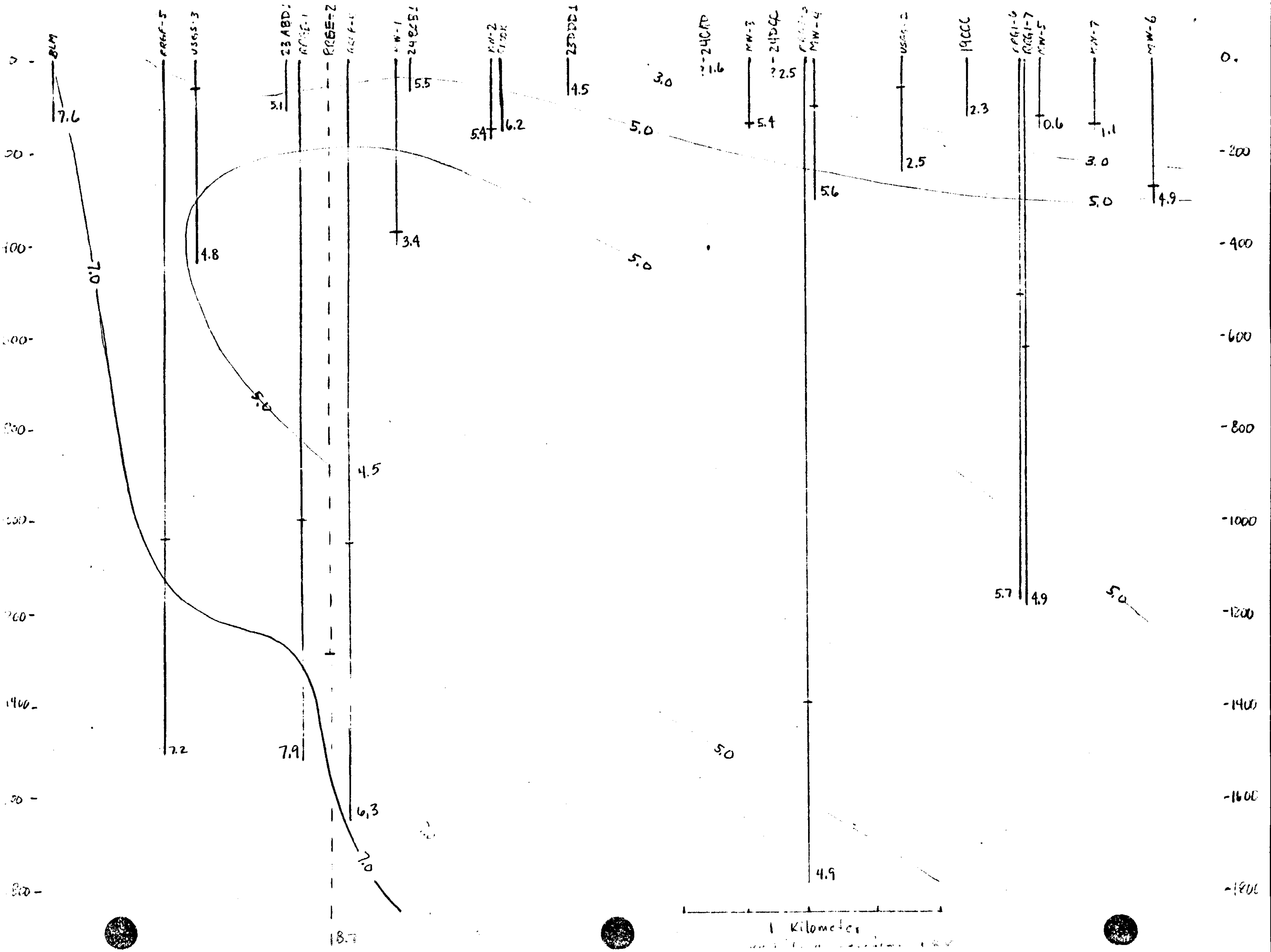
TEMPERATURE IN °C



Silica in mg/L



CALCIUM in mg/l



FLUORIDE in mg/l

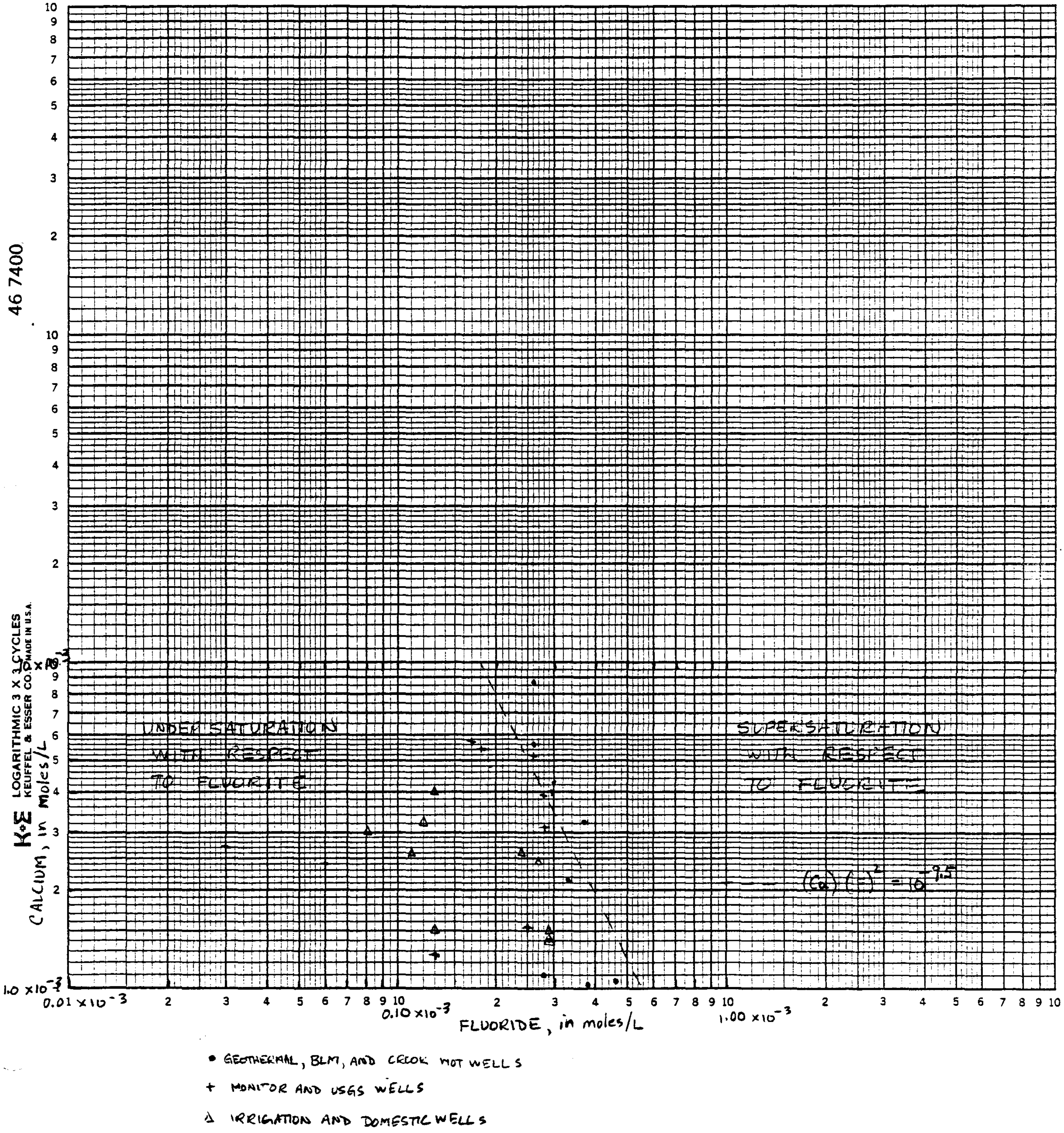
Fluorite commonly controls the maximum fluoride concentrations in hydrothermal waters (Ellis and Mahon, 1977), and may be controlling the low fluoride concentrations in the southeast of the geothermal field. Figure _ shows a plot of calcium versus fluoride, with a dashed line representing the expected calcium and fluoride concentrations in equilibrium with fluorite at about 125°C (Kharaka and Barnes, 1973). Because of temperature variations and variations in ion activities due to ionic strength variations, this dashed line does not exactly represent expected saturation with respect to fluorite for all samples. It does give the approximate upper boundary of the data, and suggests that fluorite solubility does control fluoride concentrations in the deep geothermal waters.

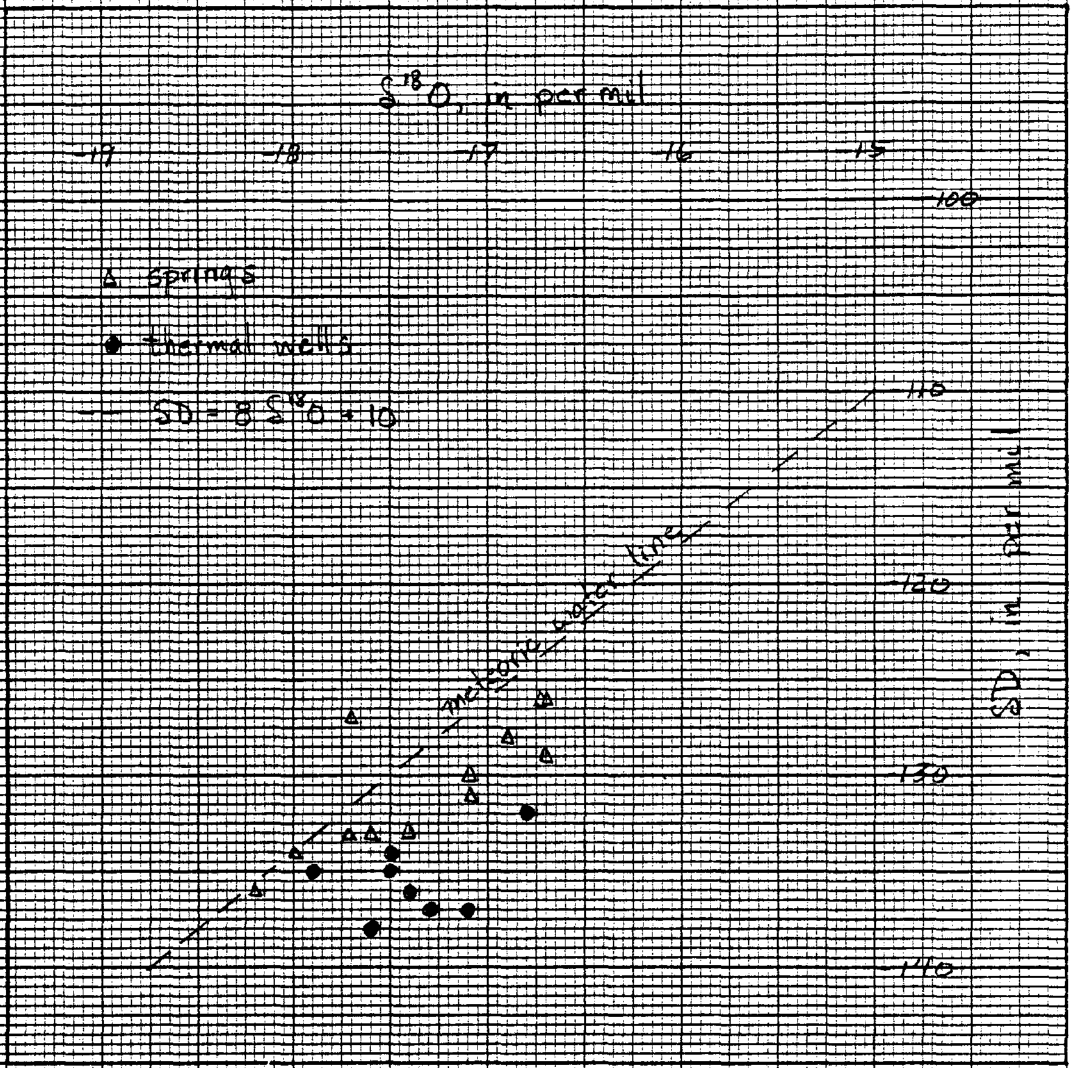
Variations in Water Chemistry

The appearance of the cross sections suggests that cooler, high conductance water moves in from the southeast at a depth between 1200 and 1600 m. This water is warmed as it passes over a heat source between wells RRGE-3 and RRGP-4, and rises by convection to the surface around the crook well. Low dissolved solids water moves in from the northwest, is heated at depth, and rises in the vicinity of the BLM well.

This suggests the presence of two different sources of water to the geothermal reservoir, having very different chemical compositions. An alternative hypothesis, is that the high dissolved solids water is derived from the low dissolved-solids water by concentration due to boiling in the reservoir or extensive alteration of rock material. Figure _ show oxygen and hydrogen isotopic compositions of ground water, both thermal waters and meteoric waters from nearby springs. Steam separation could produce large shifts in isotopic composition between waters of different dissolved solids concentrations. The graph shows no trends that would support extensive evaporation. There has been insufficient work so far to discount the derivation of salts by alteration of the rock matrix. One line of evidence against this having occurred is the small isotopic shift, which indicates relatively little isotope exchange with rock materials.

A second line of evidence against the concentration by boiling or leaching is that both require flow of water from a deep (1800 meters) zone in the northwest, diagonally upwards to shallower depths to the southeast. Current geologic evidence suggests that structural controls on both movements


46 7400
K+E LOGARITHMIC 3 X 3 CYCLES
KEUFFEL & ESSER CO. MADE IN U.S.A.
CALCIUM, in moles/L
1.0 x10⁻³
x10⁻³
UNDERSATURATION WITH RESPECT TO FLUORITE
SUPERSATURATION WITH RESPECT TO FLUORITE
(Ca)(F)² = 10⁻⁹·⁵
0.01 x10⁻³
0.10 x10⁻³
1.00 x10⁻³
FLUORIDE, in moles/L
• GEOTHERMAL, BLM, AND CROOK HOT WELLS
+ MONITOR AND USGS WELLS
Δ IRRIGATION AND DOMESTIC WELLS


δ18O, in per mil
-19
-18
-17
-16
-15
-100
-110
-120
-130
-140
δD, in per mil
△ springs
● thermal wells
— — δD = 8δ18O + 10
meteoric water line

probably are oriented in the opposite direction. That is, fracture zones dip towards the southeast.

With two waters having different chemistries, variation in the chemistry of intermediate waters can be due to mixing. This hypothesis was tested by Allen, Chaney, and McAtee (1979) for the Raft River KGRA. The low dissolved solids water from the northwest, they labeled the Bridge-Fault water (type 1), and the high dissolved solids water from the southeast, they labeled the central-valley water (type 2).

Mixing fractions are based on conductivity and calculated using equations

$$X_i C_1 + (1 - X_1) C_2 = C_i \tag{1}$$

or

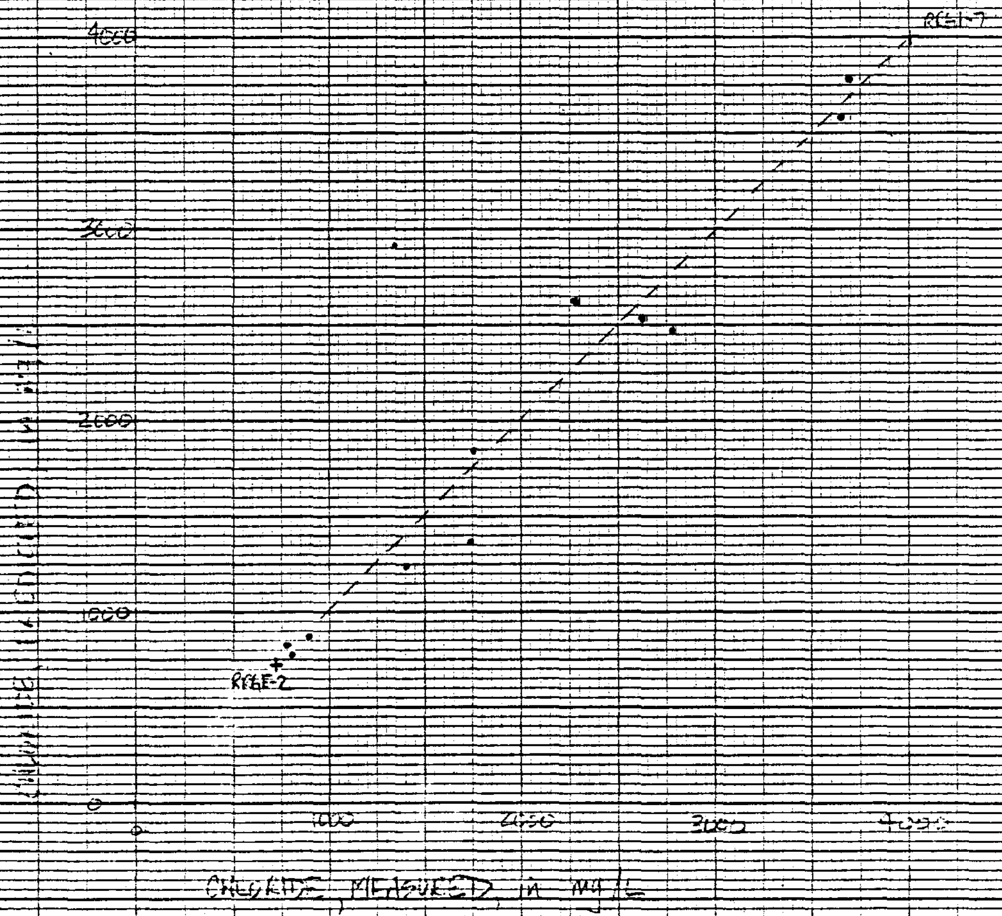
$$X_1 = \frac{C_2 - C_1}{C_2 - C_1} \tag{2}$$

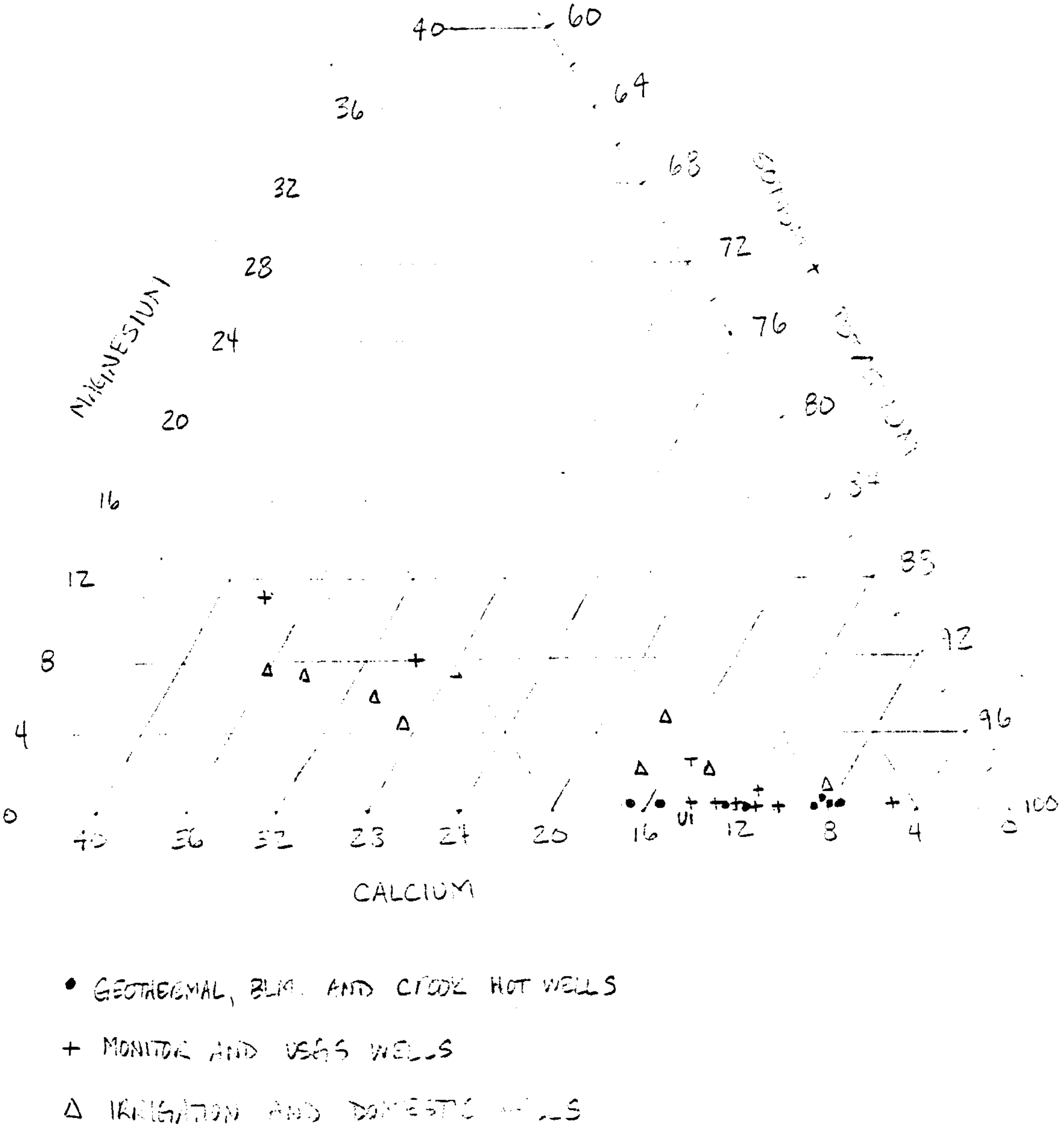
where X_i is the mixing fraction, C_i is the conductivity of mixed water, C_1 is the conductivity of Bridge-Fault water (type 1), and C_2 is the conductivity of central-valley water (type 2). For the purpose of this calculation, it is assumed that the lowest conductivity water (from RRGE-2) represents nearly pure Bridge-Fault water (C_1) and the highest conductivity water from RRGI-7 represents nearly pure central-valled water (C_2). It is recognized that these two waters probably do not represent the actual end-member waters that are mixing. This assumption will not invalidate the calculations for the purpose of mixing for intermediate waters.

Table __ shows the mixing fractions calculated by equation (2). Mixing fractions for both deep and intermediate wells are included. In the intermediate zone, the BLM well is the highest fraction of type 1 water and monitor well MW-1 the smallest fraction of type 1 water.

TABLE MIXING FRACTIONS CALCULATED FROM CONDUCTIVITY

	Well	Conductivity	Mixing Fraction of Type 1 Water
Deep	RRGE-2	2500	1,000
	RRGP-5	2700	0.979
	RRGE-1	2800	0.968
	RRGP-4	4050	0.837
	RRGE-3	8000	0.421
	RRGI-6	10800	0.126
	RRGI-7	12000	0.000
Inter-mediate	BLM	3000	0.947
	Crook	5800	0.653
	MW-2	4400	0.800
	MW-6	7600	0.463
	MW-4	7800	0.442
	MW-1	11400	0.063


CHLORIDE, CALCULATED, IN mg/L
4000
3000
2000
1000
0
0
1000
2000
3000
4000
RGEI-7
RGGE-2
CHLORIDE, MEASURED, IN mg/L


40
36
32
28
24
20
16
12
8
4
0
MAGNESIUM
60
64
68
72
76
80
84
88
92
96
100
SODIUM + POTASSIUM
40
36
32
28
24
20
16
12
8
4
0
CALCIUM
• GEOTHERMAL, BLM AND CROOK HOT WELLS
+ MONITOR AND USGS WELLS
Δ IRRIGATION AND DOMESTIC WELLS

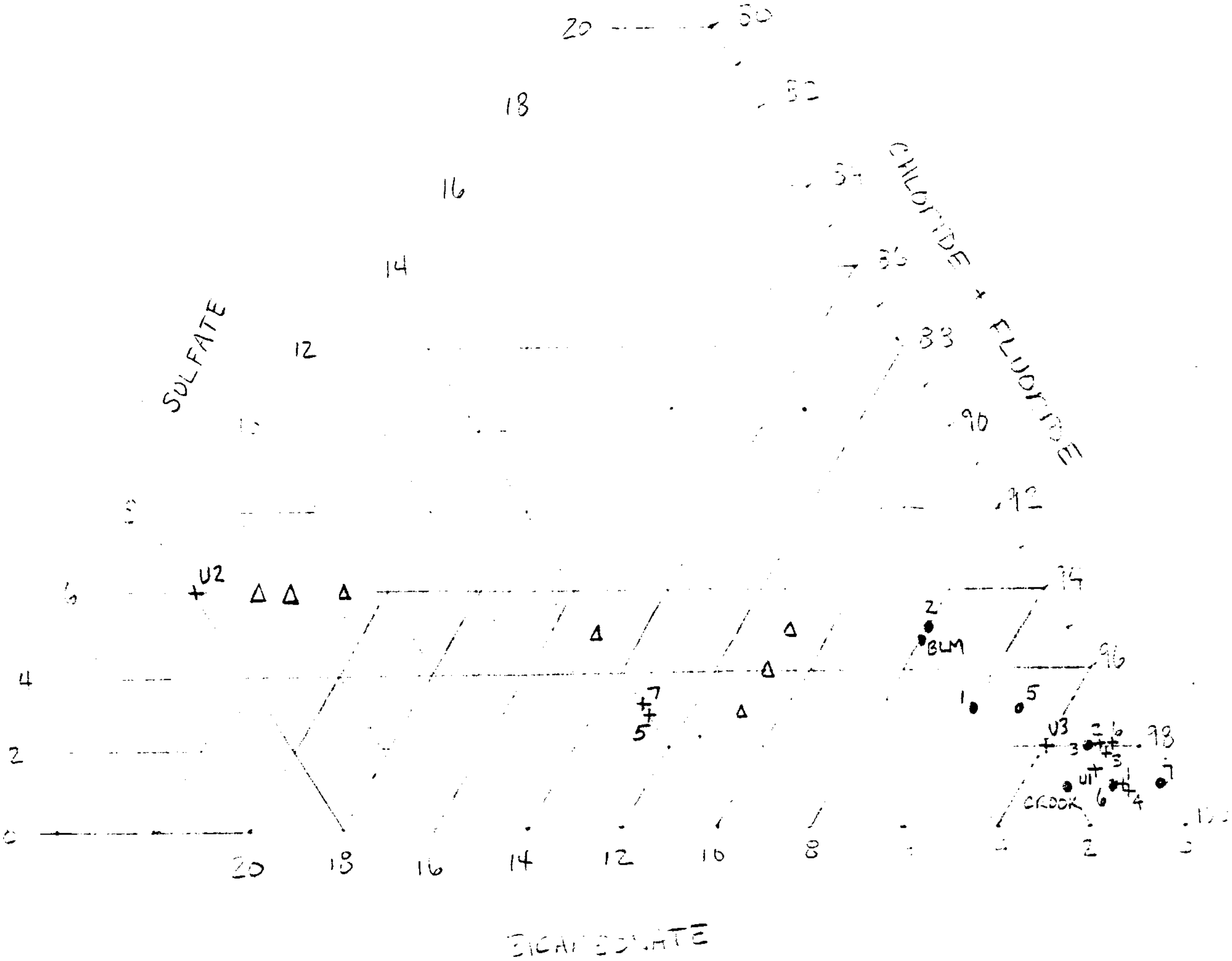
To test the mixing hypothesis, the concentration of chlonde in intermediate wells was calculated and compared to measured values. The results, illustrated in Figure __, show generally good agreement between calculated and predicted values.

Trilinear diagrams provide another convenient method for depicting the relations between water samples. Trilinear diagrams show the percent cationic and anionic compositions of water samples in terms of milliequivalents/3 per/liter (meq./L (Hem. 1970). Figures __ and __ show the trilinear diagrams for cations and anions for ground waters in the vicinity of the Raft River KGRA. Because of ion-exchange reactions that primarily affect cations, the anion trilinear diagram shows relations among water samples much more clearly. Irrigation wells and some of the monitor wells plot along a line crossing the diagram between three and six percent sulfate (Figure __). The slope of this trend changes at the point marked by wells RRGE-2 and BLM. There is a second fairly linear trend between wells RRGE-2 and RRGI-6 and RRGI-7 that depicts mixing in the geothermal reservoir.

The linear trend of the wells across the diagram and the clustering of shallow-monitor and deep-geothermal wells in the same area emphasizes the intrusion of the geothermal waters into the shallow waters. Mixing of geothermal waters with shallow ground waters is an important control on water chemistry.

Conceptual Model

Figure __ shows a block diagram depicting the movement of water in the Raft River KGRA based on geochemical and geologic evidence. The source of heat for the KGRA is in or below the quartz monzonite in sections 23, 24, 25 and 26 of township 15S, range 26E. There seems to be relatively little water associated with the heat source. Convection above this heat source draws water into the KGRA. Water from the southeast is high in dissolved solids, water from the northwest is low in dissolved solids. Movement is upwards along fracture zones dipping to the southeast associated with the Bridge Fault and various structures. The origin of the low dissolved solids water appears to be from meteoric water based on isotopic composition data. The origin of the high dissolved solids water is still unknown.



● GEOTHERMAL, BLM, AND CROOK HOT WELLS (1-7, BLM, CROOK)

\+ MONITOR AND USGS WELLS (1-7, U1, U2, U3)

Δ IRRIGATION AND DOMESTIC WELLS

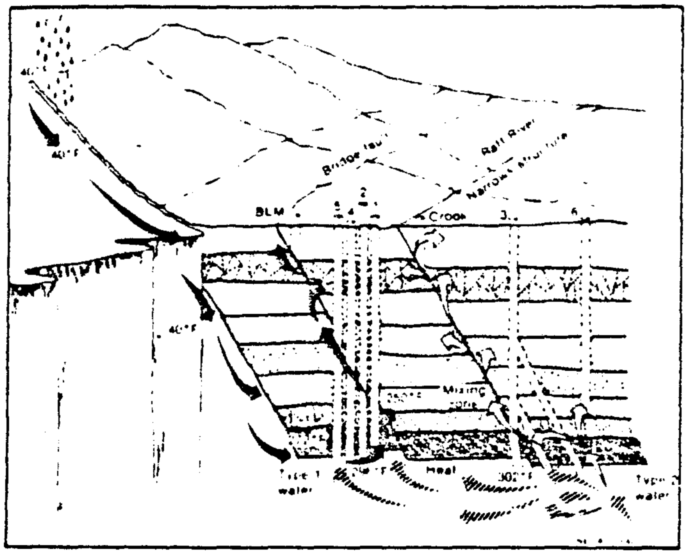


Fig. 5 Conceptual model of flow in the Raft River geothermal system.

Conclusions

Geothermal fluids in the Raft River KGRA are derived from two sources of water. Meteoric water from the northwest decends along the valley margin, is heated at depths on the order of 2,000 meters, below (and surface) moves upwards along the Bridge Fault to the surface. Water from the central-valley area, which is high in dissolved solids, is drawn into the KGRA by convection above the heat source. This water reaches the surface in the northwest corner of Section 25, township 15N, range 26E. The chemical variation in the geothermal wells can be explained by mixing of these two waters.

Shallow ground waters also show chemical evidence of mixing of meteoric waters with the higher dissolved solids geothermal waters.

Based on the conceptual model of the Raft River KGRA, the location of the two existing injection wells,RRGI-6 and RRGI-7, is very good for protecting the geothermal resource. However, their location may not be as good in terms of limiting the environmental impact of injection. The injection zone is in the plume of high dissolved solids water moving northwest from the valley center. Increased pressures from injection will increase the rate at which waters in the plume enter the shallow ground water. With more geothermal fluids rising in this area, dillution by shallow waters will decrease, and the dissolved solids in the shallow waters will increase. The limited area currently affected by the rising plume suggests that flow from the southeast is relatively small. The changes in dissolved solids in the shallow ground water expected under an increasing pressure cannot be calculated from current data.

INJECTION STUDIES

Because of environmental concerns associated with surface disposal of geothermal waters, subsurface injection of the cooled fluid from the 5MW plant is planned at the Raft River KGRA.

Two studies were carried out to evaluate potential problems of aquifer clogging during injection. The first test involved the evaluation of water compatibility, that is, the effects of mixing geothermal waters from two or more wells on the quantity of chemical precipitates formed. This indicates the potential for clogging receiving zones in injection wells due to chemical reactions. In a second test, the quantity and size distribution of suspended particulate matter was measured. This gives the potential for clogging due to physically transported material, and indicates filter sizes needed to remove particulate matter.

Water Compatibility

The water compatibility test is an empirical determination of the synergistic effects of mixing water from two or more wells. The results indicate the changes in suspended solids in the mixtures due to chemical reactions between the waters. Increases in suspended solids from precipitation reactions is an important criteria limiting the feasibility of injection. Injection of excessive particulate matter, or the formation of chemical precipitates in an aquifer can cause serious plugging problems in injection wells.

Experimental Procedure

Experiments were carried out at two temperatures to simulate two possible injection schemes. One set of experiments was carried out at $\approx 20^{\circ}$, the temperature expected for injection of water from holding ponds, and the second set was done at $\approx 70^{\circ}$C, to simulate injection of water directly from the 5MW facility. Water samples were collected from wells RRGE-1, RRGE-2, RRGE-3, RRGP-5, and RRGI-6, and filtered through 0.45 micron membrane filters to remove any suspended solids. Mixtures of one liter total volume were prepared by mixing all possible permutations of water combinations using equal portions of each water in the mixture. For example, a mixture of two craters could contain 500 mls of each. Control samples of unmixed water from each well were also included. Samples could not be collected from wells RRGP-4

~~TABLE~~

Table __ WATER COMPATIBILITY FOR GEOTHERMAL WELLS RRG-1, 2, 3, 5, AND 6

} lower case [illegible]

Sample Mixtures RRG -	Samples Collected Through a Condensor			
	Temp. 20 °C		Temp. 70 °C	
	Calculated (mg/l)	Actual (mg/l)	Calculated (mg/l)	Actual (mg/l)
1		0.6		0.0
2		1.2		0.0
3		2.4		0.5
5		0.1		0.0
6		4.1		2.4
1-2	0.9	0.1	0.0	0.0
1-3	1.5	1.1	0.3	0.0
1-5	0.4	1.1	0.0	0.0
1-6	2.4	0.9	1.2	0.0
2-3	1.8	0.5	0.3	0.0
2-5	0.7	0.2	0.0	0.0
2-6	2.7	2.6	1.2	1.2
3-5	1.3	0.1	0.3	0.0
3-6	3.3	3.6	1.5	–
5-6	2.1	2.3	1.2	0.6
1-2-3	1.4	1.9	0.2	0.0
1-2-5	0.6	0.7	0.0	0.0
1-2-6	2.0	1.2	0.8	0.0
1-3-5	1.0	0.7	0.2	0.0
1-3-6	2.4	1.6	1.0	0.0
1-5-6	1.6	1.6	0.8	0.0
2-3-5	1.2	–	0.2	0.0
2-3-6	2.6	0.0	1.0	0.0
2-5-6	1.8	1.1	0.8	1.2
3-5-6	2.3	1.5	1.0	1.0
2-3-5-6	2.0	2.5	0.7	0.2
1-3-5-6	1.8	0.9	0.7	0.0
1-2-5-6	1.5	2.6	0.6	0.0
1-2-3-6	2.1	1.7	0.7	0.5
1-2-3-5	1.1	0.0	0.1	0.0
1-2-3-5-6	1.7	0.7	0.6	0.0
mean [1]		1.25		0.19
Standard Deviation [1]		0.94		0.39
n [1]		25		25

[1] of mixtures only

– missing sample

and RRGI-7, so they were not included in the analysis.

After 24 hours at 20°C or 70°C, the mixtures were filtered through tared o.45 micron filters and the filters dried at 95°C for one hour. Residue and filter were then weighed on an analytical balance and the residue calculated by difference.

Results

The quantity of precipitate expected in the mixed samples, assuming no synergistic effects, was calculated by summing the products of the solids formed in the control samples times the fraction of the sample in the mixture. If there are no synergistic effects of mixing, the measured and calculated amounts of precipitate should be equal.

Results of the measurements and calculations are shown in Table _. The columns headed "actual" represent the weights of precipitated solids determined from filtering and weighing. The columns headed "calculated" represent the predicted quantity of precipitate assuming no interactive effects in the mixtures.

To determine if there is a significant effect on the quantity of precipitated solids due to mixing, differances between calculated and actual weights of solids were calculated. If there are no synergistic effects, the mean of the differences should equal zero. A significant positive or negative difference would indicate an enhancement or inhibition of solids formation, respectively. For the 25 mixtures held at 20°C, the average difference is -0.44 mg/l with a 95% confidence interval from -0.78 to -0.10 mg/l. For the 25 mixtures held at 70°C, the average difference is -0.37 mg/l with a 95% confidence interval from -0.53 to -0.21 mg/l. There is a significant inhibition effect due to mixing, with mixed waters producing an average of about 0.4 mg/l less precipitated solids than expected from the amount of solids precipitated from the unmixed waters.

To assess the effects of temperature on the quantity of precipitate formed, the average amount of filtered solids for the mixed samples at the two temperatures was compared. For the mixtures held at 20°C, the average was 1.25 mg/l with a standard error of the mean of 0.19 mg/l. For the samples held at 70°C, the average amount of precipitate formed was 0.19 mg/l with a standard error of 0.08 mg/l. The amount of solids formed in mixtures held at 20°C was significantly greater than for samples held at 70°C.

Examination of the amounts of solids precipitated from the unmixed samples shows that wells RRGE-1, RRGE-2 and RRGP-5 produce relatively little precipitate. Wells RRGE-3 and RRGI-6 produce from two to three times as many solids as the other wells. Hot waters injected into RRGI-6 directly from the 5MW plant can be expected to form about 0.2 mg/l of solids on the average.

Conclusions

Mixing of water from wells RRGE-1, RRGE-2, RRGE-3, RRGP-5, and RRGE-6 show no incompatibility. In fact, water mixtures show less formation of precipitated solids than anticipated from quantities formed from unmixed waters. There is a significant inhibition effect, with about 0.4 mg/l fewer solids formed than estimated. Samples held at 70°C showed significantly less precipitate formation than those held at 20°C. Injecting water directly upon leaving the power plant would minimize the formation of suspended solids. Even with only 0.2 mg/l of chemical precipitate formed, 2.2 Kg/day of solids would be injected into the aquifer assuming an average flow of 126 l/sec.

Filter Studies

Studies were carried out to evaluate the amount and particle size distribution of suspended solids in geothermal water from the Raft River KGRA. Injection of excessive suspended solids can cause clogging of injection wells, ruining their utility. Analysis of the size distribution of suspended solids would permit the sizing of filter screens for the injection system. Particle size distributions were determined for water from wells RRGE-2 and RRGE-3. Total solids were monitored during two additional tests.

Experimental Procedure

The filtering apparatus used in the tests consisted of a series of stainless steel filters in the following sizes and order - 230, 140, 90, 60, 15, and 2 microns. A 0.45 micron membrane filter was also used. The 230 and 140 micron filters were used in only one test. For determining total suspended solids, the 2.0 micron filter was used alone. The filters were

Particle Size Range (microns)	RRGE-2 -5/18/78 (mg/l)	RRGE-3 @ RRGE-3 3/21/78 (mg/l)	RRGE-3 @ RRGI-4 3/22/78 (mg/l)
0.45 - 2	0.08	0.87	1.49
2 - 15	0.09	2.12	8.12
15 - 60	0.10	0.56	6.54
60 - 90	0.11	0.51	6.41
>90	-	0.72	51.6
90-140	0.04	-	-
140-230	0.00	-	-
>230	0.06	-	-
TOTAL	0.48	4.78	74.16

Table _____ Particle size distributions of suspended solids in geothermal waters from Raft River KGRA.

placed in stainless steel filter holders, and from 20 to 100 liters of water passed through the series. Filters were dried at 105°C for three hours and weighed on an analytical balance. The quantity of suspended solids was determined by subtracting the tared weight of the filter.

Results

Table _ shows the weights of suspended solids collected on filters of various pore sizes from wells RRGE-2 and RRGE-3. The third column represents water from well RRGE-3 collected just before injection into well RRGI-4, after it had passed through the pipeline system connecting the two wells. The quantity of suspended solids from well RRGE-3 is much higher than from well RRGE-2. A major source of suspended material is from the distribution system itself. The distribution of particle sizes shows that almost all of the particles from the wells are less than 90 microns in diameter. Particles picked up in the distribution system are larger, and are larger than 90 microns.

To test for temporal effects, well RRGE-2 was tested for total suspended solids every 24 hours for five days during an injection test of well RRGI-6. There was a general increasing trend in solids from 0.17 mg/l the first day to just over 1 mg/l on the fifth day. Concentrations were in the same range as for the earlier test on well RRGE-2. Five days, however, was not sufficient time for the solids to stabalize, and the long term suspended solids concentration can not be predicted from this data.

Suspended solids were determined during a fourth injection test, when water from the holding pond at well RRGE-1 was injected into well RRGI-7. The average concentration of suspended solids in this water was 34.8 mg/l, much higher than produced from either well RRGE-2 or RRGE-3.

Conclusions

Knowing particle size of the undissolved solids in water to be injected is important in determining filter size, designing filtering systems, and determining the impact on the production zones in an injection well. The studies of particle size conducted on the injection of well RRGE-2 water into well RRGP-4 and the injection of well RRGE-3 water into well RRGP-4 indicated that ≃ 80% of the undissolved solids were smaller than 90 microns.

Also in well RRGE-3, 35.5% of the undissolved solids were between 2.0 and 15.0 microns. This would require very small filters to remove the major portion of the undissolved solids. Large amounts of suspended solids are picked up in the pipeline carrying water to the injection well. About 94% of the solids measured at the injection of RRGI-4 were from this source. Without removal of these suspended solids, 800 kg of solids per day could be injected into the ground. Even with installation of 90 micron filters, however, 245 kg of solids per day would be injected assuming a plant operating flow of 126 l/sec.. This is a rather large quantity of solids, and could significantly interfere with injection of the spent fluids.

The filter study of the water from well RRGE-2 being injected into well RRGI-6 indicated a trend of increasing amounts of undissolved solids as the test progressed. Unfortunately, the test was terminated before it could be determined if the increase in solids was the result of the wellbore being flushed of residual materials.

Water injected from holding ponds was very much higher in suspended solids than water pumped directly from wells. Holding wastes in ponds could significantly increase the quantity of solids needed to be filtered out before injection, unless an effort is made to floculate and remove these solids in the pond.

CHEMICAL LOGGING

The growth of the geothermal industry has created a need for techniques that can be used during drilling operations to determine the depth at which to complete a well, depth for casing placement, and the best method for well development. Techniques such as geophysical logging, lithologic logging, and core drilling, developed by the petroleum industry, can be useful. Little development has been oriented towards the specific conditions encountered during geothermal exploration and well drilling. Chemical logging (McAtee and Allen, 1979) is a method developed at the Raft River KGRA for geothermal applications. The concept of geochemical logging originated during the drilling of well RRGE-3, and was developed nd refined during the drilling of RRGP-4, RRGP-5, and RRGI-6.

The method involves the periodic collection of drilling fluid for chemical analysis while drilling is in progress. Chemical analyses are performed to determine the concentrations of chemical geothermometer species and other indicators of geothermal water. Changes in the chemical composition of drilling fluids indicates the entrance of formation waters into the well bore. Changes in particular species can be used to indicate the presence of geothermal water.

Changes in the chemical composition of the drilling fluid result from mixing of the fluid with water from aquifers penetrated by the drill string. Figure _ is a cross-sectional view of a drill string that has penetrated several water-bearing strata. Drilling fluid is pumped through the drill stem and bit, returning to the surface between the drill stem and the wall of the borehole carrying the drill cuttings with it. When a water-bearing stratum is penetrated, it contributes water to the drilling fluid, diluting the fluid and causing variations in its chemical composition. Generally, after the drill string passes through the water-bearing stratum, the drilling mud or sediments in the drill water form a mud cake on the walls of the borehole sealing off the aquifer. If the flow from the stratum is too great and it is not sealed by the mud cake, the incoming water will produce a permanent change in the background chemical composition of the drilling fluid. Determing the change in chemical composition of the drilling fluid as each aquifer is penetrated, and the separation of this change from the chemical background contributed by the drilling fluid, is the essence of the chemical log.

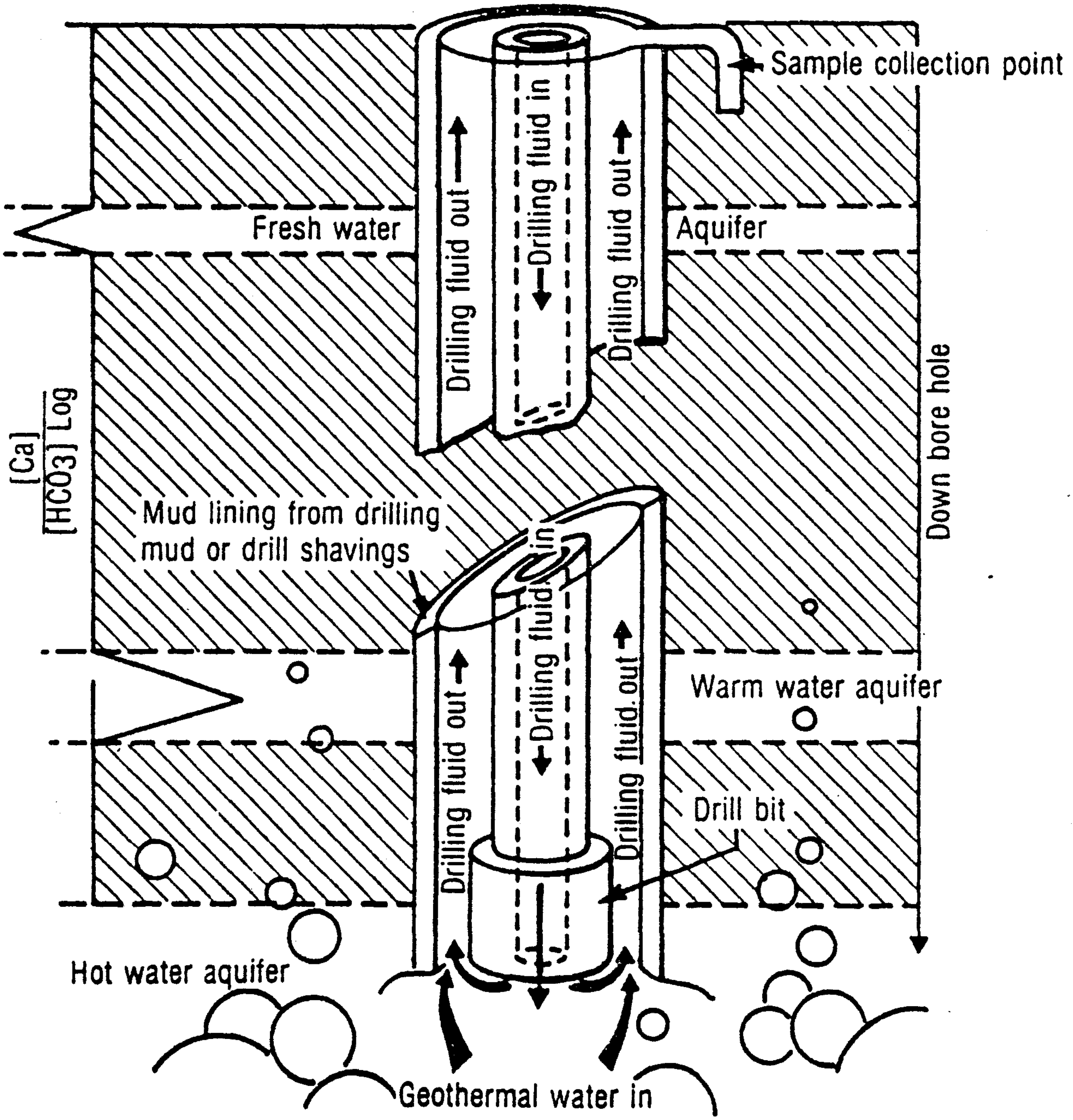


Fig. _ : Changes in drilling fluid composition by fluid from a geothermal aquifer.

Sampling Procedure

The procedure is to collect samples of the drill return fluid at specified depth intervals. Drill fluid is pumped from the mud pit through the drill string and returns up the borehole between the borehole walls and the drill stem (Figure _). Drill fluid samples are collected at the point where the drill return fluid flows into the mud pit. At Raft River, samples of the drill fluid returns were collected at 15- to 120-m intervals of drilling depth. Samples of four to five liters were collected to insure an adequate sample when drilling mud was being used. Once the borehole was cased, only geothermal water was used for a circulating medium and one-liter samples were collected. Drilling mud and other residues were separated from the water sample by centrifuging and filtering. In most cases, the centrifuge would not settle the gelatinous mud suspension. Filtering with a coarse filter was the method most often used. Samples were analyzed for conductivity, pH, alkalinity, chloride, fluoride, calcium, and silica, and chemical logs were prepared by plotting the concentrations of the chemical species versus sample depth. The sampling depths were connected for log time using information supplied from the personnel compiling the mud logs.

Interpretation of chemical logs is complicated by a number of factors, the most important of which is the effects of drilling mud on the composition of drilling fluids. Drilling muds adsorb much of the free hydrogen ion in the solution raising the pH, and consequently the alkalinity. Other cations will also be affected by ion exchange reactions, but anions will be relatively unaffected. Problems arising from this will not seriously interfer with the chemical logging technique because the plot with depth will show changes relative to the background. These changes relative to background chemistry are more important than the absolute values of species. Instances when the drilling fluid changes, for example when drilling mud is replaced by mud-free geothermal water, will make comparisons between different parts of the hole difficult if not impossible.

Results

At Raft River, upper portions of the holes were drilled with mud mixed with geothermal fluid from the other wells. Once the casing was set, further drilling was done with geothermal water alone. Because of the similarity between the drilling-fluid make-up water and penetrated geothermal zones,

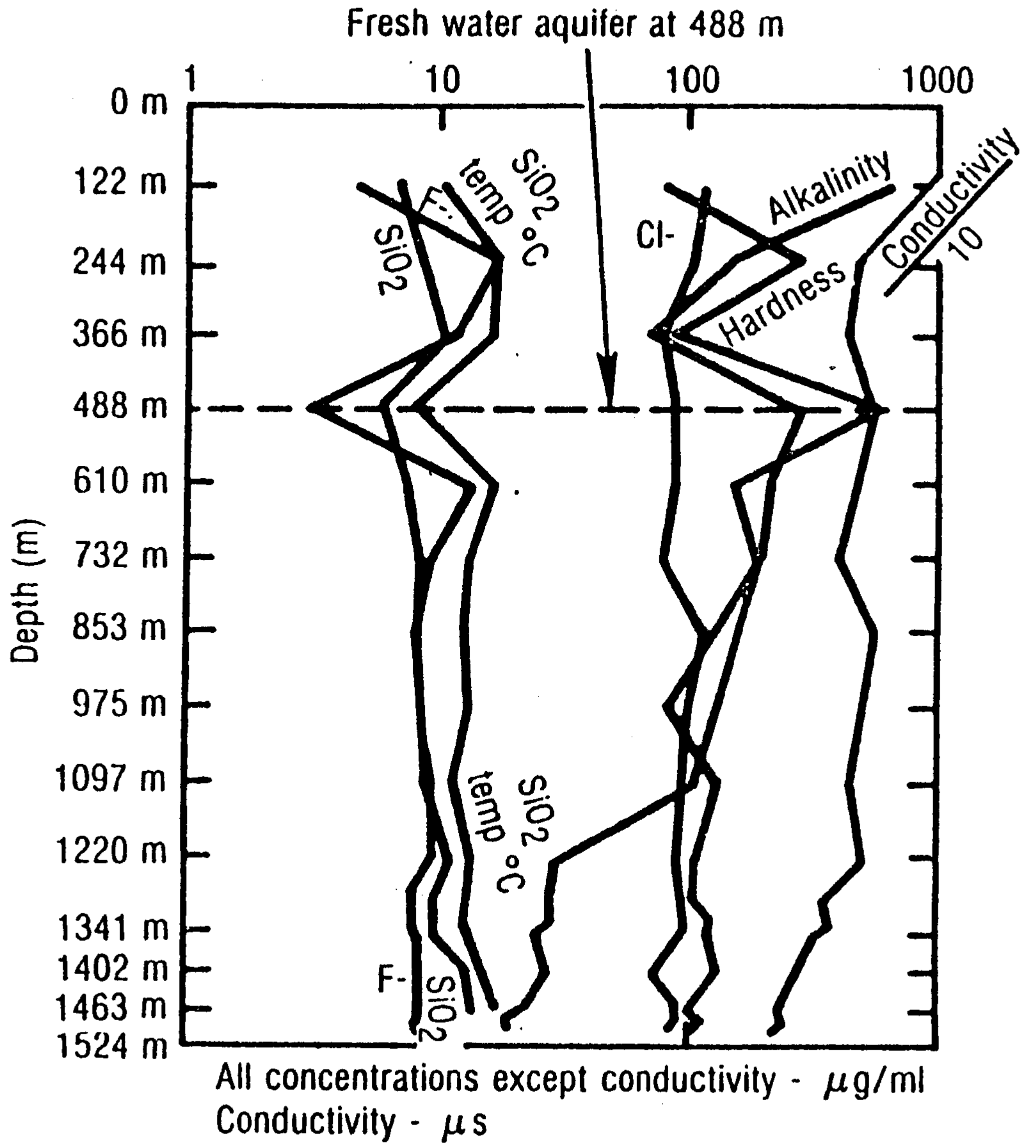


Fig. 1—Chemical log of all analyzed chemical species for well RRGP-5.

anticipated chemical composition changes in the drilling fluid would be small. For fresh-water intrusion into the drill bore, water would increase in hardness and alkalinity, and decrease in, fluoride, chloride, and conductivity. Changes induced by intrusion of mixtures of fresh and geothermal water would produce lesser changes in drilling fluid composition.

The chemical log is prepared by plotting the concentrations of the analyzed chemical species versus the drill string depth. The resulting log is a profile of the chemical change taking place in the drill fluid during the drilling operation. Figure _ is an example of this type of log, showing data collected during the drilling of RRGP-5. The log shows the influence of a fresh-water aquifer on the chemical composition of the drill fluid at 488 M.. At this depth, there are sharp increases in the alkalinity and hardness, and sharp decreases in fluoride and silica concentrations. This would be a typical change in chemical composition when fresh water dilutes the drilling water. The increase in chloride ion concentration and conductivity also indicate, however, that the fresh-water aquifer had geothermal water intrusion. The production zone of a geothermal aquifer was penetrated at 1280 m. Because the drill fluid was geothermal water similar to that in the aquifer, only small changes were observed in the drill fluid chemical composition. There was a small increase in SiO_2 concentration and a small decrease in conductivity. The decrease in alkalinity was the only large change detected at this depth.

Additional chemical logs using ratios of the analyzed chemical species were evaluated, with emphasis on ratios used to indicate hydrothermal alteration and geothermal temperatures. The chemical log of the ratio of calcium to alkalinity gave the best correlation to the temperature log of the geothermal wells. For the logs illustrated here, alkalinity has been recalculated as bicarbonate. The Ca/HCO_3 ratio log also showed that as the drill approached a geothermal zone, the ratio increased before the zone was reached, with the resulting chemical log displaced uphole relative to the temperature log. The uphole displacement varied between 16 and 120 m for the wells tested, and appears to be a function of the permeability or fracturing of material above the geothermal aquifer. This characteristic of the calcium bicarbonate ration, of anticipating geothermal aquifers, combined with the information on the permeability of stratum already penetrated, furnished by the mud logger, could be used to determine the depth at which to set the well casing.

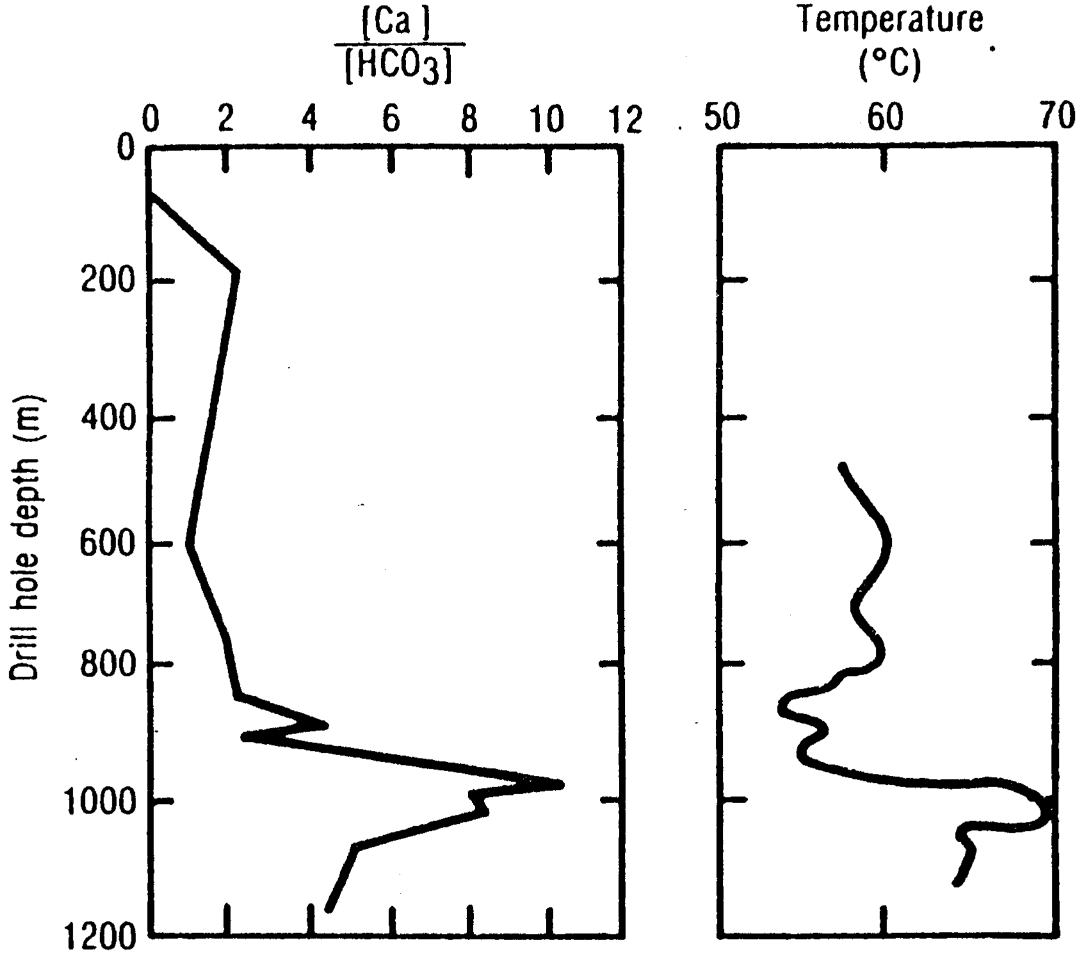


Fig. 8 $\frac{[Ca^{++}]}{[HCO_3^-]}$ chemical log and temperature log for well RRGI-6.

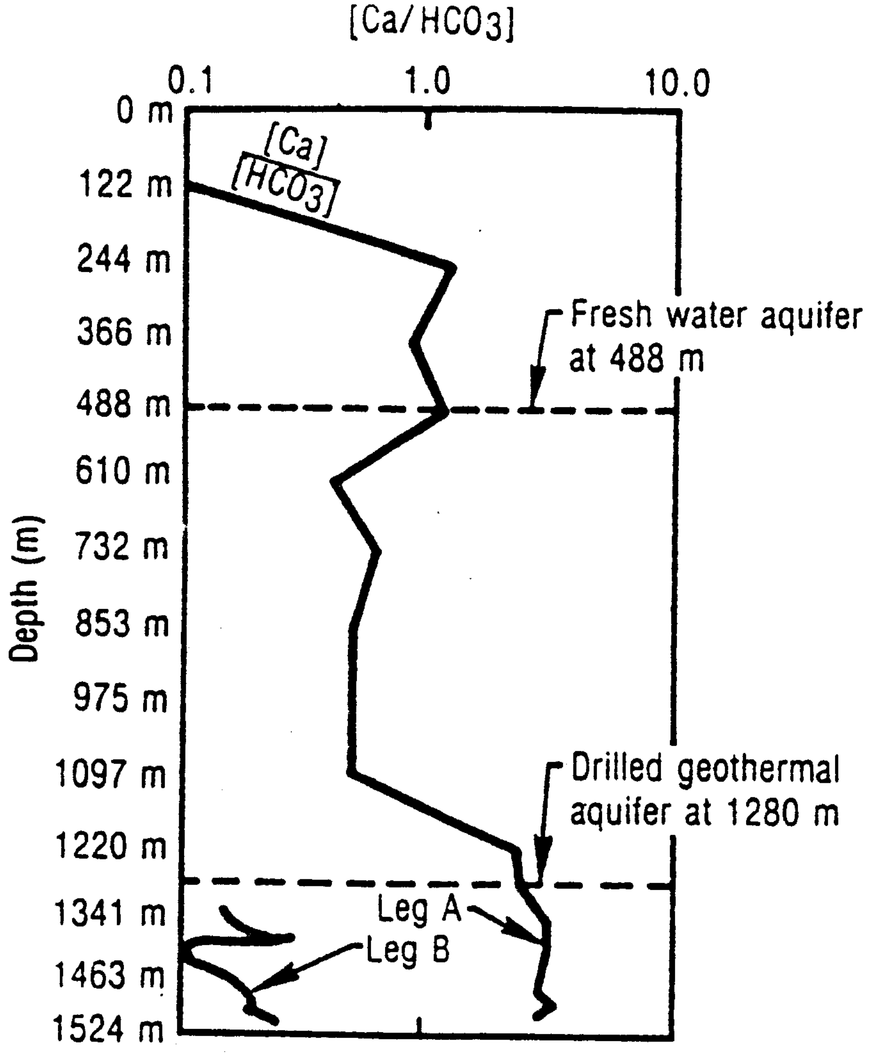


Fig. 4 $\frac{[Ca^{++}]}{[HCO_3^-]}$ chemical log for well RRGP-5.

The first program designed specifically for chemical logging of a well was conducted on well RRGI-6 at Raft River. The purpose of the program was to chemically characterize the aquifers penetrated by the drill string. Samples were collected at 120-m intervals to a depth of 911 m and then every 60 m to total depth. Comparison of the calcium/bicarbonate ratio to the temperature log revealed similarities as shown in Figure _. The calcium/bicarbonate log is displaced about 60 m uphole relative to the temperature log.

Further verification of chemical logging was accomplished during the drilling of RRGP-5. Comparison of chemical and geophysical logs collected at RRGI-6 indicated the need for more frequent sampling to increase the resolution of the chemical log.

The procedure for the well-drilling operation at RRGE-5 was:

1. Sample intervals were 120 m until changes were observed in the chemical log, indicating increasing temperature.
2. When increasing temperature was detected, the sampling interval was 60 m.
3. Samples were collected whenever the driller detected structural changes during the drilling operation.

The resulting chemical log, in which all the chemical species analyzed were plotted, is shown in Figure _, and the calcium/bicarbonate chemical log is shown in Figure _. Evaluation of the calcium/bicarbonate log reveals a sharp increase in temperature at a depth of 1220 m. This increase in the calcium/bicarbonate ratio was observed until the drill string reached a depth of 1280 m, where a flow of hot water with an estimated rate of 68 l/sec was observed. Geothermal water from the 1280 m depth washed away the chemical profile of the well for the remainder of drilling. The lower part of this borehole was lost when a concrete plug was set at 1051 m depth to install the well casing. After the well was cased and re-entry was made with the drill string, the concrete plug could not be drilled through. Sidetrack drilling was initiated at the top of the plug, but the second leg either did not penetrate the high-flow zone penetrated in the first leg or the fractures were sealed with concrete. The second leg is shown as Leg B in Figure _, and indicates the penetration of a narrow, hot-water-bearing aquifer, which flowed at about 13 l/sec with a maximum temperature of 123°C.

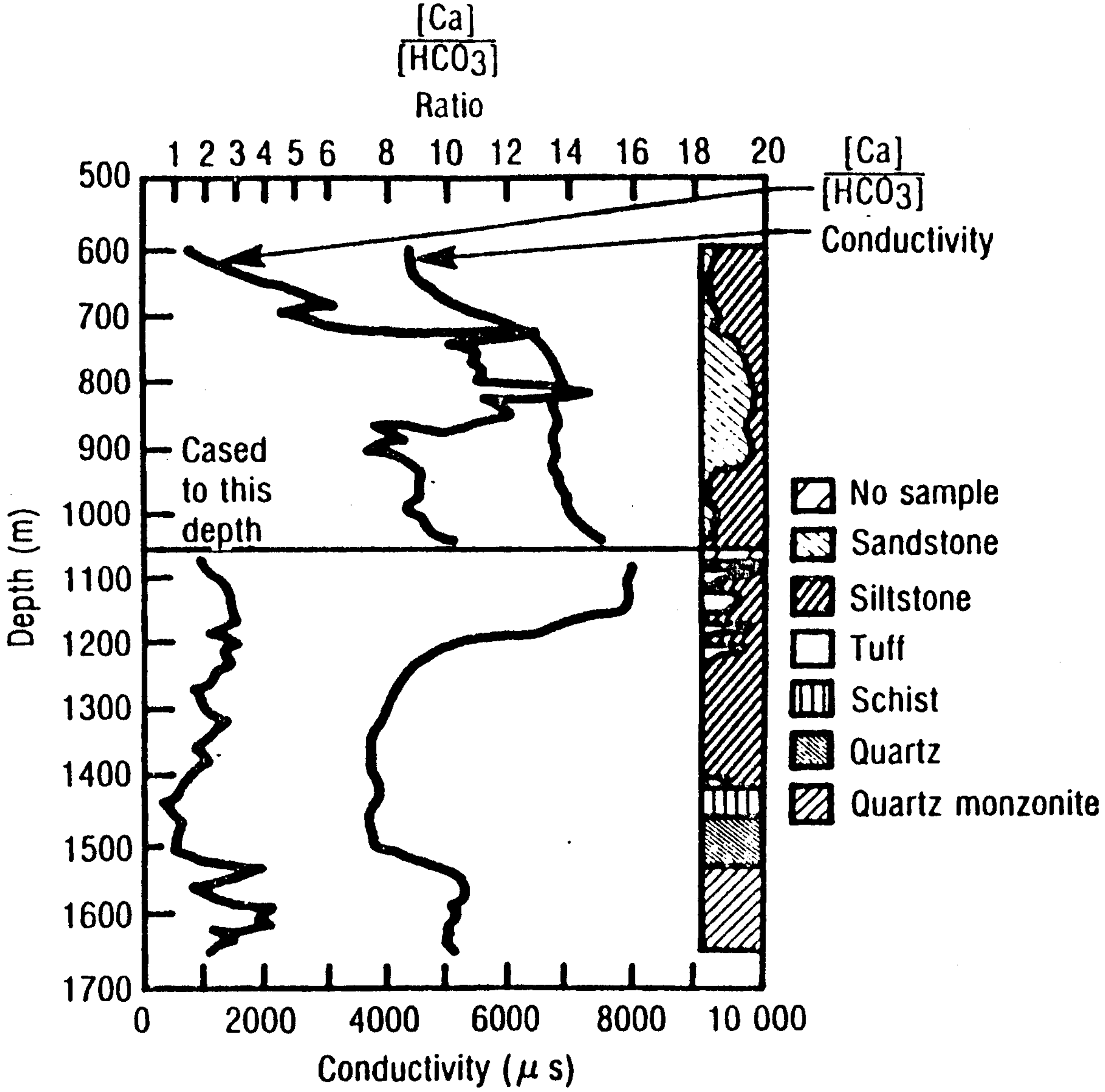


Fig. 5 $\frac{[Ca^{++}]}{[HCO_3^-]}$ chemical log for well RRGP-4A.

Figure _ shows the calcium/bicarbonate chemical log collected during the redrilling of well RRGI-4 with the object of converting an injection well into a production well. Sidetrack drilling started at 565 m to a total depth of 1650 m for Leg A. To improve resolution, samples were taken at 15 m intervals with additional samples collected at 8 m intervals where the driller detected structural changes. To make the chemical log more useful as a predictive tool, the calcium/bicarbonate chemical log was kept current with the drilling progress. The object was to anticipate any significant temperature changes before the drill string reached a production zone. At a depth of 1520 m the driller noticed a decrease in drilling rate when the drill bit encountered a hard stratum about 10 m before penetration of a narrow, low-producing, hot-water zone. The calcium/bicarbonate ratio began to increase about the time the drill reached the hard stratum, and continue to increase as the zone was penetrated. The ratio decreased after the drill passed through the producing zone. This same sequence was repeated at 1580 m. The combined flow of the two producing zones was about 2.25 l/sec, with water temperatures above the boiling point.

An upper geothermal zone was penetrated by the drill between 700 and 870 m, with the calcium/bicarbonate ratio increasing sharply through this area. In this upper portion of the hole, drilling mud was being used in the drilling fluid. Although the background chemical composition of the fluid was much different because of the presence of the drilling mud, the change in the ratio is still quite apparent. After casing the upper hole, to a depth of 1070 m, the background calcium/bicarbonate ratio changed significantly. Comparison of the chemical and lithologic logs of the upper portion of the well bore, shows that the section having high calcium/bicarbonate ratio's corresponds to a sandstone layer. Geophysical logging confirmed that this sandstone layer is an aquifer.

Conclusions

The series of chemical logging studies conducted druing the drilling operations at the Raft River geothermal site were important to the development of the method. The purpose of the study was to develop chemical logs of good resolution that could be useful as a support tool to drilling operations. It also assisted in the correlation of the various geophysical logs. It defined chemical composition of aquifer fluids and developed chemical profiles of the borehole.

The quality of the chemical logs is defined here as the ability to accurately correlate chemical concentration changes with definite well depths. This is the resolution of the log, and it is dependent on sampling frequencies. The 16-m sampling interval used in chemically logging well RRGP-4A was adequate to produce a log of good resolution. However, when comparing specific sections of the chemical log to a continuous geophysical log, the chemical log is difficult to correlate if the sampling interval of the chemical log is greater than the size of the feature on the geophysical log.

The ability of the chemical log to furnish support to the drilling operation was evident during drilling of RRGP-4A. The calcium/bicarbonate chemical log was used to determine if the drill was approaching a geothermal production zone. Although the production of the well was small, the chemical log did indicate the two small, hot-water-bearing zones prior to penetration by the drill.