

460  
10/9/84  
JP

1  
DR-0442-1

DOE/ID/12080-T1  
(DE84015553)

**Energy**

**G  
E  
O  
T  
H  
E  
R  
M  
A  
L**

**GEOHERMAL EXPLORATION IN TRANS-PECOS, TEXAS/NEW MEXICO**

**Final Report**

**By  
Robert Roy  
Bruce Taylor  
Michael P. Miklas, Jr.**

**September 1983**

**Work Performed Under Contract No. FC07-79ID12080**

**Texas Energy and Natural Resources Advisory Council  
Austin, Texas**

**Technical Information Center  
Office of Scientific and Technical Information  
United States Department of Energy**



## **DISCLAIMER**

**This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.**

## **DISCLAIMER**

**Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.**

## DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Printed Copy A07  
Microfiche A01

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements and Index (GRA and I)*; *Scientific and Technical Abstract Reports (STAR)*; and publication NTIS-PR-360 available from NTIS at the above address.

GEOHERMAL EXPLORATION IN  
TRANS-PECOS, TEXAS/NEW MEXICO

by

Robert Roy  
Bruce Taylor  
Michael P. Miklas, Jr.

FINAL REPORT

September 1983

Submitted By

Texas Energy and Natural Resources Advisory Council  
Executive Office Building  
411 West 13th Street, Suite 800  
Austin, Texas 78701  
Milton L. Holloway, Executive Director

prime funding provided by  
United States Department of Energy and  
Texas Energy and Natural Resources Advisory Council  
Cooperative Agreement No. DE-FC07-79ID12080



## TABLE OF CONTENTS

	PAGE
CHAPTER 1 GEOLOGIC SETTING AND REVIEW OF EXISTING DATA TRANS-PECOS TEXAS/NEW MEXICO	1
INTRODUCTION	1
LOCATION OF STUDY AREAS	3
CHAPTER 2 HUECO BOLSON - REGIONAL GEOLOGIC SETTING	7
CHAPTER 3 PRESIDIO BOLSON - REGIONAL GEOLOGIC SETTING	11
CHAPTER 4 EVALUATION OF GEOTHERMAL GRADIENT MEASUREMENTS IN TRANS-PECOS TEXAS/NEW MEXICO	15
DATA COLLECTION AND ASSIMILATION	15
EVALUATION OF GEOTHERMAL GRADIENTS	17
CHAPTER 5 DISCUSSION OF HEAT FLOW MEASUREMENTS	31
CHAPTER 6 POSSIBLE LOCATION OF GEOTHERMAL WATERS IN HUECO AND PRESIDIO BOLSONS	41
CHAPTER 7 GEOPHYSICAL STUDIES IN THE HUECO AND PRESIDIO BOLSONS	44
MICROEARTHQUAKE MEASUREMENTS	44
GRAVITY MEASUREMENTS	44
Hueco Bolson	44
Presidio Bolson	48
CHAPTER 8 DISCUSSION OF GEOCHEMISTRY/GEOTHERMOMETRY ANALYSES	60
HUECO BOLSON	60
PRESIDIO BOLSON	61
CHAPTER 9 SHALLOW DRILLING PROGRAM AT HUECO TANKS, PRESIDIO BOLSON, AND FINLAY MOUNTAINS	63
HUECO TANKS	63
First Stage Drilling	63
Thermal Model	66
Second Stage Drilling	70
PRESIDIO BOLSON	75
FINLAY MOUNTAINS	83

	PAGE
CHAPTER 10 CONCLUSION	91
APPENDIX I FIELD MEASUREMENT OF VARIOUS PARAMETERS	92
ELECTRICAL METHODS	92
Self-Potential Measurements	92
Electrical Resistivity Soundings	93
THERMAL GRADIENT MEASUREMENTS	103
Temperature Logging	107
Equipment	107
Procedure	107
Computer Program THERMAL	109
Thermal Gradient Estimation: Pseudogradients	109
Thermal Conductivity Measurement	113
Equipment	113
Computer Program CONDUC	113
Heat Flow Calculation	113
REFERENCES	115



## LIST OF FIGURES

	Page
Fig. 1 - General location of Study Area.....	2
Fig. 2 - Generalized tectonics of western Trans-Pecos Texas/New Mexico	5
Fig. 3 - Location of Hueco Bolson.....	8
Fig. 4 - Geology of Hueco Tanks Area.....	9
Fig. 5 - Location of Presidio Bolson with gravity traverses.....	12
Fig. 6 - Weather stations in West Texas.....	16
Fig. 7 - Geothermal gradients in West Texas.....	18
Fig. 8 - Gradients in the Salt Basin (north).....	19
Fig. 9 - Gradients in the Salt Basin (south).....	20
Fig. 10 - Gradients in the Eagle Flat.....	21
Fig. 11 - Gradients in Southern Presidio Bolson (north).....	22
Fig. 12 - Thermal Gradients in vicinity of Valentine, Texas.....	28
Fig. 13 - Gradients in Southern Presidio Bolson and adjacent areas....	29
Fig. 14 - Heat Flow measurements in West Texas.....	38
Fig. 15 - Heat Flow model for West Texas (A-A').....	40
Fig. 16 - Location of Hueco Tanks.....	42
Fig. 17 - Complete Bouger gravity map of Hueco Bolson.....	45
Fig. 18 - Bouger gravity map of Hueco Tanks Area.....	47
Fig. 19 - Two dimensional gravity model A-A'.....	49
Fig. 20 - Two dimensional gravity model B-B'.....	50
Fig. 21 - Regional Bouger anomalies.....	51
Fig. 22 - Gravity cross section along A-A' (Pinto Canyon).....	53
Fig. 23 - Gravity cross section along B-B' (Shafter Highway).....	54
Fig. 24 - Location of Geophysical Survey, Hueco Tanks Area.....	56
Fig. 25 - Self Potential Profile I.....	58
Fig. 26 - Self Potential Profile II.....	59
Fig. 27 - Geothermal gradients in El Paso County, Texas.....	64
Fig. 28 - Temperature contour map for a depth of 50m.....	67
Fig. 29 - HT-11 (grad. 60-120m).....	68
Fig. 30 - HT-12 (grad. 180-270m).....	69
Fig. 31 - Heat Flow model for Hueco Tanks geothermal area.....	71

	Page
Fig. 32 - Temperature-depth curve for HT-27.....	72
Fig. 33 - Temperature-depth curve for HT-28.....	73
Fig. 34 - Temperature-depth curve for HT-30.....	74
Fig. 35 - Location of five holes in Presidio Bolson.....	76
Fig. 36 - Temperature - Vizcaino #1.....	77
Fig. 37 - Gradient - Vizcaino #1.....	78
Fig. 38 - Temperature - Sanguijuela Springs #1.....	79
Fig. 39 - Gradient - Sanguijuela Springs #1.....	80
Fig. 40 - Temperature - Benevides #1.....	81
Fig. 41 - Gradient - Benevides #1.....	82
Fig. 42 - Temperature - Benevides #2.....	84
Fig. 43 - Gradient - Benevides #2.....	85
Fig. 44 - Temperature - Pelton #1.....	86
Fig. 45 - Gradient - Pelton #1.....	87
Fig. 46 - Location of Drill Site in Finlay Mountains.....	88
Fig. 47 - Temperature - Finlay Mountains.....	90
Appendix I	
Fig. AI-1 - Self-potential Profile I.....	94
Fig. AI-2 - Self-potential Profile II.....	95
Fig. AI-3 - Arrangement of Schlumberger electrical soundings.....	97
Fig. AI-4 - Resistivity sounding curve for VES-1.....	99
Fig. AI-5 - Resistivity sounding curve for VES-2.....	100
Fig. AI-6 - Figure 5 from Zohdy (1969).....	101
Fig. AI-7 - Resistivity sounding curve for VES-3.....	102
Fig. AI-8 - Resistivity sounding curve for VES-4.....	104
Fig. AI-9 - Plot of temperatures vs. elevation for West Texas.....	108

LIST OF TABLES

	Page
Table 1 - Summary of Geothermal Gradient Data for West Texas.....	23
Table 2 - First-order heat flow measurements, western Trans-Pecos, Texas.....	33
Table 3 - Second-order heat flow measurements, western Trans-Pecos, .. Texas.....	34& 35
Table 4 - Geological setting of heat flow holes, western Trans-Pecos,.. Texas.....	36& 37
Table 5 - Hueco Tanks geothermal gradients.....	65
Appendix I	
Table AI-1 - Index of weather stations, West Texas.....	105
Table AI-2 - Mean annual temperatures, West Texas weather stations....	106
Table AI-3 - Geothermal gradient and pseudogradient comparison for 13 stations.....	112

## ABSTRACT:

Interest in alternative energy has encouraged the investigation of possible geothermal resources in Trans Pecos, Texas/New Mexico in an area of extensive Cenozoic volcanism with several hot springs.

Geochemical analysis of groundwater samples resulted in the definition of two major areas of geothermal interest: the Hueco Bolson in northeastern El Paso County, and the Presidio Bolson. Regional temperature gradient measurements also supported the existence of anomalies in these places, and showed another smaller anomaly in the Finlay Mountains, Hudspeth County.

Detailed geophysical and geochemical studies were conducted on these three targets, yielding the following conclusions:

1. The Hueco Bolson contains warm (80°C) waters which rise along faults to near the surface giving rise to a surface temperature anomaly. The water temperature is of insufficient magnitude to be economically interesting.
2. The Presidio Bolson appears to be underlain by warm waters which emanate at the surface as hot springs. Local faulting appears to be responsible for the water movement. Based on our work, no high temperature resource is present at exploitable depths.
3. The temperature anomaly investigated in the Finlay Mountains is localized to a Tertiary intrusion. The heat source is probably fault controlled and not warm enough to be commercially exploitable.

GEOLOGIC SETTING AND REVIEW OF EXISTING DATA  
TRANS-PECOS TEXAS/NEW MEXICO

INTRODUCTION

Trans-Pecos Texas/New Mexico, as defined for the purposes of this project, is comprised of the following five westernmost counties in Texas to the west of the Pecos River: 1) El Paso, 2) Hudspeth, 3) Culberson, 4) Jeff Davis, and 5) Presidio, including a small portion of Otero County, New Mexico. Two promising areas for discovery of geothermal resources were targeted for study in this project: 1) Hueco Bolson in the vicinity of Hueco Tanks and 2) Presidio Bolson (See Figure 1).

In September, 1975, a state supported project was begun at the University of Texas at El Paso to locate and define areas of geothermal potential using geochemical reconnaissance methods. Water samples were collected from wells and springs throughout Trans-Pecos, Texas. Hoffer (1979), using the silica geothermometer technique of Fournier and Rowe (1966), identified seven possible resource areas. Of these, the most promising were Hueco Tanks and Presidio Bolson.

A parallel, federally funded geothermal assessment (Henry, 1979a) investigated the geologic setting and geochemistry of the thermal waters of West Texas. The Presidio Bolson again appeared the most favorable from the standpoint of geothermal energy, with predicted subsurface temperatures as high as 160°C. In addition, the Hueco Bolson, near El Paso, was considered a primary target for further investigation. Henry (1979a) concluded that other geochemical anomalies in the region were probably artificially produced by reaction of groundwater with near-surface evaporities or silica-rich volcanic deposits.

The present project resulted from those mentioned above. The Hueco Bolson was selected as the first study area, because of its location near the city of El Paso, which provides a market for a proven resource of either

# NEW MEXICO

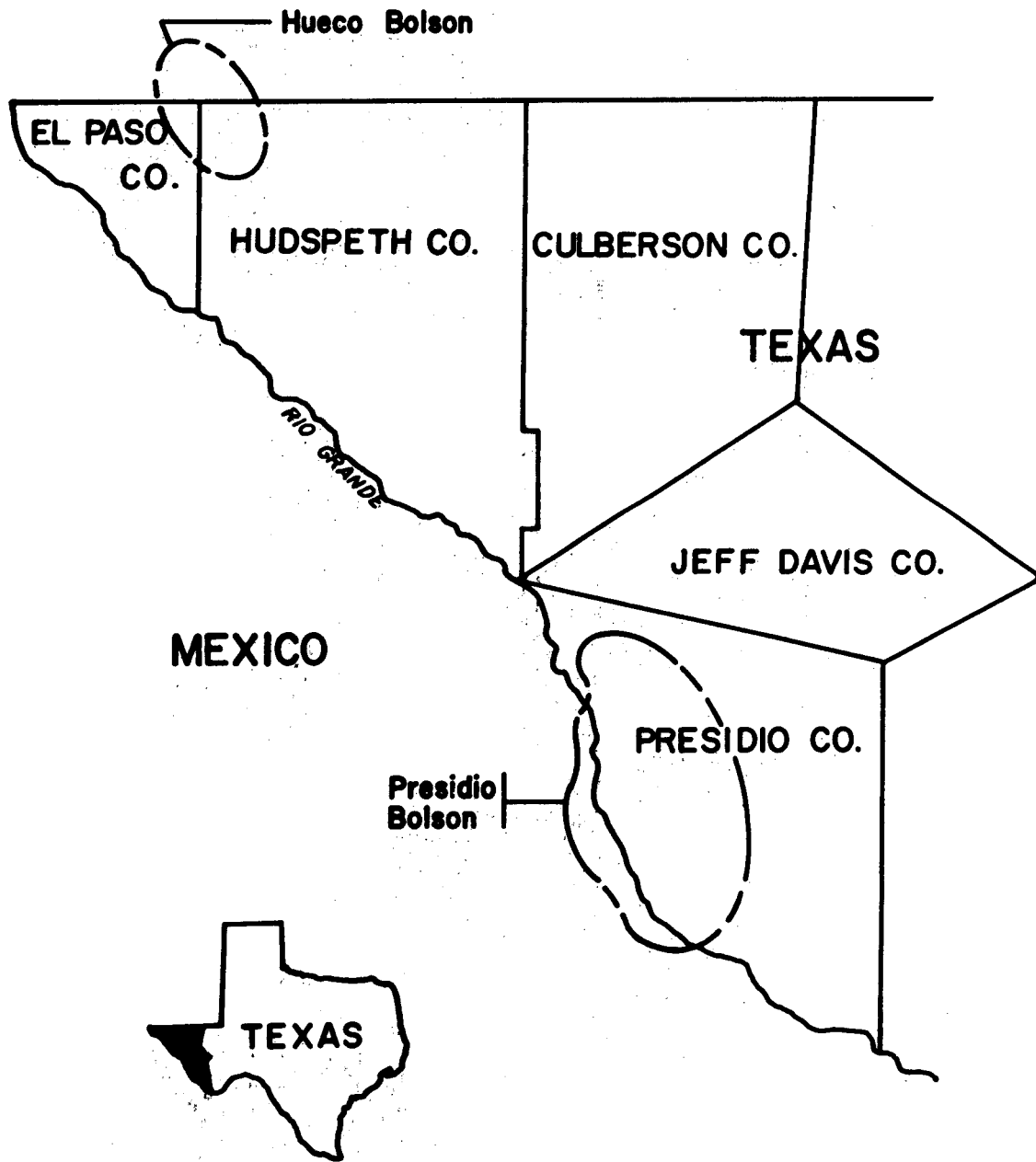


Figure 1 - General location of Study Area

electric grade (>150°C) or low-temperature applications. The Presidio Bolson, although more encouraging geothermally (predicted temperatures indicate the possibility of electric grade temperature or 150°C plus), was studied second because of its location in an area of low population and very irregular terrain.

Preliminary utilization studies (Gilliland and Fenner, 1980) funded as part of the original project identified five industries in the El Paso area which could benefit from direct-heat geothermal applications. These industries are the following: 1) meat packing, 2) dairy, 3) soft-drink bottling, 4) food canning and 5) apparel. The industry interest assumed a hot water resource at Hueco Tanks, with temperatures too low for electricity production but warm enough for use in the particular industrial need. Because of its remoteness and sparsity of population, Gilliland and Fenner(1980) concluded that the Presidio Bolson resource would have to be of electrical production quality to be commercially exploitable.

Dr. Christopher D. Henry and Mr. James K. Gluck completed a study of the geology and geochemistry of the Hueco Tanks Geothermal Area as a portion of the activities associated with this project. Their report has been bound separately as a publication of the Texas Bureau of Economic Geology - The University of Texas at Austin and is included in this report in summary in the following text and in totality as Attachment 1. A similar study by Henry (1979a) is referenced herein and deals with the geologic setting and geochemistry of thermal water and geothermal assessment of Trans-Pecos, Texas. A third pertinent study entitled "Structure of the Presidio Bolson Area, Texas, Interpreted from Gravity Data", by Mraz and Keller (1980), is quoted liberally.

#### LOCATION OF STUDY AREAS

The Trans-Pecos Texas/New Mexico study area is located in the vicinity of the Rio Grande Rift. The Rio Grande Rift extends from central Colorado to southern New Mexico. The Rift exhibits both topographic and structural

features which discriminate it from the Basin and Range province to the west and the Great Plains province to the east. The Rift area is characterized by a higher heat flow than its neighboring tectonic regions. Hot springs along the rift zone are a manifestation of the area's high intrinsic heat flow.

The extension of the Rift to the south of central New Mexico is not certain. Hot springs activity continues into central Mexico and is concentrated near the Rio Grande Valley. The Rio Grande makes an abrupt southeasterly swing in far West Texas. If the river is following a "structural trend," this trend may indicate a more complex tectonic regime than appears to exist along the Rio Grande Rift outside of Texas where the Rift follows existing north-south trends.

A long history of geological activity is represented in the rocks of Trans-Pecos Texas. Rock ages range from the metamorphics of the Precambrian to Recent alluvial sediments. Much of the present landscape is attributed to a Tertiary volcanic episode, with accompanying Basin and Range faulting. Accounts of the geology have been given by Baker (1934), Henry (1979a), Dickerson (1980) and Hoffer (1980). A generalized tectonic map of the western Trans-Pecos is shown in Fig. 2.

Geophysically, relatively little is known of the Trans-Pecos Texas/New Mexico area. The Rio Grande Rift to the north is characterized by high heat flow and electrical conductivity, and gravity and seismic anomalies. A model of crustal thinning and intrusion has been used by various writers to explain these features of the rift (See Seager and Morgan, 1979). However, extending this model southwards into Trans-Pecos Texas is difficult and not well supported.

The "basins" and "ranges" follow a typically north to northwest trend, and there is evidence of continued tectonic activity, with recent movement along the Tertiary basin faults. Recent uplift has been noted in the Diablo Plateau (Reilinger et al., 1980), where intracrustal magmatic activity has



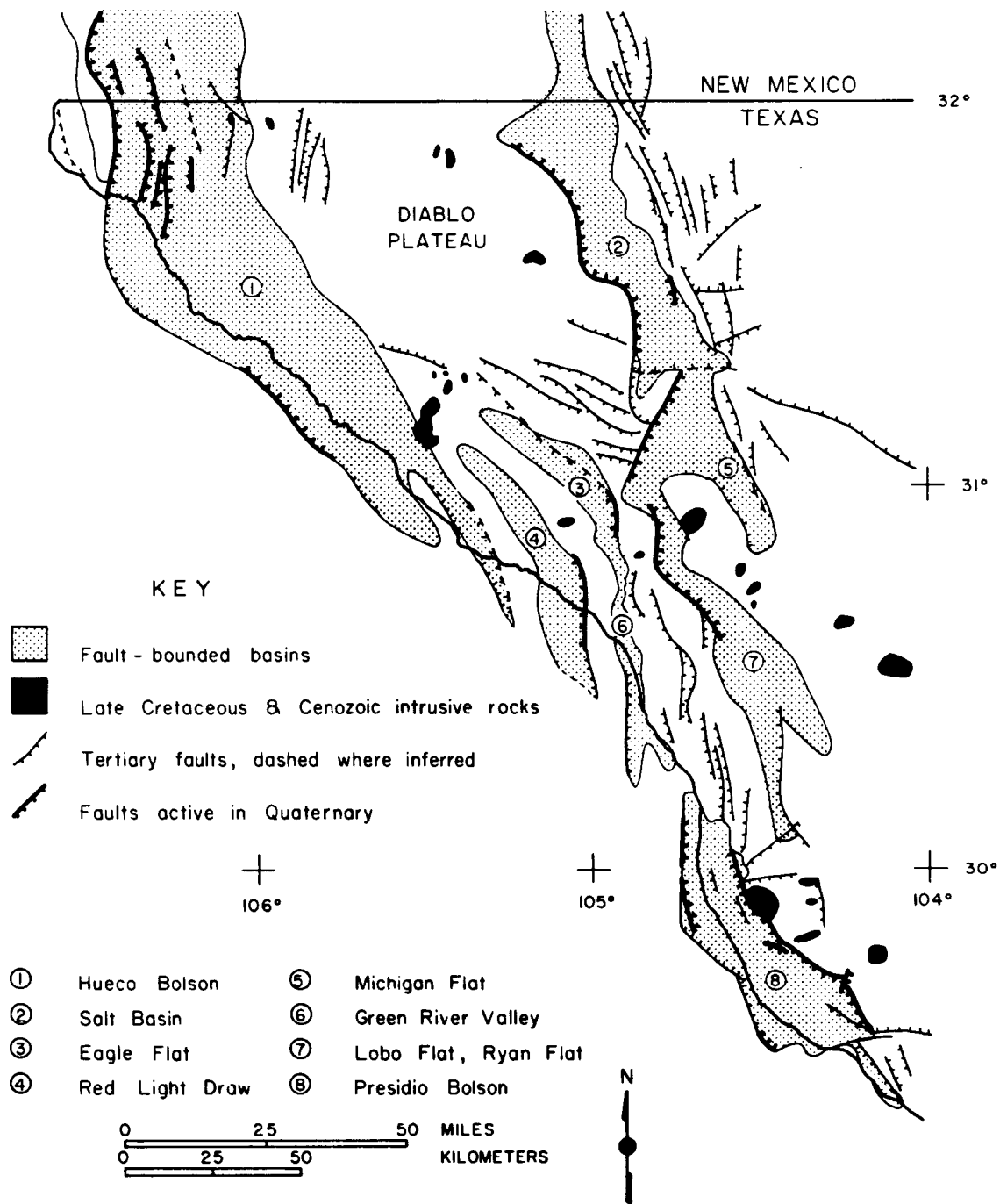


Figure 2 - Generalized tectonics of western Trans-Pecos Texas.

been postulated. The regional extension required for faulting and the presence of such an extensive igneous province have been discussed in terms of plate tectonic models (Barker, 1979; Dickerson, 1980) in which the volcanic rocks were the result of an uprising mantle diapir, triggered by a subducting lithospheric plate from the west.

## HUECO BOLSON - REGIONAL GEOLOGIC SETTING

Hueco Bolson is an asymmetric graben bordered on the west by the Franklin Mountains and on the east by the Hueco Mountains. The Franklin Mountains are made up of Pre-cambrian and Paleozoic sedimentary and igneous rocks; the Hueco Mountains are made up of mostly Upper Paleozoic carbonate and clastic sedimentary rocks (See Figures 3 & 4).

The following discussion of the Hueco Bolson is from Henry and Gluck (1980). Hueco Bolson is filled with up to 9000 ft. of clastic sediments (estimated from geophysical data) along the deeper, western side adjacent to the Franklin Mountains (Mattick, 1967). Two test wells reported by King (1935) and Mattick (1967) penetrated 4900 and 4300 ft. of basin fill. A major normal fault with as much as 18,000 ft of displacement separates the Franklin Mountains from Hueco Bolson. In contrast, displacement on boundary faults on the eastern side may be much less. Woodard et al. (1978) show a bounding fault along the east side of Tularosa Bolson but terminate it approximately 20 km north of the Hueco Tanks study area. The El Paso-Van Horn sheet of the Texas geologic atlas shows no boundary faults on the east side of Hueco Bolson, although several faults cut bedrock at the edge of the bolson. Mattick (1967) showed Hueco Bolson as a half graben with no faulting along the east side in the geothermal prospect area at Hueco Tanks. The results of this study (discussed later) show that normal faults do occur along the east side and some exhibit Quaternary displacement. A well approximately 3 km west of the irregular eastern boundary of the Hueco Bolson penetrated more than 700 m (2380 ft) of basin fill. Thus, Hueco Bolson is actually an asymmetric graben with lesser displacement and shallower bedrock on the east than on the west side.

Fill in Hueco Bolson is composed of detritus shed from the adjacent highland areas of the Franklin and Hueco Mountains. Fill near the boundaries was deposited in alluvial fans, and is coarse and relatively permeable. This material grades to less coarse material inward toward the center of the basin, where finer grained, low permeability sediments

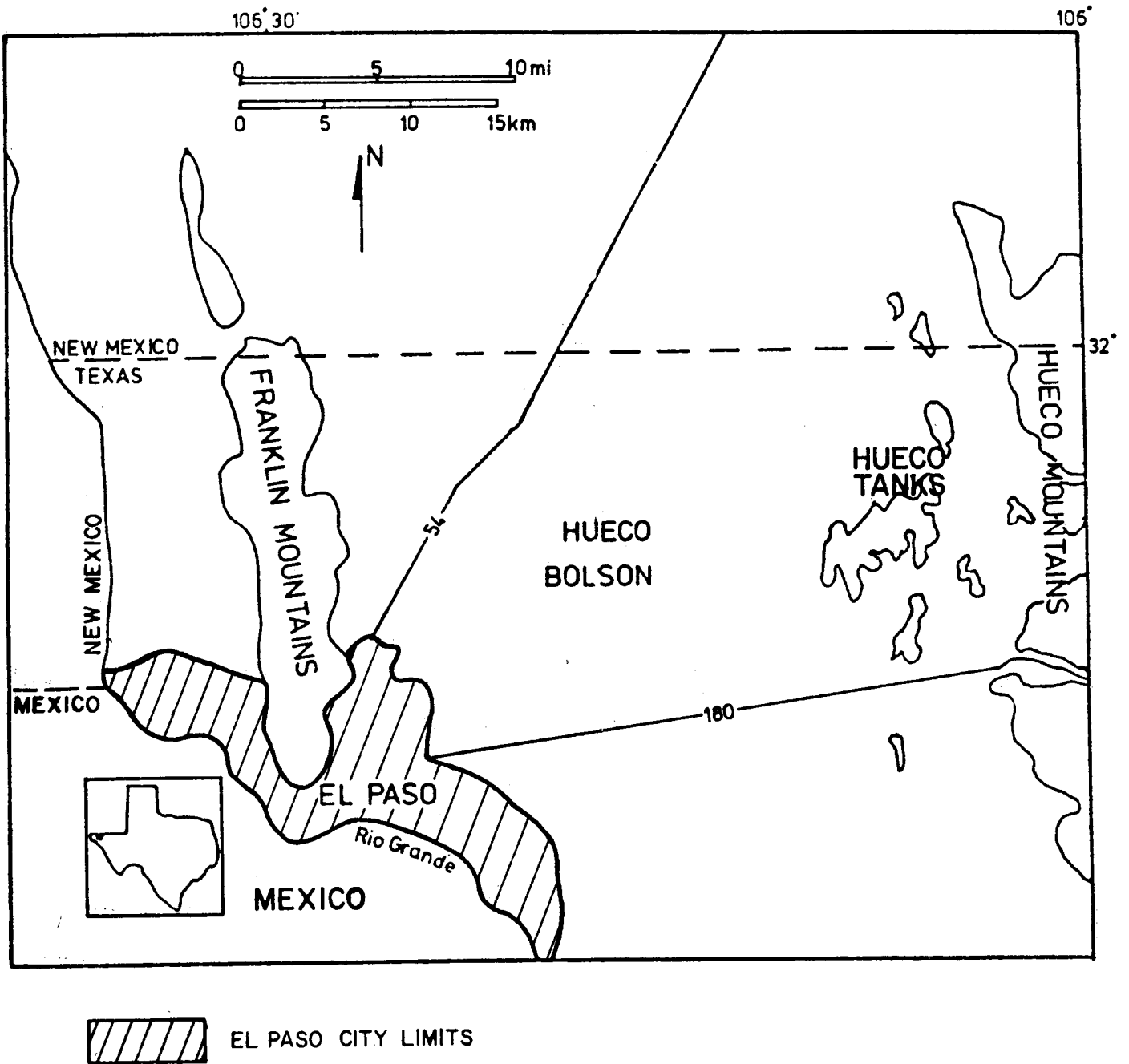


Figure 3 - Location of Hueco Bolson.

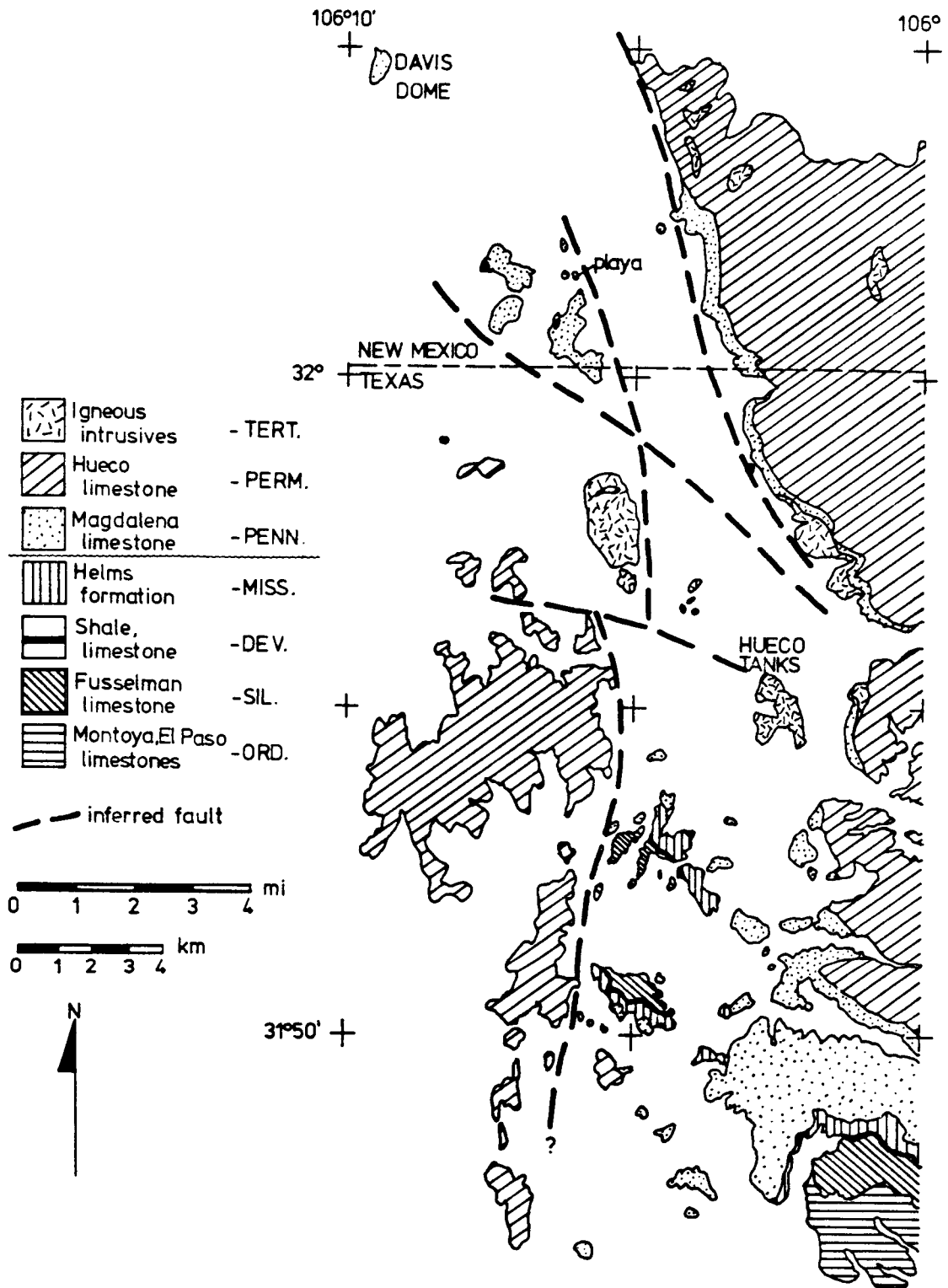


Figure 4 - Geology of Hueco Tanks area  
 (based on King et al., 1945; Wise, 1977;  
 Dane and Backman, 1965)

including lacustrine deposits (Cliett, 1969) are found. Most of the present surface of the Bolson is a depositional surface on the middle Quaternary Camp Rice Formation, which is no younger than 0.5 million years (Seager, 1980). This surface has been dissected along the Rio Grande by tributaries to the river; a distinct erosion escarpment separates the nearly flat Camp Rice Surface from the more rugged, dissected area along the river.

Geothermal waters appear to be restricted to the east side of Hueco Bolson near the Texas-New Mexico border. It is possible that the waters may rise along irregular boundary faults there.

## PRESIDIO BOLSON-REGIONAL GEOLOGIC SETTING

The following discussion is adapted from the discussion of the geology of the Presidio Bolson in Mraz and Keller (1980).

The Presidio Bolson is located in a graben approximately 70 km long and 20 km wide, which begins north of Candelaria, Texas and extends south of Presidio, Texas (Figure 5). The Bolson may be a part of the southern extension of the Rio Grande Rift (Seager and Morgan, 1979). The Presidio Bolson is the dominant Tectonic feature of the area, and in addition to being the most promising zone for geothermal exploration in West Texas (Hoffer, 1978; Henry, 1979a), the Bolson may be associated with significant mineral deposits (McAnulty, 1972). The Presidio Graben is bounded on the east by the Sierra Vieja, the Chinati Mountains, and the Bofecillos Mountains. The Chihuahua Tectonic Belt in the State of Chihuahua, Mexico, lies to the west of the graben. The Rio Grande River flows down the center of the graben.

In the northern part of Presidio County, deep drilling has penetrated Precambrian granite and arkosic sandstone (Bilbrey, 1957). These Precambrian rocks, underlying the Cambro-Ordovician Bliss Sandstone, are correlated with Precambrian outcrops in the Van Horn area to the north. This area was part of the Van Horn mobile belt that was intensely folded, metamorphosed, and intruded during late Precambrian time and was thrust eastward against the Texas Craton (Flawn, 1956). Subsequent erosion produced a low-relief surface gently sloping to the south. Paleozoic marine sediments were deposited upon this shelf as the Sauk Sea (Sloss, 1963) transgressed from the south.

The best exposure of Paleozoic rocks in the region is in the Solitario Uplift where Cambrian through Lower Pennsylvania units are found. There, marine sediments recorded a history of deposition on a stable continental shelf for most of Paleozoic time. In the Presidio area, Upper Pennsylvanian black shales and Permian sediments of the Marfa Basin are exposed in Laramide anticlines located in the Chinati Mountains and Pinto





Canyon area (Rix, 1953). In the Presidio area, the Marfa Basin was forming probably as a result of late Paleozoic tectonism associated with the Ouachita-Marathon orogenic belt to the southeast.

The Chihuahua Trough, southwest of the study area, was filling during the Jurassic and Cretaceous Periods. Jurassic evaporities were deposited in the Chihuahua Trough, but Comanchean and Gulfian sediments are the only Mesozoic rocks that have been found in the Presidio area. These units, composed of fine-grained clastics, limestones, and a basal limestone conglomerate, indicate a stable shelf area lying between the Diablo Platform and the Chihuahua Trough (Dietrich, 1965). This stability ended with Laramide thrusting and folding that formed the Chihuahua Tectonic Belt. Thrust sheets encountered in wells just north of the Presidio Graben are a buried subsurface extension of the Chihuahua Tectonic Belt (Kopp, 1977).

The Tertiary was a time of Basin and Range normal faulting and igneous activity in the Presidio area. Tertiary volcanic rocks originated from numerous eruptive centers in a northwest-trending belt extending along the boundary region between the Diablo Platform and the Chihuahua Tectonic Belt (Barker, 1977). Several features of this belt (including the Chinati Mountains) have been interpreted as resurgent cauldrons (McAnulty, 1975). In the Presidio area, eruption began along the northeastern edge of the Sierra Vieja and Chinati Mountains 30 to 40 million years ago (Wilson and others, 1968) and spread southward to the Bofecillos Mountains volcanic center (McKnight, 1970). Radiometric dating (Dasch et. al., 1969) establishes the presence of a second eruptive phase 18 to 23 million years ago (early Miocene) and through field relations dates the initiation of normal faulting in the graben area (along the Rim Rock Fault on the east side of the Presidio Bolson).

Normal faulting and infilling of the bolson (graben) continued until integration was accomplished by the Rio Grande (Strain, 1970), which was cut approximately 300m into lake-bed sediments (Groat, 1972). Arroyos have

revealed faults in the bolson gravels that imply some late Cenozoic movement along the Basin and Range trends. This movement could be related to the southern extension of the Rio Grande Rift into the area. However, the question of the nature and location of any extension of the Rio Grande Rift south of El Paso, Texas, is controversial (Seager and Morgan, 1979).

The eastern boundary fault zone of the Presidio Graben consists of the Rim Rock Fault, the Candelaria Fault, and the Chinati Fault. The Rim Rock Fault of the Sierra Vieja can be traced from the Van Horn area southward to the Chinati Mountains. This high-angle, normal fault is downthrown on the west. South of Candelaria, the fault bifurcates, displaying only 90 meters of displacement, a decrease from 900 meters observed near the abandoned town of San Carlos. The Candelaria Fault, also downthrown on the west, extends from the south end of the Sierra Vieja southward to Pinto Canyon. Displacement decreases southward from 550 to 25 m. The Chinati Fault Zone, downthrown on the west, separates the Chinati Mountains from the Presidio Bolson.

EVALUATION OF GEOTHERMAL GRADIENT MEASUREMENTS  
IN TRANS-PECOS, TEXAS/NEW MEXICO

DATA COLLECTION AND ASSIMILATION

Temperature measurements were made in various available wells and boreholes using thermistor probes at set intervals (usually 5 or 10m) down the hole. From these measurements, a temperature-depth curve was drawn, and a least-square line was fitted through the straightest section. The slope of the least-square line gave the geothermal gradient. Additional gradients were obtained from temperature logs provided by the U.S.G.S., and from successive bottom-hole temperatures given on geophysical logs run in deep oil-tests. It is recognized that the accuracy of bottom-hole temperature measurements may be questionable, but where three or more bottom-hole temperatures were available at increasing depths, the authors contend that a reasonable estimate of the deep gradient could be achieved.

In cases where only one deep bottom-hole temperature existed or a water well (shallow) bottom-hole temperature was available, a "pseudogradient" was derived. The "pseudogradient" was defined as the difference between the bottom-hole temperature and the mean annual surface temperature, minus a correction factor, divided by the depth of the well. The correction factor was obtained from a consideration of twelve wells throughout the region, for which an accurate "true" gradient and mean annual surface temperature were known. Mean annual surface temperatures were taken from the records of the nearest recording weather station of which there are eighteen in West Texas. The weather station locations and respective average annual temperatures are shown in Fig. 6. In addition, an explanation of the well-numbering system used in this portion of the study is included on the Figure.

A knowledge of the thermal conductivity is needed to calculate heat flow since heat flow is the product of the geothermal gradient and conductivity. A divided-bar apparatus was used for conductivity determinations. Both solid-core and cuttings could be accommodated by the test apparatus. Samples were taken from the depth interval over which the gradient was calculated.

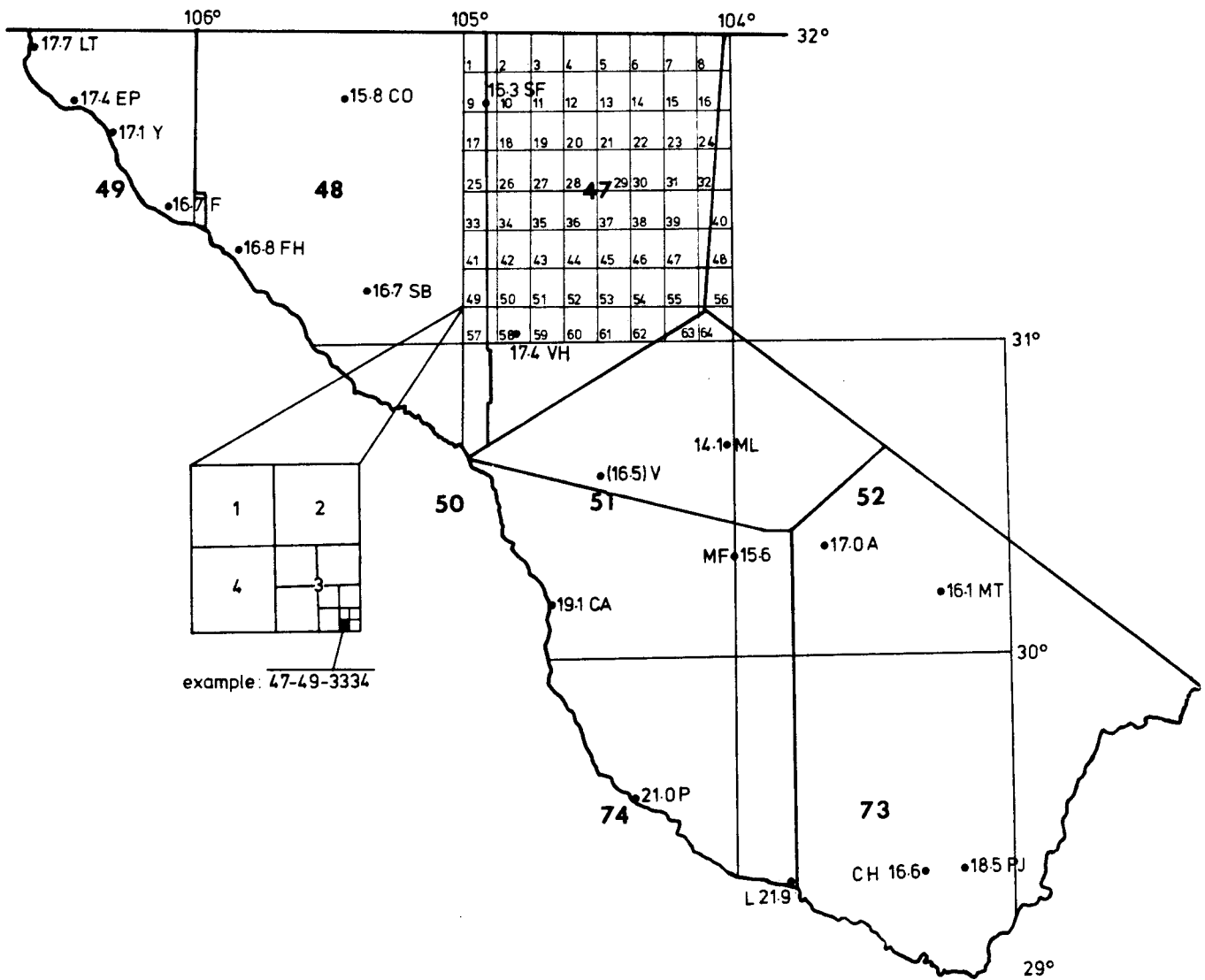


Figure 6 - Weather stations (with identifying letters) in West Texas. Mean annual surface temperatures shown in °C. Well-numbering system referred to later is shown in Block 47.

## EVALUATION OF GEOTHERMAL GRADIENTS

The gradients determined as discussed earlier have been combined to produce the map in Fig. 7. The location of and actual gradient values (in °C/km) are shown in Figs. 8, 9, 10 and 11. On the gradient maps, the following legend applies: 1) Solid Circles-gradients from temperature logs using THERML (Taylor, 1981), 2) Open Circles-gradients from successive downhole measurements in oil wells, 3) Solid Squares-pseudogradients from deep oil wells using PGRAD (Taylor, 1981), 4) Open Squares-pseudogradients from shallow water wells using PGRAD (Taylor, 1981). Table 1 summarizes the gradient information for the major basins of Trans-Pecos Texas, and adjacent highlands areas where there were sufficient data. A mean gradient is assigned to each area. Details of the wells, with corresponding temperature-depth plots, are given by Taylor (1981).

Some bias is present in the data since most temperature measurements were made in water wells, and all the shallow pseudogradients are situated in the basins of the region. However, since local geothermal manifestations are more likely to be fault-controlled, that is, in or near a basinal structure, the admitted bias toward basinal location should not impair the interpretations.

As can be seen from Fig. 7, and from the mean gradient values in Table 1, a general trend of higher gradients occurs in the west of the region, towards the Rio Grande, roughly paralleling the course of the river. This westerly location, paralleling the Rio Grande, probably has some tectonic significance. A similar observation by Henry (1979a), based on estimated gradients from deep oil tests, was thought to identify the transition between the Great Plains and Basin and Range provinces.

Some important features are examined in the following paragraphs:

### (1) Hueco Bolson (Fig. 7):

The northern Hueco Bolson (in El Paso County) in the vicinity of Hueco Tanks exhibits a high gradient. Two other higher gradient areas appear, one to the southwest of the Hueco Mountains and the other in the Finlay Mountains at the southeastern end of the bolson, mostly in El Paso County.

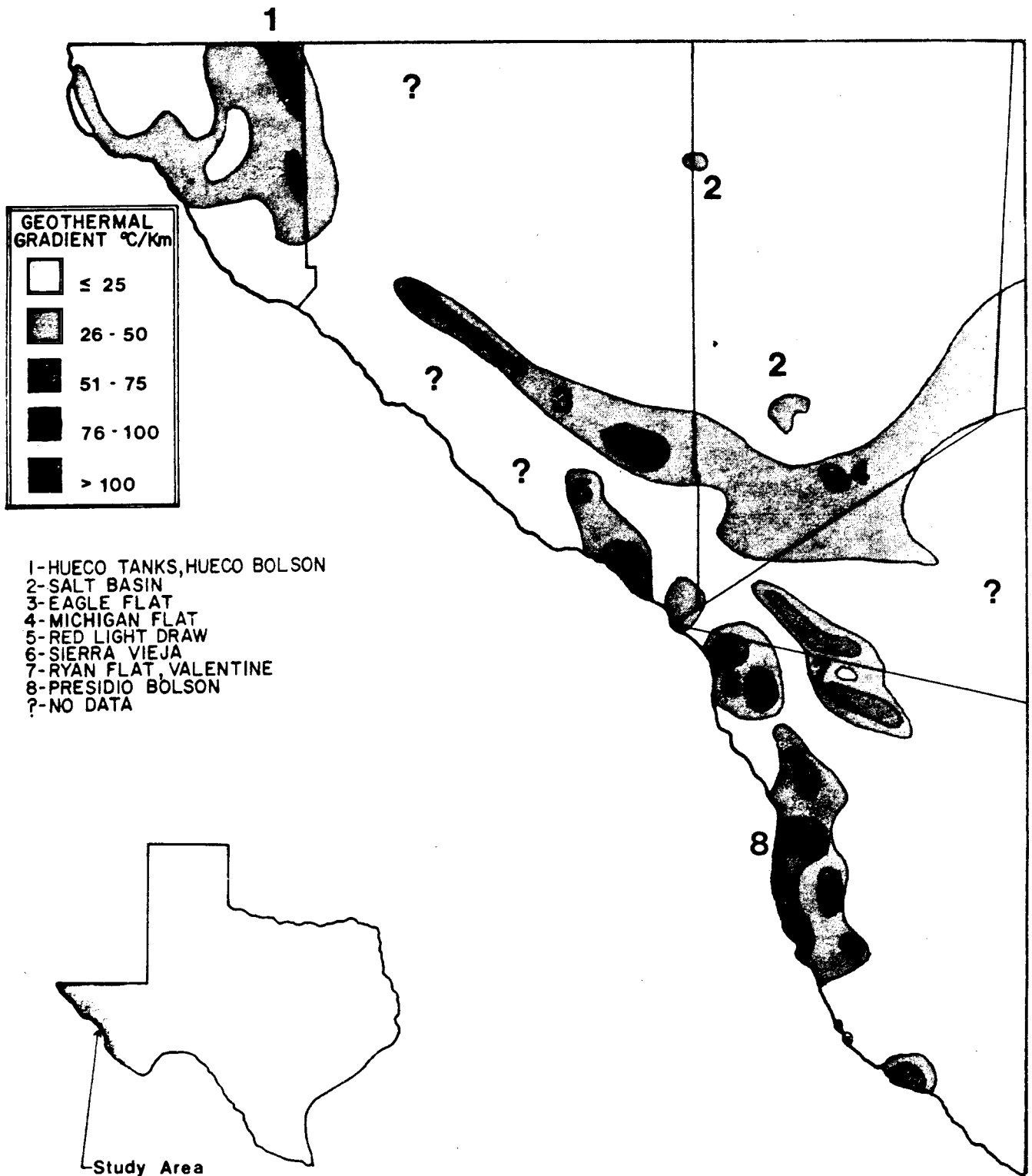


Figure 7 - Geothermal Gradients in West Texas.

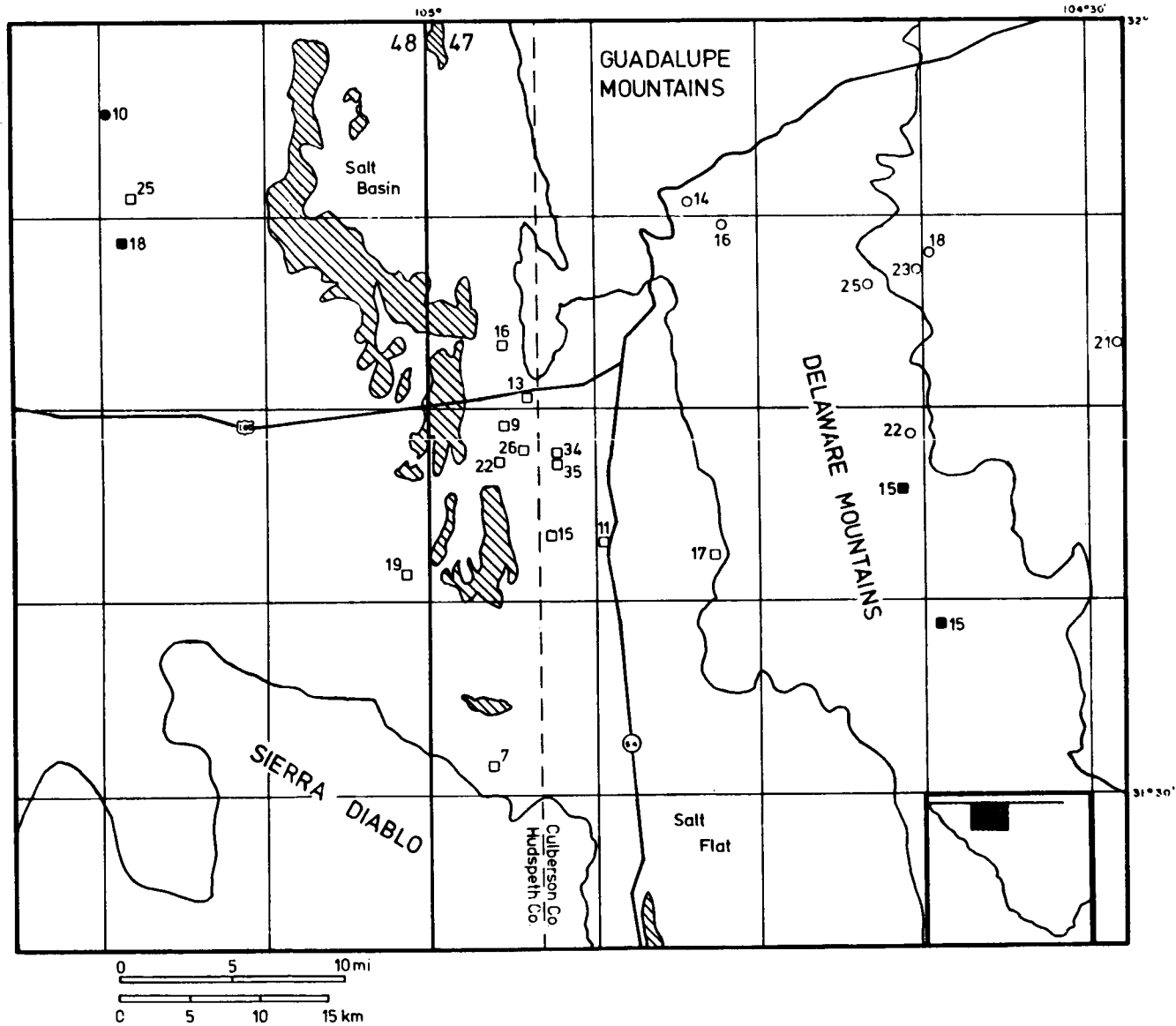


Figure 8 - Gradients in the Salt Basin (north), °C/Km.

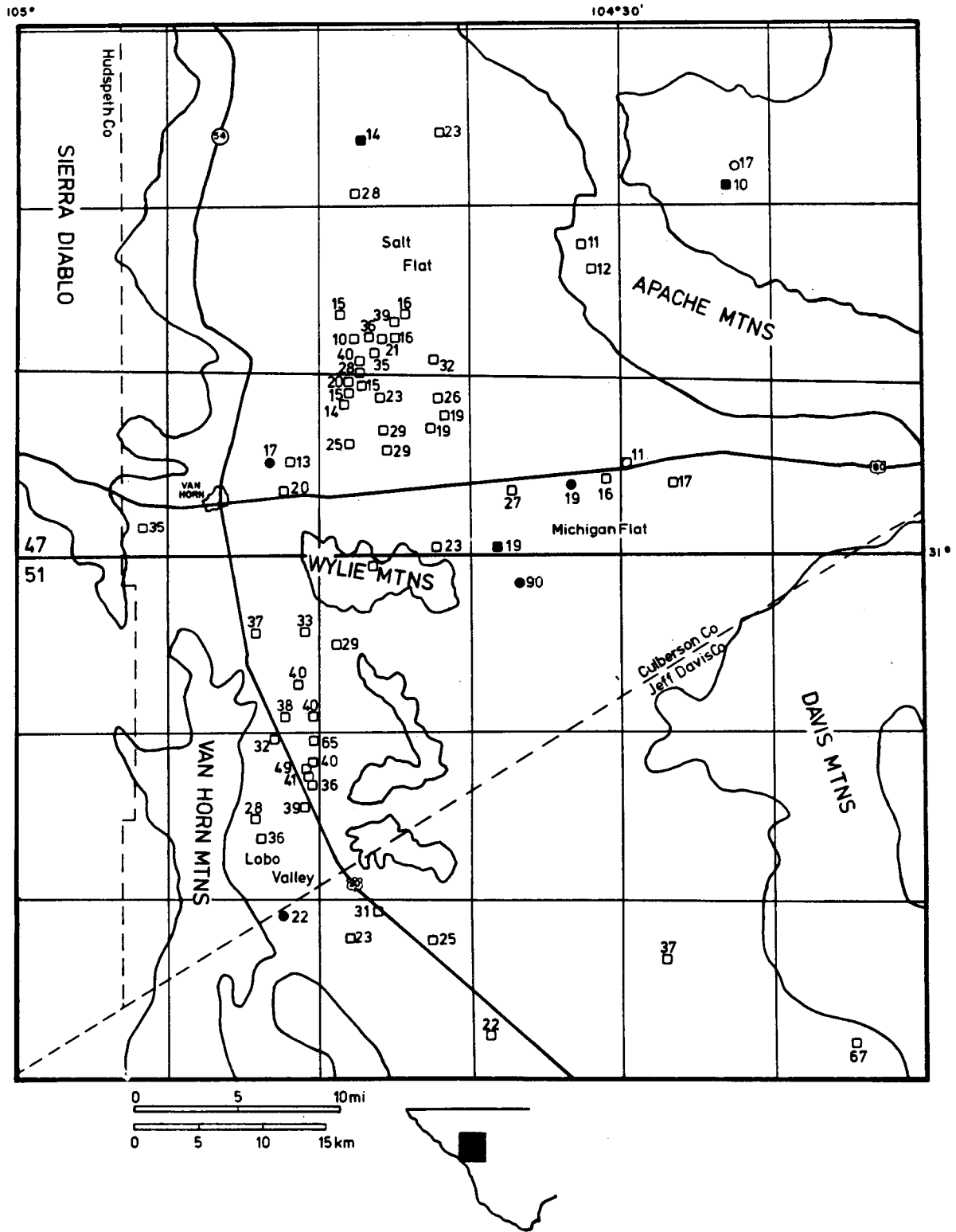


Figure 9 - Gradients in the southern Salt Basin, Michigan Flat and Lobo Valley, °C/Km.



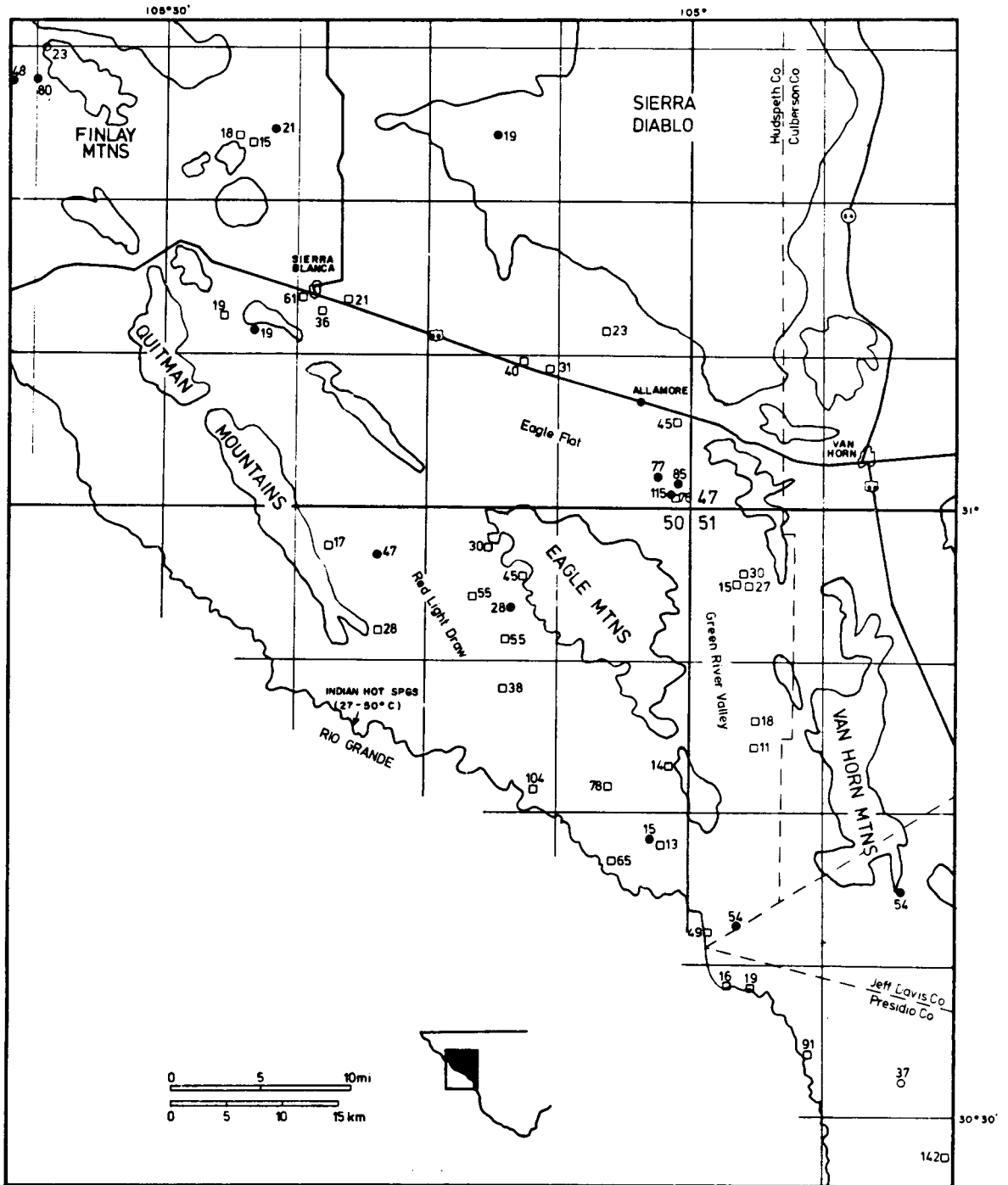


Figure 10 - Gradients in Eagle Flat, Green River Valley, Red Light Draw and adjacent Rio Grande Valley, °C/Km.



Table 1 - Summary of geothermal gradient data for West Texas

Area	Number of gradients:				
	Measured grad. (shallow)	Measured grad. (deep,oil)	P'grad. (shallow)	P'grad. (deep)	Mean value (°C/km)
Hueco Bolson	18	6	34	-	49
Diablo Plateau	4	2	2	2	19
Eagle Flat	4	-	9	-	89
Red Light Draw	3	-	12	-	42
Green River Valley	1	-	8	-	27
Salt Basin (North)	1	-	13	-	19
Delaware Mountains	-	12	1	3	19
Salt Basin (South)	1	-	28	1	22
Michigan Flat	2	-	5	1	28
Lobo Flat	1	-	20	-	35
Ryan Flat	14	-	4	2	38
Marfa Plateau	1	1	1	3	22
Sierra Vieja	12	3	4	3	46
Presidio Bolson	27	-	11	-	63
Totals:	<u>89</u>	<u>24</u>	<u>152</u>	<u>16</u>	

Note: "P'grad" = pseudogradient.

(2) Salt Basin (Figs. 8, 9):

Despite the evidence for recent tectonic movements (Reilinger et al., 1980) in the Salt Basin area, there appears to be no thermal manifestation, with gradients being "normal" for the Great Plains province. Two small areas of slightly elevated gradients correspond to heavily irrigated land, where the surface temperature is artificially lowered thus producing a higher gradient.

(3) Finlay Mountains (Fig. 10):

Measurements in two holes yielded higher than normal gradients ( $80^{\circ}\text{C}/\text{km}$  and  $48^{\circ}\text{C}/\text{km}$ ). The higher of these was in an old mineral exploration drill-hole which encountered a dioritic intrusion. The cause of the elevated gradient is not known, but probably involves a convective system.

(4) Eagle Flat (Fig.10):

A west-northwest trending fault-controlled convective system appears to be responsible for the elevated gradients near Allamoore, in Eagle Flat. The particularly high values occur in a much larger low-gradient zone of the same trend, running from east of Van Horn to the Finlay Mountains. A local well drilled by the Southern Pacific Railroad in 1907 encountered hot water (maximum temperature of  $40^{\circ}\text{C}$ , according to Henry, 1979a). The gradient in this study was found to be  $115^{\circ}\text{C}/\text{Km}$  (measured after the well pump had been inoperative for some months). A series of commercially drilled gradient holes were located on either side of the "hot well", and those still accessible in 1979 indicated a rapid decrease in gradient to the north and south.

A resistivity-sounding profile trending south from Allamoore (Gates et al., 1978) revealed a major normal fault, with a vertical displacement of some 1500m just to the north of the "hot well". This fault has been interpreted by Wiley (1970), based on gravity data, as the extension of the Rim Rock Fault. The fault trends from roughly north-south to west-northwest in orientation.

Groundwater in the area is low in dissolved solids with the "hot" well having less than 500ppm (White et al., 1978). The resistivity data (Gates

et al., 1978) give little indication of a potential geothermal fluid in the subsurface. Thermal gradients in wells to the southeast of the "hot" well are considerably lower, bolstering the assertion that the high gradient values are caused by the uprise of waters from depth, along the fault zone.

(5) Michigan Flat (Fig. 9):

With one exception, the gradients in the Michigan Flat area are comparable with those in the adjacent Salt Basin, to the north. The exception is the old "Alkaseltzer" (or "Sulphur") Well situated just to the east of the East Wylie Fault (Hay-Roe, 1957). The temperature gradient log for "Alkaseltzer" yielded 90°C/Km. This gradient was determined in 120m of air, but is nonetheless anomalous. Without further data to either support or discredit the measurement, the high value defies explanation. From the name, "Alkaseltzer", it is assumed that the water obtained from the well was originally effervescent (or sulphurous), possibly due to some chemical reaction in the underlying limestone (reported at a depth of only 20 ft in White et al., 1978)

Resistivity soundings in Michigan Flat (Gates et al., 1978) indicate high-resistivity limestone and unsaturated alluvium, giving no clue to a mechanism for the one high thermal gradient.

(6) Red Light Draw (Fig. 10):

Gradients are fairly high in Red Light Draw, increasing considerably towards the Rio Grande Valley to the south. A thin section of basin-fill overlies volcanic rocks on the west side of the draw, with a thicker section, down-dropped by faults, found to the east. Resistivity data (Gates et al., 1978) show a marked increase in depth of alluvium to the south, reaching 1200m. The material in the area of highest thermal gradients has a resistivity of less than 5 ohm-m, indicating the presence of saline, and possibly hot water.

At Indian Hot Springs resort, near the Rio Grande, hot water issues from shallow wells dug in the river alluvium near the trace of the

north-northwest trending Caballo Fault (Henry, 1979a). Reaser et al., (1975) proposed an igneous body at depth as a primary heat source, with the fault system providing conduits to the surface. A similar mechanism could be active in Red Light Draw, with the fault, inferred from the resistivity soundings, buried beneath basin fill.

(6) Northern Presidio Bolson; Sierra Vieja (Rim Rock County) (Fig. 9): The gradient anomaly in the northern part of the Sierra Vieja is of questionable authenticity, being based on three data points, two of which are shallow pseudogradients. The third point lends some credibility to the others. The  $37^{\circ}\text{C}/\text{Km}$  is derived from two downhole temperature measurements in an oil test (Gulf, First National Bank of Fort Worth, Trustee State "F" #1). The temperature at 11,688 ft (bottom hole) was  $305^{\circ}\text{F}$  ( $152^{\circ}\text{C}$ ), the highest temperature found in the region in the present study. This temperature is too low for the given depths to be of commercial interest.

Gradients as high as  $58^{\circ}\text{C}/\text{Km}$  have been measured in the southern Rim Rock Country. Two oil tests drilled by Gulf Oil Inc. produce artesian hot water with temperatures of  $72^{\circ}\text{C}$  (from 958m) and  $69^{\circ}\text{C}$  (from 874m), respectively.

(7) Valentine Valley (Ryan Flat) (Fig. 11)

A zone of intermediate geothermal gradients of up to  $75^{\circ}\text{C}/\text{Km}$  occurs in Ryan Flat, the southern limit of the Salt Basin drainage area to the southwest of the small town of Valentine. Data from twenty-four locations in the vicinity of Ryan Flat constrain the anomaly fairly well.

Gates et al. (1978) showed the Valentine Valley, which is exhibited as a gravity low (Covert, 1976; Mraz, 1977), contains varying thickness of alluvium and interbedded volcanic flows and tuffs. At its deepest point, in a north-south trending elongate trough near Valentine, the alluvium and interbedded flows and tuffs reach over 1 km in thickness.

Fig. 12 is a two dimensional representation of the three-dimensional temperature regime south of Valentine. The temperature-depth logs are shown in their relative areal positions. Each log is drawn with the same temperature and depth scales. The inset at top right shows the location of the boreholes. A severe temperature fluctuation is seen in several of the logs. The fluctuation is interpreted as a convective cell produced by uprise of warm water in a fault zone. The top of the cell probably occurs where the water flows out of volcanics into the overlying gravel (as evidenced by electrical soundings 46, 49, 50, and 51 in Fig 3e of Gates et al., 1978). This outflow causes a marked drop in temperature over a small vertical distance. The fault appears to be normal, downdropped to the west, and apparently oriented a little west of north. The fault might be an unexposed northward continuation of the fault along the Cuesta del Burro, a few kilometers to the south. Activity along fault trends in this area is known, as evidenced by the Valentine earthquakes of 1931 and 1955 (Sanford and Topozada, 1974; Dumas, 1980). A locally active fault system could provide a conduit for the observed hot water to reach the near surface.

It is unlikely that a geothermal resource of any magnitude exists in the immediate vicinity of Ryan Flat. Water at 47°C has been encountered in one irrigation well, but a convective system appears to be responsible for the occurrence of warm water at shallow depths. The somewhat elevated gradients are probably a reflection of the suspected convective system.

(9) Presidio Bolson (Fig.11, 13):

A large region of elevated gradients occurs in western Presidio County along the Rio Grande and adjacent parts of the Presidio Bolson. The bolson is a deep graben, some 70km north to south by about 20km east to west. Gravity modeling has determined the maximum thickness of fill to be greater than 1.5km (Mraz, 1977).

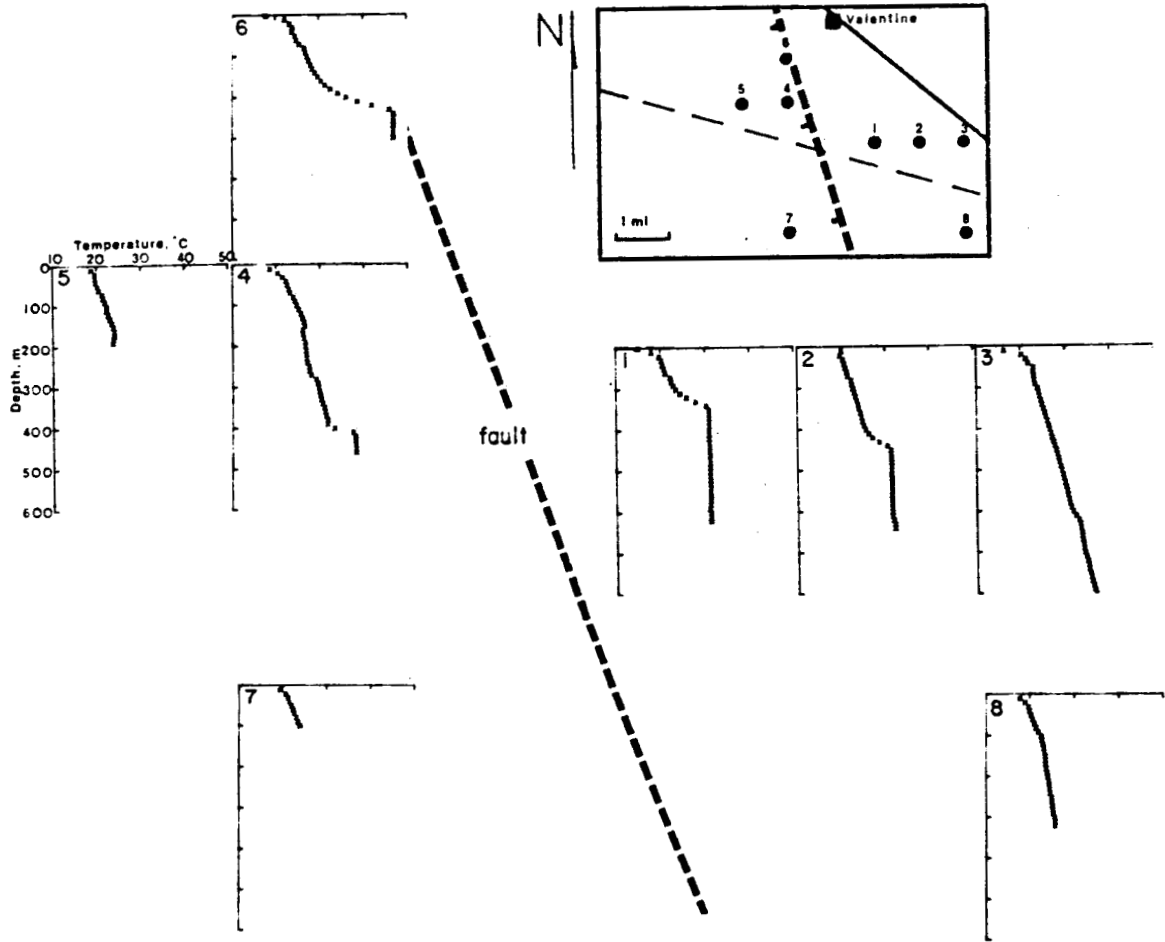


Figure 12 - Thermal gradients in the vicinity of Valentine, Texas  
 (All axes have same values as Graph 5)



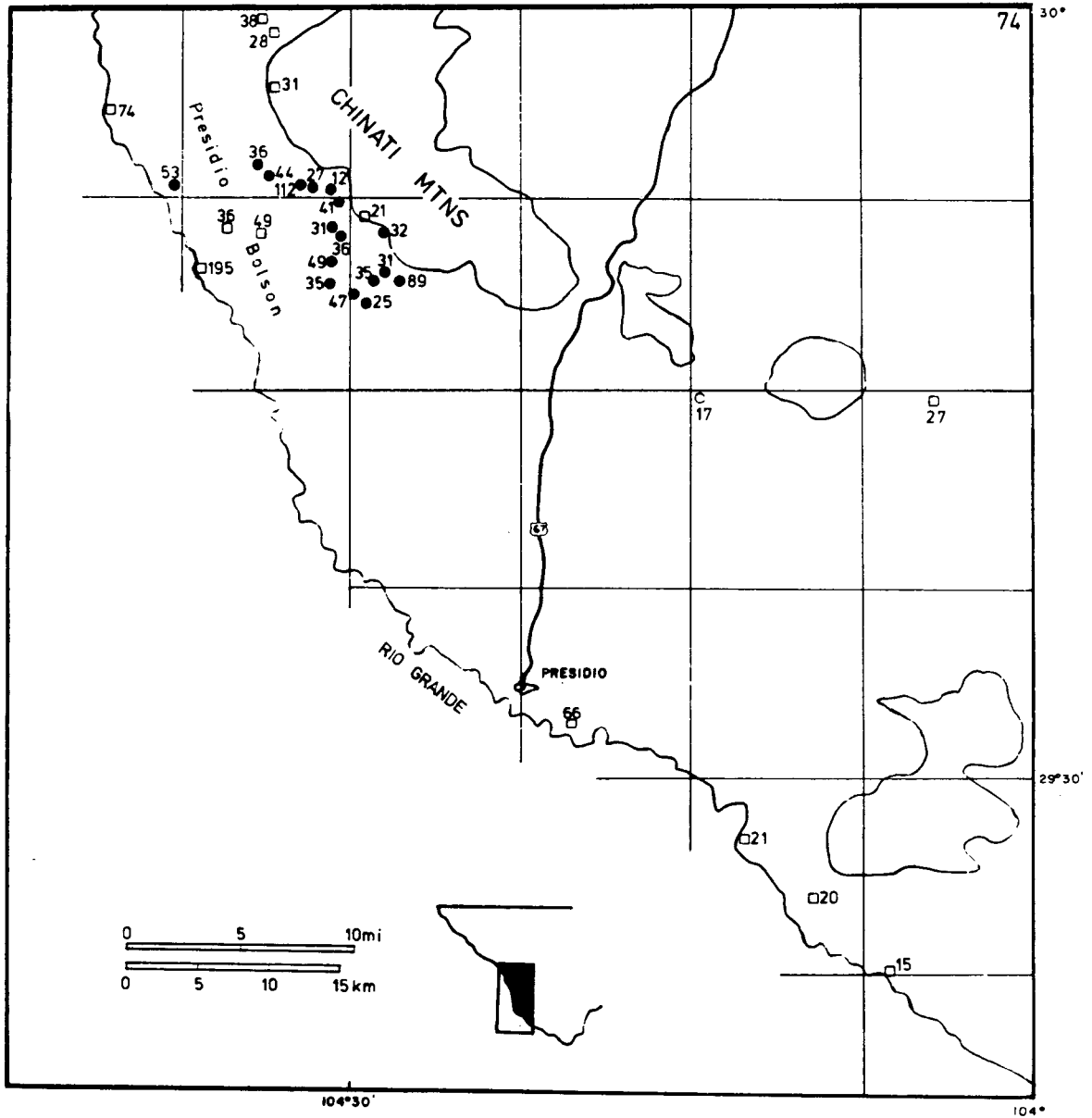


Figure 13 - Gradients in Southern Presidio Bolson and adjacent areas, (south) °C/Km.

Thermal gradients are highest in the area near Ruidosa Hot Springs, probably partly due to convection along the eastern boundary faults. It is likely that a high gradient zone exists across the Rio Grande in Mexico, where Ojos Calientes discharges water at 89°C near the western boundary fault. The 50m gradient hole drilled near Ruidosa (42°C/Km) seems to rule out a high gradient zone between the Ruidosa Hot Springs and the Ojos Calientes Hot Springs. The difference in water chemistry between the two hot springs also is not supportive of a genetic relationship between the two springs.

It is probable that a large area of the Presidio Bolson is underlain by warm but not hot waters, although indications are that the warmest part is the northern section, extending from Candelaria some 35 km southwards. Resistivity soundings (Gates et al., 1978) have shown the presence of an extensive low resistivity (less than 5 ohm-m) body in this area, interpreted as "alluvium" containing moderately saline water. This alluvium, or "bolson fill", is interbedded with calcerous and siliceous material in the northern bolson, which led Groat (1972) to suggest the existence of an old lake occupying the basin.

## DISCUSSION OF HEAT FLOW MEASUREMENTS

Heat flow data in West Texas are sparse, but the limited information supports the idea that West Texas is a transition zone between the Great Plains and Basin and Range Provinces. Herrin and Clark (1956) determined heat flows in the Permian Basin oilfields to be 1.1 Heat Flow Units<sup>1</sup>, typical of the Great Plains. Three values published by Decker and Smithson (1975) showed an increase to the west, to a maximum of 2.0 H.F.U. in northern Hudspeth County, signifying a Basin and Range heat flow. Other published measurements include a 1.3 H.F.U. in Big Bend National Park (Swanberg and Herrin, 1976), 1.5 H.F.U. near Big Bend and an anomalously low 0.6 heat flow in Chihuahua, about 60 Km west of the border town of Presidio.

During the course of the present study, 16 new heat flow values were determined in the five westernmost counties of Texas. These new measurements can be classified into two categories as follows:

- I - First-order heat flow measurements for which core or cuttings from known depths (for conductivity purposes) were available directly from the purposefully drilled holes. Five first-order measurements were made, of which three were in holes drilled for this study.
- II- Second-order heat flow measurements. In these, either cutting samples for conductivity determinations were taken from the cutting pile which collected near the top of a hole during drilling, or the conductivity was estimated from samples collected at nearby outcrops. Eleven second-order measurements were made.

---

<sup>1</sup>Heat Flow Unit (H.F.U.) =  $10^{-6}$  calories  $\text{cm}^{-2}$   $\text{sec}^{-1}$

The heat flow results are shown in Tables 2 and 3, with a summary of the geological settings in Table 4. Fig. 14 is a heat flow map of West Texas which utilizes all pre-existing and new measurements. On the map the areas over 2.5 H.F.U. and those areas between 2.0 and 2.5 H.F.U. are shaded differently for clarity. The values in the brackets are anomalous, and in the case of the Hueco Tanks, have not been used to define the shaded areas. First-order heat flows are indicated by underlining. Temperature-depth and gradient-depth plots for each hole measured prior to 1981 may be found in Taylor (1981); data for holes drilled since February 1981 are found in Appendix I. The earlier measurements were discussed in more detail by Taylor (1981).

The large area of high heat flow extending southeast through El Paso and Hudspeth Counties is fairly well defined on the eastern boundary, but the western boundary and internal conditions are not well known. The anomalously high measurement of 9.3 H.F.U. at Hueco Tanks should now be discounted because of the evidence for convective circulation found in subsequent studies, (See Figure 14). The 4.6 H.F.U. in the Finlay Mountains is thought to be valid and remain a likely target for further exploration. The 2+ H.F.U. region is characteristic of the Rio Grande Rift/Basin and Range as defined by Reiter et al. (1975) and Swanberg and Morgan (1978). Lack of data in the interior of the anomaly and adjacent Mexico precludes further interpretation.

The second feature of importance is the high heat flow area in Presidio County. Although based on second-order measurements, the data are consistent in defining an anomalous zone. It is probable that similar high heat flow values exist in neighboring Mexico, since this northern part of the Presidio Bolson has a number of hot springs on both sides of the Rio Grande.

Table 2 - First-order heat flow measurements, western Trans-Pecos.

Hole no.	Longitude/ latitude	Elevation (m)	Depth interval (m)	Gradient (°C/km)	Mean K (TCU)	Heat flow (HFU)		Ref.
						uncor.	cor**	
UTEP-1	106°30'33"	1210	80 - 115*	32.6	5.98(a)	1.96	1.97(I)	
	31°46'36"					(7) ±.02	±.02	
HT-12	106°06'05"	1264	180 - 260*	134.6	6.89(b)	9.36	9.27 J.Navar	
	31°59'30"					(12) ±.14	±.14	
PSH-1	105°23'30"	1280	30 - 60*	15.3	7.86(a)	1.20	--(II)	
	31°42'30"					(11) ±.01		
VHC-1	104°47'30"	1206	50 - 110	17.9	10.94(a)	1.95	1.96 City	of Van Horn
	31°04'20"		120 - 180	16.0	11.67(a)	1.84	1.84	
						(6) ±.05	±.05	
V-3	104°26'32"	1382	110 - 340	25.9	4.54(a)	1.18	-- C.Kov-	anda
	30°32'15"					(12) ±.10		

Notes:\*\* - terrain corrected

\* - mostly above water table

(a) - cuttings

(b) - core

I - reduced heat flow, 1.82 HFU

II - reduced heat flow, 0.58 HFU

(7) - number of conductivity measurements

Table 3 - Second-order heat flow measurements, western Trans-Pecos Texas.

Hole no.	Longitude/ latitude	Elevation (m)	Depth interval (m)	Gradient (°C/km)	K (TCU)	Heat flow (HFU)	Ref.
<u>Limited conductivity:</u>							
FM-1	105°37'08" 31°21'23"	1415	30 - 130*	79.5	5.98 (3)	4.77 ±.07	S.Wilkey, B.French
OP-4	104°30'00" 30°00'00"	1372	20 - 60*	27.8	8.16 (2)	2.27 ±.02	F.Shely
CHN-2	104°33'45" 29°53'45"	1112	30 - 67*	28.2	8.56 (2)	2.41 ±.02	C.Davis
<u>Estimated conductivity:</u>							
BR-1	104°33'45" 30°15'00"	1270	40 - 60*	43.5	4.6	2.0	J.White
LG-1	105°12'01" 30°55'17"	1233	150 - 340	27.8	7.6	2.1	U.S.G.S.
PL-1	104°32'00" 31°02'45"	1537	75 - 185	18.5	6.4	1.2	
VZ-2	104°33'45" 30°07'30"	1180	30 - 190*	60.8	4.6	2.8	Vizcaino Bros.

continued overleaf

Table 3 - Second-order heat flow measurements, western Trans-Pecos Texas. (Continued)

Hole no.	Longitude/ latitude	Elevation (m)	Depth interval (m)	Gradient (°C/km)	K (TCU)	Heat flow (HFU)	Ref.
BRM-1	105°02'00" 30°43'45"	1056	65 - 95*	15.3	7.6	1.2	J.Bramlett
AR-1	104°04'00" 30°02'30"	1372	40 - 85	25.1	4.5	1.1	W.Shirley, G.Nixon
LOV-5	104°38'30"	1151	15 - 46	36.2	4.6	1.7	B.Chambers

Note: \* - mostly above water table.

(3) - no.of conductivity measurements.

Table 4 - Geological setting of heat flow holes, western Trans-Pecos. Texas.

Hole no.	Location	Geological description	Use of hole
UTEP-1	UTEP Campus, El Paso	Tertiary andesite porphyry	Heat flow measurement
HT-12	Hueco Tanks, El Paso Co.	Bolson fill; cherty limestone (Pennsylvanian)	Geothermal exploration <sup>n</sup> , heat flow
PSH-1	Pump Stn. Hill, Hudspeth Co.	Precambrian rhyolite	Heat flow measurement
VHC-1	Van Horn Airport, Culberson Co.	Bolson fill (Quaternary)	Water supply well
V-3	Valentine, Jeff Davis Co.	Bolson fill, Tertiary volcanics	Irrigation well
FM-1	Finlay Mtns., Hudspeth Co.	Tertiary diorite porphyry	Mineral exploration
OP-4	Pinto Canyon, Presidio Co.	Tertiary rhyolite breccia	Mineral exploration
CHN-2	Chinati Mtns., Presidio Co.	Bolson fill (Quaternary)	Mineral/geothermal exploration
BR-1	Sierra Vieja, Presidio Co.	Interbedded tuffs and lava flows (Tertiary)	Water well?
LG-1	Red Light Draw, Hudspeth Co.	Bolson fill (Quaternary) and Tertiary volcanics	Water exploration
PL-1	Michigan Flat, Culberson Co.	Limestone (Permian)	Water well
VZ-2	Sierra Vieja/ Presidio	Interbedded tuff and Bolson, rhyolite (Tertiary)	Water well
BRM-1	Indio Mountains, Hudspeth Co.	Bolson fill (Quaternary)	Water well

continued overleaf



Table 4 - Geological setting of heat flow holes, western Trans-Pecos, Texas. (Continued)

<u>Hole no.</u>	<u>Location</u>	<u>Geological description</u>	<u>Use of hole</u>
AR-1	Marfa Plateau, Presidio Co.	Basalt and tuff (Tertiary)	Water well
LOV-5	Sierra Vieja, Presidio Co.	Tuff (Tertiary)	Geothermal exploration



A heat flow model derived from a finite differences computer program is presented in Fig. 15. The model represents the change in crustal thickness from Great Plains to Basin and Range, consistent with the previous models of Warren et al. (1969), Roy et al. (1972) and Decker and Smithson (1975), for the southern Rio Grande Rift. The crust is shown as an upper "granitic" layer and a lower "gabbroic" layer, separated from the upper mantle by the Moho ("M" in the Figure). Additionally, a constant temperature prism (at 1100°C) has been inserted into the lower crust to explain the sharp increase in heat flow observed. This model is a two-dimensional model. The temperature prism can be explained in terms of a "magma chamber" (albeit at 25km), however, the mechanism for the high heat flow may be a much shallower convective system, in which groundwater, circulating deep into the Presidio Bolson, becomes heated and rises to the surface. Supporting the convective system hypothesis is the presence of artesian hot wells in the area which indicate strong underground water flow.

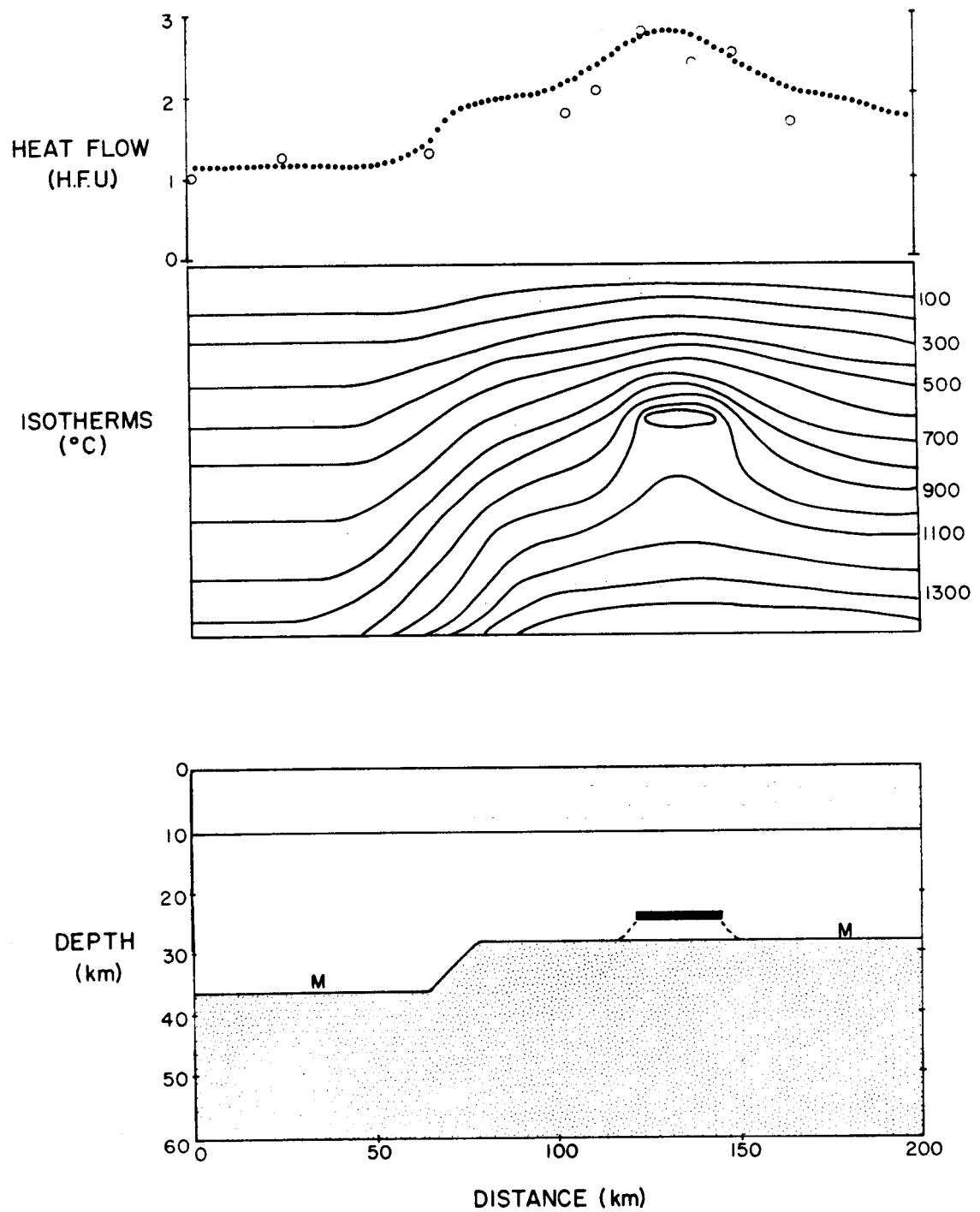
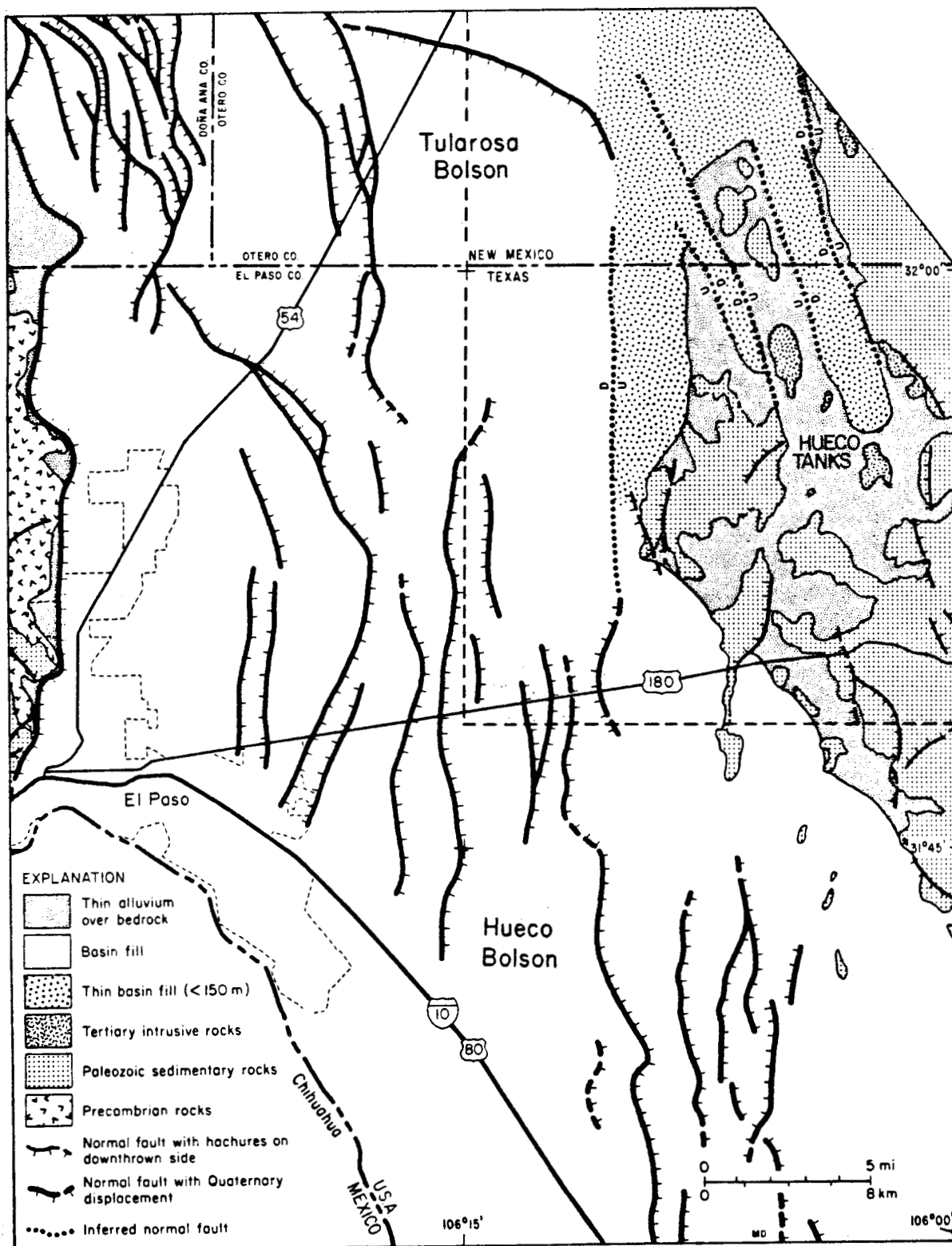


Figure 15 - Heat flow model for West Texas (A-A' in Fig. 14).

## POSSIBLE LOCATION OF GEOTHERMAL WATERS IN HUECO AND PRESIDIO BOLSONS

The Hueco Tanks area lies on the east side of the Hueco Bolson which is an asymmetric graben (See Figure 16). Boundary faults on the west side of the Hueco Bolson display the greatest displacement while smaller, lesser displaced faults form an irregular eastern boundary. Faults on the eastern side may allow the rise of geothermal waters from depth. The study team conducted tests to clarify the location of these faults and the geothermal waters potentially associated with them. As noted earlier, the rough lineation of "hot wells" along the eastern margin of the Bolson may delineate one of the faults, and, thus, this area was selected as a "target area" for our research. This lineation coupled with the findings of Hoffer (1977) in his geothermometry study further defined the area near Hueco Tanks in which various geophysical investigations were conducted.

The origin of high heat in the Hueco Bolson is thought to be the area's normal thermal gradient. Heat flow and thermal gradients in the Basin and Range Province and the Rio Grande Rift zone are typically high when compared to temperature gradients in cratonic areas. Thermal gradients of Hueco Tanks are probably of minimum of 30°C/kilometer (Henry, 1979a; Roy and Taylor, 1980) compared to a cratonic average of less than 20°C/kilometer. Decker and Smithson (1975) contend that the crust of the earth is 31 Kilometers thick in the Hueco Tanks area. This thinner crust produces a higher than normal thermal gradient. If groundwater circulated to a depth of about 2 kilometers it would be heated 60°C or more above its average surface temperature with a final near surface temperature of slightly more than 80°C. If circulation were deeper, higher water temperatures would be attained. Geothermal waters in the Hueco Tanks area may rise along the normal faults that form the eastern edge of the Hueco Bolson. The five known hot wells in the area trend along a north/northwest line from near Hueco Tanks State Park to the Davis Dome area in New Mexico. The thermal waters do not naturally discharge at the surface because the water table is 400 feet or more below ground level. Because the thermal water is probably rising along fault zones, it is important to know of the



After Seagar (1980)

Figure 16 - Location of Hueco Tanks

locations of faults or fault zones in the study area. The five positively identified hot wells and the area of anomalously high thermal gradients delineated by Roy and Taylor (1980) form a linear trend that may follow a fault zone.

The Presidio Bolson was selected for further study on the basis of its high heat flow readings, high thermal gradient measurements, indicative gravimetric data, the existence of "hot" springs including Ojos Calientes (nearby in Mexico) the presence of silicious, "hot" spring deposited material at the surface, resistivity soundings, and numerous known faults.

## GEOPHYSICAL STUDIES IN THE HUECO AND PRESIDIO BOLSONS

### MICROEARTHQUAKE MEASUREMENTS

Microseismic recording was conducted for one month in the Spring of 1980 in the Hueco Bolson. Six MEQ-800 microearthquake recorders were deployed over McGregor Range and the Hot Wells Ranch at locations where the bedrock was near the surface. It was anticipated that frequent artillery explosions and missile impacts along with the movement of heavy, tracked vehicles in the vicinity of the instruments might disrupt the microearthquake recordings. This fear proved unfounded. The equipment operated satisfactorily but did not record a single local microearthquake event in the Hueco Bolson.

Local seismic events are, however, known to occur from reports in the literature. Earthquakes have been reported in the Hueco Bolson, ranging from instrumentally detectable to a 4.3 Richter magnitude occurrence (Sanford and Topozada, 1974; G.R. Keller, personal communication). Unfortunately, the exact locations of the events are unknown.

Microearthquake measurements were taken for a thirty day period in the Presidio Bolson. Each of three emplaced Digital Event Recorders failed, while three MEQ-800 units deployed in the array performed well. No microseismic events were recorded in the interior of the array. An event did occur to the west of the array in Mexico and was recorded on three instruments. The exact location is uncertain. The event in Mexico may be encouraging, but no substantive evaluation of its importance can be made.

### GRAVITY MEASUREMENTS

#### Hueco Bolson

Figure 17 is a Bouger gravity map of the Hueco Bolson, which is bounded by the Franklin and Hueco Mountains. Figure 17 is taken from the "Complete Bouger Gravity Anomaly Map of the Rio Grande Rift" by Cordell et al.



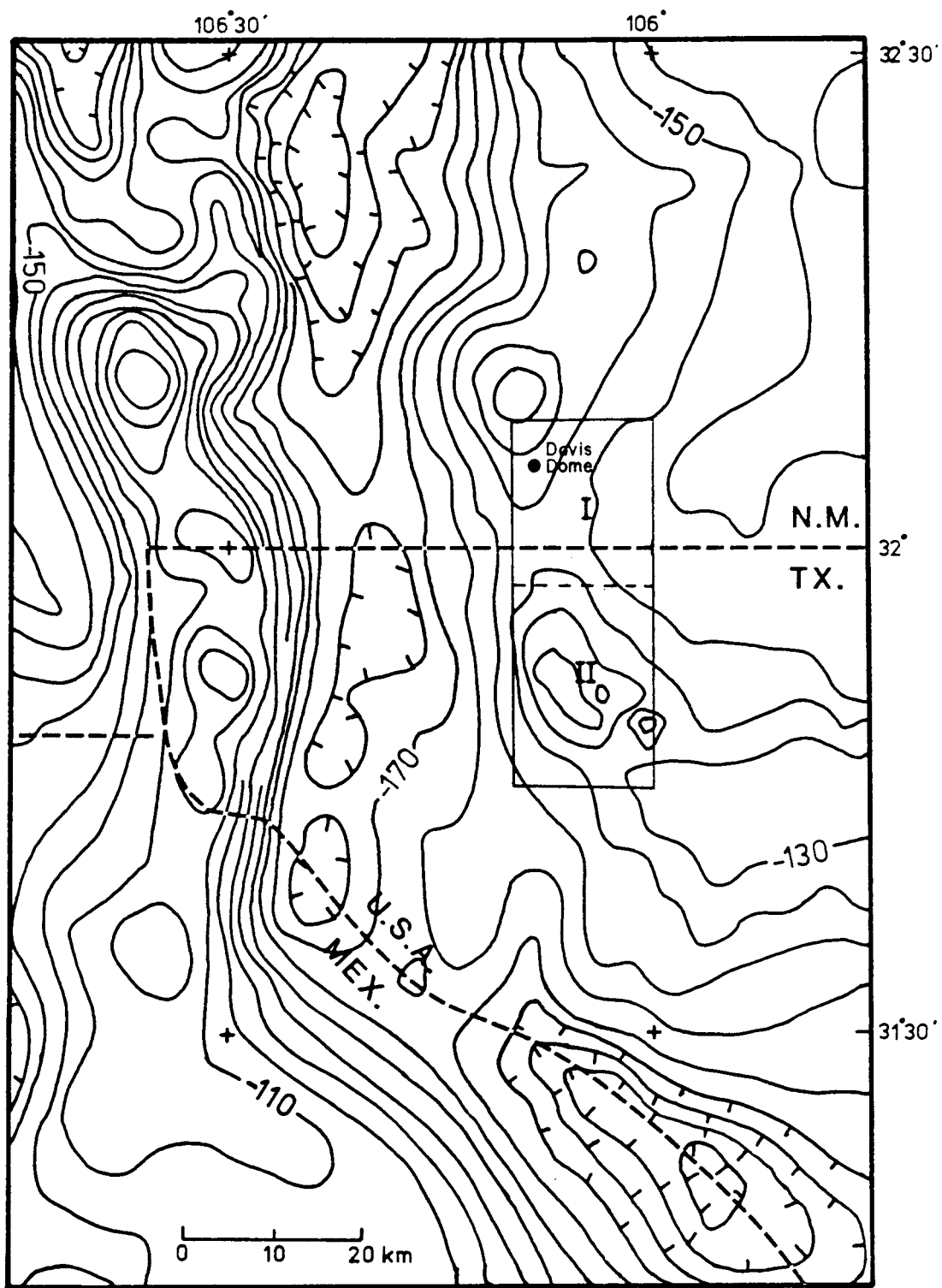


Figure 17 - Complete Bouguer gravity map of Hueco Bolson (from Cordell et al., 1978). Areas denoted by 'I' and 'II' refer to the detailed gravity survey shown in Fig. 18.

(1978), which was compiled largely from Department of Defense data. The north-trending positive anomaly on the west side of Figure 17 outlines the Franklin Mountains. To the east, the Hueco Mountains are not as well defined. The intervening gravity "low" corresponds to the Hueco Bolson and appears to be deepest to the southeast.

A detailed gravity survey was conducted for the present project in the presumed geothermal area, from Davis Dome (McGregor Range) in the north, as far south as Highway 180 (south of Hueco Tanks State Park). Zone I in Fig. 17 indicates the area of closest station spacing, and most accurate elevation measurements; Zone II is the area of wider spacings. Some 260 readings were made in all. The resulting Bouguer anomaly map is shown in Fig. 18; the contour interval is 2 mgal. Certain broad scale features are merely amplifications of those in Fig. 17: These include the "highs" in the southern and northernmost parts of the map, and the increasing "low" to the west, where the Hueco Mountain outliers drop away into the bolson.

Important features exposed by the detailed coverage are as follows:

(1) A marked northwest-southeast trend extending from about  $31^{\circ}52.5'N/106^{\circ}00'W$  (southeast of Hueco Tanks Park) to about  $32^{\circ}05'N/107^{\circ}10'W$  (west of Davis Dome) which appears to mark the trace of a fault or fault-zone. In the vicinity of Hot Well ( $32^{\circ}00'/106^{\circ}07'$ ), an adjacent high and low (hachured) probably represent respectively the up- and down- thrown blocks of this fault. The faults interpreted by the self-potential method are found in this location; (2) A less well defined north-south lineation extending south from about  $32^{\circ}07.5'N/106^{\circ}05'W$  parallels the trend of the Hueco Mountains, fading out near the southern gravity "high". Since the gravity trend follows the eastern edge of the line of outlying hills, it probably indicates another fault.

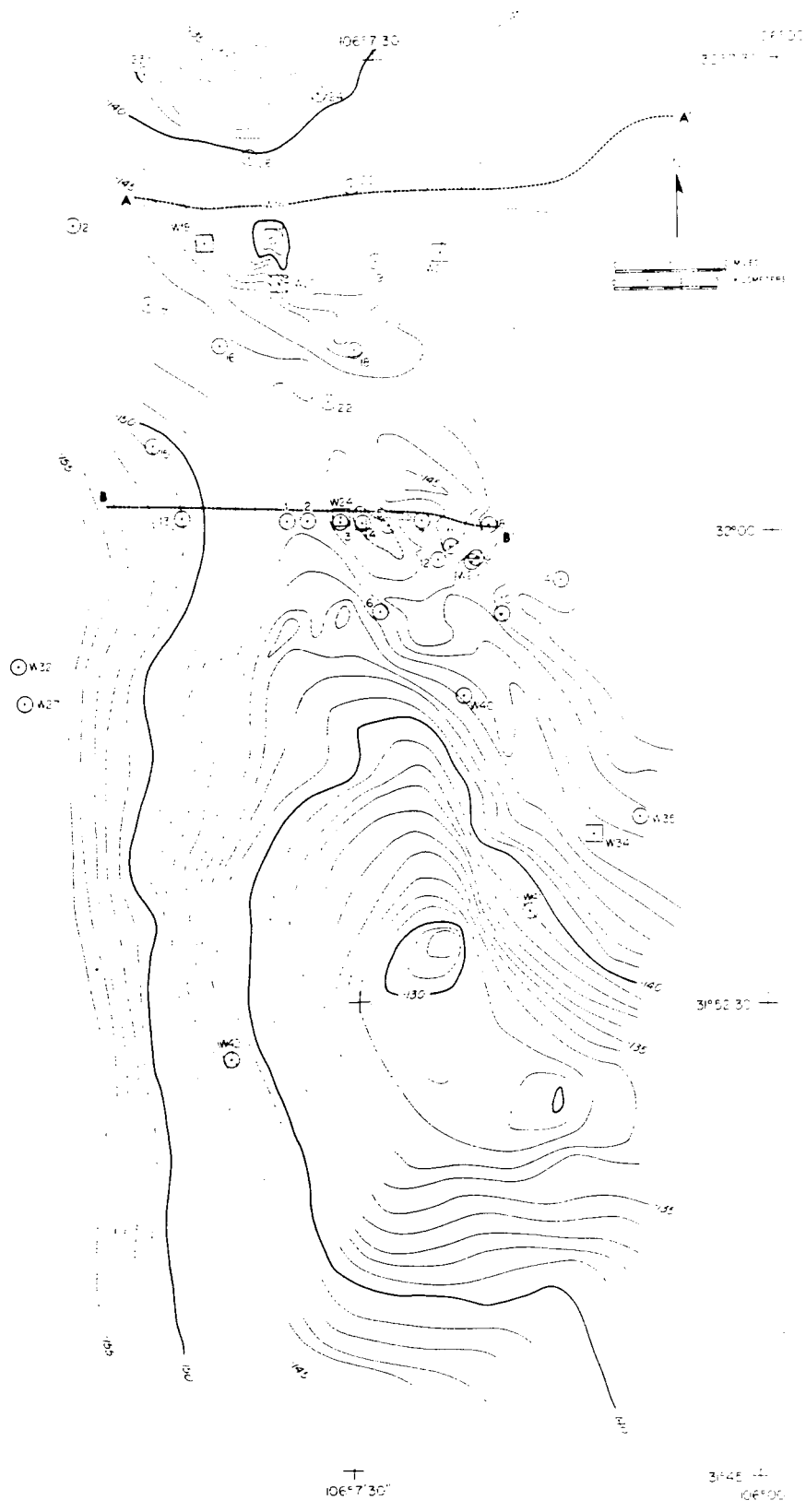


Figure 18 - Bouguer gravity map of Hueco Tanks Area. Profile lines marked A-A' and B-B'. Numbered circles are gradient holes; 'W' numbers refer to Table II (i). Circles are thermal gradient measurements, while squares are bottom-hole temperatures.

The lines A- A' and B- B' on Fig 18 locate the two-dimensional gravity models in Figs. 19 and 20. The models are crude geological sections believed to be feasible in the area based upon the gravitational attraction of different density rocks. Bolson fill is represented by a density of  $2.2\text{g/cm}^3$  which is an average value for these type unconsolidated sediments. The Hueco Bolson is seen deepening rapidly westwards on both sections, probably displaced by a fault. A small basin is proposed to the east of the limestone outliers (taken as  $2.65\text{ g/cm}^3$ ) and is apparently a graben structure downdropped between the Hueco Mountains and the outliers. Yet another small graben is modelled in section B-B', just to the east of Hot Well. Its bounding faults are coincident with those proposed from the self-potential survey.

The modeling of igneous material ( $2.67\text{g/cm}^3$ ) so close to the surface is supported by the presence of Tertiary intrusives in the Hueco Mountains and the occurrence of "granite" in logs from nearby wells.

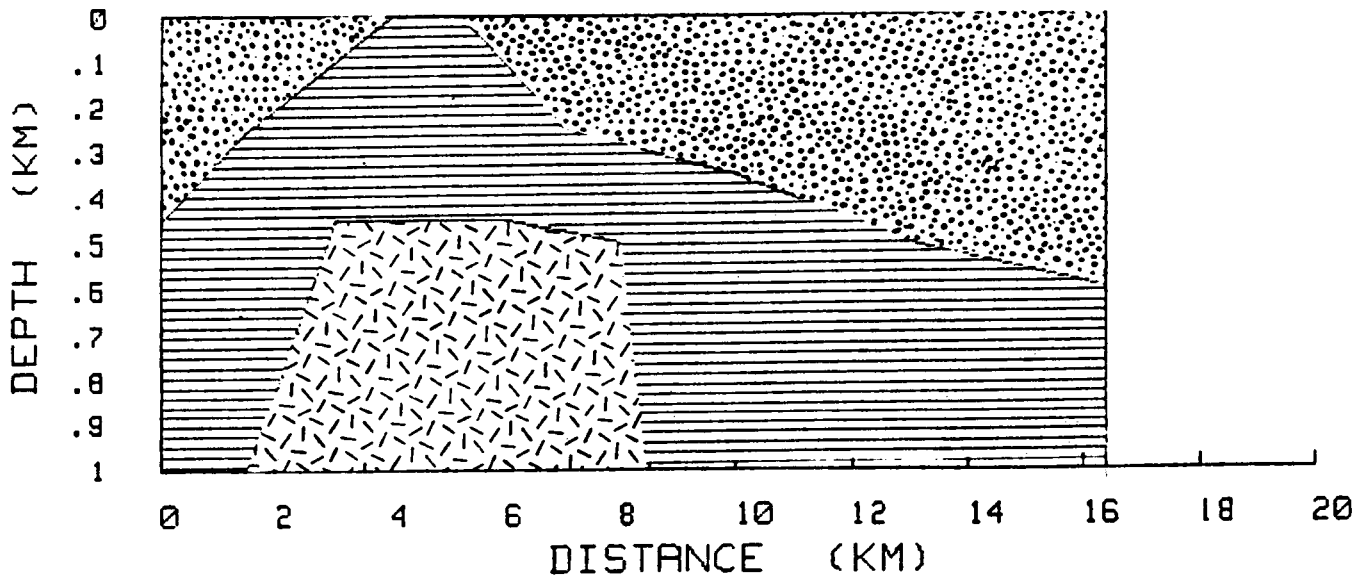
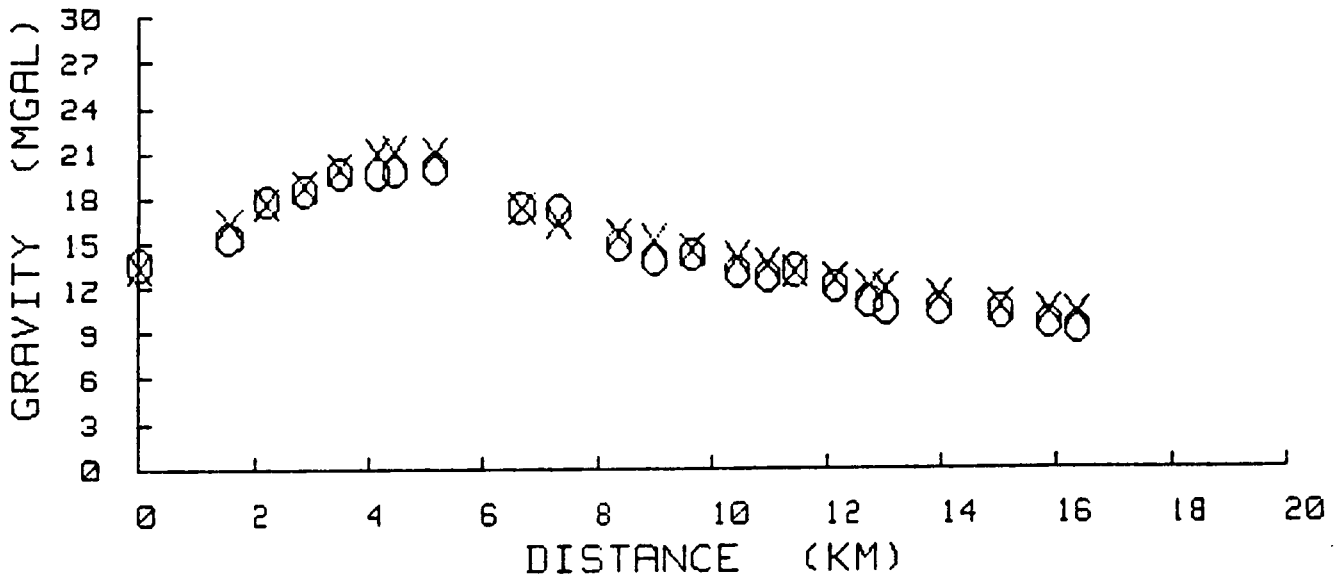
### Presidio Bolson

The project team is conducting a gravity study of the Presidio Bolson with much tighter spacing than the existing study, but results are not anticipated until late 1983. The gravity analysis is being funded by local electricity producers in Trans-Pecos, Texas. The ensuing discussion of gravity data is taken primarily from a Texas Bureau of Economic Geology publication entitled "Structure of the Presidio Bolson Area, Texas, Interpreted from Gravity Data" by Mraz and Keller (1980).

Figure 21 is the "Bouger Gravity Anomaly Map of the Presidio Bolson Study Area, Presidio County, Texas" as developed by Mraz and Keller (1980). The Chihuahua Tectonic Belt to the west of the Presidio Graben is seen as a northwest trending, linear, gravity maximum. The Presidio Graben, is seen as a gravity low paralleling the Rio Grande. The Valentine Basin

A-A'

O OBSERVED  
X THEORETICAL



Corresponding geological model.




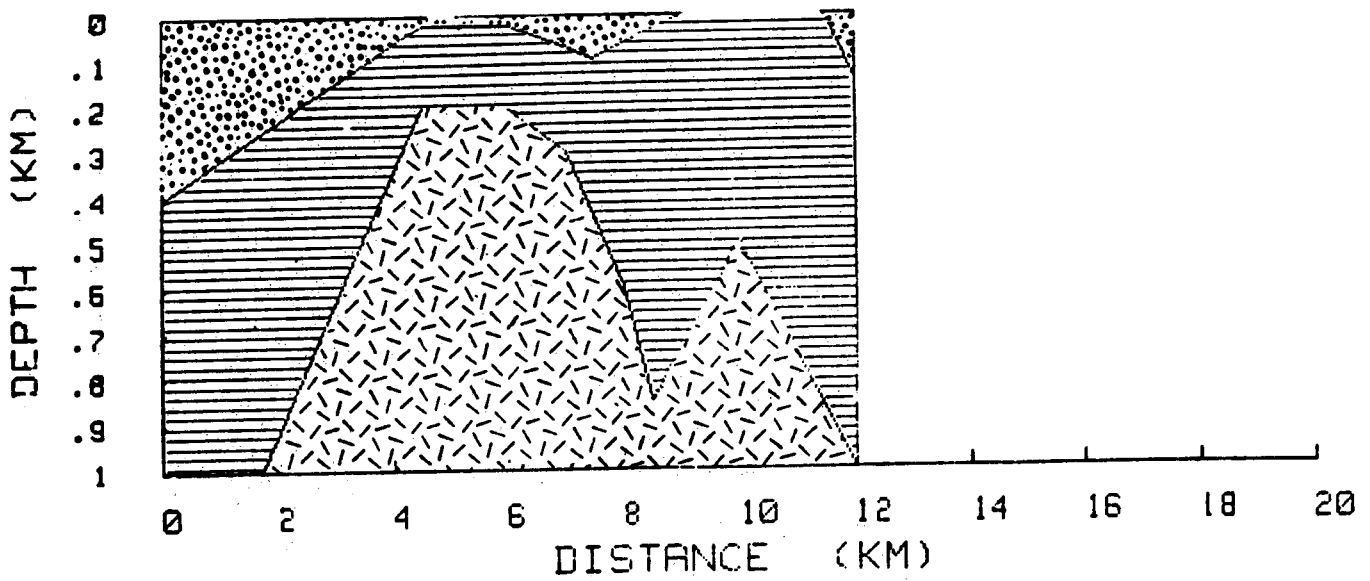
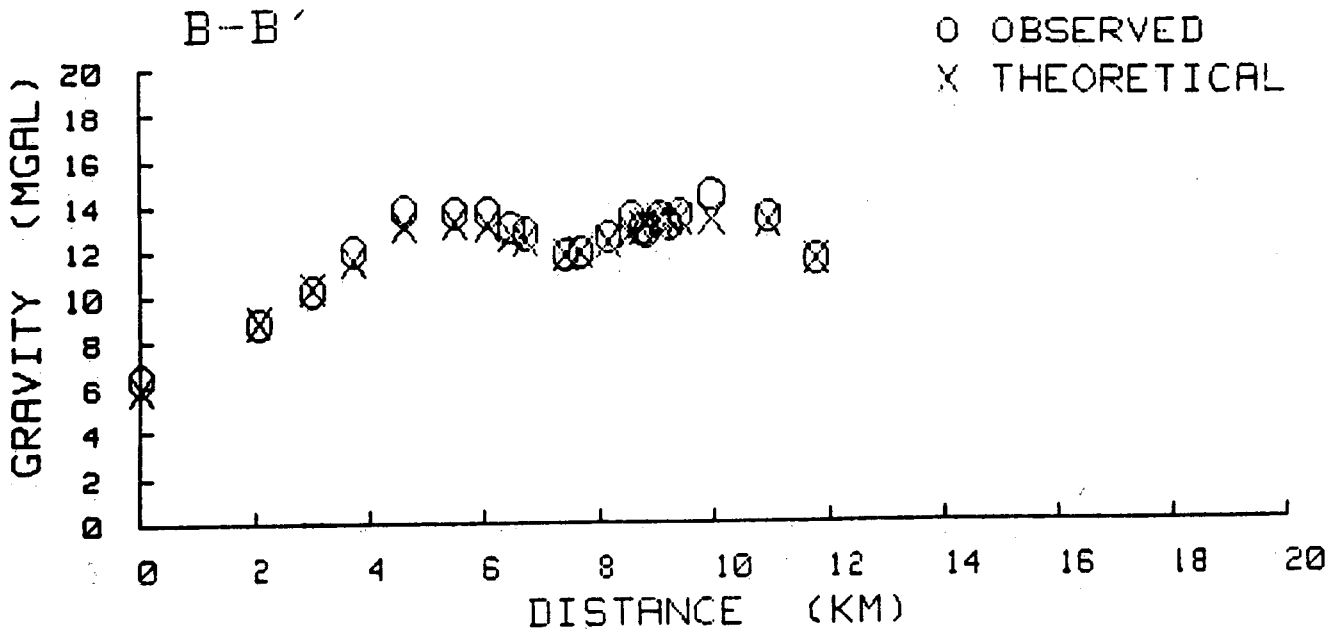
- DENSITY (g/cc)
-  2.2 Bolson Fill (unconsolidated sands, gravels, clay)
  -  2.65 Limestone
  -  2.67 Igneous Rock (syenite)

Figure 19 - Two dimensional gravity model A-A'  
(located in Fig. 18).



Corresponding geological model.

DENSITY (g/cc)




-  2.2 Bolson Fill (unconsolidated sands, gravels, clay)
-  2.65 Limestone
-  2.67 Igneous Rock (syenite)

Figure 20 - Two dimensional gravity model B-B'.

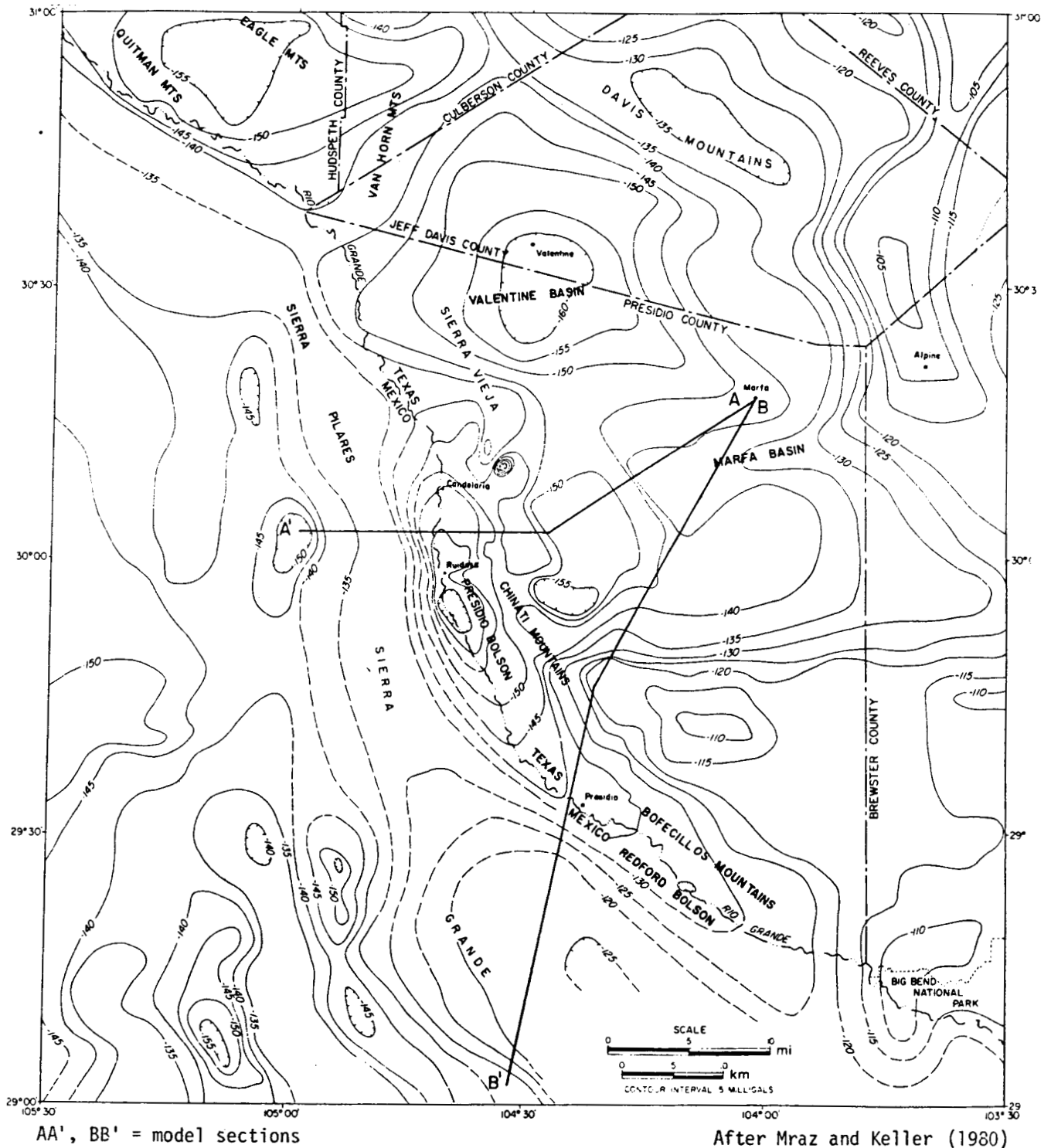
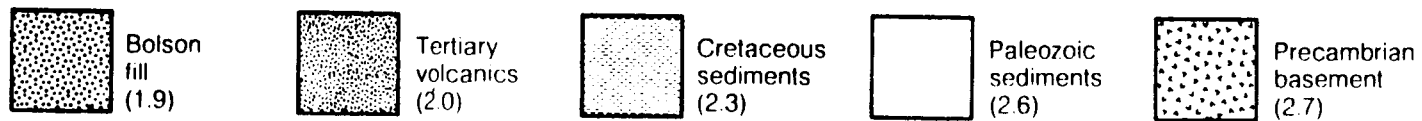
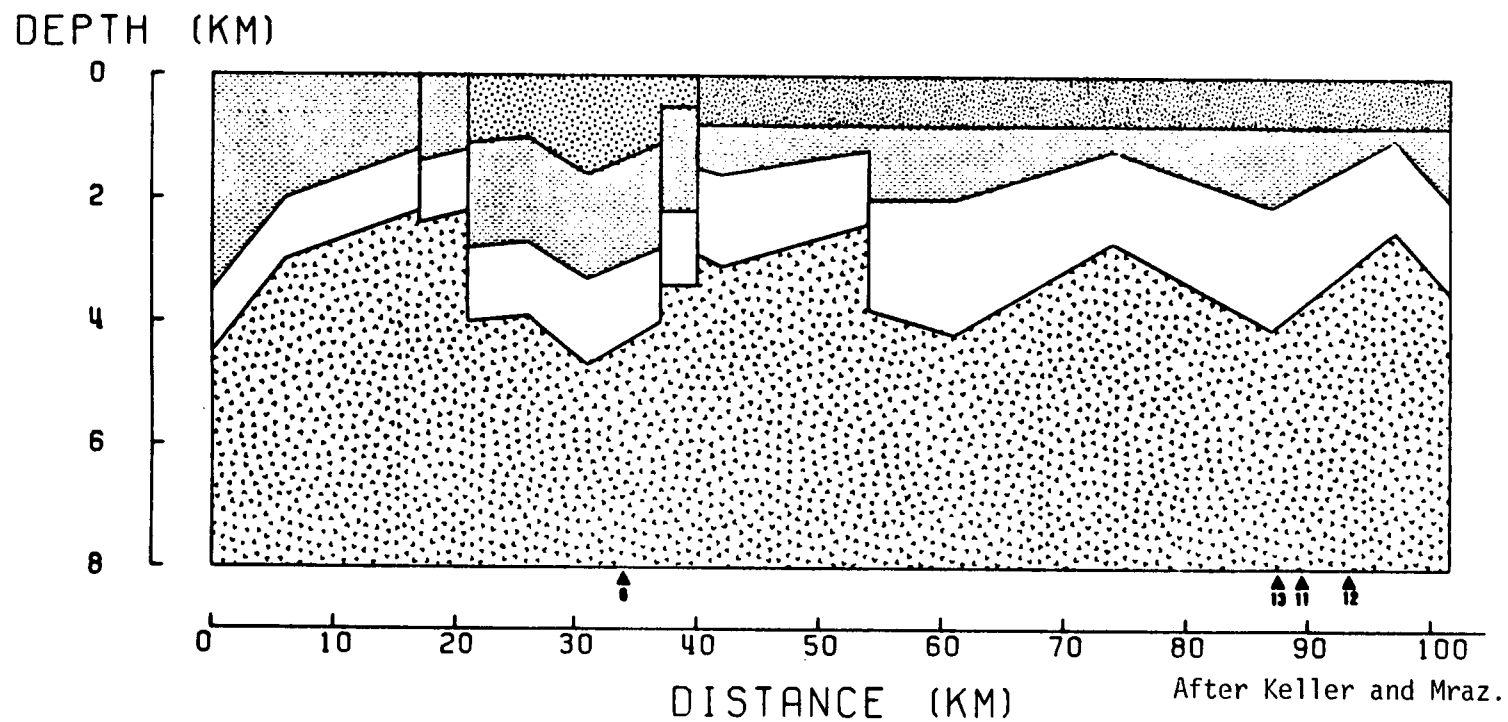
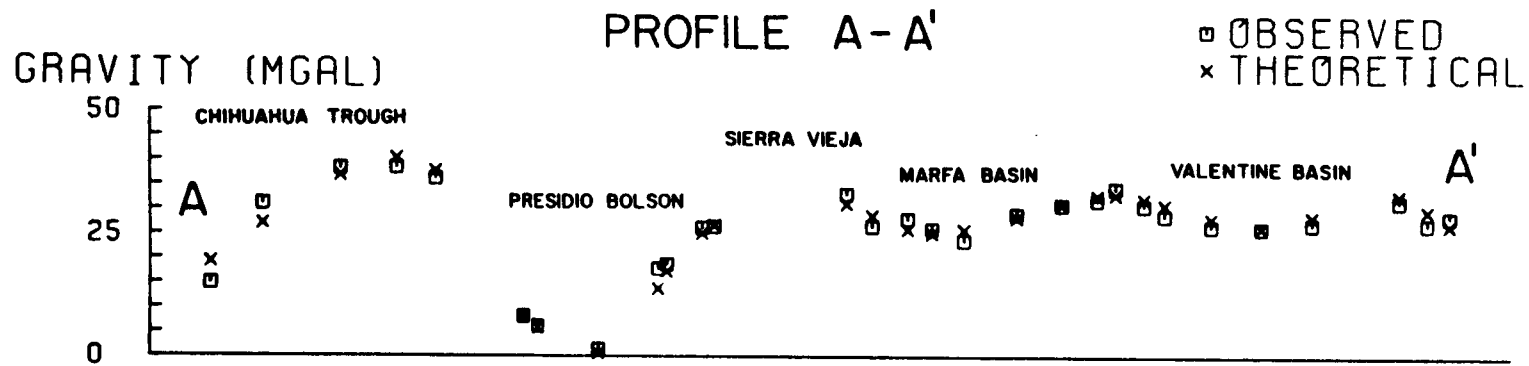


Figure 21 - Regional Bouguer anomalies of the Presidio County area.

(Covert, 1976) is represented by a gravity low centered on the Presidio/Jeff Davis county line. The Redford Bolson is shown to the south of Presidio. An extensive gravity high is seen to the east and north of Presidio. North of this high is an east-west trending low which Mraz and Keller (1980) interpret as the Marfa Basin. The Presidio Graben (Bolson) is about 70 km long and 15 to 20 km wide at its deepest (about 1.5 km) in the Ruidosa area. Based on the gravity interpretation, the west side is more steeply faulted than the east side. At its southernmost extent, the graben merges with the Redford Bolson about 15 km to the south of Presidio. The subsurface is undoubtedly complex since tertiary intrusions and other volcanic features are expected in the region and may account for some of the small gravity anomalies discovered by Mraz and Keller (1980). Three prominent local anomalies located between Capote Peak and Candelaria and trending northeast may reflect Paleozoic structures related to those in the Marathon region to the east. Fig. 22 is a computer-generated "Gravity-Structural Cross Section at A-A'" as seen on Fig. 21, while Fig. 23 is a computer generated "Gravity-Structural Cross Section at B-B'" as shown on Fig. 21. On the A-A' profile (Fig.23) the Chihuahua Tectonic belt is a gravity high, whereas the Presidio Bolson is a gravity low. The Candelaria fault forms the eastern boundary of the graben. The gravity high in the vicinity of the Sierra Vieja represents a shallowing of the Precambrian basement and/or an intrusion. Linear gravity trends east of this high indicate an eastern boundary fault for the Sierra Vieja. The gravity low, east of the Sierra Vieja, is apparently associated with the Marfa Basin. Northeast of the Marfa Basin, the Valentine Basin (Covert, 1976) is represented by another gravity low. The intervening gravity high represents a ridge in the basement that trends northwest-southeast. In the Marfa area, various wells indicate the Tertiary volcanics to be at least 500 m thick. The Davis Mountains, which are the probable sources for these volcanics, are represented by a slight gravity low.

On the Shafter Highway, profile B-B', the Paleozoic Marfa Basin is represented by a gravity low south of Marfa, Texas. This basin thins southward toward the Chinati Mountain gravity high near Shafter, Texas.





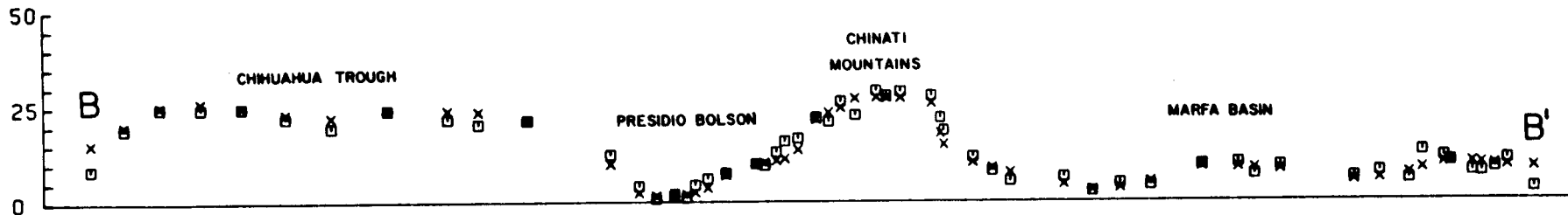
53

Figure 22 - Gravity structural cross section along profile A-A' (Pinto Canyon Highway profile). Numbered triangles refer to wells identified in the appendix. Density values ( $\text{g/cm}^3$ ) are given in parenthesis following boxes.

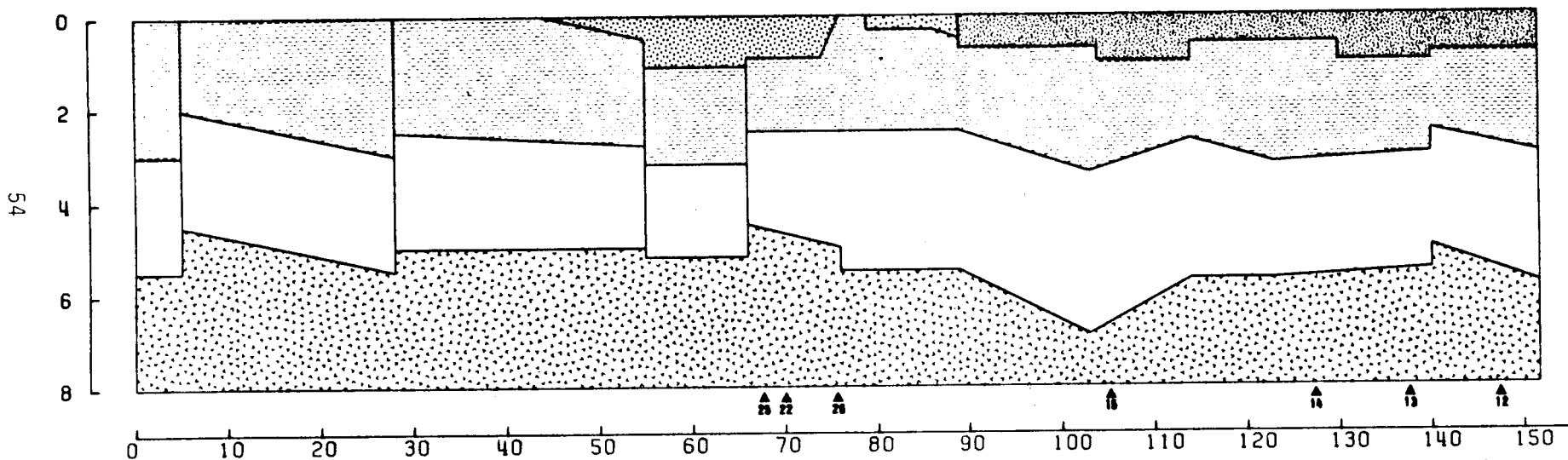
# PROFILE B-B'

□ OBSERVED  
x THEORETICAL

GRAVITY (MGAL)



DEPTH (KM)



DISTANCE (KM)

After Keller and Mraz.



Figure 23 - Gravity structural cross section along profile B-B' (Shafter Highway profile). Numbered triangle refers to wells identified in the appendix. Density values ( $\text{g/cm}^3$ ) are given in parenthesis following boxes.

Based on well data, there is at least 1 km of bolson fill over limestone in this area. The bolson is deepest (1.2 km) on this profile in the immediate vicinity of Presidio. A gravity high representing the Chihuahua Tectonic Belt is encountered to the south in Mexico.

## ELECTRICAL METHODS

### Resistivity Measurements

Four vertical electric soundings were made over the supposed geothermal area in the vicinity of Hueco Tanks (See Figure 24). Details of the method are given in Appendix I along with the sounding curves. In three of the four soundings, a low-resistivity layer was found. This layer may represent a hot, probably saline water zone. The sounding curves were complex, however, another attempt was made to map the presumed 'hot zone' using the resistivity method.

No resistivity measurements were made in the Presidio Bolson.

### Self-Potential Measurements

The self potential (spontaneous potential, or SP) method has been used for many years for mineral prospecting, but only in very recent years has an application been developed in geothermal work. Corwin and Hoover (1979) have considered geothermal applications in detail. They point out that the mechanism of generation of SP anomalies is not well understood, and the interpretation of the results must be thought out carefully. They note that among other causes, elevated temperatures (the thermoelectric effect) and streaming potentials (such as may be caused by circulating fluids i.e. the electrokinetic effect) can both give rise to SP anomalies.

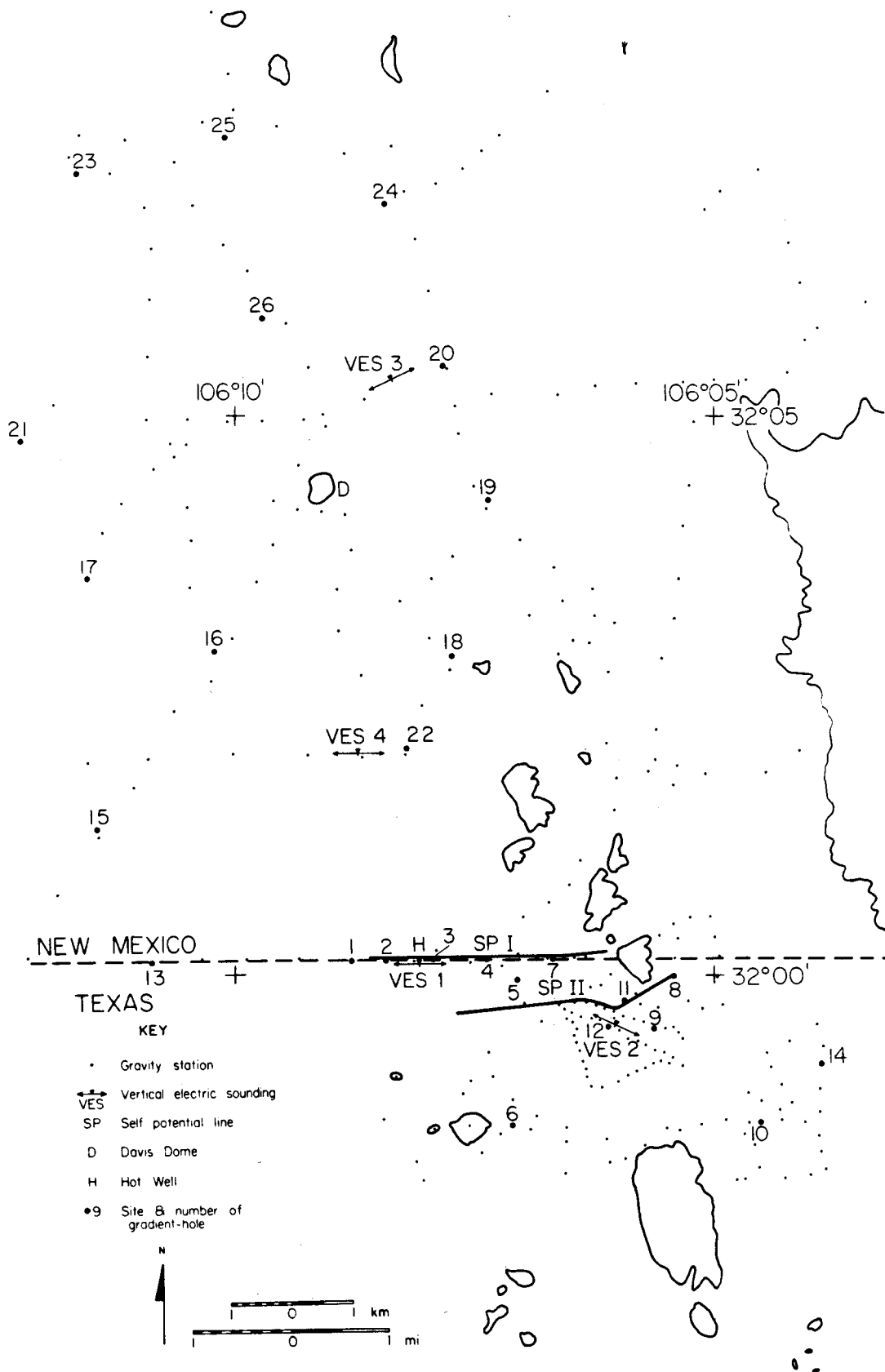


Figure 24 - Location of geophysical surveys, Hueco Tanks area.

During the course of this study, two SP traverses were made at the locations shown on Fig. 24. A 100 m dipole arrangement operating in a "leapfrog" fashion with the potentials being added successively to obtain the SP value at the new station relative to a "zero" base was used.

Telluric currents proved to be a major source of noise, and were 'allowed for' by noting the variation in voltage for each reading and taking the average value. Other commonly encountered sources of noise such as cultural activity, uneven soil moisture and spurious potentials due to chemical contamination of the soil, were considered unimportant in the present survey.

The two SP traverses are shown in Figs. 25 & 26. Both lines display a correlation with elevation, which is filtered out effectively by taking the SP gradient (in mV/100m). This gradient also resolves suspected faults more clearly. Symmetrical flanking anomalies, interpreted as faults, are seen at two positions in the gravity survey.

No SP measurements were made in the Presidio Bolson.

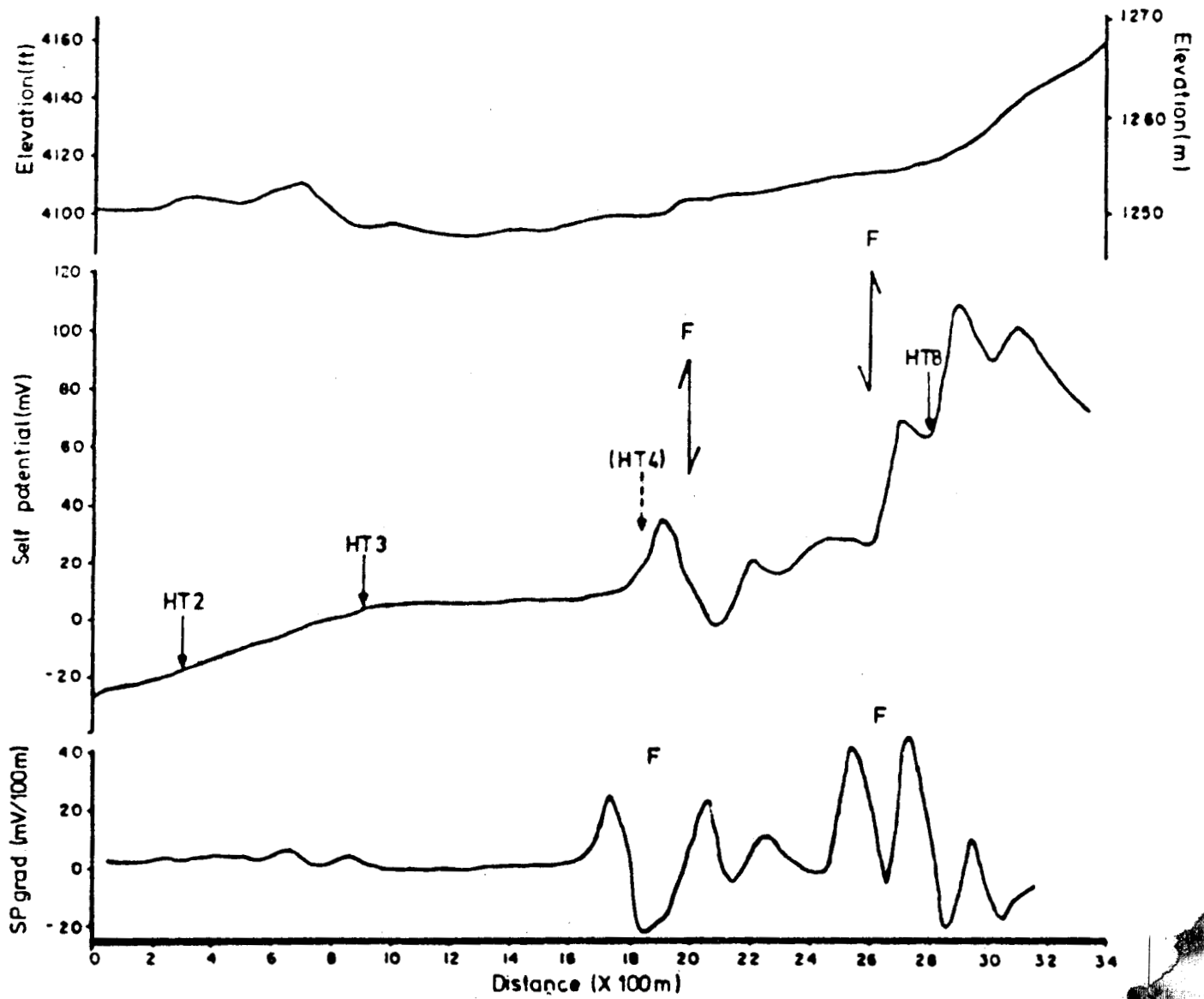


Figure 25 - Self-potential profile I. 'F' designates an inferred fault, 'HT' - refers to thermal gradient drillholes.

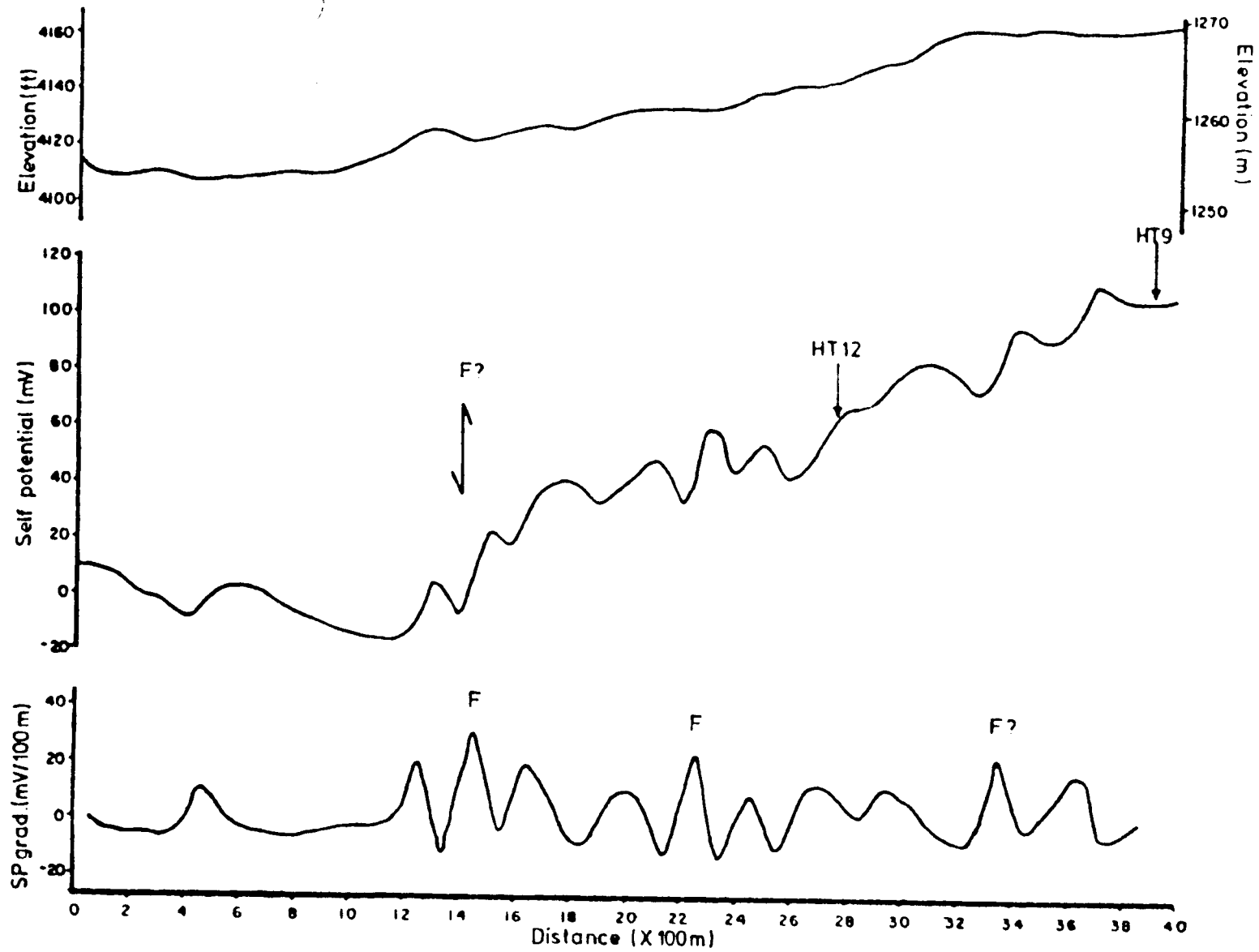


Figure 26 - Self-potential profile II.

## DISCUSSION OF GEOCHEMISTRY/GEOTHERMOMETRY ANALYSES

A complete discussion of geochemistry/geothermometry including all geochemical data collected during this project is contained in "A Preliminary Assessment of the Geologic Setting, Hydrology, and Geochemistry of the Hueco Tanks Geothermal Area, Texas and New Mexico" by Henry and Gluck (1981), which is included as Attachment I of this document. A similar study entitled "Geologic Setting and Geochemistry of Thermal Water and Geothermal Assessment, Trans-Pecos Texas with Tectonic Map of the Rio Grande Area, Trans-Pecos Texas and Adjacent Mexico" by Henry (1979a) is very pertinent and should be reviewed by the reader. The following discussion is a compilation and summation of the findings of both studies. Some supporting data are found in Attachment I.

### HUECO BOLSON

The majority of waters tested in the Hueco Bolson are Na-Cl-(CaSO<sub>4</sub>) - type waters, with the hotter waters being richest in sodium and chloride. Total dissolved solids were in the 1,000 mg/L to 12,500 mg/L range for thermal waters while only two non-thermal waters contained solids greater than 2600 mg/L. The thermal and non-waters in the area have similar ionic proportions. Water temperature and total dissolved solids correlate directly. Based on the observations, no single hypothesis can account for the range in absolute values. Probably, one or more of the following is taking place within the groundwater in the Hueco Bolson: 1) contact with evaporite or saline-rich shales of Paleozoic Age, 2) contact with evaporites contained in the more recent bolson fill, and/or 3) expulsion of saline waters from deep basin deposits. No one of these explanations is entirely satisfactory (See Henry and Gluck, 1981).

Geothermometry studies of the waters were conducted with the two most important assumptions being that the waters were in equilibrium with minerals that control dissolved solids concentrations and that mixing with nonthermal water has not occurred. Undoubtedly, neither of these assumptions is met fully by the ground waters of the Hueco Bolson.



Calculation of  $\text{SiO}_2$  temperatures were made assuming equilibrium with four different silica phases as follows: 1) quartz, 2) chaledony, 3) cristobalite, and 4) amorphous silica. Study results indicated that chaledony temperatures were the best indicators of the probable maximum temperature of about  $80^\circ\text{C}$ . Assuming equilibrium with quartz gives a shallow reservoir temperature as high as  $110^\circ\text{C}$ . Indications are that mixing of thermal and nonthermal waters has occurred. (See Henry and Gluck, 1981, p.29). It is possible that the shallow reservoir system is fed by a parent thermal water that is considerably hotter than any of the observed waters. If this is true, the observed silica concentrations may reflect only those conditions in the shallow reservoir and not be indicative of much warmer water at greater depths. The probable temperature of the possible 'parent' thermal water is not determinable due to a lack of data from deep wells.

#### PRESIDIO BOLSON

The hottest naturally occurring springs observed during this study are the Ojos Calientes located on the Mexican side of the Presidio Bolson about 7 km southwest of Candelaria, Texas. Measured water temperatures range from about  $60^\circ\text{C}$  ( $140^\circ\text{F}$ ) to  $90^\circ\text{C}$  ( $194^\circ\text{F}$ ). Extensive travertine deposits have been built-up by the springs. The Palo Pegado Fault is thought to be associated with the springs and displacement of the fault in the vicinity of Ojos Calientes is estimated at a minimum of 90 m (2953 ft) (Henry, 1979).

Another hot spring located in the Presidio Bolson in Mexico is found at Rancho Cipres. Temperatures in a small pool are in the  $35^\circ\text{C}$  ( $95^\circ\text{F}$ ) range.

In Texas, two artesian wells (known as Gulf Wells) about 4 km apart and located about 30 km north of the Presidio Bolson (in the same structurally downdropped block of the west Sierra Vieja) have thermal gradients in the  $35^\circ\text{C}$  -  $40^\circ\text{C}$  per Kilometer range (Henry 1979a, p. 14). The water discharged by the wells has total dissolved contents of 1,200 and 1,700

mg/L, respectively. These wells produce from Cretaceous limestone but their water chemistry indicates that the fluids are in contact (either physically or hydraulically) with evaporites from which a large part of the dissolved solids content are derived.

The geothermometry of the two Gulf Wells (Gulf-Presidio and Gulf Swafford) and Ojos Calientes give quartz temperatures of 112°C, 159°C. and 134°C for Gulf-Presidio, Gulf Swafford and Ojos Calientes, respectively. All three waters deposit travertine, but none of the three appears to deposit silicious sinter.

Suprisingly, Gulf-Swafford water contains twice as much silica as Gulf-Presidio water. No clear conclusions on the significance of the high silica concentration can be made. Temperature logs for the Gulf-Swafford show a temperature inversion below the hot-water-producing horizon. Below that level the temperature drops and reaches 80°C again only at a depth of about 2,500m (8,200 ft). Thus, the high temperature water of the producing horizon must be carried from greater depths by thermal convection (Henry, 1979). The geothermometry of the two Gulf Wells and Ojos Calientes indicates that the thermal system in which they lie may have potential for power generation (See Henry (1979a) for more information).

## SHALLOW DRILLING PROGRAM AT HUECO TANKS, PRESIDIO BOLSON AND FINLAY MOUNTAINS

As indicated in the introduction to this report, two promising areas were targeted for more extensive study, namely the Hueco Tanks area and the northern Presidio Bolson. Additionally, due to the acquisition of promising data, the high heat flow at the Finlay Mountains was considered to warrant further investigations. The results of geophysical surveys have been described in a previous chapter; this section will specifically address the thermal regimes as interpreted from shallow drilling done for this project.

### HUECO TANKS

Temperature measurements made in existing wells at the eastern edge of the Hueco Bolson, near Hueco Tanks State Park, indicated the presence of a thermal anomaly. Thermal gradients of 179° and 271°C/km here contrast with the background value of 30-40°C/km in the Bolson. Figure 27 is a compilation of gradient and pseudogradient data for El Paso County gathered during this study.

### First Stage Drilling

Twenty-five holes were drilled to 50 m depth in bolson fill in the Hueco Tanks area, encompassing an area 20 km by 15 km, for the purpose of measuring temperature gradients in the supposed geothermal area. The first five holes were located along the Texas/New Mexico state line from west to east across the geochemical anomaly identified and mapped by Hoffer (1979). Subsequent holes were drilled in positions located to investigate the areal extent of elevated gradients both in New Mexico and Texas. All holes were drilled to 4.5 in (11.4 cm) diameter and had 1.25 in (3.2 cm) diameter PVC piping inserted into them.

This pipe was then filled with water to facilitate the use of the thermistor probe in temperature logging. The thermal data for these holes are reported by Taylor (1981) and Rahman (1983) as temperature-depth and gradient-depth plots, and are summarized here in Table 5.

Figure 27 - Geothermal gradients in El Paso County, Texas.  
 Solid circles - measured gradients.  
 Open circles - gradients derived from deep oil tests.  
 Crosses - pseudogradients.  
 Values in °C/km.

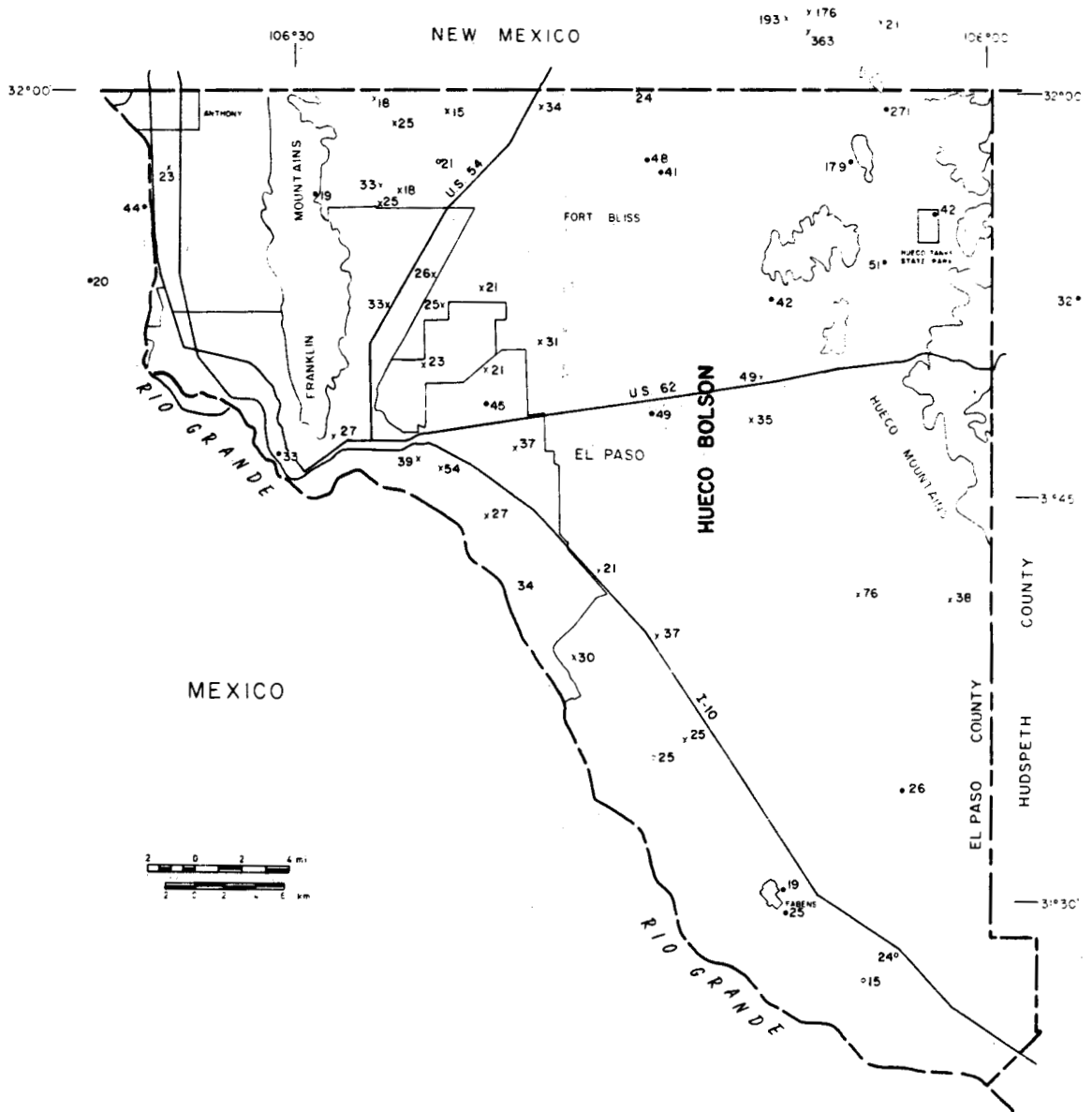


Table 5 - Hueco Tanks geothermal gradients.

Locations of boreholes are shown in Figs. 2.6, 2.15 and 2.18.

Borehole no.	Gradient (°C/km)	Depth interval (m)
HT-1	122.9	33 - 46
HT-2	107.4	15 - 45
HT-3	171.0	15 - 45
HT-4	158.9	27 - 49
HT-5	177.3	15 - 45
HT-6	110.4	15 - 45
HT-7	289.4	20 - 45
HT-8	279.7	25 - 50
HT-9	313.6	15 - 50
HT-10	153.9	25 - 50
HT-11	171.9	60 - 120
HT-12	134.6	180 - 270
HT-13	33.1	25 - 50
HT-14	57.3	30 - 50
HT-15	40.0	25 - 45
HT-16	84.0	10 - 45
HT-17	65.7	10 - 45
HT-18	362.5	10 - 45
HT-19	126.0	20 - 50
HT-20	113.7	25 - 45
HT-21	71.6	10 - 45
HT-22	85.7	10 - 45
HT-23	105.6	20 - 50
HT-24	109.7	10 - 45
HT-25	130.3	10 - 45
HT-26	164.7	20 - 50
HT-27	309.0	90 - 160
HT-28	180.0	40 - 235
HT-29	368.0	10 - 50
HT-30	340.0(isothermal below 160 m.)	20 - 160

Figure 28 is a temperature contour map for a depth of 50 m, based on the measured temperatures in the 25 drilled holes, plus six measurements in existing wells to the south (Taylor, 1981; App.D). Since gradients differ with lithology as well as temperature, the actual temperatures at a constant depth were chosen to demonstrate the thermal anomaly instead of gradients. A northwesterly-trending fault, discussed previously in connection with the gravity work, is clearly indicated with temperatures returning to normal (about 22°C) within about 6 km to either side of the center, and somewhat further to the north and south. The highest temperatures coincide with the positions of the limestone outliers, where the fault comes nearest to the surface.

Two deeper holes were drilled on the Texas side of the anomaly. The first, HT-11, was placed at a point where thermal gradients appeared to be highest. Limestone bedrock was encountered at about 120 m, and a 3 m core was taken. The second, HT-12, was situated 0.5 km to the southwest of HT-11, closer to the trace of a suspected fault. Bedrock was reached at about 134 m, 14 m lower than the previous hole (apparently on the downthrown side of the fault), and drilling was continued to 300 m in order to determine the nature of the bedrock gradient.

Gradients are high in both holes (Fig. 29 and 30), although they decrease with depth. HT-12, being the deeper of the two, is of most interest. The annual wave is dominant to about 40 m (deeper than usual, due to the conductive effect of the iron-pipe used in this hole), whence the high gradient of the bolson fill continues to 130 m. Below this, the bedrock gradient takes over, decreasing to 170 m, the point at which the hot water table is presumably encountered.

#### Thermal Model

Measurements of thermal conductivity on rock core taken from HT-12 have, when combined with the gradient, yielded an extremely high heat flow (9.3 H.F.U.). This number would appear to be the result of thermal convection in the fault system, with only a small conductive component. Igneous rocks in the area are too old to contain residual heat, and their radioactive heat generation is too low to account for the high heat flow.

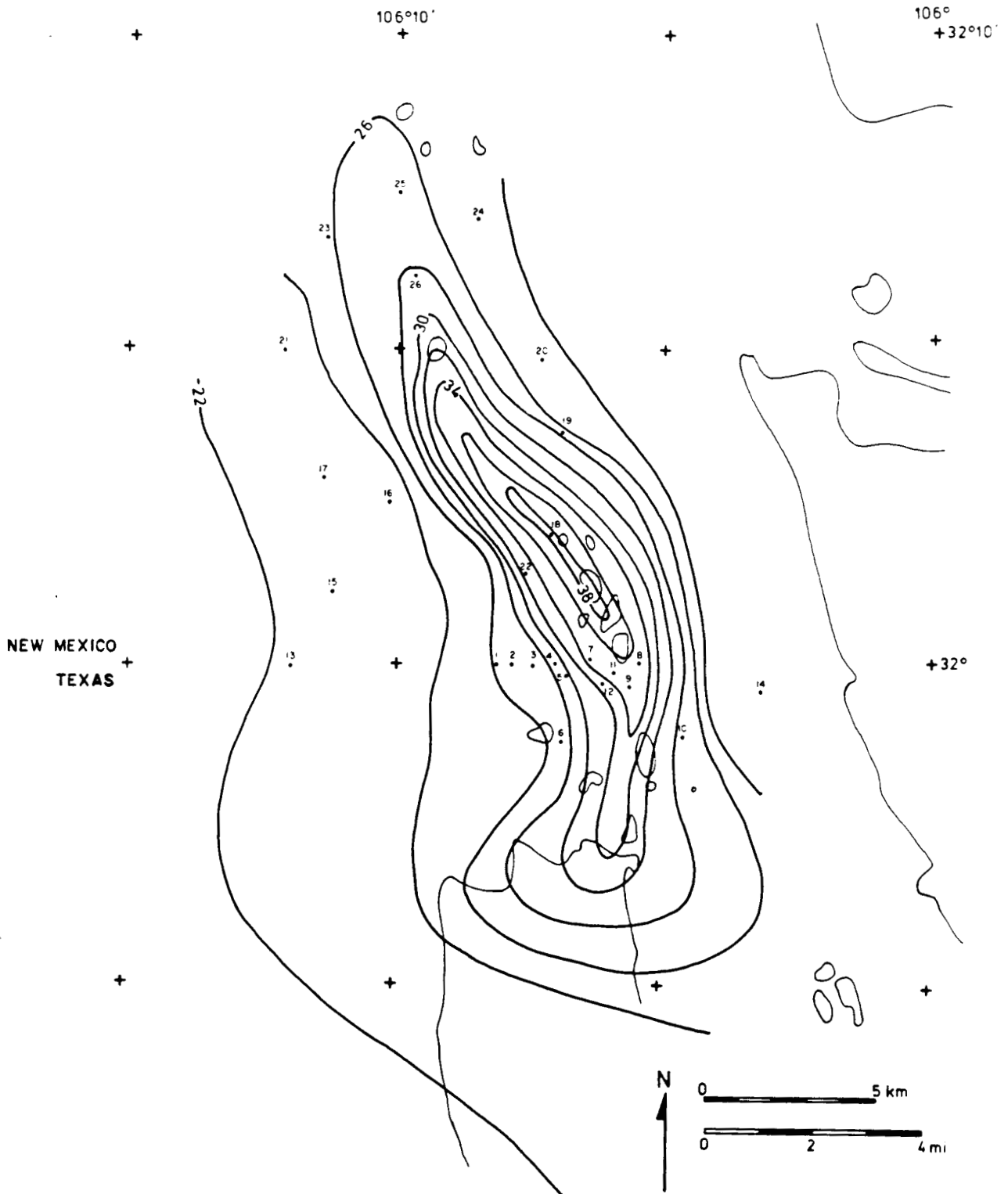


Figure 28 - Temperature contour map for a depth of 50m, Hueco Tanks existing area, based on measurements made in drilled gradient holes and wells. Contours marked in °C; Gradient holes in black dots; old wells logged a present study - squares (See Fig 5).

Fig 29 - HT - 11 (grad. 60 - 120m)

89

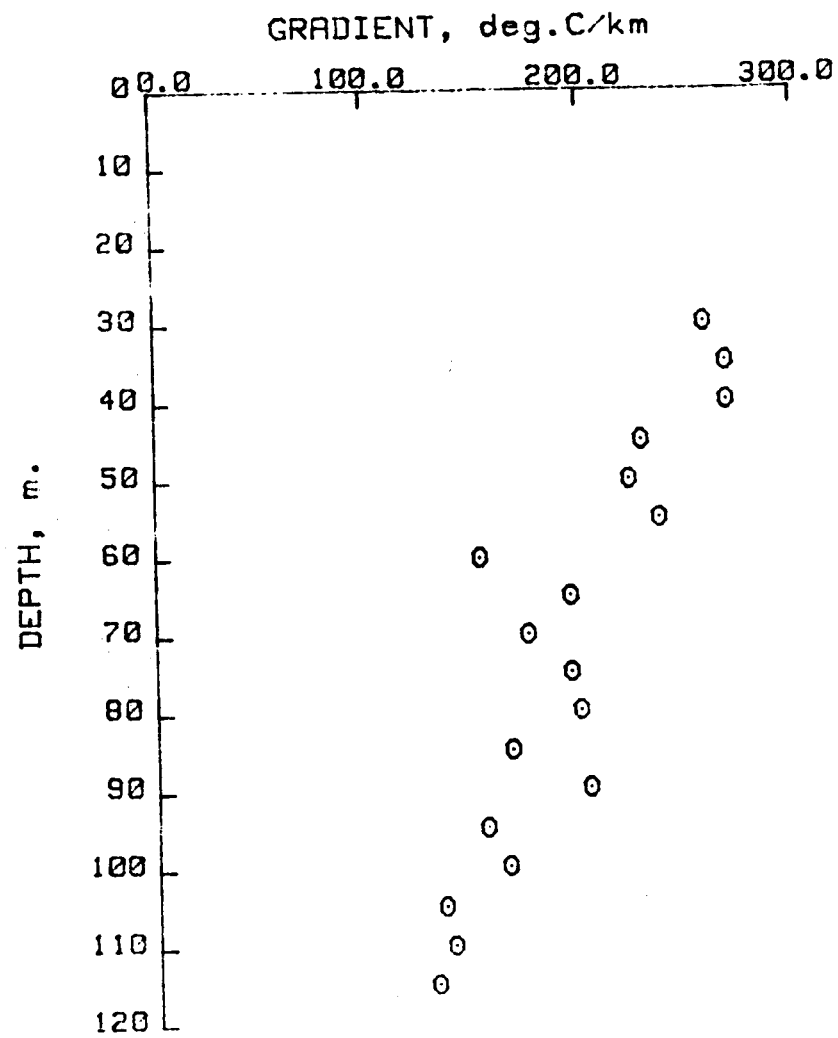
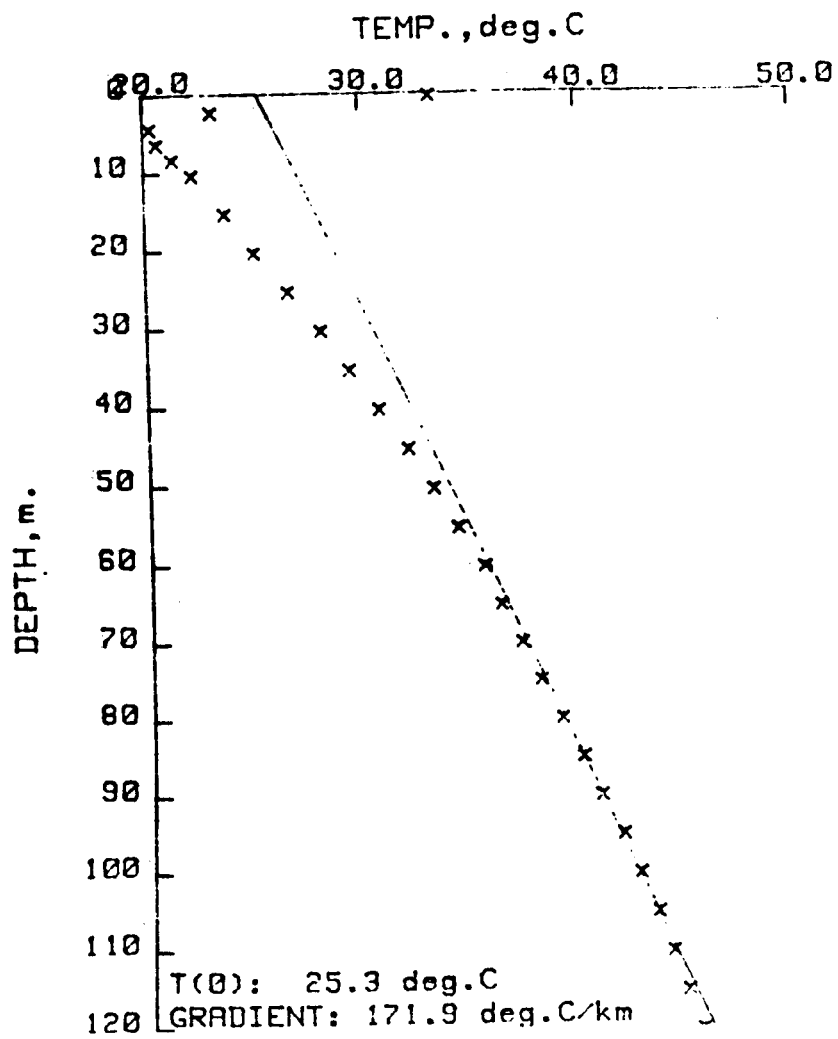
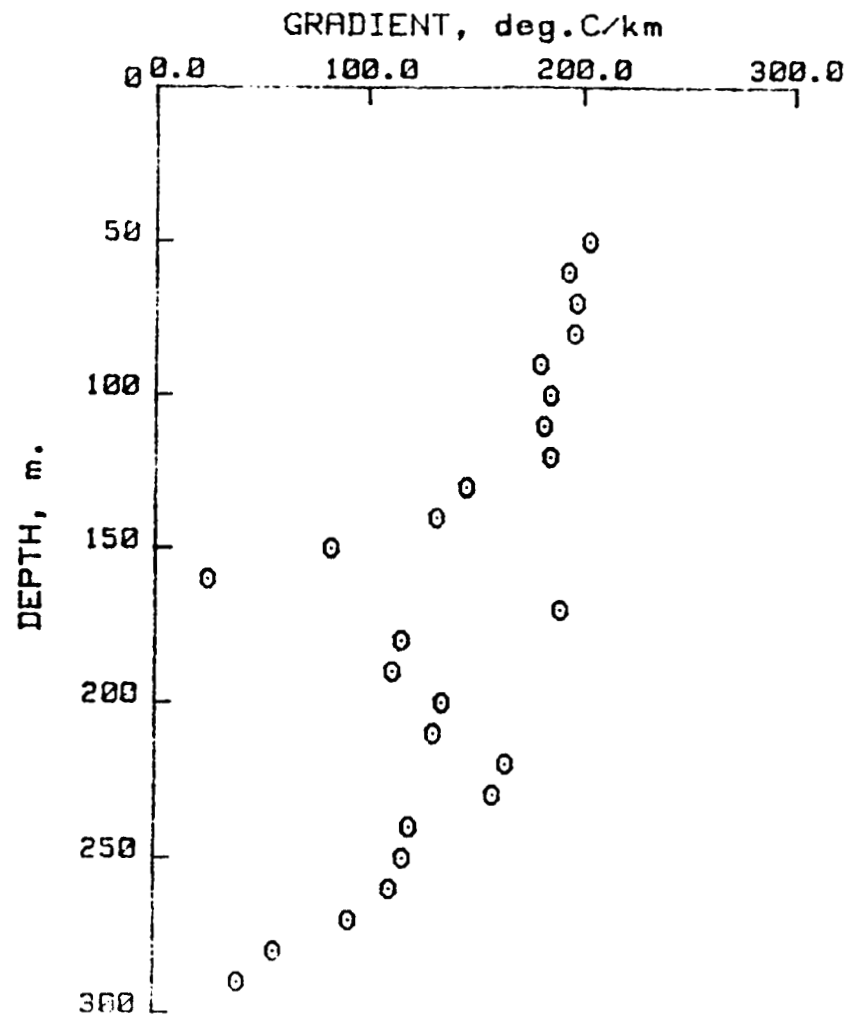
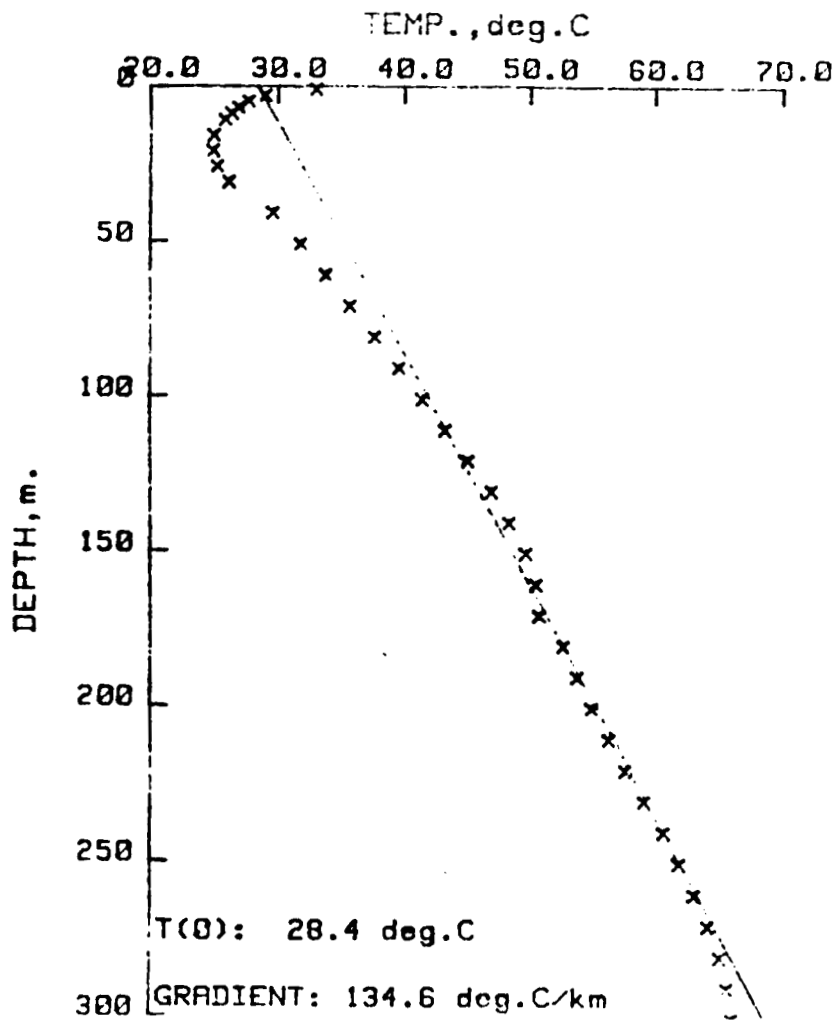




Fig. 30 HT-12 (grad. 180 - 270m)

69



A finite difference heat flow model was constructed for the Hueco Tanks area (Fig. 31). It is very simplified, owing to the restricted geometrical capabilities of the computer program. The structural configuration is based largely on the results of the gravity survey, and represents a small graben whose boundary faults carry hot water from depth. The top of the faults are thus effectively point heat sources.

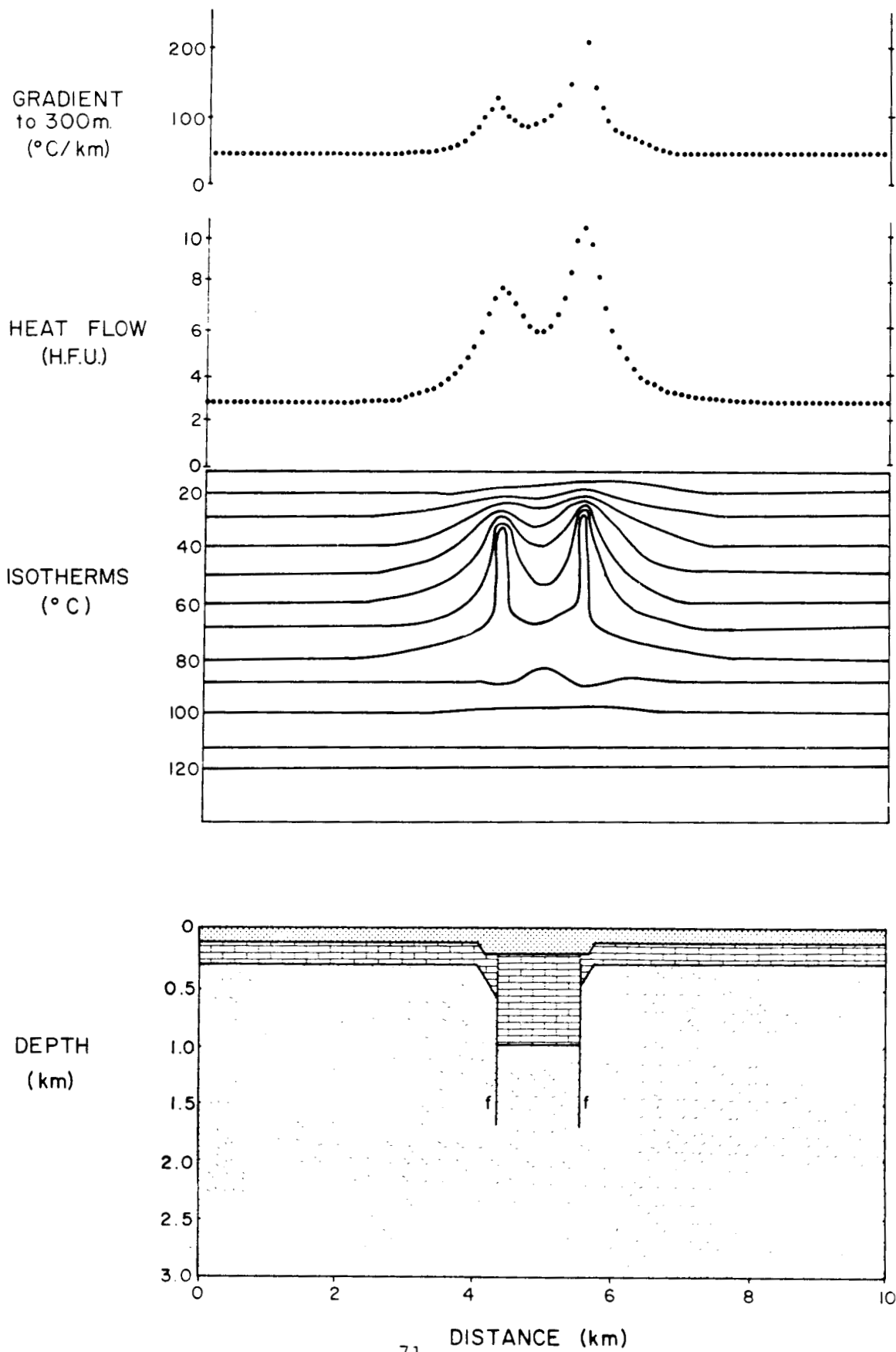
The model would thus predict high surface gradients over and in the vicinity of the faults. Drilling into the faults would encounter water at about 80°C at the 200-300 m level, after which no substantial increase would be observed until the regional gradient took over again at greater depth (approximately 2 km).

#### Second-Stage Drilling

Figure 28 shows the elongate center of the thermal anomaly to be north of the state line, on McGregor Range, New Mexico. To test the thermal model discussed above, and to determine the nature of the thermal regime here, two 300 m drill tests were undertaken on McGregor Range. The temperature logs of HT-27 and 28 are shown in Figures 32 and 33. HT-28 went effectively isothermal at 250 m exhibiting a gradient of 180°C/km above 250m; the maximum temperature attained was about 72°C. HT-27 encountered drilling problems at 180 m and was redrilled close by as HT-30 (Fig. 34). The high gradient recorded in the first-stage hole HT-18 was confirmed (340°C/km), but this turned over at 160 m (a little below 80°C) and the hole was isothermal to its total depth of 460 m.

Based on the geophysical, geothermal, and other information it is concluded at this stage that the Hueco Tanks area is a convection controlled system with moderately warm water (80°C) occurring at a shallow level (150-200 m). The source of the water is the adjacent Hueco Bolson, from which heated water rises along faults to the near surface in the vicinity of Hueco Tanks.

Figure 31 - Heat Flow model for Hueco Tanks geothermal area, west to east along the Texas/New Mexico state line.



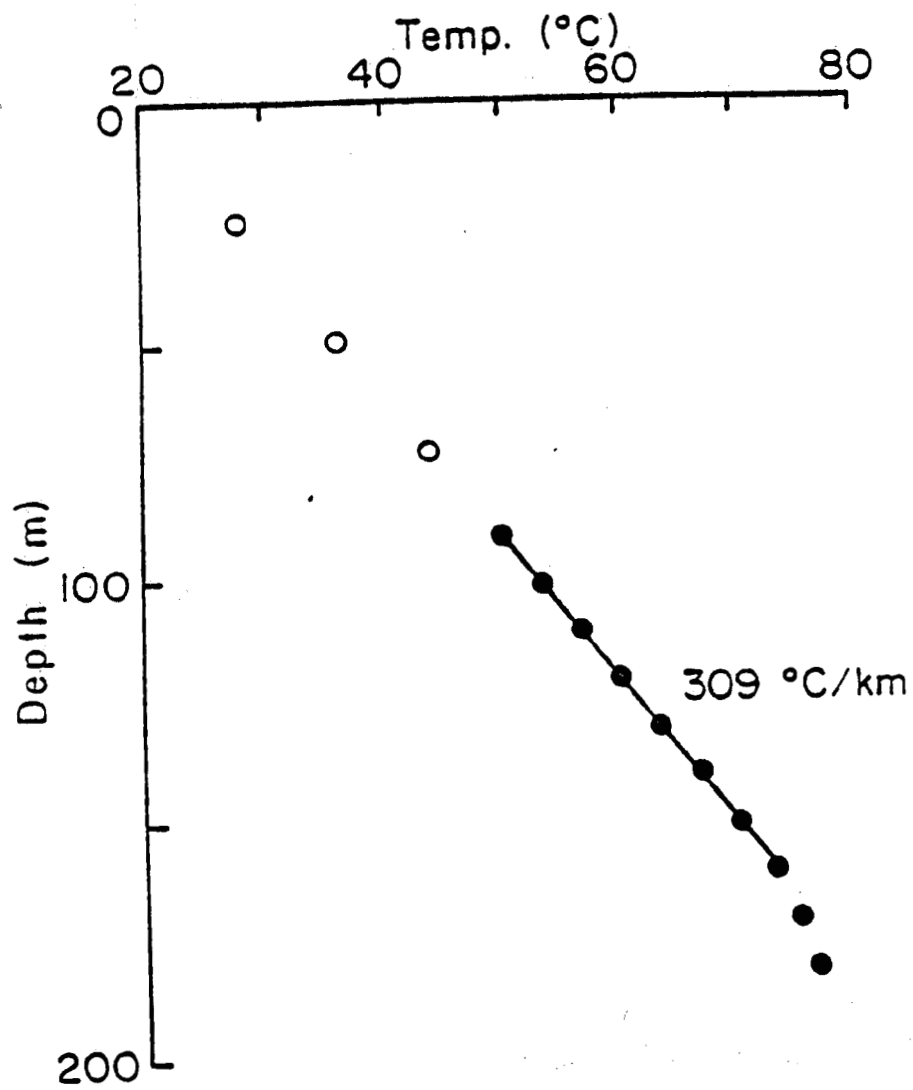


Figure 32 Temperature-depth curve for HT-27

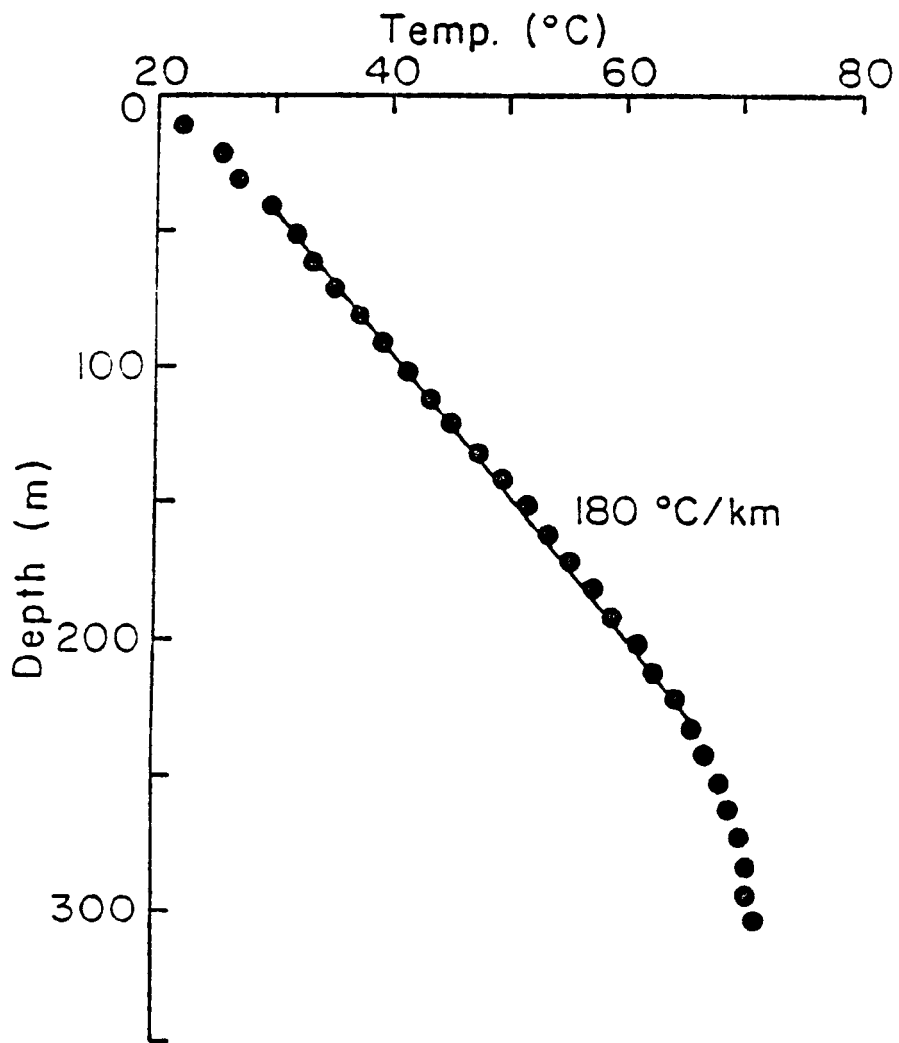


Figure 33 - Temperature-depth curve for HT-28

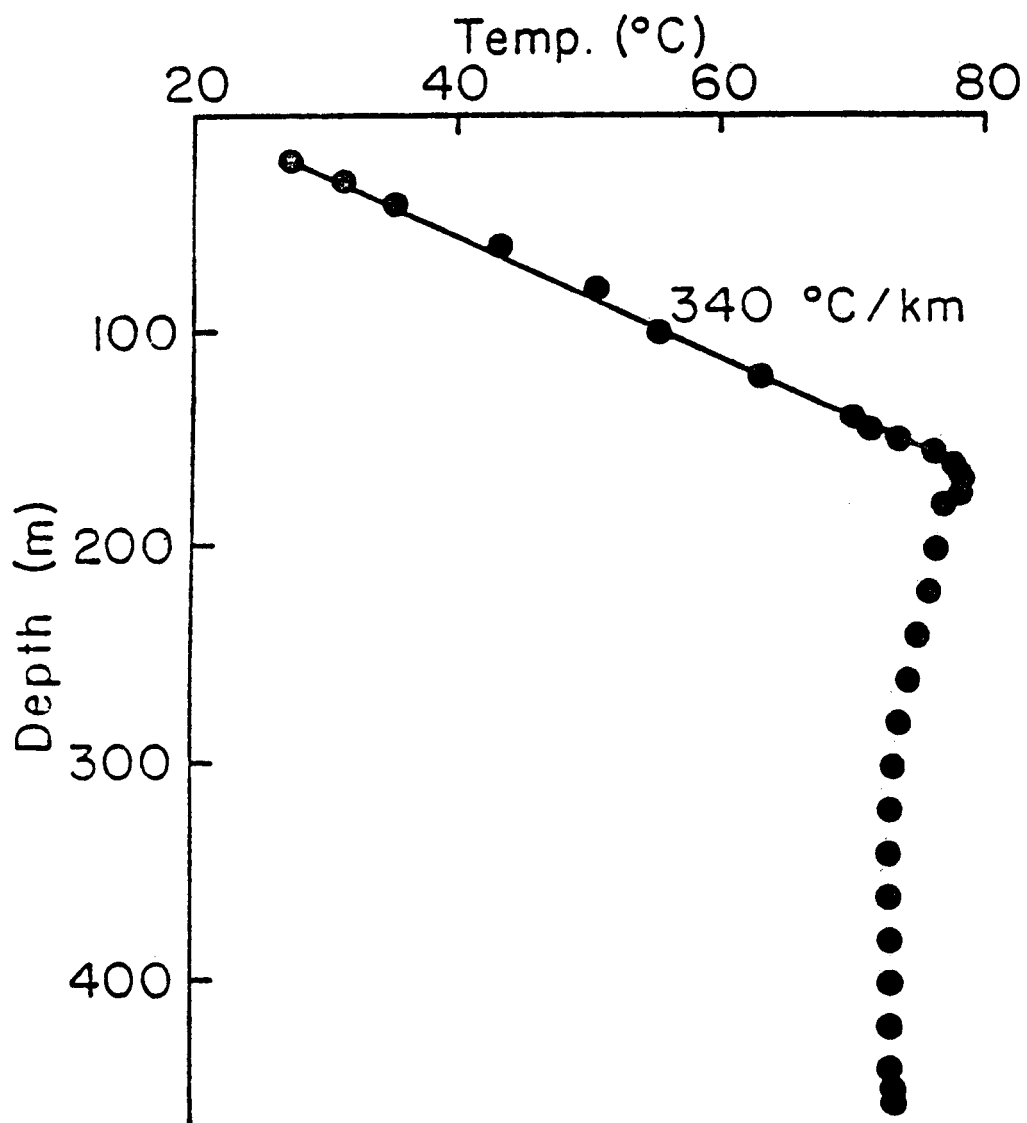


Figure 34 Temperature-depth curve for HT-30

## PRESIDIO BOLSON

Temperatures measured in abandoned wells and other drill-holes in the early stages of the project indicated a zone of high gradients in the northern part of the Presidio Bolson near Ruidosa Hot Springs (Fig.35). It was apparent that the eastern boundary faults of the Bolson, notably the Candelaria fault, were responsible for the rise of warm waters, although the source (thought to be deep in the Bolson) was unknown.

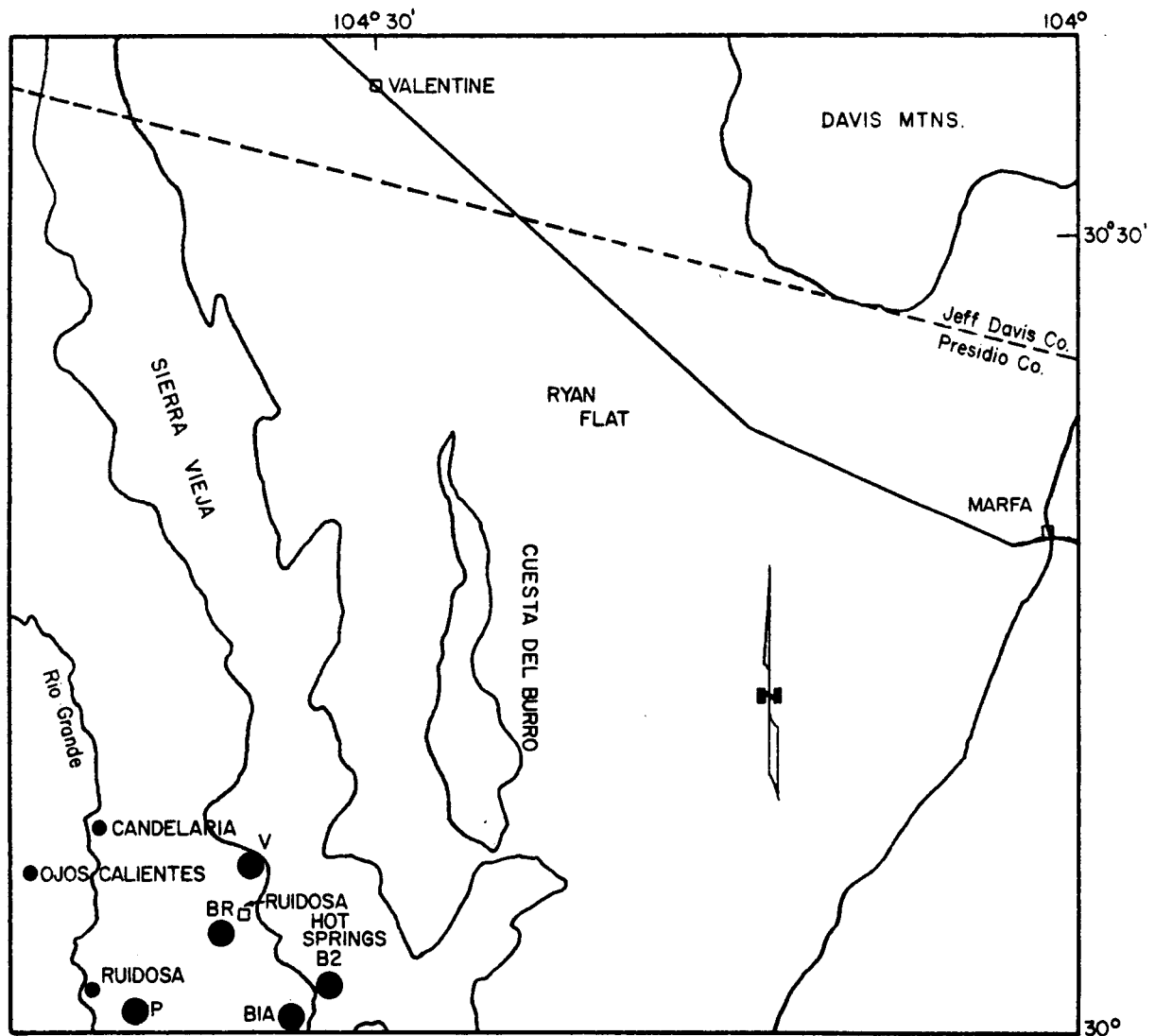
Five holes were drilled for the present project to investigate the thermal anomaly at Ruidosa; they are reported by LaFreniere (1983), and are described below:

Vizcaino #1 (Fig. 36 and 37) -- Located near the Candelaria fault about 8 km north of Ruidosa Hot Springs. This hole was drilled to 250 m in tuff and rhyolite and, despite some lost circulation, yielded a good gradient of 74.1°C/km in the bottom 100 m, apparently unaffected by water circulation. Preliminary measurements gave a thermal conductivity of about 4.5 mcal/cm°C, and this produces a heat flow of over 3 H.F.U. This is a little high, and suggests that thermal water may have been present deeper, elevating the near surface gradient.

Sanguijuela Springs #1 (Fig. 38 and 39) -- Located about 2 km. north of Ruidosa Hot Springs, this hole had a high but irregular gradient, particularly in the lower 50 m. The irregular gradient reflected a lost circulation zone from 100 to 120 m. This suggests water movement in or near a fault, since the bottom hole temperature is approaching that of the nearby hot springs (although it occurs 150 m lower in elevation than the hot springs).

Benevides #1 (Fig. 40 and 41) -- This was drilled at the site of a previous 50 m gradient measurement (261°C/km). The high gradient is still apparent, but temperatures are highly disturbed by a lost circulation zone from 65 to 90 m. Below this, a much lower gradient is observed (31.7°C/km). It is speculated that this more nearly represents the local background thermal gradient, below the zone disturbed by warm water emanating from the fault.

Figure 35 - Location of Five Holes in Presidio Bolson



- BIA - BENEVIDES NO. 1 & 1A
- B2 - BENEVIDES NO. 2
- BR - BRISCOE
- P - PELTON
- V - VISCAYNO

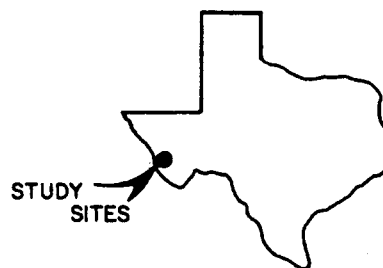




Figure 36 - Temperature - Vizcaino #1

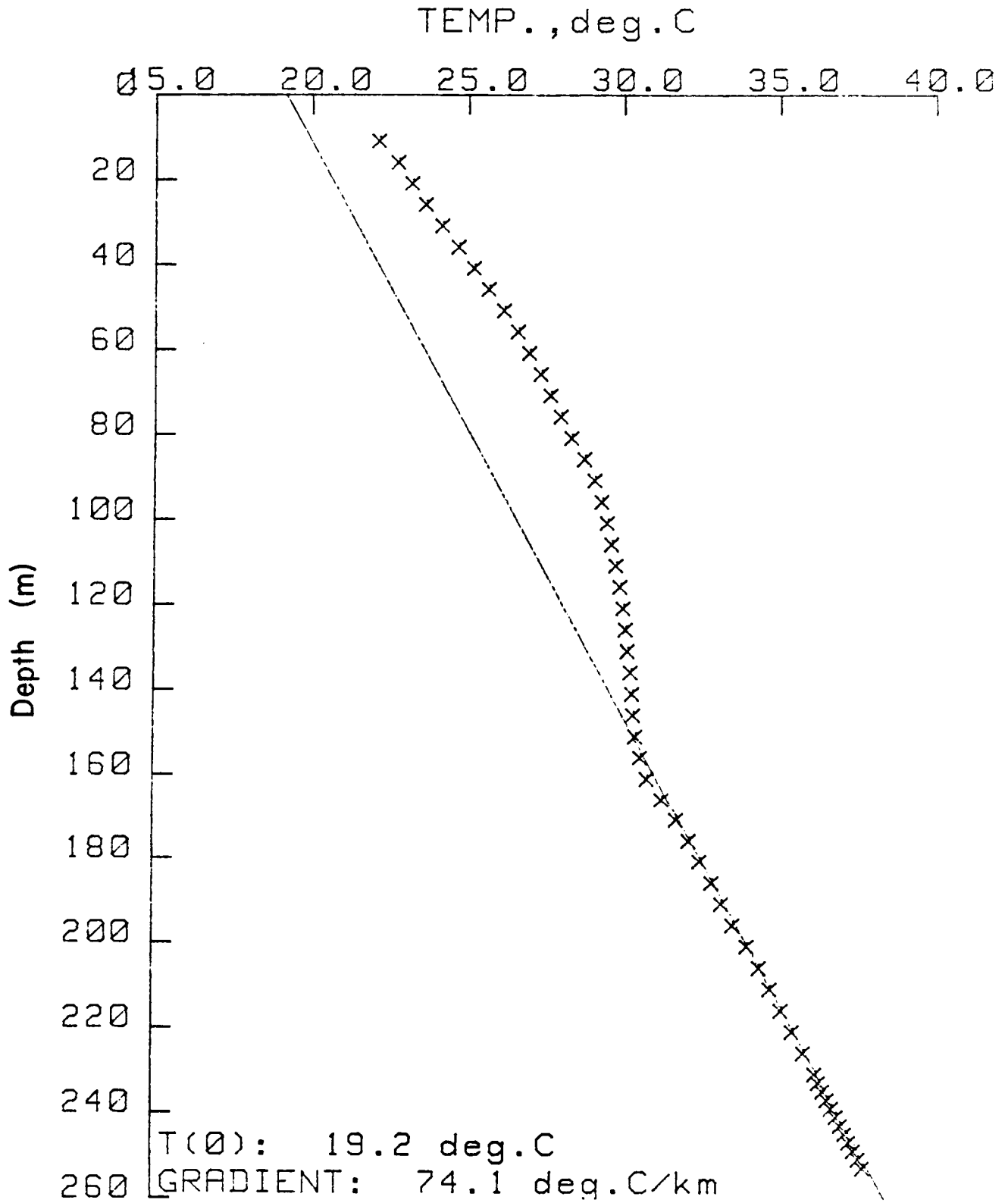


Figure 37 - Gradient - Vizcaino #1

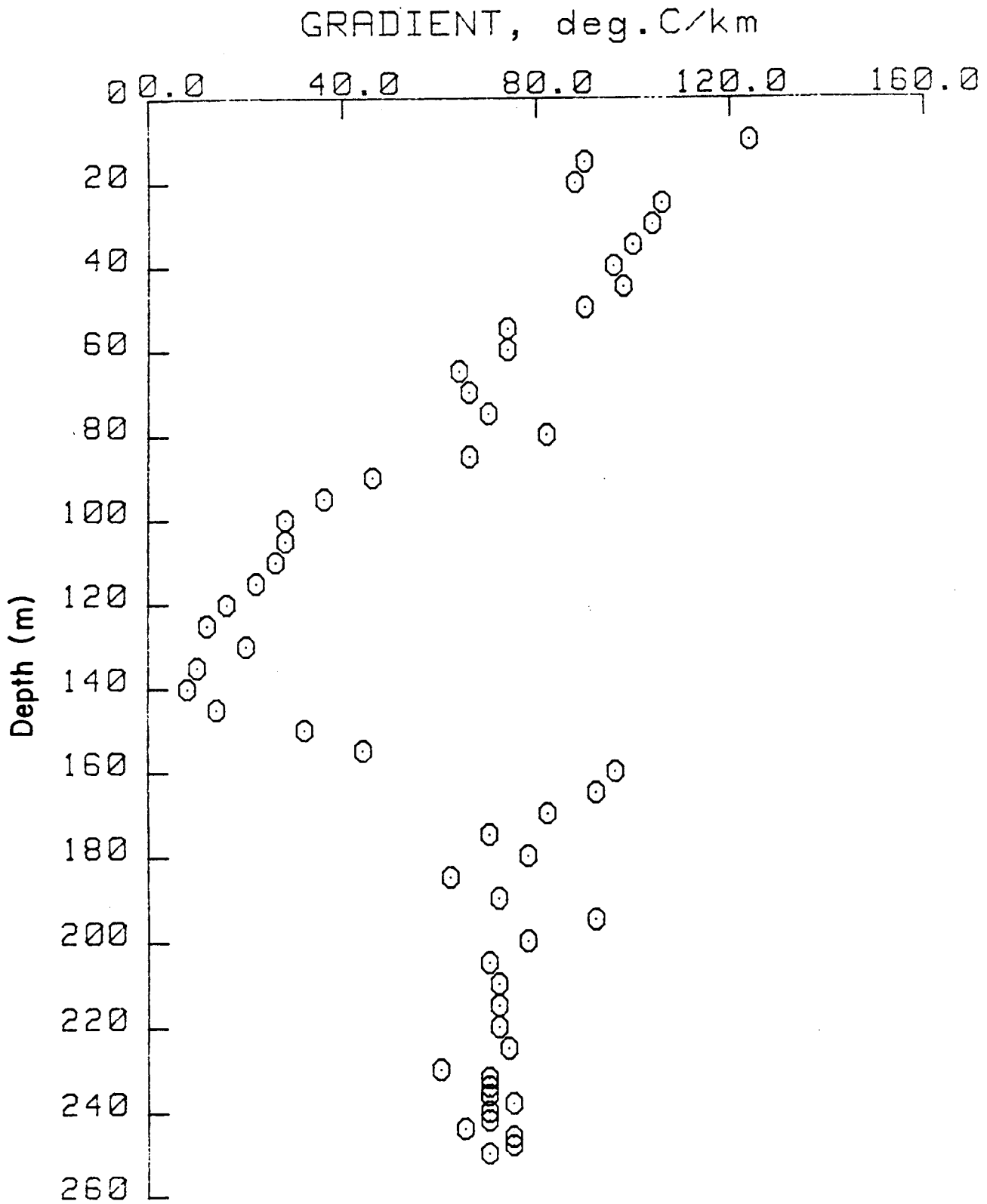


Figure 38 - Temperature - Sanguijela Springs #1

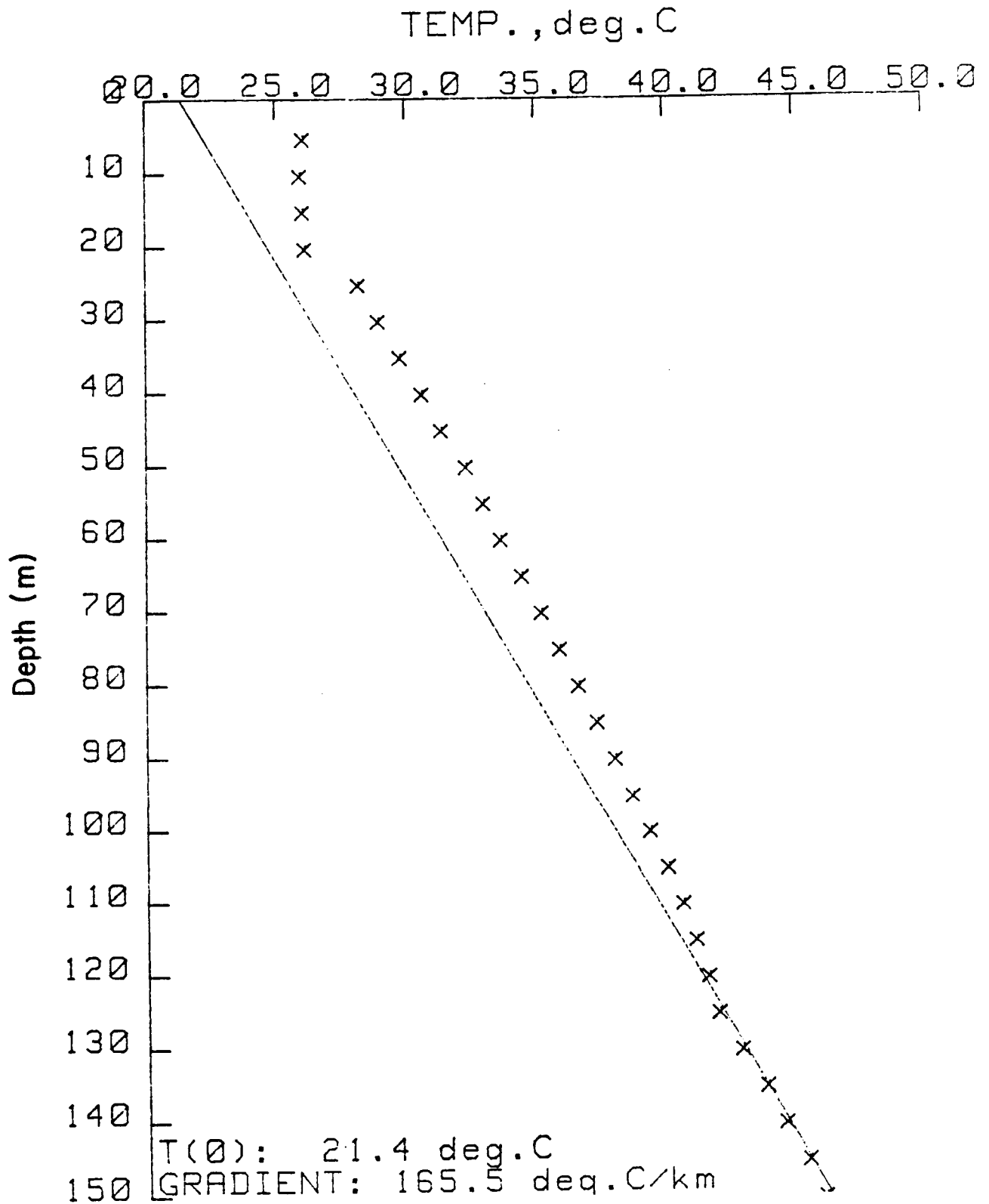


Figure 39 - Gradient - Sanguijuela Springs #1

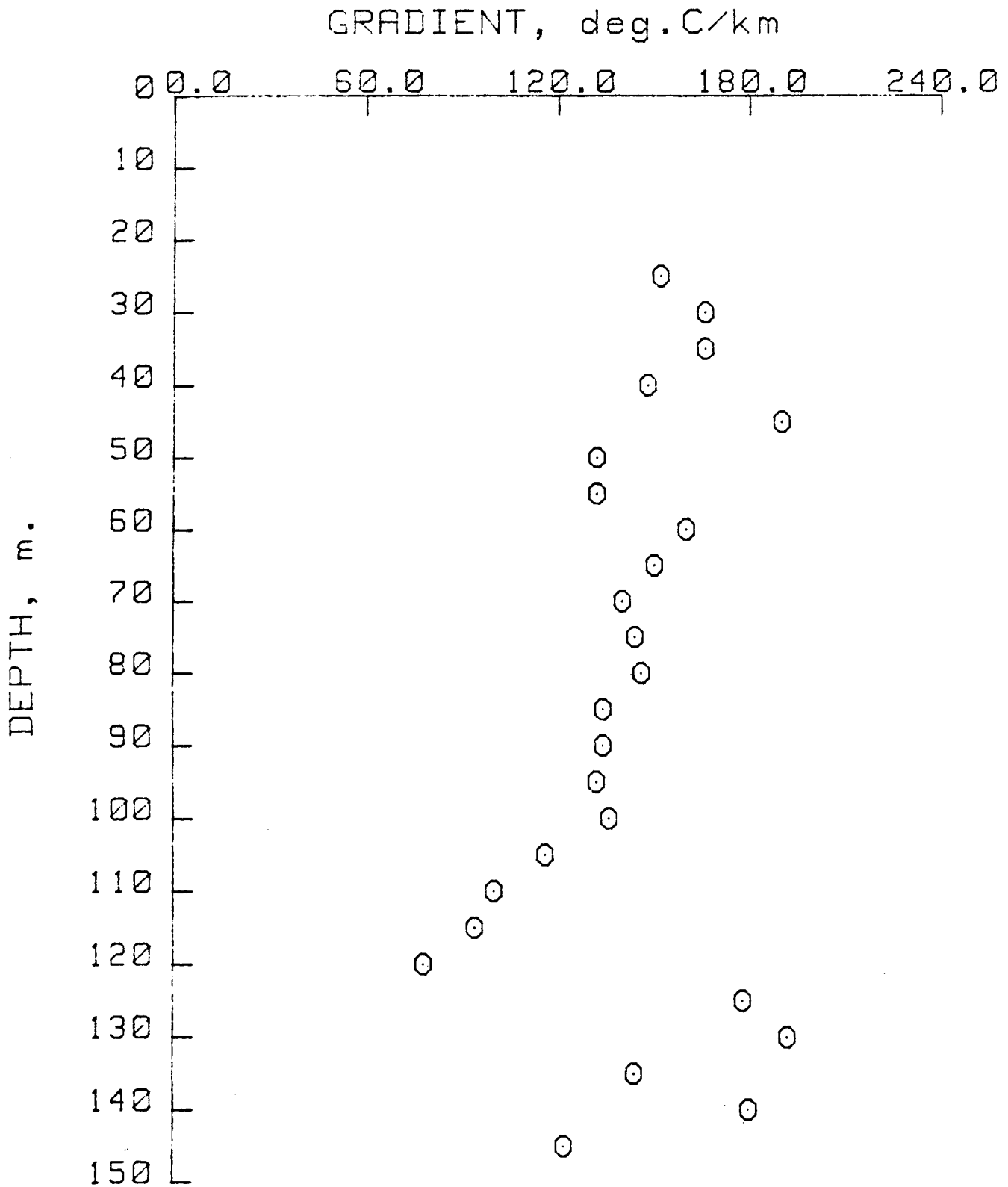


Figure 40 - Temperature - Benevides #1

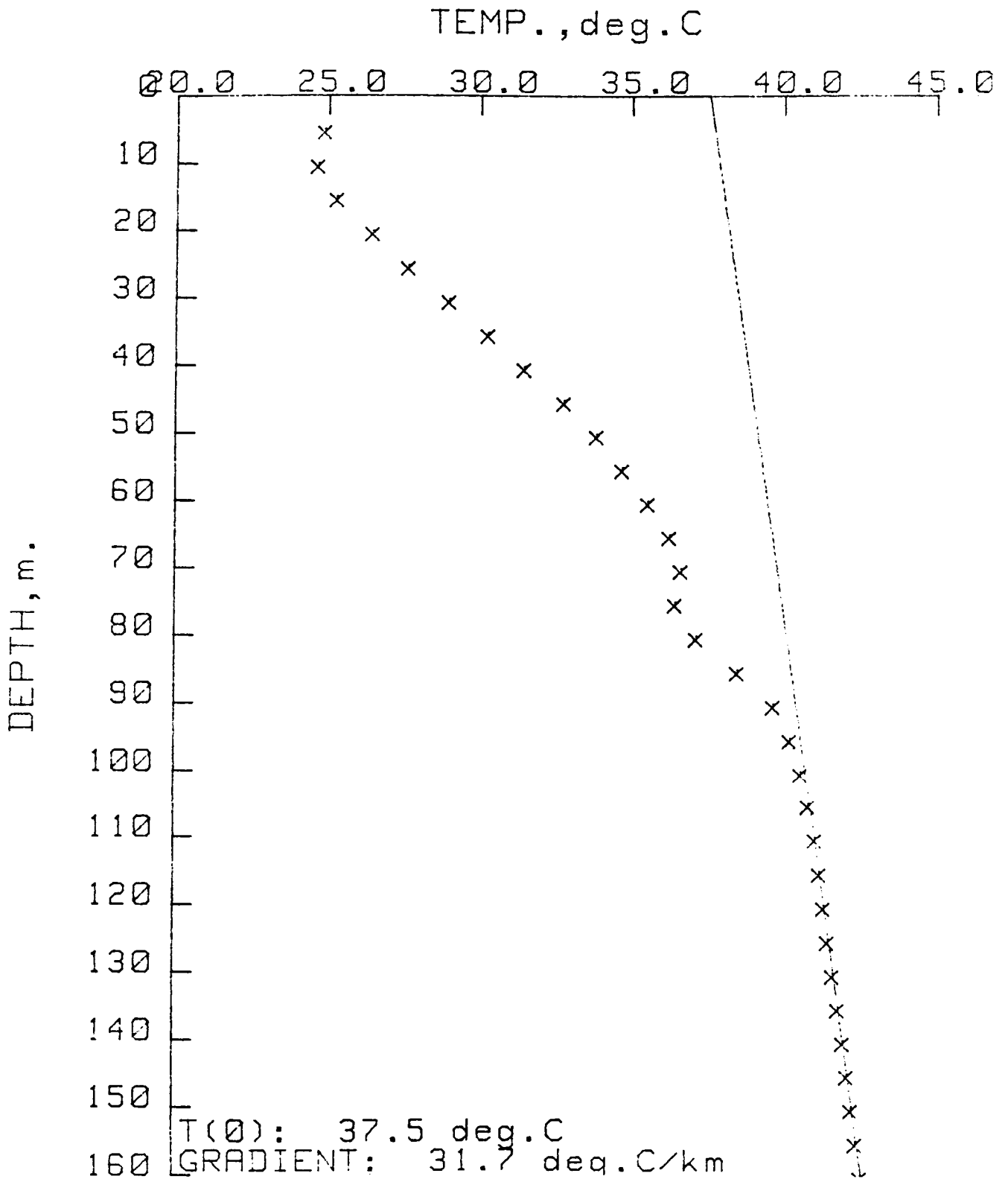
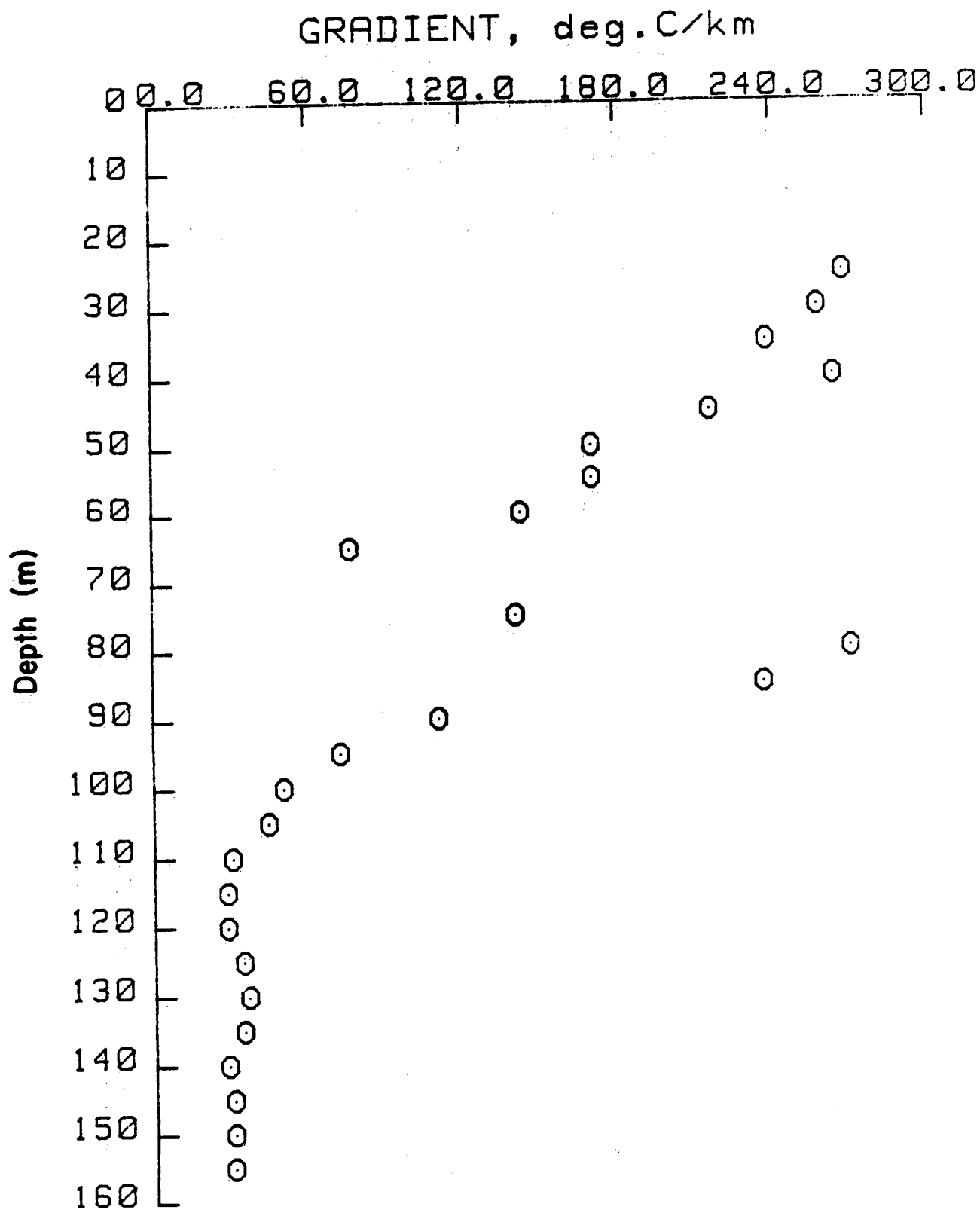


Figure 41 - Gradient - Benevides #1



Benevides #2 (Fig. 42 and 43) -- Located about 2 km east of Benevides #1, in the hills at the edge of the Presidio Bolson, east of the Candelaria fault. The gradient is disturbed throughout, reflecting the difficulty in drilling due to fractured intervals in the shaly-limestone rocks. The average gradient of 60°C/km is higher than would normally be expected, and could indicate that warm water is moving eastwards, as well as westwards, from the producing fault.

Pelton #1 (Fig. 44 and 45) -- A 50 m gradient hole drilled some 8 km to the west of Ruidosa Hot Springs to test the geothermal gradient in the central part of the bolson. The resulting 42.1°C/km is probably representative of the background gradient, and indicates that the thermal anomaly is restricted to the area of the Candelaria Fault.

It is apparent from these results that the thermal anomaly in the area of Ruidosa Hot Springs is localized to the Candelaria Fault, and caused by the presence of warm water in the near subsurface. This localization results in elevated thermal gradients which do not persist past (below) the level of warm water emanating from the fault. A high temperature resource does not, therefore, exist in this immediate area at exploitable depths.

#### FINLAY MOUNTAINS

A high thermal gradient (80°C/km) in an abandoned mineral exploration hole in the Finlay Mountains, Hudspeth County (Fig. 46) initiated interest in a drilling test in the area. Since the original drill hole was cased to about 152 m (500 ft), it was decided to deepen the existing hole and obtain a heat flow measurement therein.

The Finlay Mountains form a structural dome, caused by the intrusion of a Mid-Tertiary diorite laccolith into the Permian limestones. The drill hole was located near the apparent center of the intrusion. It was cored to 405 m, yielding all igneous material, partially mineralized and containing fragments of country rock.

Figure 42 - Temperature-Benevides #2

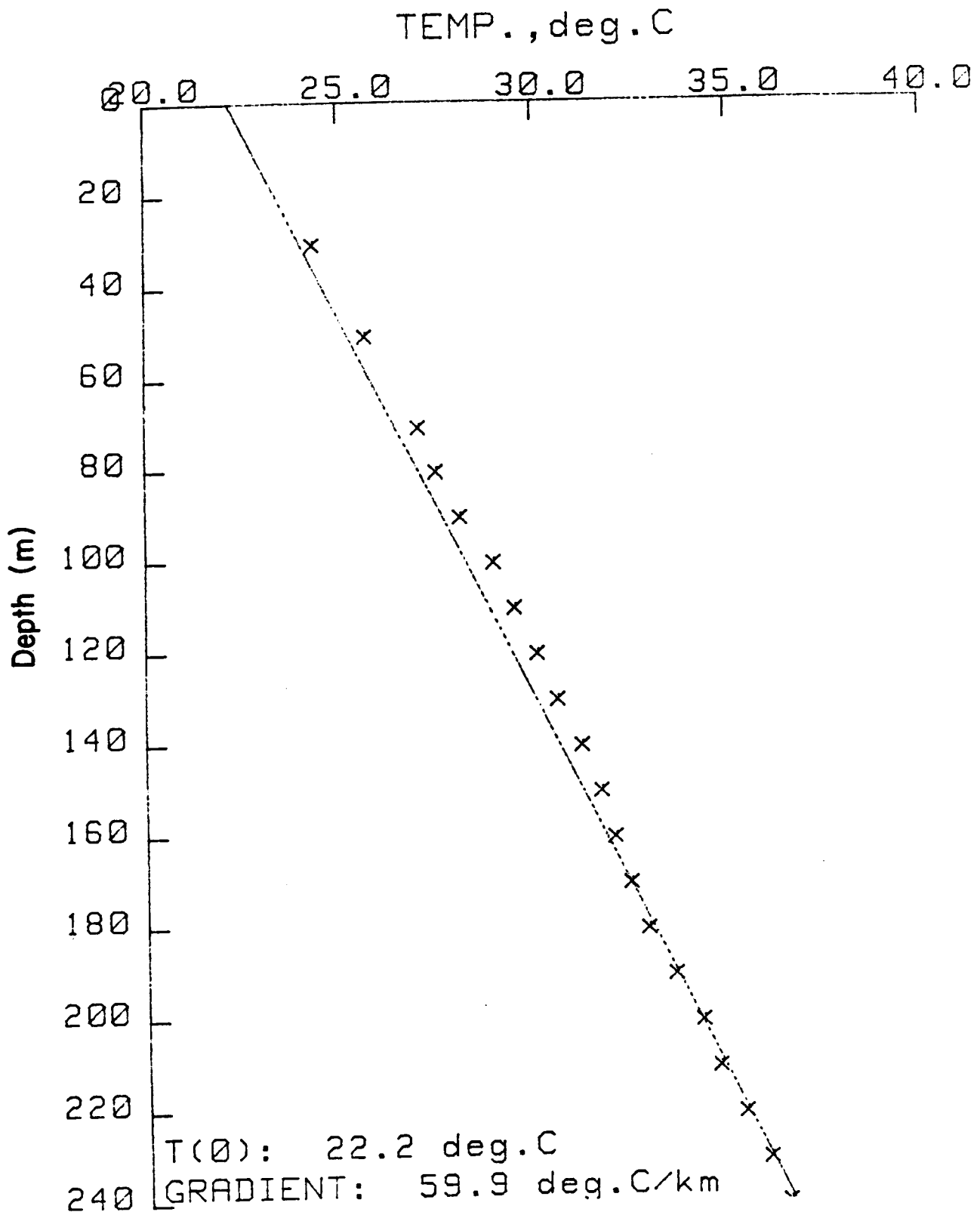




Figure 43 - Gradient - Benevides #2

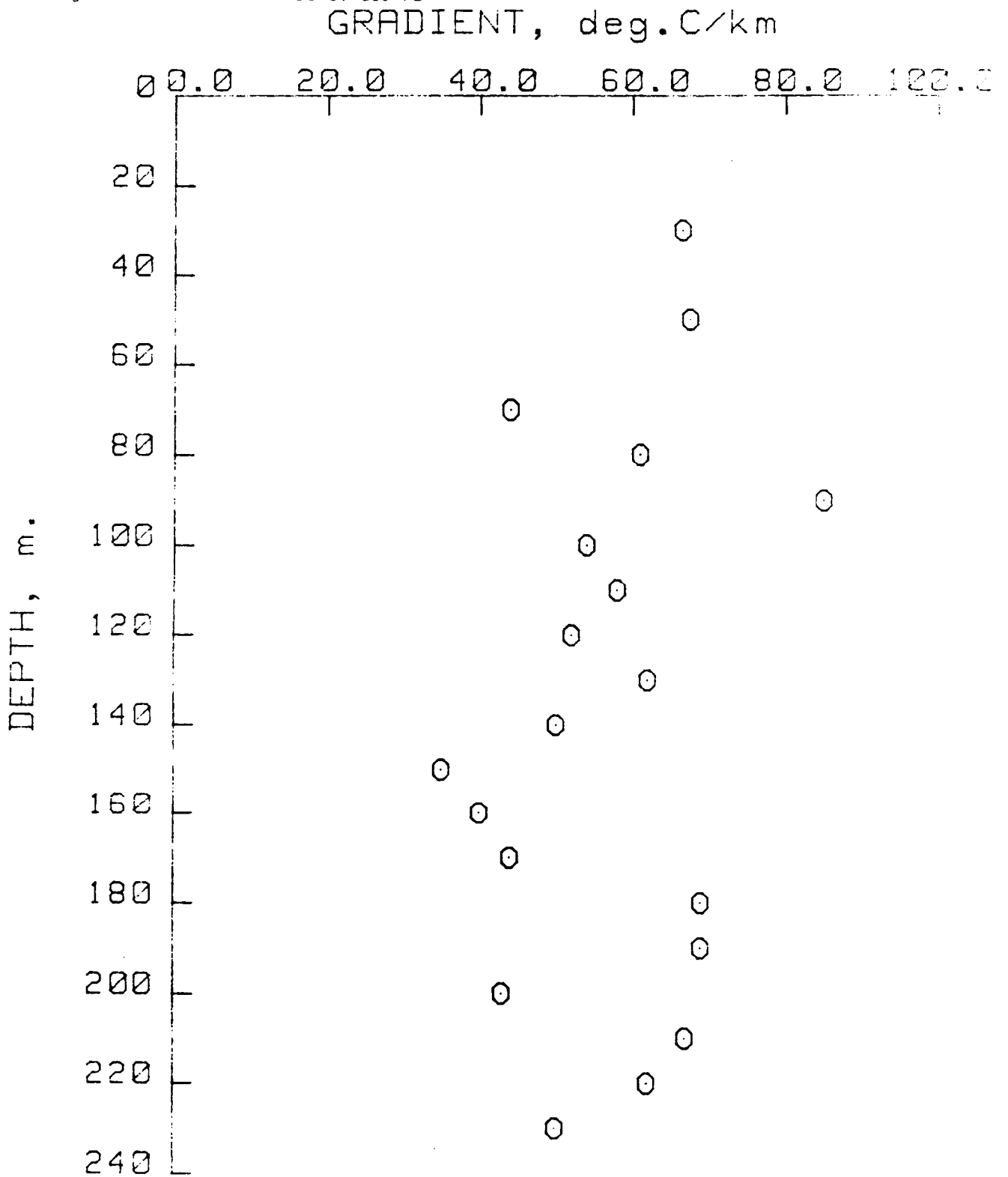


Figure 44 - Temperature-Pelton #1

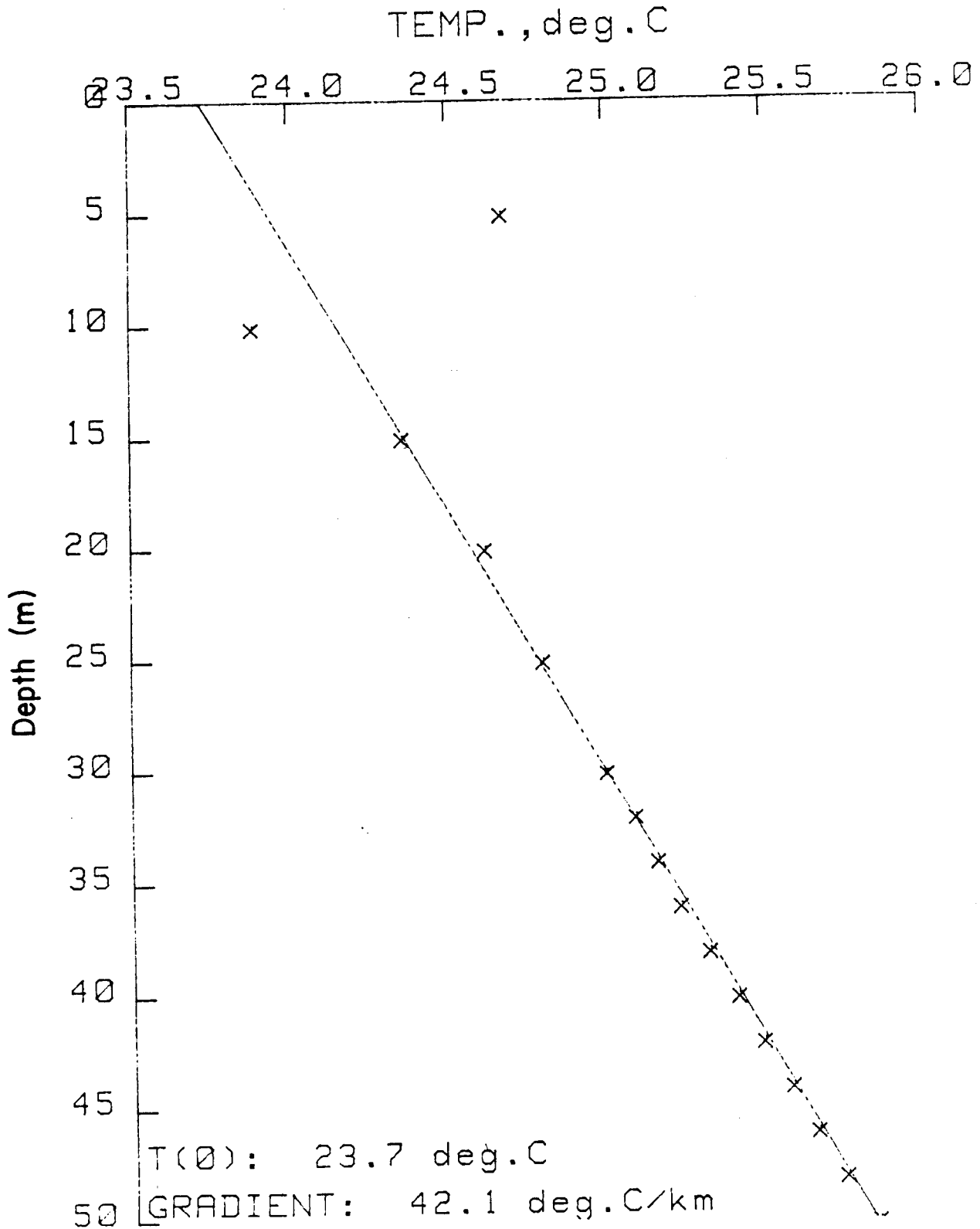
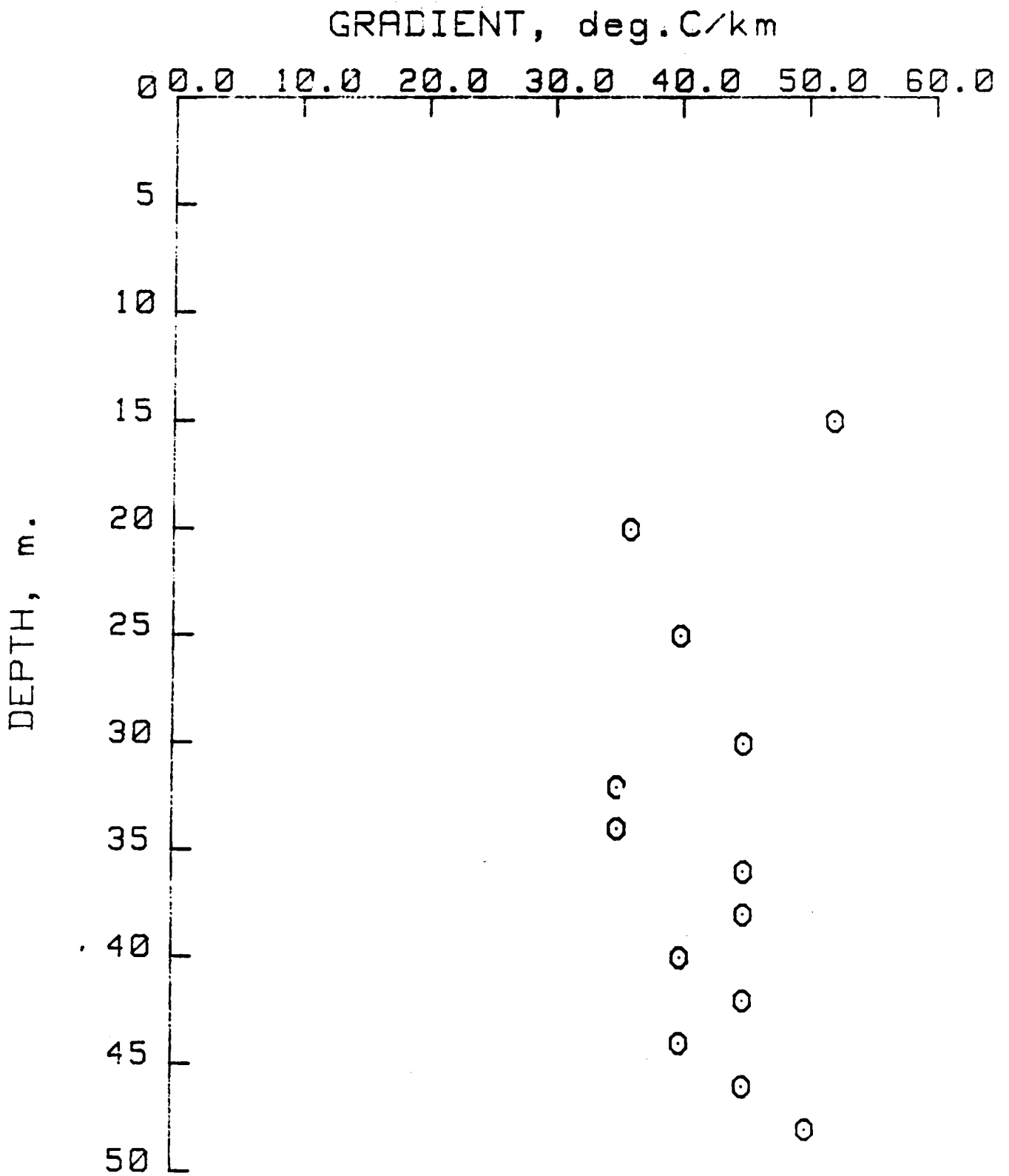


Figure 45 - Gradient-Pelton #1



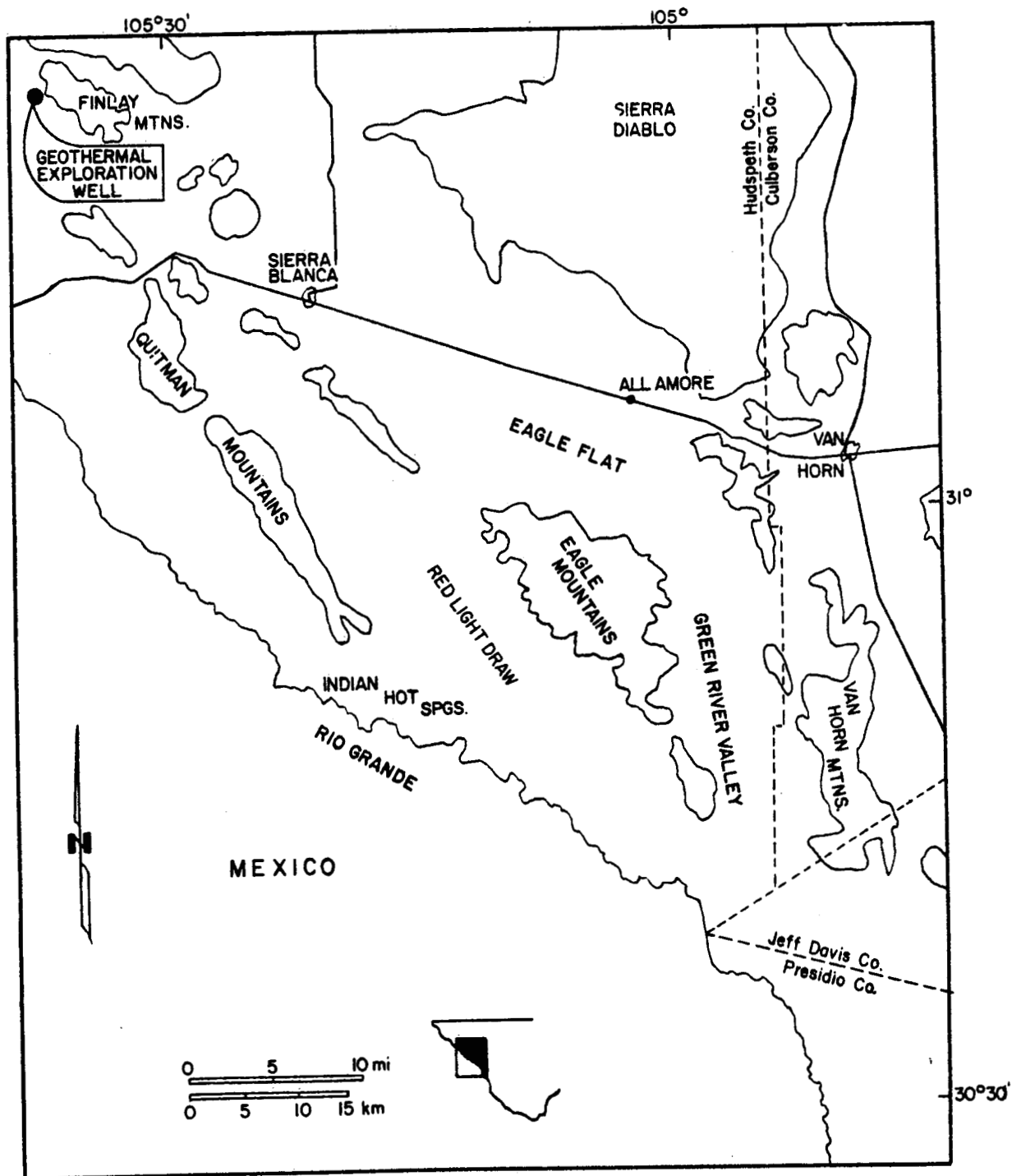


Figure 46 - Location of Test Hole in Finlay Mountains

The temperature log is shown in Fig. 47. A high gradient ( $110^{\circ}\text{C}/\text{km}$ ) persists to 300 m; a bottom hole temperature of  $56^{\circ}\text{C}$  was recorded. The 300 m level appears to mark a warm water zone, with a lower gradient below, with temperature increases again near the bottom of the hole. However, circulation problems during drilling make the reliability of measurements in the lower 100 m questionable; an equilibrated log could not be made prior to the printing of this report. Based on current knowledge, the mechanism in operation in the Finlay Mountains is probably similar to others in West Texas, i.e. warm water emanating from a fault causing a local thermal anomaly at the surface. Thermal refraction connected with the local intrusive body here may be an alternative or additional interpretation. Gradients in water wells circumscribing the dome are relatively normal for the area, thus centering the anomaly upon the Finlay Dome itself.

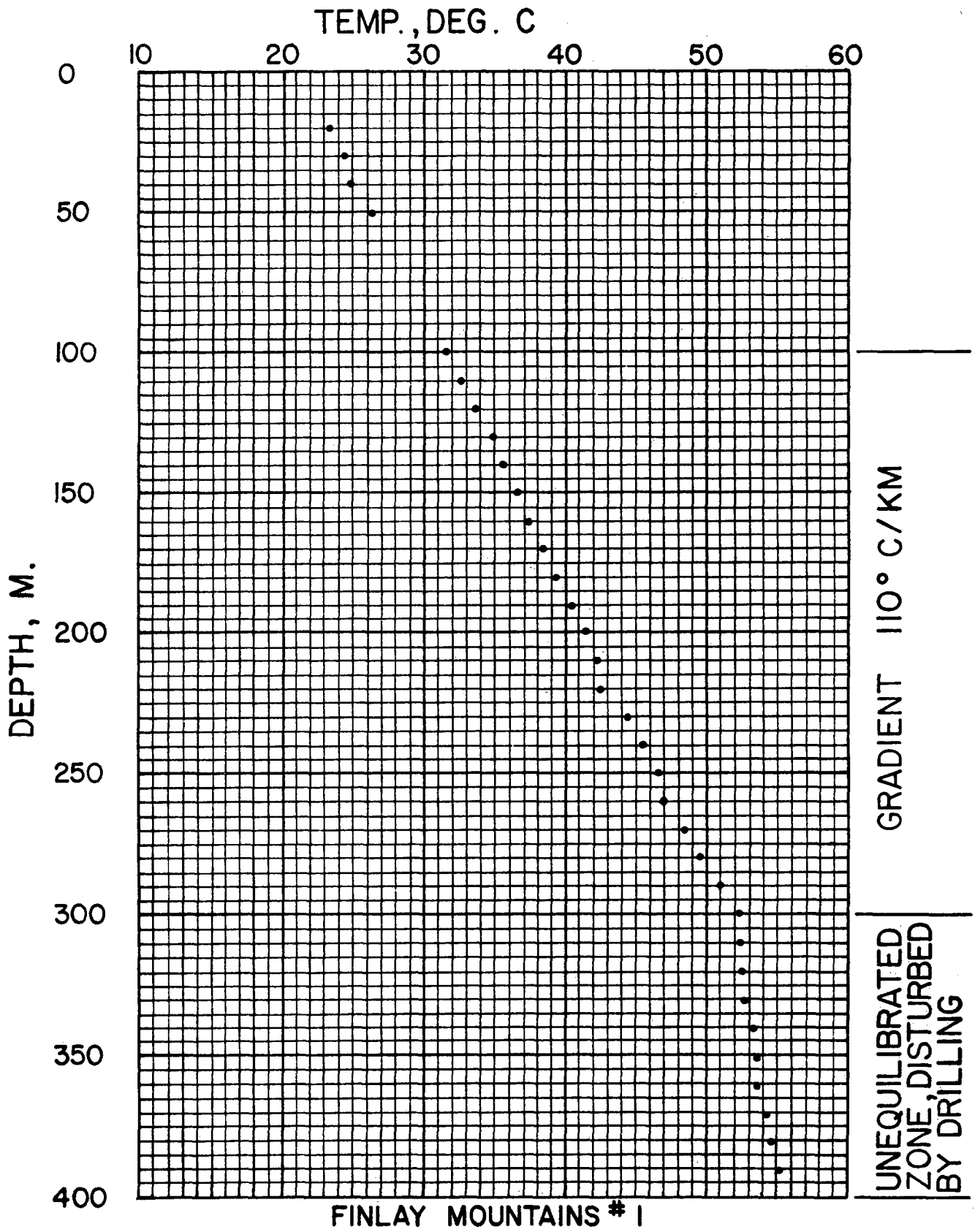


Figure 47 - Temperature Finlay Mountains

## CONCLUSION

The original intent of this study was to investigate the two areas in Trans-Pecos Texas/New Mexico known as the Hueco Bolson and the Presidio Bolson. Prior geophysical and geochemical investigations gave indications that these two areas might be underlain by geothermal anomalies which could support commercial exploitation. This study was designed to investigate both these areas (and any others in west Texas) of interest, primarily through geophysical techniques with temperature-gradient measurements in shallow holes used as guides for deeper exploration.

The geophysical/geochemical studies conducted as part of the activities of this investigative project yielded the following conclusions:

- 1) The Hueco Bolson appears to be the site of geothermal waters with a temperature no more than 80°C occurring at relatively shallow (c. 600 ft) depth. The source of the water appears to be the Hueco Bolson with upward migration routes along faults.
- 2) The Presidio Bolson, in the vicinity of Ruidosa Hot Springs, along the Calendaria Fault, has moderately warm geothermal water which evidently rises along, and is confined to the Candelaria Fault. It is thought that the locally elevated thermal gradients ranging from 71° to 9 261°C/Km, compared with a background value of 40°-45°C/Km, do not persist below the level of warm water emanating from the fault. Findings indicate that a high temperature resource at economically exploitable depths does not exist in the Ruidosa Hot Springs area.
- 3) A test hole in the Finlay Mountains exhibited a thermal gradient of 110°C/Km to 300m (984 ft) but decreased markedly thereafter. It is probable that an economically exploitable geothermal resource does not exist here, but the probable cause of the elevated gradient in the Finlay Mountains is still a subject for debate and continued scientific investigation.

## APPENDIX I - FIELD MEASUREMENT OF VARIOUS PARAMETERS

### ELECTRICAL METHODS

#### Self Potential Measurements

The self potential (spontaneous potential, or SP) method is one of the oldest geophysical tools, dating back to 1830. Since that time it has been used extensively in exploration for metallic minerals, and in very recent time has been suggested as one means of geothermal prospecting. Corwin and Hoover (1979) have considered this later use in detail, although they point out that the mechanism of generation of SP anomalies is not well understood, and interpretation of results must be considered carefully.

Among other causes, elevated temperatures (the thermoelectric effect) and streaming potentials, such as may be caused by circulating fluids (the electrokinetic effect) can both give rise to SP anomalies.

The SP traverses made in the present study (See Fig. 25, earlier) used a 100 m dipole arrangement operating in a "leapfrog" fashion, the potentials being added successively to obtain the SP value at the new station relative to a "zero" base. The dipole consisted of two Cu-CuSO<sub>4</sub> non-polarizing electrodes connected to one another through a high impedance voltmeter (the high impedance reduces the risk of inducing potentials at the electrodes from the meter). The "pots" were firmly planted in small pits dug in the ground at each station.

Telluric currents (due to variations in the earth's magnetic field) proved to be a major source of noise. To ameliorate their effect the variations in voltage for each reading were noted and the average value used. It was sometimes necessary to wait for three or four minutes to register the maximum and minimum telluric voltages. Other commonly encountered sources of noise such as cultural activity, uneven soil moisture content and spurious potentials due to chemical contamination of the electrodes (from the soil), were not considered of importance in the present survey. There



was no evidence of conductive mineralization in the locality which could give rise to anomalous readings. The "leapfrog" summation method can cause cumulative errors over long traverses, but a loop survey run previously (5.5 km in length) closed to within 0.1mV. The described traverses thus were tied to this loop, hence to a zero reference and, finally, to one another.

The results of the two traverses are shown in Figures AI-1 and AI-2 . Both lines display a correlation with elevation, but the elevation change is itself due to a geologic change from bolson fill to outcropping limestone (this change corresponds to a rise in geothermal gradient). The SP response over the bolson fill is distinctly smoother than over the limestone, suggesting fractures in the latter giving rise to small streaming potentials. One, and possibly two, faults appear to be distinguishable, particularly on the northern section, while to the south (Traverse II) the suspected fault traces are obscured by noise.

By taking a derivative, the SP gradient is obtained (in mV/100m). This derivation has the effect of removing elevation error and enhancing the suspected fault traces which are distinguishable on both lines as symmetrical flanking anomalies about 800 m apart (See Figures AI-1 , and AI-2).

#### Electrical Resistivity Soundings

Resistivity measurements have been made quite extensively in the El Paso area in the search for potable water (Sayre and Stephenson, 1937; Sayre and Livingston, 1945; Knowles and Kennedy, 1959; Zohdy, 1969; Zohdy et al. 1976; Gates et al, 1978). Of these, however, only those of Zohdy (1969) can be usefully correlated with the present study area.

Four vertical electric soundings were made over the geothermal area, in an attempt to distinguish a thermal zone using the resistivity method. The equipment used was built, described and kindly loaned by Young (1979), and

Figure AI-1 - Self-potential profile I. 'F' designates an inferred fault, 'HT' - refers to thermal gradient drillholes.

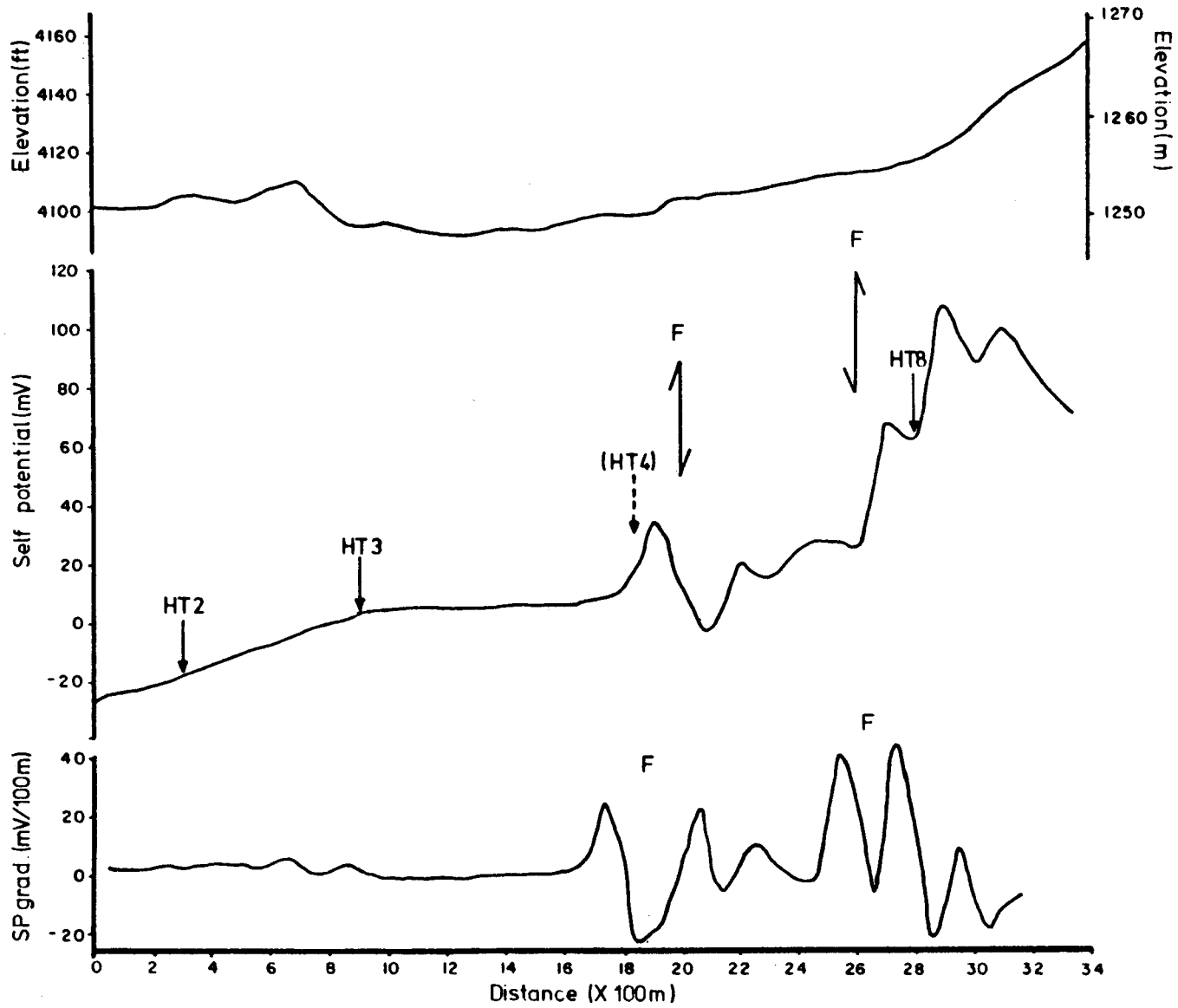
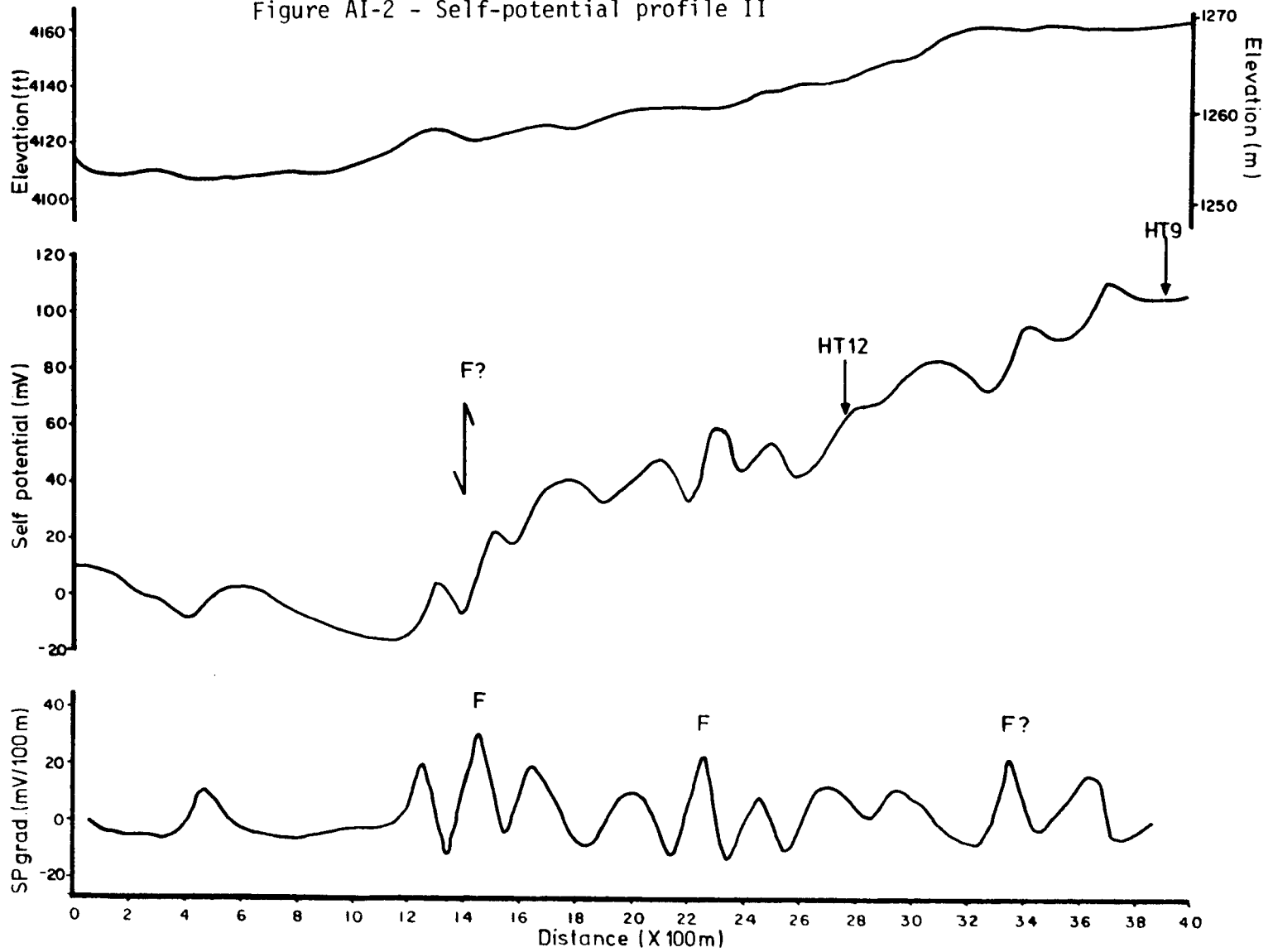


Figure AI-2 - Self-potential profile II



is illustrated diagrammatically in Figure AI-3. The Schlumberger electrodes configuration was employed, in which the outside (current) electrodes are moved apart while keeping the inner (potential) electrodes at a relatively close spacing. A "picture" of the resistivity-depth relationship, effectively below the center of the spread, is produced. The line of survey was in each case set out perpendicular to the strike of the supposed geologic structure. The maximum spacing attained was 1 km from the center, although telluric currents made readings difficult at distance. As with the SP readings, the range of telluric variation was noted and an average value recorded.

Apparent resistivity (in ohm-m) for each electrode position was calculated using the formula:

$$\rho_a(\text{ohm-m}) = \pi \frac{(a^2 - r^2)}{2r} \times \frac{V}{I}$$

where

a = length AB/w (m)

r = length NM/2 (m)

V = potential between M and N, measured with volt meter (mV)

I = current into ground at A and B, generated by d.c. transmitter (mA)

Field data were plotted as  $\rho_a$  versus AB/2 on log-log graph paper. A computer program "RESIST" (after Ghosh, 1971 and Sternberg, 1977) was then used to model a similar graph using input resistivity and thickness parameters. A horizontally layered, laterally homogeneous earth is assumed. The modelling technique produced several matching alternatives to the field data, however, only one possibility which is a likely analog is illustrated, for each. Depth estimates using this method can be incorrect due to non-homogeneity of beds. The resulting curves are discussed below. The 500 ohm-m value used for bedrock is arbitrary, and was chosen to represent an "infinite" bottom-layer resistivity.

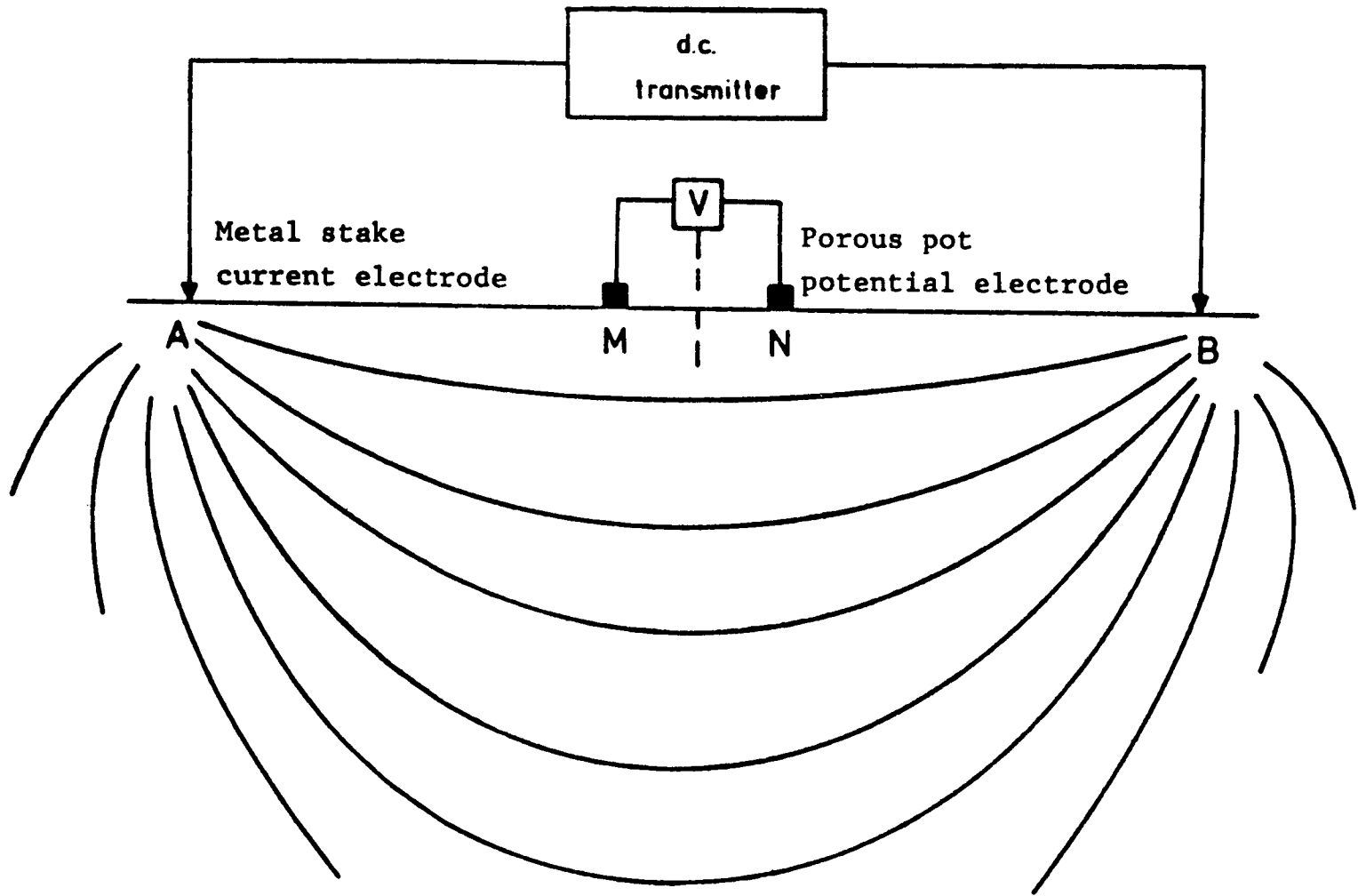


Figure AI-3 -Arrangement of apparatus for Schlumberger electrical soundings, showing the form of current flow in a semi-infinite earth.

(i) VES-1 (Figure AI-4)

This sounding was located near the site of the former "Hot Well" and is modelled as a 6-layer case. The irregularity of the field points (especially at  $AB/2 = 55$  m) suggests that the assumption of horizontal strata may not be strictly valid (a horizontally stratified medium would give rise to a smooth curve, such as that produced by the model). Indeed, a cusp like that at  $AB/2 = 55$  m may indicate a near vertical resistivity contrast, such as a fault (Kunetz, 1966, p.74). The low resistivity fifth layer almost certainly represents the "hot mineralized water" encountered by the old hot well. The model for VES-1 can be compared in form with Zohdy's (1969) Sounding-2, made 35 km to the south, but still at the eastern edge of the Hueco Bolson.

(ii) VES-2 (Figure AI-5)

A 4-layer model for this sounding again shows a low resistivity layer above the "bedrock", although with a higher value than that in VES-1. The depth estimate suggests that this is not the water table. The field curve displays a remarkable resemblance to Zohdy's Sounding-9, which is shown in Figure AI-6 for comparison. The discontinuity at  $AB/2 = 300$ m is explained by Zohdy in terms of a thin limestone ridge. This could be translatable into a small buried horst in the present example, although without further soundings to the east, this cannot be substantiated.

(iii) VES-3 (Figure AI-7)

The somewhat irregular field curve of VES-3 is not readily interpretable with the present technique. A 6-layer model is presented which excludes the two sharp resistivity minima at  $AB/2 = 4$  and 180m. This model shows a very low resistivity layer above "bedrock", and this probably corresponds to the hot water encountered by well 14. Depth estimates are unreliable due to the apparently unhomogeneous nature of the ground in this area.

VES 1 (Hotwells 1)

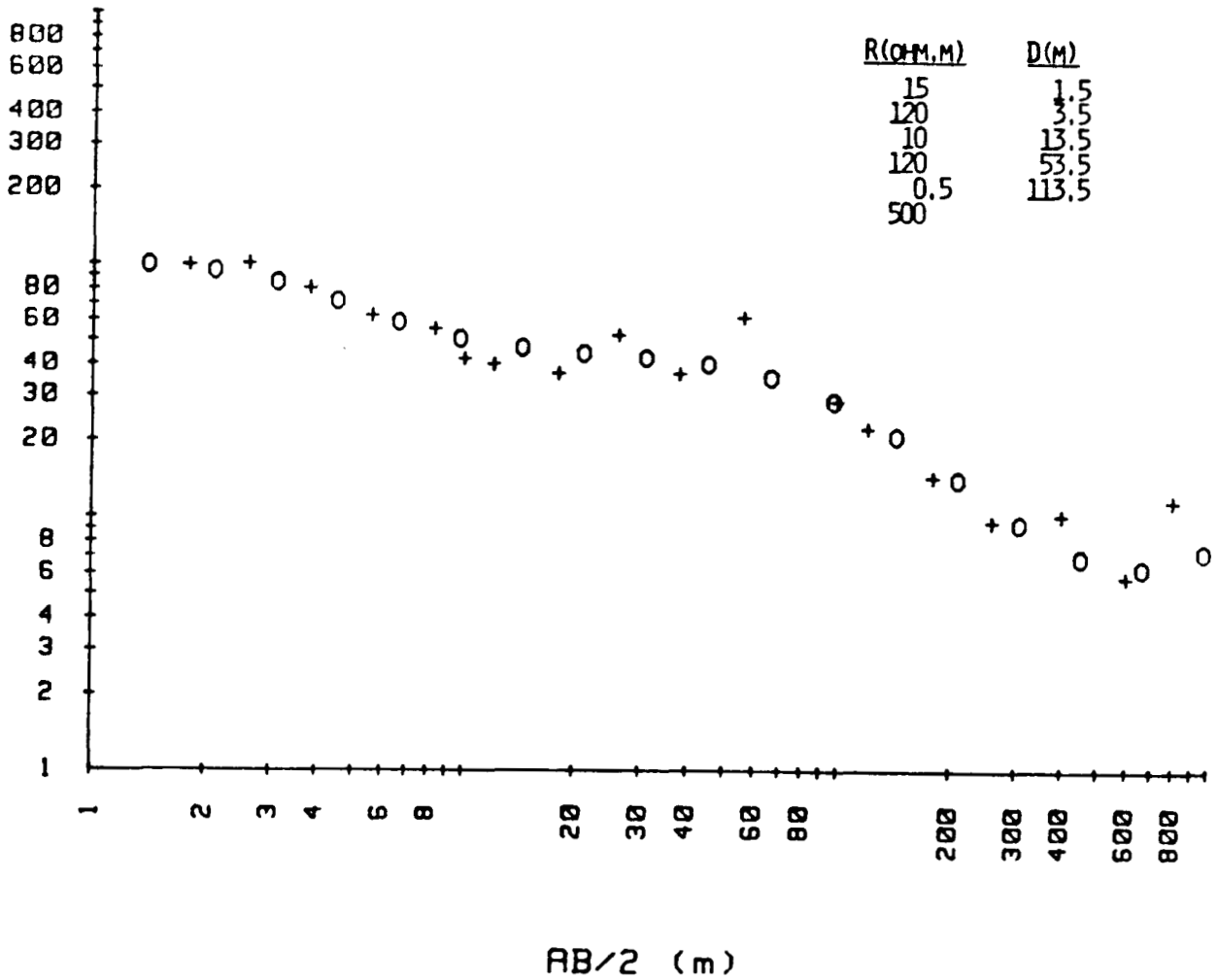


Figure AI-4 -Resistivity sounding curve for VES-1. Field points shown by crosses, computed model by circles. Model parameters (resistivity and depth) top right.

# VES 2 (Hotwells 2)

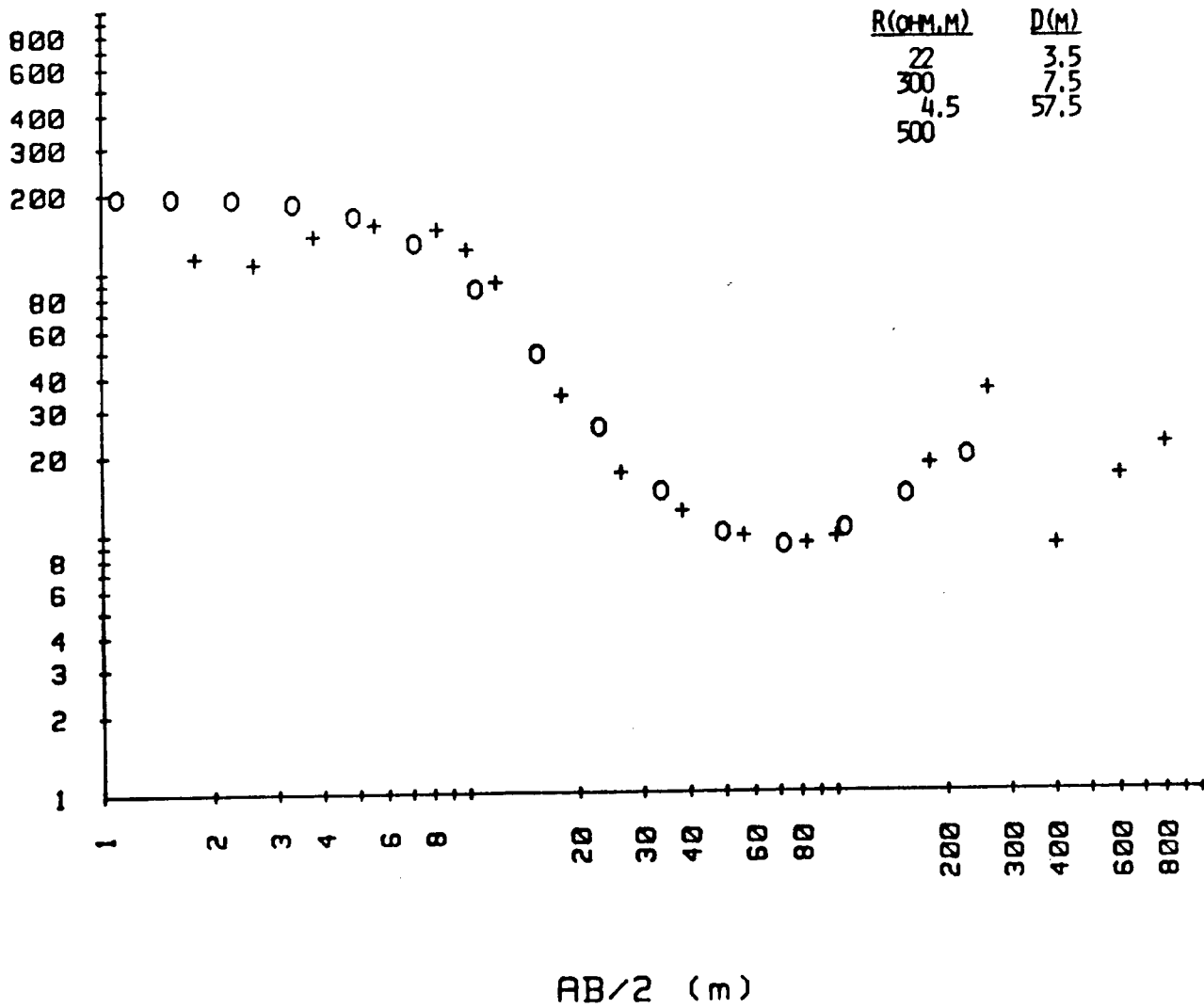
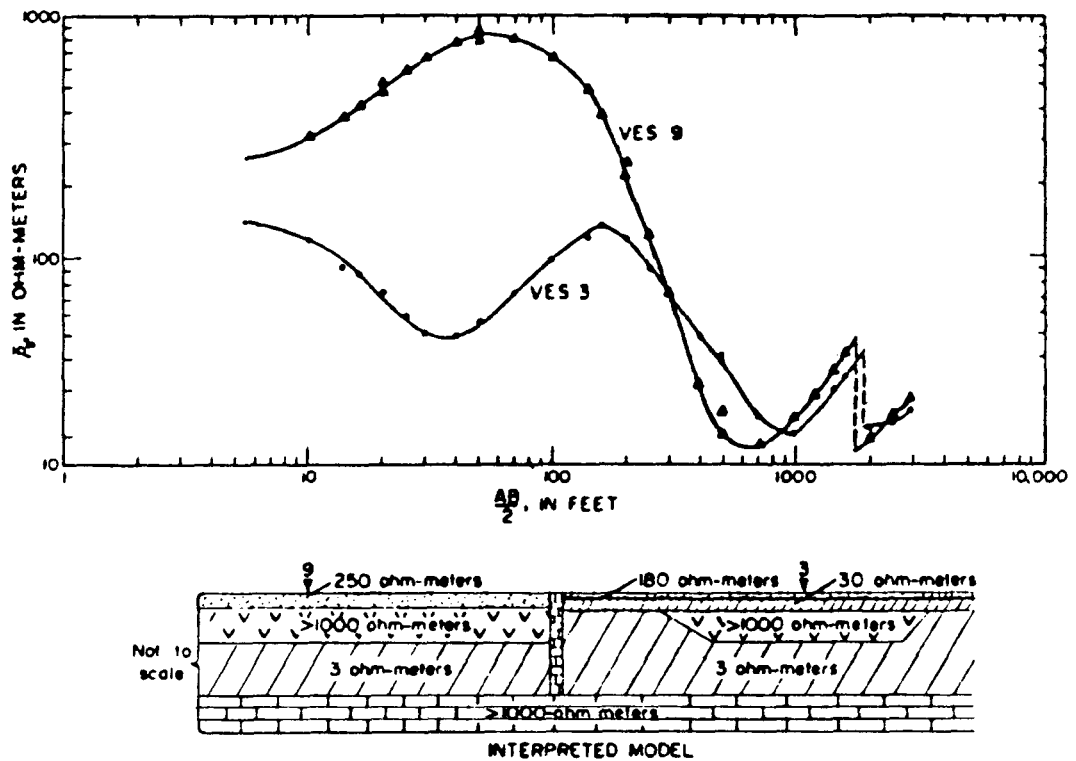


Figure AI-5 -Resistivity sounding curve for VES-2.





Curves of VES 3 and 9 showing discontinuities at  $AB/2 \approx 1800$  ft due to the crossing of a current electrode over thin vertical dike-like structure of high resistivity. The maximum on VES 3 has a sharp curvature due to the limited lateral extent of the third layer ( $>1000$  ohm-m layer beneath VES 3 in interpreted model). Horizontal distance, on interpreted model, between VES 3 and 9 is approximately 3900 ft.

Figure AI-6 -Fig. 5 from Zohdy (1969), showing his "VES-9" and "VES-3". Compare the form of the curves, and the discontinuity, with VES-2 from this study.

### VES 3 (McGregor 1)

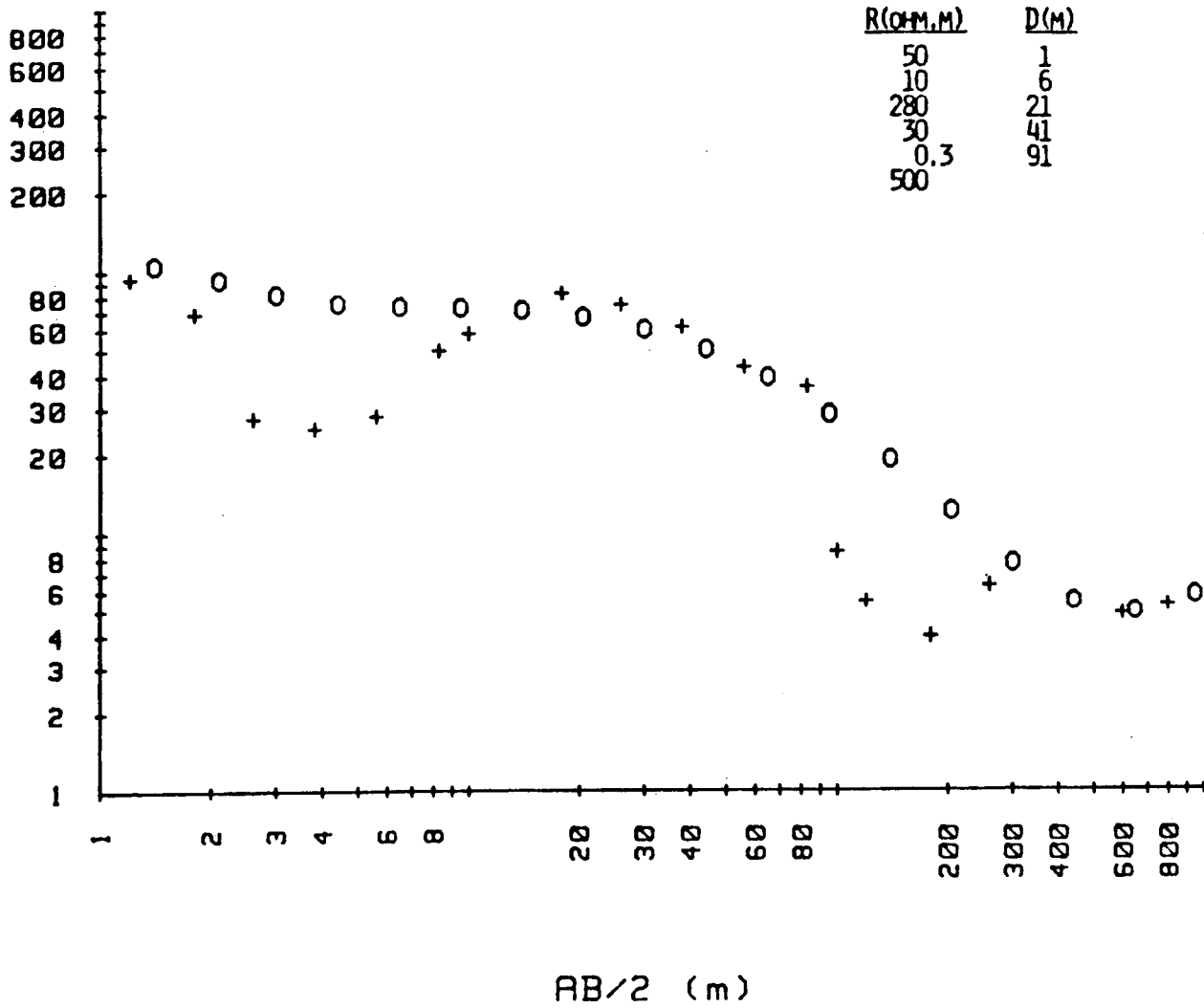


Figure AI-7 -Resistivity sounding curve for VES-3.

(iv) VES-4 (Figure AI-8)

Equipment malfunction limited sounding radius to 100m at this location, however, the existing part of the curve is similar to the same parts of VES-1 and 2. An extrapolated 6-layer model (if valid) suggests the presence of the hot water layer again, at about 100m, consistent with the other soundings and the known depth of the water table.

No attempt has been made here to define the areal extent of the hot water using resistivity soundings or profiles. An intensive resistivity survey in the area, involving several dozen soundings, might prove useful in this matter, though the quantitative ambiguities apparent from the above examples could limit the effectiveness of such work.

#### THERMAL GRADIENT MEASUREMENTS

The basic data sources behind the interpretations made in this study are a series of subsurface temperature measurements. Approximately 40% of these yielded thermal gradients, while the remainder consisted of only one temperature which was used to produce a pseudo-gradient. The various procedures which were employed to produce pseudogradients were the following:

Information on regional surface temperatures and adiabatic lapse rates for use in heat flow terrain corrections was obtained from climatological data published by the Environmental Data and Information Service of the National Oceanic and Atmospheric Administration. Mean annual temperatures for 1941-1970 (one list), and 1972-1978 (individual annual summaries, excluding 1975, which was not available) were analyzed, for the eighteen recording stations in the study area. Table AI-1 summarizes location information for these stations, and Table AI-2 lists mean annual surface temperatures for the aforementioned periods; positions of the stations are shown in Figure 6, earlier.

### VES 4 (McGregor 2)

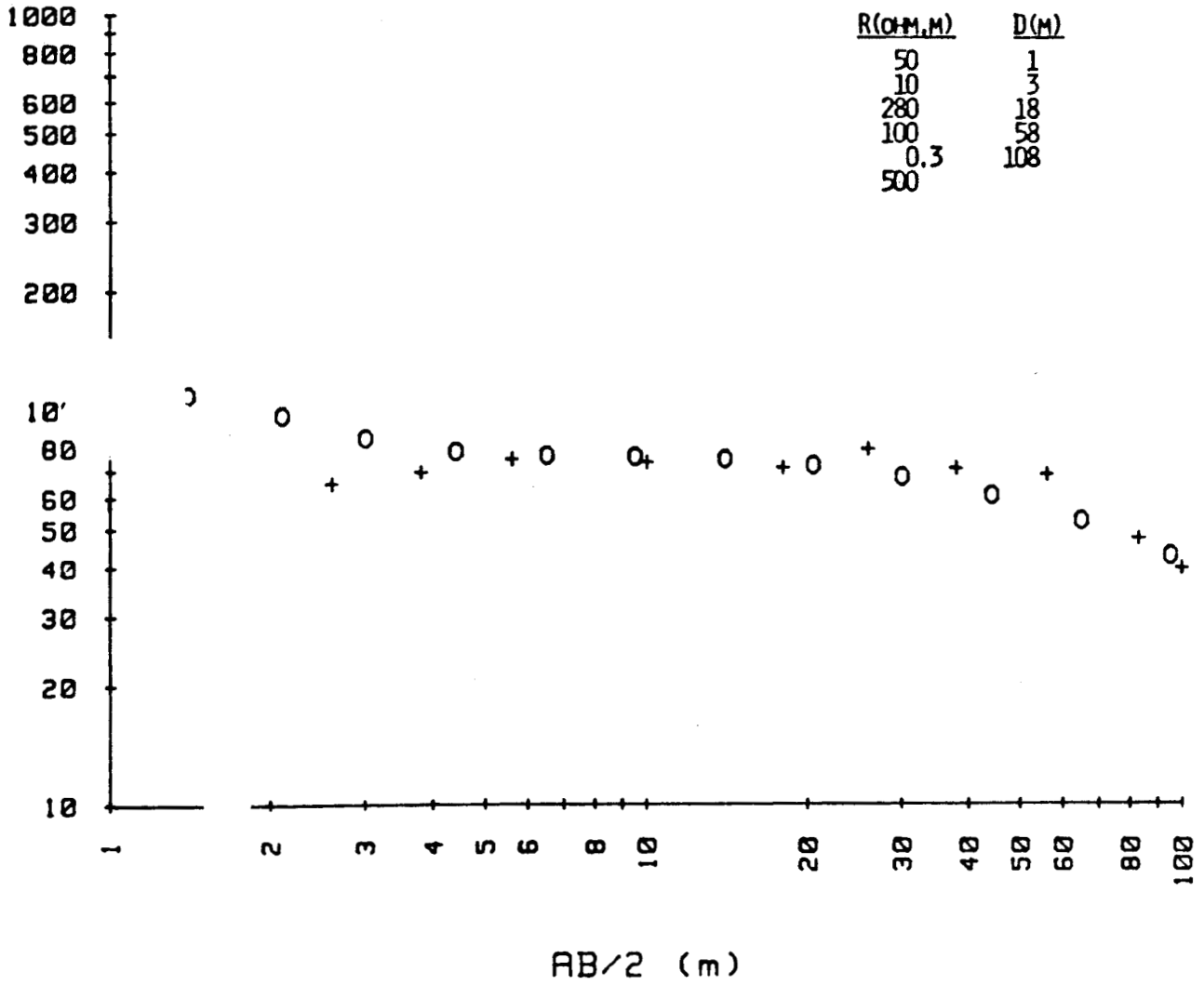


Figure AI-8 -Resistivity sounding curve for VES-4.

Table AI-1 - Index of weather stations, West Texas.

Station name	Code	Latitude	Longitude	Elevation*
Alpine, B	A	30°21'	103°40'	4430
Candelaria, P	CA	30°09'	104°41'	2875
Chisos Basin, B	CH	29°16'	103°18'	5300
Cornudas, H	CO	31°47'	105°28'	4480
El Paso, E	EP	31°48'	106°24'	3913
Fort Hancock, H	FH	31°15'	105°48'	3940
La Tuna, E	LT	31°58'	106°36'	3800
Lajitas, B	L	29°15'	103°47'	2440
Marathon, B	MT	30°13'	103°14'	4030
Marfa, P	MF	30°18'	104°01'	4710
Mt. Locke, J	ML	30°40'	104°00'	6790
Panther Jct., B	PJ	29°19'	103°13'	3740
Presidio, P	P	29°33'	104°21'	2570
Salt Flat 2, C	SF	31°47'	104°54'	3890
Sierra Blanca, H	SB	31°11'	105°21'	4590
Van Horn, C	VH	31°03'	104°50'	4050
Ysleta, E	Y	31°42'	106°19'	3670
Fabens, E	F	31°30'	106°09'	3610

\*In feet above sea level.

Notes: County abbreviations:-

- B - Brewster
- P - Presidio
- H - Hudspeth
- E - El Paso
- J - Jeff Davis
- C - Culberson

Table AI -2 - Mean annual temperatures, West Texas weather Stations.

Station code	Annual temperatures, ° F							Mean	
	1941-70	1972	1973	1974	1976	1977	1978	° F	° C
A	62.6	63.0*	61.6	64.5*	59.9	63.7	62.3	62.6	17.0
CA	--	67.7	63.6*	67.7	64.9	66.7*	67.3	66.3	19.1
CH	--	63.0	61.0	62.3	59.4	63.1	61.7	61.8	16.6
CO	--	61.2	59.2	60.5	59.0	62.0	60.2	60.4	15.8
EP	63.4	63.8	61.9	62.7	61.4	63.8	64.7	63.6	17.4
FH	--	64.2*	58.2*	62.9	60.7	63.7	63.4	62.2	16.8
LT	--	65.5	61.9*	63.7	62.5	64.8	64.8	63.9	17.7
L	--	--	--	--	--	--	77.2	71.4	21.9
MT	--	60.1*	60.4*	64.5*	58.2*	--	61.2	60.9	16.1
MF	--	61.1	58.5*	60.8	58.2	61.4	60.6	60.1	15.6
ML	57.3	57.9	56.9	57.6	54.9	58.9	57.7	57.3	14.1
PJ	--	65.9	64.4	65.6	63.2	67.0	65.4	65.3	18.5
P	70.1	69.8	69.3*	70.0	68.3	70.0	69.6*	69.8	21.0
SF	--	62.1	60.4	61.8	60.0*	62.6	--	61.4	16.3
SB	--	61.7	60.1	61.0	59.7	64.7	64.9*	62.0	16.7
VH	63.0	64.0	59.5*	64.5*	64.6*	63.6*	64.7*	63.3	17.4
Y	62.0	63.2	61.8	63.3	63.5*	64.2	63.7	62.7	17.1
F	--	62.5	60.6	61.4	63.8*	--	--	62.1	16.7

\* - data missing

The elevation and mean annual temperature for each of the eighteen locations are plotted in Figure AI-9. A least-squares line through the points gives a slope of  $-0.002867$  °F/ft, which converts to  $-5.224$ °C/km; this represents the normal adiabatic lapse rate for the region and was used to calculate 'pseudogradients'.

## Temperature Logging

### Equipment

Downhole temperatures were measured with thermistor probes connected to resistance bridges. Two such arrangements were used in the field, and are described in Taylor (1981).

### Procedure

Actual downhole temperature measurements were made in some 100 wells and boreholes in El Paso, Hudspeth, Jeff Davis, Culberson and Presidio Counties. In addition, a number of gradients were obtained from temperature logs made available by the U. S. Geological Survey. The geothermal gradients obtained are discussed earlier.

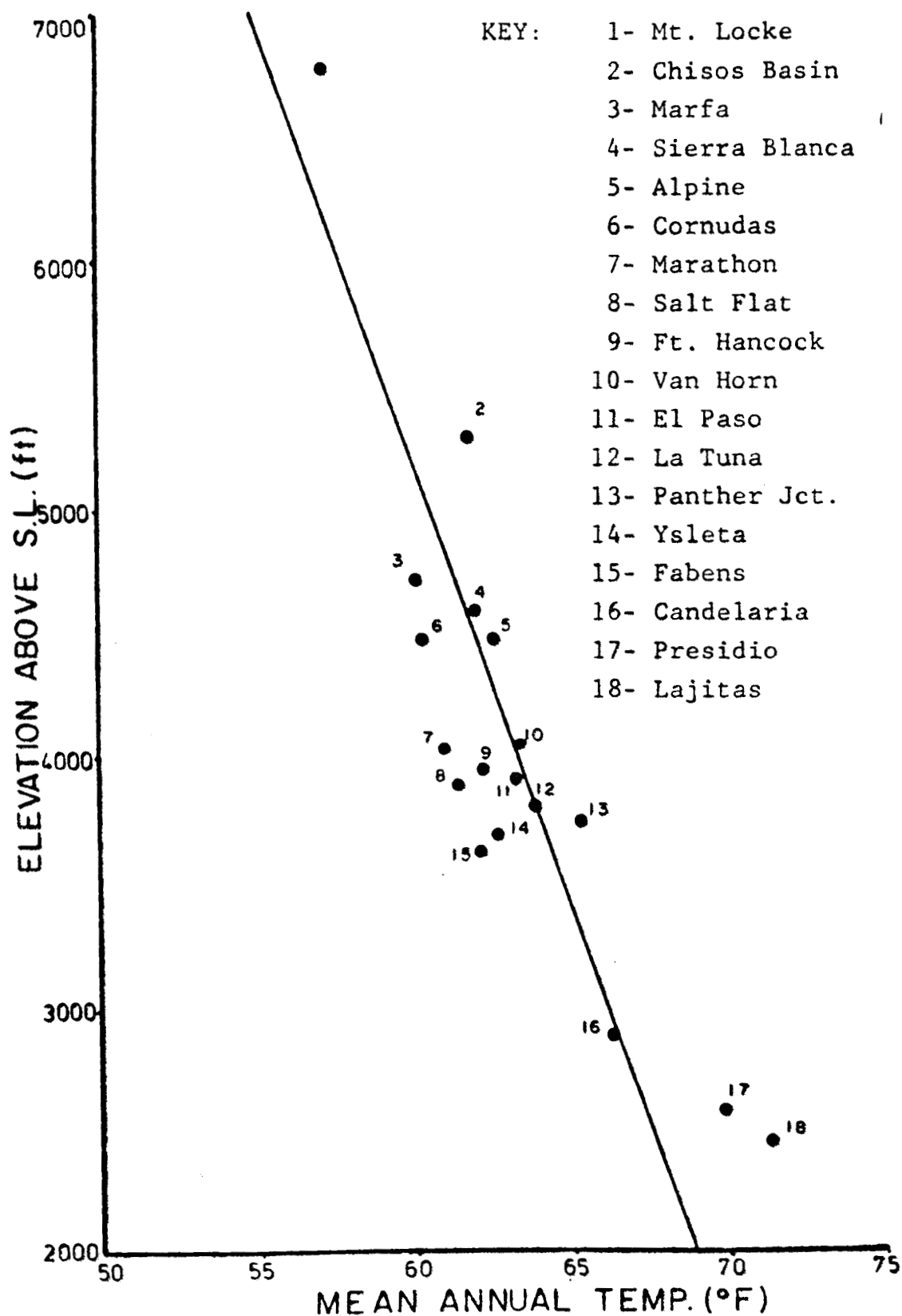
Sites ranged from geothermal gradient holes filled with water to facilitate temperature logging to abandoned wells (usually dry). Presently or recently operating water wells were avoided because of the temperature disturbance and the risk of lodging the temperature probe between pumpjack and casing.

Because of the semi-arid nature of the Trans-Pecos area, the water table generally lies fairly deep, between about 30m and 100m (Davis and Gordon, 1970), with local variations greater than 200m. For this reason, many temperature logs were taken either completely or partially in air. In such cases, since the thermistor probes used take some time to register the correct temperature when in air (as compared with very rapid equilibration in water), a series of readings were taken at each depth logged (namely, at 0, 2, 3, 5 minutes). Several functions were empirically fitted to a set of test data, in an attempt to determine the true formation temperatures (at extrapolated infinite time). The best fit was found using the function,

$$K = \frac{t}{(t - 1)} \quad (I.1)$$

where  $t$  = time (in minutes)

Figure AI-9 Plot of temperature vs. elevation for West Texas weather stations, for adiabatic lapse rate derivation.





The temperature at 2, 3, and 5 minutes were fitted by least-squares to the logarithmic equation:

$$T = A + B \ln K \quad \text{_____ (I.2)}$$

such as  $t \rightarrow \infty$ ,  $T \rightarrow A$ , the intercept on the temperature axis, thus effectively giving the temperature of equilibrium at that depth.

Temperature measurements were generally made at either 5 or 10m intervals, depending on the detail required for the ensuing geothermal gradient. Where a knowledge of the shape of the annual wave was needed, 2m readings were taken down to 10m, to closely obtain the form of the curve, and normal interval logging was commenced thereafter. Depths were obtained from a counter wheel, calibrated in meters (and reading to 0.1m), over which the logging cable ran into the hole; this served not only for depth finding, but also to facilitate movement of the probe and cable into and out of the hole. The cable was marked with tape at 10m intervals, and depths were located with these markings in instances where the counter wheel could not be used.

#### Computer Program THERMAL

The program "THERMAL" was designed to take a set of temperature - depth data, compute a least-squares gradient over a section of the curve, specified by the operator, and display the result graphically. Where desired, a plot of gradient versus depth could be produced. The program was written in Basic Language, for use on the Hewlett-Packard 9845 mini-computer. All temperature/gradient plots used in this study were generated by THERMAL. A listing of the program appears in Taylor (1981).

#### Thermal Gradient Estimation: Pseudogradients

A sizeable number of chemical analyses of water samples in the Trans-Pecos region were found to be available in various forms (White et al., 1978; Gates and White, 1976; files of U. S. Geological Survey Water Resources Division and Texas Water Development Board, El Paso); many of these included information on water temperatures and depths of wells. Also available were bottom hole temperatures from certain oil tests. A methodology was devised to make use of the bottom-hole temperatures in estimating geothermal gradients.

In the case of some of the more recent oil tests, bottom hole temperatures had been taken at progressive breaks in drilling, thus giving a series of temperature-depth points from which a gradient could be deduced. The use of bottom hole temperatures is prone to many sources of error; temperatures recorded are actually maxima, and may not necessarily represent the conditions at the base of the borehole. In addition, circulating drilling-mud can lower the effective temperature, and, unless sufficient time has elapsed between cessation of drilling and logging, thermal equilibrium may not have been established. Bearing these factors in mind, the use of these data can provide fairly reliable regional gradients, particularly when analyzed in large quantities, as has been demonstrated by various authors (Grisafi et al., 1974; Summers, 1972; Schoepel and Gilarranz, 1966).

The use of temperature data from water samples in the estimation of geothermal gradients ("pseudogradients") is subject to several errors and assumptions, as follows:

1. Accuracy of the measurement; a liquid-in-glass thermometer, being the usual tool, may be accurate to between 0.5 and 1.0°C;
2. The sample tested is assumed not to have been standing in a tank or piping where its temperature could have been artificially raised or lowered; and
3. The temperature of the recovered water represents the true temperature at the bottom of the well or at the depth in question. This is probably the least well substantiated assumption, since it cannot allow for mixing of water at higher levels within the well.

It is a commonly observed fact that the intercept on the temperature axis of a straight line drawn through a series of temperature-depth points in a geothermal gradient determination, and often designated as " $t_0$ " or "mean surface temperature," does not exactly coincide with the measured mean annual surface higher than the recorded MAST. This discrepancy must be accounted for if any gradient estimation is to be at all meaningful.

A series of thirteen geothermal gradient measurements (derived from actual temperature logs) in West Texas were chosen for investigation, on the basis of the good quality of their data and their relative proximity to a recording weather station. A quantity  $T_0$  was calculated for each, this being the difference between " $T_0$ " (derived from a least squares fit to the temperature-depth data) and the MAST of the nearest weather station.  $T_0$  varied between 2.0 and 5.6°C, the mean being 3.7°C. A "pseudogradient" was then calculated as follows:

$$\frac{(\text{Bottom hole temp.}) - (\text{MAST}) - 3.7}{\text{Depth}} = \text{Pseudogradient} \quad \text{--- (I.3)}$$

A comparison of gradients estimated by the above method and the least squares gradients to the real data are presented in Table AI-3, along with other relevant information. The similarity between the seventh and ninth columns indicate that this method is a feasible way of estimating geothermal gradients, given bottom hole temperatures and depths, and an idea of the MAST. The eighth column lists the estimates obtained without the removal of the constant 3.7°C; these estimates are noticeably in error.

A computer program, "PGRAD", was written to calculate pseudogradients in the above manner, for some 160 bottom hole temperatures. These were used in the compilation of the geothermal gradient map of West Texas (Figure 7, earlier), as a second order data set. A listing of the "PGRAD" program (written in Hewlett-Packard compatible Basic) appears in Taylor (1981).

It is thought that the "constant" alluded to is characteristic of the climate of a given area, hence will vary from one climatic region to another. All the weather stations in West Texas were considered together, as being from a similar province. Thus, it was necessary to define only one constant for the present study.

Table AI-3 - Geothermal gradient and pseudogradient comparisons for 13 stations.

Borehole location	Nearest MAST(°C)	Derived T <sub>o</sub> (°C)	ΔT <sub>o</sub> "	Bottom-hole temp.(°C)	Depth (m)	Measured grad.(°C/km)	P'grad* (°C/km)	P'grad** (°C/km)
Valentine	16.5	19.9	3.4	24.1	100.0	41.7	76.0	39.0
UTEP Campus	17.4	21.8	4.4	24.7	100.0	28.5	73.0	36.0
Hueco Tanks	17.4	19.4	2.0	27.4	45.0	172.0	222.0	140.0
Ruidosa	19.1	22.6	3.5	26.3	38.0	97.4	189.0	92.1
Chinati Mtns.	21.0	23.9	2.9	25.1	45.7	26.6	89.7	8.8
Allamoore	17.4	20.0	2.6	23.1	27.4	114.8	208.0	73.0
Capote Creek	19.1	23.3	4.2	25.4	30.5	71.7	206.6	85.2
Finlay Mtns.	16.8	21.3	4.5	31.7	130.0	79.7	114.6	86.2
El Paso Airport	17.4	20.5	3.1	29.2	280.0	44.8	42.1	28.9
Red Light Draw	17.1	22.7	5.6	34.2	350.5	27.8	48.8	38.2
Van Horn	17.4	20.8	3.4	26.6	310.0	16.6	29.7	17.7
Pump Stn. Hill	15.8	19.3	3.5	20.2	60.0	15.3	73.2	11.5
Candelaria	19.1	23.5	4.4	25.2	27.4	60.0	222.6	87.6

Mean: 3.7

Notes: " - T<sub>o</sub>-MAST

\* - uncorrected pseudogradient, i.e.  $\frac{(B.H.T.) - (MAST)}{\text{Depth}}$

\*\* - corrected pseudogradient, i.e.  $\frac{(B.H.T.) - (MAST) - 3.7}{\text{Depth}}$

## Thermal Conductivity Measurement

### Equipment

All thermal conductivity measurements were made on the divided-bar apparatus at the University of Texas at El Paso; the equipment was designed by R. F. Roy, and was similar to that described by Roy et al. (1968a). For a discussion of operating procedures, calibration technique and utilization of technique on cores or cuttings, see Taylor (1981, ppg. 35 to 63).

### Computer Program CONDOC

A computer program, "CONDOC", was written to calculate thermal conductivities by utilizing "chip-cell", polystyrene resin, and solid rock core methods. The program, in Basic (for use on the Hewlett-Packard 9845 computer), is listed in Appendix A of Taylor (1981).

### Heat Flow Calculation

The standard one-dimensional steady-state solution of the heat conduction equation can be written as follows:

$$q = K \frac{dT}{dz} \quad \text{---(I.4)}$$

where  $q$  = heat flux ( $\text{cal}/\text{cm}^2\text{d}$  or  $\text{W}/\text{m}^2$ )

$K$  = thermal conductivity ( $\text{cal}/\text{cm}\cdot\text{s}\cdot^\circ\text{C}$  or  $\text{W}/\text{m}\cdot\text{K}$ )

$\frac{dT}{dz}$  = (geo) thermal gradient ( $^\circ\text{C}/\text{km}$ )

Unless otherwise stated, these quantities are quoted in the following units:

$q$  -  $\text{cal}/\text{cm}^2\cdot\text{s}$  (= heat flow units, H.F.U.)

$K$  -  $\text{mcal}/\text{cm}\cdot\text{s}\cdot^\circ\text{C}$  (= thermal conductivity units, T.C.U)

$\frac{dT}{dz}$  -  $^\circ\text{C}/\text{km}$

In the present work, heat flow is calculated simply as the product of conductivity and gradient, over a linear portion of the temperature-depth curve. In deeper boreholes, where more than one lithologic unit is penetrated, a series of straight line sections may be seen, and in all cases the corresponding conductivity-gradient product should be the same.

In order to make a geothermal gradient, and hence heat flow, measurements meaningful, it is necessary to correct subsurface temperatures for the effect of surficial topographic irregularities, since such features can cause refraction of heat. In the present study, this has only been done in areas of severe local terrain; the correction for a borehole in a flat plain, with little or no immediate relief, is negligible. The method of terrain correction is described in Taylor (1981).

## REFERENCES

- Amsbury, D. L., 1958, Geologic map of Pinto Canyon area, Presidio County, Texas, with structure sections: Univ. Texas at Austin, Bur. Econ. Geol., Geologic Quad. Map 22 with text.
- Baker, C. L., 1934, Major structural features of Trans-Pecos, Texas, in the Geology of Texas, vol. II: Univ. Texas Bull. 3401.
- Barker, D. S., 1977, Northern Trans-Pecos magmatic province: Introduction and comparison with the Kenya rift: Geol. Soc. Am. Bull., vol. 88, pp. 1421-1427.
- Barker, D. S., 1979, Cenozoic magmatism in the Trans-Pecos Province: relation to the Rio Grande Rift, in Rio Grande Rift: Tectonics and Magmatism: Am. Geoph. Union, Washington, D.C., pp. 382-392.
- Barrie, F. J., 1975, a gravimetric survey of south-central New Mexico and West Texas: unpub. M.S. thesis, Univ. Texas at El Paso.
- Bilbrey, D. G., 1957, Economic geology of the Rim Rock Country, Presidio County, Trans-Pecos Texas: University of Texas, Austin, Master's thesis, 108 p.
- Bullard, E. C., 1940, The disturbance of the temperature gradient in the earth's crust by inequalities of height: Monthly Notices Roy. Astron. Soc., Geophys. Suppl. 4, pp. 360-362.
- Cliett, T., 1969, Ground-water occurrence of the El Paso area and its related geology, in Cordoba, D. A., Wengerd, S. A., and Shomaker, J., eds., Guidebook of the border region, Chihuahua and the United States: New Mexico Geological Society, 20th Field Conference, p. 209-214.
- Cook, F. A., Decker, E. R. and Smithson, S. B., 1973, Preliminary transient heat flow model of the Rio Grande Rift in southern New Mexico: Earth Plan. Sci. Lett., vol. 40, pp. 316-325.
- Cook, F. A., McCullar, D. B. Decker, E. R. and Smithson, S. B., 1979, Crustal structure and evolution of the southern Rio Grande Rift, in Rio Grande Rift: Tectonics and Magmatism: Am. Geoph. Union, Washington, D.C., pp. 195-208.
- Cordell, L., 1978, Regional geophysical setting of the Rio Grande Rift: Geol. Soc. Am. Bull., vol. 89, pp. 1073-1090.
- Cordell, L., Keller, G. R. and Hildenbrand, T. G., 1978 Complete Bouguer gravity anomaly map of the Rio Grande Rift: Am. Geoph. Union.

- Corwin, R. E. and Hoover, D. B. 1979, The self potential method in geothermal exploration: Geophysics, vol. 44, pp. 226-245.
- Covert, L. L., 1976, A gravity and tectonic study of Trans-Pecos Texas: unpub. M.S. thesis, Univ. Texas at El Paso.
- Dasch, J. E., Armstrong, R. L. and Clabaugh, S. E., 1969, Age of Rim Rock dike swarm, Trans-Pecos Texas: Geol. Soc. America Bull., vol. 80, pp. 1819-1824.
- Davis, M. E. and Gordon, J. D., 1970, Records of water levels and chemical analyses from selected wells in parts of the Trans-Pecos region, Texas, 1965-68: Texas Water Devel. Board, Report 114.
- Davis, M. E. and Leggatt, E. R., 1967, Preliminary results of the investigations of the saline-water resources in the Hueco Bolson near El Paso, Texas: U. S. Geol. Surv. Open-file opt.
- Decker, E. R. and Smithson, S. B., 1975, Heat flow and gravity interpretations across the Rio Grande Rift in southern New Mexico and West Texas: Jour. Geoph. Res., vol. 80, pp. 2542-2552.
- Dickerson, P. W., 1980, Structural zones transecting the southern Rio Grande Rift--preliminary observations, in Trans-Pecos Region: New Mexico Geol. Soc. Guidebook, 31st Field Conf., pp. 63-70.
- Dietrich, J. W., 1965, Geology of Presidio area, Presidio County, Texas: University of Texas, Austin, Bur. Econ. Geol. Geologic Quadrangle Map No. 28, scale 1:48,000.
- Dumas, D. B., 1979, Seismicity in and around West Texas, in Cenozoic Geology of the Trans-Pecos Volcanic Field of Texas: Univ. Texas at Austin, Bur. Econ. Geol., Guidebook 19, pp. 22-27.
- Flawn, P. T., 1956, Basement rocks of Texas and southeast New Mexico: University of Texas, Austin, Bureau of Economic Geology Publication 5606, p. 25-36.
- Fournier, R. O. and Rowe, J. J., 1966, Estimation of underground temperatures from the silica content of water from hot springs and wet steam wells: Am. Jour. Sci., vol. 264, pp. 685-697.
- Gates, J. S., White, D.E., Stanley, W. D. and Ackermann, H. D., 1978, Availability of fresh and slightly saline groundwater in the basins of westernmost Texas: U. S. Geol. Surv., Open-file report 78-663.
- Gates, J. S. and White, D. E., 1976, Test drilling for groundwater in Hudspeth, Culberson and Presidio Counties in westernmost Texas: U. S. Geol. Surv., Open-file report 76-338.



- Ghosh, D. P., 1971, Application of linear filter theory to the direct interpretation of geoelectrical resistivity sounding measurements: *Geoph. Prospecting*, vol. 19, pp. 192-217.
- Gilliland, M. W. and Fenner, L. B., 1980, West Texas geothermal resource assessment, part II: preliminary utilization assessment of the Trans-Pecos geothermal resource: Texas Energy and Natural Resources Advisory Council, Report EDF-023.
- Grisafi, T. W., Riebe, H. H. and Skidmore, D. R., 1974, Approximation of geothermal gradients in northern West Virginia using bottom-hole temperatures from electric logs: *Am. Assoc. Petroleum Geologists Bull.*, vol. 58, pp. 321-323.
- Groat, C. G., 1972, Presidio Bolson, Trans-Pecos Texas and adjacent Mexico: geology of a desert basin aquifer system: Univ. Texas at Austin, *Bur. Econ. Geol.*, Report of Investigations 76.
- Hay-Roe, H. 1957, Geology of Wylie Mountains and vicinity, Culberson and Jeff Davis Counties, Texas: Univ. Texas at Austin, *Bur. Econ. Geol.*, *Geol. Quad. Map No. 21*.
- Henry, C. D. 1979a, Geologic setting and geochemistry of thermal waters and geothermal assessment, Trans-Pecos Texas; Univ. Texas at Austin, *Bur. Econ. Geol.*, Report of Investigations 96.
- Henry, C. D., 1979b, Crustal structure deduced from geothermal studies, Trans-Pecos Texas, in *Cenozoic geology of the Trans-Pecos volcanic field of Texas*: Univ. Texas at Austin, *Bur. Econ. Geol.*, Guidebook 19, pp. 39-47.
- Henry, C. D. and Gluck, J. K., 1981, A preliminary assessment of the geologic setting, hydrology and geochemistry of the Hueco Tanks geothermal area, Texas and New Mexico: Univ. Texas at Austin, *Bur. Econ. Geol.*, Geological Circular 81-1.
- Hoffer, J. M., 1978, Thermal water occurrences in Trans-Pecos Texas: *Texas Journal of Science*, v. 30, no. 4, p.309-319.
- Hoffer, J. M., 1979, Geothermal exploration of western Trans-Pecos Texas: Univ. Texas at El Paso, Texas Western Press, Science Series no. 6.
- King, P. B., 1935, Outline of Structural development of Trans-Pecos Texas: *American Assoc. of Pet. Geol. Bull.*, vol. 19, pp. 221-261.
- Knowles, D. B. and Kennedy, R. A., 1958, Groundwater resources of the Hueco Bolson northeast of El Paso, Texas: U. S. Geol. Surv., Water Supply Paper 1426.

- Kopp, R. A., 1977, Geothermal exploration of Presidio County, Texas: unpub. M.S. thesis, Univ. Texas at El Paso.
- Kunetz, G., 1966, Principles of direct-current resistivity prospecting: Gebrueder Borntraeger, Berlin.
- LaFreniere, J. E., 1983, A gravity and geothermal study of the Presidio Bolson, Texas: M.S. Thesis, Univ. Texas, El Paso.
- Mattick, R. E., 1967, A seismic and gravity profile across the Hueco Bolson, Texas: U. S. Geol. Surv. Prof. Paper 575-D.
- McAnulty, W. N., 1972, Mineral deposits in the West Chinati Stock, Chinati Mountains, Presidio County, Texas: Univ. Texas at Austin, Bur. Econ. Geol., Circular 72-1.
- McAnulty, W. N., Jr., 1975, Fluorspar deposits and the Rio Grande Rift system: New Mexico Geol. Soc., 26th Guidebook, Las Cruces County, p. 167-168.
- McKnight, J. F., 1970, Geology of Bofecillos Mountains area, Trans-Pecos Texas: The University of Texas at Austin, Bureau of Economic Geology Geologic Quadrangle Map No. 37, scale 1:48,000.
- Mraz, J. B., 1977, A gravity and subsurface investigation of Univ. Texas at El Paso.
- Mraz, J. R., and Keller, G. R., 1980, Structure of the Presidio Bolson Area, Texas, interpreted from gravity data: Univ. of Texas at Austin, Bur. Econ. Geol. Geological Circular 80-13.
- Rahman, J. L., 1983, Geothermal studies of drill holes in northern Illinois and the Hueco Tanks region, Otero County, New Mexico: M.S. Thesis, Univ. Texas, El Paso.
- Reaser, D. F., Underwood, J. R. and Jones, B. R., 1975, Geothermal prospects of the Eagle--Eagle Mountains vicinity, Trans-Pecos Texas, in Geology of the Eagle Mountains: Permian Basin Section, Soc. Econ. Pal. Min. pub. 75-15.
- Reilinger, R., Brown, L. and Powers, D., 1980, New evidence for tectonic uplift in the Diablo Plateau region, West Texas: Geoph. Res. Lett., vol. 7, pp. 181-184.
- Reiter, M., Edwards, C. L., Hartman, M. and Weidman, C., 1975, Terrestrial heat flow along the Rio Grande Rift: Geol. Soc. Am. Bull., vol. 86, pp. 811-818.
- Rix, C. C., 1953, Geology map of Chinati Peak Quadrangle, Presidio County, Texas (preliminary edition): University of Texas, Austin, Bur. Econ. Geol. Miscellaneous Map 4, scale 1:48,000

- Roy, R. F., Decker, E. R., Blackwell, D. D. and Birch, F., 1968a, Heat flow in the United States: Jour. Geoph. Res., vol. 73, pp. 5207-5221.
- Roy, R. F., Blackwell, D. D. and Birch, F., 1968b, Heat generation of plutonic rocks and continental heat flow provinces: Earth plan. Sci. Lett., vol. 5, pp. 1-12.
- Roy, R. F., Blackwell, D. D. and Decker, E. R., 1972, Continental heat flow, in The Nature of the Solid Earth: McGraw-Hill, New York, pp. 506-544.
- Roy, R. F., and Taylor, B., 1980, West Texas Geothermal Resource Assessment, Part I, Geothermal exploration in Trans-Pecos, Texas: TENRAC, Report No. EDF-023.
- Sanford, A. R. and Topozada, T. R., 1974, Seismicity of the proposed radioactive waste disposal site in southeastern New Mexico: New Mexico Bur. Mines and Min. Res., Circular 143.
- Sass, J. H., Lachenbruch, A. M. and Munroe, R. J., 1971, Thermal conductivity of rocks from measurements on fragments and its application to heat flow determinations: Jour. Geoph. Res., vol. 76, pp. 3391-3401.
- Sayre, A. N. and Livingston, Penn, 1945, Groundwater resources of the El Paso area, Texas: U. S. Geol. Surv. Water Supply Paper 919.
- Schoepfel, R. J. and Gilarranz, S., 1966, Use of well log temperatures to evaluate regional geothermal gradients: Jour. Petroleum Technology, vol. 18, pp. 667-673.
- Seager, W. R. and Morgan, P., 1979, Rio Grande Rift in southern New Mexico, West Texas and northern Chihuahua, in Rio Grande Rift: Tectonics and Magmatism: Am. Geoph. Union, Washington, D. C., pp. 87-106.
- Seager, W. R., 1980, Quaternary fault system in the Tularosa and Hueco Basins, southern New Mexico and West Texas, in Trans-Pecos Region: New Mexico Geol. Soc. Guidebook, 31st Field Conf., pp. 131-136.
- Sloss, L. L., 1963, Sequences in the cratonic interior of North America: Geol. Soc. Amer. Bull., v. 74, pp. 93-111.
- Smith, D. L. and Jones, R. L., 1979, Thermal anomaly in northern Mexico: an extension of the Rio Grande Rift, in Rio Grande Rift: Tectonics and Magmatism, Am. Geoph. Union, Washington, D. C., pp. 269-278.

- Steenland, N. C., 1966, Aeromagnetic evidence for Hueco Mountains wrench Fault, Texas: *Geophysics*, vol. 32, pp.291-296.
- Sternberg, B. K., 1977, Interpretation of electromagnetic soundings, data-numerical methods and computer program listings: Univ. Wisconsin Geophysical and Polar Research Center, Dept. of Geology and Geophysics, Report no. 77-1.
- Strain, W. S., 1970, Late Cenozoic bolson integration in the Chihuahua Tectonic Belt, in Seewald, Ken, and Sundeen, Dan, eds., *The geologic framework of the Chihuahua Tectonic Belt: West Texas Geological Society*, pp.56-59.
- Summers, W. K., 1972, Approximation of thermal gradient in southeastern New Mexico using bottom-hole temperatures from electric logs: *Am. Assoc, Petroleum Geologists*, vol. 56, pp. 2072-2074.
- Swanberg, C. A. and Herrin, E., 1976, Heat flow and geochemical data from West Texas (abs.): *EOS, Trans. Am. Geoph. Union*, vol. 57, p. 1009.
- Swanberg, C. A. and Morgan, P., 1978, The linear relation between temperatures based on the silica content of groundwater and regional heat flow: a new heat flow map of the United States: *Pure and Applied Geophysics*, vol. 117, pp. 227-241.
- Taylor, B., 1981, Heat flow studies and geothermal exploration in Western Trans-Pecos, Texas: Univ. Texas, El Paso, Doctoral Dissertation.
- Underwood, J. R., 1963, Geology of Eagle Mountains and vicinity, Hudspeth County, Texas; Univ. Texas at Austin, *Bur. Econ. Geol., Geol. Quad. Map no. 26*.
- Warren, R. E., Sclater, J., G., Vacquier, V. and Roy, R. F., 1969, A comparison of terrestrial heat flow and transient geomagnetic fluctuations in the southwestern United States: *Geophysics*, vol. 34, pp. 463-478.
- White, D. E., Gates, J. S., Smith, J. T. and Fry, B. J., 1978, Groundwater data for the Salt Basin, Eagle Flat, Red Light Draw, Green River Valley and Presidio Bolson in westernmost Texas: *U. S. Geol. Surv., Open-file report 77-575*.
- Wiley, M. A., 1970, Gravity, magnetic and generalized geologic map of the Van Horn-Sierra Blanca region, Trans-Pecos Texas; Univ. Texas at Austin, *Bur. Econ. Geol., Geol. Quad Map no. 40, with text*.
- Wilson, J. A., Twiss, P. C., DeFord, R. K., and Clabaugh, S. E., 1968, Stratigraphic succession, potassium-argon dates, and vertebrate faunas, Vieja Group, Rim Rock country, Trans-Pecos Texas: *American Journal of Science*, v. 226, no. 7, p. 590-604.

Woodard, L. A., Callender, J. F., Seager, W. R., Chapin, C. E., Gries, J. C., Shaffer W. L., and Zilinski, R. E., 1978, Tectonic map of Rio Grande rift region in New Mexico, Chihuahua, and Texas: New Mexico Bureau of Mines and Mineral Resources, Circular 163.

Young, C. T., 1979, Schlumberger resistivity transmitter and receiver: New Mexico State Univ., Dept. of Physics, Quarterly Technical Report.

Zohdy, A. R., 1969, The use of Schlumberger and equatorial soundings in groundwater investigations near El Paso, Texas: Geophysics, vol. 34, pp. 713-728.

Zohdy, A. R., Bisdorf, R. J. and Gates, J. S., 1976, Schlumberger soundings in the lower Mesilla Valley of the Rio Grande, Texas and New Mexico: U. S. Geol. Surv., Open-file report 76-324.