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REPORT

on

INTERPRETATION OF THE DEEP HEAT FLOW AND TEMPERATURE DATA AT THE FISH LAKE GEOTHERMAL PROSPECT, NEVADA

BY

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INTERPRETATION OF THE DEEP HEAT FLOW AND TEMPERATURE DATA AT THE FISH LAKE GEOTHERMAL PROSPECT, NEVADA

Introduction Following final logging of the deep temperature gradient holes 35-1 and 55-2 in October, 1985 the results of the exploration to date were reviewed. The main object of the review was to evaluate the results to date in regard to the next step in the exploration process. The extant data were reviewed in the SRC offices on October 25, 1985 and pertinent information was brought to Dallas for further modeling and analysis. The information studied included the temperature, geological, and gravity data and a summary file of reports for the project. In this resport there are several aspects of the results that discussed in more detail. The discussion includes analysis of the implications of the shallow heat flow and temperature data, interpretation of the significance of the shallow "40 ^{o}C" aquifer, conclusions on the implications of the modeling results for interpretation of the intermediate and deep hole temperatures, and discussion of models of the nature of the deep thermal conditions. Each of these topics will be briefly discussed in turn.

Rate of Geothermal Fluid Flow The early phases of the exploration outlined a large, intense temperature/heat flow anomaly in the vicinity of the Volcanic Hills in the center of Fish Lake Valley, Esmeralda County, Nevada. Most of the shallow holes are between 40 and 90 m deep and maximum temperatures encountered are just over 40 ^{o}C. Although a large area of alteration has been mapped(in sections 10 and 14) near the center of the thermal anomaly, there is no surface evidence of hot fluid leakage at the present time. However, the large size of the thermal anomaly is evidence of such fluid flow in the very recent past, if not today. The lack of active thermal manifestations today may be because the fluid loss is entirely subsurface or because self sealing has recently plugged the channelways of flow and decreased drastically the amount of flow. Nonetheless the rate of fluid loss can be estimated from the heat loss and the information on the temperature in the deep system from the geochemistry and the results of the holes 88-11 and 88-11A.

A crude estimate was made of the total heat loss from the system by summing the heat flow and area using the SRC map of "Shallow Heat Flow(40-100 m)". The total area of anomalous heat flow is at least 92 km^2. If a background heat flow of 2 x 10^{-6} cal/cm^2 sec is subtracted, the total heat loss is approximately 5.6 X 10^6 cal/sec. If this heat is transfered to the surface by a flow of hot water at a temperature of 160 ^oC, the temperature encountered at shallow depths in hole 81-14, then the required rate of flow in the steady state to transfer the heat is 39 l/sec(liters per second). This figure for the rate of flow is probably conservative. If this flow is still active, then all the fluid is being discharged to the ground water and none actually reaches the surface.

This value may be compared to flow rates in other systems. Heat loss values of 10^6-10^7 cal/sec are typical of the more intense geothermal systems in the western Great Basin while values of 10^7-10^9 are typical of caldera systems.

For example at Roosevelt hot springs, Utah the total heat loss is about 14 x 10^6 cal/sec and at Long Valley, California the total heat loss is 4.8 x 10^7 cal/sec. The Grass Valley, Nevada system has a heat loss of about 5 x 10^6 cal/sec. Thus in spite of the lack of thermal manifestations, the Fish Lake system is a major geothermal system.

As suggested by McNitt and Klein(1985) the Desert Peak geothermal system is a good analogy to the Fish Lake system in many respects. The structural setting, system size, and the presence of several shallow aquifers(Beniot et al., 1982) are points of similarity. The mode of exploration required, primarily intermediate depth temperature gradient drilling and careful geological analysis, is also similar.

<u>Shallow Aquifers</u> The exploration activities have outlined a very extensive area that appears to be underlain by an aquifer(s) at a temperature of 40-45 °C. Because of this aquifer the results from the shallow gradient/heat flow holes cannot be directly related to deep thermal conditions. The ubiquitous 40 °C aquifer is somewhat puzzling. If the fluid is all derived from the geothermal system the aquifer temperature would be expected to increase toward the system, which it does not seem to do except locally. For example the shallow temperature-depth curves in 81-14, 54, and 44-14 are typical of those due to transient outflow from a geothermal system. The characteristics are those of transient flow in a thermal aquifer as modeled by Ziagos and Blackwell(1981). Based on the depth effect of the temperature overturn, the age of the presently active flow is on the order of

500 years. Apparently some event occurred that caused a change in the flow system at about that time. Perhaps before a few hundred years ago all the flow reached the surface and at that time the silicification and alteration were taking place.

The effects of the high temperature aquifer are present only in holes 81-14(and the two deep holes), 54, probably 9 and possibly 26(44-14). The 40 °C aquifer in many of the other holes does not show any systematic variation in temperature with position. There may be mixing of the geothermal aquifer with shallow cold ground water plus other effects that result in the undiagnostic behavior of the 40 °C aquifer. There may, in addition, be other areas of leakage from the deep system then have been located so far. The presence of this shallow 40 °C aquifer is unfortunate because it clouds the interpretation of the shallow thermal data. This type of situation is very common in the Basin and Range province, however.

Intermediate and deep holes Temperature-depth curves from the six intermediate-depth temperature gradient holes in the immediate vicinity of the thermal anomaly are shown in Figure 1. The characteristics associated with the shallow aquifers have already been discussed. A characteristic of several of the curves is a convex downward shape. The log from hole 64-11 is the most spectacular example of this sort of curve. The gradient for the upper 200 m is over 360 °C/km while the gradient for the bottom 200 m is less than 45 °C/km, a difference of over a factor of 8.

There are four possible explainations for this type of curve: uniform upward percolation of fluid in a porous medium; lateral flow of hot fluid in a uniform porous medium; margin effects in a nonporous region near a confined region of fluid flow; and thermal conductivity effects in a region of no or minor fluid flow. When a curve of this type is found in a geothermal system it is generally assumed that the first explaination is the correct one. However, the drilling results at Fish Lake indicate that the permeability in this section is limited and that a model of uniform permeability cannot be applied. The permeability distribution would seem to rule out the uniform lateral-flow model as well, although some of the temperature-depth curves seen in the shallow holes in the alluvium might be of this type. The two possibilities then are margin effects and thermal conductivity contrasts.

The results of thermal conductivity measurements on samples of the rock types encountered in the intermediate and deep subsurface are listed in Table 1. Also shown are the values corrected for the effects of <u>in situ</u> porosity and temperature assuming that the average temperature in the system is 150 ^{o}C(the temperature effect is about 1%/ 10 ^{o}C so the exact temperature assumed is not critical). The average thermal conductivity estimated for the deeper part of the volcanic section is 4.20 mcal/cm sec ^{o}C and the average temperature corrected value for the basement is 7.29 mcal/cm sec ^{o}C. These values imply a gradient ratio of about 1:1.74 between the volcanics and the basement. Because the basement rocks are anisotropic the actual ratio might vary from a low of about 1:1.2 if the folation is subhorizontal to 1:2.0 if the foliation is steep(as appears most probable). Within the volcanic section the contrast might reach 2:1 between unwelded air fall tuffs and welded tuffs or lava flows.

The temperature-depth curves show some effects of thermal conductivity variations, but in several of the holes the variations in gradient are too large to be caused by this effect. In evaluating each of the curves individually, however, the effects of thermal conductivity must be included.

The failure of the three other possibilities to explain the curvature in the temperature-depth curves leaves the margin effect as the most likely candidate. In this situation the technique of downward continuation of thermal data(Brott et al., 1981) would be the most useful for interpretation. Unfortunately the data are too sparse to be used in this kind of approach because only six holes actually give information on the deep thermal conditions. Therefore the approach of forward modeling must be used. The most appropriate model to use is a simple analytical model described by Nathenson et al.(1979) for the lateral conduction effects of fluid flow up a vertical fault. This model is only an approximate match of the actual effect desired, that of the edge of an extended reservoir, but a better solution is not available within the time constraints of this review.

The comparison of the temperature-depth curves from four of the deep holes to the temperature-depth curves calculated from four cases for the model with the parameter values of nondimensional flow rate(Q^*) equal to either 16 or 32, constant parameter R^* equal to 0.37, depth of flow equal to 3 km, surface temperature equal to 15 °C, and fluid temperature on the boundary at 3 km equal to either 180 ° or 200°C are shown in Figure 2. The curves are calculated at 100 m(330 ft) intervals from the boundary to a distance of 1 km(3300 ft) away from the boundary. The Q^* values are based on the fluid flow calculated above, and an estimated length of upflow zone along a fault zone. The model solution is based on a homogeneous medium so the actual data will show stronger curvature then predicted due to the increase in thermal conductivity with depth.

A comparison of temperature-depth curves for holes 64-11 and 81-14 suggests a best fit if the two holes are within 100-300 m (330-1000 ft) of the boundary. Furthermore to be consistent with the model 64-11 would be about 100 m(330 ft) further from the boundary than 81-14. There are two ways to interpret the comparison to holes 42-7(and 35-1 with a nearly identical curve) and 55-2. These holes could be on the order of 700-900 m(2300-3000 ft) from the boundary, or the model may not be applicable because the holes are over the anomaly and the curvature of the gradients is due only to thermal conductivity effects.

Deep Thermal Anomaly There are three configurations of the 180-200 °C isothermal surface that are consistant with the thermal data. Two of the three configurations are similar at depth so there are really two distinct models. These models are illustrated in Figure 3.

The first configuration is shown in Figure 3A. The thermal data are consistant with a north-south trending fault similar to the one shown by McNitt and Klein(1985,Figure 4) passing through the surface locations of the deep drill holes. Fluid at a temperature of at least 160 °C is leaking to shallow depths along this fault or a structure similar to it for a strike distance of at least 1 km(0.6 mi). This feature is characteristic of all of the models. Below this shallow leakage there would be a large area with a temperature of 180 °C or higher at a depth of 1.5 to 2 km(5000 to 6500 ft) within the Paleozoic units. In this case the temperature gradients in holes 55-2, 35-1, and 42-7, when extrapolated to depth taking into account thermal conductivity changes, could be used to predict deeper temperatures.

A second model is shown in Figure 3B. In this model shallow flow occurs over a longer section of the north-south fault and the temperature gradients in hole 55-2(and possibly 42-7 as well) might be due to the lateral effect of the fluid flow along the fault. In this case the gradients in the holes cannot be extrapolated to depth because their curvature is due to high temperatures to the side of, rather then below the holes.

In the third model (shown in Figure 3C) the fluid circulation on the north-south fault is responsible for the high gradients in hole 55-2 but hole 35-1 is over the anomaly.

The arguments made for the controls on the temperature-depth curve in hole 35-1 in the previous paragraphs can be made for hole 42-7 as well. For simplicity in Figure 3 holes 35-1 and 42-7 are treated similarily in each model, but the data do not require this assumption and for each of these cases one might be an edge effect and the other not, generating additional models.

The gravity data correlate quite closely with the thermal data. There is a major positive anomaly that trends east-west and appears to lie directly beneath the thermal anomaly where known. The gravity trend can be traced to the west under the adjacent valley. Regardless of the exact cause of the gravity anomaly, the close association of the two anomalies may be evidence that the structure related to the thermal anomaly is at least as large as would be required to have a deep thermal anomaly of the size of that shown in Figures 3A and 3C.

The results from the intermediate depth drilling clearly establish the fact that the geothermal system opens to the north of the deep holes. The different models can be tested in two different ways: by drilling holes 35-1 and 42-7 deeper; and by drilling intermediate depth holes between 35-1 and 42-7, and the site of holes 81-14, 88-11, and 88-11A. If hole 35-1 is off the anomaly(model of Figure 3B) then the heat flow should change with depth as predicted in Figure 2. The gradient may actually change due to changes in rock type but the heat flow should remain constant if the models of Figure 3A or 3C are appropriate.

The second way to test the models is by intermediate depth drilling at new sites. Holes drilled between the existing holes, at the site of shallow hole 7 and to its northwest and southeast for example, would allow measurement of the intervening gradients and easy distinction between the models. The very high gradients in holes 7 and 8 imply leakage of hot water along a east-west structure as well as a north-south one, but the enegmatic 40 °C aquifer clouds the interpretation.

In reviewing the logs of the deep wells the temperature step at a depth of about 2000 m(6600 ft) in the log of 7/13/84 for hole 88-11 was noticed. The other types of logs were examined for evidence of an associated structure. Between a depth of 2053.1 m(6736 ft) and 2053.7 m(6738 ft) there is indication of hole enlargement of about 2.5 cm(1 in) on the caliper log. On the neutron and density porosity logs there are changes of 10's of percent, however. These responses suggest a narrow fracture zone(too narrow for a diagnostic caliper response) that may in fact be open. Deymonez(1984) points out that there was a major change in hole deviation and drift direction between 1920 m(6300 ft) and 2073 m(6800 ft). It is possible that the zone of anomalous log response is a major fault zone as suggested and the temperature log implies that the zone is participating in active fluid flow even though it appears to be behind casing.

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Table 1 Thermal Conductivity Results on Crushed Samples

Sample Number	Depth feet	Conductivity m cal/cm sec°C	Porosity	Corrected* Conductivity
64-11	1020	5.25	10%	4.65
	1500	4.10	10%	3.69
	1850	5.38	10%	4.72
	2050	4.00	10%	3.61
	2300	4.90	10%	4.34
88-11A	8000-8010	10.64	5%	7.70
	8010-8020	10.10	5%	7.33
	8250-8260	9.84	5%	7.15
	8260-8270	9.56	5%	6.96

* Corrected for porosity and temperature effects

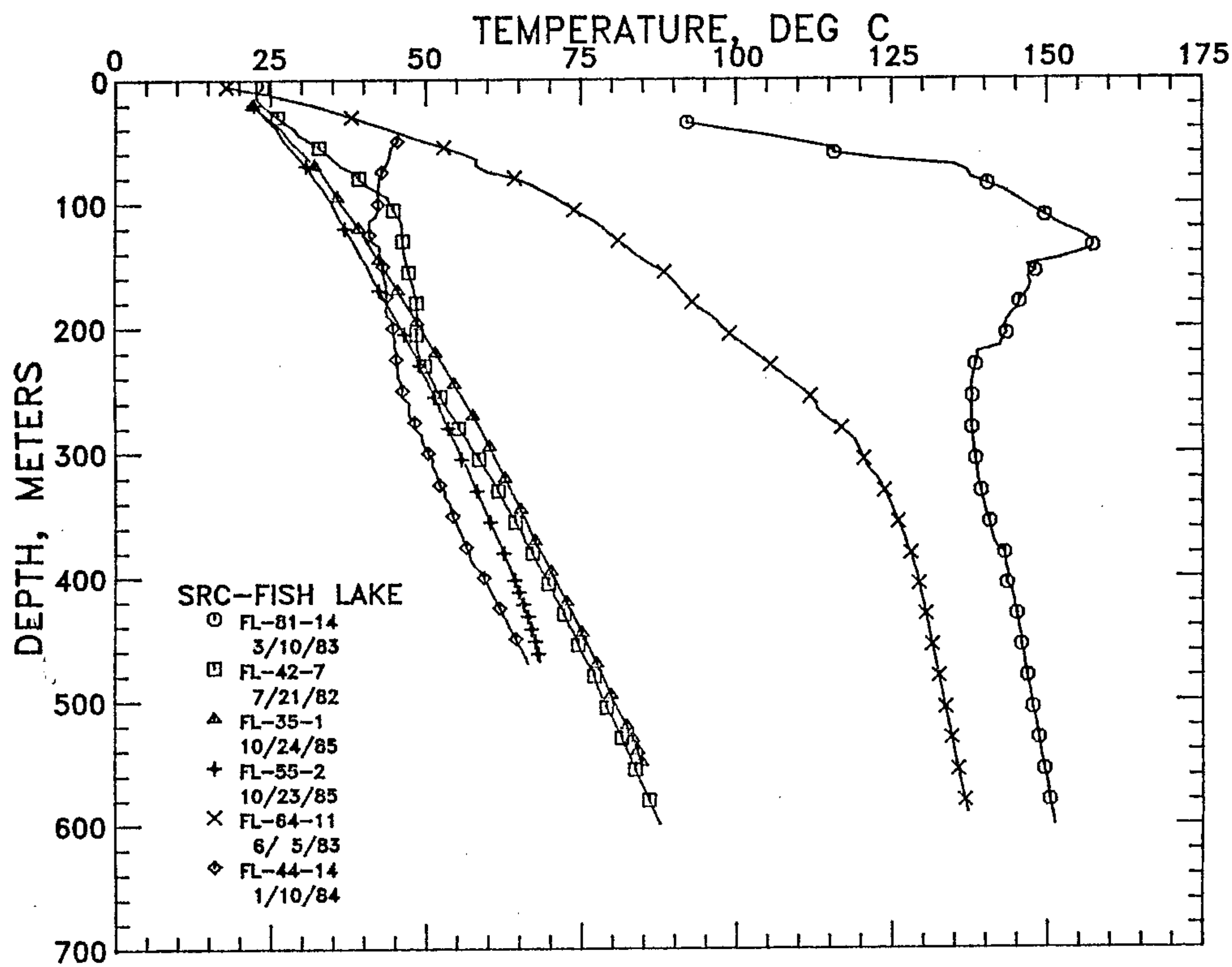


Figure 1A. Temperature-depth curves for holes 81-14, 42-7, 35-1, 55-2,64-11, and 44-14.

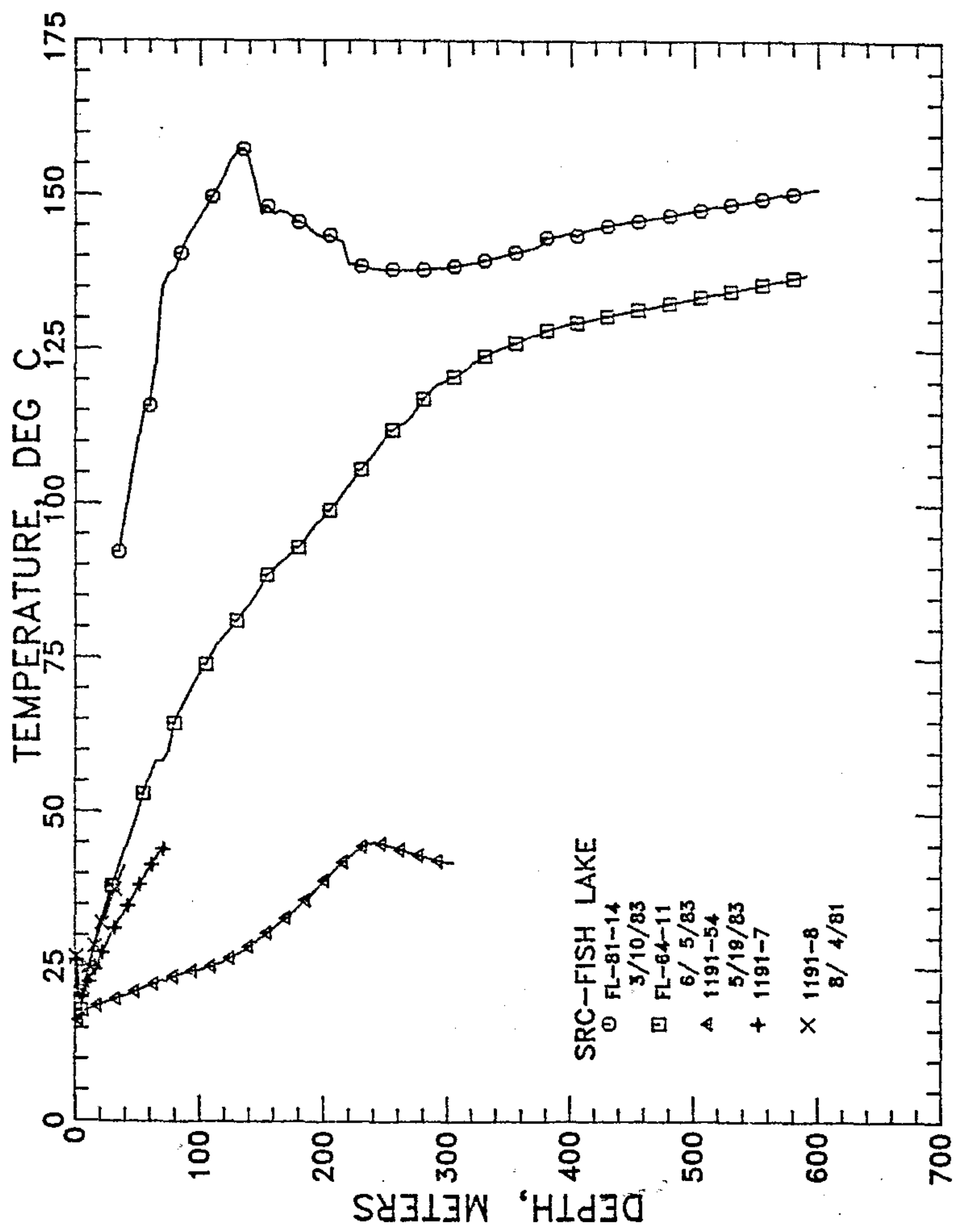


Figure 1B. Temperature-depth curves for holes 81-14, 64-11, 54, 1191-7, and 1191-8.

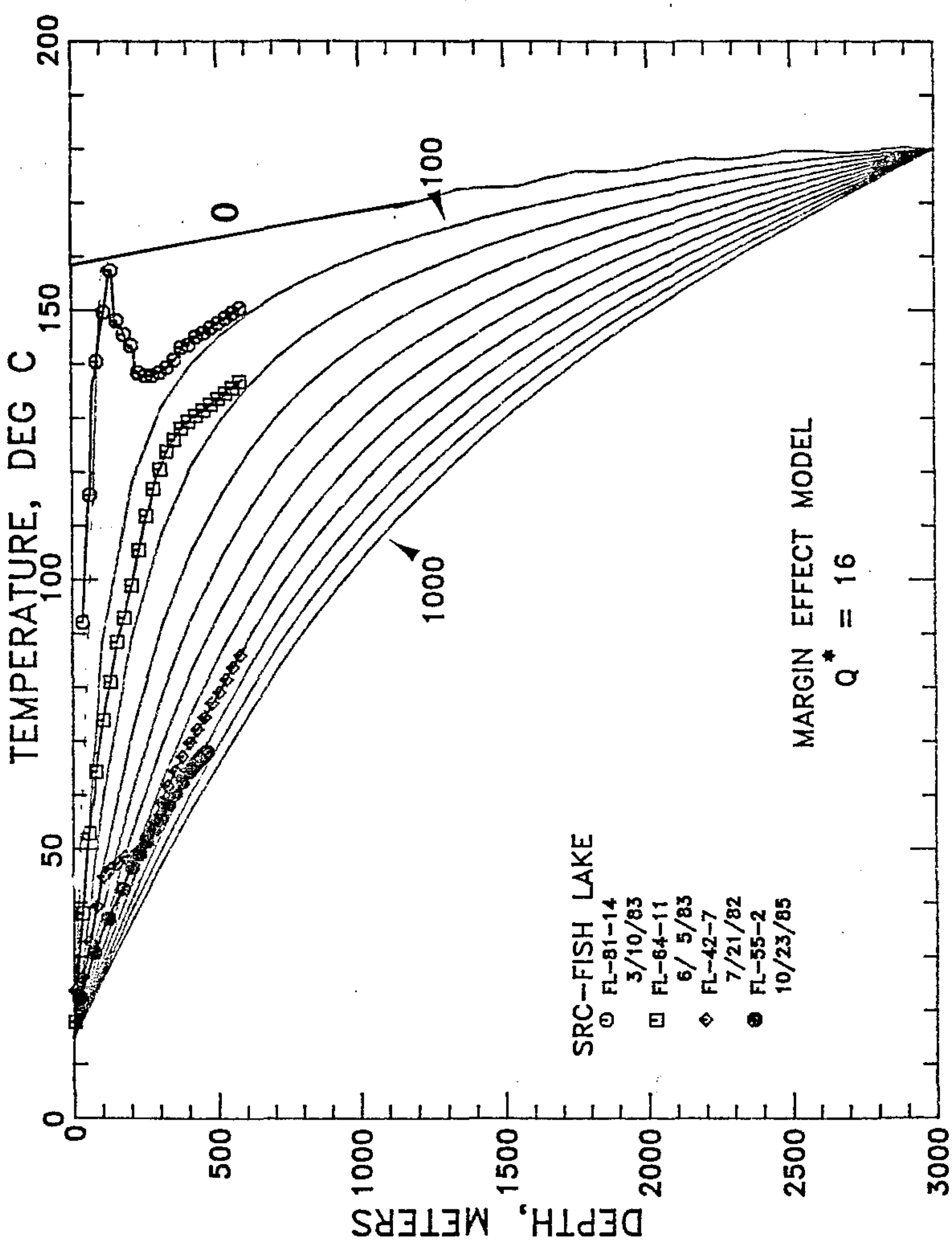


Figure 2A. Calculated temperature-depth curves from the Nathenson et al.(1979) margin effect model compared to observed temperature-depth curves. Curves calculated at 100 m(330 ft) intervals from 100 m(330 ft) to 1000 m(3300 ft) from the edge. Background temperature 180 °C at 3 km and nondimensional flow rate equal to 16.

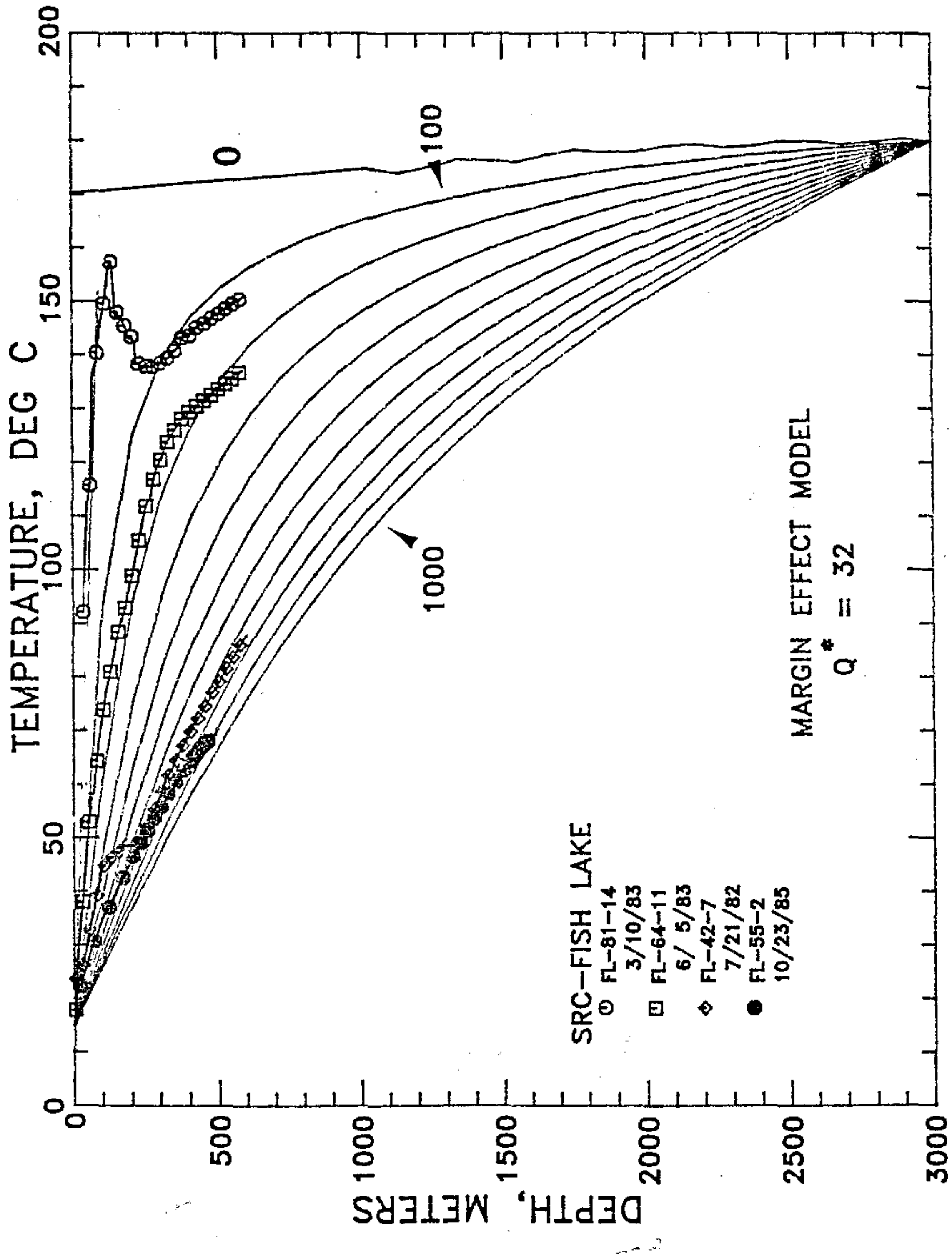


Figure 2B. Curves calculated with Nathenson model for background temperature of 180 °C at 3 km and a nondimensional flow rate equal to 32.

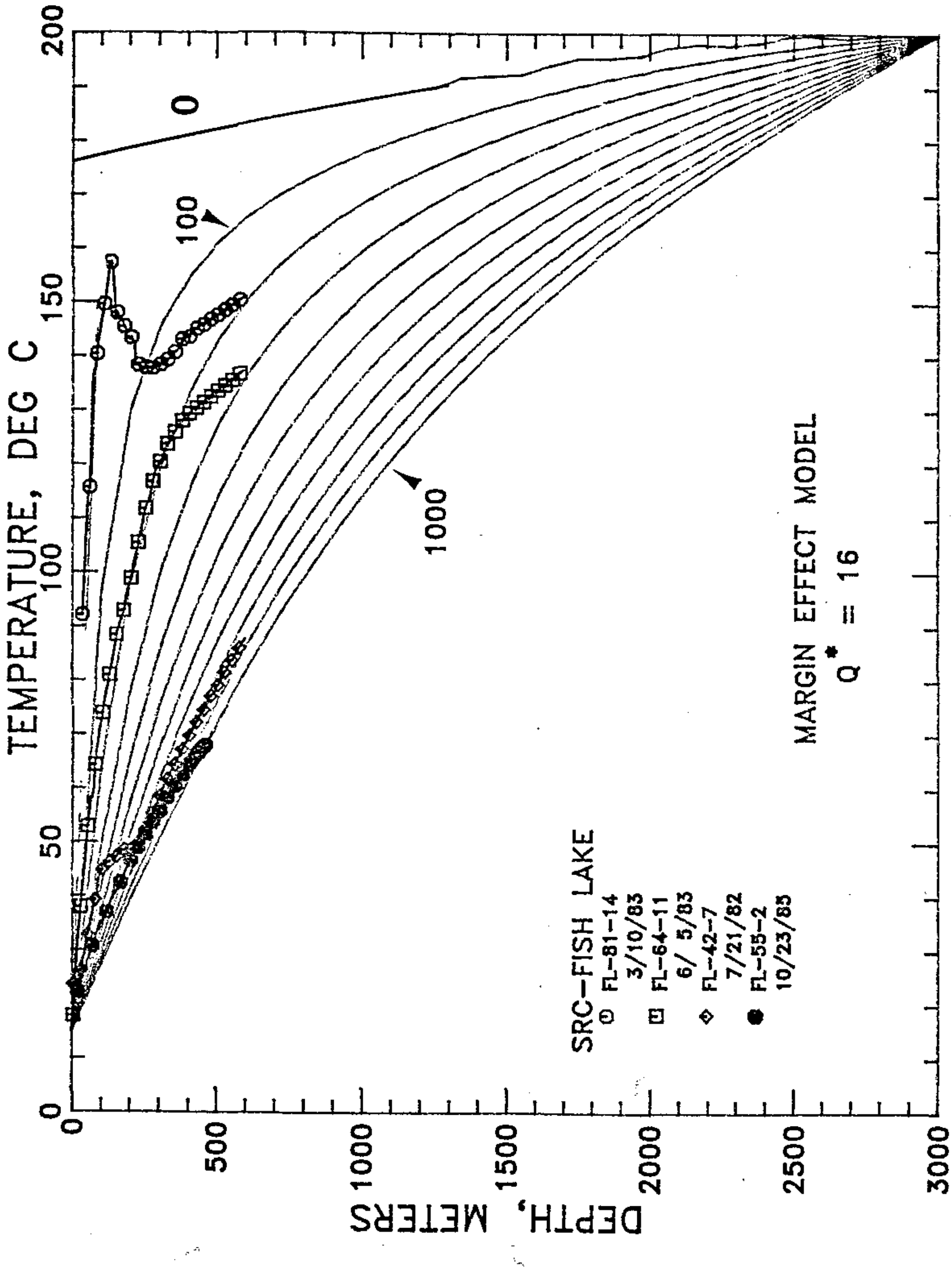


Figure 2C. Curves calculated with Nathenson model for a background temperature of 200 °C at 3 km and a nondimensional flow rate equal to 16.

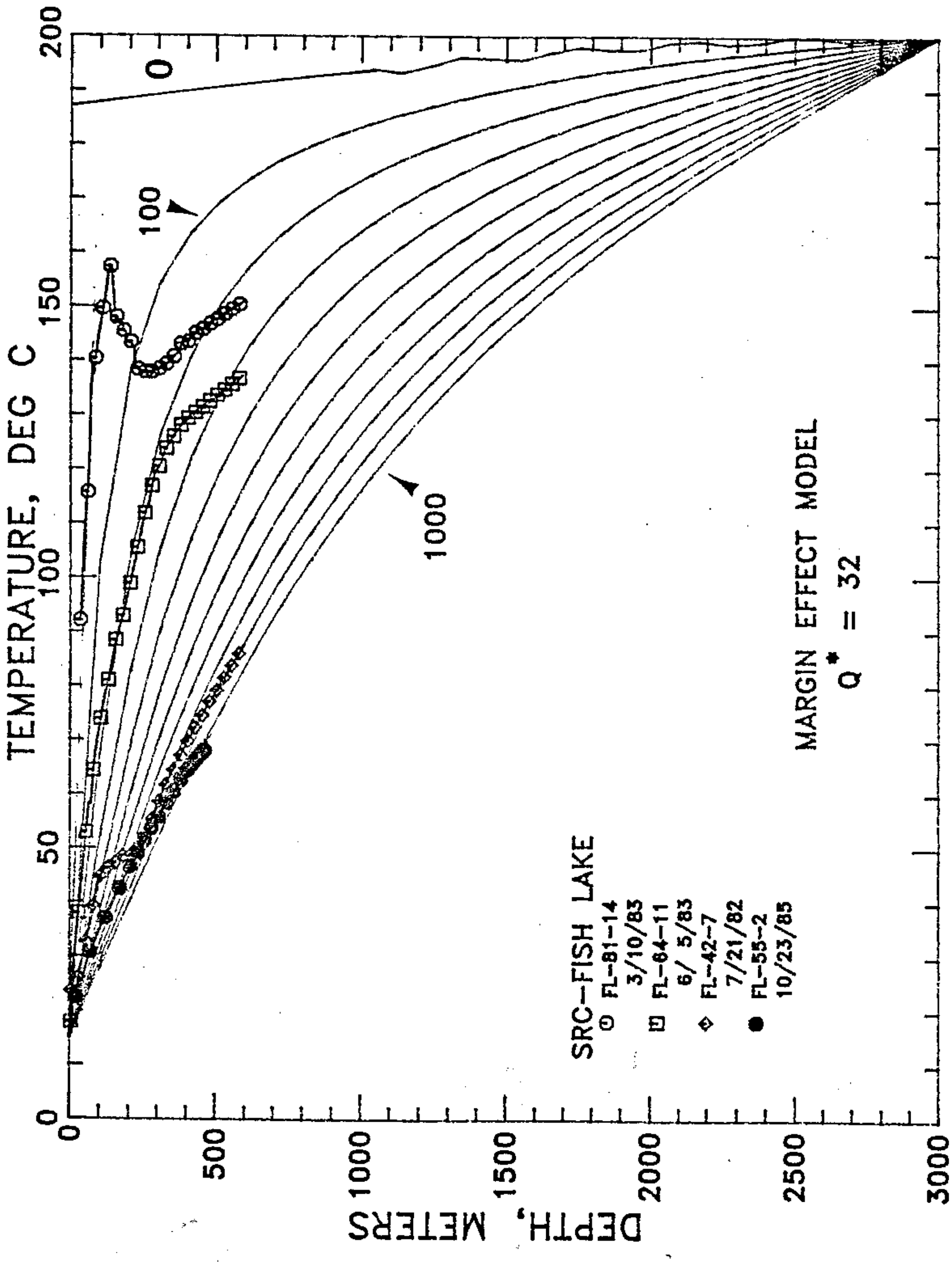
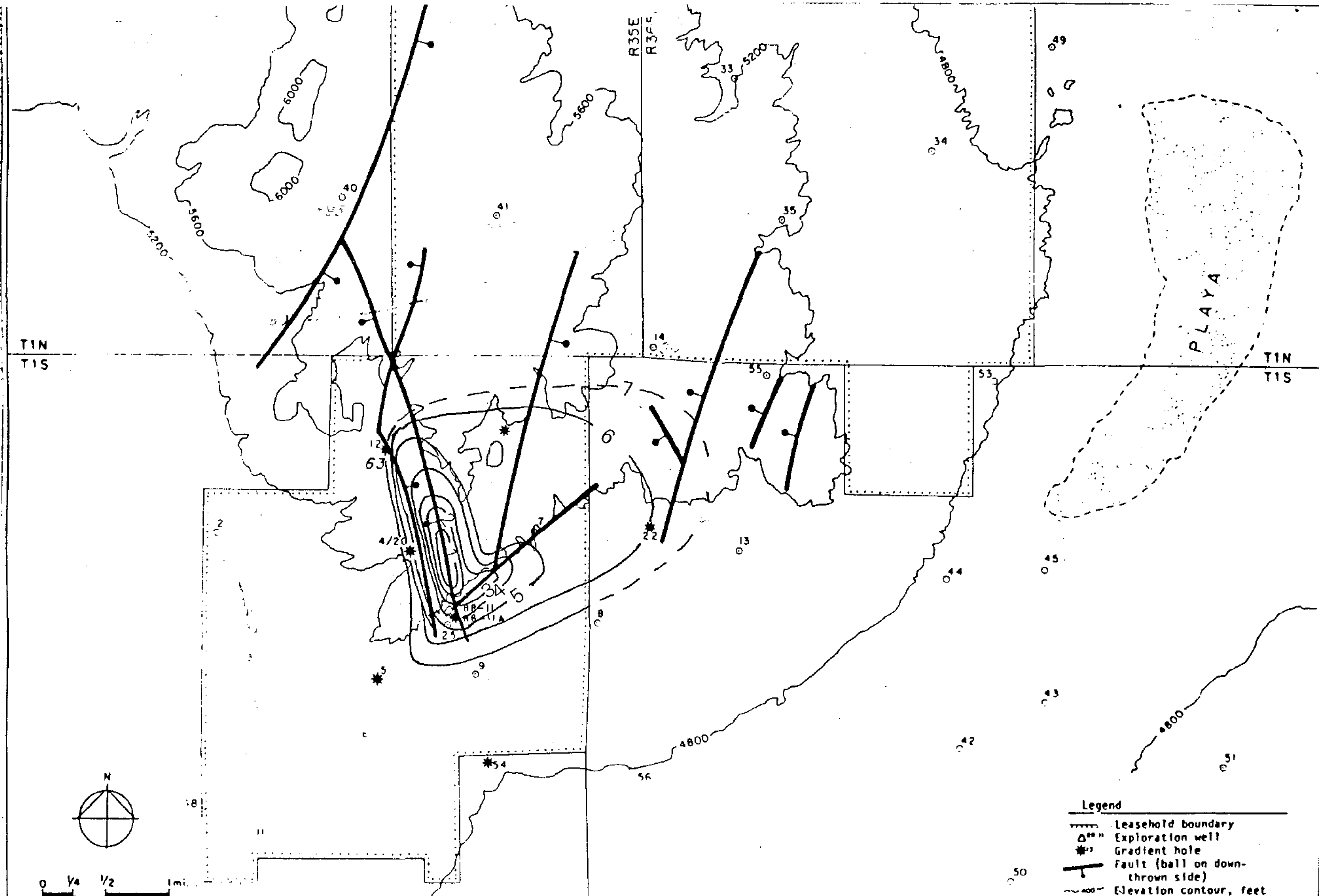


Figure 2D. Curves calculated with Nathenson model for a background temperature of 200 °C at 3 km and a nondimansional flow rate equal to 32.

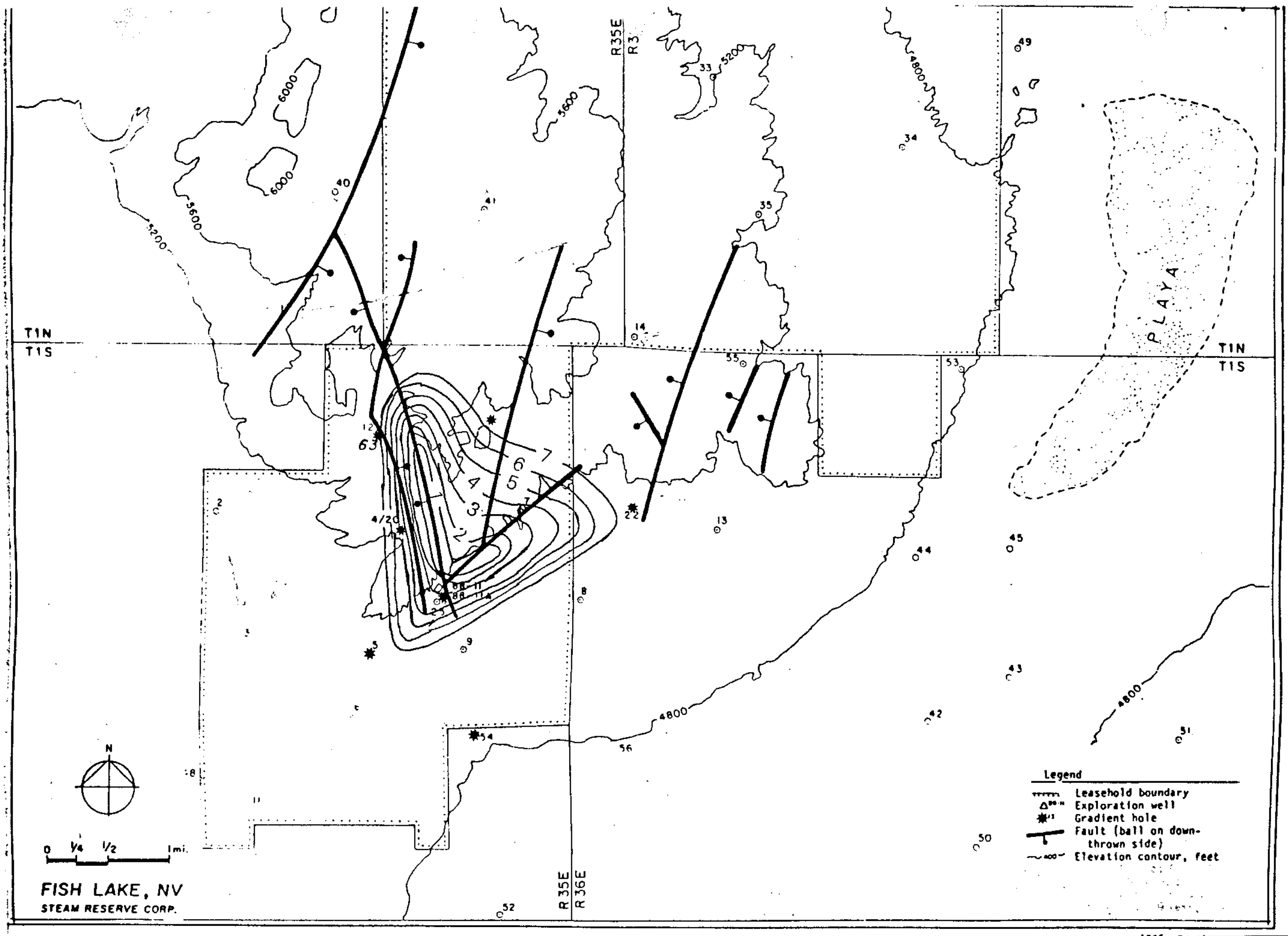
Figure 3A. A possible configuration of the 180 ^{o}C(360 ^{o}F) isotherm with holes 42-7, 35-1 and 55-2 interpreted as over the deep anomaly. Contours of depth to the isotherm are shown in thousands of feet(305 m). Base map from McNitt and Klein(1985).



FISH LAKE, NV
STEAM RESERVE CORP.

3A

Figure 3B. A possible configuration of the 180 ^{o}C(360 ^{o}F) isotherm with holes 42-7, 35-1, and 55-2 interpreted as off the edge of the anomaly. Contours of depth to the isotherm are shown in thousands of feet(305 m). Base map from McNitt and Klein(1985).



T1N
T1S
R35E
R36E
PLAYA
4800
5200
5600
6000
Legend
Leasehold boundary
Exploration well
Gradient hole
Fault (ball on down-thrown side)
Elevation contour, feet
0 1/4 1/2 1mi.
N
FISH LAKE, NV
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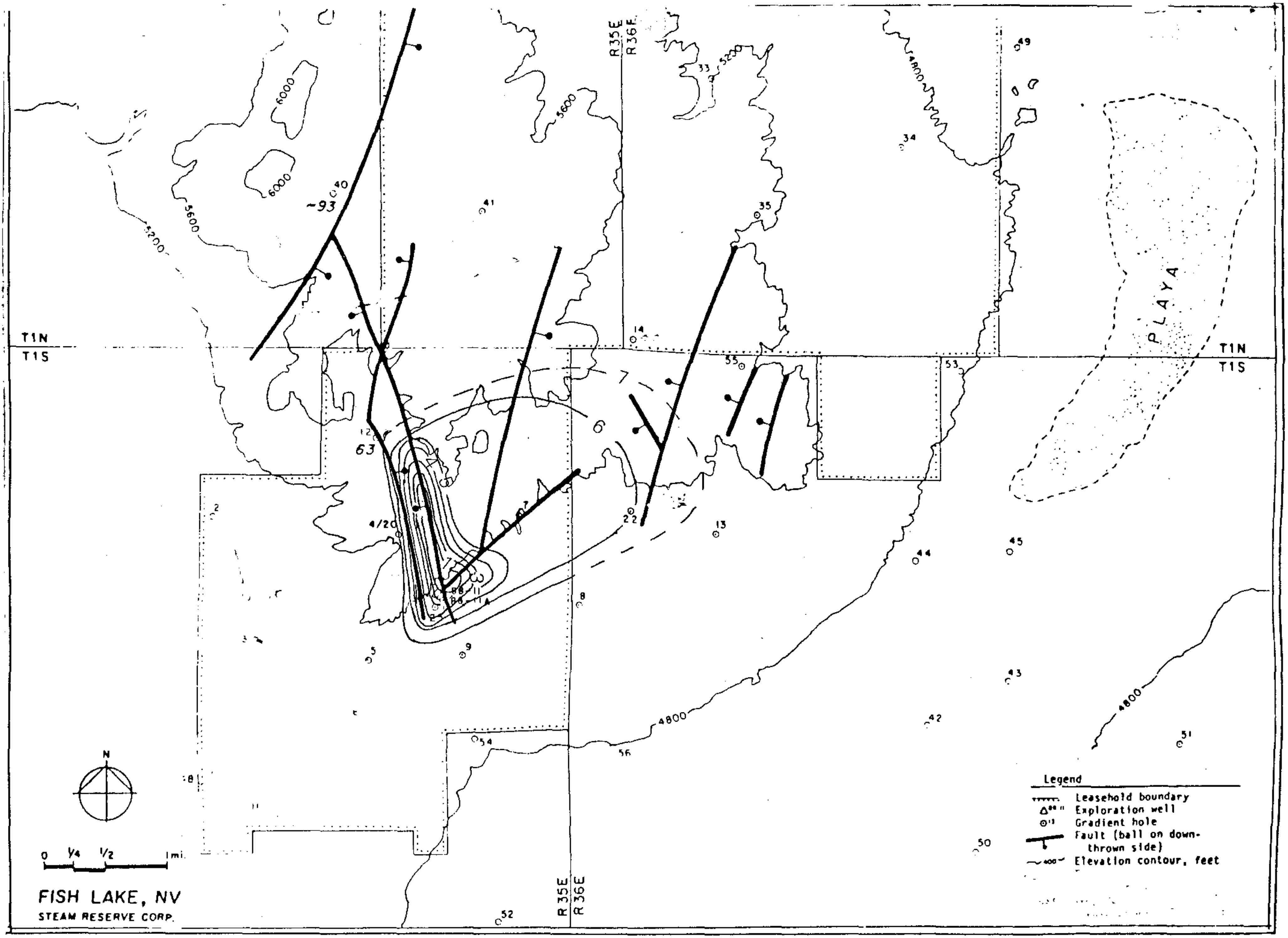
3B

Figure 3C. A possible configuration of the 180 ^{o}C(360 ^{o}F) isotherm with holes 42-7 and 35-1 interpreted as over the deep anomaly. The contours are in thousands of feet(305 m). The base map is from McNitt and Klein(1985).


R35E
R36E
T1N
T1S
PLAYA
4800
5200
5600
6000
Legend
Leasehold boundary
Exploration well
Gradient hole
Fault (ball on down-thrown side)
Elevation contour, feet
N
0 1/4 1/2 1 mi.
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