AMAX EXPLORATION, INC.
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GEOTHERMAL BRANCH

INTER-OFFICE MEMORANDUM

SUBJECT: Livermore Downward Continuation DATE: March 27, 1980

TO: William M. Dolan

FROM: Arthur L. Lange

The downward continuation of temperature isotherms performed by D. Blackwell has been replotted onto our 1:24000 Calistoga base. As presented the results were very confusing and contained numerous errors. In replotting, I have separated the various interpretations onto individual plots and overlays, so that they can be better understood.

Plot I: Heatflow contours and well locations are shown on the base map. The values are corrected for topography.

Overlay 1: Heatflow profiles are drawn for section BB' drawn through AMAX #1. The dotted curve is an alternate profile, incorporating higher values to the northeast. Below, the solid isotherms are drawn for a 240°C source at about 3km depth based on two-dimensional structure. The effect of alternate heatflow has been omitted throughout the presentation in order to keep the plots readable. Their effect is simply a slight pull-up in isotherms to the northeast.

Overlay 2: Here, dashed isotherms represent the pattern due to a 150°C source at a depth of about 2km (2-dimensional).

Plot II: Overlay 1: The geology profile along AA', through the thermal anomaly is here generalized (from KOENIG).

Overlay 2: Heatflow curves A and B are based on the assumption that the high thermal conductivity near-surface continues to depth; the dotted curve again represents the alternate higher values. The corresponding isotherms are depicted for a 240° source at about 3km in a two-dimensional environment.

Overlay 3: For the same heatflow profiles, the isotherms resulting from a 150° source at about 2km are plotted dashed (2D model).

Plot III; Overlay 1: Again, the geologic section, along AA'.

Overlay 2: Heatflow curves C and D are based on the assumption that a near-surface horizontal lenticular zone of higher conductivity occupies

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the thermal anomaly, and that below this zone, condutivities decrease. Correspondingly, thermal gradients increase to pull up the isotherms. This plot is based on two-dimensional structure.

Overlay 3: Curves C and D are here interpreted in terms of a three-dimensional model; i.e., finite strike-length is assumed, for a near-surface horizontal zone of higher conductivity.

Determination of the thermal conductivity section seems to be the crux of the problem and holds the answer to the question of whether or not a deep test in James Creek Canyon will reach production temperature. Interpretations of gravity, EM, and MT results hopefully will reveal a lithologic contrast that might relate to thermal conductivty. Ultimately a temperature hole drilled to 600m or more should penetrate this zone and detect the conjectured increase in temperature gradient corresponding to decreasing thermal conductivity.

Arthur L. Lange

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MODELING OF GEOTHERMAL GRADIENT DATA AT THE LIVERMORE PROPERTY, CALIFORNIA

by

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March 23, 1976

Modeling of Geothermal Gradient Data
at the Livermore Property, California

INTRODUCTION

Past exploration experience indicates that heat flow and geothermal gradient are among the most useful geophysical exploration techniques at The Geysers, California. In general the heat flow outside the steam reservoir is conductive and measured gradients in 100-150 meter drill holes can be extrapolated with reasonable confidence, assuming no major changes in thermal conductivity, to calculate the depth to the steam zone (see Urban and others, 1976, for an example).

When observed gradients are high enough that projected drilling depths are 1-2 km and the area is not near the field boundaries, simple extrapolations can be used to predict drilling depths. As projected drilling depths increase then the method of calculation of such depths becomes more important. Such factors as terrain effects, variations in thermal conductivity, and data uncertainties must then be taken into account. This study was undertaken in order to evaluate some of these variables for the Livermore Property, California. In particular the object of this study was to evaluate the effects of terrain on the available data, to attempt to construct in a mathematically correct way the subsurface isotherms, and to calculate an estimate of the depth and shape of the steam reservoir beneath the property.

DATA USED

The data used in the study are shown in Plate 1. The base of Plate 1 is a topographic map of the general area and included on the map are the location, average gradient(s), thermal conductivity, and heat flow for available wells in the area. Some data are shown for the area of the Castle Rock Springs field of Aminoil as well as the Livermore property. In addition to the information on Plate 1 the details of the temperature-depth data and the thermal conductivity measurements, and the lithologies encountered in the three 600 m test holes were available.

Using the available data three cross-sections were prepared for analysis. The locations of the three sections are shown on Plate 1 (AA', BC, and BD). Profile AA' was chosen to investigate the nature of the solution over a demonstrated steam field. Profiles BC and BD were chosen to sample as much of the Livermore property exploration target as possible with profiles. The results obtained for profile BD were essentially the same as those found for profile BC and so BD will not be discussed further in the report.

PROCEDURES OF STUDY

The method of study consisted of solving the downward (sourceward) continuation problem for conductive heat flow in a homogeneous medium and calculating the temperature at depth from the calculated gradient field as a function of depth. The solution technique is similar to the continuation techniques as applied to aeromagnetic data to match different flight elevations or to gravity data to calculate equivalent density layers. In the heat flow problem the surface boundary condition (temperature specified) must be satisfied in addition. In many geothermal areas the earth's surface can be considered a plane, but in The Geysers region this approximation may not be acceptable. Therefore in this analysis the solution was obtained for a two-dimensional model with a variable surface topography, surface temperature, and subsurface source strength. The solution technique is described by Brott (1977).

The two-dimensional solution was used because the topography and the heat flow contours in the area to be considered are two-dimensional to a first approximation and because the data available are not sufficiently dense to furnish the constraints necessary to justify the full three-dimensional solution. A three-dimensional solution program is available for use if necessary, however.

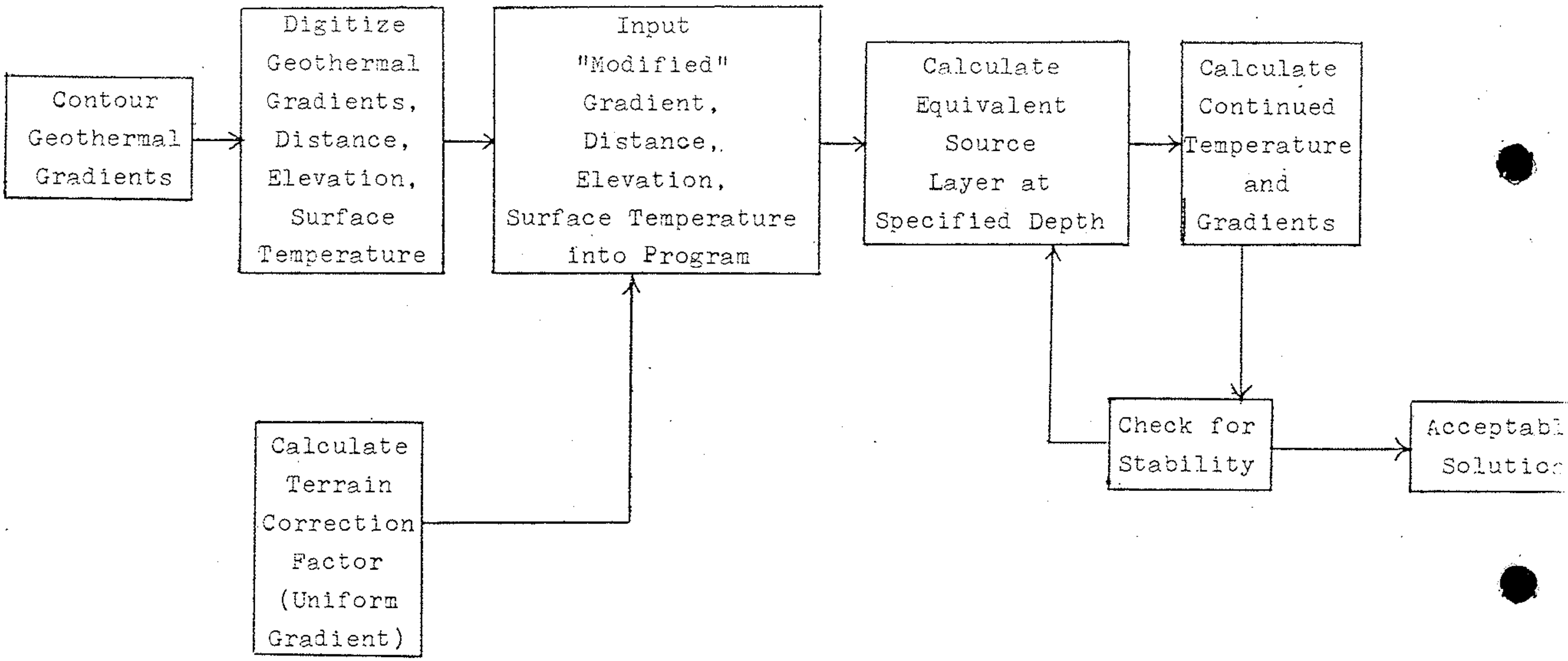
The solution technique requires the input of elevation, surface temperature, and observed geothermal gradient on a regular spacing along the profile. Typically 10-30 points are used. One of the major limitations of the present technique is that the earth is required to be homogeneous in thermal conductivity. Therefore only geothermal gradient is directly input into the solution instead of the heat flow. In The Geysers this assumption is not a major limitation, although the assumption should be kept in mind when comparing the results to the real world.

There are not enough points along either profile AA' or BC for determination of gradient at the density needed for a satisfactory solution (10-25 points). Therefore model data must be input based in large part on an idealized contouring of the heat flow data. The contouring is subjective because at the present time the heat flow data are widely spaced. The contours digitized for use in the solution are shown in red on Plate 1. The contours are somewhat different from those shown in black. In the Livermore area the data were recontoured to follow the strike of the structure to be more consistent with the two-dimensional situation assumed for the modeling. Certainly the contours used are no better than any other possible contour patterns and thus the results must be viewed as an example of the results that can be obtained given a contour map rather than an exhaustive investigation of possible solutions. Given the experience obtained, additional cases can be rapidly run for alternate contour patterns if desired.

The contoured data represent the gradient in the absence of the topography. The solution requires the input of the gradient actually observed in a shallow hole. Thus to actually input the data into the program the data must essentially have an inverse terrain correction applied to the digitized data from the contour map Thus the first step (in Table 1) was to calculate a "terrain correction factor" for each point along the profiles. Then the gradient at each point digitized from Plate 1 was corrected for the effect of the topography. These corrected gradients were then input into the continuation program (Table 1). Also input were the distance, elevation, and surface temperature of each profile point. The surface temperatures were obtained from a correlation between surface temperature and elevation at The Geysers of the form

$$T(z) = T_o - 6 \cdot z$$

Table 1. Flow chart for calculation of continuation results



where $T_o = 17^oC$ and z is the point elevation in kilometers.

A solution was then obtained for the temperature and the gradient at points below the surface and above a fictious layer of sources used to model the anomaly. The solution was then examined for behavior at depth. Downward continuation results in large amplification of high frequencies and the solution at depth may become unstable and oscillate, producing spurious results. In these cases the data must be low-pass filtered. In the profiles studied the results of the continuation of the 20 and 24 point data sets became unstable below sea level and the filtering was accomplished by the simple method of omitting every other data point in the calculation of temperature at depths below sea level.

RESULTS

Profile AA'. The results of the analysis are presented in Tables 2-5 and Figures 1, 2, and 3. In Table 2 the input data (location, gradient, and elevations) for profile AA' are listed along with the ideal gradient from Plate 1, and the gradients calculated by the solution at depths of -70 m and -1070 m (depth below sea level). Table 3 lists the point number, input gradient, and calculated elevation for specified isotherms (depth below sea level is negative) from the best solution obtained. Where possible the solution was carried to the 240^oC isotherm or a depth of -2200 m. If no number is shown for a particular isotherm at a given surface point then the isotherm occurs below -2200 m or severe oscillations prevented determination of the depth of the isotherm at that point.

These data are plotted in Figure 1. Figure 1a shows the topographic profile along AA' and a section showing the 20, 30, 40, 50, 100, 150, 200, and 240^oC isotherms. The solution for this profile is relatively well behaved and the derived isotherms are smooth. The minimum projected depth to the 240^oC isotherm is 2000 m in the vicinity of the field. The steam zone seems to be about 3 to 4 km wide dropping off sharply on both sides. Of course the solution depends on the contouring of the surface

Table 2. Gradients for Profile AA'. Negative numbers are depths below Sea Level.

Point No.	Elevation meters	Input Surface °C/km	Ideal Surface °C/km	-70 m °C/km	-1070 m °C/km
1	171	30	30	30.0	32.5
2	122	34	30		
3	146	36	30	36.0	32.9
4	195	38.5	35		
5	268	38.5	35	37.9	36.2
6	549	38	35		
7	610	41	41	39.1	25.9
8	707	52.2	58		
9	805	60.0	75	57.4	38.5
10	963	51.0	85		
11	914	74.0	92	92.4	128.9
12	744	94.5	105		
13	610	115.0	115	114.0	128.0
14	561	134.0	122		
15	549	102.0	114	104.0	108.9
16	488	102.0	102		
17	488	83.7	93	84.3	96.8
18	390	78	78		
19	390	55.8	62	53.9	38.0
20	335	40	40		

Table 3. Isotherms for prof'le AA'. Distance to isotherm from sea level giv'n in meters (negative below sea level). Maximum depth of solution is -2.3 km.

Point No.	Gradient °C/km	20°C	30°C	40°C	50°C	100°C	150°C	200°C	240°C
1	30.0	0	-310	-520	-950	-2150			
2	34.0	-15	-300	-580					
3	36.0	15	-250	-530	-830	-2100			
4	38.5	50	-190	-420					
5	38.5	140	-90	-300	-640	-1930			
6	38.0	310	95	-120					
7	41.0	395	155	-90	-325	-1900			
8	52.2	405	300	130	-120				
9	60.0	605	425	255	150	-750			
10	51.1	670	500	280					
11	74.0	630	550	435	330	-180	-701	-1094	-1383
12	94.5	570	460	350	260				
13	115.0	470	360	300	230	-165	-595	-995	-1310
14	134.0	460	370	290	220				
15	102.3	450	340	240	140	-280	-750	-1210	-1585
16	102.	305	265	180	100				
17	83.7	350	230	115	20	-530	-1080	-1560	-1840
18	78.0	240	130	30	-90				
19	55.8	215	65	-105	-270	-1570			
20	40.0	150	-80	-310					

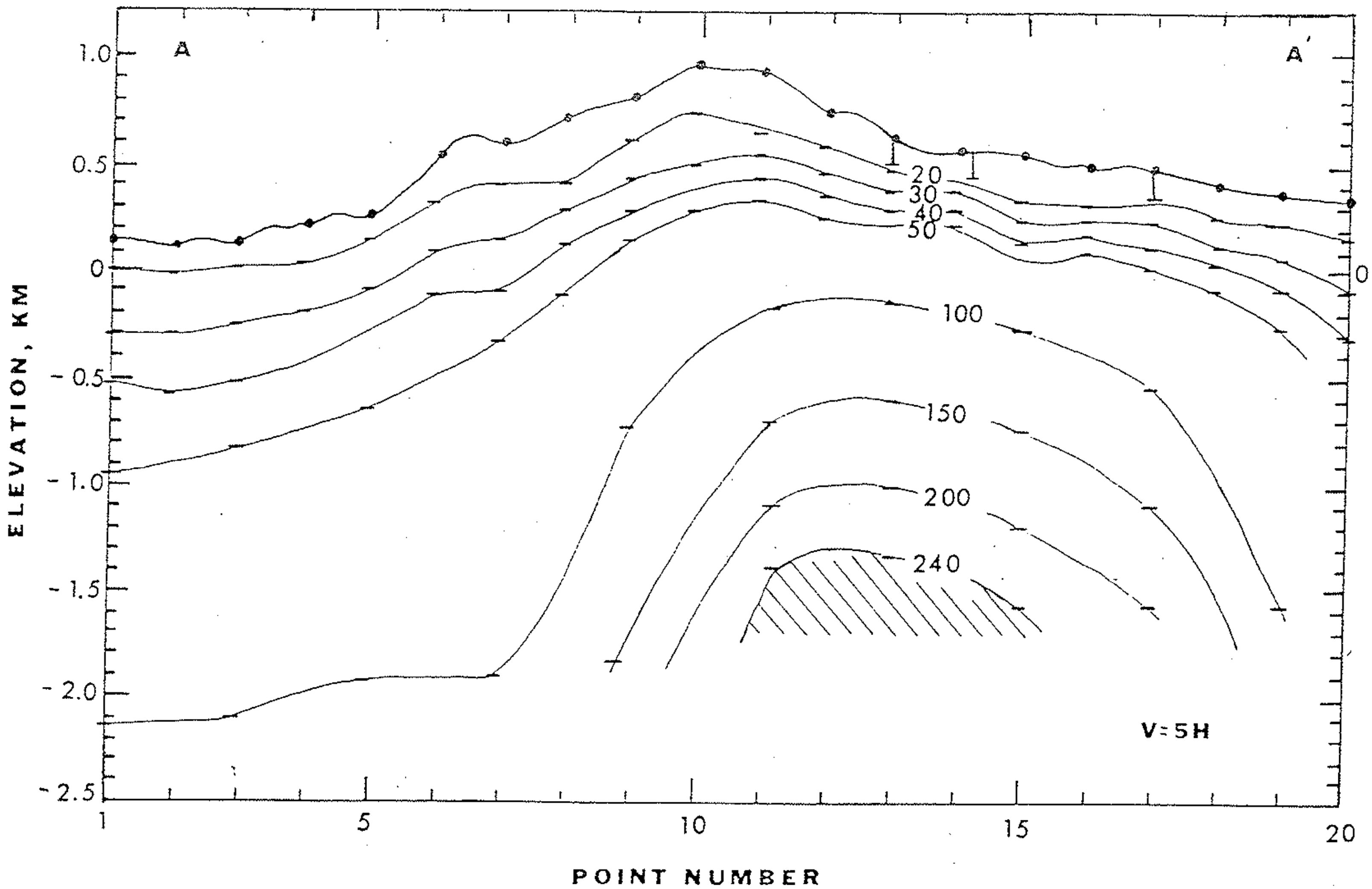


Figure 1a. Isothermal section and digitized topography (dots) for profile AA'. Isotherms (°C) shown were constructed using data from Table 3 (horizontal bars).

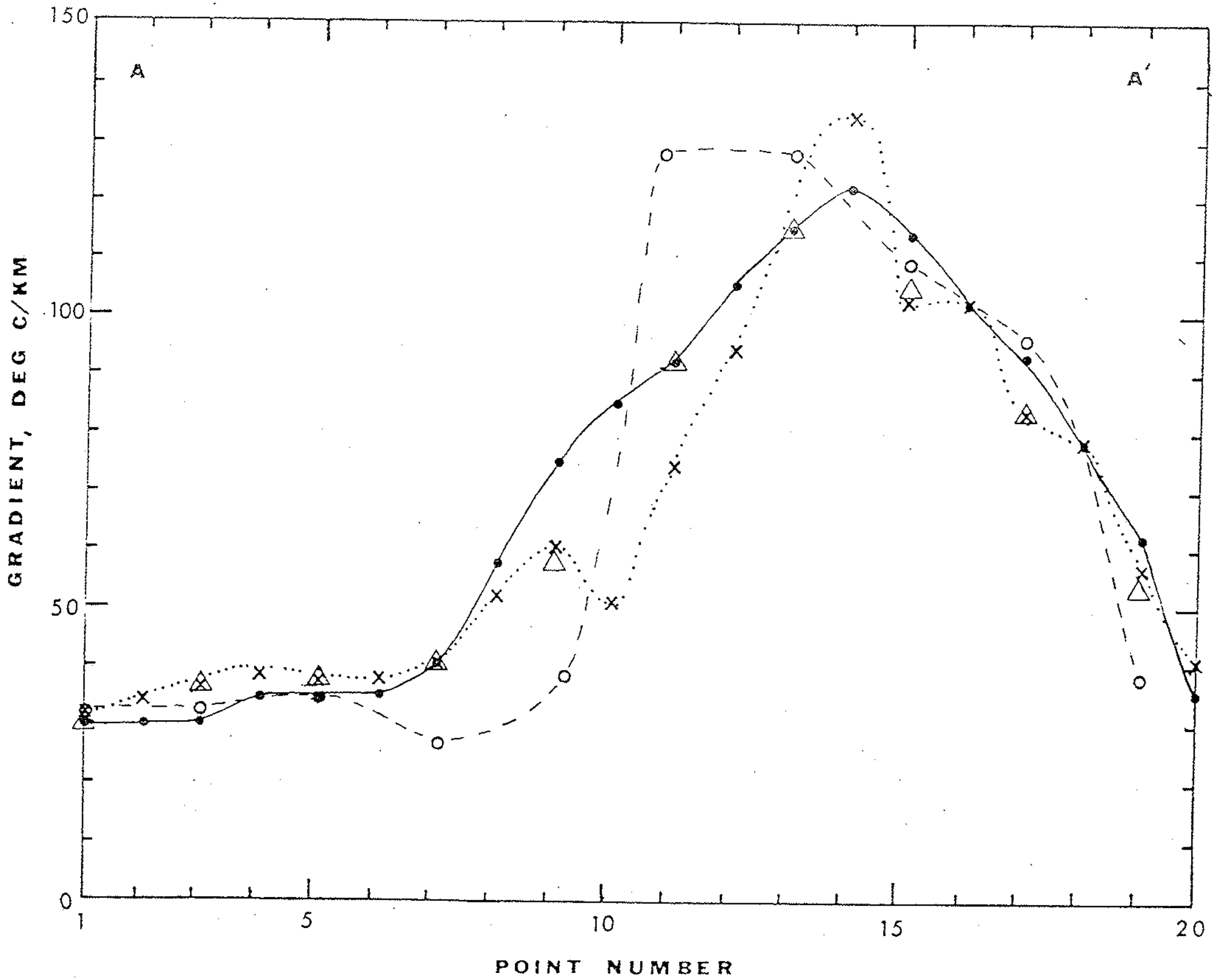


Figure 1b. Gradients for profile AA'. Dots are ideal (contoured) gradients, X's are input "terrain corrected" gradients, △'s are gradients calculated at -70 m, and O's are gradients calculated at -1070 m.

gradients which is subjective, especially on the west end of the profile.

Various gradient profiles are shown in Figure 1b. Shown are the gradient at the surface, the ideal gradient (from the contour map), the gradient at -70 m and the gradient at -1070 m. The difference between the first two gradients is strictly the effect of topography. Differences in the gradients calculated at -70 and -1070 m illustrate the effect of continuation on the gradient at depth. In general the gradient at -70 meters tends to be closest to the ideal gradient since the effect of the topography is less as one moves away from the surface. The gradient at -1070 m shows more of the effects of continuation; i.e., the gradient at the margins of the anomaly has dropped to the regional value and the gradient beneath the anomaly has increased slightly. The results show that, as shown in the section, the data imply a very sharp western boundary to the steam zone and a more gentle one to the east.

The solution and the resulting isotherms behave in the expected manner in this case and may, given the assumptions stated above, represent in a simple way the configuration of the steam zone.

Profile BC With Topography. The results for Profile BC are shown in Tables 4 and 5 and in Figure 2. This profile crosses the Livermore property as shown on Plate 1. There is a jog in the profile between points 11 and 12. The profile passes near or through deep gradient test holes 9, 10, and 11 (shown on Figure 2). As pointed out in a previous section the results were recontoured and two rather than one anomalies are shown on the profile. This contouring is purely arbitrary and is shown for example only.

The 20, 30, 40, 50, 100, and 150°C isotherms are shown on Figure 2a. The 200 and 240°C isotherms are not show for reasons discussed below. The gradients are plotted in Figure 2b. The ideal gradient curve is a digitized version of the contour map. The input gradient is irregular due to the effects of the varying topography along the profile. On this section there is not

Table 4. Gradients for Profile BC. Negative numbers are depths below Sea Level.

Point No.	Elevation meters	Input Surface °C/km	Ideal Surface °C/km	-130 m °C/km	-2000 m °C/km
1	419.8	49.5	45	49.1	33.3
2	478.9	68.2	62		
3	478.9	88.0	80	85.6	120.1
4	498.6	93.5	85		
5	718.3	80.0	80	79.8	75.6
6	1000	74.4	62		
7	1361	56.0	56	56.4	60.3
8	2099	45.9	51		
9	2480	38.4	48	40.5	23.5
10	2401	42.3	47		
11	2401	48.0	48	47.2	59.4
12	2319	45.0	50		
13	2401	55.8	62	53.0	23.2
14	2001	77.0	72		
15	2299	73.8	80	81.1	115.3
16	2440	72.8	90		
17	1899	104.5	95	95.8	61.7
18	2358	81.0	85		
19	2840	75.0	75	100.1	173.7
20	2358	78.0	68		
21	2401	66.6	62	63.1	18.6
22	1758	62.0	50		
23	1581	64.0	40	59.8	61.6
24	1200	60.5	35		

Table 5. Isotherms for profile BC. Distance to isotherm from sea level given in meters (negative below sea level). Maximum depth of solution is -2.3 km.

Point No.	Gradient °C/km	20°C	30°C	40°C	50°C	100°C	150°C	200°C
1	49.5	100	-115	-290	-500			
2	68.2	100	-25	-160	-300			
3	88.0	120	20	-100	-200	-735	-1060	-1460
4	93.5	100	20	-85	-180			
5	80.0	150	50	-70	-175	-840	-1550	
6	74.4	250	120	-10	-130			
7	56.0	330	130	10	-210	-1050	-1690	-2030
8	45.9	450	250	60	-135			
9	38.4	550	280	105	-150	-1040		
10	42.3	550	295	140				
11	48.0	565	360	170	-40	-1030	-1620	
12	45.0	565	350	200	50			
13	55.8	600	425	250	120	-1000		
14	77.0	550	410	295	150			
15	73.8	600	490	340	220	-380	-910	-1290
16	72.8	600	475	355	225			
17	104.5	500	400	300	210	-280	-870	
18	81.0	620	500	380	260			
19	75.0	760	600	480	370	-160	-600	-930
20	78.0	610	490	360	210			
21	66.6	590	450	315	195	-670		
22	62.0	425	260	90				
23	64.0	340	210	90	-60	-950	-1600	-1920
24	60.5	135	-20	-170				

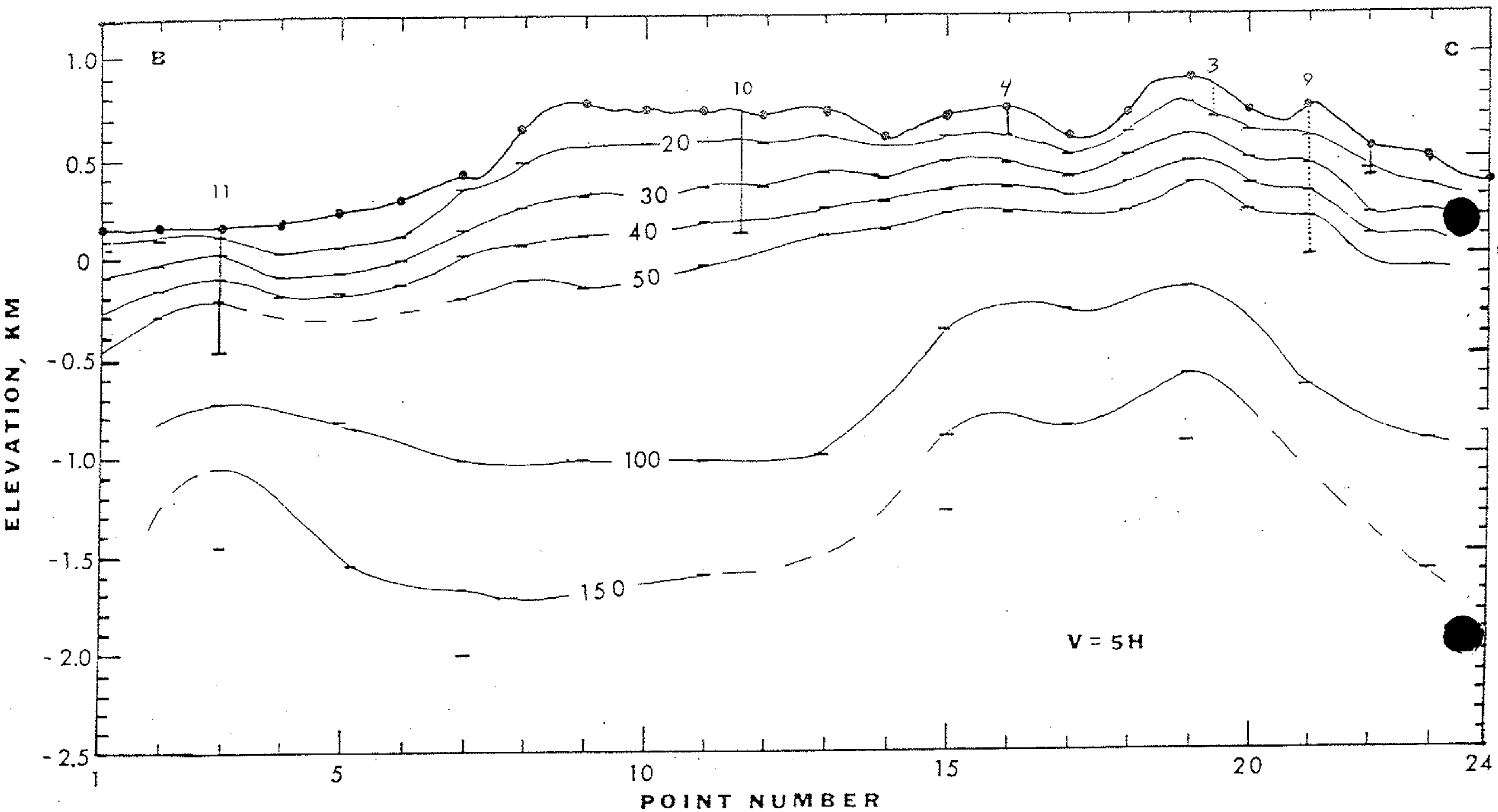


Figure 2a. Isothermal section and digitized topography (dots) for profile BC. Isotherms (°C) shown were constructed using data from Table 5 (horizontal bars). Hole locations shown.

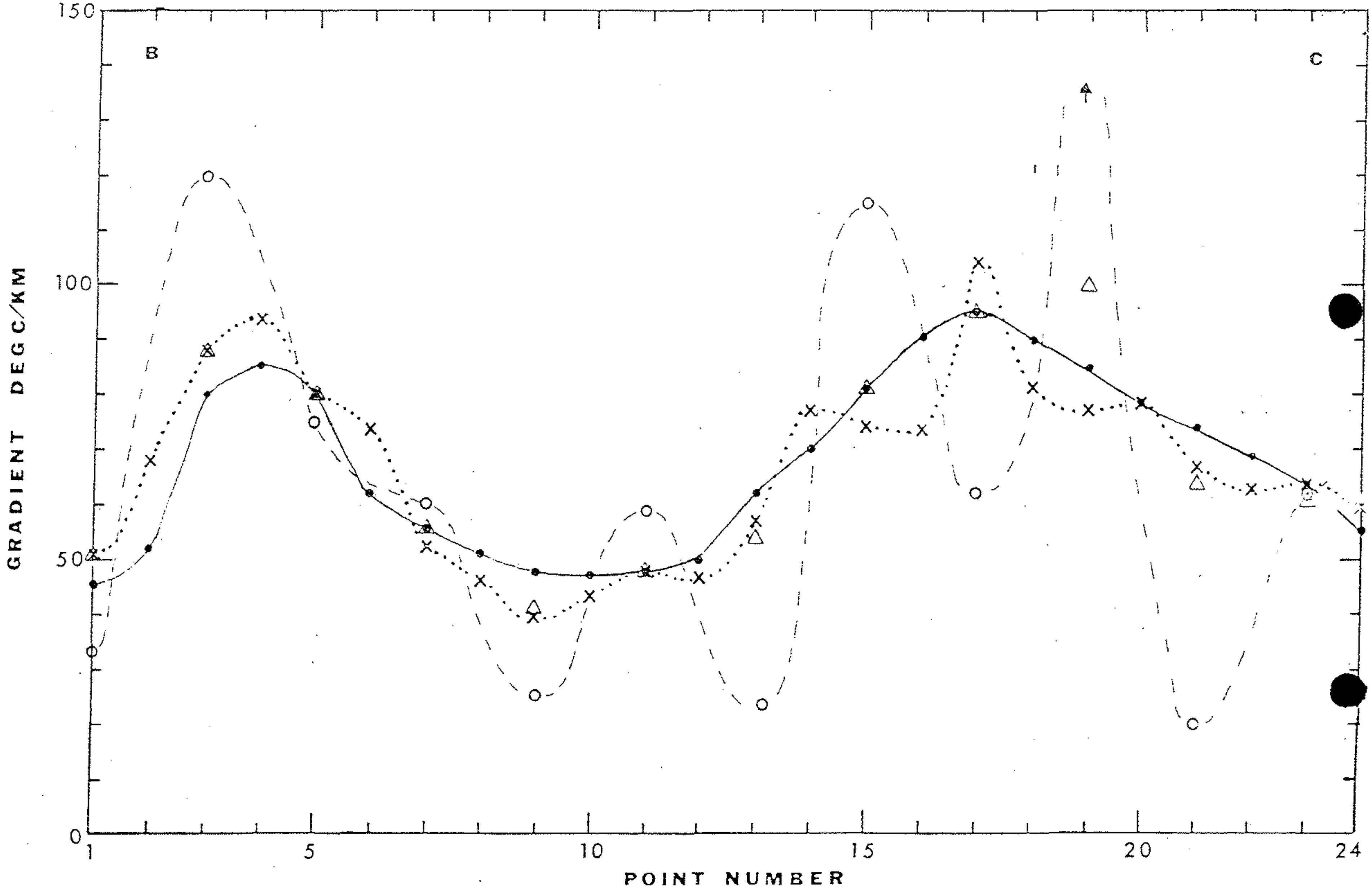


Figure 2b. Gradients for profile BC. Dots are ideal (contoured) gradients, X's are input "terrain corrected" gradients, △'s are gradients calculated at -130 m, and O's are gradients calculated at -1000 m.

a single dominant topographic feature as in profile AA' and so the sign of the topographic correction changes several times along the length of the profile. The calculated gradient at -70 m is most similar to the ideal gradient as the effects of the topography become less important. At -1070 m, however, the picture is very different. There the gradient is very irregular and oscillates about the other gradient curves from point to point. This oscillation indicates that the solution has become unstable and is no longer valid. The data need to be filtered more strongly, the shape of the input curve needs to be changed, or some other adjustment needs to be made to the data. I do not feel that I have the information to pursue the different possibilities in detail and so the results are presented "as is" at this time.

The contours in the vicinity of RDH-11 are based on one point only and so will not be discussed. Along the east side of the profile there is another more completely outlined anomaly that is of more direct interest. This anomaly will be discussed below.

Profile BC - plane surface. It is clear that in comparing profiles AA' and BC there is no dominant topographic feature on BC as in AA'; although topographic effects are large on BC they vary in sign from point to point along the profile. I felt that a better solution might be obtained by ignoring the effect of the topography and investigating the solution with the simplification that the bounding surface was a plane. In this case it is difficult to specifically compare the depths derived at one point along the resulting section to those at another, particularly those to the east and west of point number 8 where the major change in elevation occurs. Since there are no actual data in the area of point 8, the results there are of little consequence anyway. Therefore in comparing Figures 2a and 3a and Tables 5 and 6 the comparison should be made relative to the mean elevation in the areas compared. This mean elevation is on the order of 700 m east of point 8 and 200 m west of point 8.

The results for the contours of Plate 1 for the plane boundary solution are shown in Table 6 and Figures 3a and 3b. Again only 12 points were used to calculate the solution. The solution seems

Table 6. Input data and results for profile BC, "plane surface".

Point No.	Input Gradient °C/km	Calculated Gradient 0 m °C/km	Calculated Gradient -1000 m °C/km	Depth to given isotherm in meters 50°C	100°C	150°C	200°C	250°C
1	45	46.3	40.5	660	-	-	-	-
2								
3	80	77.0	90.2	386	986	1490	1877	2175
4								
5	80	78.0	86.6	389	1000	1527	1971	2250
6								
7	56	57.5	50.2	527	1625	-	-	-
8								
9	48	48.5	47.5	622	1641	2283	-	-
10								
11	48	49.3	43.9	620	1800	-	-	-
12								
13	62	63.2	62.0	482	1287	2000	2420	-
14								
15	80	79.8	79.3	375	1000	1666	-	-
16								
17	95	92.8	103.1	322	841	1313	(1712)	(1970)
18								
19	85	85.1	83.9	353	943	1558	2300	-
20								
21	74	74.0	73.9	405	1081	1755	2350	-
22								
23	64	63.7	65.5	470	1022	1948	2550	-
24								

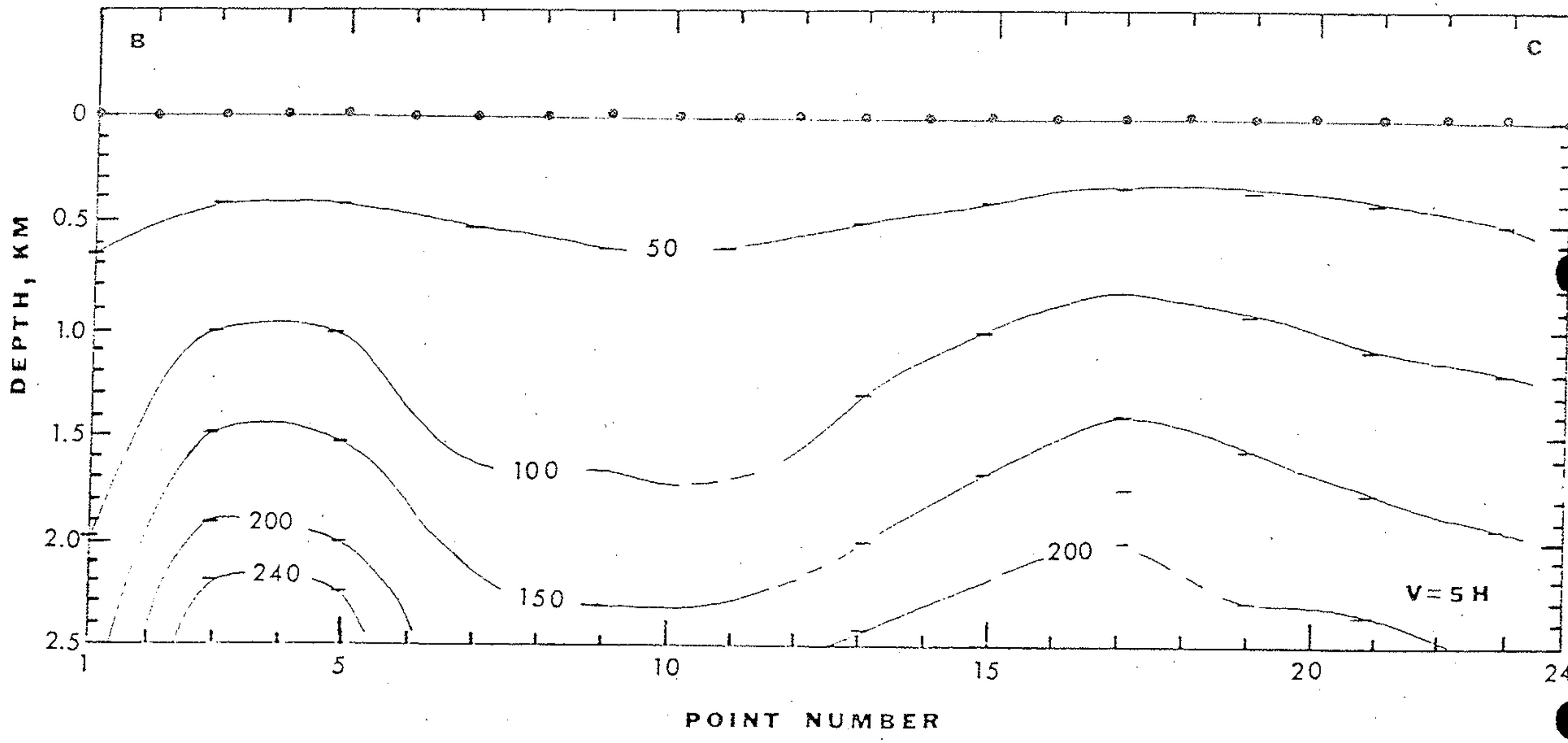


Figure 3a. Isothermal section for profile BC assuming a plane surface. Isotherms (°C) constructed using data from Table 6.

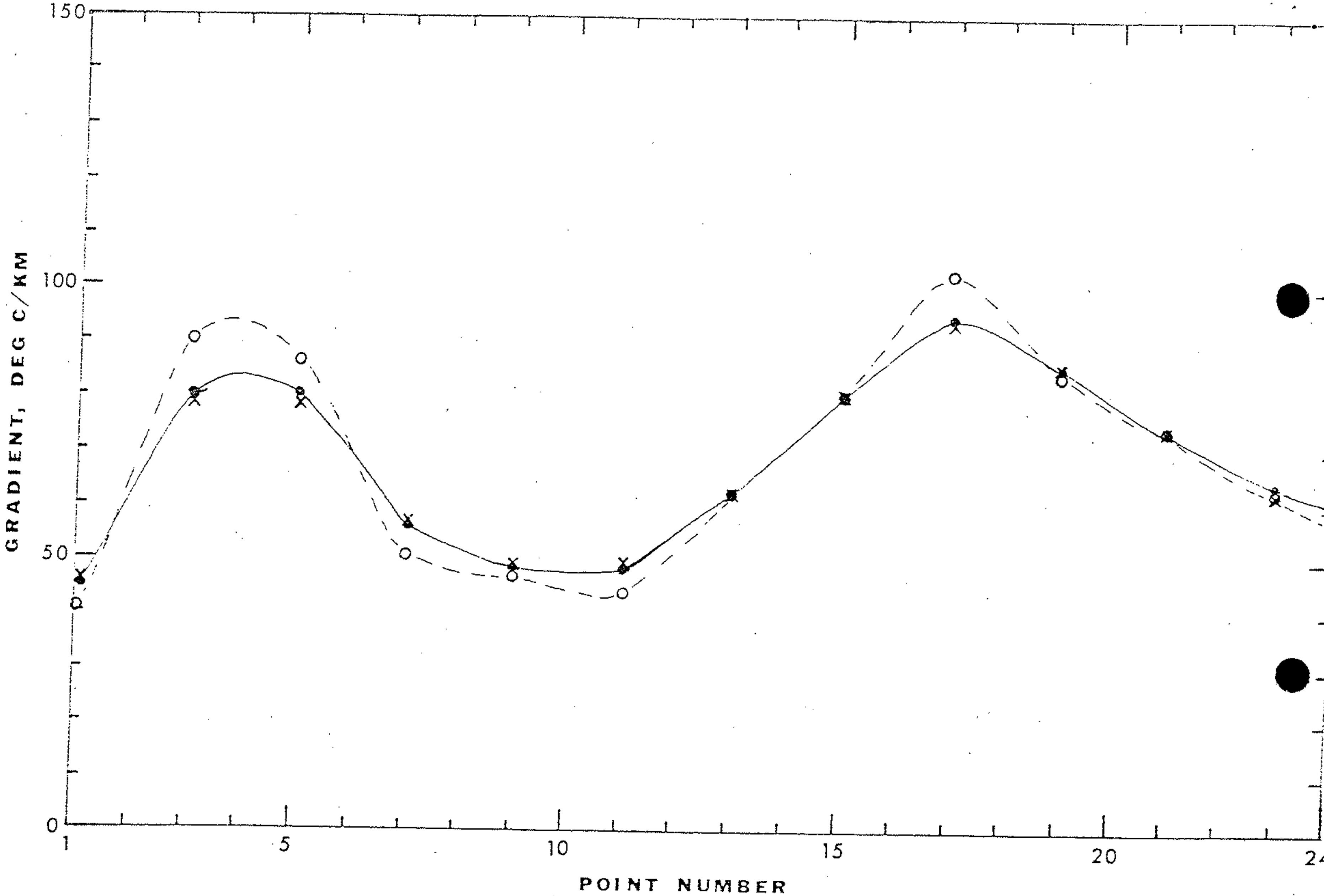


Figure 3b. Gradients for profile BC with "plane surface". Dots are gradients at surface, X's are fit (calculated) gradients at the surface, and O's are calculated gradients at a depth of 1000 m.

to be stable except below 2.0 km at point 17. The effects of the continuation are obvious on the west side of the profile (points 1-6) where the gradients over the anomaly steepen with increasing depth and those off the anomaly decrease (remember, however, that the contours **there are** based on only one point). On the other hand there is not much change in gradient on the east side of the profile (points 13-23) between the surface and 1000 m. This lack of change means that the anomaly is wide enough that, to 1000 m depth anyway, continuation effects are minor. If the input anomaly showed sharper variations such a conclusion might not necessarily apply. The edge of the anomaly is not shown on this section as the gradient at point 23 is 64°C/km, compared to a regional gradient on the order of 30-35°C/km (see profile AA').

DISCUSSION

Based on the results presented above some tentative comments can be made about temperatures and a possible reservoir beneath the Livermore property. Only the eastern half of profile BC is discussed because the western half is based on the contouring of one point. Furthermore these conclusions for the eatern half of the profile are dependant on the contouring of the available data and fill-in holes are needed before definite conclusions can be drawn.

The boundaries are not clearly delineated by the solutions, although one boundary may be associated with the structure bounding the Sonoma volcanics in the vicinity of point 15 (see Figures 2a and 3a). This conclusion is strengthened if the mean thermal conductivity of the Sonoma volcanics is lower than the Franciscan (as is the case in RDH-10) and is weakened if the thermal conductivity is higher (as appears to be the case in RDH-11). The steam reservoir, if present, is at a depth of 2.2 - 2.7 km beneath the mean surface elevation, along the east side of profile BC. It is probably at least 3 km wide, extending between points 15 and 20 (each point represents 625 m horizontally).

CONCLUSIONS

The results of the continuation solutions for temperature and geothermal gradient for two profiles in the vinicity of The Geysers steam field are presented in several tables and figures. The nature of the results has been briefly discussed. The main conclusions of the study are that:

1) Calculations of the configuration of the steam zone, as modeled by the 240°C isotherm for the Castle Rock Springs Field are consistent with known data.

2) The solution for the isotherms beneath the Livermore Property show more instability because the effects of the topography are less systematic, the reservoir is deeper, and the anomaly is not well known.

3) Some general limits for the possible steam reservoir beneath the Livermore Property, dependant on available data as contoured, are a depth of 2.2 - 2.7 km^2, width of 3 km, and a possible control by Sonoma volcanics structure.

4) Solutions for additional data or other contour shapes can easily be obtained in the future if desired.

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Urban, T. C., W. H. Diment, J. H. Sass, and I. M. Jamieson, Heat Flow at The Geysers, California, USA, in 2nd U.N. Symp. on Dev. Use of Geothermal Resources, U.S. Gov. Printing Office, pp. 1241-1245, 1976.