With compliments of
Ken Cook

REPRINT

Botton Gravity Meter Regional Survey of the Great Salt Lake, Utah

by

Kenneth L. Cook, Edward F. Gray, Robert M. Iverson, and Martin T. Strohmeier

Reprint from

Great Salt Lake -- a Scientific, Historical and Economic Overview
Edited by J. Wallace Gwynn
Utah Geological and Mineral Survey Bulletin 116, p. 125-143
June 1980

BOTTOM GRAVITY METER REGIONAL SURVEY OF THE GREAT SALT LAKE, UTAH

by Kenneth L. Cook[1], *Edward F. Gray*[2], *Robert M. Iverson*[3], *and Martin T. Strohmeier*[4]

[1] Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah, 84112
[2] Formerly Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah, 84112
[3] Formerly Defense Mapping Agency, Topographic Center, 6500 Brookes Lane, Washington, D. C., 20315
[4] Defense Mapping Agency, Hydrographic/Topographic Center, Geodetic Survey Squadron, F. E. Warren Air Force Base, Wyoming 82001

ABSTRACT

A bottom gravity meter regional survey of the Great Salt Lake (64 stations during 1968) resulted in the compilation of a simple Bouguer gravity anomaly map (with 5-mgal contour interval) and interpretive geologic cross sections along four east-west gravity profiles across the lake that provided information concerning the geologic structures beneath the lake. The large gravity low, that extends for a distance of about 70 miles, essentially the entire length of the lake, indicates a large north-northwestward trending graben beneath the lake, herein designated the Great Salt Lake graben. The closely spaced gravity contours, with steep gravity gradients, indicate that the graben is bounded on each side by large Basin and Range fault zones. On the northwestern side is the East Lakeside Mountains fault zone; on the southwestern side is the East Carrington-Stansbury Islands fault zone; and on the east side is the East Great Salt Lake fault zone. All fault names are newly designated. The large gravity low centers that lie north and south of the gravity saddle that extends between Bird (Hat) Island and the Promontory Point-Fremont Island area, indicate that at least two Cenozoic structural basins of deposition probably formed within the great graben between the Dolphin Island-Rozel Hills area and the Tooele Valley graben. The two basins are designated the "northern Cenozoic basin" and "southern Cenozoic basin" to the north and south, respectively, of the gravity saddle.

The geologic cross sections along the gravity profiles, based on a density contrast of 0.5 gm/cc between the bedrock and valley fill, indicate that the maximum thickness of the Cenozoic structural basins (valley fill) is more than 7,100 feet and 9,700 feet in the northern and southern Cenozoic basins, respectively. An assumed larger or smaller density contrast would result in correspondingly smaller or larger thicknesses, respectively.

The new gravity data over the Great Salt Lake, used in conjunction with the previous gravity data over the adjoining mainland (Cook and others, 1966), afforded an interpretation of the continuity and interrelationships of the geologic structures. For example, the Great Salt Lake graben is continuous with the Tooele Valley graben. Also, an arm of the northern Cenozoic basin within the Great Salt Lake graben probably extends southward, with some constriction, between the Lakeside Mountains and Carrington Island, to connect with the Cenozoic structural basin within the Lakeside-Stansbury graben.

INTRODUCTION

During July and August 1968 a regional gravity survey of the entire Great Salt Lake, Utah was made by the U. S. Defense Mapping Agency, Topographic Center (formerly designated U. S. Army Map Service) in cooperation with the Utah Geological and Mineral Survey (formerly designated Utah Geological and Mineralogical Survey). Figure 1 shows an index map of the survey area.

Sixty-four new gravity stations were taken at the bottom of the Great Salt Lake, (plate 2, in pocket) using a bottom gravity meter. The new gravity data were combined with the gravity data on land peripheral to the Great Salt Lake and along the Southern Pacific Railroad causeway across the lake that was previously published by Cook and others (1966).

The combined gravity data were used in compiling 1) a simple Bouguer gravity anomaly map of the Great Salt Lake and vicinity (plate 2) and 2) four interpretive geologic cross sections indicating the general geologic structures under and adjacent to the Great Salt Lake. A knowledge of the geologic structures will be helpful not only in deciphering the tectonic patterns and geologic

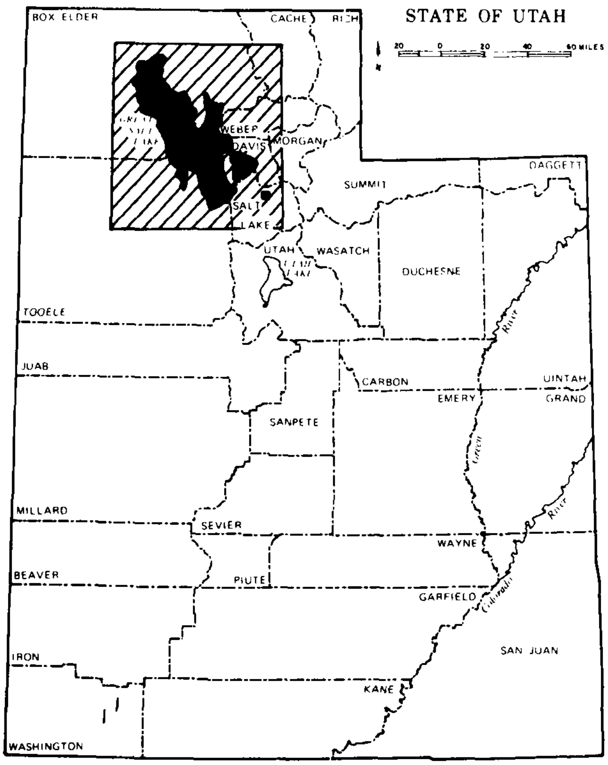


Figure 1. Index map of Utah, showing survey area.

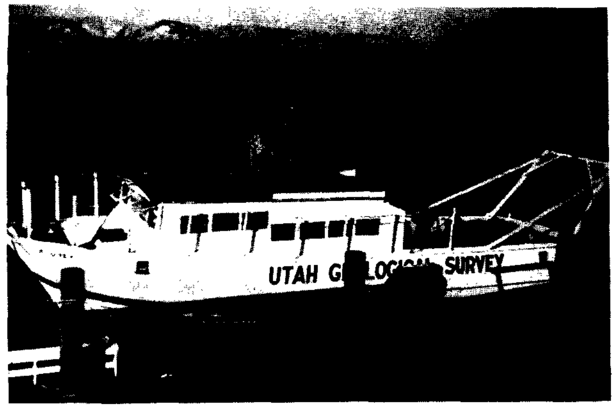


Figure 2. The boat *G. K. Gilbert* at dock in Little Valley Harbor, Great Salt Lake. Tellurometer on tripod on top of cabin. Bottom gravity meter and power winch inside boat at stern. Note cable to pulley on wooden yoke over stern of boat. Photograph taken by K. L. Cook on August 4, 1968.

history of the region, but also in the evaluation of the potential for natural resources. For example, the existence of deep Cenozoic (including Quaternary and Tertiary) basins beneath the Great Salt Lake makes the area favorable for the exploration of petroleum and/or natural gas.

TECHNIQUES AND BACKGROUND DATA

Using a LaCoste and Romberg bottom gravity meter, readings at 64 stations were taken along east-west profiles spaced approximately 5 miles apart. The stations were at 2- and 5-mile intervals on alternate traverses. Plate 2 shows the station coverage over the Great Salt Lake and surrounding areas. In the extreme northern part of the lake, the gravity coverage was less detailed than in other parts of the lake because of the difficulty in taking gravity readings in the shallow water. In this area, the wave action on the surface of the lake caused motion of the water at the bottom and hence instability (i.e., accelerations) of the bottom gravity meter that prevented the taking of accurate measurements. To await periods of perfectly calm surface water conditions for satisfactory gravity measurements would have prolonged the survey unduly.

The *G. K. Gilbert*, a boat owned by the Utah Geological and Mineral Survey, was used for the survey (figure 2). The boat, which was 42 feet long, 13 feet wide and 6 tons in weight, was propelled by two water-jet-type propulsion engines and had a draft of 1½ feet. The gravity meter was lowered over the stern of the boat on a cable that passed through a pulley to a power winch (figure 3).

Horizontal control was obtained to an accuracy of generally a few meters with a Tellurometer (Model MRA3). The master was mounted on top of the cabin of the boat (figure 2) and the two slave stations were either on the mainland or on the islands of the lake. Vertical control was obtained to an accuracy of half a foot with a lead line dropped over the side of the boat.

Two principal base stations on land were used for the survey (plate 2): (1) for the survey of the southern part of the lake, the station was on the breakwater forming the County Boat Harbor at Silver Sands Beach and (2) for the survey of the northern part of the lake, the station was adjacent to the wharf at Little Valley Harbor (northwest of Promontory Point). Using LaCoste and Romberg land gravity meter No. 123, these base stations were tied to the Salt Lake City K base station (at the Salt Lake City airport), which is a United States National Gravity Base Net station (Cook and others, 1971). A description of the location of each of these base stations is given in Appendix 1.

Figure 3. LaCoste and Romberg bottom gravity meter being lifted over side of boat before lowering by cable and power winch into Great Salt Lake. Note metal flanges on tripod legs of instrument housing to facilitate stability in muddy bottom of lake. Photograph taken by K. L. Cook on August 4, 1968.

The gravity data were reduced during 1968 by the Gravity Division of the U. S. Army Map Service in Washington, D.C. to give simple Bouguer gravity anomaly values. In making the Bouguer corrections, an average density of 1.22 gm/cc was used for the salt water of the lake, and a density of 2.67 gm/cc was used from the bottom of the lake to mean sea level. Listings of the elevations of the Great Salt Lake during the gravity survey, the density of the salt waters of the Great Salt Lake during the summer of 1968, and the principal facts of the bottom gravity stations are given in Appendices 2, 3, and 4, respectively.

The simple Bouguer gravity anomaly values for the bottom gravity stations were contoured on a map using a 5-milligal (mgal) contour interval. This map was then fitted to the corresponding gravity map values of Cook and others (1966) along the shores of the lake and the causeway across the lake. The resulting simple Bouguer gravity anomaly map, at a 5-mgal contour interval, is shown in plate 2. Four profiles (A-A′ through D-D′, plate 2) were selected for the construction of the interpretive geologic cross sections, which were computed using the two-dimensional modeling technique of Talwani and others (1959).

The resulting interpretive geologic cross sections, in conjunction with the characteristics and patterns on the gravity map and the mapped surface geology, were used to delineate the major geologic structures of the region. The results of the gravity studies were also compared with the results of the available seismic data to provide as reasonable a geologic interpretation as possible.

GEOLOGY

The Great Salt Lake lies along the active rift system in the eastern part of the Basin and Range province (Cook, 1969). The region is characterized by north-south trending mountains and valleys which generally are large horsts and grabens, respectively. The mountain ranges are generally bounded by major Basin and Range fault zones, many of which are seismically active today.

North-south trending mountain ranges surround the Great Salt Lake in most areas. These mountains, which are generally composed of Paleozoic rocks, include the Hogup Mountains, Terrace Mountains, Lakeside Mountains, Promontory Mountains, Oquirrh Mountains, and Stansbury Mountains (plate 2).

Several islands and peninsulas of the Great Salt Lake are composed of Precambrian and/or Paleozoic rocks (plate 2). Antelope Island, Fremont Island, Carrington Island, and Bird (Hat) Island are composed of Precambrian rocks. Stansbury Island and Promontory Point are composed of Precambrian and Paleozoic rocks. South Little Mountain is composed of Precambrian rocks.

Volcanic rocks of Tertiary age are the principal composition of (1) the Rozel Hills, (extending northwest of Rozel Point) which lie along the northeastern margin of Great Salt Lake and (2) the Wildcat Hills and Cedar

Hill, both of which lie near the northern margin of Great Salt Lake and off the map of plate 2.

Most of the surficial valley fill surrounding the Great Salt Lake is Quaternary alluvium. However, several isolated outcrops of Tertiary age (including the Salt Lake group) occur along or near the flanks of the mountain ranges adjacent to the lake.

Within several of the mountain ranges, major north-south trending faults and minor east-west trending faults have been mapped (plate 2). Examples of such faulting are found in the Stansbury Mountains, Lakeside Mountains, Terrace Mountains, and Hogup Mountains.

The Great Salt Lake is approximately 75 miles long and up to 30 miles wide. At the time of the gravity survey (1968), the lake had a maximum depth of 30 feet, and the surface elevations were 4,194 feet and 4,195 feet (i.e., a difference of 1 foot) for the north and south arms, respectively (see Appendix 2). The Great Salt Lake itself is a playa lake, the remanent of the historic Lake Bonneville which covered most of western Utah and parts of Nevada and Idaho during Pleistocene time. In modern times, the lake has receded to its present size and has no outlet.

The Southern Pacific Railroad causeway, completed during 1959 between Lakeside and Promontory Point, isolates the northern portion of the lake from the southern part, except for two small culverts between them. Because all surface water inflow is into the southern part of the lake, the southern part is much less saline than the northern part and at a higher elevation (about 1 foot during 1968). The density of the lake waters during 1968 was 1.21 to 1.23 gm/cc in the north arm and 1.14 gm/cc (shallow water) to 1.21 gm/cc (deep water) in the south arm (See Appendix 3).

INTERPRETATION

Gravity Patterns and Geologic Structures

The simple Bouguer gravity anomaly map (plate 2) of the Great Salt Lake and vicinity contains gravity patterns which correspond to geologic structures. The correspondence of the broader gravity patterns with the broader regional geologic structures of the Great Salt Lake region, especially the land region peripheral to the lake, are given in a previous publication (Cook and others, 1966), and will not be discussed in detail here. In the present paper, emphasis will be given to the correspondence of the gravity patterns and geologic structures in the Great Salt Lake area proper. However, the interrelationships of geologic structures and those of the surrounding mainland areas will be treated briefly to provide an overview.

On the gravity map (plate 2), the large elongate gravity lows indicate grabens. These are generally Cenozoic basins that contain sedimentary and/or volcanic rocks of Quaternary and Tertiary age possibly up to 12,000 feet in thickness (Cook and others, 1966, p. 69). The large elongate gravity highs indicate horsts, which generally form the mountain blocks in the region. The zones of closely spaced ("tight") gravity contours, with steep gravity gradients, generally indicate Basin and Range fault zones. These fault zones generally result in a large density contrast between the rocks in the mountain blocks and the valley fill material within the grabens.

The main trend of the gravity contours is north to north-northwest and parallel to the principal Laramide and older structures, as well as the major Basin and Range faults in the region (Cook and Berg, 1961). However, some locally pronounced trends are northeastern and are probably caused by Basin and Range or perhaps earlier faulting.

Horsts. On the northwestern end of the Great Salt Lake, the Lakeside Mountains horst (newly designated herein) is indicated by an elongate northward-trending gravity high (maximum of about -140 mgal) which is more than 40 miles long. This high overlies the Lakeside Mountains and extends northward over the lake to include Gunnison Island, Cub Island, and the lake area north thereof (plate 2). The horst is interpreted as one large block that includes the Lakeside Mountains, Gunnison Island, and Cub Island as outcrops of the horst.

On the western side of the Great Salt Lake, the Carrington-Stansbury Islands horst (newly designated herein) is indicated by the elongate northward-trending belt of gravity highs which is more than 30 miles long. This belt overlies Stansbury Island (-140 mgal) and extends northward over Carrington Island (maximum of about -130 mgal), Bird (Hat) Island (-133 mgal) and the lake area north thereof. The horst is interpreted as one large block that includes all three islands as outcrops of the horst.

Along the eastern margin of the Great Salt Lake, the continuous belt of gravity highs over the Promontory Range (maximum of about -130 mgal), Fremont

Island (-130 mgal) South Little Mountain (-135 mgal) and Antelope Island (-130 mgal) indicates a large essentially continuous fault block throughout this area. This interpretation was first suggested by Cook and others (1966, p. 60). For convenience of nomenclature, however, the newly designated "Promontory Mountains horst" and "Antelope Island horst" shown on plate 2 are used for the respective portions of the large block covered by these topographic features, and a single name is not given to the fault block as a whole. Moreover, the existence of previously mapped east-west trending faults within this large block indicates that the block is broken in places. Even as recently as Basin and Range faulting, this block has probably had internal faulting, but presumably on a minor scale. The same principle also applies to the Lakeside Mountains horst and the Carrington-Stansbury Islands horst.

Grabens. In a previous publication (Cook and others, 1966), the following grabens and their corresponding gravity features were described; that discussion will not be repeated here, except in so far as it concerns the overall tectonic interrelationships: the Strongknob graben (minimum simple Bouguer gravity anomaly value of about -155 mgal), the Rozel graben (-165 mgal), the Bear River Bay graben (-160 mgal), the Lakeside-Stansbury graben (-165 mgal), the East Antelope Island graben (-160 mgal); the Farmington graben (-195 mgal), and the Tooele Valley graben (-185 mgal) (plate 2).

The Great Salt Lake graben (newly designated, plate 2) is indicated by the large gravity low that extends for about 70 miles from the Dolphin Island-Rozel Hills area on the north to the Tooele Valley graben area on the south (Cook and others, 1969). The graben constitutes a large Cenozoic structural basin filled with thick sequences of sedimentary and/or volcanic rocks.

In the region between Bird (Hat) Island and the Promontory Point-Fremont Island area, the large Cenozoic structural basin may have been separated at times into at least two major Cenozoic structural basins of deposition within the graben during its development. This is evidenced by the gravity saddle and the constriction of the main gravity low associated with the Great Salt Lake graben. The "northern Cenozoic basin" lies north of the gravity saddle and the "southern Cenozoic basin" lies south thereof.

In that part of the northern Cenozoic basin between the Hogup Mountains and Rozel Hills, the gravity data indicate that the thickness of rocks in the basin is relatively small in comparison with the area within the same basin south thereof. The Bouguer gravity values over the lake in this area are about -150 to -153 mgal in comparison with values of about -140 mgal over the Hogup Mountains and Rozel Hills, a difference of only 10 to 13 mgal.

The gravity data indicate that the deepest part of the northern Cenozoic basin, where the rocks are the thickest, is probably in the area of the Southern Pacific Railroad causeway, at a point about midway between Lakeside and Promontory Point (plate 2). Here the Bouguer gravity anomaly values form a minimum of less than -165 mgal, in contrast with values of about -130 mgal over the Paleozoic bedrock in the Lakeside Mountains to the west and the Promontory Mountains to the east, a difference of about 35 mgal.

The gravity data further indicate that the southern Cenozoic basin, within the Great Salt Lake graben, is probably longer and deeper than the northern Cenozoic basin. South of the gravity saddle (about -160 mgal) between Bird (Hat) Island and the Promontory Point-Fremont Island area, the decrease of the Bouguer gravity values along the axis of the gravity low, to reach values of less than -185 mgal within the Tooele Valley graben, indicates southward deepening of the basin. These low values are in contrast with gravity values of about -130 mgal over Carrington Island and Antelope Island, a difference of about 55 mgal. It should be noted that along the axis of the gravity low, the values do not decrease consistently; rather, there are two subsidiary gravity low centers over the lake: 1) one (about -170 mgal) midway between Carrington Island and the northern tip of Antelope Island; and 2) another (about -175 mgal) midway between Stansbury Island and the southern part of Antelope Island. These gravity low centers are provisionally interpreted as being caused by undulations of the bedrock surface and may be related to subsidiary structural basins along the axis of the main southern Cenozoic basin.

The Great Salt Lake graben is continuous with the Tooele Valley graben, their trends departing from each other by about 45°. An interpretive geologic cross section along a gravity profile across the southern part of the Tooele Valley graben by Cook and others (1966) indicates the depth to bedrock to be 12,000 feet. A density contrast of 0.4 gm/cc between the bedrock and valley fill was assumed. A well (WG1 on plate 2) within the Tooele Valley graben and about 2 miles south of this gravity profile, was drilled to a depth of 7,993 feet without completely penetrating the valley fill of Cenozoic age (Cook and others, 1966, p. 68). The great thickness of Cenozoic valley fill penetrated in the Tooele Valley graben supports the interpretation that comparable thicknesses should occur beneath the southern Cenozoic basin of the Great Salt Lake graben.

It should be noted that the gravity trough between the Lakeside Mountains and Bird (Hat) Island, that extends southwest of the gravity low center over the northern Cenozoic basin, indicates a southern arm of the northern Cenozoic basin. This gravity trough continues southward, with some constriction between the Lakeside Mountains and Carrington Island, to join the pronounced gravity low center over the Lakeside-Stansbury graben. Such continuation indicates that this arm of the northern Cenozoic basin probably extends southward to connect with the Cenozoic structural basin within the Lakeside-Stansbury graben.

Faults. The gravity data indicate many major Basin and Range fault zones, which are shown on plate 2. The location of each fault, indicated by the gravity data was obtained from either the gravity map (plate 2) or the interpretive geologic cross sections along the four profiles (to be discussed later). Most of the faults shown on plate 2 are newly designated but will be only briefly mentioned.

The Great Salt Lake graben is bounded by the following fault zones: 1) on the northwestern margin, by the East Lakeside Mountains fault zone; 2) on the southwestern margin, by the East Carrington-Stansbury Islands fault zone; and 3) on the eastern margin, by the East Great Salt Lake fault zone, which extends continuously from the Rozel Hills south-southeastward along or near the western margin of the Promontory Range, Fremont Island, South Little Mountain, and Antelope Island.

The Strongknob graben is bounded on the east by the West Lakeside Mountains fault zone. The Bear River Bay graben is bounded on the west by the East Promontory Mountains fault zone. The Lakeside-Stansbury graben is bounded on the west by the East Lakeside Mountains fault zone and on the east by the West Carrington-Stansbury Islands fault zone. The Antelope Island horst is bounded on the east by the East Antelope Island fault zone.

Each of the Basin and Range fault zones are generally comprised of individual step faults that form a sinuous and/or braided pattern on the geologic map (plate 2). The indicated locations and throws of the faults and the configuration of the bedrock are shown in the profiles.

Profiles

Interpretive geologic cross sections were constructed along four east-west profiles (A-A′ through D-D′, figures 4 - 7) across the Great Salt Lake, using the two-dimensional modeling technique of Talwani and others (1959). Simple two-layer models were assumed in each cross section. A density contrast of 0.5 gm/cc was assumed between the bedrock (bottom layer, with rocks of pre-Tertiary age) and the top layer (valley fill, with rocks of Quaternary and/or Tertiary age); vertical or steeply dipping faults were assumed in all models. It should be noted that all interpretive geologic cross sections have a vertical exaggeration so that apparent dips are greatly exaggerated. The water in the Great Salt Lake is too shallow (less than 30 feet during 1968) to be included in the cross sections.

The figure for each profile is divided into three parts: (1) part "a", which shows the "observed" simple Bouguer gravity anomaly values, in milligals, with the assumed regional gravity trend; (2) part "b" which shows the residual gravity values, in milligals, after the assumed regional gravity trend has been removed from the observed gravity values; and (3) part "c" which shows the interpretive geologic cross section with the gravity station locations marked on the profile. In part "c" of three profiles, "contour stations" are indicated at locations along those portions of each profile for which the gravity control was based on contoured values only. These values were taken from the gravity map (plate 2).

Because of the inherent ambiguity of gravity data, the models should not be considered unique; however, based on all available information, they are believed to represent a reasonable interpretation of the structural configuration of the contact between the valley fill and the bedrock. For those faults already mapped at the surface (Stokes, 1963), the locations of the faults shown on the profiles agree with those of the mapped faults. For those faults interpreted from the shallow reflection seismic survey over the lake during 1969, reported by Mikulich (1971) and Mikulich and Smith (1974), the location of the faults shown on the profiles generally agree well with those interpreted from the seismic survey, with a few notable exceptions that will be discussed later. This seismic survey had a maximum depth of penetration of only 4,000 feet below the surface of the lake. It should be noted that the actual number of faults along each profile, especially those at great depth, may be more or less than those shown in the profile. However, for the density contrast assumed for each profile and the total thickness of the valley fill,

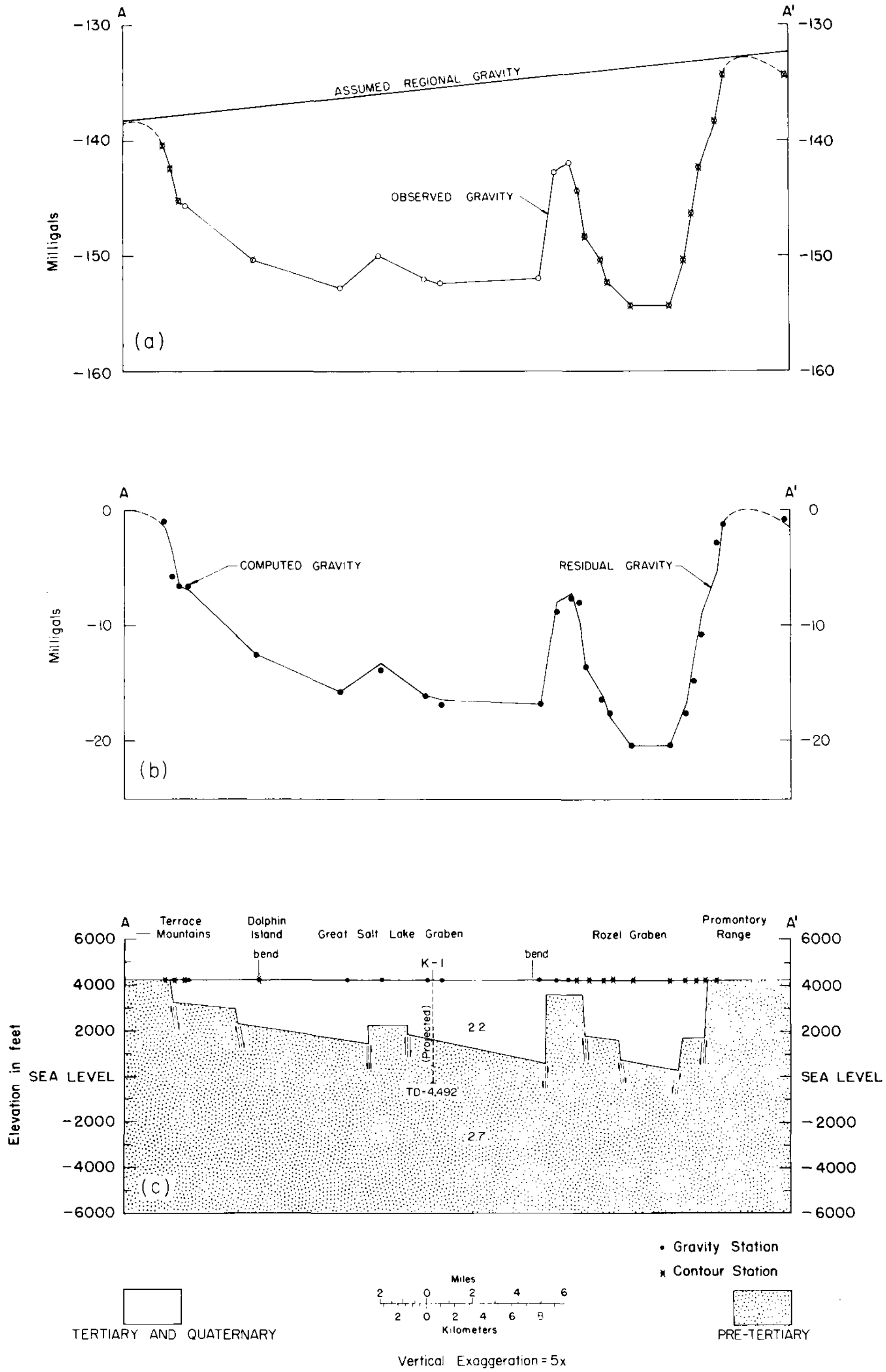


Figure 4. Gravity and interpretive geologic cross section along profile A-A' across Great Salt Lake and Rozel grabens. Assumed density contrast is 0.5 gm/cc.

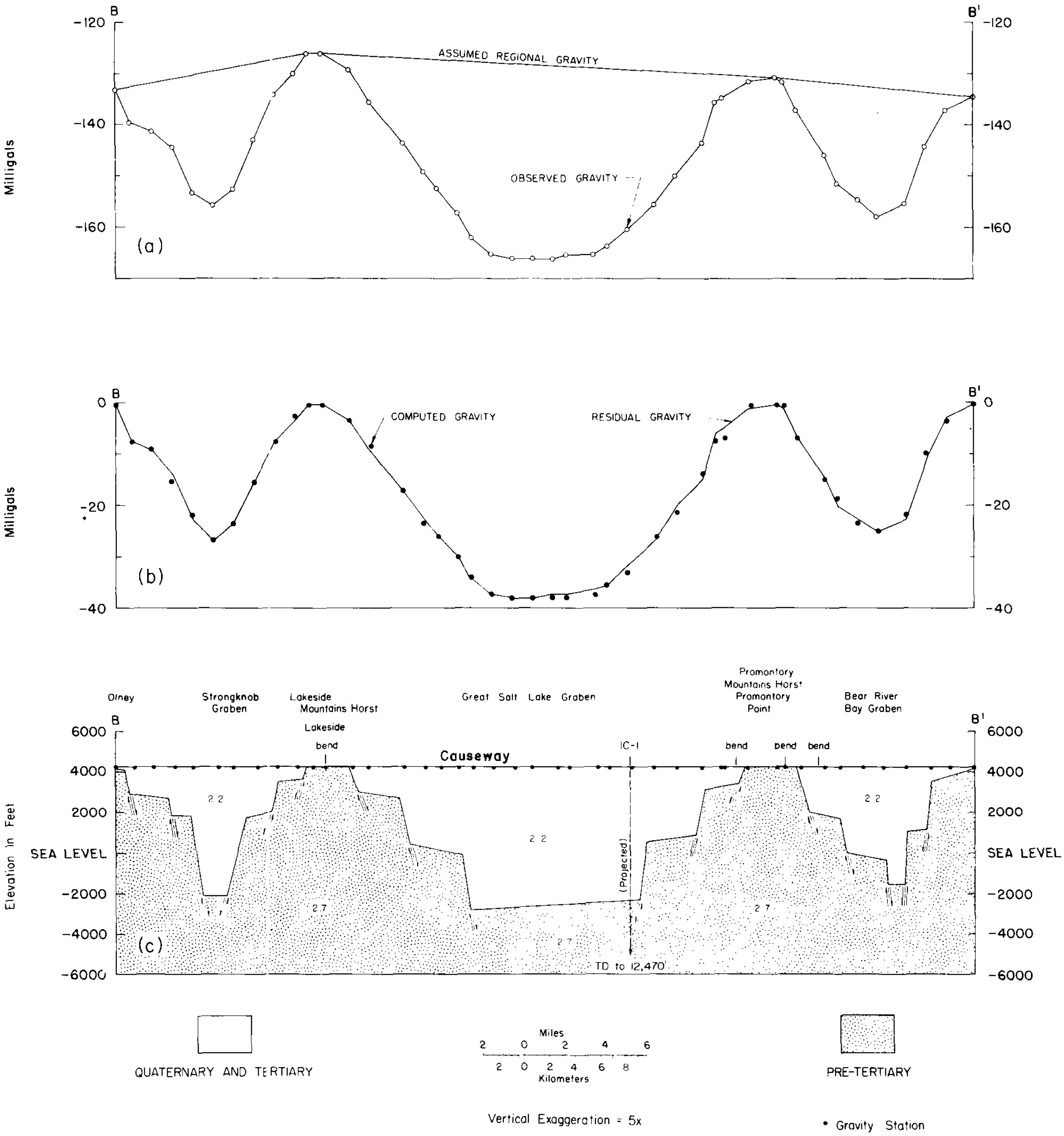


Figure 5. Gravity and interpretive geologic cross section along profile B-B' across Strongknob, Great Salt Lake, and Bear River Bay grabens and across Lakeside Mountains and Promontory Mountains horsts. Assumed density contrast is 0.5 gm/cc.

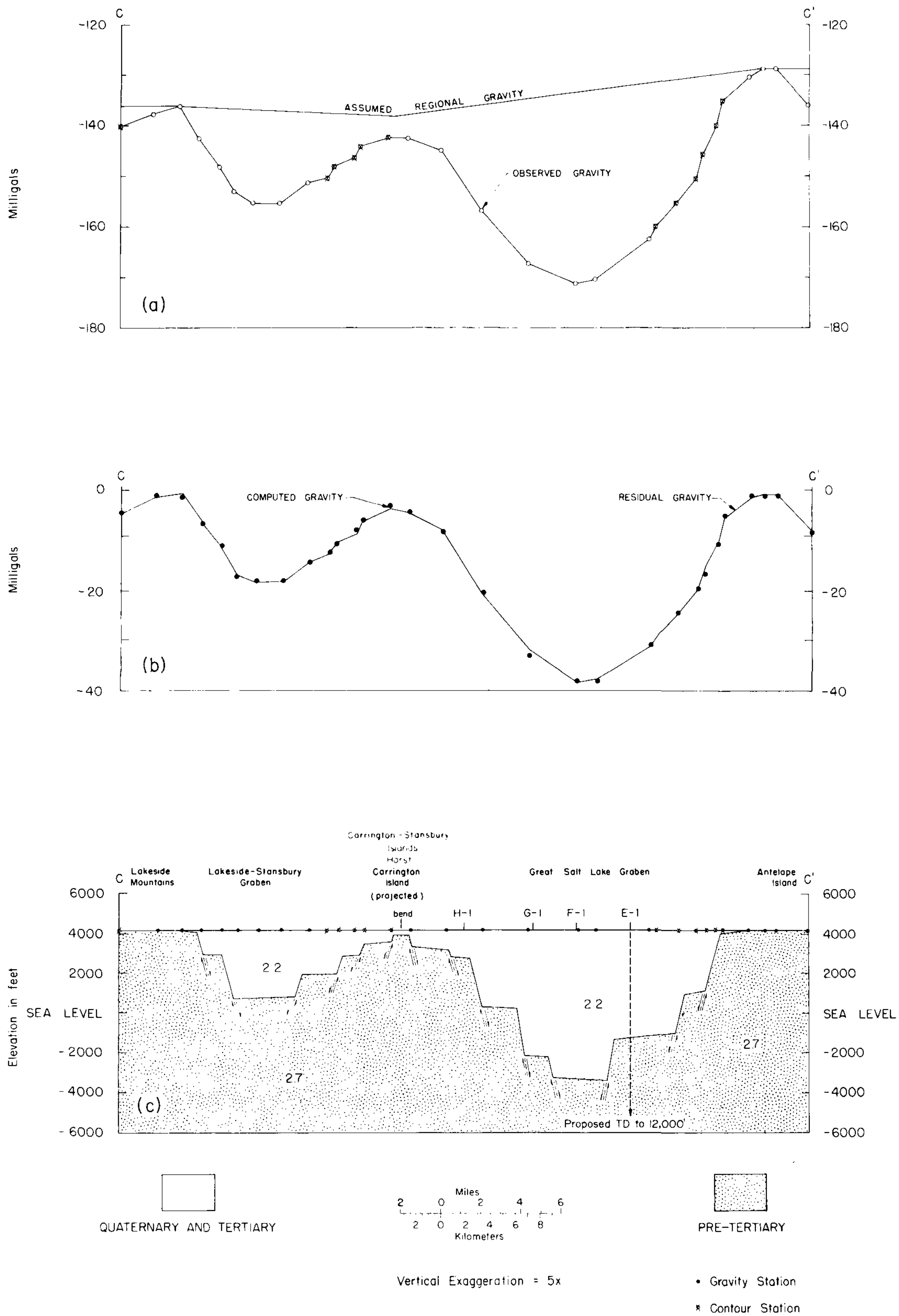


Figure 6. Gravity and interpretive geologic cross section along profile C-C′ across Lakeside-Stansbury and Great Salt Lake grabens and Carrington-Stansbury Islands horst. Assumed density contrast is 0.5 gm/cc.

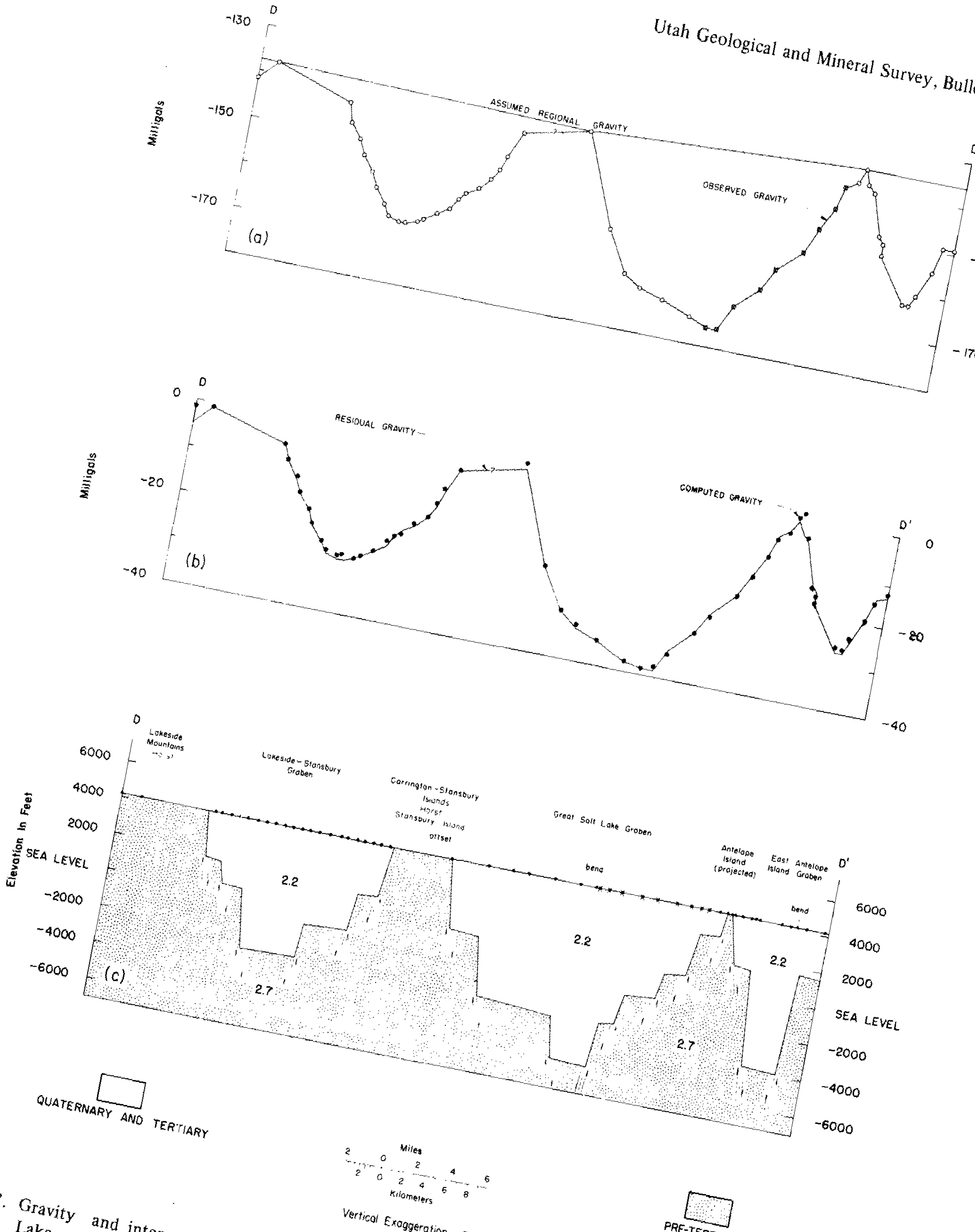


Figure 7. Gravity and interpretive geologic cross section along profile D-D′ across Lakeside-Stansbury, Great Salt Lake, and East Antelope Island grabens and across Lakeside Mountains, Carrington-Stansbury Islands, and Antelope Island horsts. Assumed density contrast is 0.5 gm/cc.

the overall configuration of the bedrock surface is considered reasonable. It should be emphasized that if the true density contrast between the top (valley fill) and bottom (bedrock) layers of rocks is less or greater than the assumed value of 0.5 gm/cc, the thickness of the top layer (valley fill) will be correspondingly greater or less, respectively, than that shown in the models.

Profile A-A′. Profile A-A′ (figure 4) extends for about 29 miles along lat 41°28′ N approximately across the northern Cenozoic basin between the Terrace Mountains and the western flank of the Promontory Mountains (see plate 2). The model shows the Great Salt Lake graben with a small, buried horst in the bedrock approximately midway between the Terrace Mountains and the Rozel Hills. This small, narrow horst is apparently the northern continuation of the Lakeside Mountains horst, a large block which forms the Lakeside Mountains, and Gunnison and Cub islands, as discussed earlier. The maximum depth to bedrock in the Great Salt Lake graben along profile A-A′ is positioned just west of the Rozel Hills, and is indicated as being about 3,600 feet.

Just east of the Great Salt Lake graben is a small horst which comes to within about 600 feet of the surface. This horst separates the Great Salt Lake graben from the Rozel graben, which lies under the Rozel Hills. The Rozel graben has been described elsewhere in detail by Cook and others (1966).

Profile B-B′. Profile B-B′ (figure 5) extends for about 38 miles at lat 41°15′ N approximately along the Southern Pacific Railroad between the Olney siding, west of Strongknob Mountain, and South Little Mountain, east of Promontory Point (plate 2). The profile passes through Lakeside and Promontory Point. Approximately 19 miles of the profile lie along the causeway which crosses the lake.

On the west, the model shows the Strongknob graben, which has been described elsewhere in detail by Cook and others (1966). To the east of the Strongknob graben are successively, the Lakeside Mountains horst, the Great Salt Lake graben, the Promontory Mountains horst, and the Bear River Bay graben. Along profile B-B′, the maximum depth to bedrock is apparently along the deep western margin of the Great Salt Lake graben, which corresponds with the deep eastern base of the Lakeside Mountains horst. Moreover, the northern Cenozoic basin is apparently deepest here; and the maximum basin fill is indicated as about 7,100 feet. The Bear River Bay graben has been described elsewhere in detail by Cook and others (1966).

Profile C-C′. Profile C-C′ (figure 6) extends for about 34 miles along lat 40°47′ N approximately between the Lakeside Mountains and Antelope Island (plate 2). The profile crosses over a narrow peninsula of Quaternary rocks extending south of Carrington Island and continues eastward for about 20 miles over the lake itself. Beneath the western part of the profile is the Lakeside-Stansbury graben, which has been described elsewhere in detail by Cook and others (1966). Beneath the central part of the profile is the Carrington-Stansbury Islands horst, the top of which is buried beneath a thin cover of Quaternary rocks. The Great Salt Lake graben lies between Stansbury Island and Antelope Island. The maximum depth to bedrock along the profile is approximately midway between the two islands and is indicated as 7,600 feet. It should be noted that this part of the Great Salt Lake graben is in the southern Cenozoic basin.

Profile D-D′. Profile D-D′ (figure 7) extends for about 41 miles along lat 40°50′ N approximately from the Lakeside Mountains eastward across Stansbury Island (with a slight offset in the profile), the southern part of the Great Salt Lake (with a slight bend in the profile in the central part of the lake), the southern tip of Antelope Island, and along the road causeway between Antelope Island and the mainland (plate 2). The profile crosses the following structures, successively from west to east: Lakeside Mountains horst, Lakeside-Stansbury graben, Carrington-Stansbury Islands horst, Great Salt Lake graben, Antelope Island horst, East Antelope Island graben, and Farmington Bay horst. The East Antelope Island graben and Farmington Bay horst have been described elsewhere in detail by Cook and others (1966).

Along profile D-D′, the basement configuration is strikingly asymmetrical. In particular, the Great Salt Lake graben is deepest toward Antelope Island where the maximum depth to bedrock is indicated as about 9,700 feet. It should be noted that although the maximum depth to bedrock within the Great Salt Lake graben is greater along profile D-D′ than profile C-C′, the deepest part of the southern Cenozoic basin lies south of profile D-D′, where the Great Salt Lake graben joins the Tooele Valley graben (plate 2). Consequently the maximum thickness of the valley fill in the southern Cenozoic basin probably exceeds 9,700 feet.

Summary of profiles

The maximum depths to bedrock indicated within the various grabens along the four profiles A-A′ through

D-D′ are summarized in table 1. Also in the table, a comparison between the maximum depth to bedrock indicated in this paper with depth estimates given by Cook and others (1966) shows good agreement. The discrepancy in the estimated depths to bedrock for the East Antelope Island graben can be explained partly because an assumed regional gravity trend is removed in this paper, whereas none was removed by Cook and others (1966).

Although the structures shown in the interpretive geologic cross sections are considered a reasonable interpretation, based on the available gravity and geologic control, they should not be considered a unique interpretation. An equally good fit of the computed and residual gravity could be obtained by assuming a larger number of step faults than those actually shown. Also, the angle of dip shown on the faults is subject to much uncertainty, but the values assigned are considered reasonable. For an assumed density contrast greater or less than the value of 0.5 gm/cc used, the interpreted locations of the inferred faults would not have changed appreciably. However, the total throw of the postulated faults would be correspondingly less or greater, respectively, and the maximum thickness of the Cenozoic valley fill in the central part of the grabens would be correspondingly less or greater, respectively, than that shown in the profiles.

A significant result of the interpretive geologic cross sections is that within the Great Salt Lake graben, the maximum thickness of the Cenozoic valley fill in the southern Cenozoic basin (indicated as about 9,700 feet on profile D-D′) is much greater than that in the northern Cenozoic basin (indicated as about 7,100 feet on profile B-B′).

COMPARISON OF RESULTS OF SEISMIC AND GRAVITY SURVEYS

During 1969, an extensive seismic reflection survey was made over the Great Salt Lake (Mikulich, 1971; Mikulich and Smith, 1974). The maximum depth of penetration of the Bolt air gun used for this survey was only 4,000 feet.

A comparison of the results of the seismic and gravity surveys shows that most of the faults that were indicated by the seismic data (not shown on plate 2) correspond well with the faults interpreted from the gravity data (shown on plate 2). In particular, the best correspondence is noted for the larger, elongate, north-south trending Basin and Range faults that delineate the east and west margins of the complexly faulted Great Salt Lake graben. Some of the individual step faults along fault zones marginal to the graben probably have vertical throws of 1,000 feet or more, and are indicated

Table 1. Summary of indicated maximum depths to bedrock along profiles.

Name of graben	Profile	Maximum depth to bedrock -- this paper (feet) [1]	Estimated depth to bedrock (Cook and others, 1966) (feet)[2]
Great Salt Lake (Northern basin)	A-A′	3,600	– –
Rozel	A-A′	3,900	>2,350
Strongknob	B-B′	6,400	>1,500
Great Salt Lake (Northern basin)	B-B′	7,100	– –
Bear River Bay	B-B′	5,800	>1,500
Lakeside-Stansbury	C-C′	3,500	>1,500
Great Salt Lake (Southern basin)	C-C′	7,600	– –
Lakeside-Stansbury	D-D′	7,000	>2,500
Great Salt Lake (Southern basin)	D-D′	9,700	– –
East Antelope Island	D-D′	8,100	6,100[3]
Tooele Valley	4	– –	12,000[4]

[1] Based on an assumed density contrast of 0.5 gm/cc between the bedrock and valley fill.

[2] Estimated from the Bouguer approximation and an assumed density contrast of 0.4 gm/cc or 0.5 gm/cc between the bedrock and valley fill – – unless otherwise noted.

[3] Value along profile B-B′, figure 4, Cook and others, 1966, p. 70. Based on an assumed density contrast of 0.5 gm/cc. Also depths to bedrock of 4,600 feet and 7,900 feet are indicated for assumed density contrasts of 0.6 gm/cc and 0.4 gm/cc, respectively.

[4] Value along profile A-A′, figure 3, Cook and others, 1966, p. 66. Based on an assumed density contrast of 0.4 gm/cc between the bedrock and valley fill.

by both gravity and seismic data at approximately the same locations. The faults that show good correspondence are in the following areas: 1) along the East Great Salt Lake fault zone west of Antelope Island (along profile D-D′) and west of Promontory Point (along profile B-B′) and 2) along the East Lakeside Mountains fault zone east of Lakeside (along profile B-B′).

As expected, several faults interpreted from the seismic data were not indicated by the gravity data because the faults were in either Quaternary or Tertiary sediments with insufficient density contrast on either side of the fault. Also some faults interpreted from the seismic data were of insufficient vertical throw to be resolved in a regional-type bottom gravity survey.

SUMMARY AND CONCLUSIONS

The bottom gravity meter survey of the Great Salt Lake made possible the compilation of a simple Bouguer gravity anomaly map and interpretive geologic cross sections along four east-west gravity profiles across the lake that provided helpful information concerning the geologic structures beneath the lake. The large gravity low, that extends for a distance of about 70 miles, essentially the entire length of the lake, indicates a large north-northwestward trending graben beneath the lake. The closely spaced gravity contours, with steep gravity gradients, indicate that the graben is bounded on each side by large Basin and Range fault zones. On the northwestern side is the East Lakeside Mountains fault zone; on the southwestern side is the East Carrington-Stansbury Islands fault zone; and on the east side is the East Great Salt Lake fault zone. All fault names are newly designated. The large gravity low centers that lie north and south of the gravity saddle that extends between Bird (Hat) Island and the Promontory Point-Fremont Island area, indicate that at least two Cenozoic structural basins of deposition probably formed within the large graben between the Dolphin Island-Rozel Hills area and the Tooele Valley graben. The two basins are designated the "northern Cenozoic basin" and "southern Cenozoic basin" to the north and south, respectively, of the gravity saddle.

The geologic cross sections along the gravity profiles, based on a density contrast of 0.5 gm/cc between the bedrock and valley fill, indicate that the maximum thickness of the Cenozoic structural basins (valley fill) are 1) about 7,100 feet in the northern Cenozoic basin, along profile B-B′ and 2) about 9,700 feet in the southern Cenozoic basin, along profile D-D′. An assumed larger or smaller density contrast would result in correspondingly smaller or larger thicknesses, respectively.

The new gravity data over the Great Salt Lake, used in conjunction with the previous gravity data over the adjoining mainland (Cook and others, 1966), afforded an interpretation of the continuity and interrelationships of the geologic structures. For example, the Great Salt Lake graben is continuous with the Tooele Valley graben. Also, an arm of the northern Cenozoic basin within the Great Salt Lake graben probably extends southward, with some constriction, between the Lakeside Mountains and Carrington Island to connect with the Cenozoic structural basin within the Lakeside-Stansbury graben.

ADDENDUM

Since the final draft of the simple Bouguer gravity anomaly map (Plate 2) and interpretive geologic cross sections along the four gravity profiles across the Great Salt Lake were completed (during April 1975), in preparation for oral presentation at scientific meetings during 1975 (Cook and others, 1975; Cook and others, 1976), the Amoco Production Company initiated a test drilling program of the Great Salt Lake during May, 1978. Nine drill holes were planned, five in the north arm of the lake and four in the south arm. The locations of the test holes were apparently based on the results of a deep reflection seismic survey started on July 25, 1973, by the Amoco Production Company.[1] This survey used a specially constructed barge 60 feet long, with a total of 14 air guns (7 air guns mounted on each side of the barge). The depth of penetration was at least 12,000 feet.

The locations of all 9 Amoco test holes, presently drilled or proposed, in the Great Salt Lake are shown on plate 2. Some of the test holes are projected into the appropriate nearest interpretive geologic cross sections along the gravity profiles. At the time of submittal of

[1] The information herein concerning the deep reflection seismic survey by the Amoco Production Company is based on notes taken by K. L. Cook during a joint lecture by Craig Hansen and Charles (Bud) Ervin, geophysicists of the Amoco Production Company, Denver, Colorado. The lecture was presented on December 3, 1974, as part of a Great Salt Lake Seminar conducted at the University of Utah, under the supervision of Professor James A. Whelan, Department of Geology and Geophysics.

Table 2. Amoco Production Company, State of Utah drilled or proposed well locations in Great Salt Lake (Source - Utah Geological and Mineral Survey, August 1979 and Survey Notes, August 1979).

Well Designation	Section, Township, Range	Latitude N[8] deg min	Longitude W[8] deg min	Total Depth (TD) (feet) and Status[1]	Lithology at TD
NORTH BASIN					
J-1 (South Rozel)	C-NE-SW Sec. 21-8N-7W	41° 24.36′	112° 39.24′	6,802 (D)	Paleozoic carbonates[4]
K-1 (North Gunnison)	C-NE-SE Sec. 11-8N-9W	41° 26.04′	112° 49.21′	4,492 (D)	Paleozoic carbonates
D-1 (West Rozel)	C-NW-SW Sec. 23-8N-8W	41° 24.36′	112° 44.04′	8,503 (T)	[2]
Indian Cove No. 1 (IC-1 on plate 2)	C-SW-SE Sec. 23-7N-7W	41° 19.06′	112° 36.59′	12,470 (D)	Precambrian schist[5]
West Rozel No. 2 (WR-2 on plate 2)	S-NW-SW Sec. 15- 8N-8W	41° 25.25′	112° 45.18′	2,700 (approx.) (T)	Rozel Point basalt[3]
SOUTH BASIN[6] E-1	C-NW-SW Sec. 19-3N-4W	40° 58.56′	112° 21.09′	Proposed to 12,000[7]	– –
F-1	C-NW-SW Sec. 15-3N-5W	40° 59.42′	112° 24.59′	Proposed	– –
G-1	C-SE-NW Sec. 29-3N-5W	40° 57.97′	112° 26.66′	Proposed	– –
H-1	C-NW-SW Sec. 11-3N-6W	41° 00.28′	112° 30.36′	Proposed	– –

[1](T) = Temporarily abandoned.
(D) = Dry and abandoned.
Source – Survey Notes, August 1979.

[2]Paleozoic carbonates at about 6,325 feet. Tested heavy oil from basalt at 2,300 feet depth. (Survey Notes, August 1979).

[3]Pump tests recovered 8,000 barrels of heavy oil at rates as high as 1,500 barrels per day from 2,300 feet to total depth. (Survey Notes, August 1979).

[4]Paleozoic carbonates at 6,000 feet (Survey Notes, August 1979).

[5]No Paleozoic rocks penetrated. Precambrian at 12,450 feet (Survey Notes, August 1979).

[6]Drilling operations are scheduled to begin in late summer of 1979 (Survey Notes, August 1979).

[7]Survey Notes, August 1979.

[8]Coordinates of latitude and longitude of the wells were determined from a map (on which the well locations had been determined from the citation by section, township, and range) kindly furnished by Howard R. Ritzma, Utah Geological and Mineral Survey.

this paper for publication (August, 1979), the five test holes on the north arm of the lake had been completed, and the first test hole on the south arm of the lake was still in preparation to be drilled. No well logs were available because, under the terms of the state of Utah land leases to the Amoco Production Company, these data are to be considered proprietary until 7 months following the completion of each well.

Table 2 gives 1) the names and locations (both by section, township, and range and also by latitude and longitude) of all 9 Amoco test holes in the Great Salt Lake (both those already drilled and those proposed); 2) the total depth of each test hole drilled to date (August 1979); and 3) miscellaneous lithologic information that has been released by the Amoco Production Company.

It should be emphasized that in projecting the Amoco test holes into the appropriate nearest geologic cross sections along the gravity profiles, the projection was made along the trend of the gravity contours (plate 2), and hence along the indicated trend of the geologic structure (i.e., Basin and Range fault zones). Because the distances of the projections were necessarily large for the two profiles (A-A′ and B-B′) along which the Amoco test holes have been completed, and especially because the complete well logs are not yet available, any comparison between the available drilling data and the indicated maximum depth to bedrock, as shown on the profiles, is of limited value.

For example, test hole K-1, which is projected onto profile A-A′ (figure 4), actually lies about 3 miles south-southeast of profile A-A′ at a point within the north Cenozoic basin where the lower gravity values indicate a somewhat larger thickness of valley fill than along profile A-A′. Similarly, test hole IC-1, which is projected onto profile B-B′, (figure 5), lies about 7 miles north-northwest of profile B-B′; but here a comparison is more difficult. In particular, it is reported (Survey Notes, August 1979) that in test hole IC-1 (1) no Paleozoic rocks were penetrated and (2) Precambrian rocks were penetrated at a depth of 12,450 feet.

These early drilling results indicate that the maximum depth to bedrock shown along profile B-B′ (figure 5) is probably too small and that therefore the assumed average density contrast of 0.5 gm/cc between the bedrock and valley fill is probably too large for the northern Cenozoic basin. This indication has been corroborated by the measurement of the density of a dense gray siltstone core sample from Amoco test hole IC-1 (the one projected into profile B-B′, figure 5) from a depth of approximately 5,500 feet. The density was 2.54 gm/cc (J. W. Gwynn, Utah Geological and Mineral Survey, August 14, 1979, personal communication).

ACKNOWLEDGMENTS

Appreciation is expressed to Colonel David B. Conard, formerly Commanding Officer, Army Map Service, Corps of Engineers, Department of the Army, Washington, D. C., and William P. Hewitt, former Director, Utah Geological and Mineralogical Survey, Salt Lake City, Utah, for their original authorization of the bottom gravity meter survey. The work was done during 1968 as a cooperative project between the two organizations. Encouragement to publish the results of the survey has been given by Dr. S. H. Ward, Chairman, Department of Geology and Geophysics, University of Utah and Dr. L. H. Lattman, Dean, College of Mines and Mineral Industries, University of Utah.

The U. S. Army Map Service personnel, who performed the bottom gravity meter survey, consisted of: 1) Supervisor - R. M. Iverson; 2) Party Chiefs and bottom gravity meter instrument operators - Lawrence Hunt, during the early part of the survey and M. T. Strohmeier, during the latter part of the survey; 3) Electronic Technician (for repairs and maintenance of gravity meter) - Glen Cobb, 4) Tellurometer operators - Lewis Phillips, in charge, assited by Ronald Creel, James D. Hutchison, Carl Kaywood, and Don Zeal.

The *G. K. Gilbert* was operated for the Utah Geological and Mineralogical Survey by Leonard Hedberg, captain, and Dave Sekino, first mate.

Robert H. Brown, a graduate student in Geophysics at the University of Utah, made the gravity ties between the Salt Lake City airport base station K and the Little Valley and Silver Sands base stations.

The gravity data were reduced under the immediate supervision of Robert Ziegler, Gravity Division, Army Map Service, Corps of Engineers, Department of the Army, Washington, D. C.

Appreciation is expressed to the Gravity Division, Army Map Service, Corps of Engineers, Department of the Army, Washington, D. C., for the loan of LaCoste and Romberg land gravity meter No. 123, which was used to make the ties of the various gravity base stations on land.

Leonard Hedberg and J. A. Whelan provided density values of the waters of the Great Salt Lake given in Appendix 3.

Financial support for the compilation and interpretation of the gravity map and profiles and the preparation of the paper for publication was given by 1) the National Science Foundation under Research Grants GA-30182 and DE71-00422-AO2, 2) the Mineral Leasing Funds, College of Mines and Mineral Industries, University of Utah, and 3) the Utah Geological and Mineral Survey.

REFERENCES

Cook, K. L., 1969, Active rift system in the Basin and Range province: Tectonophysics, v. 8, p. 469-511.

Cook, K. L., and J. W. Berg, Jr., 1961, Regional gravity survey along the central and southern Wasatch front, Utah: U.S. Geological Survey Professional Paper 316-E, p. 75-89.

Cook, K. L., J. W. Berg, Jr., W. W. Johnson, and R. T. Novotny, 1966, Some Cenozoic structural basins in the Great Salt Lake area, Utah, indicated by regional gravity surveys: *in* The Great Salt Lake, Guidebook to the Geology of Utah, no. 20, W. L. Stokes, Editor, Utah Geological Society, Salt Lake City, Utah, p. 57-75.

Cook, K. L., J. W. Berg, Jr., and Daniel Lum, 1967, Seismic and gravity profile across the northern Wasatch trench: *in* Refraction Seismic Prospecting, edited by A. W. Musgrave, Society of Exploration Geophysicists, Tulsa, Oklahoma, p. 539-549.

Cook, K. L., R. M. Iverson, and M. T. Strohmeier, 1969, Bottom gravity meter survey of the Great Salt Lake, Utah (abstract): EOS, American Geophysical Union Transactions, v. 50, p. 321. Abstract also published in Abstracts with Program, Part 5, Rocky Mountain Section, 22nd Annual Meeting, Geological Society of America, Salt Lake City, Utah, May 7-11, p. 16.

Cook, K. L., R. M. Iverson, M. T Strohmeier, and E. F. Gray, 1975, Interpretive geologic cross sections along gravity profiles across the Great Salt Lake, Utah (abstract): Abstracts with Programs, v. 7, no 5, March 1975, 28th Annual Meeting, Rocky Mountain Section, Geological Society of America, Boise, Idaho, May 3-6, 1975, p. 597-598.

Cook, K. L., R. M. Iverson, R. T. Strohmeier, and E. F. Gray, 1976, Interpretive geologic cross sections along gravity profiles across the Great Salt Lake (abstract): Geophysics, v. 41, no. 2, p. 346.

Cook, K. L., T. H. Nilsen, and J. F. Lambert, 1971, Gravity base station network in Utah - 1967: Utah Geological and Mineralogical Survey Bulletin 92, 57 p.

Duerksen, J. A., 1949, Pendulum gravity data in the United States: U. S. Coast and Geodetic Survey Special Publication 244, 218 p.

McDonald, R. E., 1976, Tertiary tectonics and sedimentary rocks along the transition, Basin and Range provinces to Plateau and Thrust Belt province, Utah: *in* Symposium on Geology of the Cordilleran Hingeline, Rocky Mountain Association of Geologists, J. G. Hill, editor, Denver, Colorado, p. 281-317.

Mikulich, M. J., 1971, Seismic reflection and aeromagnetic surveys of the Great Salt Lake, Utah: Ph.D. dissertation, University of Utah, 108 p.

Mikulich, M. J., and R. B. Smith, 1974, Seismic reflection and aeromagnetic surveys of the Great Salt Lake, Utah: Geological Society of America Bulletin, v. 85, p. 991-1002.

Rocky Mountain Region Report, 1979, Southern Rockies, v. 52, no. 126, June 28, 1979, published by Petroleum Information Corporation, Denver, Colorado.

Stokes, W. L., 1963, Geologic map of northwestern Utah: College of Mines and Mineral Industries, University of Utah.

Survey Notes, 1979, Utah Geological and Mineral Survey, August, 1979.

Talwani, Manik, L. J. Worzel, and Mark Landisman, 1959, Rapid gravity computations for two-dimensional bodies with applications to the Mendocino submarine fracture zone: Journal of Geophysical Research, v. 64, p. 49-59.

APPENDIX 1

DESCRIPTION OF GRAVITY BASE STATIONS

1 Little Valley Gravity Base Station

The station is located on U. S. government benchmark "BM 4205" on the land surface at Little Valley

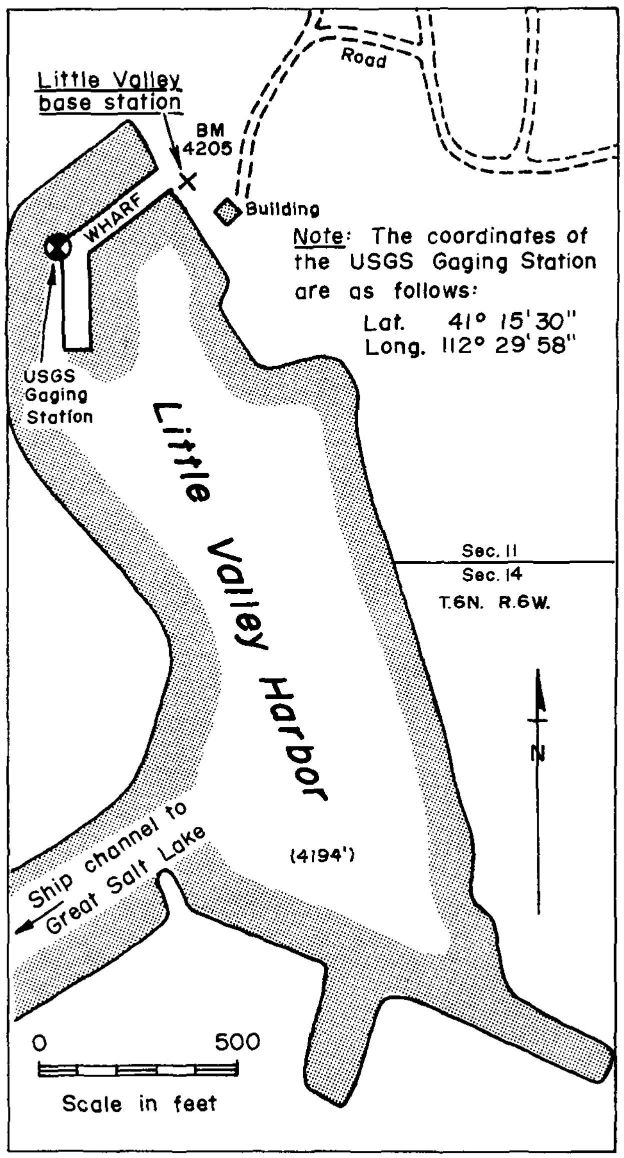


Figure 8. Sketch map showing location of Little Valley gravity base station.

Harbor northwest of Promontory Point (figure 8). The benchmark is shown on 1) the U. S. Geological Survey 7-1/2 minute topographic quadrangle map "Pokes Point, Utah" and 2) the map entitled "Great Salt Lake and Vicinity, Utah" published in 1974 jointly by the U. S. Geological Survey and the Utah Geological and Mineral Survey. The coordinates of the station are: lat 41°15.53′ N and long 112°29.90′ W.

2. Silver Sands Gravity Base Station

The station is located at Silver Sands Beach near the southwest end of the 60-foot-wide breakwater that forms the County Boat Harbor about 0.12 mile (0.2 km) southwest of U. S. government benchmark "BM 4209" that is shown on the 1) Garfield, Utah (1952) 7-1/2 minute topographic quadrangle map of the U. S. Geological Survey and 2) the map entitled "Great Salt Lake and Vicinity, Utah," published in 1974 jointly by the U. S. Geological Survey and the Utah Geological and Mineral Survey. The station is located on top of a sand bar that lies immediately southeast of the breakwater about 120 feet northeast of the southwest end of the breakwater (figure 9). The elevation of the top of the sand bar is about 5 feet below that of the top of the breakwater and was about 2 feet above the level of the south arm of the Great Salt Lake on July 28, 1968 during the time of the gravity survey. The station, which was marked in 1968 by a metal stake driven onto the sand bar, is 15 feet southeast of the bottom of the breakwater and 30 feet northeast of the northeast side of the boathouse which in 1968 contained the water-level marker for the Great Salt Lake in this area. The coordinates of the station are: latitude 40° 44.11′ N and longitude 112° 12.81′ W.

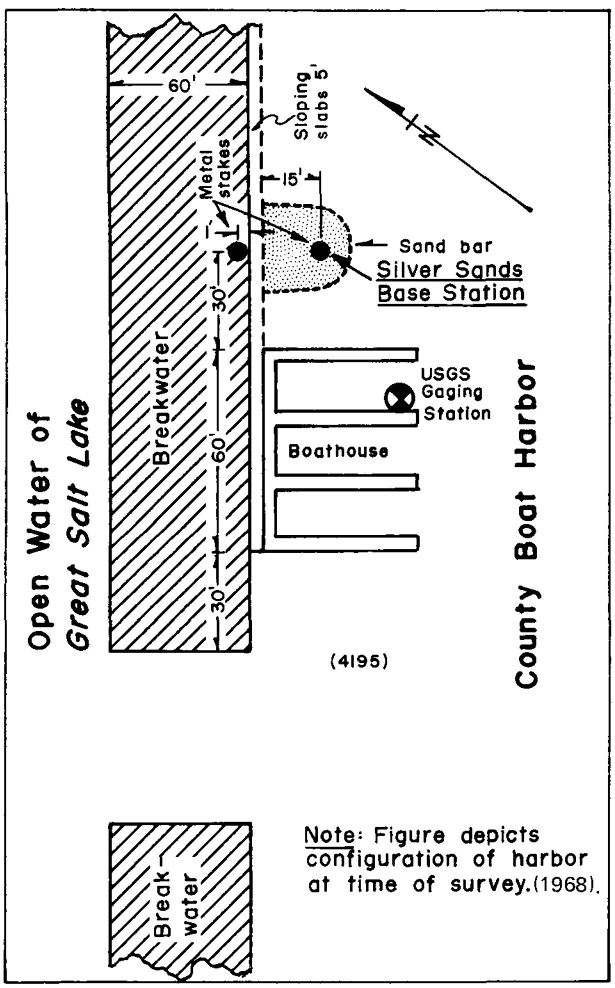


Figure 9. Sketch map showing location of Silver Sands gravity base station.

APPENDIX 2

Elevations of the Great Salt Lake during the gravity survey (data supplied by Leonard Hedberg, Utah Geological and Mineralogical Survey, August 1968).

Elevation of Great Salt Lake –South Arm (Boat Harbor Gage) For Period July 1-27, 1968

Date	Elevation (Ft.) Above MSL
July 1	4,195.48
2	4,195.45
3	4,195.45
4	4,195.40
5	4,195.40
6	4,195.40
7	4,195.38
8	4,195.38
9	4,195.38
10	4,195.35
11	4,195.33
12	4,195.33
13	4,195.33
14	4,195.28
15	4,195.25
16	4,195.25
17	4,195.28
18	4,195.22
19	4,195.18
20	4,195.18
21	4,195.13
22	4,195.05
23	4,195.05

24	4,195.05
25	4,195.05
26	4,195.03
27	4,195.00

Considerable storm activity occurred during July 22-23.
Maximum elevation: 4,195.42
Minimum elevation:..................4,194.05

Elevation of Great Salt Lake – – North Arm (Saline Gage) For Period July 28–August 9, 1968

July	28	4,194.30
	29	4,194.28
	30	4,194.30
	31	4,194.30
Aug.	1	4,194.25
	2	4,194.23
	3	4,194.23
	4	4,194.20
	5	4,194.20
	6	4,194.15
	7	4,194.15
	8	4,194.15
	9	4,194.13

Large storm occurred on August 3, from about 6:00 p.m., until midnight.
Maximum elevation 4,195.25
Minimum elevation:..................4,193.32

APPENDIX 3

Data on density of waters of the Great Salt Lake during the summer of 1968 (data supplied by James A. Whelan, Department of Geological and Geophysical Sciences, University of Utah, and Leonard Hedberg, Utah Geological and Mineral Survey, September 1968).

North Arm

Density varies from 1.21 to 1.23 gm/cc.
Average density is 1.22 gm/cc.

South Arm

Density of water from surface of lake to a depth of 20 feet is 1.14 gm/cc.
Density of water layer between this depth (20 feet) and bottom of the lake is 1.21 gm/cc.

APPENDIX 4

Principal facts of gravity stations for the bottom gravity meter survey of the Great Salt Lake (as compiled by the U. S. Army Map Service during December 1968) are shown on table 3.

EXPLANATION

The listing contains consecutively, from left to right:
Station name.
Station number.
Latitude, in degrees and minutes.
Longitude, in degrees and minutes.
Elevation of Great Salt Lake, in meters, when station was taken.
Depth to bottom of lake, in meters, at location of station.
Observed gravity, in milligals.
Free-air gravity anomaly value, in milligals.
Simple Bouguer gravity anomaly value, in milligals (using, for the Bouguer correction, an average density of 1.22 gm/cc for the lake water and 2.67 gm/cc for the material between the lake bottom and mean sea level).
Theoretical gravity at mean sea level, using the International Gravity Formula, in milligals.

Notes: The observed gravity value at Salt Lake City airport base station K was taken as 979,815.444 mgal (Cook and others, 1971). Using this value, the ties to the Little Valley and Silver Sands gravity base stations, which were made with the LaCoste and Romberg land gravity meter No. 123, resulted in observed gravity values of 979,906.540 mgal and 979,825.407 mgal, respectively, for these base stations. It should be noted that the arbitrary (and incorrect) values given in the listing for the latitudes and longitudes of these two base stations only do not affect the accuracy of the values of the observed gravity of these base stations.

The simple Bouguer gravity anomaly values used in contouring the map shown on plate 2 over the Great Salt Lake itself (i.e., for the bottom gravity meter stations only) were obtained by adding algebraically 4.36 mgal to the simple Bouguer gravity anomaly values shown in the listing. This adjustment was made so that the gravity contours over the Great Salt Lake would fit smoothly with the simple Bouguer gravity anomaly contours (obtained from the land gravity meter surveys) over the land adjacent to the lake published by Cook and others (1966). For these land gravity meter surveys (Cook and others, 1966, p. 59), the reference for observed absolute gravity was the U. S. Coast and Geodetic Survey pendulum station No. 49, in the Temple Grounds in Salt Lake City, for which the absolute gravity value was accepted as 979,806 mgal (Duerksen, 1949, p. 8).

PRINCIPAL FACTS AT GRAVITY STATIONS

STA NAME AND NUM		LATITUDE NORTH +	LONGITUDE EAST +	ELEVATION METERS	SUPP ELEV METERS	OBSERVED G MGAL	FREE AIR MGAL	BOUGUER MGAL	THEOR G MGAL
SILVER SANDS	3000	40 60.00	-111 60.00	1278.715	1.524	979826.260	-49.173	-192.156	980269.574
N-1	1	40 44.96	-112 23.38	1278.715	1.067	979826.017	-26.895	-169.910	980247.194
P-1	2	40 42.36	-112 22.07	1278.715	2.134	979803.983	-45.393	-188.335	980243.328
N-2	3	40 45.69	-112 15.10	1278.715	7.010	979815.710	-40.122	-182.727	980248.281
M-1	4	40 49.60	-112 26.00	1278.715	2.591	979840.408	-19.877	-162.786	980254.096
M-2	5	40 49.80	-112 24.40	1278.715	4.724	979832.444	-28.796	-171.559	980254.394
M-3	6	40 49.70	-112 23.30	1278.715	6.096	979830.194	-31.321	-173.989	980254.245
M-4	7	40 49.70	-112 21.60	1278.715	6.248	979828.221	-33.341	-175.998	980254.245
M-5	8	40 49.80	-112 20.00	1278.715	7.010	979826.163	-35.784	-178.389	980254.394
M-6	9	40 49.70	-112 18.80	1278.715	7.772	979824.890	-37.142	-179.695	980254.245
L3	10	40 53.66	-112 18.73	1278.724	7.925	979838.544	-29.425	-171.968	980260.137
L2	11	40 53.72	-112 21.92	1278.724	7.772	979827.201	-40.810	-183.364	980260.226
L1	12	40 54.54	-112 23.31	1278.724	5.639	979841.303	-27.269	-169.970	980261.447
SILVER SAND	4000	40 60.00	-111 60.00	1278.724	3.048	979825.407	-50.493	-193.373	980269.574
SS2 HBR LND	20000	40 60.00	-111 60.00	1278.678	.000	979825.596	-49.379	-192.463	980269.574
K-1	13	40 57.37	-112 31.87	1278.654	1.829	979865.762	-5.668	-148.824	980265.660
K-2	14	40 57.88	-112 27.27	1278.654	6.248	979845.349	-28.405	-171.056	980266.418
K-3	15	40 58.19	-112 23.43	1278.654	8.077	979842.448	-32.331	-174.856	980266.880
J-5	16	41 .86	-112 21.52	1278.654	7.925	979852.737	-25.971	-168.507	980270.855
K-4	17	40 57.63	-112 29.83	1278.654	4.724	979855.371	-17.540	-160.296	980266.047
K-5	18	40 58.24	-112 24.39	1278.654	7.772	979841.432	-33.328	-175.874	980266.955
K-6	19	40 58.66	-112 19.26	1278.654	7.772	979851.332	-24.053	-166.599	980267.579
J-4	20	41 2.02	-112 26.55	1278.654	8.077	979848.140	-32.343	-174.868	980272.582
I-12	21	41 7.80	-112 18.30	1278.654	1.676	979894.963	7.846	-135.120	980281.193
I-11	22	41 7.40	-112 20.70	1278.654	4.724	979886.563	-.899	-143.655	980280.597
I-10	23	41 7.20	-112 22.50	1278.654	6.096	979878.225	-9.362	-152.024	980280.298
I-5	24	41 5.40	-112 35.10	1278.654	2.286	979886.642	2.912	-140.012	980277.617
H-4	25	41 11.60	-112 29.00	1278.648	1.981	979885.738	-7.138	-150.082	980286.856
H-3	26	41 11.40	-112 32.80	1278.648	7.468	979870.846	-23.425	-165.991	980286.557
H-2	27	41 11.60	-112 37.60	1278.648	8.687	979866.515	-28.431	-170.913	980286.856
H-1	28	41 11.60	-112 43.30	1278.639	6.858	979878.335	-16.049	-158.656	980286.856
H-1A	29	41 11.60	-112 47.70	1278.639	1.524	979896.121	3.383	-139.592	980286.856
I-3	30	41 6.10	-112 37.60	1278.639	1.676	979878.929	-5.660	-148.624	980278.660
I-4	31	41 8.10	-112 41.50	1278.639	7.163	979864.605	-24.658	-167.244	980281.640
J-2	32	41 3.90	-112 41.50	1278.639	5.334	979863.455	-18.986	-161.698	980275.383
I-6	33	41 5.90	-112 33.10	1278.639	3.505	979882.202	-2.654	-145.492	980278.362
I-7	34	41 6.00	-112 31.10	1278.639	6.096	979874.893	-10.912	-153.572	980278.511
I-8	35	41 6.00	-112 29.30	1278.639	7.010	979866.236	-19.849	-162.446	980278.511
I-9	36	41 6.10	-112 27.20	1278.639	8.230	979860.136	-26.475	-168.988	980278.660
J-3	37	41 3.50	-112 31.00	1278.639	2.591	979870.939	-10.059	-152.961	980274.788
LITTLE VALLY	50000	40 60.00	-111 60.00	1278.407	.000	979906.540	31.481	-111.573	980269.574
F1	38	41 20.33	-112 50.48	1278.395	1.097	979914.838	9.141	-133.836	980299.871
F2	39	41 19.73	-112 43.72	1278.395	8.534	979887.035	-20.063	-162.528	980298.976
F3	40	41 20.34	-112 39.03	1278.395	7.468	979881.515	-26.163	-168.701	980299.886
F4	41	41 20.09	-112 31.05	1278.395	4.877	979904.792	-1.713	-144.430	980299.513
G-1	42	41 14.11	-112 32.42	1278.395	1.219	979882.121	-14.339	-157.308	980290.597
G-2	43	41 14.93	-112 34.84	1278.395	7.620	979876.434	-23.224	-165.751	980291.819
G-3	44	41 14.97	-112 37.76	1278.395	8.230	979873.605	-26.301	-168.787	980291.879
G-4	45	41 15.14	-112 40.29	1278.395	8.230	979873.207	-26.952	-169.438	980292.132
G-5	46	41 15.40	-112 43.21	1278.395	8.839	979877.052	-23.683	-166.126	980292.520
G-6	47	41 15.54	-112 45.75	1278.395	6.096	979885.210	-14.887	-157.520	980292.729
G-7	48	41 15.63	-112 47.89	1278.395	3.048	979899.812	.523	-142.320	980292.863
E-1	49	41 24.61	-112 39.38	1278.380	3.353	979894.952	-17.831	-160.651	980306.257
E-6	50	41 26.26	-112 48.08	1278.380	4.267	979906.066	-9.461	-152.218	980308.717
E-7	51	41 26.23	-112 49.43	1278.380	3.658	979908.345	-6.948	-149.747	980308.674
E-2	52	41 24.74	-112 41.41	1278.380	5.486	979895.049	-18.586	-161.259	980306.450
E-3	53	41 24.80	-112 43.03	1278.380	6.706	979896.747	-17.353	-159.942	980306.540
E-4	54	41 25.01	-112 44.94	1278.380	5.639	979900.797	-13.287	-155.950	980306.853
E-5	55	41 25.29	-112 47.41	1278.380	4.724	979902.967	-11.253	-153.979	980307.270
E-8	56	41 25.00	-112 53.12	1278.380	2.286	979914.325	1.289	-141.604	980306.837
D-1	57	41 28.41	-112 45.93	1278.380	5.029	979905.697	-13.273	-155.977	980311.926
D-2	58	41 28.58	-112 51.77	1278.380	4.877	979905.798	-13.378	-156.093	980312.180
D-3	59	41 28.61	-112 55.86	1278.380	1.829	979904.732	-13.549	-156.474	980312.224
C-1	60	41 33.71	-112 52.32	1278.380	2.743	979916.163	-10.013	-152.875	980319.837
C-2	61	41 33.80	-112 50.16	1278.380	2.896	979916.963	-9.394	-152.245	980319.971
B-1	62	41 39.01	-112 48.72	1278.380	.914	979920.761	-12.764	-155.752	980327.751
D-4	63	41 28.41	-112 54.04	1278.374	2.743	979907.162	-11.104	-153.965	980311.926
D-5	64	41 28.62	-112 50.99	1278.374	3.962	979905.441	-13.514	-156.291	980312.239

D. Foley
ESL

THE UNIVERSITY OF UTAH

DEPARTMENT OF GEOLOGY AND GEOPHYSICS
COLLEGE OF MINES AND MINERAL INDUSTRIES
717 MINERAL SCIENCE BLDG.
SALT LAKE CITY, UTAH 84112

Jan. 21, 1981

To: GG Department faculty

Re: <u>Unfolded</u> reprint of gravity map of Great Salt Lake.

If you prefer an <u>unfolded</u> copy of the attached gravity map of the Great Salt Lake, please return to me the attached <u>folded</u> copy, along with this note; and I will see that you get an <u>unfolded</u> copy later ~~today~~.

K. L. Cook

LAW OFFICES OF
MARTINEAU, ROOKER, LARSEN & KIMBALL
A PROFESSIONAL CORPORATION
1800 BENEFICIAL LIFE TOWER
36 SOUTH STATE STREET
SALT LAKE CITY, UTAH 84111
TELEPHONE (801) 532-7840

CLAYTON J. PARR

January 21, 1980

Dennis Nielson
Earth Science Lab
420 Chipeta Way
Salt Lake City, Utah 84108

Dear Dennis:

Enclosed as we discussed are two memoranda with attachments pertaining to the proposed Utah Geothermal Resource Conservation Act. One is a discussion of the bill (which has been introduced as SB 48) and its background. We support the bill in that form.

The other memorandum discussions amendments proposed by Utah Power & Light Company which have not yet been considered by the Senate. It is our opinion that the UP&L amendments would emasculate the bill.

Let me know if you have any questions.

Very truly yours,

Clayton J. Parr

CJP:pf
Encl.

MEMORANDUM

COMMENTS ON
AMENDMENTS TO PROPOSED UTAH
GEOTHERMAL RESOURCE CONSERVATION ACT
PROFERRED BY UTAH POWER AND LIGHT COMPANY

Introduction

As the proposed Utah Geothermal Resource Conservation Act, S.B. 279, was being considered by the Utah House of Representatives during the waning hours of the 1979 General Session, Utah Power and Light Company prepared and submitted an amendment which had the effect of grandfathering all applications to appropriate water for geothermal resources previously filed by the power company. The apparent objective of the amendment was to cause the bill to lend credence to whatever rights UP&L held by reason of its prior water applications for geothermal, which were not tied to geothermal leases, or to cause the bill's demise, which happened.

A proposed bill, essentially the same as S.B. 279, has been approved for introduction in the 1980 Budget Session and recommended for passage by the Joint Natural Resources Legislative Study Committee. The changes suggested by UP&L discussed in this Memorandum were delivered to the State Engineer on January 7, 1980, one week before the Budget Session was scheduled to begin. They were not reviewed specifically with geothermal producer proponents of the bill.

The changes suggested by UP&L are designed primarily to protect whatever rights the company holds under its prior geothermal water applications. A secondary effect is to completely frustrate the effort that was made in the original bill to reconcile the realities of geothermal resource development with the state water laws. Thus, it appears that UP&L has the same objectives in mind as it did with the amendment proposed at the 1979 General Session. Only the appearances have changed.

A. Objectives of Original Bill.

The draftsmen of the Geothermal Resources Conservation Act had five primary objectives in mind. These were:

(a) to define the resource so that it would adequately identify the resource as found in nature;

(b) to give the State Engineer necessary authority to carry out his responsibilities to regulate the development of high temperature geothermal resources;

(c) to acknowledge proprietary rights in the owner of lands in which geothermal resources are found;

(d) to ensure that the rights of prior conventional water users and the power of the state over its water resources were protected; and

(e) to avoid problems created by attempting to apply traditional water law concepts, particularly with respect to priorities, to activities pertaining to the development of a high temperature geothermal reservoir.

1. Definition of Geothermal Resources

The definition of geothermal resources, in the original proposed bill, although not identical to, is consistent with definitions utilized in federal, state, and fee leases and with definitions utilized in other states. The objective of the draftsmen was to describe the resource in terms of its physical characteristics, its function as a source of energy, and its high temperature condition. The definition includes the material medium which serves as a heat transfer medium so that the definition will include the physical substance that is extracted and utilized.

Utah Power and Light Company proposes to modify the definition to limit it to "the natural heat of the earth in the form of solids or gases" but specifically excluding water. By excluding water and other material media which would perform the function of heat transfer, the definition excludes the physical matter containing the heat that is extracted to generate power. This definition not only leads to problems with respect to imposing water law rules on geothermal resources as is discussed below, but it is also inconsistent with definitions generally accepted in federal, state, and fee leases.

The obvious objective of UP&L, however, is not to create a workable definition, but to provide for separate treatment of water, which they would argue is subject to their applications.

2. Authority of the State Engineer.

One of the principal deficiencies with the current law dealing with geothermal resources in the State of Utah, Section 73-1-20, Utah Code Annotated, is that it gives jurisdiction to the State Engineer to regulate geothermal energy production, but it does not specifically give him specific authority to take actions that are necessary to carry out this responsibility. A geothermal field is much like an oil and gas field where there is diverse land ownership over a reservoir containing fluids or gases that are interconnected as part of the same system. Accordingly, the State Engineer needs to have spacing, pooling, and unitization authority similar to that possessed by the Division of Oil, Gas and Mining with respect to oil and gas. The proposed bill would give the State Engineer such authority.

It is, however, not possible for the State Engineer to exercise such authority under the state water laws because water rights to subsurface waters are not necessarily related to overlying land ownership and because the priority system gives the first applicant who perfects his appropriation the right to quantity and pressure without interference from junior appropriators. Thus, the authority given to the State Engineer to exercise necessary regulatory powers over geothermal resources has little real significance unless the remaining parts of the bill, which attempt to forego water law principles in favor of the doctrine of correlative rights, are also adopted. As is discussed below, the changes suggested by Utah Power and Light Company have just the opposite effect, thereby leaving the State Engineer with the same problems as exist under the current law.

3. Proprietary Rights to Geothermal Resources.

When interest in geothermal resources as a source of electrical power began to develop, some interested parties suggested that the resource was water and should be developed exclusively under water laws. This approach has been almost universally abandoned as being unrealistic and inconsistent with prevailing legal principles. Throughout the entire western United States, the acknowledged basis for rights to geothermal resources is land ownership. No known challenge has been made to the proprietary rights of the landowner where there has been no severance of surface from mineral rights. In California, three cases involving situations where the surface owner claimed he had rights to geothermal resources through his ownership of water rights all resulted in decisions that ownership of geothermal resources could not be claimed through water rights. A decision involving federal lands was rendered by the 9th U.S. Circuit Court of Appeals and was left to stand by decision of the Supreme Court not to hear an appeal.

The position of Utah Power and Light Company, by reason of its geothermal water applications which are not supported by leases, has been that proprietary rights to geothermal resources can be acquired only under the water law. The changes in the bill proposed by Utah Power and Light Company achieve the same end, simply in a more circuitous manner.

The draftsmen of the original bill provided that an application to appropriate geothermal fluids be made by an owner of geothermal resources, thereby establishing that ownership is derived from some source other than the water application. Further by applying the doctrine of correlative rights as the basis for measuring rights of owners to common geothermal resources and associated geothermal fluids (such as would be the case where there is diverse ownership of tracts overlying a geothermal reservoir), the traditional oil and gas practice of basing rights to the resource on ownership rights in overlying land was adopted.

As a result of concern expressed by Senator Waddingham, an amendment which explicitly stated that an appropriation of geothermal fluids does not in itself establish ownership rights to geothermal resources was proposed. Even though it was felt that the bill already accomplished such a result, the amendment was prepared in response to Senator Waddingham's request and adopted in the House of Representatives.

The changes proposed by Utah Power and Light Company lead to just the opposite result. They propose that the water associated with the geothermal resource be handled completely independently from the resource itself, (as defined by UP&L). Their language statesthat "water used as the material medium for geothermal resources shall be acquired independently from geothermal resources and in accordance with the applicable laws of this state." They further state that "any existing applications on the date of this enactment for water in a geothermal area shall be deemed an application for water as a material medium." The result of this is twofold. First, setting up an independent basis for acquiring rights to water associated with geothermal resources without limiting the exercise of those rights to the owner of the resource would lead to possible conflicting claims of ownership of the substance which is to be extracted and utilized for the generation of power. Second, by in effect grandfathering their earlier blanket water applications, UP&L would be putting itself in a position where it would lay claim to the water and steam that is actually to be used to generate power in accordance with a priority system that would give them control over many geothermal reservoirs in the state.

Further, UP&L proposes that the owner of the geothermal resource, (as defined by UP&L), obtain a separate appropriation from the State Engineer to permit him to extract the resource. This suggestion is simply ludicrous, if for no other reason than that it suggests that heat can be appropriated under the water laws. Moreover, UP&L would not only require that there be an appropriation of water and steam associat~~ion~~ed with a geothermal resource under the state water laws, but they would also require a separate appropriation procedure for the resource itself. In the first step, they would effectively deprive the owner of any real claim to the resource; in the second step, they would add insult to injury by requiring the owner go through an appropriation procedure for a substance that is not even water before he can exercise his ownership rights.

Adoption of the concept suggested by UP&L would simply create a frustrating morass of confusion and uncertainty that could only lead to litigation between landowners and geothermal water appropriators who do not have leases from the landowners, thereby stalling and frustrating the development of this energy resource.

4 Protection of Prior Water Rights.

High temperature geothermal reservoirs will generally be separated from near surface fresh water sources that may be the subject of prior appropriations. Recognizing this, some states have adopted a procedure whereby a presumption of noninterference is established. This approach has been supported by scholars on the subject.

Nevertheless, in Utah, the proposed bill establishes a procedure whereby a geothermal owner has to obtain an appropriation of water and assume a burden of showing non-interference with conventional water users. Although this provision imposes a burden on producers that some feel is unneeded, it was nevertheless adopted out of concern that prior water rights be protected and the rights of the state over water resources be preserved. The intent was to provide such protection to conventional water appropriators without forcing a confrontation with landowners over proprietary rights to the resource itself.

By separating geothermal resources entirely from associated water, which would be acquired exclusively under conventional water law, Utah Power & Light Company would frustrate that effort. Although the Utah Power and Light position would purport to hold supreme the state system for appropriating water, the effort might ultimately backfire since there is a strong possibility that landowners, particularly the federal government, could by litigation establish that ownership of the resource cannot be so limited. This result would be especially distressing, since apparently it is only Utah Power and Light Company which intends to benefit from holding water applications for geothermal which are not connected to leases.

5. Problems Created by Water Law Concepts.

Problems are posed in connection with drilling and producing geothermal reservoirs when traditional water law concepts are applied. A typical hydrothermal reservoir of the type found in Utah is an interconnected concentration of high temperature water and/or steam within defined boundaries. Land ownership over such a reservoir is often in different parties. Common sense dictates that such a reservoir be developed according to a single coordinated plan. The regulatory agency insures that this is accomplished through its spacing, pooling, and unitization powers.

Imposition of the priority system inherent in state water law, however, is totally inconsistent with this concept. The water law contemplates that the first applicant who has his appropriation approved can draw without interference from junior appropriators. Consequently, the draftsmen of the proposed bill attempted to set up a mechanism for coordinated development independent of problems created by the water law priority system. A water appropriation filed by a geothermal owner would establish a priority as between himself and owners of water that were not geothermal fluids but it would establish no priority as between himself and other appropriators of geothermal fluids in the same reservoir. Rights among appropriators in the same reservoir would be determined by the doctrine of correlative rights.

The proposal made by UP&L completely destroys the effort of the draftsmen. By providing for independent appropriation of waters associated with the resource, UP&L in effect causes the traditional water laws of the state, including the priority system, to be imposed on a geothermal reservoir. UP&L does make reference to correlative rights by suggesting that the separate appropriation filed by the geothermal owner (the absurdity of which is discussed above) would create only correlative rights. Correlative rights in the owner of the resource is absolutely meaningless if the priority system is imposed by the separate application for water that UP&L suggests be required.

Once again, the attempt to provide order and a rational basis for geothermal development would be totally frustrated by the suggestion made by UP&L Company.

Conclusion

In summary, the UP&L proposal, rather than being a step toward resolution of differences that exist, is a big step backward. It would throw unnecessary confusion into the administration of geothermal resources and totally defeat the original objectives of the bill. That this proposal is made not out of a good faith concern over achieving an effective statutory scheme, but out of a desire to add credence to an effort made by the power company to achieve control over geothermal resources by blanketing promising areas with questionable geothermal water applications, is most disappointing.

C.J. Parr
1/8/80

Market Copy

UP&L VERSION

(GEOTHERMAL RESOURCE CONSERVATION ACT)

1980

BUDGET SESSION

____ B. No. ___ By_____________________

____

____

AN ACT RELATING TO THE DEVELOPMENT OF GEOTHERMAL RESOURCES IN THE STATE; DECLARING THE PUBLIC INTEREST IN THIS DEVELOPMENT AND ASSIGNING REGULATORY AUTHORITY REGARDING THIS TO THE DIVISION OF WATER RIGHTS; DEFINING THE RESOURCE AND ITS RELATIONSHIP TO WATER; PROVIDING FOR THE PROTECTION OF CORRELATIVE RIGHTS AND THE PREVENTION OF WASTE; AUTHORIZING AND ESTABLISHING PROCEDURES FOR UNITIZING OF GEOTHERMAL AREAS; AND PROVIDING FOR PROCEDURES TO GOVERN REGULATION BY THIS DIVISION.

THIS ACT REPEALS AND REENACTS SECTION 73-1-20, UTAH CODE ANNOTATED 1953, AS ENACTED BY CHAPTER 189, LAWS OF UTAH 1973; AND ENACTS SECTIONS 73-1-21 THROUGH 73-1-27, UTAH CODE ANNOTATED 1953.

Be it enacted by the Legislature of the State of Utah:

Section 1. Section 73-1-20, Utah Code Annotated 1953, as enacted by Chapter 189, Laws of Utah 1973, is repealed and reenacted to read:

73-1-20. It is declared to be in the public interest to foster, encourage, and promote the discovery, development, production, utilization, and disposal of geothermal resources in the State of Utah in such manner as will prevent waste, protect correlative rights, and safeguard the natural environment and the public welfare; to authorize, encourage, and provide for the development and operation of geothermal resource properties in such manner that the maximum ultimate economic recovery of geothermal resources may be obtained through, among other things,

AMENDMENT SHEET

January 7, 1980

GEOTHERMAL RESOURCE CONSERVATION ACT:

Page 2, substitute the entire page for the following:

agreements for cooperative development, production, injection, and pressure maintenance operations.

Section 2. Section 73-1-21, Utah Code Annotated 1953, is enacted to read:

73-1-21. As used in this act:

(1) "Correlative rights" mean the rights of each geothermal owner in a geothermal area to produce without waste his just and equitable share of the geothermal resource underlying the geothermal area.

(2) "Division" means the division of water rights, department of natural resources.

(3) "Geothermal area" means the general land area which is underlain or reasonably appears to be underlain by geothermal resources.

(4) "Geothermal fluid" means water and steam naturally present in a geothermal system.

(5) "Geothermal resource" means the natural heat of the earth in the form of solids or gasses other than hydrocarbon gasses at temperatures greater than 120 degrees centigrade measured at the well head, or the energy, in whatever form,

present in, resulting from, created by, or which may be extracted from that natural heat, including pressure. Water, regardless of form or temperature, is not a geothermal resource.

(6) "Geothermal system" means any strata, pool, reservoir, or other geologic formation containing geothermal resources.

(7) "Material medium, means geothermal fluids, or water and other substances artificially introduced into a geothermal system to serve as a heat transfer medium.

(8) "Operator" means any person drilling, maintaining, operating, producing, or in control of any well.

(9) "Owner" means any person who has the right to drill into, produce, and make use of the geothermal resource.

(10) "Person" means any individual, business entity (corporate or otherwise), or political subdivision of this or any other state.

(11) "Waste" means any inefficient, excessive, or improper production, use, or dissipation of geothermal resources. Wasteful practices include, but are not limited to: (a) transporting or storage methods that cause or tend to cause unnecessary surface loss of geothermal resources; or (b) locating, spacing, constructing, equipping, operating, producing, or venting of any well in a manner that results or tends to result in unnecessary surface loss or in reducing the ultimate economic recovery of geothermal resources.

(12) "Well" means any well drilled, converted, or reactivated for the discovery, testing, production, or subsurface injection of geothermal resources.

Section 3. Section 73-1-22, Utah Code Annotated 1953, is enacted to read:

73-1-22. This act shall apply to all lands in the State of Utah, including federal and Indian lands to the extent allowed by law. When these lands are committed to a unit agreement involving lands subject to federal or Indian jurisdiction, the division may, with respect to the unit agreement, deem this act or any part of this act complied with if the unit operations are regulated by the United States and the division finds that conservation of geothermal resources and prevention of waste are accomplished under the unit agreement.

Section 4. Section 73-1-23, Utah Code Annotated 1953, is enacted to read:

73-1-23. (1) The division is granted jurisdiction and authority over all persons and property, public and private, necessary to enforce the provisions of this act and shall have the power and authority to promulgate and enforce rules, regulations, and orders and do whatever may reasonably be necessary to carry out the provisions of this act.

(2) Any affected person may apply for a hearing before the division, or the division may initiate proceedings upon any question relating to the administration of this act, and jurisdiction is conferred upon the division to hear and determine the same and enter its rule, regulation, or order with respect to the matter.

(3) The division shall have the power to summon witnesses, to administer oaths, and to require the production of records, books, and documents for examination at any hearing or investigation conducted by it.

(4) In case of failure or refusal on the part of any person to comply with a subpoena issued by the division, or in case of refusal of any witness to testify as to any matter regarding which he may be interrogated, any district court in the state, upon the application of the division, may issue an order compelling the person to comply with the subpoena and to attend before the division and produce any records, books, and documents covered by the subpoena or to give testimony or both. The court shall have the power to punish for contempt as in the case of disobedience to a like subpoena issued by the court, or for refusal to testify in the court.

(5) Whenever it appears that any person is violating or threatening to violate any provision of this act or any rule, regulation, or order made under this act, the division may bring suit in the name of the state against that person in the district court in the county of that person's residence, in the county of the residence of any defendant if there be more than one defendant, or in the county where the violation is alleged to have occurred, to restrain that person from continuing the violation or from carrying out the threat of violation. In the suit the court may grant injunctions.

(6) Nothing in this act, no suit by or against the division, and no violation charged or asserted against any person under any provision of this act, or any rule, regulation, or order issued under it, shall impair or abridge or delay any cause of action for damages which any person may have or assert against any person violating any provision of this act, or any rule, regulation, or order issued under it. Any person so damaged by the violation may sue for and recover such damages as he otherwise may be entitled to receive.

Section 5. Section 73-1-24, Utah Code Annotated 1953, is enacted to read:

73-1-24. (1) The division shall have authority to require:

(a) Identification of the location and ownership of all wells and producing geothermal leases.

(b) Filing with the division of a notice of intent to drill, redrill, deepen, permanently alter the casing of, or abandon any well. Approval of the notice of intent must be obtained from the division prior to commencement of operations.

(c) Keeping of well logs and filing true and correct copies with the division. These records are public records when filed with the division, unless the owner or operator requests, in writing, that the records be held confidential. The period of confidentiality shall be established by the division, not to exceed five years from the date of production or injection for other than testing purposes or five years from the date of abandonment, whichever occurs first, as determined by the division. Well records held confidential by the division are open to inspection by those persons authorized in writing by the owner or operator. Confidential status shall not restrict inspection by state officers charged with regulating well operations or by authorized officials of the Utah state tax commission for purposes of tax assessment.

(d) The spacing, drilling, casing, testing, operating, producing, and abandonment of wells so as to prevent: (i) geothermal resources, water, gases, or other fluids from escaping into strata other than the strata in which they are found (unless in accordance with a subsurface injection program approved by the division); (ii) pollution of surface and groundwater; (iii) premature cooling of any geothermal system by water encroachment or otherwise which tends to reduce the ultimate economic recovery of the geothermal resources; (iv) blowouts, cavings, and seepage; and (v) unreasonable disturbance or injury to neighboring properties, prior water rights, human life, health, and the environment.

(e) The operator to file cash or individual surety bonds with the division for each new well drilled and each abandoned well redrilled. The amount of surety required shall be determined by the division. In lieu of bonds for separate wells, the operator may file a blanket cash or individual surety bond in an amount set by the division to cover all the operator's drilling, redrilling, deepening, maintenance, or abandonment activities for wells in the state. Bonds filed with the division shall be executed by the operator, as principal, conditioned on compliance with division regulations in drilling, redrilling, deepening, maintaining, or abandoning any well or wells covered by the bond and shall secure the state against all losses, charges, and expenses incurred by it to obtain such compliance by the principal named in the bond.

(f) The geothermal owner or operator to measure geothermal production according to standards set by the division and maintain complete and accurate production records. The records, or certified copies of them, shall be preserved on file by the owner or operator for a period of five years and shall be available for examination by the division at all reasonable times.

___ B. No. ___

(g) Filing with the division any other reasonable reports which it prescibes regarding geothermal operations within the state.

(2) Any bond filed with the division in conformance with this act may, with the consent of the division, be terminated and canceled and the surety be relieved of all obligations under it when the well or wells covered by the bond have been properly abandoned or another valid bond has been substituted for it.

(3) The division may enter onto private or public land at any time to inspect any well or geothermal resource development project to determine if the well or project is being constructed, operated, or maintained according to any applicable permits or to determine if the construction, operation, or maintenance of the well or project may involve an unreasonable risk to life, health, property, the environment or subsurface, surface, or atmospheric resources.

Section 6. Section 73-1-25, Utah Code Annotated 1953, is enacted to read:

73-1-25. (1) The division upon its own motion may hold, and upon the application of any affected person shall hold, a hearing to consider the need for cooperative or unit operation of a geothermal area.

(2) The division shall make an order providing for the cooperative or unit operation of part or all of a geothermal area if the division finds that this operation is reasonably necessary to prevent waste, to protect correlative rights, or to prevent the drilling of unnecessary wells and will not reduce the ultimate economic recovery of geothermal resources.

(3) An order for cooperative or unit operations shall be upon terms and conditions that are just and reasonable and satisfy the requirements of subsection (2).

(4) An order by the division for unit operations shall prescribe a plan, including:

(a) A description of the geothermal area to be so operated, termed the unit area.

(b) A statement of the nature of the operations contemplated, the time they will commence, and the manner and circumstances under which unit operations shall terminate.

(c) An allocation to the separately-owned tracts in the unit area of the geothermal resources produced and of the costs incurred in unit operations. The allocations shall be in accord with the agreement, if any, of the affected parties. If there is no such agreement, the division shall determine the allocations from evidence introduced at a hearing before the division. Production shall be allocated in proportion to the relative value that each tract bears to the value of all tracts in the unit area. The acreage of each tract in proportion to the total unit acreage shall be the measure of relative value, unless the division finds after public hearing that another method is likely to result in a more equitable allocation and protection of correlative rights. Resource temperature, pressure, fluid quality, geological conditions, distance to place of use, and productivity are among the factors that may be considered in evaluating other methods. The method for allocating production in unit operations shall be revised if after a hearing the division finds that the revised method is likely to result in a more equitable allocation and protection of correlative rights. The division shall hold a hearing to consider adoption of a revised allocation method upon the application of any affected person, but the application may not be made until three years after the initial order by the division or at less than two-year intervals after that.

(d) A provision for adjustmeht among the owners of the unit area (not including royalty owners) of their respective investment in wells, tanks, pumps, machinery, materials, equipment, and other things and services of value attributable to the unit operations. The amount to be charged unit operations for each item shall be determined by the owners of the unit area (not including royalty owners), but if the owners of the unit area are unable to agree upon the amount of the charges or to agree upon the correctness of same, the division shall determine them after due notice and hearing, upon the application of any affected party. The net amount charged against the owner of a separately-owned tract shall be considered an expense of unit operation chargeable against that tract. The adjustments provided for in this subsection may be treated separately and handled by agreements separate from the unitization agreement.

(e) A provision providing how the costs of unit operations, including capital investments, shall be determined and charged to the separately-owned tracts and how these costs shall be paid, including a provision providing when, how, and by whom the unit production allocated to an owner who does not pay the share of the cost of unit operation charged to that owner, or the interest of that owner, may be sold and the proceeds applied to the payment of the costs. The operator of the unit shall have a first and prior lien for costs incurred pursuant to the plan of unitization upon each owner's geothermal rights and his share of unitized production to secure the payment of the owner's proportionate part of the cost of developing and operating the unit area. This lien may be established and enforced in the same manner as provided by sections 38-1-8 through 38-1-26. For these purposes any nonconsenting owner shall be deemed to have contracted with the unit operator for his proportionate part of the cost of developing and operating the unit area. A transfer or conversion of any owner's interest or any portion of it, however accomplished, after the effective date of the order creating the unit, shall not relieve the transferred interest of the operator's lien on the interest for the cost and expense of unit operations.

(f) A provision, if necessary, for carrying or otherwise financing any person who elects to be carried or otherwise financed, allowing a reasonable interest charge for this service payable out of that person's share of the production.

(g) A provision for the supervision and conduct of the unit operations, in respect to which each person shall have a vote with a value corresponding to the percentage of the costs of unit operations chargeable against the interest of that person.

(h) Such additional provisions that are found to be appropriate for carrying on the unit operations.

(5) No order of the division providing for unit operations shall become effective unless and until the plan for operations prescribed by the division has been approved in writing by those persons, who under the division's order, will be required to pay 66% of the costs of the unit operation, and also by the owners of 66% of the production or proceeds of same that are free of costs, such as royalties, overriding royalties, and production payments; and the division has made a finding that the plan for unit operations has been so approved. If the persons owning the required percentage of interest in the unit area do not approve the plan within six months from the date on which the order is made, the order shall be ineffective and shall be revoked by the division unless for good cause shown the division extends this time.

(6) An order providing for unit operations may be amended by an order of the division in the same manner and subject to the same conditions as an original order for unit operations; but if this amendment affects only the rights and interests of the owners, the approval of the amendment by the owners of royalty, overriding royalty, production payments, and other interests which are free of costs shall not be required. Production allocation may be amended only according to the provisions of subsection 73-1-25(4)(c).

(7) All operations, including, but not limited to, the commencement, drilling, or operation of a well upon any portion of the unit area shall be deemed for all purposes the conduct of such operations upon each separately-owned tract in the unit by the several owners of tracts in the unit. The portions of the unit production allocated to a separately-owned tract in a unit area shall, when produced, be deemed for all purposes to have been actually produced from that tract by a well drilled on it. Good faith operations conducted pursuant to an order of the division providing for unit operations shall constitute a complete defense to any suit alleging breach of lease or of contractual obligations covering lands in the unit area to the extent that compliance with these obligations cannot be had because of the order of the division.

(8) The portion of the unit production allocated to any tract, and the proceeds from the sale of this production, shall be the property and income of the several persons to whom, or to whose credit, the same are allocated or payable under the order providing for unit operations.

(9) Except to the extent that the parties affected so agree and as provided in subsection 73-1-25(4)(e), no order providing for unit operations shall be construed to result in a transfer of all or any part of the title of any person to the geothermal resource rights in any tract in the unit area. All property, whether real or personal, that may be acquired in the conduct of unit operations shall be acquired for the account of the owners within the unit area and shall be the property of these owners in the proportion that the expenses of unit operations are charged.

(10) An order of the division for unit operations shall constitute a complete defense to any suit charging violation of any statute relating to trusts, monopolies, and combinations in restraint of trade on account of unit operations conducted pursuant to the order.

AMENDMENT SHEET

January 7, 1980

GEOTHERMAL RESOURCE CONSERVATION ACT:

Page 12, substitute the following for the entire page:

Section 7. Section 73-1-26, Utah Code Annotated 1953, is enacted to read:

73-1-26. (1) Geothermal resources are deemed to be a special kind of underground resource, potentially affecting the water resources of the state. The utilization or distribution of the geothermal resource for its thermal content and subsurface injection or disposal of same when carried by the material medium of water shall constitute a beneficial use of the water resources of the state. Water rights, however, to water used as a material medium for geothermal resources shall be acquired independently from geothermal resources and in accordance with the applicable laws of this state. Any existing application on the date of this enactment for water in a geothermal area shall be deemed an application for water as a material medium.

(2) (a) Geothermal owners shall, prior to the commencement of, or increase in, production from a well or group of wells to be operated in concert, file an application with the division to appropriate such geothermal resources as will be extracted from the well or group of wells. Publication of applications shall be made as provided in section 73-3-6, and protests may be filed as provided in section 73-3-7. The division shall approve an

application if it finds that the proposed extraction of geothermal resources will not impair existing rights to the waters of the state, but this determination shall be made without regard to possible impairment of rights to geothermal resources. Rights of geothermal owners to common geothermal resources shall be based on the principle of correlative rights.

(b) The division may grant the quantity of an application on a provisional basis, to be finalized upon stabilization of well production. Flow testing of a discovery well shall not require an application to appropriate geothermal resources.

____ B. No. ____

Section 8. Section 73-1-27, Utah Code Annotated 1953, is enacted to read:

73-1-27. (1) Any person adversely affected by any rule, regulation, or order issued under this act may within 60 days after the effective date of the rule or regulation or entry of the order bring a civil suit against the division in the district court of Salt Lake County or in the district court of the county in which the complaining person resides, to test the validity of the rule, regulation, or order, or to secure an injunction or to obtain other appropriate relief, including all rights of appeal.

(2) An action or appeal involving any provision of this act, or a rule, regulation, or order issued under it shall be determined as expeditiously as feasible. The trial court shall determine the issues on both questions of law and fact and shall affirm or set aside the rule, regulation, or order, or remand the cause to the division for further proceedings. The court is authorized to enjoin permanently the enforcement by the division of this act, or any part of it, or any act done or threatened under it, if the plaintiff shall show that as to him the act or conduct complained of is unreasonable, unjust, arbitrary, or capricious, or violates any constitutional right of the plaintiff or if the plaintiff shows that the act complained of constitutes or results in waste or does not in a reasonable manner accomplish an end that is the purpose of this act.

(3) Any person who, for the purpose of evading this act or any rule, regulation, or order of the division issued under it, shall make or cause to be made any false entry in any report, record, account, or memorandum required by this act, or by any rule, regulation, or order issued under it or shall omit or cause to be omitted from the report, record, account, or memorandum, full, true and correct entries as required by this act, or by the rule, regulation, or order, or shall remove from this state or

destroy, mutilate, alter, or falsify the record, account, or memorandum, is guilty of a class A misdemeanor.

(4) No suit, action, or other proceeding based upon a violation of this act or any rule, regulation, or order of the division issued under it shall be commenced or maintained unless same shall have been commenced within two years from the date of the alleged violation.

Section 9. If any provision of this act, or the application of any provision to any person or circumstance, is held invalid, the remainder of this act shall not be affected thereby.

MEMORANDUM

UTAH GEOTHERMAL RESOURCE CONSERVATION ACT

Attached hereto is a copy of the proposed Geothermal Resource Conservation Act together with a summary of the Bill.

Legislation was introduced in 1973 which would have given regulatory jurisdiction over geothermal resources to the Division of Oil, Gas and Mining. In response to a lobbying effort by Utah Power and Light Company, however, a substitute bill was enacted which gave jurisdiction to the Division of Water Rights. Section 73-1-20, Utah Code Annotated, simply gives the Division of Water Rights jurisdiction and authority to require that all wells for the discovery and production of water to be used for geothermal and energy production in the State of Utah be drilled, operated, maintained, and abandoned in such manner as to safeguard life, health, property, the public welfare, and to encourage maximum economic recovery. The effect of this statute is to give responsibility to the State Engineer without defining the resource or giving him the powers to carry out his responsibility. In addition the statute does not effect a reconciliation between water law and real property law aspects of the resource.

Recognition of inadequacies of the present law prompted consideration of more meaningful legislation. The task was taken up by the Joint Natural Resources Interim Committee of the Utah State Legislation which was active prior to the 1979 General Session. At the request of the Committee, initial drafting of a new Bill was performed by the National Conference of State Legislatures. Other interested parties, including representatives of the State Engineer, the Attorney General, Utah Power & Light Company and producers, also participated.

The original draft prepared by the National Conference of State Legislatures defined geothermal resources as mineral without any reference to the state water laws. After extensive discussion of the possible relationship of high temperature geothermal resources to conventional fresh water sources, a point which was emphasized by the Utah Power and Light Company representative, major revisions were made to deal with the problem.

As modified, the proposed legislation received the approval of all participants except Utah Power and Light Company which was still concerned about possible adverse effects the Bill might have on water applications for geothermal resources filed by the power company primarily in 1973.

The Bill deals just with high temperature (greater than 120° centigrade or 250° farenheit) resources which are those suitable for electric power generation. Although there appears to be little likelihood of any interference between deep high temperature geothermal reservoirs and near surface water sources, the draftsmen thought it vital to insure that the law would protect prior vested water rights. This has been accomplished by requiring that the geothermal owner make a water appropriation prior to developing the resource. The burden of showing non-interference is on the geothermal producer, which differs from actions taken by some other states. The application will establish a priority date as between the geothermal user and conventional water users, but it will not establish any priority with respect to other geothermal producers. The rights of geothermal producers will be determined by application of the doctrine of correlative rights.

Since a geothermal field is much like an oil and gas field, regulatory powers similar to those held by the Division of Oil, Gas and Mining are needed by the State Engineer. The Bill attempts to provide this authority. In order for the State Engineer to exercise the powers of spacing, pooling, and unitization, however, it is absolutely essential that the oil and gas doctrine of correlative rights be applied. Application of the priority system inherent in the Utah water law, would tie the State Engineer's hands with respect to dealing with multiple land ownership over a geothermal reservoir.

The effect of the Bill is to establish a dual system for geothermal resource development in Utah. Proprietary rights will be acquired from the landowner, but a water right must be obtained before the proprietary rights can be exercised. The property interests are sometimes referred to as the primary right with the water permit being an ancillary right.

The whole thrust of this procedure is to enable geothermal resources to be developed under state, federal and private leases while insuring that prior water rights are protected and the state's interest in managing its water is preserved. One result of this is that the State Engineer retains some control over the utilization of water in connection with geothermal development on federal lands while a confrontation with the federal government over the question of proprietary rights to the resource is avoided. In view of the decision of the United States Court of Appeals for the Ninth Circuit in United States v. Union Oil Co., 549 F.2d 1271 (9th Cir. 1977), Cert. Denied, 434 U.S. 930 (1977) to the effect that geothermal resources are mineral resources subject to leasing under the Geothermal Steam Act of 1970, there can be little doubt that the proprietary rights of the United States to geothermal resources found in federal lands will be upheld if a challenge is made that the resource can be acquired exclusively under state water laws.

Although the Bill does not deal with the subject, its exclusion of geothermal resources found at temperatures less than 120° centigrade implicitly gives the State Engineer the authority to regulate such resources under the state water laws.

Utah Power and Light Company has steadfastly maintained opposition to the Bill since it was first considered. The basis for this opposition is UP&L's fear that its passage would diminish whatever rights the company holds under geothermal water applications filed primarily in 1973. (Summary enclosed.) UP&L apparently does not hold geothermal leases in the areas affected by their water applications. The UP&L applications affect almost every potential geothermal area in the state, including Roosevelt Hot Springs. Even lands adjoining the areas where the water applications describe proposed wells are affected because of possible assertions of priority rights to common reservoirs under the state water law.

In order to provide substance to their applications, UP&L must take the position that geothermal resources, or at least the constituent water, should be governed entirely by water law. At stake as a result of this position is the validity of geothermal leases obtained from landowners, including private citizens, the federal government, and the Utah State Land Board, which alone has geothermal leases covering some 160,000 acres. If, as UP&L argues, rights to geothermal resources or rights to constituent water can be acquired only under conventional water law, then the effectiveness of existing leases, which provide royalties to landowners, and which form the basis for operations by geothermal producers, will be in doubt.

Excerpts from an article entitled "Geothermal Development and Western Water Law" by Professors Owen Olpin, A. Dan Tarlock, and Carl F. Austin published in the Utah Law Review, which discusses the Bill and the posture of Utah Power and Light Company, are attached.

C.J. Parr
1/12/80

SUMMARY

Geothermal Resource Conservation Act S.B. 48

In general, the Geothermal Resource Conservation Act gives the Division of Water Rights authority to regulate the development of high temperature geothermal resources similar to the authority exercised by the Division of Oil, Gas and Mining over oil and gas resources. A limited application of the doctrine of water appropriation is made to insure that development of geothermal resources does not jeopardize the water resources of the state or the prior rights of conventional water users.

Provisions are included which accomplish the following:

(1) A separate statutory and regulatory framework is established in the State of Utah for high temperature (greater than 120° centigrade) geothermal resources, which are generally used for the production of electric power.

(2) The Division of Water Rights is given clear authority to regulate the development of geothermal resources in the State of Utah subject to the provisions of the Act to assure that operations are carried out in a safe and nonwasteful manner.

(3) Water resources of the state and the rights of prior water appropriators are protected by a requirement that a geothermal producer make an appropriation of such water as will be utilized in the course of production of the geothermal resource and by providing that such appropriation will be subject to the rights of prior appropriators of conventional water.

(4) As between owners or lessees of geothermal resources in separate tracts of land overlying a single reservoir, rights will be determined under the doctrine of correlative rights, in a manner similar to the way that rights to oil and gas are determined.

(5) The Division of Water Rights is given authority to unitize separately owned tracts of land over a geothermal reservoir in a manner which will ensure that the rights of each landowner will be protected.

(6) The Division of Water Rights is given authority to initiate enforcement actions, hold hearings, and subpoena witnesses in order to carry out its authority under the Act. A right of appeal to the District Court is provided.

The following benefits will flow from the Geothermal Resource Conservation Act:

<u>Private Landowners</u>

The rights of private landowners to geothermal resources found within their lands and to royalties from lessees will be strengthened through the avoidance of possible conflicting claims to the resource under independent geothermal water applications.

<u>Water Users</u>

Prior rights will be protected. Geothermal developers must appropriate associated water and demonstrate noninterference with prior rights.

<u>Division of Water Rights</u>

By application of the rule of correlative rights to geothermal resources, the State Engineer will be able to prevent waste and secure orderly development through the exercise of unitization, spacing, and pooling authority given to him by the Act.

<u>State Control Over Water</u>

The state's control over its water resource will be preserved. Geothermal resources which are associated with water cannot be developed, even on federal lands, unless an appropriation is first made under state water law.

<u>Division of State Lands</u>

Development of geothermal resources on state lands subject to geothermal leases (currently about 160,000 acres) will be facilitated and the receipt of income from royalties realized through the avoidance of conflicts arising from application of water law principles to geothermal resources.

<u>Geothermal Producers</u>

Efforts to produce geothermal resources for the generation of electric power will be stimulated due to the establishment of clear statutory guidelines and the removal of uncertainty arising through application of water law principles to geothermal resources.

12-12-79

(GEOTHERMAL RESOURCE CONSERVATION ACT)

1980

BUDGET SESSION

S. B. No. 48 By ______________________

AN ACT RELATING TO THE DEVELOPMENT OF GEOTHERMAL RESOURCES IN THE STATE; DECLARING THE PUBLIC INTEREST IN THIS DEVELOPMENT AND ASSIGNING REGULATORY AUTHORITY REGARDING THIS TO THE DIVISION OF WATER RIGHTS; DEFINING THE RESOURCE AND ITS RELATIONSHIP TO WATER; PROVIDING FOR THE PROTECTION OF CORRELATIVE RIGHTS AND THE PREVENTION OF WASTE; AUTHORIZING AND ESTABLISHING PROCEDURES FOR UNITIZING OF GEOTHERMAL AREAS; AND PROVIDING FOR PROCEDURES TO GOVERN REGULATION BY THIS DIVISION.

THIS ACT REPEALS AND REENACTS SECTION 73-1-20, UTAH CODE ANNOTATED 1953, AS ENACTED BY CHAPTER 189, LAWS OF UTAH 1973; AND ENACTS SECTIONS 73-1-21 THROUGH 73-1-27, UTAH CODE ANNOTATED 1953.

Be it enacted by the Legislature of the State of Utah:

Section 1. Section 73-1-20, Utah Code Annotated 1953, as enacted by Chapter 189, Laws of Utah 1973, is repealed and reenacted to read:

73-1-20. It is declared to be in the public interest to foster, encourage, and promote the discovery, development, production, utilization, and disposal of geothermal resources in the State of Utah in such manner as will prevent waste, protect correlative rights, and safeguard the natural environment and the public welfare; to authorize, encourage, and provide for the development and operation of geothermal resource properties in such manner that the maximum ultimate economic recovery of geothermal resources may be obtained through, among other things,

____ B. No. ____

agreements for cooperative development, production, injection, and pressure maintenance operations.

Section 2. Section 73-1-21, Utah Code Annotated 1953, is enacted to read:

73-1-21. As used in this act:

(1) "Correlative rights" mean the rights of each geothermal owner in a geothermal area to produce without waste his just and equitable share of the geothermal resource underlying the geothermal area.

(2) "Division" means the division of water rights, department of natural resources.

(3) "Geothermal area" means the general land area which is underlain or reasonably appears to be underlain by geothermal resources.

(4) "Geothermal fluid" means water and steam naturally present in a geothermal system.

(5) "Geothermal resource" means: (a) the natural heat of the earth at temperatures greater than 120 degrees centigrade; (b) the energy, in whatever form, present in, resulting from, created by, or which may be extracted from that natural heat, including pressure; (c) the material medium containing that energy; and (d) all minerals, gasses, or other substances in solution with or obtained from that material medium but excluding oil, hydrocarbon gas, and other hydrocarbon substances.

(6) "Geothermal system" means any strata, pool, reservoir, or other geologic formation containing geothermal resources.

(7) "Material medium" means geothermal fluids, or water and other substances artificially introduced into a geothermal system to serve as a heat transfer medium.

(8) "Operator" means any person drilling, maintaining, operating, producing, or in control of any well.

(9) "Owner" means any person who has the right to drill into, produce, and make use of the geothermal resource.

(10) "Person" means any individual, business entity (corporate or otherwise), or political subdivision of this or any other state.

(11) "Waste" means any inefficient, excessive, or improper production, use, or dissipation of geothermal resources. Wasteful practices include, but are not limited to: (a) transporting or storage methods that cause or tend to cause unnecessary surface loss of geothermal resources; or (b) locating, spacing, constructing, equipping, operating, producing, or venting of any well in a manner that results or tends to result in unnecessary surface loss or in reducing the ultimate economic recovery of geothermal resources.

(12) "Well" means any well drilled, converted, or reactivated for the discovery, testing, production, or subsurface injection of geothermal resources.

Section 3. Section 73-1-22, Utah Code Annotated 1953, is enacted to read:

73-1-22. This act shall apply to all lands in the State of Utah, including federal and Indian lands to the extent allowed by law. When these lands are committed to a unit agreement involving lands subject to federal or Indian jurisdiction, the division may, with respect to the unit agreement, deem this act or any part of this act complied with if the unit operations are regulated by the United States and the division finds that conservation of geothermal resources and prevention of waste are accomplished under the unit agreement.

Section 4. Section 73-1-23, Utah Code Annotated 1953, is enacted to read:

73-1-23. (1) The division is granted jurisdiction and authority over all persons and property, public and private, necessary to enforce the provisions of this act and shall have the power and authority to promulgate and enforce rules, regulations, and orders and do whatever may reasonably be necessary to carry out the provisions of this act.

(2) Any affected person may apply for a hearing before the division, or the division may initiate proceedings upon any question relating to the administration of this act, and jurisdiction is conferred upon the division to hear and determine the same and enter its rule, regulation, or order with respect to the matter.

(3) The division shall have the power to summon witnesses, to administer oaths, and to require the production of records, books, and documents for examination at any hearing or investigation conducted by it.

(4) In case of failure or refusal on the part of any person to comply with a subpoena issued by the division, or in case of refusal of any witness to testify as to any matter regarding which he may be interrogated, any district court in the state, upon the application of the division, may issue an order compelling the person to comply with the subpoena and to attend before the division and produce any records, books, and documents covered by the subpoena or to give testimony or both. The court shall have the power to punish for contempt as in the case of disobedience to a like subpoena issued by the court, or for refusal to testify in the court.

(5) Whenever it appears that any person is violating or threatening to violate any provision of this act or any rule, regulation, or order made under this act, the division may bring suit in the name of the state against that person in the district court in the county of that person's residence, in the county of the residence of any defendant if there be more than one defendant, or in the county where the violation is alleged to have occurred, to restrain that person from continuing the violation or from carrying out the threat of violation. In the suit the court may grant injunctions.

____ B. No. ____

(6) Nothing in this act, no suit by or against the division, and no violation charged or asserted against any person under any provision of this act, or any rule, regulation, or order issued under it, shall impair or abridge or delay any cause of action for damages which any person may have or assert against any person violating any provision of this act, or any rule, regulation, or order issued under it. Any person so damaged by the violation may sue for and recover such damages as he otherwise may be entitled to receive.

Section 5. Section 73-1-24, Utah Code Annotated 1953, is enacted to read:

73-1-24. (1) The division shall have authority to require:

(a) Identification of the location and ownership of all wells and producing geothermal leases.

(b) Filing with the division of a notice of intent to drill, redrill, deepen, permanently alter the casing of, or abandon any well. Approval of the notice of intent must be obtained from the division prior to commencement of operations.

(c) Keeping of well logs and filing true and correct copies with the division. These records are public records when filed with the division, unless the owner or operator requests, in writing, that the records be held confidential. The period of confidentiality shall be established by the division, not to exceed five years from the date of production or injection for other than testing purposes or five years from the date of abandonment, whichever occurs first, as determined by the division. Well records held confidential by the division are open to inspection by those persons authorized in writing by the owner or operator. Confidential status shall not restrict inspection by state officers charged with regulating well operations or by authorized officials of the Utah state tax commission for purposes of tax assessment.

(d) The spacing, drilling, casing, testing, operating, producing, and abandonment of wells so as to prevent: (i) geothermal resources, water, gases, or other fluids from escaping into strata other than the strata in which they are found (unless in accordance with a subsurface injection program approved by the division); (ii) pollution of surface and groundwater; (iii) premature cooling of any geothermal system by water encroachment or otherwise which tends to reduce the ultimate economic recovery of the geothermal resources; (iv) blowouts, cavings, and seepage; and (v) unreasonable disturbance or injury to neighboring properties, prior water rights, human life, health, and the environment.

(e) The operator to file cash or individual surety bonds with the division for each new well drilled and each abandoned well redrilled. The amount of surety required shall be determined by the division. In lieu of bonds for separate wells, the operator may file a blanket cash or individual surety bond in an amount set by the division to cover all the operator's drilling, redrilling, deepening, maintenance, or abandonment activities for wells in the state. Bonds filed with the division shall be executed by the operator, as principal, conditioned on compliance with division regulations in drilling, redrilling, deepening, maintaining, or abandoning any well or wells covered by the bond and shall secure the state against all losses, charges, and expenses incurred by it to obtain such compliance by the principal named in the bond.

(f) The geothermal owner or operator to measure geothermal production according to standards set by the division and maintain complete and accurate production records. The records, or certified copies of them, shall be preserved on file by the owner or operator for a period of five years and shall be available for examination by the division at all reasonable times.

(g) Filing with the division any other reasonable reports which it prescibes regarding geothermal operations within the state.

(2) Any bond filed with the division in conformance with this act may, with the consent of the division, be terminated and canceled and the surety be relieved of all obligations under it when the well or wells covered by the bond have been properly abandoned or another valid bond has been substituted for it.

(3) The division may enter onto private or public land at any time to inspect any well or geothermal resource development project to determine if the well or project is being constructed, operated, or maintained according to any applicable permits or to determine if the construction, operation, or maintenance of the well or project may involve an unreasonable risk to life, health, property, the environment or subsurface, surface, or atmospheric resources.

Section 6. Section 73-1-25, Utah Code Annotated 1953, is enacted to read:

73-1-25. (1) The division upon its own motion may hold, and upon the application of any affected person shall hold, a hearing to consider the need for cooperative or unit operation of a geothermal area.

(2) The division shall make an order providing for the cooperative or unit operation of part or all of a geothermal area if the division finds that this operation is reasonably necessary to prevent waste, to protect correlative rights, or to prevent the drilling of unnecessary wells and will not reduce the ultimate economic recovery of geothermal resources.

(3) An order for cooperative or unit operations shall be upon terms and conditions that are just and reasonable and satisfy the requirements of subsection (2).

(4) An order by the division for unit operations shall prescribe a plan, including:

____ B. No. ____

(a) A description of the geothermal area to be so operated, termed the unit area.

(b) A statement of the nature of the operations contemplated, the time they will commence, and the manner and circumstances under which unit operations shall terminate.

(c) An allocation to the separately-owned tracts in the unit area of the geothermal resources produced and of the costs incurred in unit operations. The allocations shall be in accord with the agreement, if any, of the affected parties. If there is no such agreement, the division shall determine the allocations from evidence introduced at a hearing before the division. Production shall be allocated in proportion to the relative value that each tract bears to the value of all tracts in the unit area. The acreage of each tract in proportion to the total unit acreage shall be the measure of relative value, unless the division finds after public hearing that another method is likely to result in a more equitable allocation and protection of correlative rights. Resource temperature, pressure, fluid quality, geological conditions, distance to place of use, and productivity are among the factors that may be considered in evaluating other methods. The method for allocating production in unit operations shall be revised if after a hearing the division finds that the revised method is likely to result in a more equitable allocation and protection of correlative rights. The division shall hold a hearing to consider adoption of a revised allocation method upon the application of any affected person, but the application may not be made until three years after the initial order by the division or at less than two-year intervals after that.

(d) A provision for adjustment among the owners of the unit area (not including royalty owners) of their respective investment in wells, tanks, pumps, machinery, materials, equipment, and other things and services of value attributable to the unit operations. The amount to be charged unit operations for each item shall be determined by the owners of the unit area (not including royalty owners), but if the owners of the unit area are unable to agree upon the amount of the charges or to agree upon the correctness of same, the division shall determine them after due notice and hearing, upon the application of any affected party. The net amount charged against the owner of a separately-owned tract shall be considered an expense of unit operation chargeable against that tract. The adjustments provided for in this subsection may be treated separately and handled by agreements separate from the unitization agreement.

(e) A provision providing how the costs of unit operations, including capital investments, shall be determined and charged to the separately-owned tracts and how these costs shall be paid, including a provision providing when, how, and by whom the unit production allocated to an owner who does not pay the share of the cost of unit operation charged to that owner, or the interest of that owner, may be sold and the proceeds applied to the payment of the costs. The operator of the unit shall have a first and prior lien for costs incurred pursuant to the plan of unitization upon each owner's geothermal rights and his share of unitized production to secure the payment of the owner's proportionate part of the cost of developing and operating the unit area. This lien may be established and enforced in the same manner as provided by sections 38-1-8 through 38-1-26. For these purposes any nonconsenting owner shall be deemed to have contracted with the unit operator for his proportionate part of the cost of developing and operating the unit area. A transfer or conversion of any owner's interest or any portion of it, however accomplished, after the effective date of the order creating the unit, shall not relieve the transferred interest of the operator's lien on the interest for the cost and expense of unit operations.

(f) A provision, if necessary, for carrying or otherwise financing any person who elects to be carried or otherwise financed, allowing a reasonable interest charge for this service payable out of that person's share of the production.

(g) A provision for the supervision and conduct of the unit operations, in respect to which each person shall have a vote with a value corresponding to the percentage of the costs of unit operations chargeable against the interest of that person.

(h) Such additional provisions that are found to be appropriate for carrying on the unit operations.

(5) No order of the division providing for unit operations shall become effective unless and until the plan for operations prescribed by the division has been approved in writing by those persons, who under the division's order, will be required to pay 66% of the costs of the unit operation, and also by the owners of 66% of the production or proceeds of same that are free of costs, such as royalties, overriding royalties, and production payments; and the division has made a finding that the plan for unit operations has been so approved. If the persons owning the required percentage of interest in the unit area do not approve the plan within six months from the date on which the order is made, the order shall be ineffective and shall be revoked by the division unless for good cause shown the division extends this time.

(6) An order providing for unit operations may be amended by an order of the division in the same manner and subject to the same conditions as an original order for unit operations; but if this amendment affects only the rights and interests of the owners, the approval of the amendment by the owners of royalty, overriding royalty, production payments, and other interests which are free of costs shall not be required. Production allocation may be amended only according to the provisions of subsection 73-1-25(4)(c).

(7) All operations, *including*, but not limited to, the commencement, drilling, or operation of a well upon any portion of the unit area shall be deemed for all purposes the conduct of such operations upon each separately-owned tract in the unit by the several owners of tracts in the unit. The portions of the unit production allocated to a separately-owned tract in a unit area shall, when produced, be deemed for all purposes to have been actually produced from that tract by a well drilled on it. Good faith operations conducted pursuant to an order of the division providing for unit operations shall constitute a complete defense to any suit alleging breach of lease or of contractual obligations covering lands in the unit area to the extent that compliance with these obligations cannot be had because of the order of the division.

(8) The portion of the unit production allocated to any tract, and the proceeds from the sale of this production, shall be the property and income of the several persons to whom, or to whose credit, the same are allocated or payable under the order providing for unit operations.

(9) Except to the extent that the parties affected so agree and as provided in subsection 73-1-25(4)(e), no order providing for unit operations shall be construed to result in a transfer of all or any part of the title of any person to the geothermal resource rights in any tract in the unit area. All property, whether real or personal, that may be acquired in the conduct of unit operations shall be acquired for the account of the owners within the unit area and shall be the property of these owners in the proportion that the expenses of unit operations are charged.

(10) An order of the division for unit operations shall constitute a complete defense to any suit charging violation of any statute relating to trusts, monopolies, and combinations in restraint of trade on account of unit operations conducted pursuant to the order.

____ B. No. ____

Section 7. Section 73-1-26, Utah Code Annotated 1953, is enacted to read:

• 73-1-26. (1) Geothermal fluids are deemed to be a special kind of underground water resource, related to and potentially affecting other water resources of the state. The utilization or distribution for their thermal content and subsurface injection or disposal of same shall constitute a beneficial use of the water resources of the state.

(2) (a) Geothermal owners shall, prior to the commencement of, or increase in, production from a well or group of wells to be operated in concert, file an application with the division to appropriate such geothermal fluids as will be extracted from the well or group of wells. Publication of applications shall be made as provided in section 73-3-6, and protests may be filed as provided in section 73-3-7. The division shall approve an application if it finds that the proposed extraction of geothermal fluids will not impair existing rights to the waters of the state, but this determination shall be made without regard to possible impairment of rights to geothermal fluids. Rights of geothermal owners to common geothermal resources and associated geothermal fluids shall be based on the principle of correlative rights.

(b) The division may grant the quantity of an application on a provisional basis, to be finalized upon stabilization of well production. Flow testing of a discovery well shall not require an application to appropriate geothermal fluids.

(3) The date of an application to appropriate geothermal fluids, when approved by the division, shall be the priority date as between the geothermal owner and the owners of rights to water other than geothermal fluids. No priorities shall be created among geothermal owners by the approval of an application to appropriate geothermal fluids.

____ B. No. ____

Section 8. Section 73-1-27, Utah Code Annotated 1953, is enacted to read:

73-1-27. (1) Any person adversely affected by any rule, regulation, or order issued under this act may within 60 days after the effective date of the rule or regulation or entry of the order bring a civil suit against the division in the district court of Salt Lake County or in the district court of the county in which the complaining person resides, to test the validity of the rule, regulation, or order, or to secure an injunction or to obtain other appropriate relief, including all rights of appeal.

(2) An action or appeal involving any provision of this act, or a rule, regulation, or order issued under it shall be determined as expeditiously as feasible. The trial court shall determine the issues on both questions of law and fact and shall affirm or set aside the rule, regulation, or order, or remand the cause to the division for further proceedings. The court is authorized to enjoin permanently the enforcement by the division of this act, or any part of it, or any act done or threatened under it, if the plaintiff shall show that as to him the act or conduct complained of is unreasonable, unjust, arbitrary, or capricious, or violates any constitutional right of the plaintiff or if the plaintiff shows that the act complained of constitutes or results in waste or does not in a reasonable manner accomplish an end that is the purpose of this act.

(3) Any person who, for the purpose of evading this act or any rule, regulation, or order of the division issued under it, shall make or cause to be made any false entry in any report, record, account, or memorandum required by this act, or by any rule, regulation, or order issued under it or shall omit or cause to be omitted from the report, record, account, or memorandum, full, true and correct entries as required by this act, or by the rule, regulation, or order, or shall remove from this state or

destroy, mutilate, alter, or falsify the record, account, or memorandum, is guilty of a class A misdemeanor.

(4) No suit, action, or other proceeding based upon a violation of this act or any rule, regulation, or order of the division issued under it shall be commenced or maintained unless same shall have been commenced within two years from the date of the alleged violation.

Section 9. If any provision of this act, or the application of any provision to any person or circumstance, is held invalid, the remainder of this act shall not be affected thereby.

Waters appurtenant to land.

Water appurtenant to a tract of land is that amount which was beneficially used upon it before and at the time of the conveyance. Stephens v. Burton, 546 P. 2d 240.

73-1-20. Geothermal energy production—Regulation by division of water rights.—(1) The division of water rights is given jurisdiction and authority to require that all wells for the discovery and production of water to be used for geothermal energy production in the state of Utah, be drilled, operated, maintained, and abandoned in such manner as to safeguard life, health, property, the public welfare, and to encourage maximum economic recovery.

(2) In carrying out its responsibility under this act, the division of water rights may utilize personnel, equipment, or other assistance of any division or department and may transfer funds to that division or department to reasonably compensate it for use of its personnel or facilities.

History: C. 1953, 73-1-20, enacted by L. 1973, ch. 189, § 1.

Title of Act.

An act enacting section 73-1-20, Utah Code Annotated 1953; granting to the division of water rights specific authority to regulate geothermal energy and associated resources.

CHAPTER 2—STATE ENGINEER

Section
73-2-1.1. Division of water rights—Creation—Power and authority.
73-2-10. Reports to the governor.
73-2-13. Attorney general and county attorneys to counsel.
73-2-14. Fees of state engineer—Payment into general fund.
73-2-15. Agreements with federal and state agencies—Investigations, surveys or adjudications.
73-2-17. Authorization of co-operative investigations of ground-water resources.
73-2-21. Artesian wells—Wasting public water—State engineer, power to plug, repair or control—Co-operative agreements with owners.

73-2-1. State engineer, etc.

Powers and duties of engineer.

In action to have defendant's right to use water declared forfeited for non-use and to enjoin any further use thereof, trial court improperly granted summary judgment for plaintiff since state engineer had granted extension of time for defendant to resume use and plaintiff did not use proper remedy of civil action in district court for review of state engineer's decision, but rather filed action to have defendant's rights declared forfeited which resulted in an attempt by plaintiff to exercise authority granted specifically to state engineer to enjoin unlawful diversion. Glenwood Irr. Co. v. Myers, 24 U. (2d) 78, 465 P. 2d 1013.

73-2-1.1. Division of water rights—Creation—Power and authority.—There is created the division of water rights, which shall be within the department of natural resources under the administration and general supervision of the executive director of natural resources. The division of water rights shall be the water rights authority of the state of Utah and is vested with such powers and required to perform such duties as are set forth in law.

History: C. 1953, 73-2-1.1, enacted by L. 1967, ch. 176, § 8; L. 1969, ch. 198, § 5.

Compiler's Notes.

The 1969 amendment substituted "executive director" for "co-ordinating council."

Cross-References.

Creation of department of natural resources and boards and divisions within department, 63-34-3.

UTAH LAW REVIEW

VOLUME 1979 NUMBER 4

TABLE OF CONTENTS

Editors' Page 645

ENERGY SYMPOSIUM:
CURRENT ISSUES IN ENERGY DEVELOPMENT,
RESOURCE ALLOCATION, AND ENVIRONMENTAL PROTECTION

Introduction 647

Essay in Law—Irrational but Not Arbitrary: Should Reviewing Courts Draw So Fine a Line? *William J. Lockhart* 649

Public Land Exchanges, Sales, and Purchases Under the Federal Land Policy and Management Act of 1976 *Frederick R. Anderson* 657

The Efficacy of Federal Environmental Legislation: The TVA Experience with Endangered Species and Clean Air *John H. Gibbons*, *Holly Gwin*, *William Chandler* 701

Managing a Limited Resource: The Political Constraints on Water Policy in the Four-Corners States *Helen Ingram*, *Nancy Laney*, *John R. McCain* 719

Permits and Approvals Required to Develop an Energy Project in Utah *Richard B. Johns* 747

Geothermal Development and Western Water Law *Owen Olpin*, *A. Dan Tarlock*, *Carl F. Austin* 773

Index to Volume 1979 889

Geothermal Development and Western Water Law†

*Owen Olpin**
*A. Dan Tarlock***
*Carl F. Austin****

TABLE OF CONTENTS

I. INTRODUCTION 774
II. THE ROLE OF GEOTHERMAL ENERGY IN MEETING ENERGY NEEDS 776
III. THE GEOSCIENCE OF THE RESOURCE 777
  A. *The Nature of the Resource* 777
  B. *A Closer Look at Geothermal Fluids* 781
IV. CHARACTERISTICS OF A PROPERTY RIGHTS REGIME 792
V. THE INITIAL PROPERTY CLASSIFICATIONS ATTEMPTS 797
  A. *The Ownership Lawsuits* 798
  B. *State and Federal Legislation* 803
VI. POSSIBLE WATER RIGHTS CLAIMS BY FEDERAL LESSEES 807
VII. THE CASE AGAINST APPLICATION OF WESTERN WATER LAW DOCTRINES TO GEOTHERMAL DEVELOPMENT 810
  A. *Assumptions Underlying Mineral and Water Exploitation* 812
  B. *Western Water Law Doctrines Inapplicable to Geothermal Development* 813
    1. *Inappropriate Forms and Procedures* 817

---

† This article was written pursuant to a grant to Indiana University and the University of Utah to study the relationship between Western water law and geothermal resources development, funded by the United States Department of Energy. We gratefully acknowledge the support. The authors and the Utah Law Review Society expressly disclaim copyright in this article, thereby placing it in the public domain as mandated by the DOE grant.

Professors Olpin and Tarlock would like to thank Vilate Stewart, J.D., 1978, University of Utah; John Davis, J.D., 1979, University of Utah; Dan Stewart, J.D., 1979, Indiana University, Bloomington; and Richard Waller, J.D., 1977 Indiana University, Bloomington, for their valuable research assistance in the preparation of this article.

* Partner, O'Melveny & Myers, Los Angeles, Cal.; B.S., 1955, Brigham Young University; LL.B., 1958, Columbia University; Member, California and Washington, D.C., Bars.

** Professor of Law, Indiana University, Bloomington; A.B., 1962, LL.B., 1965, Stanford University.

*** Head of the Geothermal Utilization Division of the Naval Weapons Center, China Lake, California; involved in geothermal exploration for both industry and government for the past 18 years. A.A., 1952, College of Marin; B.S., 1954, M.S., 1955, Ph.D., 1958, University of Utah. Dr. Austin is primarily responsible for the technical and scientific material, especially the section on geothermal fluids and their relationship to groundwater sources.

2. *Necessity to Prove an Adequate Available Supply* 817
3. *Denial of Entry to Groundwater Basin in Overdraft* 818
4. *Protection of Prior Surface Users' Rights* 818
5. *Groundwater Mining* 820
6. *Assertion of a Right to Lift* 821
7. *Restrictions on Use of Groundwater in California and Arizona* 821
8. *Application of Public Interest Restrictions on Right to Appropriate* 822
9. *Application of the Relation Back Doctrine* 823

VIII. STATE GEOTHERMAL AND GROUNDWATER LAWS 824
A. *Arizona* 824
B. *California* 829
C. *Colorado* 834
D. *Hawaii* 840
E. *Idaho* 843
F. *Montana* 847
G. *Nevada* 851
H. *New Mexico* 854
I. *Oregon* 857
J. *South Dakota* 861
K. *Utah* 862
L. *Washington* 867
M. *Wyoming* 871

IX. THE WATER POLLUTION PROBLEM 874
A. *Reinjection and Geothermal Waste Water* 874
B. *Federal and State Pollution Laws Affecting Reinjection* 876

X. CONCLUSION 881

I. Introduction

Geothermal energy is derived from heat beneath the earth's surface. High temperature geothermal resources can be used to generate electricity. Moderate and low temperature resources are less likely to be used in the generation of electricity, but can be used for space heating, food processing, and cooling. Geothermal resources are also potential sources of extractable minerals and irrigation water.

A geothermal deposit is an accumulation of heat within the crust of the earth. Temperatures beneath the earth's surface "are controlled principally by conductive flow of heat through solid rocks, by convective flow in circulating fluids, or by mass transfer dards are liberal.

Prior to 1972, South Dakota followed the 1933 Idaho Supreme Court's opinion in *Noh v. Stoner*,[321] and recognized a senior pumper's absolute right to artesian pressure. In 1972 the Water Resources Commission was given the right to adopt rules which provide "for regulation of the use of large-capacity wells in the degree necessary to maintain an adequate depth of water for reasonable domestic needs and for a prior appropriator at his point of diversion."[322] Water Rights Commission rules require "reasonable efforts to maintain sufficient artesian pressure in the aquifer to maintain water supplies in existing individual domestic wells which are dependent upon such artesian pressure but continuance of such artesian pressure at all times will not be assured."[323]

The Commission has power to deal with seasonal shortages which threaten domestic supplies. It may suspend the doctrine of prior appropriation.[324] Large capacity wells may be subjected to pro rata cutbacks or other methods such as rotation and limitations on pumping hours "to assure domestic water supplies in adequate wells."[325]

K. *Utah*

Utah's water laws grew out of the Mormon colonizing practices, rewarding those whose industry put the water to use and discouraging speculation and monopolization. By statute all waters in Utah, whether above or under the ground, are declared public property.[326] Utah gradually adopted the appropriative water rights regime of the Far West. Rights in all categories of water may be obtained only by application for appropriation to the State Engineer, and acquisition of water rights by adverse use or adverse possession is specifically precluded.[327]

An application to appropriate water must be approved by the State Engineer if the following conditions are met:

> (1) There is unappropriated water in the proposed source; (2) The proposed use will not impair existing rights, or interfere with the more beneficial use of the water; (3) The proposed plan is physically and

321. 53 Idaho 651, 26 P.2d 1112 (1933). *See* Comment, *South Dakota's Artesian Pressure—Should It Be a Protected Means of Diversion*, 16 S.D. L. Rev. 481 (1971).
322. E.D. Rules, *supra* note 320, 46B.504-506, 46B.201-217.
323. *Id.* 46B.506 (3).
324. S.D. Comp. Laws Ann. § 46-6-6.2 (Supp. 1978).
325. S.D. Rules, *supra* note 320, 46B.508.
326. Utah Code Ann. § 73-1-1 (1968).
327. *Id.* § 73-3-1.

> economically feasible unless the application is filed by the United States Bureau of Reclamation and would not prove detrimental to the public welfare; and (4) The applicant has the financial ability to complete the proposed works and the application was filed in good faith and not for purposes of speculation or monopoly.[328]

It is up to the applicant to provide evidence of his entitlement to an appropriative right, but, in keeping with the state's policy to promote development, the State Engineer must resolve doubts in favor of the applicant.[329] After final proof that the appropriation procedure has been followed and the water has been put to beneficial use, the State Engineer issues a certificate of appropriation which is prima facie evidence of the water right.[330]

Utah's system generally follows the customary prior appropriation pattern: a senior appropriator is entitled to receive his whole supply before a subsequent appropriator obtains any right.[331] A statutory hierarchy of preferences, however, qualifies this. In times of scarcity, while priority of appropriation gives the better right between those using water for the same purpose, domestic use without unnecessary waste has preference over all other purposes and agricultural uses have preference over all uses except domestic.[332]

In 1935, the Utah Supreme Court abandoned the overlying ownership and correlative rights doctrine, and held that percolating groundwater was publicly owned and subject to appropriation.[333] Later that same year, the legislature provided that rights in groundwater could only be acquired by appropriation, and presently the same appropriation procedures apply to both groundwater and surface water.[334]

Utah may recognize a senior's right to pressure, which would likely impede geothermal development. The Utah Supreme Court initially held, over a strong dissent, that the rights of a prior appropriator extended not only to a quantity of water, but also to the static pressure in the underground water source.[335] The court or-

328. *Id.* § 73-3-8 (Supp. 1979).

329. Little Cottonwood Water Co. v. Kimball, 76 Utah 243, 289 P. 116 (1930).

330. UTAH CODE ANN. § 73-3-17 (1968).

331. *Id.* § 73-3-21.

332. *Id.*

333. Wrathall v. Johnson, 86 Utah 50, 40 P.2d 755 (1935). There is a minor qualification in that the *overlying owner* has been held to own the nontributary soil moisture that immediately nourishes the plants growing in his soil. Riordan v. Westwood, 115 Utah 215, 203 P.2d 922 (1949). This qualification appears to cause no significant problems in water rights administration.

334. UTAH CODE ANN. § 73-3-1 (1968).

335. Current Creek Irr. Co. v. Andrews, 9 Utah 2d 324, 344 P.2d 528 (1959).

dered a junior appropriator to compensate a senior appropriator for the cost of pursuing water to greater depths. A subsequent case reached a somewhat contrary conclusion, but did not overrule the earlier case. In the later case, a city attempted to change its point of diversion, and a claim was made that the city's improved well would reduce the pressure for the wells of others.[336] The Utah court distinguished this case from the earlier one in that "this is not a situation where [there is] a *new* withdrawal in a basin which adversely affects the flow of wells prior in time and right . . . ."[337] The court went on to articulate a "rule of reasonableness."[338] With the earlier case not being overruled, it may still be that Utah law protects static pressure of senior appropriators. If such a rule were rigorously applied, the geothermal developers may be liable to earlier appropriators and even to early geothermal drillers who possess prior water rights. The more recent opinion indicates that a rule of reasonableness will control the issue; if so, geothermal development will benefit from the change.

Developed water rights are recognized in Utah. One who can demonstrate that he has developed a supply of water that is not a part of a known system or source of supply is entitled to the developed water.[339] The appropriation procedure, however, must be followed.

One of the earliest attempts at legal classification of geothermal resources in Utah occurred in 1963. The Director of the Utah State Land Board (the agency responsible for mineral development on state lands) requested an attorney general's opinion on (i) whether the state could lease geothermal rights in lands containing reserved state mineral rights and (ii) whether the State Engineer had any control over geothermal uses. The Attorney General issued a lengthy opinion which drew a sharp distinction between minerals in solution in geothermal fluids and "water."[340] If solution minerals are valuable in themselves and justify mining, the Attorney General concluded they would be covered by the state's reservation. If, on the other hand, the minerals are merely an inseparable part of the

336. Wayman v. Murray City Corp., 23 Utah 2d 97, 458 P.2d 861 (1969).

337. *Id.* at 101, 458 P.2d at 863.

338. The court explained:

> *All users are required where necessary to employ reasonable and efficient means of taking their own waters in relation to others to the end that wastage of water is avoided and the greatest amount of available water is put to beneficial use.*

Id. at 104, 458 P.2d at 865.

339. UTAH CODE ANN. § 73-3-1 (1968). *See, e.g.*, Bullock v. Tracy, 4 Utah 2d 370, 294 P.2d 707 (1956); Silver King Consol. Mining Co. v. Sutton, 85 Utah 297, 39 P.2d 682 (1934).

340. Utah Att'y Gen. Op. No. 63-016 (Mar. 6, 1963).

water, the water rights regime alone would cover them and there would be no state mineral ownership. Although the opinion is unclear on the application of water laws, the Attorney General expressed the belief that all associated water would be governed in toto by Utah water laws. Thus, the State Engineer would have control of geothermal fluid uses—including the beneficial use of heated and pressurized fluids—to generate power.

A Utah statute enacted ten years ago followed the Attorney General's lead and gave primary control of geothermal resources to the State Water Agency.

> The division of water rights is given jurisidction and authority to require that all wells for the discovery and production of water to be used for geothermal energy production in the state of Utah, be drilled, operated, maintained, and abandoned in such manner as to safeguard life, health, property, the public welfare, and to encourage maximum economic recovery.[341]

The geothermal law embodied in this statute and the Attorney General's opinion could logically support acquisition of a water right, but the State Land Board has taken the position that more than a water right is needed to recover geothermal resources from state-owned land. The State Land Board prepared a lease form for state-owned lands indicating an intention to act as proprietor and collect royalties. The royalties are expressly payable on the sale of "water, steam and any other product."[342] In other respects, the lease form follows traditional mineral concepts.

In order to carry out his assigned statutory responsibilities,[343] the State Engineer has now promulgated regulations which provide the first Utah definition of geothermal resources.

> "Geothermal Resource" means the natural heat energy of the earth, the energy in whatever form which may be found in any position and at any depth below the surface of the earth, present in, resulting from or created by, or which may be extracted from such natural heat and

341. Utah Code Ann. § 73-1-20 (Supp. 1979).

342. Utah State Land Board form "Geothermal Steam Lease and Agreement." There is a provision in the form acknowledging a possibly conflicting claim of state patentees who received titles subject to state mineral reservations. In the event the supreme court adjudges geothermal rights to be in such patentees, the state agrees to refund previously paid royalties but not previously paid rentals. In no event, however, does the State Land Board form take account of any possibility that geothermal rights in state lands could be obtained merely by appropriating a water right. In lands wholly owned by the state, the form clearly contemplates that woule-be geothermal developers need both a geothermal lease and an appropriative water right.

343. *See* Wells Used for the Discovery and Production of Geothermal Energy in the State of Utah, Ad. Rules, Utah § A63-01-2 (1978).

all minerals in solution or other products obtained from the material medium of any geothermal resource.[344]

Predictably, water notions predominate in the draft, and one section would provide redundant proceedings for any water used outside the geothermal operations. An appropriation right would have to be obtained prior to drilling and producing a geothermal well. That appropriation, however, does not make the produced fluids interchangeable with water for any other purposes; any water, brine, steam, or condensate produced may be subjected to a further appropriation "if physical conditions permit."[345]

The first full-fledged geothermal appropriation proceeding before the Division of Water Rights occurred in December of 1974, when the Phillips Petroleum Company filed an application to appropriate 1,680 cubic feet per second of groundwater for power purposes in the Roosevelt Hot Springs area of Utah.[346] The application was filed in connection with federal geothermal leases acquired by Phillips under the Geothermal Steam Act of 1970, but the Interior Department took no position in the matter and left the entire proceeding to Phillips.

In a lengthy hearing before the State Engineer in April of 1976, Phillips attempted to prove its entitlement to an appropriation by introducing evidence on each of the statutory appropriation requirements with particular attention to availability of water in the source and nonimpairment of existing rights. These were important issues because the area's conventional groundwater sources were already fully appropriated, and there was a moratorium on further water well drilling. Phillips attempted to counter this by invoking the developed water doctrine, contending that the water source it sought to tap was 5,000 feet below the groundwater source and therefore physically distinct. Phillips also argued that the water produced from its geothermal wells would be totally unusable for irrigation. Although some interconnection was conceded, Phillips contended that the flow from the groundwater source to the geothermal reservoir took hundreds of years and that geothermal production would not significantly hasten this flow since eighty percent of the produced fluids would be reinjected.

Several protests to the Phillips application were filed, but a full-scale water conflict was avoided. Phillips secured the with-

344. *Id.* § A63-01-2(2)(k).

345. *Id.* § A63-01-2(3)(a)(1)(b).

346. Applications to Appropriate Water No. 44509 (71-3274, 71-3299), filed by Phillips Petroleum Company (Dec. 20, 1974).

drawal of these protests by promising to monitor any possible interference with prior appropriators.[347]

Protests were also filed by Utah Power & Light Company and an associated geothermal developer. The stated ground for their protests was to protect their prior applications to appropriate for geothermal development.[348] They alleged that the Phillips appropriation "would diminish, deplete or otherwise adversely affect the appropriations" sought by them under their prior applications. Subsequently, those protests were also withdrawn, but the withdrawals were without prejudice to the protestants' rights to later assert prior rights and to seek protection.

Utah Power & Light has staked out a simple, if not simplistic, geothermal-is-water position and has held fast to that position. The company has blanketed prospective geothermal areas in Utah with applications to appropriate water rights and has maintained that only appropriative water rights are required to authorize geothermal operations. It has not bothered to secure development rights from either public or private landowners by lease or otherwise. The implausibility of the company's positon on federal lands is self-evident, and there will clearly be no geothermal development on federal lands except by holders of geothermal leases issued pursuant to the Geothermal Steam Act of 1970. As to nonfederal lands, the company's position is only slightly less ludicrous. Would-be geothermal developers armed with leases regard the Utah Power & Light applications as nuisances that will have to be addressed in administrative process before the State Engineer, in court proceedings, or perhaps in direct negotiations with the company.[349]

L. *Washington*

Washington, like Oregon, lies outside the Rocky Mountain energy basket. The Cascade range and Eastern Washington have the right geology for the existence of geothermal reservoirs, and there

347. The only protest that has not been withdrawn as of this time is that of a miner claiming water rights in the area.

348. The Phillips' application is still pending before the State Engineer.

349. A bill was introduced in the Utah Legislature in the 1979 general session to provide a comprehensive regulatory regime, and in particular, to deal specifically with the water law issues that here concern us. Regulatory powers would have continued in the water agency, but mechanisms would have been provided to substantially extricate geothermal fluids from the prior appropriation system and treat geothermal rights *inter se* as correlative. S.B. 279 Utah Legis. (1979). The bill passed the Senate, but an amendment in the House of Representatives gutted the bill of any meaning, and its sponsors let the bill die. Utah Power & Light is credited with engineering the amendment that resulted in the bill's demise. The unsuccessful Utah bill is discussed at greater length in the concluding section of this paper.

closed reservoir or (2) a reinjection of geothermal brines is not within the definition of "pollution or pollutant" because disposal in this manner is not "likely to create a public nuisance or render such waters harmful, detrimental, or injurious to public health, safety, or welfare . . . ."[409]

State pollution laws are, therefore, also an appropriate place to apply the presumption that geothermal reservoirs are *separate* from conventional groundwater aquifers.[410] One objection to this analysis is that there is a difference between the rights of prior water rights appropriators against a geothermal operator and the rights of the public to clean water. A prior appropriator has a property right in the water put to beneficial use, and, should a geothermal development in fact interfere with the right, after-the-fact compensation can make the water right holder substantially whole. If, however, a geothermal well causes groundwater contamination, any after-the-fact damage remedy will not make the public whole except at great expense. This risk can be minimized by subjecting geothermal development to state pollution laws with a recognition that geothermal development is a special problem, and a regulatory structure that allows the developer to present his case for exemption before making a substantial capital investment should be provided.

X. Conclusion

There is a temptation to solve new resource allocation problems by reasoning from analogy to a familiar legal classification. Sometimes this process is satisfactory, but if the familiar category is un-

409. Ariz. Rev. Stat. Ann. § 36-1851(8) (1974). Arizona defined pollution as

> such contamination, or other alteration of the physical, chemical, or biological properties of any waters of the state, including change in temperature, taste, color, turbidity, or odor of the waters, or such discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state as will or is likely to create a public nuisance or render such waters harmful, detrimental, or injurious to public health, safety, or welfare, or to domestic, agricultural, commercial, industrial, recreational, or other beneficial uses, or to livestock, wild animals, birds, fish or other aquatic life.

Id. Recently, Arizona adopted a more streamlined definition of pollution. "'Pollution' means the man-made or man-induced alteration of the chemical, physical, biological and radiological integrity of water." *Id.* § 36-1851(12) (Supp. 1978-1979).

410. This was recognized in the well-reasoned California Superior Court opinion in Geothermal Kinetics, Inc. v. Union Oil Co., 75 Cal. App. 3d 56, 141 Cal. Rptr. 879 (1977), which held that the owner of the severed mineral estate was entitled to the geothermal resource because, in part, the reservoir litigated (at The Geysers) was sealed off from shallower groundwater aquifers. California water pollution laws define pollution as "an alteration of the quality of the waters of the state by waste to a degree which unreasonably affects: (1) such waters for beneficial uses, or (2) facilities which serve such beneficial uses." Cal. Water Code § 13050(1) (West 1971).

suitable, reasoning by analogy can impede the development of fair and functional allocation rules. The suggested adoption of groundwater rules for geothermal resources illustrates the dangers of reasoning by analogy. The two resources differ significantly. The application of water law doctrines to geothermal resources results in a legal regime where constraints on development are not offset by clear benefits.

The efficient allocation of geothermal resources will be served best by a presumption that geothermal deposits are separate from freshwater aquifers. Thus, geothermal resource exploitation can be governed by a separate legal regime. In some instances there will be a physical interconnection between geothermal and freshwater resources. Efficiency will be better served, however, by a legal regime that starts from a presumption of noninterference, and provides a mechanism for the early assessment of potential interference to assure prior vested water right holders that the geothermal developer will be liable for any injuries caused.

The right to exploit the resource should be assigned to the overlying property owner. Recognizing a presumption of noninterference between ground and geothermal resources is a logical corollary of this basic principle. A geothermal right should be a right to capture the resource. Judicial rules designed to prevent waste and to protect correlative rights should modify the right to capture. Judicial protection of correlative rights should be supplemented—as it already has been in some states—by pooling and unitization statutes. Oil and gas law provides useful analogies, although there is a need to realize that the geothermal resource is heat, not the heat transfer medium. To promote the capture of geothermal resources, the overlying owner needs the maximum possible assurance that his right to exploit will not be challenged by others unless he is wasteful. Because geothermal resources may be physically interconnected with other resources, it is not possible to give an overlying owner complete assurance that his exploitation will be exclusive. The best that the law can do is to give the overlying owner the benefit of a presumption of noninterference.

The presumption would be implemented by assigning the appropriate state agency the responsibility and authority to gather information and make findings concerning the relevant physical facts early in the development of a geothermal area. In extreme cases, it may even be appropriate for the agency to drill additional wells to monitor the interrelationships of freshwater pumping and geothermal production. The proposed inquiry would extend beyond the narrow scope of the certificate of primary purpose device available by statute in California,[411] which deals only with geothermal wells and inquires only whether the water content of those wells is fit for domestic and irrigation uses without further treatment. Rather, the proposed inquiry by the state agency would deal with all matters that bear on the possible relationship between freshwater pumping and geothermal development.

Temperature, pressure connection, and depth are the most likely variables for monitoring a physical interconnection. As information is accumulated over time, the agency might be able to formulate *per se* categories of noninterference through administrative rulemaking. Although depth and temperature appear to be the best basis for *per se* rules, legislation is not the best way to implement a *per se* rule. A common theme that emerged from our study of western state geothermal legislation is that legislative classifications were usually designed to solve jurisdictional conflicts among state agencies, and not based on the best available scientific information about the resource. For the foreseeable future the presumption will have to be applied on a reservoir-by-reservoir basis.

The presumption of noninterference must, of necessity, be a rebuttable one. Vested water rights are protected by the due process clause of the federal Constitution and by state constitutions as well. It might be argued that the presumption is unconstitutional because it takes groundwater rights. This should not be the case, however, because groundwater pumpers can be adequately protected. The presumption rests on a sound scientific basis, designed to insure that a geothermal driller's right is not a water right. The presumption also recognizes that interference with vested rights is a defense to a geothermal well, but it seeks to limit the application of the defense to situations where there is a substantial risk of actual interference.

The major problem with classifying geothermal resources as water is that the protection of existing groundwater pumpers is accomplished at too high a cost. A water right is only good if the holder can make a call against rival claimants under the worst foreseeable hydrological conditions. The resulting shadow boxing in water rights disputes could impede geothermal development since a geothermal developer placed in this regime may never be given the opportunity to demonstrate noninterference. Socially useful energy development may be precluded because of hypothetical situations which never materialize.

---

411. See note 169 *supra* and accompanying text.

The proposed presumption of noninterference strikes a balance between would-be geothermal developers and vested water rights holders. At a minimum, a pumper is guaranteed compensation should a geothermal driller interfere with his water right. The pumper also has an administrative remedy equivalent to a suit for injunctive relief, since arguments about interference can, of course, be raised before the administrative agency. The benefit of the agency remedy is that a more accurate assessment of impairment can be made. Remedies such as physical solutions can be more easily developed before the rival resource claimants commit themselves to rigid positions.

New Mexico and Utah have recently considered legislation which would address geothermal-water conflicts more directly than does California's certificate of primary purpose. The proposed legislation, drafted with the assistance of the National Conference of State Legislatures, provides a useful model for other states to follow with appropriate revisions for local conditions and other modifications which we suggest. Unfortunately, the defeat of the proposed legislation in the Utah Legislature demonstrates the power of one strong lobbyist to preclude a rational accommodation in the public interest.

A. *New Mexico*

As we discussed in the section on New Mexico, both the State Engineer and the Oil Conservation Division presently assert jurisdiction over geothermal resources. Legislation proposed in 1978 would have eliminated the jurisdictional split by limiting the state's definition of geothermal resources to "the natural heat of the earth at temperatures greater than 120° centigrade."[412] A reservoir containing thermal water below 120° centigrade is designated as a "low-temperature thermal reservoir."[413] A geothermal driller must apply to the State Engineer for a permit to drill a geothermal well. Protestors may appear, but the State Engineer's discretion to deny a permit is limited, as a permit must be granted if:

> The intended geothermal operation will not cause substantial interference with and impairment of existing surface and groundwater rights or existing stream flows; or
>
> . . . As a condition of the granting or the permit of amendment, . . . the geothermal owner [has obtained] adequate water rights to

412. See note 296 *supra* and accompanying text.
413. *Id.*

offset any impairment to existing water rights or stream flows . . . .[414]

The date of the application for a permit is the priority date between a geothermal developer and a conventional water right holder. The permit creates no priority among geothermal drillers because the rule of capture applies except as modified by rules of the New Mexico Oil Conservation Division to protect correlative rights. The significance of giving the geothermal developer a water priority is basically to protect him against subsequent water users. The State Engineer may set economic drilling levels for any groundwater basin associated with a geothermal field, and a geothermal driller is not liable for any additional lifting costs imposed on groundwater pumpers so long as water levels remain at the designated economic drilling level. New Mexico law does not recognize a fixed right to lift on the part of senior groundwater pumpers. The State Engineer has the discretion to permit pumpers to lower groundwater tables in designated basins without liability to senior pumpers for increased lifting costs. However, the State Engineer also has discretion to recognize rights to fixed pumping levels, and thus the proposed legislation would somewhat limit the State Engineer's discretion to protect groundwater pumpers from geothermal developers. The term "economic drilling levels" makes it clear that existing pumpers could be made to suffer some disadvantage in the interest of geothermal development.

A second reason why the placement of the geothermal developer in the New Mexico water rights regime will not benefit prior pumpers to the same extent as if the new entrant were a conventional water user is the burden of proof placed on existing pumpers to demonstate impairment of a vested right. After an allegation of impairment of vested rights, the proposed legislation provides:

> The State Engineer shall hold a hearing on the matter at which the complaining party shall have the burden of establishing such interference and impairment. Should the complaining party sustain such burden of proof, the State Engineer shall instruct the geothermal owner to remedy the impairment through the provision of offset water, if available, or the payment of compensation. The right of eminent domain is hereby granted geothermal owners for the purpose of payment of compensation as provided herein. The protection of this section shall extend to only those water rights which predate the date of an application for a permit to produce geothermal fluids.[415]

414. *Id.*
415. *Id.*

A New Mexico appropriator must bear the burden of proving that unappropriated water exists and that vested rights will not be impaired. The proposed legislation would place on the geothermal developer the burden of demonstrating that unappropriated water is available, and give the existing water right holder the burden of showing interference and impairment. This allocation effectively allows a geothermal developer to enter a basin with adequate assurance that existing pumpers cannot bar the development. The reversal of the burden of proof is necessary; otherwise geothermal development may be frustrated in situations where the risk of impairment of vested rights is small. In effect, the proposed legislation precludes the award of injunctive relief against a geothermal development by giving the geothermal driller a preference against conventional water users.[416]

B. *Utah*

A comparable bill, also drafted by the Conference of State Legislatures, failed to gain passage in the 1979 general session of the Utah Legislature.[417] The Utah bill also would have provided ways to accommodate geothermal development at some cost to those whose claims are grounded solely on water law doctrines. That is what caused the bill's ultimate downfall.

As indicated in the Utah section above, Utah Power & Light Company blanketed many of the state's promising geothermal areas with water rights applications.[418] This course of conduct was premised on the assumption that geothermal resources *are* water, pure and simple, and that no property rights other than water rights and incidential surface and subsurface user rights would be required to exploit the resource. No attempt was made by the company to secure geothermal leases from either private or public landowners.

Before the legislative session convened, attempts were made to accommodate divergent interests, and several meetings were held which were attended by representatives of concerns interested in geothermal development in the state. Utah Power & Light participated in those discussions, but that company alone insisted that the existing law made geothermal resources simply water. The company

416. A legislature may not immunize an activity which results in a taking from all common law liability. But, subject to this Constitutional constraint, the state is free to restrict a property right holder's choice of remedies. *See* W. Rogers, Environmental Law § 2.10 (West 1977).

417. See note 349 *supra*.

418. See text accompanying notes 348-49, *supra*.

would not agree to any legislative solution that failed to accord a priority or an exception for its existing water applications. Because of the wide area blanketed by the Utah Power & Light applications, the other participants in the discussion were unwilling to agree to a bill that failed to address the status of claims solely grounded on prior water filings. An impasse was reached and the bill died.

The Utah problem presents a classic case in the difficulty of achieving idealistic reform in a real and political world. A great deal of give and take in the legislative process by all participants, save one, resulted in a good, but far from perfect, bill being introduced. The complete intransigence of Utah Power & Light Company prevented reasonable accommodation from becoming law.

December 15, 1978

Mr. Peter J. Murphy
Utah Geological and Mineral Survey
606 Blackhawk Way
Salt Lake City, UT 84108

Dear Peter:

The results of the November 7, 1978 pump test of the flowing geothermal well near Crystal Hot Springs are encouraging. The aquifer can probably support several more low-capacity wells without diminishing the natural discharge to the ponds at Crystal Hot Springs.

The alluvial aquifer is tight, and large diameter wells may not be able to produce more water than smaller, less costly wells. All wells should be completed in bedrock.

I believe that the fractured quartzite is leaking hot water to the overlying alluvial aquifer. An observation well and an additional pump test will be needed to assess this inferred leakage and the accompanying vertical movement of water and delayed yield from storage.

A thin hole within 30 feet of the flowing well, similar to the temperature gradient holes but with perforated PVC casing, would be an adequate observation well, which might later be adaptable to production.

Sincerely,

Christian Smith

Christian Smith

CS/smk

encl.

cc: P.M. Wright
D. Foley
S.H. Ward
L.L. Mink

CRYSTAL HOT SPRINGS PUMP TEST ANALYSIS

The flowing geothermal well on the grounds of the Utah State Prison near Crystal Hot Springs, Jordan Narrows Quadrangle, Utah, was pumped at an average rate of 30 gpm for more than six hours on November 7, 1978. This report summarizes the data and results of this short-term pump test.

Figure 1 is a sketch of the well and the geologic units it penetrates. The well diameter is 6 in, its total depth 285 ft; it is cased to the bottom of the hole. Torch-cut slots in the bottom 110 ft of the casing were used to complete the well. The artesian head is inferred to be 9 ft above ground level; artesian flow is about 8 gpm at 180°F. The 195 ft thick, fine-grained alluvial aquifer is confined above by approximately 90 ft of clay and below by pervasively fractured quartzite bedrock. While it is not known whether the quartzite yields water directly to the well, all evidence indicates that it does leak hot water to Crystal Hot Springs, a few hundred feet to the south.

The pump test was designed to be, but did not satisfy the strict requirements for, a step-drawdown test and numerical analysis. Attempts to apply the step-drawdown analysis suggest well-losses are minimal and that the well is efficient. Completion of the well may even have improved the transmissivity of the aquifer within a short distance of the well.

The raw pump test data are plotted in Figure 2. Discharge, Q, in gallons per minute and drawdown (the increasing depth to water), s, in feet are plotted against the logarithm of time. A nearly constant rate of discharge at 30 gpm was sustained for 288 minutes. During most of this interval the drawdown was also nearly constant at 57 feet. Drawdown increased to 93 ft only when discharge exceeded 30 gpm between 183 and 188 minutes. These observations indicate that there is a source of hot water near the well capable of supplying about 30 gpm instantaneously to the aquifer. The constant drawdown (136 ft) during the final pumping interval indicates that the source of hot water may be capable of supplying as much as 35 gpm.

The source of hot water also fills the ponds at Crystal Hot Springs. It is possible but unlikely that the well is pumping water that would otherwise rise to these ponds. It is also possible that the quartzite is leaking water directly to the well. In either case, pumping 30 gpm should have no observable effect upon the natural regime of the ponds.

Since no observation wells were available, the log-log type curve solution for transmissivity, T, and storage, S, cannot be found. To estimate T, the 'Harrill time', t_H, was used in a conventional straight-line analysis of the recovery data (Fig. 3). This value compensates for the changes in discharge and the nonequal periods of pumping at the different discharges recorded during the test (Harrill, 1970). Two straight-line segments emerged, an 'early' segment and a 'late' segment, from which the corresponding transmissivities T_e and T_l can be computed.

$$T_e = 34.4 \text{ ft}^2/\text{day}$$
$$T_l = 18.7 \text{ ft}^2/\text{day}$$

These values are low but are typical of tight, fine-grained artesian aquifers.

The two estimates of T are sufficiently low to limit the rate at which the aquifer can deliver water to the well. When pumped at a rate less than it can deliver, an aquifer with a low T and a nearby source of water is likely to sustain a constant drawdown. The response in an artesian system may be instantaneous: an increased discharge can cause the water level to drop immediately. If the pumping rate is again dropped to the lower rate, the water level will again remain constant, but at a lower level. This is thought to be what happened during the pump test at Crystal Hot Springs.

Given an estimate of T and the pump-test data, it is possible to estimate the value of storage, S. The well was pumped for 0.26 days at an average discharge of 30 gpm; the total drawdown was 135 ft. The results are:

$$T_e = 34.4 \text{ ft}^2\text{/day} \qquad S = 0.001$$

$$T_1 = 18.7 \text{ ft}^2\text{/day} \qquad S = 0.05$$

The solutions are not strictly valid for reasons discussed below. Figure 4 is a graph of drawdown as a function of the logarithm of distance from the pumping well for these two solutions. Tables 1 and 2 are the values plotted in Figure 4. Data from an observation well within 30 ft of the pumping well would discriminate between these two solutions. Both values of S are high for artesian systems; the value of S = 0.05 is so high that the T_1 solution is less likely.

The Theis equation has been used to predict the effects of continued pumping on the aquifer (Theis, 1935), This general equation assumes an infinite isotropic aquifer with no recharge areas near the pumping well, conditions violated at Crystal Hot Springs. Since a recharge area is present, the Theis equation will predict drawdowns greater than those that will probably be observed. The drawdowns listed in Tables 3a-d and 4a-d and shown in Figures 5 and 6 may be excessive and the values of S maybe too great.

Figures 5 and 6 plot the drawdown as a function of the logarithm of distance from a well pumping 10 gpm for periods of one day, one month, one year, and ten years. It can be seen that continued pumping of the present well is predicted to have little effect on the Crystal Hot Springs area. The aquifer may be able to support several properly spaced small-diameter wells pumping 10 gpm in a well field.

Before production is contemplated, an observation well should be drilled near the present well and a flow test run. The leaky confined aquifer equation of Hantush (1959) could then be used to refine the conclusions presented here.

REFERENCES

Harrill, J. R., 1970, Determining transmissivity from water-level recovery of a step-drawdown test: U.S. Geol. Survey Prof. Paper 700-C, p. C212-C213.

Hantush, M. D., 1959, Nonsteady flow to flowing wells in leaky aquifers: Jour. Geophys. Research, v. 64, no. 8, p. 1043-1052.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Amer. Geophys. Union Trans. pt. 2, p. 517-524

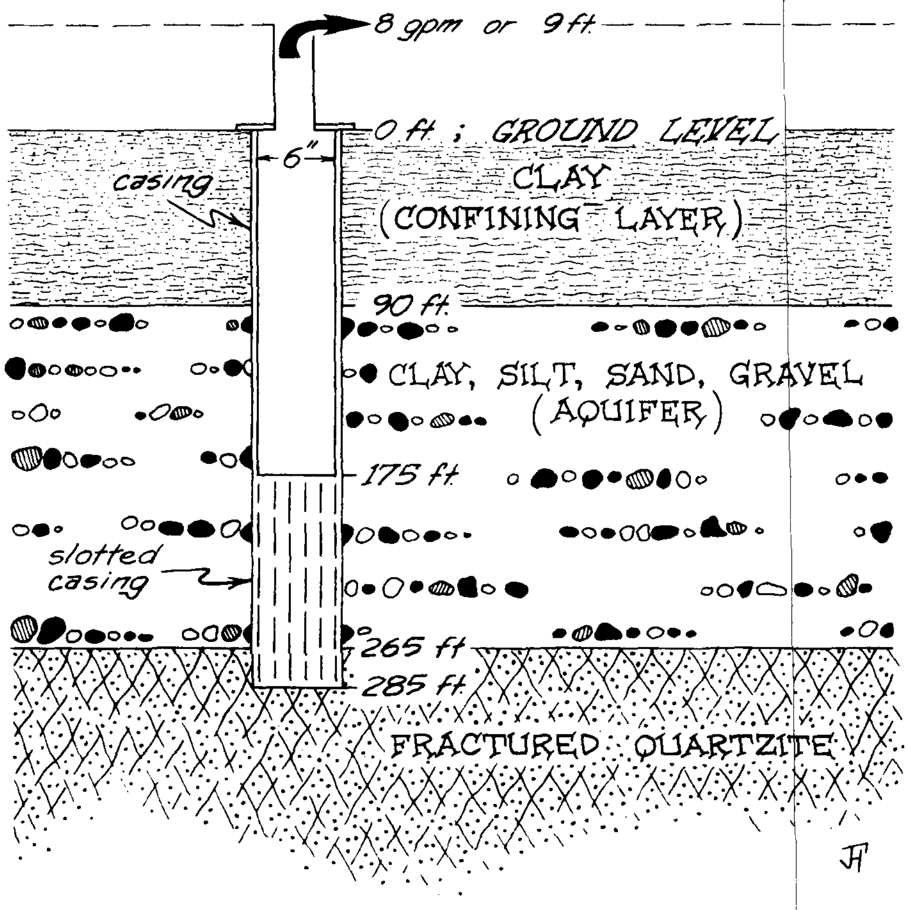


FIGURE 1. DIAGRAMMATIC SKETCH OF CRYSTAL SPRINGS/UTAH STATE PRISON FLOWING GEOTHERMAL WELL

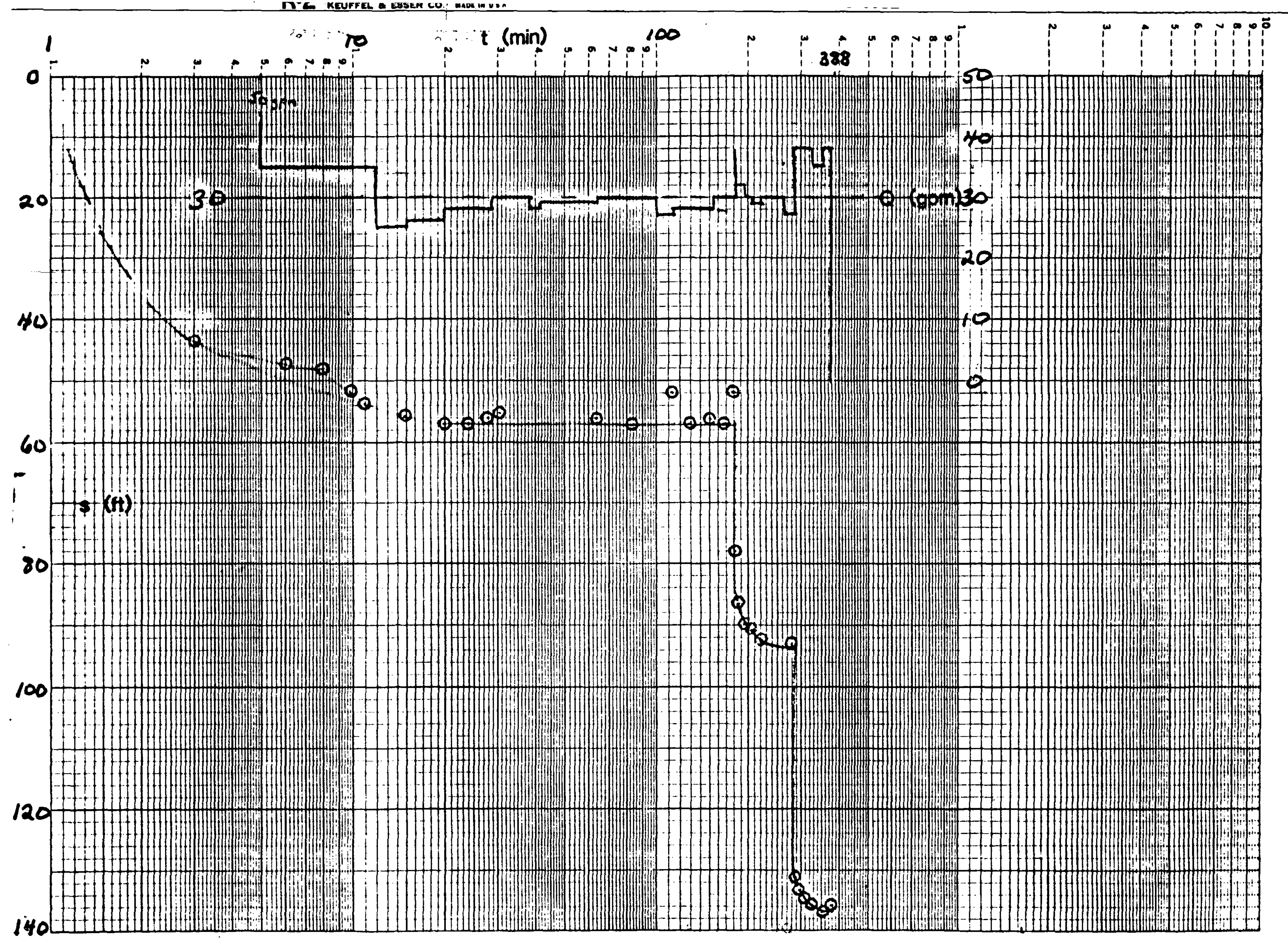


Fig 2 Pump-test data - Discharge, Q, and drawdown, s, vs. log time, t

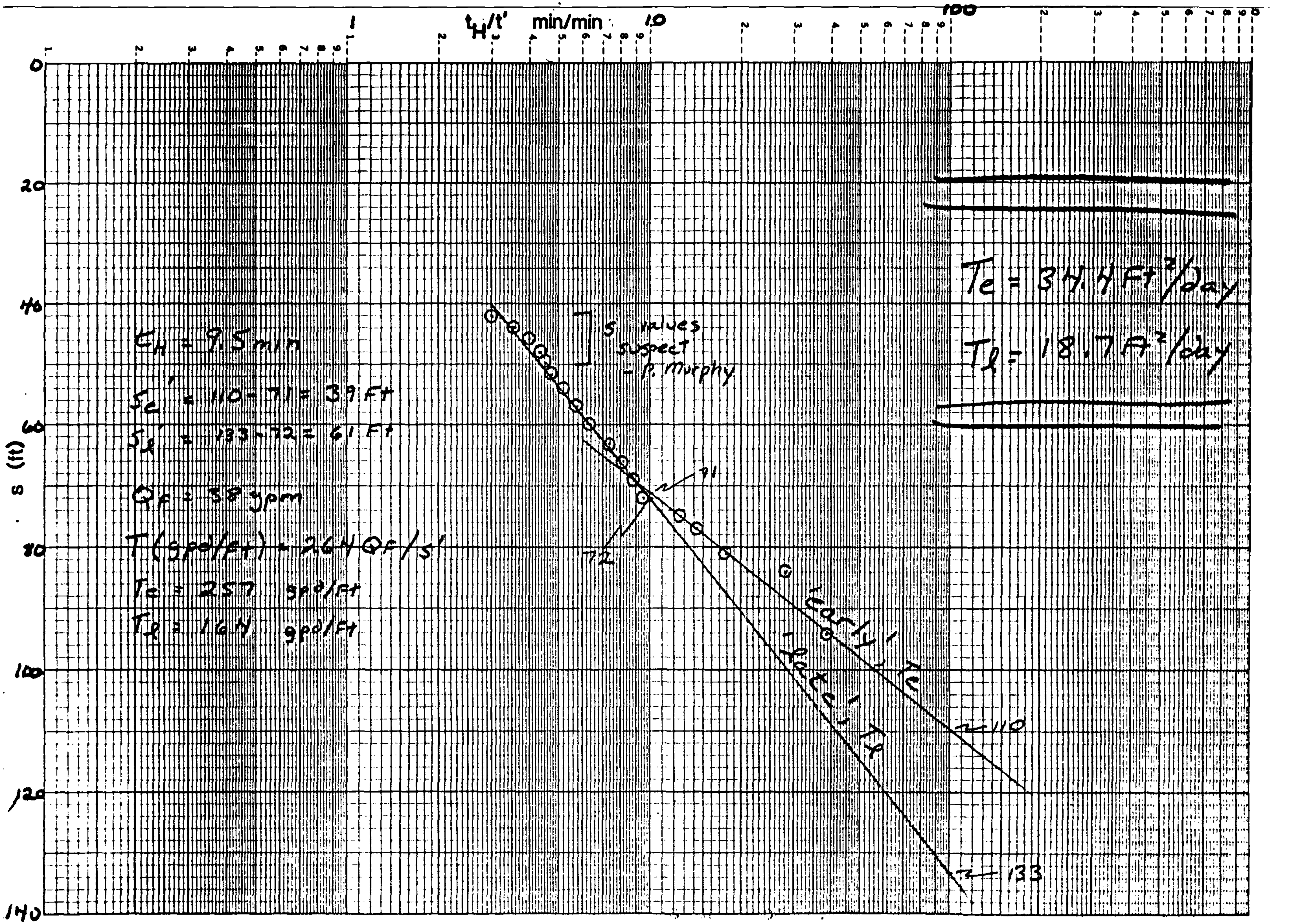


Fig 3 Straight-line solution for transmissivity, T

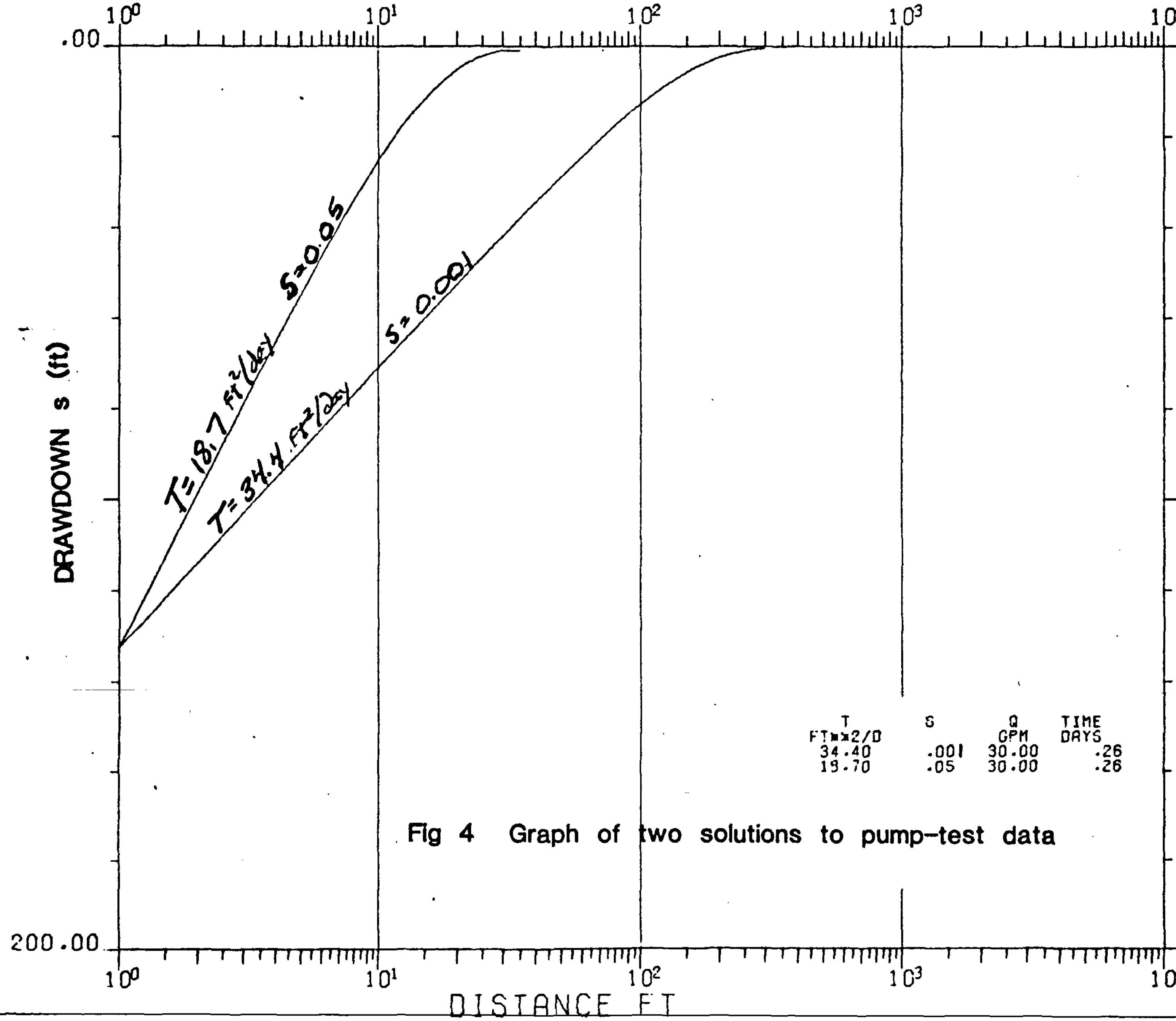


Fig 4 Graph of two solutions to pump-test data

Table 1 Solution to pump-test data, Te.

DRAWDOWN # 1

T= 34.4000 S= .0010 Q= 30.0000TIME= .2600

#	DISTANCE	DRAWDOWN
1	1.0000	132.361
2	1.2000	127.490
3	1.4000	123.372
4	1.6000	119.804
5	1.8000	116.657
6	2.0000	113.843
7	2.2000	111.296
8	2.4000	108.972
9	2.6000	106.834
10	2.8000	104.854
11	3.0000	103.011
12	3.5000	98.894
13	4.0000	95.327
14	4.5000	92.182
15	5.0000	89.369
16	5.5000	86.824
17	6.0000	84.501
18	6.5000	82.365
19	7.0000	80.387
20	8.0000	76.825
21	9.0000	73.685
22	10.0000	70.877
23	12.0000	66.022
24	14.0000	61.922
25	16.0000	58.377
26	18.0000	55.255
27	20.0000	52.468
28	22.0000	49.953
29	24.0000	47.662
30	26.0000	45.561
31	28.0000	43.621
32	30.0000	41.820
33	35.0000	37.821
34	40.0000	34.391
35	45.0000	31.398
36	50.0000	28.755
37	55.0000	26.397
38	60.0000	24.277
39	65.0000	22.360
40	70.0000	20.617
41	80.0000	17.567
42	90.0000	14.995
43	100.0000	12.806
44	120.0000	9.327
45	140.0000	6.755
46	160.0000	4.849
47	180.0000	3.442
48	200.0000	2.413
49	220.0000	1.669
50	240.0000	1.138
51	260.0000	.768
52	280.0000	.521
53	300.0000	.379

Table 2 Solution to pump-test data, TI

DRAWDOWN # 2

T= 18.7000 S= .0500 Q= 30.0000TIME= .2600

#	DISTANCE	DRAWDOWN
1	1.0000	132.432
2	1.2000	123.499
3	1.4000	115.955
4	1.6000	109.429
5	1.8000	103.683
6	2.0000	98.552
7	2.2000	93.921
8	2.4000	89.702
9	2.6000	85.830
10	2.8000	82.255
11	3.0000	78.937
12	3.5000	71.563
13	4.0000	65.232
14	4.5000	59.706
15	5.0000	54.819
16	5.5000	50.454
17	6.0000	46.526
18	6.5000	42.967
19	7.0000	39.727
20	8.0000	34.046
21	9.0000	29.237
22	10.0000	25.130
23	12.0000	18.555
24	14.0000	13.641
25	16.0000	9.954
26	18.0000	7.194
27	20.0000	5.142
28	22.0000	3.631
29	24.0000	2.531
30	26.0000	1.743
31	28.0000	1.193
32	30.0000	.835
33	35.0000	.825

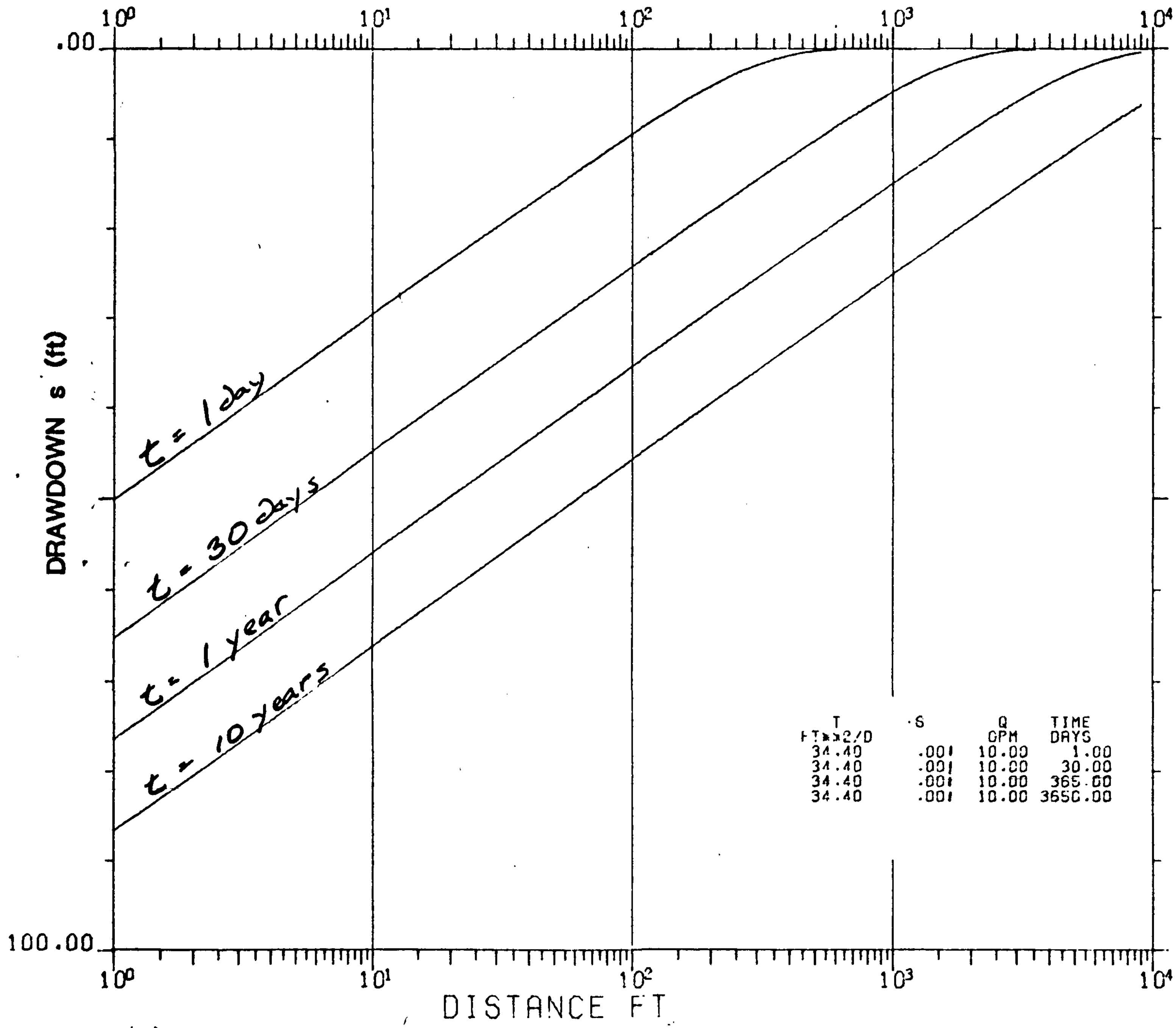


Fig 5 Graph of predicted effects of continued pumping, Te

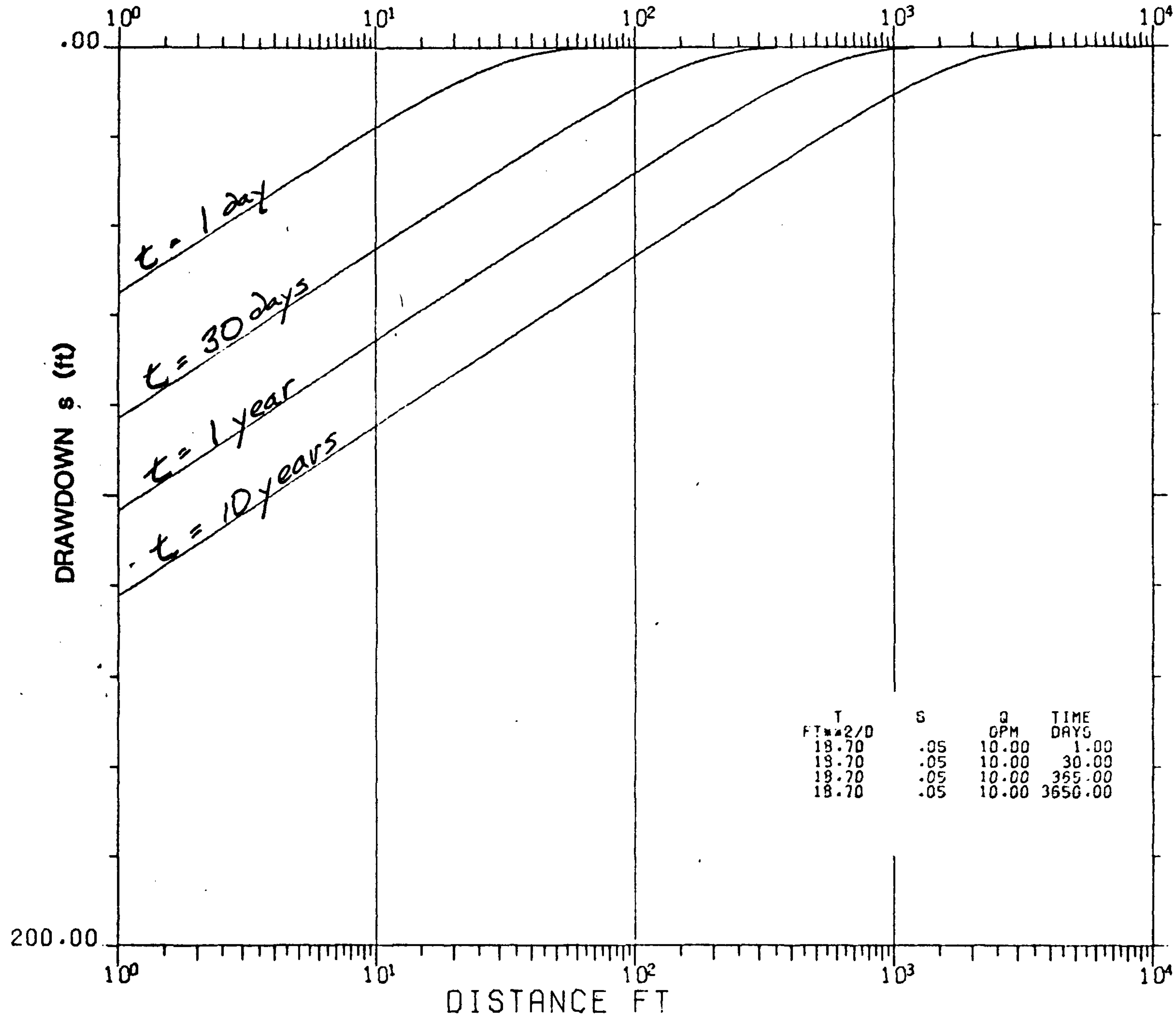


Fig 6 Graph of predicted effects of continued pumping, TI

T= 34.4000 S= .0010 Q= 10.0000 TIME= 1.0000

#	DISTANCE	DRAWDOWN
1	1.0000	50.119
2	1.2000	48.495
3	1.4000	47.122
4	1.6000	45.933
5	1.8000	44.884
6	2.0000	43.946
7	2.2000	43.097
8	2.4000	42.322
9	2.6000	41.609
10	2.8000	40.949
11	3.0000	40.335
12	3.5000	38.962
13	4.0000	37.773
14	4.5000	36.724
15	5.0000	35.786
16	5.5000	34.937
17	6.0000	34.162
18	6.5000	33.450
19	7.0000	32.790
20	8.0000	31.601
21	9.0000	30.553
22	10.0000	29.615
23	12.0000	27.993
24	14.0000	26.621
25	16.0000	25.434
26	18.0000	24.387
27	20.0000	23.451
28	22.0000	22.605
29	24.0000	21.833
30	26.0000	21.124
31	28.0000	20.467
32	30.0000	19.856
33	35.0000	18.494
34	40.0000	17.317
35	45.0000	16.281
36	50.0000	15.358
37	55.0000	14.526
38	60.0000	13.770
39	65.0000	13.077
40	70.0000	12.438
41	80.0000	11.297
42	90.0000	10.301
43	100.0000	9.422
44	120.0000	7.935
45	140.0000	6.720
46	160.0000	5.710
47	180.0000	4.860
48	200.0000	4.137
49	220.0000	3.521
50	240.0000	2.993
51	260.0000	2.540
52	280.0000	2.152
53	300.0000	1.818
54	350.0000	1.178
55	400.0000	.748
56	450.0000	.465
57	500.0000	.283
58	550.0000	.172
59	600.0000	.119

a - 1 day

T= 34.4000 S= .0010 Q= 10.0000 TIME= 30.0000

#	DISTANCE	DRAWDOWN
1	1.0000	65.265
2	1.2000	63.641
3	1.4000	62.268
4	1.6000	61.079
5	1.8000	60.030
6	2.0000	59.091
7	2.2000	58.243
8	2.4000	57.468
9	2.6000	56.755
10	2.8000	56.095
11	3.0000	55.480
12	3.5000	54.107
13	4.0000	52.918
14	4.5000	51.869
15	5.0000	50.931
16	5.5000	50.082
17	6.0000	49.307
18	6.5000	48.594
19	7.0000	47.934
20	8.0000	46.745
21	9.0000	45.696
22	10.0000	44.758
23	12.0000	43.134
24	14.0000	41.761
25	16.0000	40.572
26	18.0000	39.523
27	20.0000	38.585
28	22.0000	37.736
29	24.0000	36.961
30	26.0000	36.248
31	28.0000	35.588
32	30.0000	34.974
33	35.0000	33.602
34	40.0000	32.413
35	45.0000	31.364
36	50.0000	30.426
37	55.0000	29.578
38	60.0000	28.804
39	65.0000	28.092
40	70.0000	27.432
41	80.0000	26.245
42	90.0000	25.197
43	100.0000	24.261
44	120.0000	22.642
45	140.0000	21.275
46	160.0000	20.092
47	180.0000	19.050
48	200.0000	18.120
49	220.0000	17.280
50	240.0000	16.515
51	260.0000	15.813
52	280.0000	15.165
53	300.0000	14.562
54	350.0000	13.224
55	400.0000	12.075
56	450.0000	11.071
57	500.0000	10.182
58	550.0000	9.388
59	600.0000	8.673
60	650.0000	8.024
61	700.0000	7.433
62	800.0000	6.395
63	900.0000	5.514
64	1000.0000	4.760
65	1200.0000	3.547
66	1400.0000	2.634
67	1600.0000	1.943
68	1800.0000	1.422
69	2000.0000	1.029
70	2200.0000	.737
71	2400.0000	.521
72	2600.0000	.364
73	2800.0000	.253
74	3000.0000	.176
75	3500.0000	.124

b - 1 month

Table 3 Predicted drawdown, Te

DRAWDOWN # 3

T= 34.4000 S= .0010 Q= 10.0000TIME= 365.0000

#	DISTANCE	DRAWDOWN
1	1,0000	76.392
2	1,2000	74.768
3	1,4000	73.395
4	1,6000	72.206
5	1,8000	71.157
6	2,0000	70.218
7	2,2000	69.370
8	2,4000	68.595
9	2,6000	67.882
10	2,8000	67.222
11	3,0000	66.607
12	3,5000	65.234
13	4,0000	64.045
14	4,5000	62.996
15	5,0000	62.058
16	5,5000	61.209
17	6,0000	60.434
18	6,5000	59.721
19	7,0000	59.061
20	8,0000	57.872
21	9,0000	56.823
22	10,0000	55.884
23	12,0000	54.261
24	14,0000	52.888
25	16,0000	51.699
26	18,0000	50.650
27	20,0000	49.711
28	22,0000	48.862
29	24,0000	48.087
30	26,0000	47.375
31	28,0000	46.715
32	30,0000	46.100
33	35,0000	44.727
34	40,0000	43.538
35	45,0000	42.489
36	50,0000	41.551
37	55,0000	40.702
38	60,0000	39.927
39	65,0000	39.214
40	70,0000	38.554
41	80,0000	37.365
42	90,0000	36.316
43	100,0000	35.378
44	120,0000	33.755
45	140,0000	32.382
46	160,0000	31.194
47	180,0000	30.145
48	200,0000	29.208
49	220,0000	28.359
50	240,0000	27.585
51	260,0000	26.873
52	280,0000	26.214
53	300,0000	25.601
54	350.0000	24.231
55	400,0000	23.045
56	450,0000	22.000
57	500,0000	21.065
58	550,0000	20.221
59	600,0000	19.451
60	650,0000	18.744
61	700,0000	18.090
62	800,0000	16.914
63	900,0000	15.880
64	1000,0000	14.958
65	1200,0000	13.373
66	1400,0000	12.045
67	1600,0000	10.908
68	1800,0000	9.918
69	2000,0000	9.045
70	2200,0000	8.267
71	2400,0000	7.569
72	2600,0000	6.940
73	2800,0000	6.369
74	3000,0000	5.849
75	3500,0000	4.736
76	4000,0000	3.837
77	4500,0000	3.104
78	5000,0000	2.506
79	5500,0000	2.014
80	6000,0000	1.612
81	6500,0000	1.285
82	7000,0000	1.018
83	8000,0000	.628
84	9000,0000	.378

c - 1 year

DRAWDOWN # 4

T= 34.4000 S= .0010 Q= 10.0000TIME= 3650.0000

#	DISTANCE	DRAWDOWN
1	1,0000	86.646
2	1,2000	85.021
3	1,4000	83.649
4	1,6000	82.459
5	1,8000	81.410
6	2,0000	80.472
7	2,2000	79.623
8	2,4000	78.848
9	2,6000	78.135
10	2,8000	77.475
11	3,0000	76.861
12	3,5000	75.488
13	4,0000	74.299
14	4,5000	73.250
15	5,0000	72.311
16	5,5000	71.462
17	6,0000	70.688
18	6,5000	69.975
19	7,0000	69.315
20	8,0000	68.125
21	9,0000	67.076
22	10,0000	66.138
23	12,0000	64.514
24	14,0000	63.141
25	16,0000	61.952
26	18,0000	60.903
27	20,0000	59.965
28	22,0000	59.116
29	24,0000	58.341
30	26,0000	57.628
31	28,0000	56.968
32	30,0000	56.354
33	35,0000	54.981
34	40,0000	53.792
35	45,0000	52.743
36	50,0000	51.804
37	55,0000	50.955
38	60,0000	50.180
39	65,0000	49.468
40	70,0000	48.808
41	80,0000	47;618
42	90,0000	46.569
43	100,0000	45.631
44	120,0000	44.007
45	140,0000	42.634
46	160,0000	41.445
47	180,0000	40.396
48	200,0000	39.458
49	220,0000	38.609
50	240,0000	37.834
51	260,0000	37.122
52	280,0000	36.462
53	300,0000	35.847
54	350.0000	34.475
55	400,0000	33.286
56	450,0000	32.237
57	500,0000	31.299
58	550,0000	30.451
59	600,0000	29.676
60	650,0000	28.964
61	700,0000	28.305
62	800,0000	27.117
63	900,0000	26.069
64	1000,0000	25.133
65	1200,0000	23.513
66	1400,0000	22.144
67	1600,0000	20.960
68	1800,0000	19.917
69	2000,0000	18.986
70	2200,0000	18.144
71	2400,0000	17.378
72	2600,0000	16.673
73	2800,0000	16.023
74	3000,0000	15.419
75	3500,0000	14.074
76	4000,0000	12.918
77	4500,0000	11.906
78	5000,0000	11.009
79	5500,0000	10.205
80	6000,0000	9.480
81	6500,0000	8.828
82	7000,0000	8.217
83	8000,0000	7.154
84	9000,0000	6.245

d - 10 years

DRAWDOWN # 1
T= 18.7000 S= .0500 Q= 10.0000 TIME= 1.0000

#	DISTANCE	DRAWDOWN
1	1.0000	55.163
2	1.2000	52.179
3	1.4000	49.656
4	1.6000	47.472
5	1.8000	45.546
6	2.0000	43.824
7	2.2000	42.267
8	2.4000	40.846
9	2.6000	39.540
10	2.8000	38.332
11	3.0000	37.208
12	3.5000	34.700
13	4.0000	32.533
14	4.5000	30.626
15	5.0000	28.926
16	5.5000	27.393
17	6.0000	25.998
18	6.5000	24.721
19	7.0000	23.543
20	8.0000	21.436
21	9.0000	19.597
22	10.0000	17.972
23	12.0000	15.216
24	14.0000	12.960
25	16.0000	11.077
26	18.0000	9.486
27	20.0000	8.129
28	22.0000	6.966
29	24.0000	5.965
30	26.0000	5.101
31	28.0000	4.355
32	30.0000	3.710
33	35.0000	2.459
34	40.0000	1.601
35	45.0000	1.022
36	50.0000	.639
37	55.0000	.394
38	60.0000	.254
39	65.0000	.214

a - 1 day

DRAWDOWN # 2
T= 18.7000 S= .0500 Q= 10.0000 TIME= 30.0000

#	DISTANCE	DRAWDOWN
1	1.0000	83.020
2	1.2000	80.033
3	1.4000	77.507
4	1.6000	75.320
5	1.8000	73.390
6	2.0000	71.664
7	2.2000	70.103
8	2.4000	68.677
9	2.6000	67.366
10	2.8000	66.152
11	3.0000	65.022
12	3.5000	62.497
13	4.0000	60.310
14	4.5000	58.381
15	5.0000	56.656
16	5.5000	55.095
17	6.0000	53.671
18	6.5000	52.361
19	7.0000	51.148
20	8.0000	48.963
21	9.0000	47.036
22	10.0000	45.313
23	12.0000	42.334
24	14.0000	39.818
25	16.0000	37.642
26	18.0000	35.724
27	20.0000	34.012
28	22.0000	32.466
29	24.0000	31.057
30	26.0000	29.764
31	28.0000	28.569
32	30.0000	27.460
33	35.0000	24.993
34	40.0000	22.872
35	45.0000	21.019
36	50.0000	19.377
37	55.0000	17.908
38	60.0000	16.584
39	65.0000	15.382
40	70.0000	14.285
41	80.0000	12.354
42	90.0000	10.711
43	100.0000	9.299
44	120.0000	7.015
45	140.0000	5.280
46	160.0000	3.953
47	180.0000	2.938
48	200.0000	2.164
49	220.0000	1.578
50	240.0000	1.139
51	260.0000	.812
52	280.0000	.574
53	300.0000	.403
54	350.0000	.213

b - 1 month

Table 4 Predicted drawdown, TI

DRAWDOWN # 3

T= 18.7000 S= .0500 Q= 10.0000TIME= 365.0000

#	DISTANCE	DRAWDOWN
1	1.0000	103.486
2	1.2000	100.501
3	1.4000	97.976
4	1.6000	95.708
5	1.8000	93.656
6	2.0000	92.132
7	2.2000	90.571
8	2.4000	89.145
9	2.6000	87.836
10	2.8000	86.620
11	3.0000	85.489
12	3.5000	82.964
13	4.0000	80.776
14	4.5000	78.847
15	5.0000	77.121
16	5.5000	75.559
17	6.0000	74.134
18	6.5000	72.822
19	7.0000	71.608
20	8.0000	69.421
21	9.0000	67.491
22	10.0000	65.765
23	12.0000	62.779
24	14.0000	60.254
25	16.0000	58.068
26	18.0000	56.139
27	20.0000	54.414
28	22.0000	52.854
29	24.0000	51.429
30	26.0000	50.119
31	28.0000	48.907
32	30.0000	47.778
33	35.0000	45.258
34	40.0000	43.076
35	45.0000	41.152
36	50.0000	39.433
37	55.0000	37.880
38	60.0000	36.463
39	65.0000	35.161
40	70.0000	33.956
41	80.0000	31.791
42	90.0000	29.887
43	100.0000	28.189
44	120.0000	25.267
45	140.0000	22.818
46	160.0000	20.719
47	180.0000	18.888
48	200.0000	17.273
49	220.0000	15.832
50	240.0000	14.538
51	260.0000	13.368
52	280.0000	12.306
53	300.0000	11.337
54	350.0000	9.254
55	400.0000	7.562
56	450.0000	6.175
57	500.0000	5.033
58	550.0000	4.089
59	600.0000	3.311
60	650.0000	2.669
61	700.0000	2.141
62	800.0000	1.357
63	900.0000	.840
64	1000.0000	.510
65	1200.0000	.217

c - 1 year

T= 18.7000 S= .0500 Q= 10.0000TIME= 365

#	DISTANCE	DRAWDOWN
1	1.0000	122.351
2	1.2000	119.364
3	1.4000	116.838
4	1.6000	114.650
5	1.8000	112.721
6	2.0000	110.995
7	2.2000	109.433
8	2.4000	108.007
9	2.6000	106.696
10	2.8000	105.482
11	3.0000	104.352
12	3.5000	101.826
13	4.0000	99.638
14	4.5000	97.709
15	5.0000	95.982
16	5.5000	94.421
17	6.0000	92.995
18	6.5000	91.684
19	7.0000	90.470
20	8.0000	88.282
21	9.0000	86.353
22	10.0000	84.626
23	12.0000	81.639
24	14.0000	79.114
25	16.0000	76.926
26	18.0000	74.997
27	20.0000	73.271
28	22.0000	71.709
29	24.0000	70.284
30	26.0000	68.973
31	28.0000	67.759
32	30.0000	66.628
33	35.0000	64.103
34	40.0000	61.916
35	45.0000	59.987
36	50.0000	58.262
37	55.0000	56.701
38	60.0000	55.276
39	65.0000	53.966
40	70.0000	52.753
41	80.0000	50.567
42	90.0000	48.640
43	100.0000	46.917
44	120.0000	43.936
45	140.0000	41.419
46	160.0000	39.240
47	180.0000	37.320
48	200.0000	35.605
49	220.0000	34.056
50	240.0000	32.645
51	260.0000	31.348
52	280.0000	30.150
53	300.0000	29.037
54	350.0000	26.560
55	400.0000	24.428
56	450.0000	22.561
57	500.0000	20.904
58	550.0000	19.420
59	600.0000	18.078
60	650.0000	16.857
61	700.0000	15.740
62	800.0000	13.766
63	900.0000	12.075
64	1000.0000	10.612
65	1200.0000	8.216
66	1400.0000	6.361
67	1600.0000	4.918
68	1800.0000	3.772
69	2000.0000	2.880
70	2200.0000	2.182
71	2400.0000	1.641
72	2600.0000	1.222
73	2800.0000	.902
74	3000.0000	.660
75	3500.0000	.301
76	4000.0000	.223

d - 10 years

June 11, 1979

MEMORANDUM

TO: Duncan Foley and Howard Ross

FROM: Kip Smith

RE: Field Trip to Midway, Utah, Friday, June 8, 1979

Jim Kohler, a native of Midway and a MS student in geology at Utah State and a six year employee of the USGS, conducted a field trip of his thesis area - the Midway hot pot area - for David Chapman, UUGG, and several of his students, including me. Jim gave a lucid account of the regional and local geology and explained what is known about the local hydrology and heat flow. He also proposed a likely model for a heat source and plumbing system for the Midway hot spring system. His thesis will be completed in the future.

He directed a drilling program of four 85m wells from which he gathered both water-pressure and temperature data. The legal suit brought against UGMS as a result of his success has been dropped. (?)

The four hot springs and hot pot areas are alined along two structures, two thermal areas to each SW-NE structure. The more northerly is a thrust fault that covers potentially cavernous Mesozoic and Paleozoic limestones with the generally impermeable Weber Quartzite. The more southerly is a small anticline that apparently caused intense extensional fracturing of the Weber Quartzite. Wells near the thrust and along the crest of the anticline produce as much as 700 gal/min of water as hot as 44^{o}C from the shattered Quartzite. Elsewhere the quartzite acts as a confining bed for thermal fluids in the underlying limestones.

The alluvium in the Midway Valley is a poorly sorted glacial outwash that is impressively permeable and is saturated with cold water. Hot water occurs in the alluvium only where the underlying quartzite allows hot water in the limestone to escape. The temperature and pressure of the rising hot water decreases resulting in precipitation of $CaCO_3$ and the formation of Tufa. Partial to complete self-sealing of the hot-water conduits and the alluvium has been noted.

The thrust fault that runs NW through Midway turns north and heads straight for the Mayflower Mine. This mine, five miles north of Midway, is the only lead and zinc mine in the area to encounter 150^{o}F water in the mine works. The ore and water were found in the Tertiary Mayflower stock and in the intruded highly altered Paleozoic limestones. Jim believes that hot water like that encountered in the mine may flow south along the plane of the thrust fault and in the limestones, becoming saturated with respect to $CaCO_3$ and emerging at Midway.

This is a novel idea that sounds real good. Jim has done a good job with the available data.

Kip Smith

UNIVERSITY OF UTAH RESEARCH INSTITUTE

UURI

EARTH SCIENCE LABORATORY
420 CHIPETA WAY, SUITE 120
SALT LAKE CITY, UTAH 84108
TELEPHONE 801-581-5283

August 6, 1979

Roger Harrison
Terra Tek
420 Wakara Way
Salt Lake City, UT 84108

Dear Roger:

On July 17, 1979 you requested a brief analysis of pump-test data from an artesian geothermal well at Monroe, Utah. Curve-fitting techniques were used to quanitify the hydrologic properties of the alluvial aquifer and to estimate the distance to an infinite-recharge boundary, the Sevier fault. More elaborate testing and modeling will be required to evaluate the hydrologic properties of the fault.

This analysis of the 70-hour pump-test indicates that the 1471 foot deep well can be outfitted to produce as much as 600 gpm (gallons per minute), enough to satisfy the projected near-term requirements for the City of Monroe. Additional development of the well and a larger pump will be required to meet this peak demand. It is doubtful that the alluvium at the Monroe "Mound" can support greater discharges. Any future production wells should be sited near Red Hill.

Sincerely,

Kip Smith
Associate Geophysicist

KS:ls

Encl.

MONROE KGRA PUMP TEST ANALYSIS

by

Christian Smith

The flowing geothermal well at Monroe, Utah was pumped at a reported average rate of 330 gpm for 70 hours. This report summarizes the data, their utility, and the results of this successful pump-test. The results favor the limited development of the hydrothermal system and can be better appreciated in the light of the geologic and geophysical background material provided by Mase et al (1978).

Figure 1 is a sketch of the pumped well and the geologic units it penetrates. The 9 5/8 inch hole enters a 400 foot thick limestone, playa or limestone conglomerate below the valley fill. This unit is consolidated and may impede the vertical migration of thermal fluids. The well penetrates the Sevier fault system that acts as the conduit for upwelling thermal fluids at a depth near 1100 feet. The hole bottomed at 1471 feet, is open below 1313 feet and was completed with 7 5/8 inch slotted casing in the interval between 945 and 1313 feet. The well is cased off from all formations above 945 feet.

This construction seriously constrains the performance of the well and the response of the two observation wells that are completed in the alluvium. The lime-rich unit separates the producing interval of the pumped well (945-1471 feet) from the alluvium tapped by the monitor wells. Estimates of transmissivity from the production well and the deeper monitor well (MC-2) can be expected to be lower than those from the shallower monitor well (MC-1). The alluvium above the lime-rich unit may communicate only partially with the deeper producing interval especially at early times in the pump test.

A more serious complication is the presence of the Sevier fault system. The hot springs at Monroe and Red Hill occur at apparent changes in the trend of the surface trace of the Sevier fault. Several heat-flow holes located near the fault trace are isothermal (Mase et al 1978). An interpretation of precision gravity data indicates a calculated throw of 1760 meters (5800 feet) along three parallel step faults within the fault system. This throw may be sufficient to juxtapose a permeable massive granular aquifer (Jurassic Navajo Sandstone) against tight welded tuffs (Tertiary Bullion Canyon Volcanics). Mase et al (1978) suggest that the Navajo Sandstone yields thermal fluids to the fault system at depth and that surface discharge is controlled by flexures in the fault system. Wells that tap the fault system or adjacent permeable material respond to the endless quantity of recharge it supplies. They respond much like wells drilled in the shore of a large deep lake: they very quickly begin to draw water from the lake and give little information about the material in which they are completed.

The monitor wells do not penetrate the fault system but are in hydraulic communication with it. When the pumped well intercepts water flowing in the fault system it deprives the alluvial aquifer of this water. The response of the monitor wells is indicative of the hydraulic properties of the alluvium, not of the fault. No quantitative assessment of the hydraulic properties of the fault system can be made from the data from this pump test. An additional pump test will be required and is recommended in the concluding remarks.

The results of the pump test analyses are given in Table 1. They are internally consistant and are supported with sufficient data. A brief discussion of each analysis follows some general comments on the reliability of the various types of analyses used.

TABLE 1

SUMMARY OF PUMP TEST RESULTS

WELL	ANALYSIS TYPE	TRANSMISSIVITY FT^2/day	STORAGE %	COMMENTS
Production	Semilog Drawdown	170	--	Unreliable, Fig. 3
	Semilog recovery	400	--	Unreliable, Fig. 4
MC-1	Stallman drawdown	560	.002	360 ft. deep, Fig. 5
	Stallman recovery	470	.004	400 ft. to fault, Fig. 7
MC-2	Theis drawdown	460	.003	620 ft. deep, Fig. 6
	Stallman recovery	280	.001	600 ft. to fault, Fig. 8
Production	Semilog drawdown	350	--	after stimulation, Fig. 10

Table 1 shows a range of estimated transmissivities from 170 to 560 $feet^2$/day. The low value (170 $feet^2$/day) is unreliable. It is the product of a straight-line, semilogarithmic approximation to the Theis (1935) solution to the equation of transient ground-water flow. The Theis solution assumes that a homogeneous isotropic aquifer with a constant storage coefficient has been fully penetrated by all wells used in the test. When any of these assumptions is invalid, the semilog approximation produces erroneous results. It is, however, the only method that can be used to assess data from a pumping well. The range between the remaining six estimates of transmissivity is small and probably represents the true heterogeneity of the aquifer.

The semilog approximation cannot be used to estimate the storage coefficient. The estimates from the two monitor wells are typical of artesian systems in poorly consolidated materials. Table 1 suggests that the aquifer is more confined at 620 feet than it is at 360 feet.

The values given in Table 1 are representative for the aquifer material that separates the pumped well and the monitor wells. Lithologic logs given by Mase et al (1978) suggest that the aquifer is composed of gravel with minor clay: coarse valley-fill alluvium. The low values of transmissivity suggest a higher percentage of fine material than they indicate. It is realistic to suppose that much of the silt or clay fraction was not observed in drill cuttings. The aquifer responds like a fine-grained, fairly tight, poorly consolidated sediment. The restricted area of low resistivity near the wells (Mase et al 1978) supports the contention that the aquifer is "tight".

Figure 2 is a log-log plot of drawdown in the pumping well as a function of time. Wells that pump compressible fluids display a unit slope at early times. Since no unit slope is seen, Figure 2 indicates that the thermal fluids contain only a small fraction of dissolved gasses. It also reveals that data taken at small times can be used validly to assess transmissivity and storage (Earlougher, 1977).

Figure 3 is a plot of drawdown in the pumping well as a function of the logarithm of time (the semilog plot discussed above). The straight line approximation to the Theis solution yields a low estimate of transmissivity (170 feet^2/day). This low value suggests that the well may have been inefficient. (Its efficiency was improved by surging after the test was completed.) The most interesting features of the plot are the halving of the slope and the horizontal line that appears after about half an hour. These features indicate that the well is producing water from a lateral inhomogeneity, an "infinite" recharge boundary--the Sevier fault system conduit. Unfortunately, the uniform drawdown after half an hour precludes any analysis of the transmissivity of the fault system

After 70 hours of pumping, the well was shut in and the recovery of the water level monitored. Figure 4 is the plot of the recovery as a function of the logarithm of the ratio between the time since the pump started (t) to the time since the pump stopped (t'). This ratio of times is always used when plotting recovery data because the recovery is a function of both pumping time and recovery time. When the pump has just been shut off (t>>t'), the ratio is large and plots near the right-hand side of the graph. As recovery progresses, the data points "move" from right to left.

Three straight lines appear on Figure 4. The steepest line appears at the earliest time and represents the interval when intersticial storage is being replenished. The slope of the second line produces an estimate of transmissivity of 700 $feet^2$/day; that of the third line 400 $feet^2$/day, nearly half. This halving again suggests the influence of a recharge boundary. Only the third line can be expected to yield a reliable (?) estimate of transmissivity

Since the fault system affected the drawdown and recovery of the pumped well, an attempt was made to assess its impact on the monitor wells. Figure 5 is a Stallman (1963) analysis of the drawdown in monitor well MC-1. No recharge boundary was noted. The curve follows the Theis solution and yields reliable estimates for both transmissivity and the coefficient of storage. Figure 6 is a conventional Theis curve analysis of the drawdown in monitor well MC-2. It too shows no effect of the recharge boundary and yields reliable estimates.

Figure 1 may help explain why the effect of the fault system is not apparent in the drawdown data from the monitor wells. When the pumped well intercepts the water flowing up the fault system, the water in the alluvial aquifer responds by reversing its usual direction of flow. The fault system acts as a drain. The rate at which the aquifer drains is dependant only on the hydraulic properties of the alluvium, not on those of the fault system.

On the other hand, when the pump is shut off, water begins to rise along the fault system and to infiltrate the alluvial aquifer. The recovery of the monitor wells is dependant not only on the hydraulic properties of the alluvium but also on their distance to the source of recharge. The nearer a well is to the recharge boundary, the sooner the recharge will effect its recovery. Figures 7 and 8 are Stallman plots of the recoveries in monitor wells MC-1 and MC-2 respectively. MC-1 responds to the recharge much more quickly then MC-2. Well MC-1 is estimated by the Stallman method to be about 400 feet and well MC-2 to be about 600 feet from the fault system. Both analyses give reasonable estimates for transmissivity and storage.

Figure 9 is a sketch map, provided by Terra Tek, of the well locaions. The circles are the radii to the Sevier fault system recharge boundary computed by the Stallman method. If the distances are correct, the intersections of the circles ought to reveal the most probable areas where the fault system is acting as a conduit. In this case the circles intersect northeast of the wells, in the direction of Red Hill. The thermal fluids at Monroe may be flowing from near Red Hill. Future exploratory drilling should be sited closer to Red Hill. A spontaneous potential (SP) survey may delineate the conduit area if cultural noise is sufficiently low.

After the wells had recovered to near their pre-pumping levels, development of the pumped well was undertaken by surging. A short-term (2 hr) drawdown test was then performed to evaluate the success of the development. Figure 10 is a semilog plot of this drawdown. It displays two distinct straight lines, the slope of the second is half that of the first. The fault system was again encountered. However, the pumping was not continued long enough for the drawdown to become constant, as it did during the 70-hour pump-test. Had the test continued for a day, the drawdown would have stablized. The estimate of transmissivity (350 feet^2/day) agrees well with all the estimates given above and indicates that the surging operation was successful.

The success of the surging operation encourages the following proposal for continued hydrologic field work. The well can probably be improved even more with conventional, commercial techniques (acidizing, etc.). Following the additional development a 12- or 24-hr multiple-rate pump test should be conducted. The first flow rate should be less than 400 gpm and should be held constant until the drawdown level has stablized for at least half a log cycle. The flow rate should then be instantaneously increased to above 400 gpm and the water level again allowed to stablize. If time and pumping power allow, this process of step increases in discharge should be repeated. The final flow rate should be about 250 gpm--barely more than the natural artesian flow. The resulting drawdowns in the pumped well and the monitor wells can be analyzed to assess the hydraulic properties of the fault system.

The values given in Table 1 suggest that 450 feet^2/day and 0.003 are reasonable averages for the estimates of transmissivity and storage. To determine whether these averages reproduce the observed drawdowns at the end of the pumping period, the Theis solution was calculated for 70 values of distance from the pumped well, Table 2. The agreement is very good at 340 feet from the pumped well, the distance to monitor well MC-1 but not so good at 165 feet, the distance to well MC-2. This may be due to the lower average transmissivity shown for well MC-2 in Table 1. Granting the documented stratagraphic and structural inhomogeneity of the area, the disagreement is not a cause for alarm.

Tables 3 and 4 show the predicted drawdowns at distances as great as a mile for the Monroe well pumping 600 gpm for periods of 2 and 8 days. These predictions reveal that the well can be pumped "safely" for longer than a week at 600 gpm. The estimated drawdowns do not take into account the "infinite" recharge boundary effect of the Sevier fault system and therefore represent greater-than-expected declines in water level.

CONCLUSIONS

1) The Monroe well can safely yield 600 gpm for periods as long as a week.

2) The thermal fluids rise along the fault system and communicate with the alluvial aquifer in an area northeast of the wells, in the direction of Red Hill.

3) Future exploratory drilling should be sited near Red Hill.

4) The Monroe well should be further developed and a step drawdown test (with recovery) be conducted to assess the degree of hydraulic communication between the alluvium and the Sevier fault system.

REFERENCES CITED

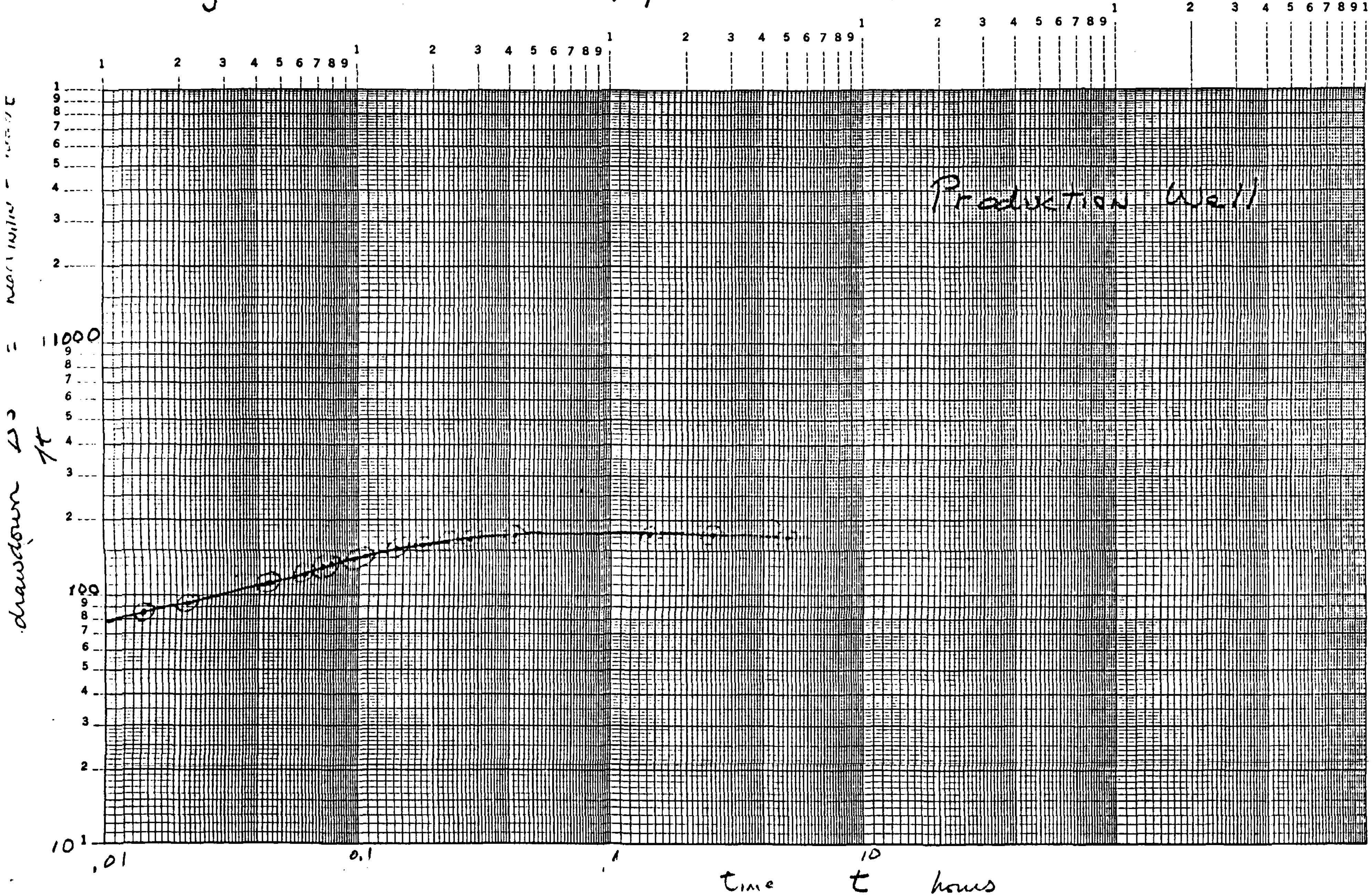
Earlougher, R. C., Jr., 1977, Advances in well test analysis: Monograph 5, Soc. Pet. Eng. AIME, 264 p.

Mase, C. W., Chapman, D. S., and Ward, S. H., 1978, Geophysical study of the Monroe--Red Hill geothermal system: Univ. Utah Dept. Geol. and Geophysics, Topical Report., DOE grant EY-76-S-07-1601, 89 p.

Theis, C. V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., v. 16, p. 519-524.

Stallman, R. W., 1963, Type curves for the solution of single boundary problems, in Bentall, Ray, compiler, Shortcuts and special problems in aquifer tests: U. S. Geol. Survey Water-Supply Paper 1545-C, p. C45-47.

Fig. 2 Drawdown vs Time, production well, log-log



Test for wellbore storage

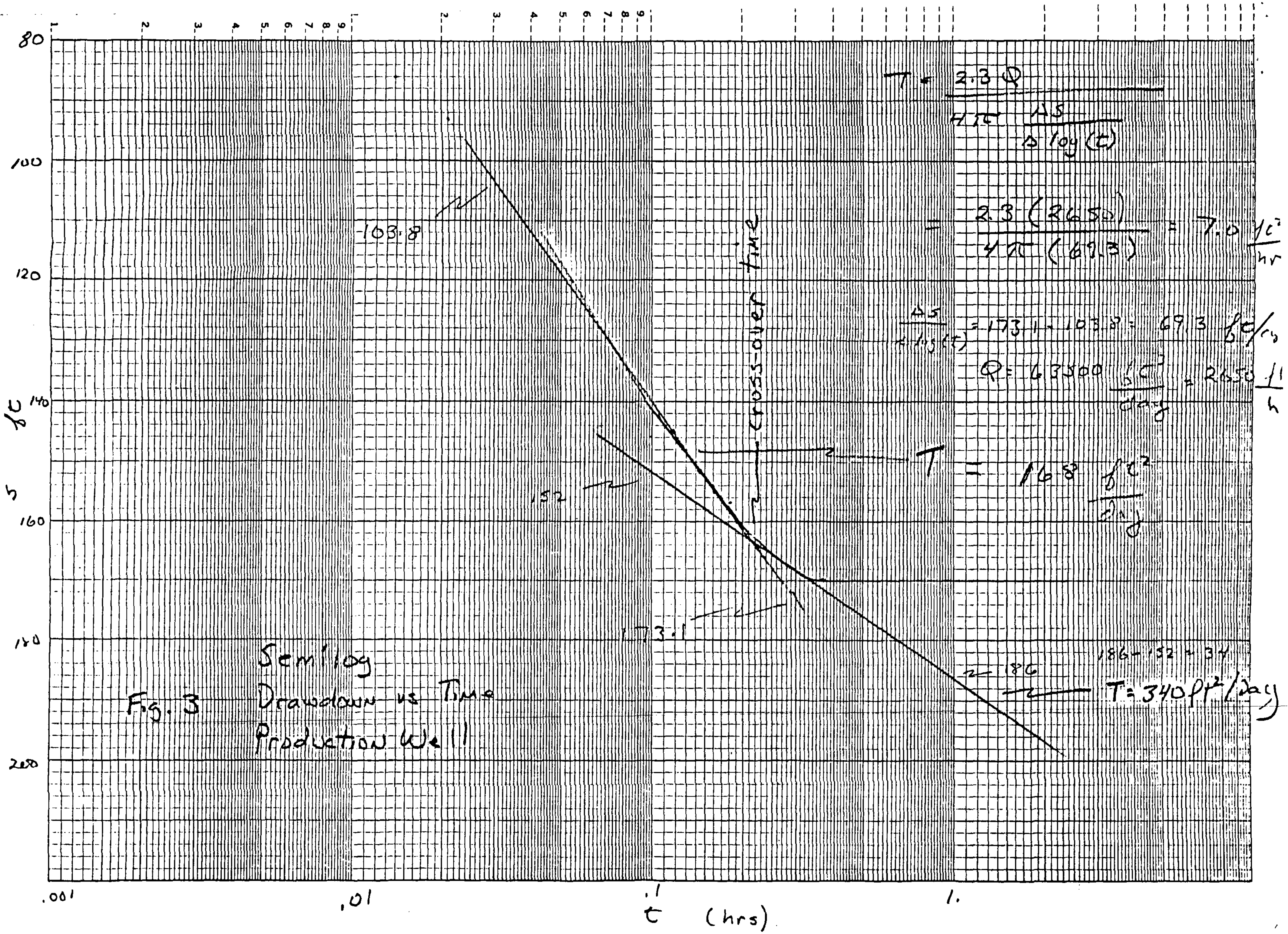


Fig. 3 Semilog Drawdown vs Time Production Well

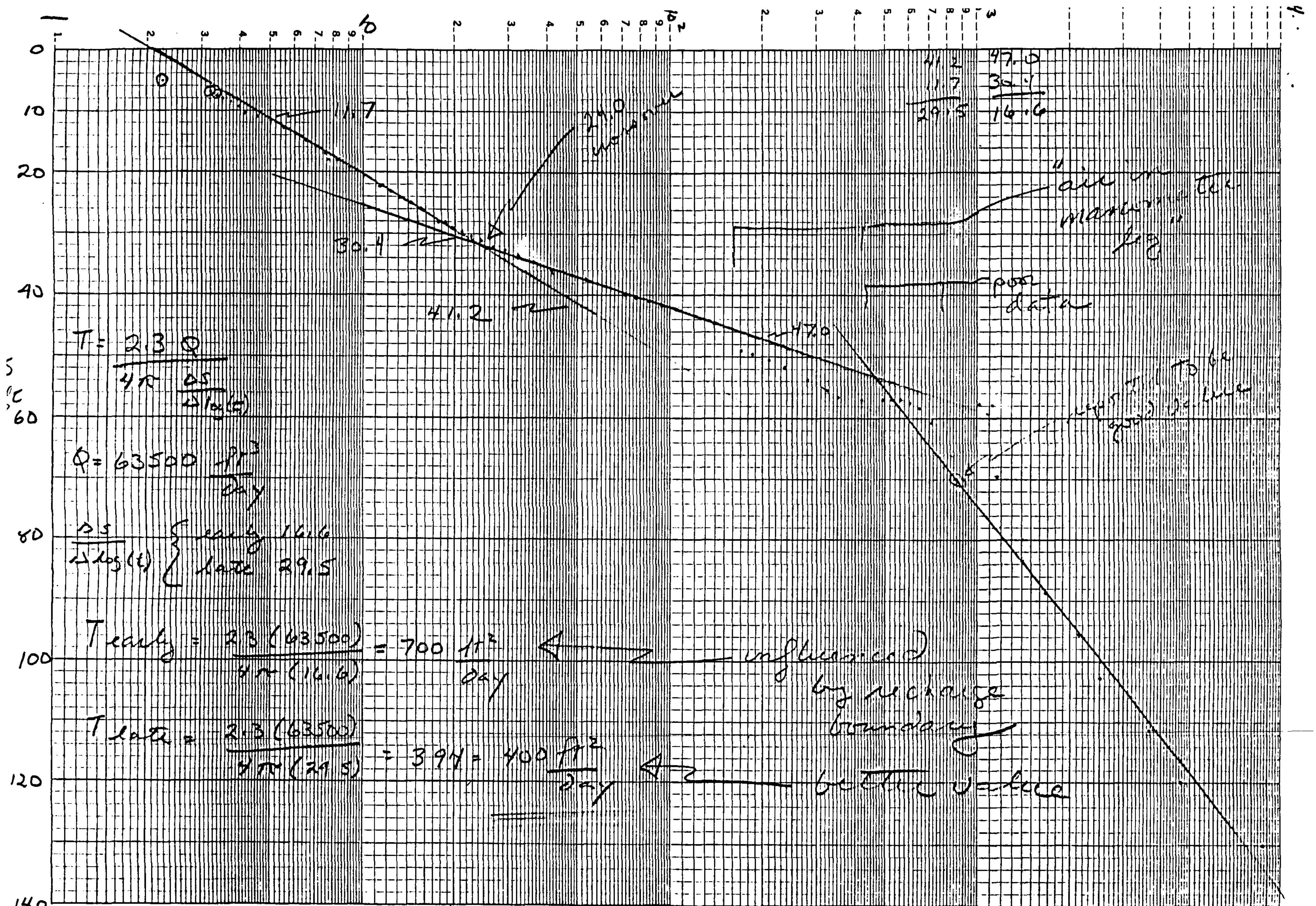


Fig 4- Semilog recovery, production well

$t_1 = \frac{t + t'}{t'}$ day t = time since pump on

day t' = time since pump off

Fig 5 Stallman log-log drawdown, Well MC-1 – no sign of recharge boundary

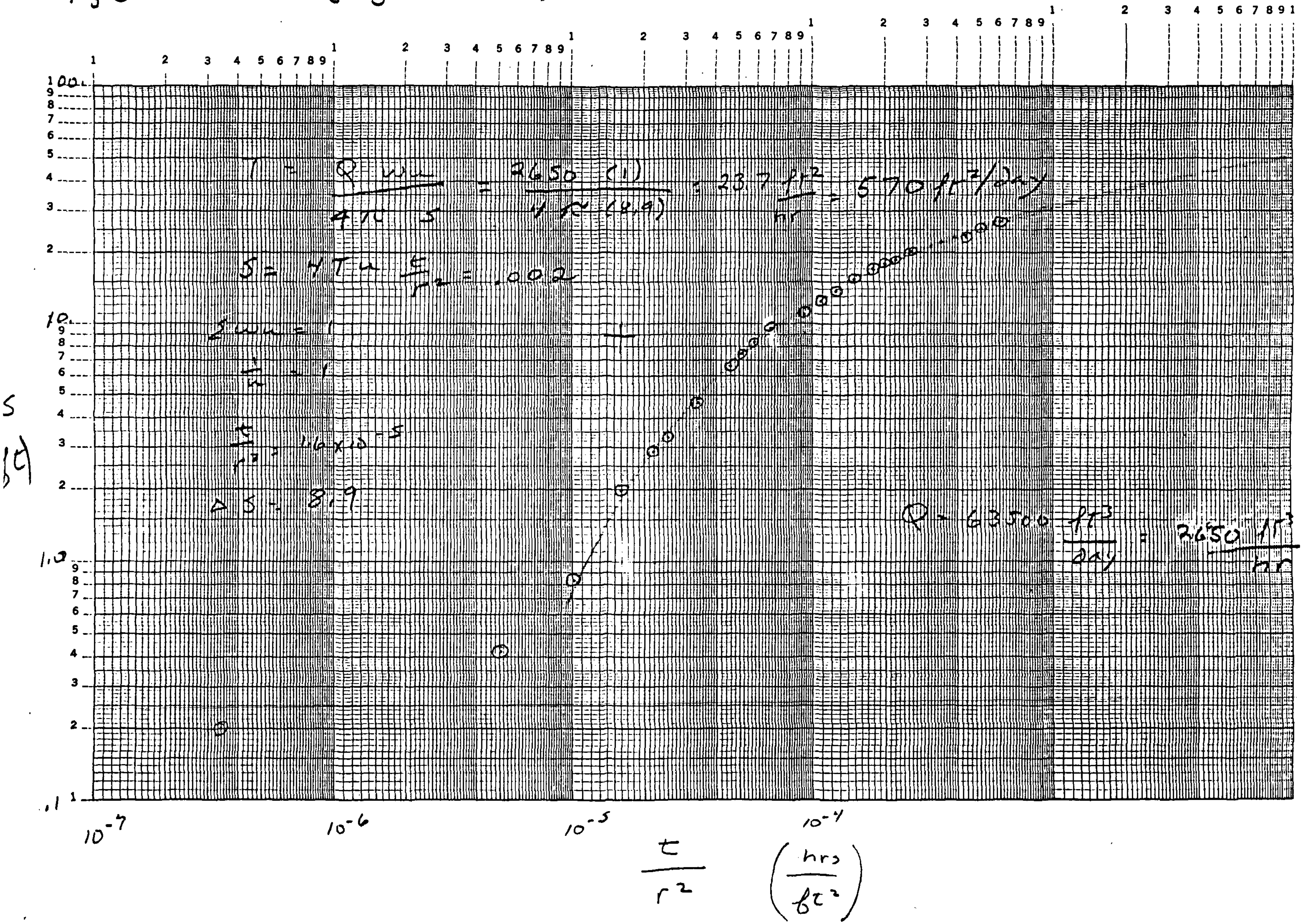


Fig. 6 Theis log-log drawdown, Well MC-2

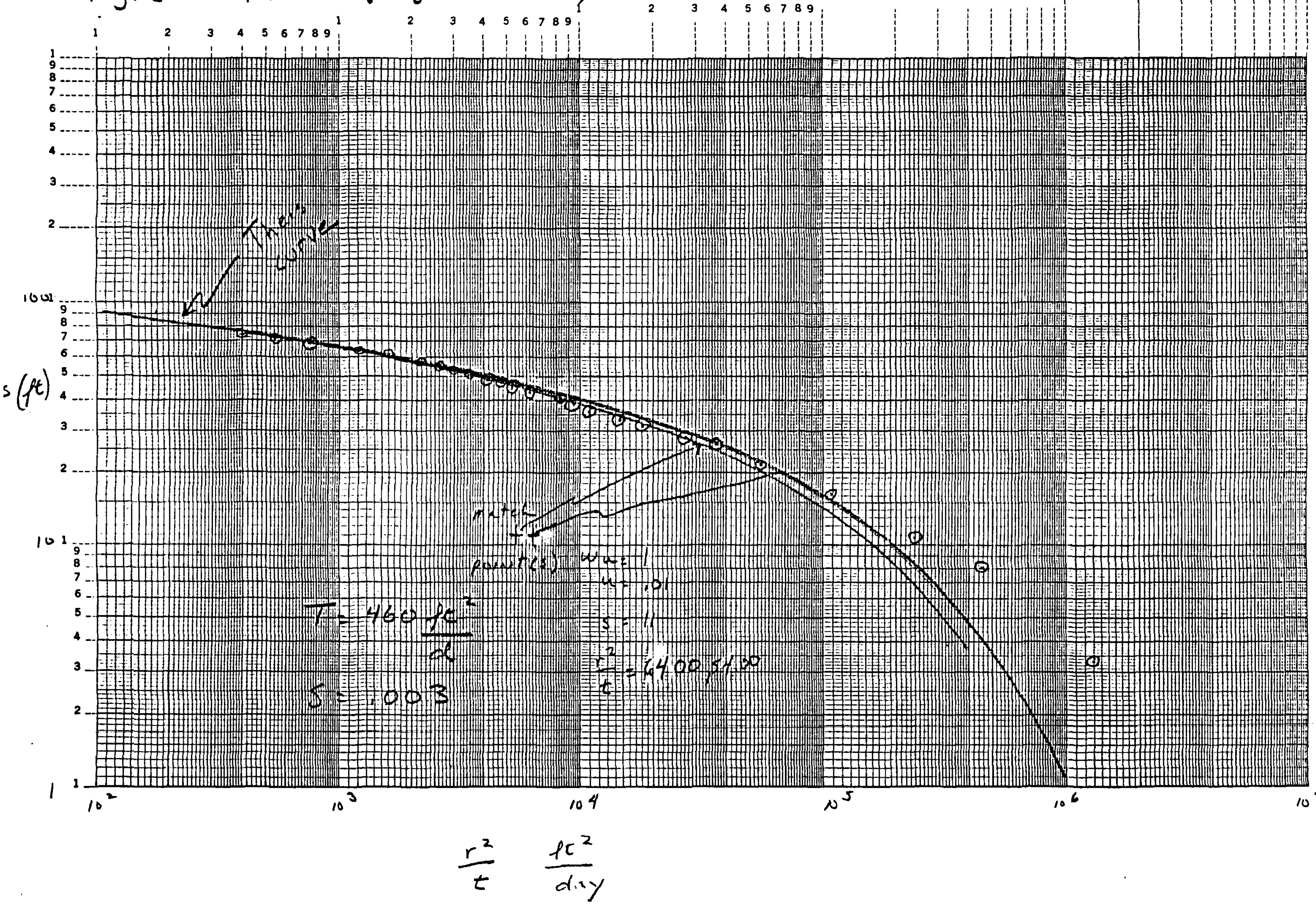
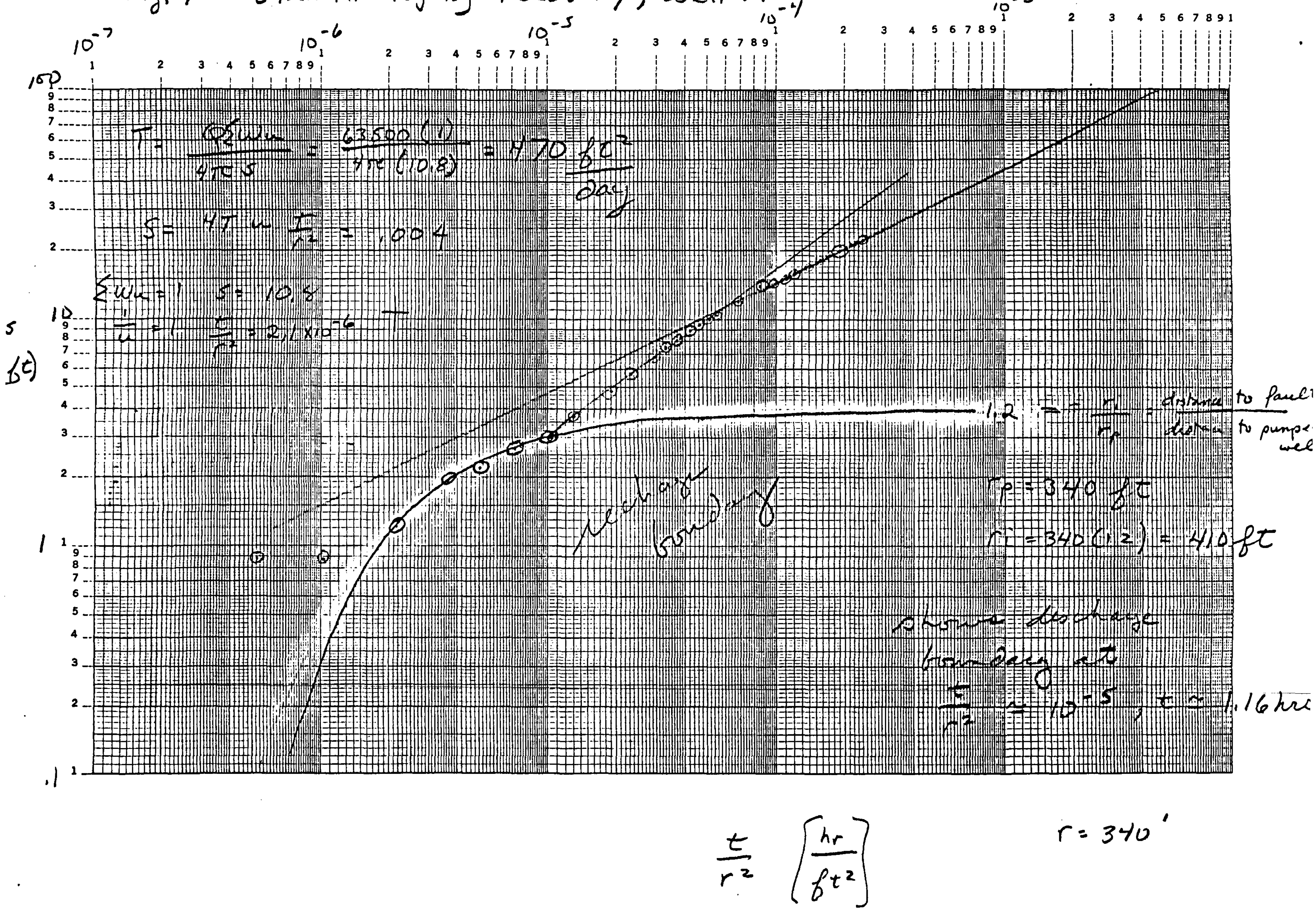
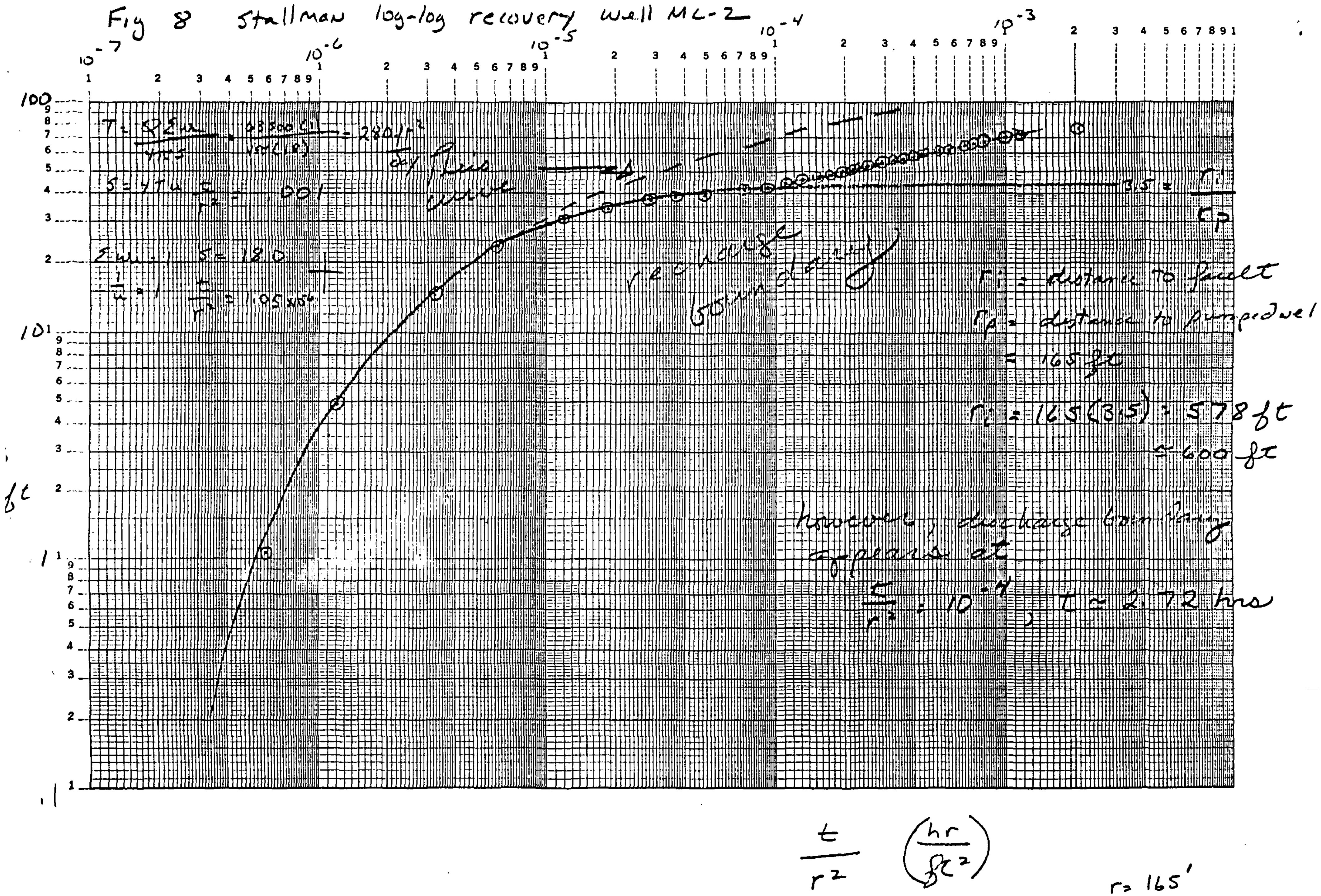


Fig. 7 Stallman log-log recovery, well MC-1



⊙ MC 2

Fig 8 Stallman log-log recovery well MC-2



r = 165'

Well Depth

MC1	360'
MC2	620'
MC3	1471'
M4	247'
RH4	205'

MAP OF SPRINGS AND WELLS AT MONROE MOUND

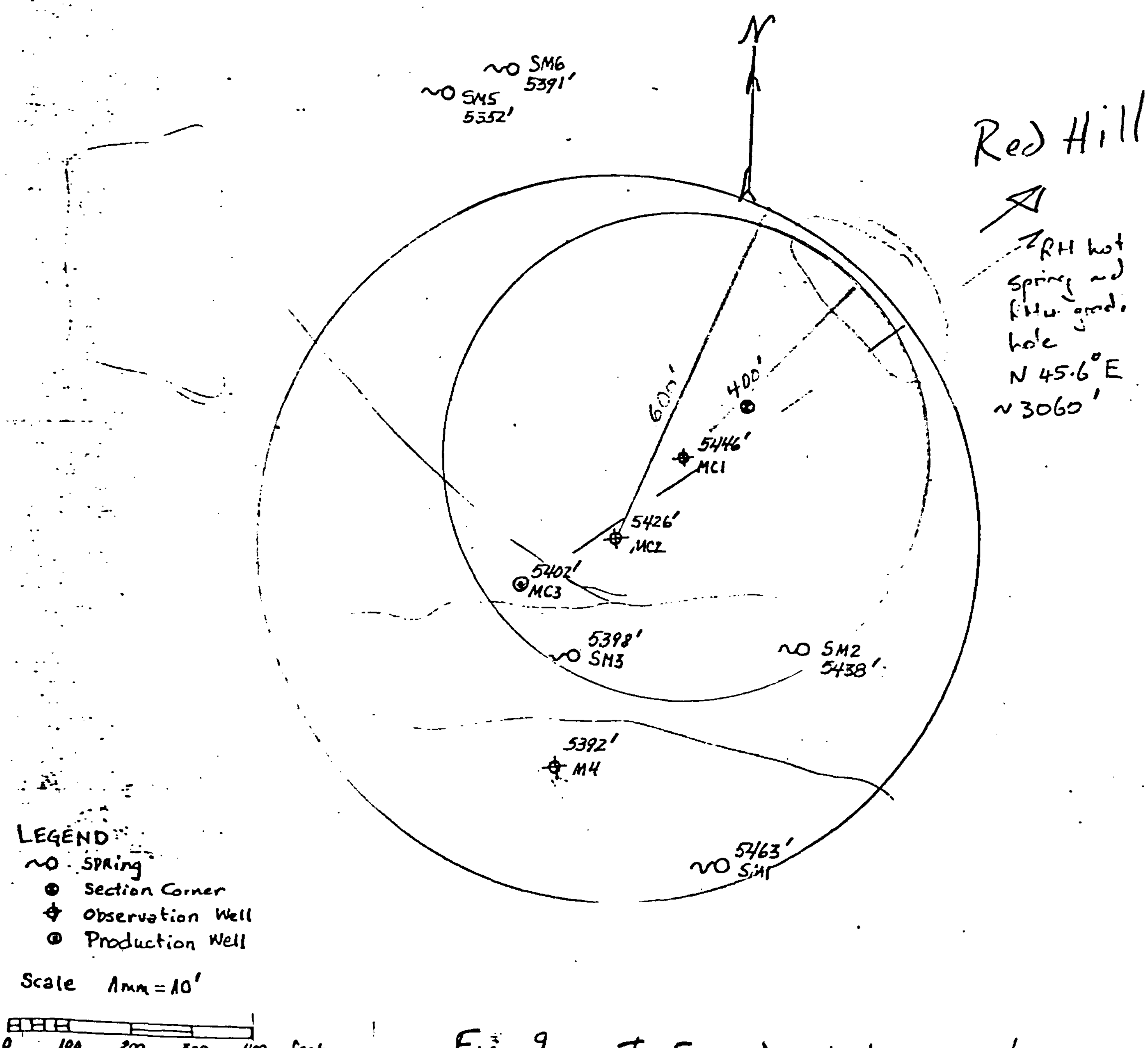
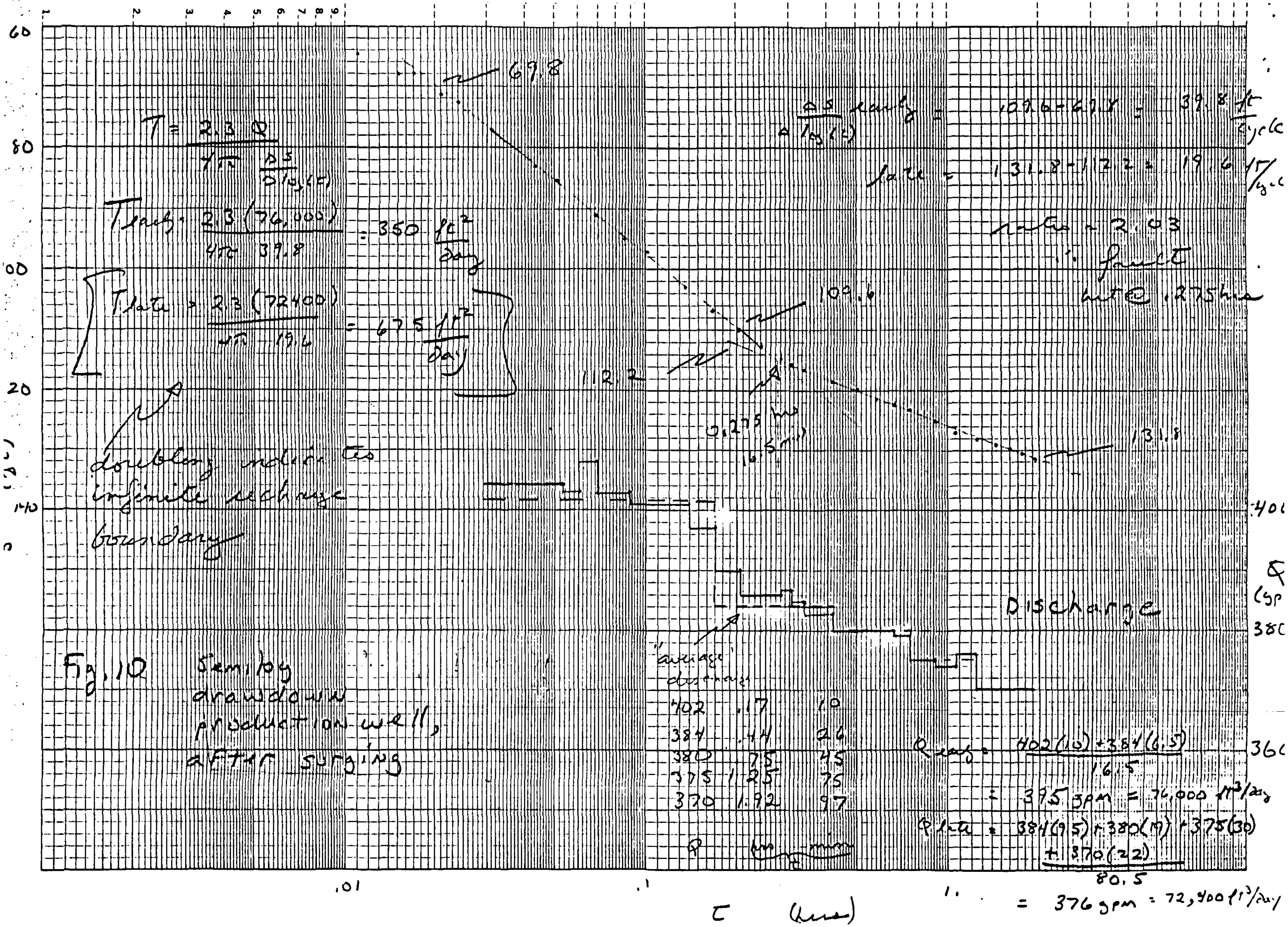


Fig 9 Inferred distances to recharge boundary



69.8
T = 2.3 Q / 4π (Δs/Δlog(t))
Δs/Δlog(t) early = 109.6 − 69.8 = 39.8 ft/cycle
late = 131.8 − 112.2 = 19.6 ft/cycle
T early = 2.3 (76,000) / 4π 39.8 = 350 ft²/day
ratio = 2.03
∴ fault
at @ .275 hrs
T late = 2.3 (72400) / 4π 19.6 = 675 ft²/day
109.6
112.2
0.275 hrs
16.5 min
131.8
doubling indicates infinite recharge boundary
Discharge
Q (gpm)
400
380
360
Fig. 10 Semilog drawdown production well, after surging
"average discharge"
402 .17 10
384 .44 26
380 .75 45
375 1.25 75
370 1.92 97
Q early = 402(10) + 384(6.5) / 16.5 = 395 gpm = 76,000 ft³/day
Q late = 384(9.5) + 380(19) + 375(30) + 370(22) / 80.5 = 376 gpm = 72,400 ft³/day
.01
.1
1.
t (hrs)

DRAWDOWN # 1

T= 450.0000 S= .0030 Q= 600.0000TIME= 2.0000

#	DISTANCE	DRAWDOWN
1	1.0000	274.113
2	1.2000	266.666
3	1.4000	260.369
4	1.6000	254.914
5	1.8000	250.103
6	2.0000	245.799
7	2.2000	241.905
8	2.4000	238.351
9	2.6000	235.081
10	2.8000	232.054
11	3.0000	229.236
12	3.5000	222.939
13	4.0000	217.464
14	4.5000	212.673
15	5.0000	208.369
16	5.5000	204.476
17	6.0000	200.921
18	6.5000	197.652
19	7.0000	194.625
20	8.0000	189.170
21	9.0000	184.359
22	10.0000	180.055
23	12.0000	172.608
24	14.0000	166.312
25	16.0000	160.859
26	18.0000	156.048
27	20.0000	151.745
28	22.0000	147.854
29	24.0000	144.301
30	26.0000	141.033
31	28.0000	138.006
32	30.0000	135.191
33	35.0000	128.900
34	40.0000	123.451
35	45.0000	118.647
36	50.0000	114.351
37	55.0000	110.467
38	60.0000	106.922
39	65.0000	103.663
40	70.0000	100.647
41	80.0000	95.218
42	90.0000	90.436
43	100.0000	86.164
44	120.0000	78.791
45	140.0000	72.532
46	160.0000	67.228
47	180.0000	62.531
48	200.0000	58.354
49	220.0000	54.601
50	240.0000	51.200
51	260.0000	48.096
52	280.0000	45.247
53	300.0000	42.620
54	350.0000	36.852
55	400.0000	32.000
56	450.0000	27.660
57	500.0000	24.293
58	550.0000	21.197
59	600.0000	18.498
60	650.0000	16.136
61	700.0000	14.065
62	800.0000	10.647
63	900.0000	8.008
64	1000.0000	5.975
65	1200.0000	3.236
66	1400.0000	1.682
67	1600.0000	.854
68	1800.0000	.532

Table 3

Predicted drawdown

600 gpm

2 days

DRAWDOWN # 2 (gpm) (days)

T= 450.0000 S= .0038 Q= 600.0000 TIME= 8.0000

N	DISTANCE	DRAWDOWN	N	DISTANCE	DRAWDOWN
1	1.0000	302.428	55	400.0000	58.354
2	1.2000	294.980	56	450.0000	53.721
3	1.4000	288.633	57	500.0000	49.614
4	1.6000	283.229	58	550.0000	45.938
5	1.8000	278.417	59	600.0000	42.620
6	2.0000	274.113	60	650.0000	39.605
7	2.2000	270.220	61	700.0000	36.852
8	2.4000	266.666	62	800.0000	32.000
9	2.6000	263.395	63	900.0000	27.8[illegible]
10	2.8000	260.369	64	1000.0000	24.293
11	3.0000	257.559	65	1200.0000	18.498
12	3.5000	251.253	66	1400.0000	14.065
13	4.0000	245.799	67	1600.0000	10.647
14	4.5000	240.987	68	1800.0000	8.008
15	5.0000	236.633	69	2000.0000	5.975
16	5.5000	232.799	70	2200.0000	4.419
17	6.0000	229.256	71	2400.0000	3.236
18	6.5000	225.965	72	2600.0000	2.345
19	7.0000	222.939	73	2800.0000	1.682
20	8.0000	217.484	74	3000.0000	1.197
21	9.0000	212.673	75	3500.0000	.556
22	10.0000	208.369		(Ft)	(Ft)
23	12.0000	200.921			
24	14.0000	194.625			
25	16.0000	189.170			
26	18.0000	184.359			
27	20.0000	180.055			
28	22.0000	176.162			
29	24.0000	172.638			
30	26.0000	169.339			
31	28.0000	166.312			
32	30.0000	163.494			
33	35.0000	157.199			
34	40.0000	151.746			
35	45.0000	146.936			
36	50.0000	142.634			
37	55.0000	138.743			
38	60.0000	135.191			
39	65.0000	131.924			
40	70.0000	128.900			
41	80.0000	123.451			
42	90.0000	118.647			
43	100.0000	114.351			
44	120.0000	106.922			
45	140.0000	100.647			
MC 2 → 46	160.0000	95.218			
47	180.0000	90.436			
48	200.0000	86.104			
49	220.0000	82.306			
50	240.0000	78.791			
51	260.0000	75.553			
52	280.0000	72.582			
MC 1 → 53	300.0000	69.812			
54	350.0000	63.652			

Table 4

Predicted drawdown

600 gpm

8 days

D. Foley

10-79

MEAD LEROY JENSEN

CONSULTING GEOLOGIST AND GEOPHYSICIST

2327 BERKELEY STREET
SALT LAKE CITY, UTAH 84109
(801) 466-4384

SURFACE EVIDENCE OF GEOTHERMAL SITES BY MERCURY SOIL-GAS COLLECTING

by

MEAD L. JENSEN, Ph.D.
PROFESSOR OF GEOLOGY AND GEOPHYSICS
DEPARTMENT OF GEOLOGY AND GEOPHYSICS
UNIVERSITY OF UTAH
SALT LAKE CITY, UTAH 84112

and

HAYAT QIDWAI, Ph.D.
DEPARTMENT OF GEOLOGY AND GEOPHYSICS
UNIVERSITY OF UTAH

TO

UTAH GEOLOGICAL AND MINERAL SURVEY
606 BLACK HAWK WAY
RESEARCH PARK - UNIVERSITY OF UTAH
SALT LAKE CITY, UTAH 84112

TABLE OF CONTENTS

Abstract 1

Introduction 3

General Background 4

Geology 4

Mercury in Geothermal Areas 6

Thermodynamics of Mercury 7

Collecting Techniques 9

Results 11

1. New Mexico Geothermal Area 11

2. Roosevelt Hot Spring Geothermal Area, Utah 14

3. Midway Hot Spring Area, Wasatch County, Utah 17

4. Crystal Springs Area, Salt Lake County, Utah 21

Summary 22

Recommendations 23

References 24

ABSTRACT

The association of mercury with hot springs and epithermal mineral deposits has been noted since man became interested in the remarkable substance of liquid metal or, as he called it, "quicksilver".

Atomic absorption instrumentation allows the measurement of less than 0.01 ppb of mercury. Considering the association of mercury with hot spring and geothermal sites, the ability to trap or collect mercury in soil-gas as an amalgam, and the use of mercury as a trace element escaping from mineralized areas or geothermal sites obviously led to the useful application of measuring mercury contents in nature.

Soil, rock, and water samples were first analyzed with soil and rock samples containing between 10 to 50 ppb Hg. Water samples are comparatively low in mercury content, generally containing a few ppb or less. Background soil-gas samples of mercury generally range between 40 to 100 ppb.

Collecting mercury in soil-gas by suction devices and passing the air through silver or gold screens, whereby the mercury is collected as an amalgam, provides larger samples of mercury by a very precise measuring technique, and gives more sensitive results.

The measurement of mercury in soil-gas has been applied to the Crystal Springs areas in the southern portion of Salt Lake Valley and to the Midway hot spring area, Wasatch County, Utah.

Mercury soil-gas analyses of 16 samples collected at Crystal Springs vary between 82 ppm to a low of 10 ppb. The average is about 10 ppm with blank samples of silver containing 3.5 ppb Hg. At least 4 prominent anomalous sites were detected that contain about 80 ppm Hg.

One of these anomalies is corroborated by three juxtaposed collection sites (sta 12, 13, and 14) that cover a linear distance of about 1,000 feet.

Although the Midway area still had snow in the fields, samples were collected along the road side where snow had melted. Along the N-S trending road west of the Homestead, samples varied between 46 ppb to a high of 86 ppm. At first glance there is little correlation of anomalous values with the sites of hot springs along this road. Nevertheless, these studies do exhibit the higher Hg readings obtained by soil-gas samples in contrast to soil samples. The latter contain 11 to 0.1 ppb Hg. Almost all of the soil-gas samples are considered to be anomalous as background values would vary between 40 to 100 ppb. Additional soil-gas samples were collected and analyzed in 1978 near Memorial Hill and west and northwest of Memorial Hill in hot spring sediments. As Memorial Hill is not a geothermal mound, it is puzzling that anomalous values of Hg content were obtained there even though a low sample of 15 ppb did exist there. It is concluded that anomalous Hg values would probably be obtained throughout the Midway area.

A mercury soil-gas survey near the Utah State prison at Crystal Springs provided anomalous concnetrations varying from 10 ppb to 85 ppm with an average of about 46 ppm. This is certainly anomalous, which is to be expected in this area of potential geothermal development.

SURFACE EVIDENCE OF GEOTHERMAL SITES BY MERCURY SOIL-GAS COLLECTING

by

Mead L. Jensen and Hayat Qidwai
Department of Geology and Geophysics
University of Utah
Salt Lake City, Utah 84112

INTRODUCTION

The purpose of this study is a preliminary study to determine the validity, practical application, and innovative techniques of the surface collection and quantitative measurement of mercury vapor that escapes to the surface of the earth and the association of greater mercury flux from geothermal sites.

This study was supported by a grant from the U.S. Department of Energy administered by the Utah Geological and Mineral Survey (606 Black Hawk Way, University of Utah Research Park).

GENERAL BACKGROUND

Geothermal sites and the development of geothermal energy require the application of an array of scientific and technical disciplines in order to better understand the feasibility of developing economic geothermal energy. Possibly all of these topics for consideration could be grouped under two categories, namely (1) Geosciences and (2) Engineering. The first is a broad category that utilizes geology, geophysics, isotope geology, geochemistry and almost all geospecialties. These subjects provide information about the sites and sources of the heat; the bearing of structural and stratigraphic geology upon the form of the geothermal sites; and allow estimates of thermal water volume, pressures, and sources. Geoscience also pertains to the environmental factors of thermal water composition (salt toxification of vegetation) and re-injection of cooled water to the geothermal reservoir without potential dilatant effects that are known to trigger earthquakes. The engineering factors deal primarily with the development and application of science and technology for economic recovery and utilization of the geothermal energy. This study pertains to the collection, application, and measurement of mercury soil-gas as an aid in locating geothermal sites.

Geology. Although geothermal sites have been recognized during the history of Man, it has only been during recent years that development of such sites has resulted in energy production. Of course, the Tuscany, Italy; Wairaki, N.Z.; some Japanese sites and Iceland geothermal sites are the earlier pioneers of the utilization of geothermal energy. The Geysers area in California is a recent development by PP&L and Union Oil Co. that with about 900 million mega watt production in two years will exceed the energy output of all of the above mentioned geothermal sites and provide about one-half of the electrical need required by the City of San Francisco.

Prior to the present time, determining the subsurface geology of geothermal sites has been done predominately by drill hole exploration, sometimes while drilling for other purposes, such as the Niland, California discovery. Geophysical techniques have been thought to be somewhat of a panacea but it is of primary importance to initially undertake thorough geological mapping and determine the stratigraphic properties (units, lithology, porosity and permeability) and the structural configurations and positions of the formations, along with the recognition of faults, fractures, and jointing. Isotopic studies, especially δD and $\delta^{18}O$ measurements, are capable of providing important temperature estimates, thermal fluid sources, and other important pre-drilling and post-drilling information. Geophysical techniques are used as an additional "tool" to determine some of these structural and physical factors.

The economic potential of a geothermal site is determined by numerous factors. Some of these factors are the source of heat, the reservoir volume and water recharging rates. These factors are in the realm of geology, geophysics, and geochemistry. Excessive costly drilling may be more readily curtailed if a geological - geochemical appraisal of a potential geothermal site is done providing more specific information upon the economic potential of the geothermal site before even considering drill target sites.

MERCURY IN GEOTHERMAL AREAS

The association of mercury with epithermal deposits (Dickson, and Tunnel, 1968) and present or past hot spring and geothermal sites is well known. Sulfur Bank, California, for example was a mercury mine until the depth of open-pit mining reached temperatures unbearable to the miners, not to mention the health hazard through inhalation of mercury vapor. Monte Alimata, Italy, is well known for its mercury content. In this deposit, the storage reservoir rock apparently underwent post-volcanic collapse that fragmented the reservoir rock and provided the "plumbing system" for deposits that lie below a partially impermeable thrust sheet that confined and controlled the mercury vapor escape to the atmosphere.

The relationship between "mercury mineralization, and hot spring activity is observed at many geothermal fields throughout the world." (Kruger and Otte, 1973; Berce, 1965). In fact, when nuclear or conventional explosive techniques are used to enhance the output of geothermal wells, the danger of post-shot mercury escape to the surface and the resulting potential toxicity to human beings will have to be considered, a subject that has received very little study to date. (Austin, Austin, and Leonard, 1971; Siegel and Siegel, 1975; Weissberg, Zobell, 1973; Robertson et al., 1977).

Actually much of the mercury in developed geotheraml areas escapes to the atmosphere as elemental mercury vapor in cooling tower exhausts. The "facts are that mercury has been shown to be associated in elevated concentrations in a wide variety of natural thermal fluids" (Robertson, 1977).

Detailed studies have been made of the mercury released at Cerro Prieto and at the Geysers. Roughly 100 to 1000 times as much mercury existed in the steam condensates and cooling tower waters than the concentrations in most uncontaminated river, lake, or ocean waters. The predominant form of the mercury is Hg° (elemental mercury). These measurements apply to both Cerro Prieto and the Geysers areas.

THERMODYNAMICS OF MERCURY

Mercury is an element and the only element and metal that exists naturally as a liquid at the surface of the earth. It has an atomic number of 80 and atomic weight of 200.59. It has seven stable isotopes and is commonly referred to as a chalcophilic element, that is one that tends to concentrate in sulfides. It is commonly referred to, especially by the layman as "Quicksilver". The silvery liquid metal is approximately 13 1/2 times as heavy as water. Even so, as a liquid, it vaporizes and condenses, of course, according to the thermodynamic properties of the element.

In a comparison of the vapor pressures of water to mercury, at 100°C, water has a vapor pressure of 760 mm of Hg; mercury has the same vapor pressure at 357°C. At room temperature of 20°C, water has a vapor pressure of 17.54 mm of Hg, while the vapor pressure of mercury at this temperature is 0.0012 mm of Hg. A temerature of 200°C is required to provide mercury with the same vapor pressure of water at 20°C.

Mercury, however, is present in the atmosphere at concentrations of 1 to 20 nanograms per cubic meter or ppb (parts per billion). In metallic mineral deposits, the concentrations may exceed several hundred

Figure 1. Soil-gas mercury collecting instrument consisting of plastic hemisphere, fan powered by 4 D cells (6 v DC), and 40-mesh layers of silver screen in orifice.

ppb. At hot spring and geothermal sites, concentrations exceeding 100,000 ppb (100 ppm) are not uncommon.

Apparently most mineral deposits contain mercury as a trace element. But because of its comparatively high vapor pressure, it constantly "bleeds off" from such deposits and ultimately reaches the surface of the earth. (Vaughn, 1967; and Vaughn and McCarthy, 1965).

COLLECTING TECHNIQUES

One of the initial techniques used for collecting mercury in soil-gas was first ued by the U.S. Geological Survey (Vaughn, 1967). It consisted of a plastic pyramid, scotch-taped at the edges, with an orifice at the top of the pyramid consisting of a screen covered with fine gold. The "Green house" effect of sunlight shining through the plastic caused the expanding warmer interior air to escape through the screen where any soil-gas mercury was captured as an amalgam with the gold. Of course with this technique, corrections for the hourly fluctuation of barometric pressure had to be considered.

Shortly after this time, I improved upon the technique by using plastic hemispheres with an orifice with a battery powered fan that would draw the mercury soil-gas from below the surface forcing it through layers of silver screen of 40, 60, and 120 mesh. Of course, silver also forms an amalgam with mercury (Fig. 1).

The effectiveness of this technique over other methods of measuring Hg soil-gas amounts is that the fan negates the effect of atmospheric barometric pressure and the diurnal variations as the fan draws several inches of Hg suction and has a capacity of about 10 ft^3/min.

The fans used are Hico-Micro-kwl V 241L fans that operate on 6 V DC. Current requirements are so low that 4-1 1/2 V D cells will last for 6 weeks of continuous daily operation. Detailed tests have been made of the volume of air/minute of operation with measurements varying between 6 to 14 ft^3/min. Variations are the result of variable porosity of the ground. The collectors are now being fitted with micro Pitot tubes to allow the measurement of air flowage in the field.

Of equal importance is the proof of the precision of repetitive Hg collective amounts. Tests used to indicate such have been done in laboratory chemical hoods where the collecting apparatus is placed with a fixed amount of elemental Hg located within the hood. Various times of collection were tested with resultant Hg collection amalgam varying, for example, on a specific test by less than 4 percent when amounts of 140±10 ppb Hg was collected. The precision incidentally of a flameless atomic absorption instrument, used to measure the mercury that is released by heating the amalgam, is less than 0.010 ppb as verified by heating fixed amounts of Hg in the instrument repetitively during the assaying of the Hg-Ag screen samples.

Contaminants, such as organic compounds can be prevented from reaching the Hg screen by chemical filtering attachments. In addition, this instrument draws or "sucks" soil-gas through the mercury screen which provides a larger sample than an instrument that merely measures the mercury at a given position. Mercury samples collected in ambient air over a site do not contain anywhere near as much Hg as is obtained by fan drawn soil-gas samples.

The mercury present on the screens is assayed by flameless atomic absorption using a model 351 Instrumentation, Ltd. AA with a Control

Temperature Graphite Furnace, Model 558. Concentrations of approximately two parts per billion with a precision of ±2 ppb are obtained for samples containing >5 ppb. Greater precision is obtained on samples containing < 1 ppb. The results are plotted at sample locations in plan or profile form. In some cases, averaging techniques are employed to smooth the scatter that is sometimes evident in the method. This scatter is typical of most geochemical surveys and has given rise to many averaging techniques of both manual and computer types.

The third basic technique of measuring mercury at the surface is based on the measurable decrease in the electrical resistance of a specific amount of gold as it absorbs mercury to form amalgam. The value of this technique is that it allows the monitoring of mercury absorption amounts in the field at the time of collecting. The initial instrument merely measured mercury at the ground level or a few feet above without the technique of drawing soil-gas from the ground. There would be no difficulty in modifying this instrument with an enclosure housing a fan to draw soil-gas from the ground.

Finally, soil samples may be collected and assayed in the laboratory. Repetitive assaying of such samples indicates that much less Hg exists in soil samples than the amount collected in soil-gas.

RESULTS

1. Geothermal Area.

One of the earlier applications of collecting mercury from soil-gas is shown in Fig. 2, a known geothermal area in New Mexico. Proprietary

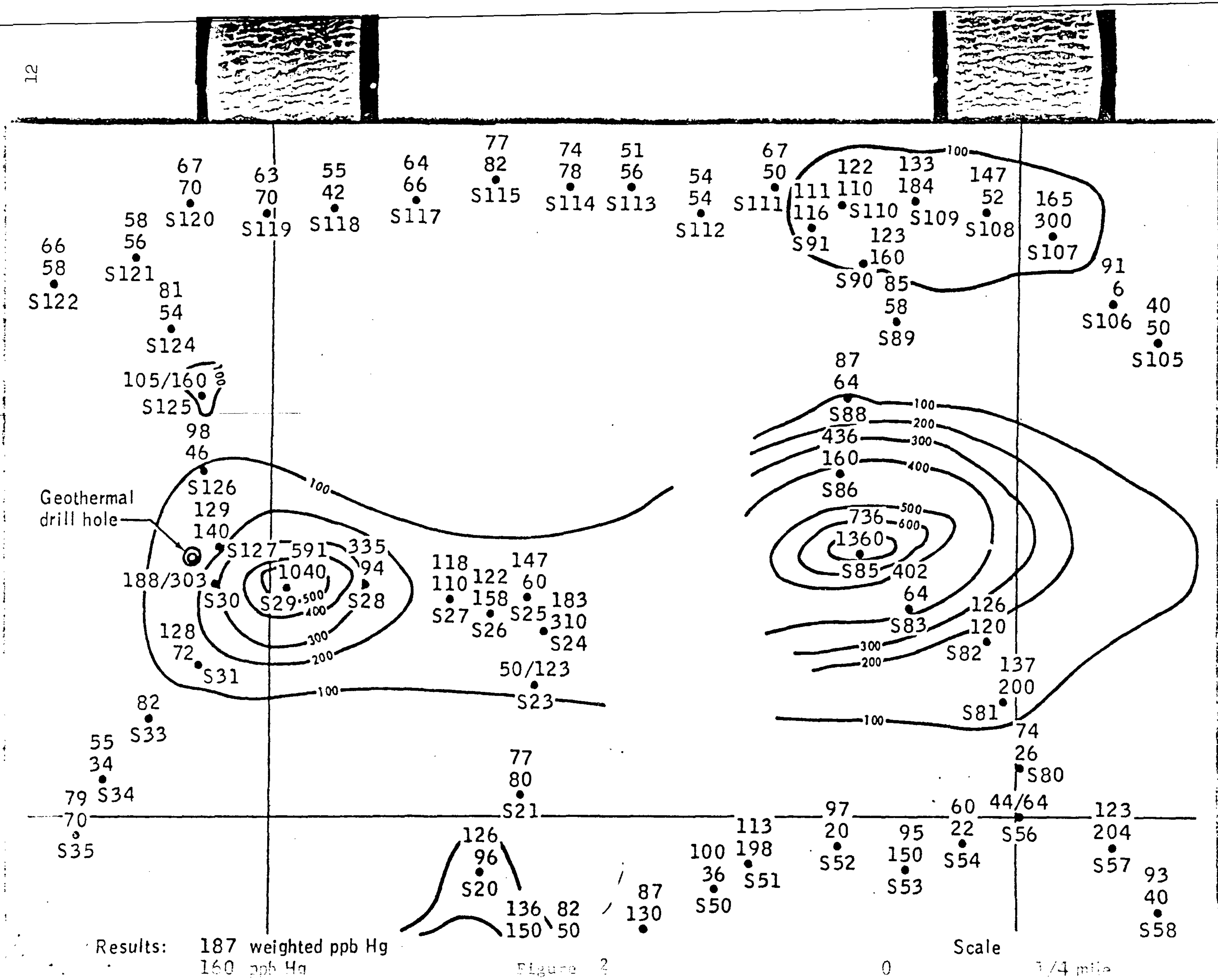

Geothermal drill hole
67 70 S120
63 70 S119
55 42 S118
64 66 S117
77 82 S115
74 78 S114
51 56 S113
54 54 S112
67 50 S111
111 116 S91
122 110 S110
133 184 S109
147 52 S108
165 300 S107
123 160 S90
85 58 S89
91 6 S106
40 50 S105
58 56 S121
66 58 S122
81 54 S124
105/160 S125
98 46 S126
129 140 S127
188/303 S30
591 1040 S29
335 94 S28
128 72 S31
118 110 S27
122 158 S26
147 60 S25
183 310 S24
50/123 S23
82 S33
55 34 S34
79 70 S35
77 80 S21
126 96 S20
136 150
82 50
87 130
100 36 S50
113 198 S51
97 20 S52
95 150 S53
60 22 S54
44/64 S56
123 204 S57
93 40 S58
87 64 S88
436 160 S86
736 1360 S85
402 64 S83
126 120 S82
137 200 S81
74 26 S80
100
200
300
400
500
600
Results: 187 weighted ppb Hg
160 ppb Hg
Scale
0
1/4 mile
Fig 2

Figure 2

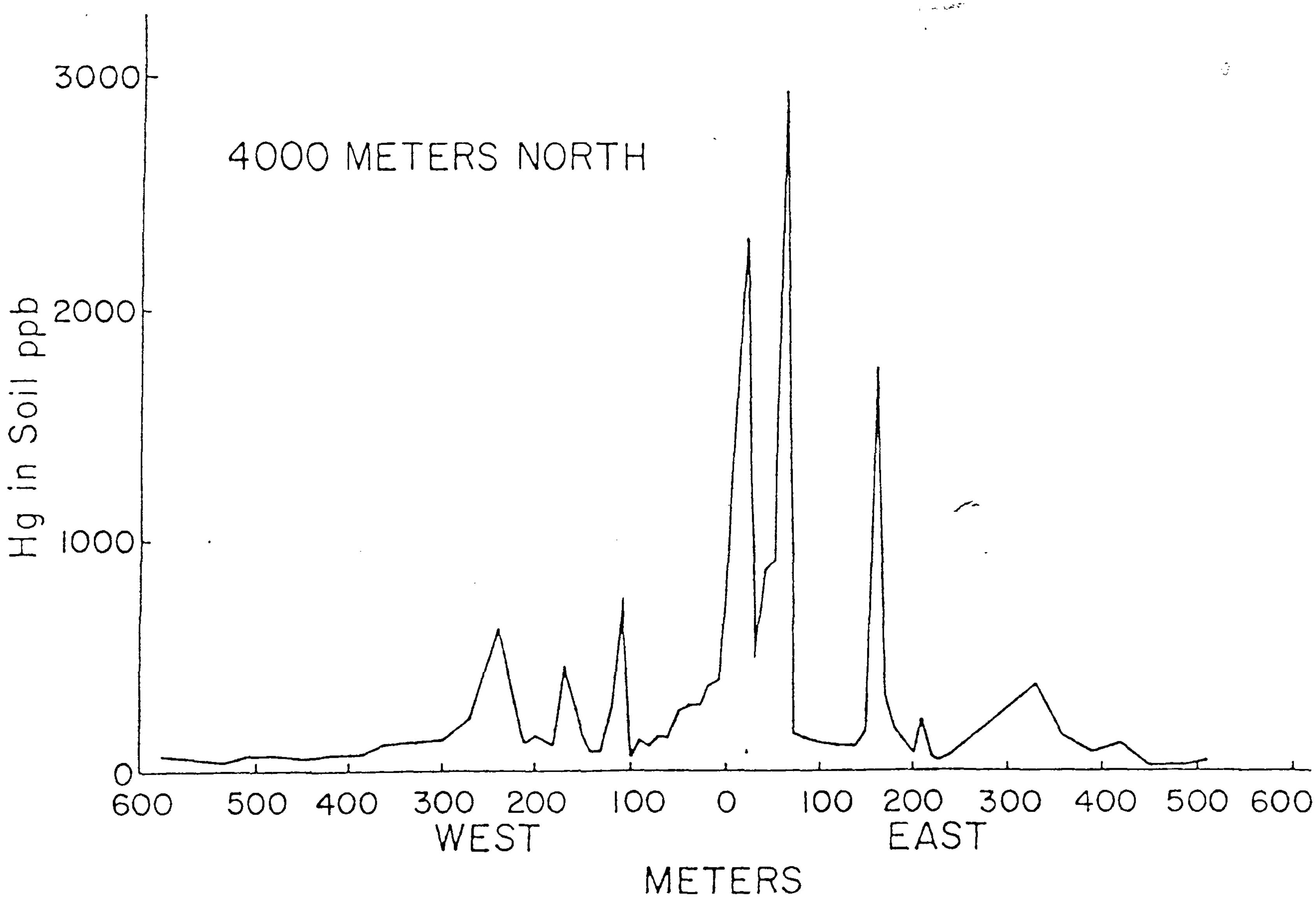


Figure 3. Profile of mercury measurements at Roosevelt Hot Springs, Millard County, Utah. From Parry, et. al. 1976, Geochemistry and hydrothermal alteration of selected hot spring sites in Utah. Dept. of Geology and Geophysics, University of Utah,

requests prevent indicating the precise site. Nevertheless, the figure indicates a general background of predominately less than 100 ppb with the most anomalous value of 1,360 ppb. The large anomally near the drill hole covers an area of 0.25 mi in diameter; the larger anomalous area measures about 0.5 mi by 0.4 mi. Neither of the anomalous areas are based on single station values but show a half dozen or more consistently increasing values from the background measurements to the highest anomalous values. More closely spaced soil-gas analyses for mercury in the anomalous areas would exhibit more irregularity of the contours showing equal mercury values. This survey was made with the plastic hemisphere instrument with fan shown in Fig. 1. Collection time equalled 10 min/sample on several one inch diamerer, 40 mesh silver screens.

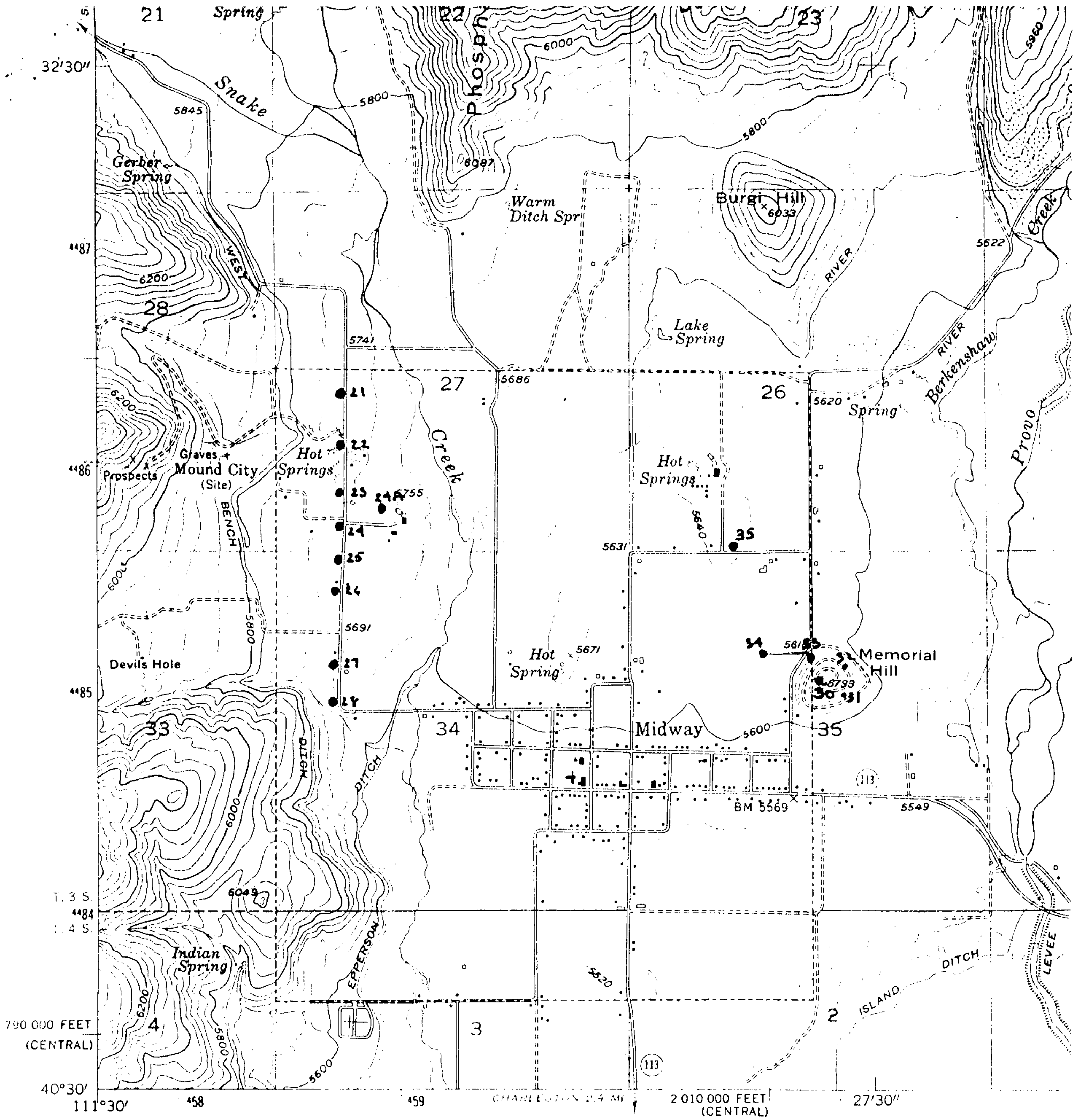
2. Roosevelt Hot Spring Geothermal Area

A recent survey line was made across the Roosevelt known geothermal area in Millard County, Utah, an area that has been under study, including a drilling program, for several years. The mercury analyses obtained by Parry, Benson, and Miller (1976) are shown by Fig. 3. Anomalous values in excess of 2000 ppb were noted. It would be worthwhile to repeat this study using an instrument that would draw soil-gas from the ground and determine the expected much higher mercury content of these samples for contrast.

3. Midway Hot Spring Area

As a test in Utah of the plastic hemisphere collecting unit shown by Fig. 1, the Midway, Wasatch County, Utah, area was proposed as a test site for a validity test.

This area is located about two miles west of Heber at the foot



Mapped, edited, and published by the Geological Survey

Control by USGS and USC&GS

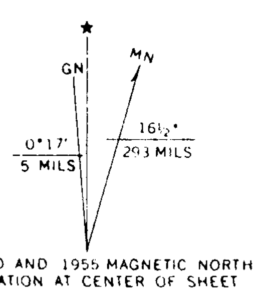
Topography from aerial photographs by multiplex methods
Aerial photographs taken 1953. Field check 1955

Polyconic projection. 1927 North American datum
10,000-foot grids based on Utah coordinate system, central and north zones

Red tint indicates areas in which only landmark buildings are shown

Dashed land lines indicate approximate locations

1000-meter Universal Transverse Mercator grid ticks, zone 12, shown in blue

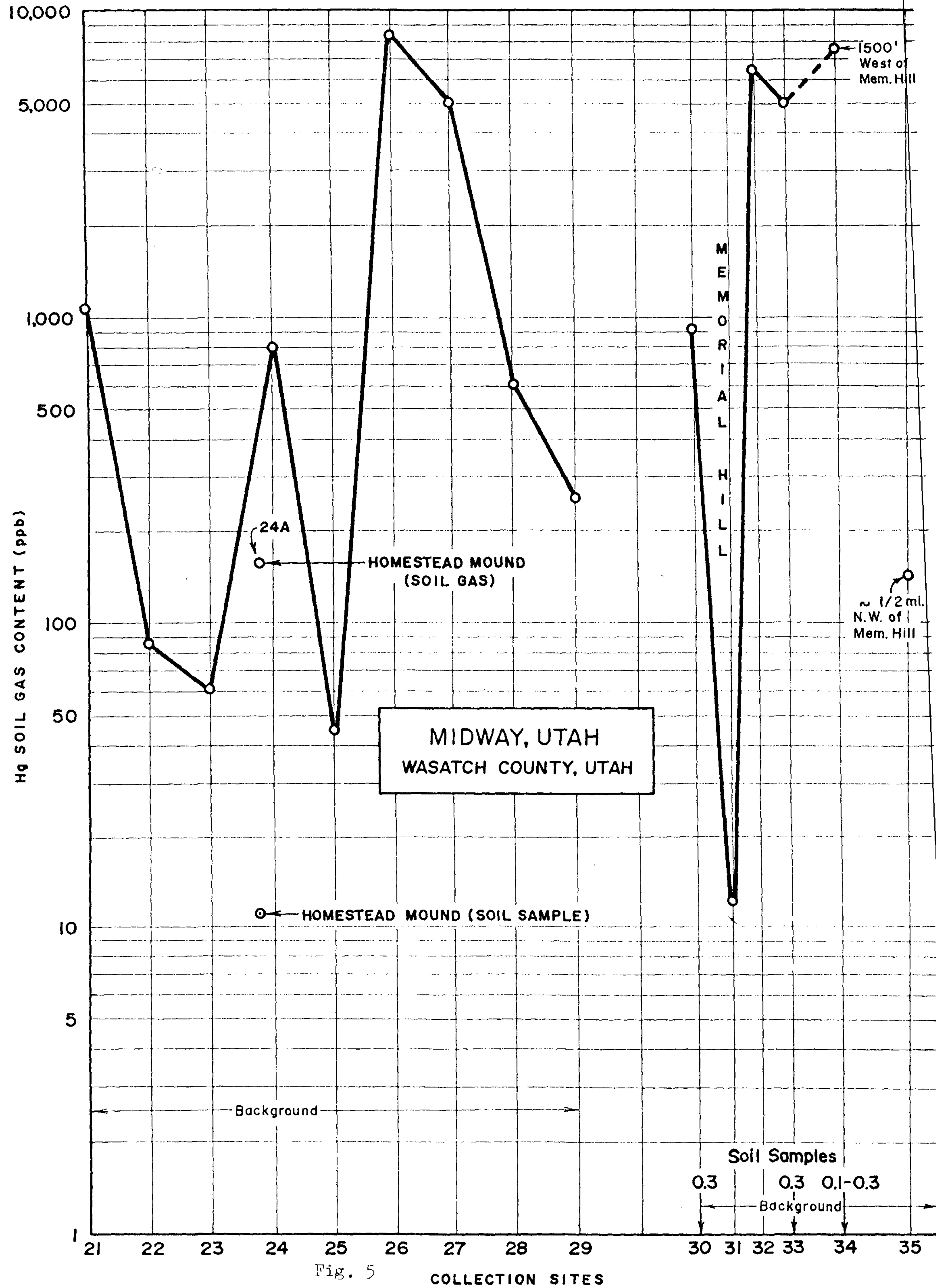


UTM GRID AND 1955 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

THIS I
FOR SALE BY U.S. GEOLC
A FOLDER DESCR

Fig. 4. HEBER CITY, UTAH, QUAD.

Fig. 4. Heber City, Utah, Quadrangle



10,000
5,000
1,000
500
100
50
10
5
1
Hg SOIL GAS CONTENT (ppb)
MIDWAY, UTAH
WASATCH COUNTY, UTAH
24A
HOMESTEAD MOUND
(SOIL GAS)
HOMESTEAD MOUND (SOIL SAMPLE)
MEMORIAL HILL
1500' West of Mem. Hill
~ 1/2 mi. N.W. of Mem. Hill
Background
Soil Samples
0.3
0.3
0.1-0.3
Background
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
COLLECTION SITES

Fig. 5

of the Wastach Range. Mounds formed by hot springs and composed of calcite layers varying in height from a few feet to few tens of feet spot the area (Fig. 4). Most of the hot springs are dormant but a few of the smaller ones in small concnetrated areas are quite evident (Fig. 4). The largest mound, known as Memorial Hill is presumably not a hot spring mound but a formational remnant. Cool stagnant water still exists in the Homestead mound but hot water for the swimming pool is derived by wells and piped from other existing hot springs, located a short distance NW of the Homestead.

Sample results at Midway

a. A soil-gas sample collected near the base of the Homestead mound contained an anomalous ~ 155 ppb of mercury. In contrast a rock and soil sample at the same site contained only 11 ppb (Fig. 4 and Fig. 5). It is noticeable in all of the following analyses that soil samples generally contain significantly less mercury than do the soil-gas samples.

Incidentally, the precision of these measurements, made by atomic absorption, is about 0.1 ppb, less than usual because of new heating techniques.

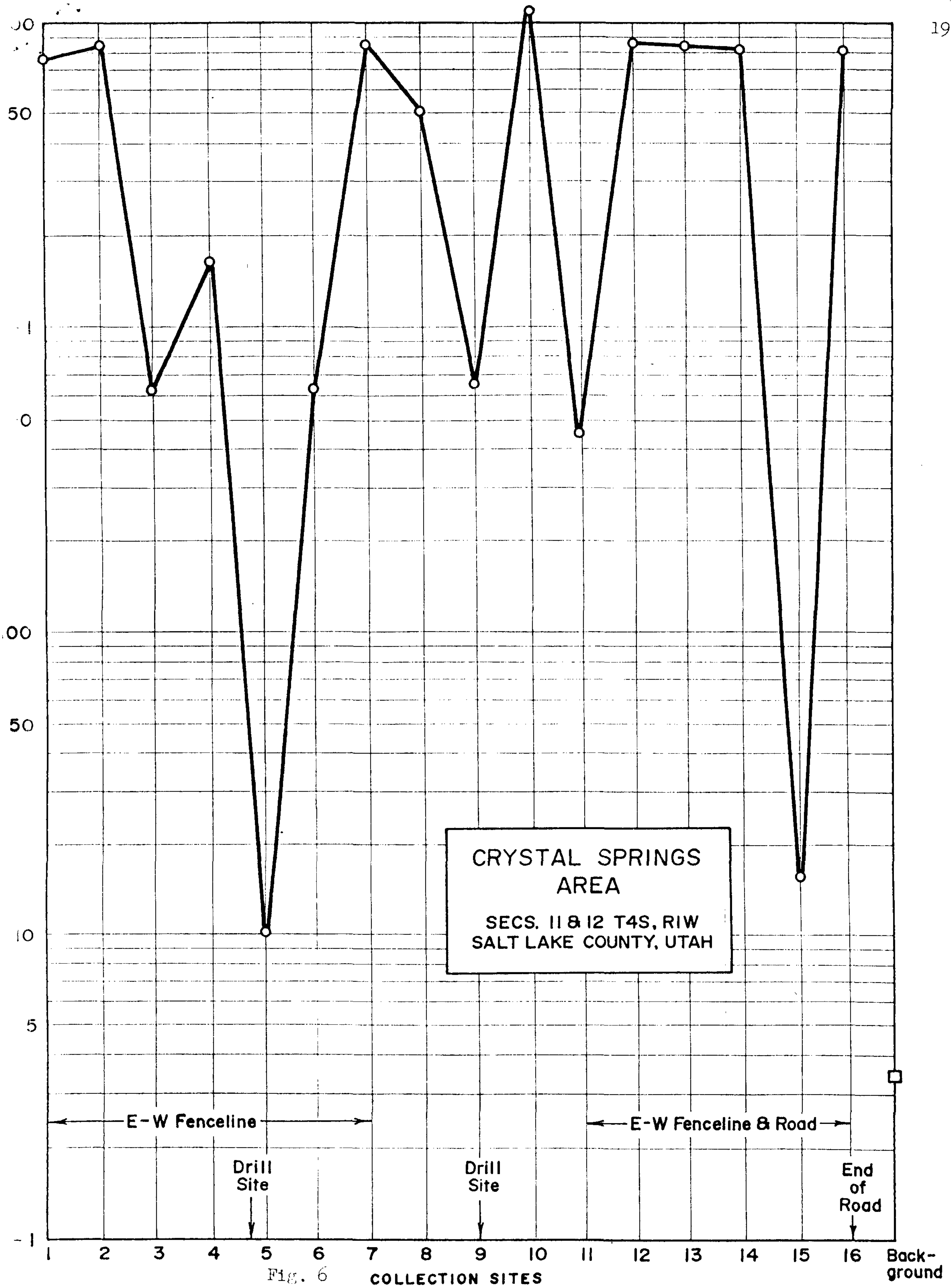
b. A small mound, only a few feet high, located about one mile northwest of the large mound contained 140 ppb mercury similar to the Homestead soil-gas sample.

c. A line of samples (21 to 28) were collected 330 feet apart along the side of the road shown in Fig. 4. The plot of these results is shown in Fig. 5. The values varied from a high of 1850 ppm to a low of 45 ppb but with an average for all samples of about 10 ppm.

Numerous studies including hundreds of samples have been made by Jensen in non-geothermal and unmineralized areas where background values of mercury in soil-gas varied from ~40 to 100 ppb. Wittcopp (1979) reported background values adjacent to a gold deposit in California varying between 40 to 80 ppb with values of 1000 ppb correlating with the gold veins. Even Fig. 2 shows background values near a geothermal site in New Mexico averaging about 70 ppb. Certainly, the average value obtained along the road west of the Homestead of about 10,000 ppb indicates an anomalous Hg content.

What is puzzling is the comparatively three high Hg values at Memorial Hill, even though the higher values are located near the base of the hill. There are at least three suggestions that may explain these high values, viz., 1) The Midway area releases so much Hg to the surface that its redeposition throughout the area can provide anomalous Hg content values almost anywhere in the area; 2) The depth of the thermal source and the widespread occurrence of present and defunct hot springs would not result in vertical conduits to the surface. These may be intricate conduits that reach the surface some distance laterally from the deep source; and 3) Memorial Hill may be partially, at least, an old defunct hot spring mound. Much of the exposed rock appears to be calcareous tufa rather than Mesozoic sediments. Of the above suggestion, however, number 2 is the most likely explanation.

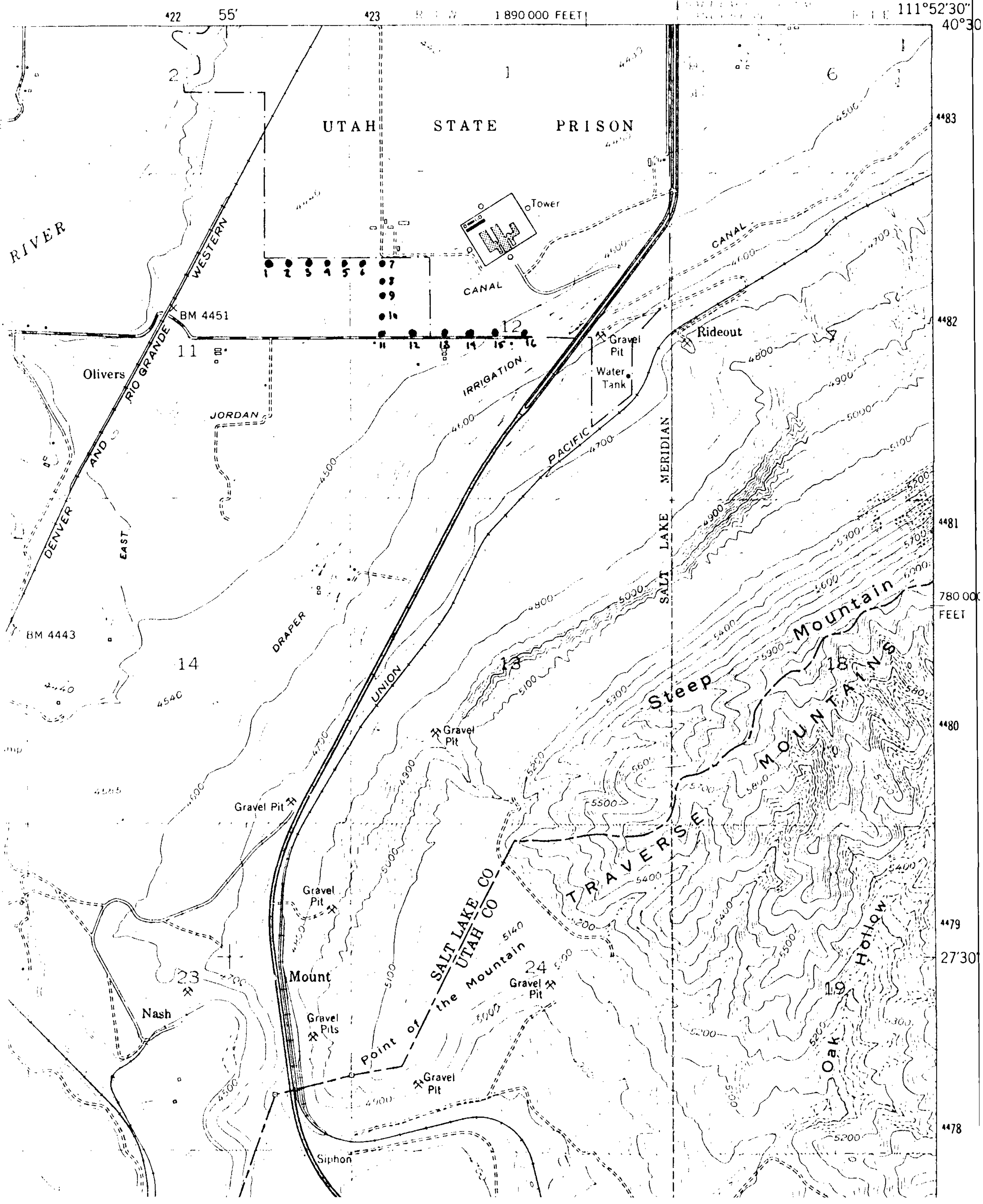
There is little doubt that Hg soil-gas samples collected several miles from Midway would give < 100 ppb values indicating that the geothermal extent of Midway is either widespread or Hg soil-gas values could be



50
1
0
00
50
10
5
-1
CRYSTAL SPRINGS AREA
SECS. 11 & 12 T4S, R1W
SALT LAKE COUNTY, UTAH
E-W Fenceline
E-W Fenceline & Road
Drill Site
Drill Site
End of Road
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Back-ground
COLLECTION SITES

Fig. 6

Fig. 7 JORDAN NARROWS QUADRANGLE
UTAH
7.5 MINUTE SERIES (TOPOGRAPHIC)



expected to be high throughout the area. Additional sampling in the area would undoubtedly provide results similar to those obtained.

4. The results of Hg soil-gas sampling at Crystal Springs in south Salt Lake Valley are shown on Fig. 6. The collection sites, 330 feet apart are plotted on Fig. 7.

The results obtained in this area are consistently anomalous at least between stations 6 to 14, a distance of half a mile. Temperatures measured at drill site 9 should show an anomalous correlation with the soil-gas samples. The blank silver screen samples in this area still provided the low values of $\sim$3.5 ppb as shown by the small square on the right margin of Fig. 6. The anomalous values are more than 2500 times more anomalous than the blank samples and at least several hundred times more anomalous than background values.

In conclusion, this preliminary study does indicate that mercury is an effective indicator of geothermal sites. In addition, not only can Hg be collected, but its concentration can be measured in ppb amounts with great accuracy and precision.

What is both surprising and pleasing about these initial mercury measurements is the comparatively high amount of mercury in the soil-gas samples in contrast to the low amount in rock and soil samples. It has been noticed for some time that soil-gas samples contain much more mercury than do surface soil or rock samples in any given area. The prime reason for this is the large amount of air pumped from the subsurface that passes through the orifice and is captured as amalgam on the silver screen.

SUMMARY

In summary, it does appear that soil-gas samples, measured for the amount of mercury therein, provide a prime tool that should be used more extensively in the search and study of geothermal sites.

The cost and use of the collecting unit shown on Fig. 1 is so low that it would seem imperative that these mercury measurements in soil-gas should be made almost routinely in the study of geothermal sites. It is recommended that much more extensive measurements be made in geothermal areas to exhibit the significance of these studies. The Midway area is a prime area where an extensive mercury in soil-gas study should be done.

In contrast, the measurement of surface samples of rock, soil, and water appear to be much less useful and diagnostic in measuring the amount of mercury escaping from below the surface.

RECOMMENDATIONS

1. The collecting apparatus, 80 mesh silver screen, and the accurate measurement of even ppb by Atomic Absorption result in a low-cost geothermal study. Probably no other phase of geothermal study provides more significant information at such a low cost as Hg soil-gas analysis.

2. Mercury soil-gas analysis should be done routinely on all potential geothermal areas in Utah. In doing so, the spacing of stations can be greater than 330 feet and sampling should be done at some distance from the anomalous areas in order to determine the background values.

3. Drilling sites can be located more precisely based on a grid map of a mercury soil-gas studied area, even though it is realized that the Hg may have moved up-dip and laterally rather than vertically. Even so, geothermal areas are so comparatively large that the Hg soil-gas isograd map can still be of significance in locating drill sites.

4. In light of the abnormally high mercury contents released to the atmosphere from geothermal developments, an environmental consideration of the potential toxidity of mercury on life in these areas should be addressed.

REFERENCES

Mercury in the Environment, 1970, U.S. Geol. Survey Prof. Paper T 13, p. 1-67, no author listed.

Austin, C.F., Austin, W.H., and Leonard, G.W., 1971, Geothermal science and technology; A national program; Naval Weapons Center, China Lake, California; p. 4, Tech. Series 45-029-72.

Dickson, F.W., and Tunnel, G., 1968, Mercury and antimony deposits associated with active hot springs in the western United States, in Ore Deposits of the U.S. 1933-1967. Edited by J. Ridge.

Berce, B., 1915, The use of mercury in geochemical prospecting for mercury, Econ. Geol., v. 60, p. 1516-1528.

Parry, Wm., Benson, N.C., and Miller, C.D., 1976, Geochemistry and hydrothermal alteration at selected Utah hot springs, Department of Geology and Geophysics, University of Utah, Final Report, v. 3, Nat'l Sci. Foundation Contract GI-14371, 131 p.

Kruger, P. and Otte, C., 1973, Geothermal Energy - Resources and Production Stimulation, Stanford Press, p. 1-360.

Robertson, D.E., Creceliuis, E.A., Fruchtor, J.S., and Ludwick, J.D., 1977, Mercury emmissions from Geothermal Power Plants, Science, v. 196, No. 4294, p. 1095-1097.

Siegel, S.M. and Siegel, B.Z., 1975, Environ. Sci. Technol., v. 9, p. 473.

Tindall, F.M., 1967, Mercury analysis by atomic absorption spectrophotometry, Atomic Absorption Newsletter, v. 6, p. 104-106.

Vaughn, W.W., 1967, A simple mercury vapor detector for geochemical prospecting. U.S. Geol. Survey Circ. 540, p. 8.

Vaughn, W.W., and McCarthy, J.H., Jr., 1965, An instrumental technique for the determination of submicrogram concentrations of mercury in soils, rocks, and gas. U.S. Geol. Survey Prof. Paper 501-D, p. D 123-D 127. (This was first reported in Geol. Survey Research, 1964).

Weissberg, B.G. and Zobell, M.G.R., 1973, Bull. Environ. Contam. Toxicol., v. 9, p. 148.

Wittkopp, R.W., 1979, Mercury bearing atomic gold, Allegany district, Sierra County, Calif., Calif. Geology, Jan. Issue, p. 20-21.