DOE/ID/12065--T1

52
1-12-83
U.S. Department of Energy
Energy and Technology Division
Idaho Falls, Idaho

Agreement No. DE-FC07-79ID 12065

MASTER

**DO NOT MICROFILM
COVER**

The Cerro Prieto Geothermal Field

Exploration During Exploitation

Contribution to
Geothermal Model Development Database

**DO NOT MICROFILM
COVER**

July 1982

INTERNATIONAL ENGINEERING COMPANY, INC.
A MORRISON-KNUDSEN COMPANY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

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.

DOE/ID/12065--T1

U.S. Department of Energy
Energy and Technology Division
Idaho Falls, Idaho

Agreement No. DE-FC07-79ID 12065

DOE/ID/12065--T1

DE83 003448

The Cerro Prieto Geothermal Field:
Exploration During Exploitation

Contribution to
Geothermal Model Development Database

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE. It
has been reproduced from the best available
copy to permit the broadest possible avail-
ability.

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.

July 1982

*checked con. no. for city
reb*

950 4658

INTERNATIONAL ENGINEERING COMPANY, INC.
A MORRISON-KNUDSEN COMPANY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

fly

CONTENTS

<u>Chapter</u>		<u>Page</u>
	ACKNOWLEDGEMENTS	
	ABSTRACT	
1	INTRODUCTION	1-1
	1.1 Purpose of Study	1-1
	1.2 Summary of Exploration	1-1
2	REGIONAL SETTING	2-1
	2.1 Geographical Location	2-1
	2.2 Volcanism	2-1
	2.3 Tectonics	2-2
	2.4 Structural Geology	2-2
	2.5 Stratigraphy	2-3
	A. Mesozoic	2-3
	B. Quaternary	2-4
3	PRE-EXPLOITATION STUDIES	3-1
	3.1 Geology	3-1
	3.2 Geophysics	3-5
4	ABSTRACTS FROM GEOLOGICAL INVESTIGATIONS	4-1
	4.1 Introduction	4-1
	4.2 Estudio Preliminar Geologico del Area al Sur y Sureste de Mexicali, B. C. para Aprovechar los Recursos Geotermicos - Calderon A. (1958)	4-1
	4.3 A Preliminary Report on the Geology and Geochemistry of the Cerro Prieto Geothermal Field - M. Reed (1972)	4-2
	4.4 Geology of the Cerro Prieto Geothermal Field - Puente and de la Pena (1978)	4-3
	4.5 Geophysical Well Log Correlations Along Various Cross Sections of the Cerro Prieto Geothermal Field - Abril and Noble (1978)	4-4
	4.6 Lithologic Correlations Based on Interpretation of Geophysical Well Logs at the Cerro Prieto Field - Prian (1978)	4-4
	4.7 Analyses of Cerro Prieto Well Logs: Some Results and Problems - Noble and Abril (1978)	4-5

<u>Chapter</u>		<u>Page</u>
4.8	Hydrothermal Mineral Zones in the Geothermal Reservoir of Cerro Prieto - Elders, et. al. (1978)	4-5
4.9	Geologic Model of the Cerro Prieto Geothermal Field - de la Pena et. al. (1979)	4-7
4.10	Stratigraphic and Sedimentological Analysis of the Cerro Prieto Geothermal Field, Baja California, Mexico - Noble (1979)	4-7
4.11	Studies of Water/Rock Interaction in the Cerro Prieto Geothermal Field, Baja California, Mexico - Elders and Hoagland (1979)	4-8
4.12	Vitrinite Reflectance and Geothermometry in Wells M-84, M-93, M-94 and M-105 in the Cerro Prieto Geothermal Field - Barker and Elders (1979)	4-9
4.13	Paleomagnetic Dating of the Cerro Prieto Volcano - de Boer (1979)	4-10
4.14	Geology and Mineralogy of the Cerro Prieto Geothermal Field - Cobo (1979)	4-11
4.15	Intersecting Faults and Sandstone Stratigraphy at the Cerro Prieto Geothermal Field - Vonder Haar and Howard (1979)	4-11
4.16	Microfossils from Cerro Prieto Geothermal Wells, Baja California, Mexico - Cotton and Vonder Haar (1980)	4-12
4.17	Vertical Movement Along the Cerro Prieto Transform Fault, Baja California, Mexico - A Mechanism for Geothermal Energy Renewal - Vonder Haar, et. al. (1979)	4-13
4.18	Physical and Mechanical Properties of Core from the Cerro Prieto Geothermal Field - Abou-Sayed and Schatz (1979) Tables	4-13
5	ABSTRACTS FROM GEOPHYSICAL INVESTIGATIONS	5-1
5.1	Introduction	5-1
5.2	Levantamiento Gravimetrico de la Zona Geotermica de Mexicali, Baja California - CRNNR (1963)	5-1
5.3	Geophysical Survey with the Resistivity Method in the Cerro Prieto Geothermal Zone - Garcia (1973)	5-2
5.4	Aeromagnetic Study of the Colorado River Delta - de la Fuente (1973)	5-2
5.5	Movement of Geothermal Fluids and Temperature Distribution in the Cerro Prieto Geothermal Field - Mercado (1975)	5-3

ChapterPage

5.6	Geoelectrical Study of the Geothermal Zone at Cerro Prieto, Baja California, Mexico - Garcia (1975)	5-3
5.7	Campo Geotermico de Cerro Prieto Sobre la Falla de San Jacinto y su Posible Ampliacion Hacia la Falla Imperial - Soto (1975)	5-4
5.8	Primer Informe Preliminar del Estudio de Microsismicidad del Sistema de Fallas Transformadas Imperial - Cerro Prieto - CICESE (1977)	5-4
5.9	Prospeccion Electrica de la Porcion Norte del Valle de Mexicali y Campo Geotermico de Cerro Prieto, Baja California - Informe 6-78 - Razo and Arellano (1978)	5-5
5.10	Self-Potential Survey at the Cerro Prieto Geothermal Field, Baja California, Mexico - Corwin, et. al. (1978)	5-5
5.11	LBL Resistivity Studies at the Cerro Prieto Geothermal Field - Wilt, et. al. (1978)	5-6
5.12	CFE Self-Potential Studies Northwest of the Cerro Prieto Volcano - Diaz (1978)	5-6
5.13	Referenced Magnetotellurics at Cerro Prieto - Gamble et. al. (1978)	5-6
5.14	Seismicity Studies in the Region of the Cerro Prieto Geothermal Field - Albores et. al. (1978)	5-7
5.15	Seismological Studies at Cerro Prieto - Majer, et. al. (1978)	5-8
5.16	Precision Gravity Studies at Cerro Prieto - Chase, et. al. (1978)	5-8
5.17	Segundo Informe de Avance del Estudio de Microsismicidad del Sistema de Fallas Transformadas Imperial - Cerro Prieto-II- CICESE (1977)	5-9
5.18	Proseccion Gravimetrica y Magnetometrica en el Valle de Mexicali, B. C. - Informe 5-78- Razo and Fonseca (1978)	5-9
5.19	Gravimetric, Magnetometric, and Seismic Reflection Studies at the Cerro Prieto Geothermal Field - Fonseca and Razo (1979)	5-10
5.20	Precision Gravity Measurements in the Cerro Prieto Geothermal Area - Grannell, et. al. (1979)	5-10
5.21	Self-Potential and Resistivity Surveys South of the Cerro Prieto Fault - Diaz and Arellano (1979)	5-11
5.22	Interpretation of Self-Potential Data from the Cerro Prieto Geothermal Field - Corwin and Fitterman (1979)	5-12

<u>Chapter</u>		<u>Page</u>
	5.23 A Digital Seismological Telemetry Network at Cerro Prieto - Medina and Duarte (1979)	5-12
	5.24 Earthquake-Monitoring at the Cerro Prieto Geothermal Field - Majer and McEvelly (1979)	5-13
	5.25 Seismic Studies and its Correlation with Potential Anomalies - Reyes and Razo (1979)	5-14
	5.26 Preliminary Studies of Attenuation in the Region of the Cerro Prieto Geothermal Field - Albores, et. al. (1979)	5-14
	5.27 Magnetotelluric Studies at Cerro Prieto - Gamble, et. al. (1980)	5-14
6	ABSTRACTS FROM GEOCHEMICAL INVESTIGATIONS	6-1
	6.1 Introduction	6-1
	6.2 Early Geochemical Investigations of S. Mercado	6-1
	6.3 Complete Hydrologic Survey of the Aquifers in the Mexicali Valley, B. C., and San Luis Mesa, Son - Ariel Construcciones, S. A., (1968)	6-5
	6.4 Hydrogeologic Evaluation of the Cerro Prieto Geothermal System Utilizing Isotopic Techniques - Crosby, et. al. (1972)	6-6
	6.5 Extensive Geochemical Studies in the Geothermal Field of Cerro Prieto, Mexico - Manon, et. al. (1979)	6-7
	6.6 Preliminary Geochemical Model of the Cerro Prieto Geothermal Field - Manon, et. al. (1978)	6-12
	6.7 Preliminary Isotopic Studies of Fluids from the Cerro Prieto Geothermal Field - Truesdell (1979)	6-13
	6.8 Gas Chemistry and Helium Isotopes at Cerro Prieto - Welhan, et. al. (1978)	6-15
	6.9 Gases in Steam from Cerro Prieto Geothermal Wells - Nehring and Fausto (1978)	6-15
	6.10 Geochemical Evidence of Drawdown in the Cerro Prieto Geothermal Field - Truesdell, et. al. (1978)	6-16
	6.11 Geochemical Indications of Boiling in the Aquifer of the Cerro Prieto Geothermal Field - Truesdell and Manon (1978)	6-19
	6.12 The Origin of the Cerro Prieto Geothermal Brine - Truesdell, et. al. (1980)	6-20
7	GEOHERMAL FIELD MODELS	7-1
	7.1 Introduction	7-1
	7.2 Model 1	7-1

<u>Chapter</u>		<u>Page</u>
	7.3 Model 2	7-2
	7.4 Model 3	7-2
	7.5 Model 4	7-3
	7.6 Model 5	7-4
	7.7 Model 6	7-4
8	CFE/DOE/LBL GEOTHERMAL FIELD MODEL	8-1
	8.1 Introduction	8-1
	8.2 Geology	8-1
	8.3 Geophysics	8-1
	A. Self-potential Surveys	8-2
	B. Electrical Resistivity Studies	8-2
	C. Seismic Reflection Studies	8-3
	8.4 Geochemistry	8-3
9	SUMMARY OF EXPLORATION METHODS AND RESULTS	9-1
	REFERENCES	

LIST OF FIGURES

<u>Figure</u>		<u>Following Page</u>
1-1	Cerro Prieto Project - U. S. Program Schedule (FY 78)	1-3
1-2	Cerro Prieto Project - U. S. Program Schedule (FY 78) (Continued)	1-3
1-3	Cerro Prieto Project - U. S. Field Activities (FY 79)	1-3
2-1	Structural Setting of the Salton Trough and Location of the Cerro Prieto Geothermal Field	2-1
2-2	Cerro Prieto Geothermal Field Well Locations	2-1
2-3	Regional Tectonic Setting	2-2
2-4	Postulated Spreading Centers in the Salton Trough	2-2
2-5	Geological Cross-section of the Cerro Prieto Geothermal Field	2-3
3-1	Geological Cross-section, Sierra de Juarez - Cerro Prieto	3-1
3-2	Exploration Well Locations	3-2
3-3	Isotherms in the Mexicali Valley, Based on Surface Manifestations	3-5
3-4	Bouguer Gravity Anomalies of the Colorado Delta	3-5
3-5	Location of Seismic Lines and Section D-D'	3-5
3-6	Interpretation of Seismic Refraction Line D-D'	3-5
3-7	Location of Earthquake Epicenters which Occurred During April & May, 1969	3-6
4-1	Generalized East-West Geologic Section through Well M-10	4-2
4-2	Distribution of Mineras as a Function of Temperature and Depth, Well M-5	4-2
4-3	Generalized Stratigraphic Column of the Cerro Prieto Area	4-3
4-4	NE-SW Geologic Cross-section	4-3
4-5	NW-SE Cross-section Showing Basement Topography Based from Well Data and Seismic Refraction Surveys	4-3
4-6	Surficial Fractures of the Cerro Prieto Area	4-3
4-7	Location of Cross-sections in Figures 4-8 to 4-11	4-4
4-8	Section I-I"	4-4
4-9	Section II-II"	4-4
4-10	Section III-III"	4-4
4-11	Section IV-IV"	4-4
4-12	Symbols Used in the Correlation of Electrical Surveys	4-4
4-13	Location of Faults	4-4
4-14	Idealized E-W Cross-section of the Cerro Prieto Field	4-4
4-15	W-E Schematic Cross-section	4-4
4-16	NW-SE Schematic Cross-section	4-4
4-17	Major Lithologic Units Delineated by Well- Log Correlation	4-5

LIST OF FIGURES

<u>Figure</u>		<u>Following Page</u>
4-18	Mineral Zones in Sandstones at Cerro Prieto as a Function of Temperature	4-5
4-19	Distribution of Mineral Zones in Sandstones along the Profile A-A'	4-5
4-20	Isotherms Modified from Mercado (1976) Distribution of Mineral Zones in Shales along the Profile A-A'	4-5
4-21	Isotherms Modified from Mercado Faults in the Vicinity of the Cerro Prieto Field Showing Cross-faults and Well M-103	4-11
4-22	Sandstone Units Defined, etc.	4-12
4-23	Simplified Geology of the Cerro Prieto Geo- thermal Field, Baja California, Mexico	4-13
5-1	Iso-resistivity Map of the Cerro Prieto Region	5-1
5-2	Location of the Panga de Abajo Spreading Center, Baja California, Mexico	5-2
5-3	Subsurface Temperature Distribution at Cerro Prieto	5-2
5-4	Subsurface Temperature Distribution at Cerro Prieto	5-2
5-5	Results from Schlumberger Soundings	5-3
5-6	Real Resistivity at 1200m Depth in the Cerro Prieto Geothermal Field	5-3
5-7	Seismic Events 1970 - 1976	5-4
5-8a	Seismicity April 20-22, 1977	5-4
5-8b	Aftershocks of January 17, 1977 Event	5-4
5-9	Self-potential Countours, Cerro Prieto Area	5-5
5-10	Two Dimensional Model of the Earth's Resistivity	5-6
5-11	Regional Map Showing Station and Earthquake Locations	5-7
5-12	Bouguer Anomaly Map of the Cerro Prieto Geothermal Field	5-8
5-13	Seismicity 1971-1977	5-8
5-14	Magnetic and Gravimetric Intrepretation of Line 1	5-9
5-15	Magnetic and Gravimetric Intrepretation of Line 2	5-9
6-1	Location Map of the Surface Emissions of Cerro Prieto	6-2
6-2	Na/K Distribution in Underground Drill Hole Flow	6-3
6-3	Flow and Na/K Distribution	6-3
7-1	Model 3 - Geological Section and Partial View of the Mexicali Valley, B. C.	7-2
7-2	Model 5 - Geologic Cross-section	7-4
8-1	Faults and Isotherms Map	8-1
8-2	Magnetic Anomaly Map of Cerro Prieto Area	8-1
8-3	Bouguer Gravity Anomaly Map of Cerro Prieto Area	8-1
8-4	Fluid Circulation Based on Mineral Zonation	8-3

LIST OF TABLES

<u>Table</u>		<u>Following Page</u>
3-1	Lithologic Descriptions from Two Wells at Cerro Prieto Field	3-2
4-1	Mineralogy of the Plutonic Rocks of the Sierra De Los Cucapas and of the Cerro Prieto Geothermal Field	4-2
4-2	The Chemical Composition of Igneous Rocks in Cerro Prieto Region	4-2
4-3	Semiquantitative X-ray Mineralogy of Selected, High Feldspar Content, Samples from Well M-3	4-2
4-4	Checklist by Geothermal Well and Sample Depth of Microfossils from Cerro Prieto	4-3
4-5	Foraminifera Identified with Certainty in the Cerro Prieto Well Samples	4-3
4-6	Nannoplankton Observed in Cerro Prieto Well Cuttings	4-3
6-1	Weighted Composition of the Most Concentrated Sample of Each Well, mg/l	6-9
6-2	Observed and Calculated Aquifer Temperatures and Calculated Aquifer Chloride Concentrations for Cerro Prieto Wells M-5, M26, M-21A and M-11 in 1972-74 and 1977-78	6-18

CHAPTER 1

INTRODUCTION

1.1 PURPOSE OF STUDY

All pertinent and available data concerning the Cerro Prieto geothermal field were collected, reviewed and summarized in this report. The history of exploration was subdivided into two sections: pre-exploitation studies, and exploration concurrent with exploitation. After operation of the power plant started in 1973, an agreement was signed with the U.S. Department of Energy to study the field using various geotechnical sciences. This effort produced a large number of reports dealing with all aspects of the geothermal reservoir. Before 1973, however, there were few studies performed and even fewer reports available. Abstracts of the available studies dealing with geology, geophysics and geochemistry are presented.

The regional setting is described with respect to (1) geographical location (2) volcanism (3) tectonics (4) structure, and (5) stratigraphy.

Models of the geothermal field, as it was viewed at various exploration stages from 1964 to 1979, are presented and discussed. These models show the evolution and refinement of the field model as more data were generated. Certain exploration techniques contributed more than others to an understanding of controlling processes.

1.2 SUMMARY OF EXPLORATION

Only a few reports on early exploration studies at Cerro Prieto were available. Therefore, a brief history of early investigation is presented. Most of this information is taken from Manon et al., (1978)

Exploration at Cerro Prieto geothermal field started in 1959 with surface geology and aerial photo interpretation studies. Between that year and 1961 three wells were drilled: P-1A - 523 m deep, P2 - 755 m deep, and P-2A - 402 m deep. Only well P1A was thought to be productive; however, the low enthalpies and chemical characteristics of the fluid indicated the well was unfavorable for production. It appears that the first three shallow pilot holes, P-A1, P-2, and P-2A, were sited in different tectonic blocks at varying distances from the Cerro Prieto volcano. The volcano may have been considered the heat source in the initial discovery period. A brief summary of the information obtained from these wells is given by Alonso (1966). At this time a reconnaissance gravity survey was performed in the Mexicali Valley, from which a Bouguer anomaly map was prepared (Kovach and Monges, 1961). From results of seismological and gravimetric studies performed from 1962 to 1964, a second exploratory phase was initiated (GEOCA, 1962). Wells M-3, M-4, M-5, and M-6 were drilled, of which M-3, M-5 and M-6 were productive while M-4 was dry. Well locations are shown in Figure 3-2. A complete description of Well M-3 and the results obtained are given by Alonso and Mooser (1964). Information obtained from the other wells may be found in Alonso (1966) and summarized in Chapter 3.

During 1965 isotherm maps were drawn from results of 50 shallow holes. The first geochemical survey was performed in 1965 and 1966 (Mercado, 1968). Between 1966 and 1968 fifteen production wells were drilled, from which the field productivity was estimated at 75 MW. Hydrological and stable isotope studies were subsequently carried out (Ariel Construcciones, 1968; Crosby et al., 1972). These studies were simultaneous with production tests. Lomnitz et al. (1970) performed a seismicity and tectonics study of the northern Gulf of California.

Plant construction started in 1970 and in April 1973 commercial operation was initiated. In 1971 and 1972 regional aeromagnetic and geo-electrical studies were performed in the Mexicali Valley (De la Fuente,

1973; Garcia, 1973). From 1972 to 1977 eighteen more wells were drilled, nine of which were to supply another 75 MW plant (Units 3 and 4). Additional geochemical studies were performed by Mercado (1975, 1977), Molina and Banwell (1970), and Crecelius (1976). During 1977 other geoelectric and geophysical studies were performed, including seismic, magnetic, and gravity surveys, which covered a total area of 620 km² (Razo and Fonseca, 1978; CICESE, 1977; Razo and Arellano, 1978).

In July 1977, the Comision Federal de Electricidad (CFE) of Mexico and the U.S. Department of Energy (DOE) signed a cooperative agreement to study the Cerro Prieto field. This project incorporated studies of the geologic, hydrogeologic, geochemical, and geophysical setting of the field as well as its structural, reservoir engineering, and subsidence characteristics (Witherspoon et al., 1978). The program schedule for 1978 and field activities for 1979 are outlined in Figures 1.1, 1.2, and 1.3. The reports generated from these studies, along with documents from previous work, are summarized in the following chapters.

▲ = REPORT

Figure 1-1. Cerro Prieto Project - U.S. Program Schedule (FY 78)

TASK	O	N	D	J	F	M	A	M	J	J	A	S
<u>GEOCHEMISTRY</u> (USGS/UCR/LBL)												
-BRINES AND GASES			▲								▲	
-MINERALS			▲				▲					▲
<u>SUBSIDENCE</u> (USGS)												
-REGIONAL TRILATERATION	—								▲			
-LOCAL HORIZONTAL NET	—								▲			
<u>CONFERENCES</u> (LBL-COORDINATED)												
-DOE/CFE TECHNICAL MEETINGS							*					
-CERRO PRIETO SYMPOSIUM												*

▲ = REPORT

Figure 1-2. Cerro Prieto Project - U.S. Program Schedule (FY 78) (Cont'd)

TASK	O	N	D	J	F	M	A	M	J	J	A	S
<u>GEOLOGY-HYDROGEOLOGY</u> (LBL)												
-SELECT SAMPLES OF CORES AND CUTTINGS	-				-				-			
<u>GEOPHYSICS</u> (LBL)												
-PASSIVE SEISMIC												
-MAGNETOTELLURICS												
-SELF-POTENTIAL												
-DIPOLE-DIPOLE RESISTIVITY												
-PRECISION GRAVITY												
<u>RESERVOIR ENGINEERING</u> (LBL)												
-WELL TESTING												
<u>SUBSIDENCE</u> (USGS)												
-REGIONAL TRILATERATION												
-LOCAL HORIZONTAL NET												
<u>GEOCHEMISTRY</u> (USGS/LBL/UCR)												
-FLUID SAMPLING												
<u>REINJECTION</u> (LBL)												
-FIELD TESTS												

Figure 1-3. Cerro Prieto Project - U.S. Field Activities (FY 79)

CHAPTER 2

REGIONAL SETTING

2.1 GEOGRAPHICAL LOCATION

The Cerro Prieto geothermal field is located in the southern part of the Salton-Mexicali Trough, near the eastern flank of the Sierra de los Cucapas, Baja California, Mexico (Figure 2.1). The area lies near the Laguna Volcano hydrothermal zone which has numerous thermal manifestations such as hot springs, geysers, mud volcanoes, and fumaroles. Elders et. al. (1972), propose that Cerro Prieto is related to a spreading center formed by the San Jacinto and Imperial faults. The field lies in the alluvial plain of the Mexicali Valley and is partly underlain by Quaternary piedmont sediments from the Sierra Cucapas and by deltaic sediments deposited by the meandering Colorado River (Puente and de la Pena, 1978). The dominant topographic feature in the area is the Cerro Prieto volcano.

2.2 VOLCANISM

The only apparent volcanism is the Cerro Prieto volcano, located northwest of the geothermal field. It is calc-alkaline rhyodacite cone of Pleistocene age (Gastil, et. al. 1979) with an elevation of 260 meters and covering an area of approximately 400 ha (1000 acres). The Laguna Volcano hydrothermal area lies south of the geothermal field and is the site of intense fumarolic activity, and numerous hot springs and mud volcanoes (Figure 2.2). No current volcanic activity is observed in the area. The Cerro Prieto volcano, along with five rhyolite domes along the south edge of the Salton Sea, are part of the suite of volcanic activity associated with the East Pacific Rise (Elders, 1979). Further discussions on volcanism associated with crustal spreading in Southern California may be found in Elders et. al., 1972.

Figure 2-1. Structural setting of the Salton Trough and location of the Cerro Prieto Geothermal Field. (After Biehler, et.al., 1964)

Figure 2-2. Cerro Prieto geothermal field well locations.

2.3 TECTONICS

A considerable amount of literature on the tectonics of this area has been published and only a brief summary will be presented in this report. Further information may be obtained from Hamilton (1961), Wilson (1965), Larson, et al. (1968), Moore and Buffington (1968), Atwater (1970), Lomnitz, et. al. (1970), Anderson (1971), Larson (1972), Elders et. al. (1972), Garfunkel (1972), Moore (1973), and Elders (1979).

The San Andreas fault system forms part of the boundary between the North American plate and the North Pacific plate, and divides part of California from the rest of North America (Figure 2.3). The San Andreas fault system is the tectonic framework of the Cerro Prieto field, which is located along the Cerro Prieto fault, a possible extension of the San Jacinto Fault (Puente and de la Pena, 1978). This and other segments are believed to be transform faults which connect the spreading centers described by Elders, et. al. (1972), as shown in Figure 2.4. The transform faulting with right-lateral motion has caused secondary faults trending oblique to the principal faults. The major faults were termed the NW-SE Cerro Prieto system, and the oblique secondary faults as the NE-SW Volcano System by Puente and de la Pena, (1978). All recent volcanic and geothermal activity, earthquakes, and oceanic depressions in the area are concentrated in these systems which combine to localize the Cerro Prieto geothermal field in a horst and graben structural complex.

2.4 STRUCTURAL GEOLOGY

The major structural features are illustrated in Figure 2.4. The Cerro Prieto Fault System has strike-slip displacement, while the Volcano Fault System is en-echelon with downthrow to the southeast (Puente and de la Pena, 1978). These faults, together with the zone of subsurface fracturing, are areas capable of steam production.

Figure 2-3. Regional Tectonic Setting (From Garfunkel, 1972)

Figure 2-4. Postulated spreading centers in the Salton Trough.
(From Elders, et.al., 1972)

The Mexicali-Imperial Valley is a triangular basin partially filled with late Tertiary to Recent sediments deposited by the Colorado River (Sharp, 1972). Elders (1979) describes it as a complex rift valley bordered by mountains consisting of Mesozoic, and older, granitic and metamorphic rocks, with some Tertiary volcanic rocks. The step-faulted margins and the nearly flat basement floor covered by sediments are illustrated in Figure 2.5.

Analysis of well data by Paredes (1975) revealed the presence of deltaic and non-deltaic sediments. The former contain clay, sand lenses of varied grain sizes, and occasional gravel, and have a thickness of about 600 to 700 m, although, in the southern and eastern parts of the field Wells M-51 and M-53 revealed a thickness of over 1200 m. These sediments overlie non-deltaic sediments consisting of shales and sandstones of unknown thickness.

2.5 STRATIGRAPHY

A summary of the stratigraphy of Cerro Prieto is given by Paredes (1975) from which the following description is taken:

A. Mesozoic

Intrusive and metamorphic rocks - Intrusive and metamorphic rocks constitute the most clearly defined physiographic unit in the area. Sierra Cucapas, to the east of the field, has a northwest-southeast trend and consists of granites outcropping over large areas and of regionally metamorphosed sediments, probably of Cretaceous age.

The intrusive rocks in the area are part of the Peninsular Range Batholith that runs along most of the Baja California peninsula and extends into southern California; its outcrops are interrupted locally by Cenozoic sediments and by extrusive rocks. Tectonic activity has resulted in discontinuities of the batholithic rock on the surface.

Figure 2-5. Geological cross-section of the Cerro Prieto geothermal field. (From IIE, 1979)

The probable age of the batholith is Cretaceous, although a pre-Cretaceous age has been suggested.

Non-deltaic deposits - During the early Tertiary, intensive erosion of the granitic and metamorphic rocks took place, the products of which were deposited in a large graben of what is today the Mexicali Valley. These products of erosion became shales and fine-to-medium-grained sandstones, some of which possess considerable porosity and permeability.

Additional porosity and permeability were induced by fracturing related to basement faulting which has continued from the Tertiary to the present. The basement rock in the Mexicali Valley shows considerable en-echelon faulting. These faults have led to the development of a graben, and affected all the deposits overlying the granitic rocks.

Toward the end of the Tertiary, the Colorado River contributed large volumes of water to the graben from which the Mexicali Valley originated. The erosion products referred to above were carried and deposited in a mixture of fresh and salt water. As a result, the permeable sandstones have their pore space filled with brackish water.

The thickness of sediments as measured in Well M-3 is about 1800 m and should increase toward the center of the valley and decrease toward the edges. The very few fossils in these sediments to date have been mostly fresh water ostracodes.

B. Quaternary

Extrusive igneous rocks - Very few outcrops of extrusive igneous rocks are found in the area, mostly near the Cerro Prieto volcano.

Sedimentary rocks and deltaic deposits - Sedimentary rocks are alluvial sediments and deltaic deposits (clays, sands, gravels, and pebbles) which were deposited by the Colorado River over a wide area which today includes the Valley of Mexicali in Mexico and the Imperial (California) and Yuma (Arizona) Valleys in the USA.

Recent deposits - Recent deposits overlying the deltaic sediments in the Mexicali Valley are represented by the talus deposits found on the slopes of the Sierra Cucapas.

CHAPTER 3

PRE-EXPLOITATION STUDIES

3.1 GEOLOGY

The only geologic reports of the Cerro Prieto field before exploitation are those by Alonso and Mooser (1964) and Alonso (1966). A regional tectonics study by Alonso and Mooser (1964) revealed the first view of the field substructure; the basement is depicted as a series of faulted blocks (Figure 3.1). Two fault-fracture systems were described: one running parallel to the Gulf of California fracture belt and the other composed of smaller fractures oriented obliquely to the former. An earlier geophysical study by Kovach and Monges (1961) indicates a major fault, now designated the Cerro Prieto Fault, which was considered an extension of the San Jacinto Fault.

The extrusive rocks in the region, including those of the Cerro Prieto volcano, were identified as olivine basalts of Quaternary age. Elders (1979), however, classified the Cerro Prieto volcano as a calc-alkaline rhyodacite cone. The Laguna Volcano hydrothermal area was briefly described and believed to extend approximately 10 km² by Alonso and Mooser (1964), who also suggested there was no direct magmatic connection between this area and the Cerro Prieto volcano.

A brief description of the subsurface stratigraphy was generated from cores and cuttings obtained from the drilling of Well M-3. It was decided that drill hole M-3 should continue into the basement formation even though geothermal fluids might be encountered. High temperatures and permeable horizons were encountered between 650 and 950 m depth. The well was terminated in granite at 2550 m. M-3 has since been producing a water-steam mixture slightly over 200°C and 24 kg/cm² pressure. Temperature measurements taken throughout the drilling revealed two high temperature zones in this well: at 720 m depth and between 2400 and 2529 m.

Figure 3-1. Geological cross-section, Sierra de Juarez - Cerro Prieto. (From Alonso and Mooser, 1964)

Well M-4 was located 18 km north-northwest of the Cerro Prieto geothermal zone. Seismic studies in this area indicated a system of normal faults and probable impermeable horizons which were supposed to overlie a permeable zone and thus act as a cap for the accumulation of steam. This hole encountered neither geothermal fluids nor elevated temperature gradients. Well M-5, about 3 km southeast of M-3, was located partly as a step-out from M-3 and partly because of reinterpretation of the seismic survey. The reinterpretation confirmed a major fault zone east of Cerro Prieto running northwest-southeast. The well was undistinguished until 1100 m when altered shales and sandstones were penetrated. The temperature increased and from 1285 m to 1303 m (total depth) drilling difficulties persisted. Eventually the well produced a water/steam mixture just above 200°C, although the temperature from 1100 m to 1303 m was a constant 340°C. Well M-6 was located within the Laguna Volcano thermal manifestations area and between the trace of two northwest-southeast faults observed on air photos. The well was terminated at a 2040 m depth and flowed a water/steam mixture at 120°C. Pressure was low and after three days of flow the well became totally encrusted.

A comprehensive regional geologic study encompassing tectonics and stratigraphy of the Cerro Prieto area, including descriptions of the Cerro Prieto and Cucapas Faults, is summarized in Alonso (1966). Much of this information was derived from the drilling of Wells M-2, M-2A, M-3, M-4, M-5 and M-6 from which some lithologic columns were produced (Table 3.1). Some results from these wells, as described by Alonso (1966), are presented:

- o Well M-2: Drilled east of Cerro Prieto volcano to a total depth of 755 m (Figure 3.2). Circulation temperatures never exceeded 60°C and steam was not encountered. The well was abandoned.

Figure 3-2. Exploration well locations (well M-4 18 km. Northwest of Cerro Prieto Volcano)

TABLE 3.1
LITHOLOGIC DESCRIPTIONS FROM TWO WELLS
AT CERRO PRIETO FIELD (FROM ALONSO, 1966)

<u>Well M-3</u>	<u>Description</u>	<u>Well M-6</u>
363 - 384 m	Fine sandstone cemented with calcite, interbedded with limonite and shale. Ostracods present.	390 - 398 m
911 m	Sand and loose coarse gravels.	932 m
Not Found	Extrusive volcanics, pumice and obsidian.	994 - 1024 m
Not Found	Limonite, shale, fine and coarse grained sandstone.	1024 - 1114 m
1115 - 1936 m	Coarse sand and gravel with some sandstone. Sand, gravel, sandstone and limonite.	1114 - 1159 m 1159 - 1980 m
2133 - 2537 m	Fine grained, well cemented sandstone. Alkali biotite granite.	1908 - 2010 m

- o Well M-2A: Drilled close to the southeastern slopes of Cerro Prieto volcano to a total depth of 402 m. A maximum drilling mud temperature of 80°C was measured but the well remained unproductive.
- o Well M-3: Well siting was based on seismic refraction studies. Drilling mud temperatures reached 75.5°C at a depth of 670 to 850 m. Steam was encountered at 1010 m with a temperature of 135°C; however, drilling continued to a total depth of

2550 m and showed decreasing temperature with increasing depth. The bottom 100 m was in the granitic basement. All attempts to make the well productive from these deep horizons were unsuccessful and subsequently abandoned. The high temperature shallow horizons were again studied, the well plugged at 925 m, and shortly thereafter a water-steam mixture was produced. Since then the well has been in constant production with a temperature of 207°C and a well-head pressure of 24 kg/cm².

- o Well M-4: This well was sited 18 km northwest of the explored geothermal area in order to investigate a new zone. A maximum temperature of 45°C was measured at 900 m depth. Drilling continued to a total depth of 2006 m, but failure to encounter high temperatures or steam resulted in abandonment.
- o Well M-5: Well siting was based on reinterpretation of seismic studies which defined the northwest trending fault zone east of Cerro Prieto. Considerable circulation loss was encountered at 1285 m depth. A down-hole temperature of 198°C was measured at 1303 m and drilling stopped. A steam/water mixture spewed out forcefully, breaking the discharge pipes at the surface. Once under control, Well M-5 was considered one of the most productive wells in the field, with a temperature of 340°C and a pressure of 117 kg/cm² at a depth of 1300 m.
- o Well M-6: This well was sited east of Laguna Volcano hydrothermal area in order to investigate this zone. A maximum temperature of 95°C was recorded at a depth of 670 m with decreasing temperatures thereafter. Drilling continued to a depth of 2,040 m but steam was never encountered. Like Well M-3, the well was plugged at 939 m and shortly thereafter a water/steam mixture spewed out with a temperature of 120°C.

Chemical constituents from the fluid started encrustation in the pipes and in three days the pipes were blocked and the well ceased production.

The success of these wells prompted full scale production drilling. Concurrent geological and geophysical studies combined with exploration well drilling determined the feasibility of steam exploitation at Cerro Prieto (Paredes, 1975).

3.2 GEOPHYSICS

In 1961 the Mexican Federal Electricity Authority (CFE) conducted a regional temperature survey. An isotherm map of the Mexicali Valley was prepared from these results, as shown in Figure 3-3. Zones of high surface temperatures are delineated and cover the areas of Tulecheck, Cerro Prieto and Mesa de Andrade.

Kovach and Monges (1961) performed a gravity study which resulted in the first Bouguer gravity anomaly map of the Cerro Prieto region. This map, shown in Figure 3-4, shows gravity of approximately -80 mgals for the Laguna Salada basin and -20 mgals for the Sierra Cucapas with respect to the international ellipsoid. The area encompassing the geothermal field has a mean gravity value of -40 mgals. Gravity data correlated well with some of the known faults in the region.

Seismic refraction surveys carried out in 1962 and 1963 by GEOCA (1962) and SEISA (1963) consisted of 9 profiles averaging 11 km in length. The location of the lines is shown in Figure 3-5. Figure 3-6 shows the interpretation along one of the profiles. Velocities of 5500 to 6000 m/sec are related to the granite basement, 3700 to 4400 m/sec to the indurated sandstones and shales, and 1700 to 2500 m/sec with the local gravels, sands and clays.

Figure 3-3. Isotherms in the Mexicali Valley, based on surface manifestations (from Manon, et.al., 1978).

Figure 3-4. Bouguer gravity anomalies of the Colorado Delta. (After Kovack and Monges, 1961)

Figure 3-5. Location of seismic lines and section D-D'. (From GEOCA (1962) and SEISA (1963))

Figure 3-6. Interpretation of Seismic Refraction Line D-D' across Cerro Prieto Field.
(From GEOCA (1962) and SEISA (1963))

In 1963 the Consejo de Recursos Naturales No Renovables (CRNNR) performed a second gravity survey consisting of 340 stations. The results were combined with those from the seismic refraction survey in order to understand more clearly the basement structure and the overlying sediments. Based on the results of these studies, four additional exploratory wells were drilled (M-3, M-4, M-5 and M-6).

Measured temperature isotherm maps were drawn in 1965 from data collected in 50 shallow holes. These reports were not available for review in the present study. Seismological studies were performed in 1969 by CFE, Universidad Nacional Autonoma de Mexico (UNAM) and Centro de Investigacion Cientifica y de Educacion Superior de Ensenada, B. C. (CICESE). Figure 3-7 shows the location of epicenters of earthquakes which occurred during April and May, 1969.

Figure 3-7. Location of earthquake epicenters which occurred during April and May, 1969. (From CICESE, 1977)

CHAPTER 4

ABSTRACTS FROM GEOLOGICAL INVESTIGATIONS

4.1 INTRODUCTION

In 1973, commercial operation of a 75 MW geothermal power plant began at Cerro Prieto. A number of geotechnical studies were carried out at this time in order to define and delineate the geothermal field. In 1979 the power capacity was doubled to 150 MW. The geological reports generated in the period from 1970 to 1980 are briefly summarized in this section.

4.2 ESTUDIO PRELIMINAR GEOLOGICO DEL AREA AL SUR Y SURESTE DE MEXICALI, B. C. PARA APPROVECHAR LOS RECURSOS GEOTERMICOS - CALDERON, A. (1958)

This study described the geologic setting of the Cerro Prieto and surrounding areas and included a discussion of the vegetation, precipitation, drainage, topography, and general hydrology. The resulting maps showed the general geology and also outlined zones of thermal activity and gave the fluid temperatures of the hot springs. Generalized lithologies and chemical analyses of waters from approximately 13 domestic wells were reported. Petrographic studies aided the determination of the stratigraphy of this area.

- o Intrusives and metamorphics form a physiographic unit which includes the Sierra Cucapas. These rocks are granite-tonalite.
- o Extrusives are confined to the Cerro Prieto volcano and consist of basaltic tuffs, lavas, agglomerates and breccias.

- o Sedimentary deposits consist of deltaic arkosic sandstones and talus deposits along the Sierra Cucapas.

The extension of the San Andreas fault which crosses this area is believed to consist of a four-fault system distributed along a 70 km width. Six geothermal sites were investigated, including Cerro Prieto area which had temperatures of 200°F. A deep source of magmatic origin was postulated for the steam of the hydrothermal areas. Three drill sites were recommended and located east and north of the Cerro Prieto volcano.

4.3 A PRELIMINARY REPORT ON THE GEOLOGY AND GEOCHEMISTRY OF THE CERRO PRIETO GEOTHERMAL FIELD - MARSHALL REED (1972)

This paper discusses the regional and surface geology as well as the subsurface geology based on samples of cores and cuttings. Figure 4.1 shows the resulting generalized geologic section through Well M-10. Fanglomerates and alluvial sands from the Sierra Cucapas interfinger with sandstones and shales similar in mineralogy to the central Colorado delta deposits. Volcanic ash beds were penetrated in some wells and these are believed to have originated from Holocene activity of Cerro Prieto volcano. The basement rocks which crop out in the Sierra Cucapas are probably the same as the basement rocks under the Cerro Prieto geothermal field. The mineralogy of these rocks is presented in Table 4-1. Chemical compositions (Table 4-2) were calculated for the plutonic rocks from their mineralogy. Petrographic and x-ray analyses of core samples and cuttings enabled the description of sediments deposited at Cerro Prieto. The mineralogy of locally derived sediments partly modified by metamorphic reactions is shown in Table 4-3. A petrographic study of metamorphic minerals revealed a number of mineralogical changes with increasing depth (Figure 4-2). At shallow depth (400-700 m, 100-170°C) interlayered montmorillonite-mica and some montmorillonite-mica-chlorite appear. At intermediate depth (800 m,

- / FAULTS (dashed where approximately located)
 — CONTACTS (division of sedimentary units is by marker beds)
 MARKER BEDS (average thickness)
 A — Alluvial Sand (15m)
 B — Conglomerate (10m)
 C — Alluvial Sand (10m)
 D — Alluvial Sand (7m)

Location of geothermal wells in the Cerro Prieto field.

Figure 4-1. Generalized east-west geologic section through well M-10 (other wells projected onto the plane of section). Interpretation based on well log and seismic refraction data from the Department of Geothermal Works. (From Reed, 1972)

Figure 4-2. Distribution of minerals as a function of temperature and depth. The temperatures given are based on a composite of all wells. The depths given are for well M-5. All samples also contained quartz, calcite, mica, microcline, and plagioclase. (From Reed, 1972)

TABLE 4-1

MINERALOGY OF THE PLUTONIC ROCKS OF THE SIERRA DE LOS CUCAPAS
AND OF THE CERRO PRIETO GEOTHERMAL FIELD* (FROM REED, 1972)

Minerals	Rock Samples (Mineralogy in wt %)		
	La Puerta Tonalite	Cucapas Granodiorite	M-3 2563 m Granodiorite
Plagioclase (Composition)	52.1 andesine An ₃₃	43.3 oligoclase An ₂₄	46 oligoclase An ₂₂
Quartz	21.5	30.6	25
Microcline	2.4	19.0	20
Biotite	13.7	6.8	7
Hornblende	9.2	.1	
Muscovite		.2	
Sphene	1.1		
Chlorite			1
Calcite			1

* M-3 values are from semiquantitative x-ray analysis with plagioclase composition determined optically. Values for the other samples are calculated from the volume % of Barnard (1968).

TABLE 4-2

THE CHEMICAL COMPOSITION OF IGNEOUS ROCKS
IN THE CERRO PRIETO REGION 1/ (FROM REED, 1972)

<u>Oxides</u>	<u>Rock Types (Composition in wt %)</u>			
	<u>La Puerta</u> <u>Tonalite</u>	<u>Cucapas</u> <u>Granodiorite</u>	<u>M-3</u> <u>Granodiorite</u>	<u>Cerro Prieto</u> <u>Rhyodacite</u>
SiO ₂	63.9	72.7	69.8	68.4
TiO ₂	1.0	.2	.3	.54
Al ₂ O ₃	16.9	14.7	15.6	15.6
Fe ₂ O ₃ <u>2/</u>	5.0	1.9	2.1	5.59
MnO	.1			.08
MgO	2.2	.6	.6	.86
CaO	4.9	2.2	3.7	3.89
Na ₂ O	4.2	3.9	4.2	5.44
K ₂ O	1.7	3.8	4.0	1.29

1/ Cerro Prieto Rhyodacite values from x-ray spectrograph analysis by Robinson (personal communication, 1971). Values for other rocks calculated from mineral weight % in Table 2.

2/ Total iron is given as Fe₂O₃.

TABLE 4-3

SEMIQUANTITATIVE X-RAY MINERALOGY OF SELECTED,
HIGH FELDSPAR CONTENT, SAMPLES FROM WELL M-3 (FROM REED, 1972)

Depth of Cuttings (m)	Quartz	Microcline	Plag.	Mica	Chlorite	Calcite	Dolomite	Kaolin.	Mont.
342-345	37	27	7	12		6	4	5	2
672-675	52	30	4	3	1	10			
824-827	63	28	2	5		2			
974-977	38	46	4	4		8			
1152-1155	48	29	2	5		16			
1334-1337	53	27	11	5	1	3			
1514-1517	49	21	16	4		8		2	
1664-1667	44	31	13	4	1	6			1
1842-1845	39	36	11	4	1	7		2	
2172-2175	58	22	9	3	1	5		2	
2503-2506	63	20	6	3	1	7			
2533-2536	53	20	10	7	1	9			

200°C) montmorillonite disappears. At greater depth (950 m, 250°C) mica and chlorite are completely separate phases. From these and other results it was concluded that metamorphism was initiated after most of the sedimentary section has been deposited.

4.4 GEOLOGY OF THE CERRO PRIETO GEOTHERMAL FIELD - IGNACIO PUENTE CRUZ AND A. DE LA PENA (1978)

This paper describes the general geology of the Cerro Prieto area, including tectonics, aerial photo interpretation of fractures occurring in the geothermal field, and some seismic interpretation which correlates with the subsurface geologic configuration. The NW-SE striking Sierra de los Cucapas was briefly described as consisting of Upper Cretaceous granite which intruded and metamorphized Cretaceous and Paleozoic sediments. The deltaic sediments overlying the granitic basement were divided into two lithostratigraphic units:

Unit A:

Unconsolidated Quaternary sediments composed of clays, sands and gravels. Bottom of unit has semiconsolidated, brown shale layers.

Unit B:

Consolidated, Tertiary deltaic sediments composed of alternating layers of shales, limestones and sandstones. This unit contains the high temperature aquifers.

Figure 4-3 shows the generalized stratigraphic column of the Cerro Prieto area. Based on well data and seismic surveys several cross-sections of the geothermal field were developed (Figures 4-4 and 4-5). Figure 4-6 shows the superficial fractures at Cerro Prieto mapped from aerial photographs. Two fault systems were defined: the Cerro Prieto

Figure 4-3. Generalized stratigraphic column of the Cerro Prieto area.
(From Puente and de La Pena, 1978)

Figure 4-4. NE-SW geologic cross-section. (From Puente and de la Pena, 1978)

Figure 4-6. Surficial fractures of the Cerro Prieto area, based on aerial photo interpretation. (From Puente and de la Pena, 1978)

TABLE 4-4
(Sheet 1 of 2)

CHECKLIST BY GEOTHERMAL WELL AND SAMPLE DEPTH OF
MICROFOSSILS FROM CERRO PRIETO
(From Cotton and Vonder Haar, 1980)

<u>Well</u>	<u>Sample Depth (m)</u>	<u>Foraminifera</u>	<u>Ostracodes</u>	<u>Nannofossils</u>	<u>Other</u>
M3	839				
	2339			X	X
	2500			X	
M4	1200			X	
	1975			X	
M6	962		X		
	1245			X	
M8	964	X	X		
	906			X	
	1167			X	X
	1265				
M11	351	X	X	X	X
	470	X	X	X	X
	678		X		
	753		X	X	X
	879				
	882				
	912				
	921				
	1050				
	1161				
	1245				
	1365				
	1377				
M14	786		X	X	
	1041			X	
	1254				
M15	693	X	X	X	
	1008			X	
	1164			X	

TABLE 4-4
(Sheet 2 of 2)

CHECKLIST BY GEOTHERMAL WELL AND SAMPLE DEPTH OF
MICROFOSSILS FROM CERRO PRIETO
(From Cotton and Vonder Haar, 1980)

<u>Well</u>	<u>Sample Depth (m)</u>	<u>Foraminifera</u>	<u>Ostracodes</u>	<u>Nannofossils</u>	<u>Other</u>
M38	372	X	X		X
	480	X	X		
	718		X		
	864				
	961				
	969				
	1157				
	1239				
	1338				
	1479				
	1490				
M92	1998			X	
	2202			X	
	2446			X	
M93	1806			X	
	138		X	X	X
	606		X	X	
	996				
	1158				
	1680				
	1897				
0473	567		X	X	
	804				
	1062		X		
	1434			X	
Prian	3243		X		
	3495		X	X	
T366	2052				X
	2601				

TABLE 4-5

FORAMINIFERA IDENTIFIED WITH CERTAINTY
IN THE CERRO PRIETO WELL SAMPLES
(From Cotton and Vonder Haar, 1980)

<u>Well</u>	<u>Depth (m)</u>	<u>Foraminifera Found</u>
M11	351	<u>Cassigerinella</u> sp. cf. <u>C. chipolensis</u> (Cushman and Ponton)
M11	470	<u>C.</u> sp. cf. <u>C. chipolensis</u> <u>Hedbergella</u> sp. cf. <u>H. holmdelensis</u> (Olsson)
M8	694	<u>Heterohelix globulosa</u> (Ehrenberg) possible benthic form
M15	693	Possible Cretaceous globigerine form
M38	372	<u>Hedbergella</u> sp. cf. <u>H. monmouthensis</u> (Olsson)
M38	480	<u>C.</u> sp. cf. <u>C. chipolensis</u> Globigerina Possible Tertiary turborotalids

TABLE 4-6

NANNOPLANKTON OBSERVED IN CERRO PRIETO WELL CUTTINGS
(From Cotton and Vonder Haar, 1980)

<u>Well</u>	<u>Depth (m)</u>	<u>Nannoplankton Found</u>
M6	1245	<u>Zygodiscus diplogrammus</u> Gartner <u>Lithraphadites carniolensis</u> Deflandre <u>Tranolithus</u> sp. <u>Watznaueria barneseae</u> Perch-Neilsen <u>Vagalapilla</u> sp. <u>Eifellithus turrisEIFELLI</u> Deflandre <u>E. eximius</u> Perch-Nielson
M11	470	<u>Nannoconus multicaudus</u> Deflandre and Deflandre-Rignaud <u>W. barneseae</u>
M92	2466	<u>Micula</u> sp. cf. <u>M. staurophora</u>
0473	1434	<u>Discoaster</u> sp. cf. <u>D. deflandrei</u> Bramlette and Riedel base of spheolith
Prian	3495	<u>W. barneseae</u>

system striking NW-SE, and the Secondary Volcano system striking NE-SE. These structures have created a step-faulted, horst-and-graben topography. It was concluded that the most productive horizon lies between 1200 and 1700 m depth in the zone classified for intermediate exploitation.

4.5 GEOPHYSICAL WELL LOG CORRELATIONS ALONG VARIOUS CROSS-SECTIONS OF THE CERRO PRIETO GEOTHERMAL FIELD - A. ABRIL AND J. NOBLE (1978)

Based on analyses of geophysical and temperature logs, four cross-sections were developed to define the geologic structure of the field. Their locations are depicted in Figure 4-7 and the cross-sections are shown in Figures 4-8 and 4-11. The lithologic units were subdivided to correlate with the electrical logs, as shown in Figure 4-12. The well log data used in this report were the self-potential (SP) and formation resistivity curves. The faults shown in Figure 4-13 were identified from these studies.

4.6 LITHOLOGIC CORRELATIONS BASED ON INTERPRETATION OF GEOPHYSICAL WELL LOGS AT THE CERRO PRIETO FIELD - R. PRIAN (1978)

This paper presents a sketch of the reservoir structure and its stratigraphic sequence, based on analyses of geophysical well logs and well temperatures. Two main reservoirs, A and B, were defined at depths of 1400 and 1800 m respectively. A shallow secondary "lenticular" reservoir is present only in parts of the field. (Figures 4-14 and 4-16). It was concluded that the storage structure is formed by one of several paleochannels that may have been the distributaries of a deltaic paleo-system. This structure is divided by a NW-SE striking longitudinal fault system, and a NW-SW striking transverse system. It was also postulated that thinning of the basement rocks enhances heat flow to the reservoir.

Figure 4-7. Location of cross-sections in Figures 4-8 to 4-11.
(From Abril and Noble, 1978)

Figure 4-8. Section I-I". (From Abril and Noble, 1978)

Figure 4-9. Section II-II". (From Abril and Noble, 1978)

Figure 4-10. Section III-III'. (From Abril and Noble, 1978)

Figure 4-11. Section IV-IV". (From Abril and Noble, 1978)

Figure 4-12. Symbols used in the correlation of electrical surveys.
(From Abril and Noble, 1978)

Figure 4-13. Location of faults. (From Abril and Noble, 1978)

Figure 4-14. Idealized E-W cross-section of the Cerro Prieto field. (From Prian, 1978)

Figure 4-15. W-E schematic cross-section. (From Prian, 1978)

Figure 4-16. NW-SE schematic cross-section. (From Prian, 1978)

4.7 ANALYSIS OF CERRO PRIETO WELL LOGS: SOME RESULTS AND PROBLEMS - J. NOBLE AND A. ABRIL (1978)

This paper discusses LBL's efforts in applying various interpretation methods to the Cerro Prieto well logs, resulting in the delineation of lithologic units by means of well-log correlation techniques and the auto-correlation program, COR4LOG. This correlation is depicted by the schematic diagram shown in Figure 4-17.

The mineralogic composition of formations affect the well log responses, therefore, quantitative mineralogic studies of cores and cuttings are essential for an accurate log evaluation. Also necessary is an understanding of the influence of the thermal gradient (between the wellbore and the formations) on logging responses.

4.8 HYDROTHERMAL MINERAL ZONES IN THE GEOTHERMAL RESERVOIR OF CERRO PRIETO - W. ELDERS, J. HOAGLAND, S. McDOWELL, AND J. COBO (1978)

Detailed petrologic studies from cuttings and cores of 23 wells in the Cerro Prieto field have led to recognition of regularly distributed prograde metamorphic mineral zones. The progressive changes in mineralogy exhibit a systematic relationship with reservoir temperature.

The following progressive stages of postdepositional alteration in response to increasing temperature have been observed (Figure 4-18):

- o Diagenetic zone (low temperature)
- o Illite-chlorite zone (above 150°C)
- o Calc-aluminum silicate zone (above 230°C) and the biotite zone (above 325°C).

These zones are transitional and can be further subdivided based on the appearance or disappearance of various minerals (Figures 4-19 and 4-20).

Figure 4-17. Major lithologic units delineated by well-log correlation. (From Noble and Abril, 1978)

Figure 4-18. Mineral zones in sandstones at Cerro Prieto as a function of temperature. (From Elders, et.al., 1978)

Figure 4-19. Distribution of mineral zones in sandstones along the profile A-A'. Isotherms modified from Mercado (1976). (From Elders, et.al., 1978)

Legend

MONTMORILLONITE DESTROYED	DOLOMITE DESTROYED
-.-.-.- KAOLINITE DESTROYED	-.-.-.- INTERLAYERED ILLITE/MONTMORILLONITE DESTROYED
———— INTERLAYERED ILLITE/MONTMORILLONITE WITH >50% EXPANDABLE LAYERS DESTROYED	——— WAIRAKITE

Figure 4-20. Distribution of mineral zones in shales along the profile A-A'. Isotherms modified from Mercado (1976). (From Elders, et.al., 1978)

The first major hydrothermal effect to occur with increasing temperature is the transformation of the detrital and diagenetic clay mineral assemblage to illite and chlorite. This transition occurs over a temperature range of 150-200°C, and usually follows this sequence: disappearance of montmorillonite and increase in illite and mixed-layer illite/montmorillonite (> 150°C); progressive decrease in montmorillonite content of mixed-layer clays, and subsequent disappearance of kaolinite, dolomite and most mixed-layer clays with corresponding increases in illite and chlorite (> 180°C). There is a dramatic increase in quartz and K-feldspar overgrowths on sand grains at temperatures > 180°C. Sphene first occurs near the beginning of the illite-chlorite range.

The illite-chlorite zone extends to the first occurrence of hydrothermal epidote (230-250°C), marking the beginning of the calc-aluminum silicate zone. Wairakite usually first occurs at this level and persists to the first occurrence of prehnite (300°C) and sometimes to higher temperatures; however, in some boreholes wairakite is observed at temperatures of approximately 200°C.

Illite abundance decreases noticeably where prehnite is abundant, and sporadic actinolite and more rarely diopside-hedenbergite occur at temperatures higher than the prehnite isograd. Calcite decreases markedly in abundance at the prehnite isograd, and in some wells is completely eliminated. This level also marks the onset of recrystallization of original framework grains, often producing a dense hornfelsic texture in the reservoir rocks.

The final major mineral zone encountered at Cerro Prieto is the biotite zone, defined at the first occurrence of that mineral (325°C). Epidote and actinolite persist through this zone, but illite is generally absent and chlorite is present only in trace amounts. No new phases occur between 325°C and the maximum temperature of 347°C encountered in the wells so far investigated.

One immediate application of these studies is the capability, from a study of cuttings obtained during well drilling, to predict the temperatures which will be observed when the well is completed.

In boreholes on the flanks of the producing field, alternating zones of calcite-cemented and of quartz-feldspar-cemented sandstones are observed at temperatures below 300°C. Simple solubility relations suggest that the calcite-rich zones form where relatively cold water is flowing into hotter rocks, whereas the quartz-feldspar zones mark areas of hot water incursions into colder rocks. Mapping these mineral zones around the field helps delineate its temperature distribution and hydrology.

4.9 GEOLOGIC MODEL OF THE CERRO PRIETO GEOTHERMAL FIELD - DE LA PENA, I. PUENTE, E. DIAZ, AND A. ABRIL (1979)

In this paper, the previous structural interpretations of the main geologic features were confirmed by additional geological, geophysical and geochemical data. The correspondence between the previous and present model is mainly because of the two fault systems affecting the basement. It was concluded these systems originated by the right lateral transform fault tectonic movements acting in this area. A detailed analysis of the structural behavior, vertical position, and faults and fractures affecting the geothermal hot water aquifers was presented.

4.10 STRATIGRAPHIC AND SEDIMENTOLOGICAL ANALYSIS OF THE CERRO PRIETO GEOTHERMAL FIELD, BAJA CALIFORNIA, MEXICO - J. NOBLE (1979)

This paper discusses how Cerro Prieto well logs were used to correlate major stratigraphic reservoir units and to further subdivide them into individual rock units which were then correlated between various cross-sections. Lenticularities were recognized from the correlations and

showed the thickening or pinching out of rock units between wells. Various faults and stratigraphic unconformities were identified. Dip-meter data, when integrated with other log data, were useful in making stratigraphic interpretations. Cores and cuttings of various wells were also studied in order to interpret the distribution of sedimentary units in the Cerro Prieto field. Because many wellbore measurements reflect depositionally derived physical rock properties, the well bore data were used to understand the mechanism and environment of sedimentary deposition.

4.11 STUDIES OF WATER/ROCK INTERACTION IN THE CERRO PRIETO GEOTHERMAL FIELD, BAJA CALIFORNIA, MEXICO - W. ELDERS AND J. HOAGLAND (1979)

Subsurface fluid samples from forty wells, in addition to surface samples, have produced data relating to the lithologic and mineralogic distribution, petrology, bulk rock and mineral chemistry, oxygen and carbon isotope ratios, fluid inclusion and vitrinite reflectance geothermometry, and fission track dating. Most observations were consistent with the hypothesis that Cerro Prieto is a very open system which has undergone a single recent episode of progressive heating. Based on isotope data, minimum water/rock volume ratios are 2:1 to 5:1, in the least permeable rocks. However, whole rock chemical analyses of sandstones suggest that this extensive fluid flow did not cause major changes in the chemistry of the rocks, apart from loss of CO₂. This, in turn, suggests that solution and precipitation of most components of the rock does not involve transport in solution over log distances.

4.12 VITRINITE REFLECTANCE AND GEOTHERMOMETRY IN WELLS M-84, M-93, M-94
AND M-105 IN THE CERRO PRIETO GEOTHERMAL FIELD - C. BARKER AND W.
ELDERS (1979)

Thermal metamorphism of microscopic organic particles found in most sedimentary rocks (phytoclats) can be used to determine reservoir temperatures in the Cerro Prieto geothermal system. The phytoclats were extracted from mudstone chip samples by disaggregation of the rock in HCl and HF followed by heavy-liquid density separation. Polished sections of a single phytoclast type (vitrinite), derived from woody plant tissues, were used to determine the degree of thermal alteration (rank) by measurement of reflectance.

Thermal maturation of phytoclats is considered to be largely independent of pressure and fluid chemistry, and is therefore superior to inorganic geothermometers in these respects. The basis for vitrinite reflectance geothermometry is the change of optical properties resulting from devolatilization and condensation of the phytoclast in response to temperature and duration of heating. The effects of time and temperature on phytoclats are irreversible, as the volatile components are no longer available for retrograde reactions. The lack of adequate theoretical models relating time-temperature and rank in young, open, geochemical systems makes it necessary to use empirical rank-temperature functions for geothermometry.

For temperature prediction in this study, the reflectance temperature measurements from Well M-105 were used.

This empirical vitrinite reflectance geothermometer was tested by using data from Well M-84 to predict temperature, and subsequently good agreement with the measured logs was found. In this well, the temperature gradients had been confirmed by repeated logging showing little change in the temperature profile with time. The measured temperatures are corroborated by prograde mineral assemblages, fluid inclusion

homogenization temperatures and oxygen isotope geothermometry. The temperatures estimated from reflectance data are compatible with those derived by other methods. Similar relationships were obtained in Wells M-93 and M-94.

The agreement of these independent temperature estimates suggests that the measured temperatures in the deeper portion of these wells are equilibrium reservoir temperatures. It was concluded that vitrinite reflectance appears to be an accurate and simple geothermometer in this system. These temperatures are the maximum yet experienced by the reservoir, as there is no evidence of falling temperatures, such as retrograde mineral zones. Since reflectance data also depends on duration of heating as well as on temperature, some statements on the time factors involved can be made. The reflectance temperature data from four widely-spaced wells at Cerro Prieto show no significant heating time difference between these wells. Therefore, it appears that the heating event at Cerro Prieto is contemporaneous across the field. A comparison of the Salton Sea and Cerro Prieto geothermal fields using this method indicates that the latter field is younger.

4.13 PALEOMAGNETIC DATING OF THE CERRO PRIETO VOLCANO - J. DE BOER (1979)

Paleomagnetic samples were collected from two volcanic units of the Cerro Prieto volcano: a NE-trending subvertical dike-like feature in the center of the crater, and fine-grained subhorizontal pyroclastics, along the southeastern flank.

The paleomagnetic pole for the dike is located at 70.1°N , 197.5°E , a common position for Brunhes poles. A pole computed for a sample plots on the path of the Gothenburg excursion ($\pm 10,000$ years B.P.). The VGP for the pyroclastics is located at low latitude 24°N , 162°W , clearly indicating an excursion. This pole lies close to the polar path for

magnetic zone B of Manabe (1974) which supposedly represents the Blake excursion (114,000 to 108,000 years B.P.). Volcanism at Cerro Prieto thus appears to have been initiated approximately 110,000 years B.P. and may have continued periodically until about 10,000 years ago.

4.14 GEOLOGY AND MINERALOGY OF THE CERRO PRIETO GEOTHERMAL FIELD - J. COBO (1979)

This paper partly reiterates previous geological work concerning the fault system and the Cucapas Range. Tertiary deltaic sandstones were divided into three zones based on mineralogy and cementing materials.

The cement in the upper zone is mainly calcium carbonate; in the intermediate calcium carbonate and silica, and in the lower zone, silica.

4.15 INTERSECTING FAULTS AND SANDSTONE STRATIGRAPHY AT THE CERRO PRIETO GEOTHERMAL FIELD - S. VONDER HAAR AND J. HOWARD (1979)

The northwest-southeast trending Cerro Prieto fault is part of a major regional lineament that extends into Sonora and has characteristics of both a wrench fault and an oceanic transform fault. This fault penetrates into the granitic basement to serve as a conduit for thermal fluids. Where the Cerro Prieto fault obliquely intersects the shorter northeast-southwest trending faults, such as near Well M-103, there is greater permeability and hence increased natural convective fluid flow (Figure 4-21). A fault shear zone in the southern portion of the field, near Wells M-48, M-91 and M-101, illustrates another type of fracture flow. This shear zone appears to aid in rapidly distributing the geothermal fluid away from the Cerro Prieto fault.

Figure 4-21. Faults in the vicinity of the Cerro Prieto field showing cross-faults and the very productive well M-103. (From von der Haar and Howard, 1979)

Sandstone stratigraphy within the field has been studied by comparing data from well cuttings, cores, and downhole electrical well logs to the suite of geochemical and geophysical interpretations (Figure 4-22). At depths between 700 m and 3500 m the deltaic sediments consist of approximately 50% sandstone units, from 30 m to a few cm in thickness and 50% siltstone and shales. Across the earliest developed portion of the field, along a 1.25 km southwest-northeast section from Well M-9 to M-10, intersecting correlations emerge. In the upper portion of Reservoir A of this stratigraphic section, between approximately 1200 m and 1400 m, the total percentage of sandstone varies between 20 and 55. Temperatures range from 225 to 275°C based on well logs, isotope data and Na-K-Ca indices. Initial research indicates that the isothermal high corresponds to the lowest total percentage of sandstone. Scanning electron photomicrographs of well cores and cuttings from sandstone and shale units reveal clogging, mineral dissolution and mineral precipitation along microfractures. A working hypothesis is that these sandy shale and siltstone facies are most prone to produce microfractures.

4.16 MICROFOSSILS FROM CERRO PRIETO GEOTHERMAL WELLS, BAJA CALIFORNIA, MEXICO - M. J. COTTON AND S. VONDER HAAR (1980)

To aid in a paleoenvironmental reconstruction of the Cerro Prieto field, 59 samples of well cuttings were analyzed for microfossils. The cuttings were obtained at depths from 351 to 3495 m in 14 geothermal wells. Microfossils encountered include benthic and pelagic foraminifera, ostracodes, calcareous nannofossils, and gastropod and pelecypod shell fragments (Table 4-4). Ostracodes and nannofossils are most abundant and are found in a majority of the samples. Because of their large amount of real dispersion, however, information as to age and environment of deposition of the sediments in the area was difficult to assess. The shell morphology of the ostracodes is typical of those from marine/brackish water environments, possibly from lagoonal or estuarine conditions. The foraminifera and nanoplankton encountered

[illegible]

Figure 4-22. Sandstone units defined by relatively continuous major shale zones. Within the production reservoir the sandstone percentage, as in unit 3, varies from 20% to 50% with a minimum near well M-14 (see Figure 4-21 for well locations). (From Vonder Haar and Howard, 1979)

are listed in Tables 4-5 and 4-6. Due to the small number and size of foraminifera no definite conclusions were drawn from them. The fact that the specimens were of similar size, however, suggests they were transported and "winnowed" into position.

4.17 VERTICAL MOVEMENT ALONG THE CERRO PRIETO TRANSFORM FAULT, BAJA CALIFORNIA, MEXICO - A MECHANISM FOR GEOTHERMAL ENERGY RENEWAL - S. VONDER HAAR, J. NOBLE AND I. PUENTE CRUZ (1979)

Data from 53 geothermal wells to depths of 1 to 3 km on both sides of the right-lateral Cerro Prieto fault, as well as geophysical data, indicate vertical displacements along this fault of 400 to 600 m. This vertical movement was episodic and has offset deltaic sandstone reservoirs that are primarily at 1200 m and 1800 m depth and contain 250°C to 345°C water (Figure 4-23). The movement has kept this major fracture system open for convective fluid transport. It is suggested that the Cerro Prieto fault be considered a hybrid between the Gulf of California transform faults and the long portions of the San Andreas transcurrent system. A characteristic of such a hybrid system would be a vertical to horizontal movement ratio of 1:5 or 1:10, accompanied by migrating geothermal fluids.

4.18 PHYSICAL AND MECHANICAL PROPERTIES OF CORE FROM THE CERRO PRIETO GEOTHERMAL FIELD - A. ABOU-SAYED AND J. SCHATZ (1979)

This paper presents a study of the effects of pore pressure reduction due to reservoir drawdown on rock compaction and permeability. Preliminary short-duration test results on core from Wells T-366 and M-123 tested at reservoir effective stresses and temperatures up to 95°C indicate an effective bulk modulus for loading of 927,000 $\pm$ 50,000 psi. Unloading moduli are considerably higher and indicate some inelastic response and permanent compaction. Permeability of material from T-366 at 3000 psi confining pressure and room temperatures is 345 $\pm$ 47d.

CHAPTER 5

ABSTRACTS FROM GEOPHYSICAL INVESTIGATIONS

5.1 INTRODUCTION

Geophysical investigations at Cerro Prieto were increased after commercial operation of a 75 MW power plant began in 1973. Before this time, most of the investigations performed to explore the geothermal reservoir and leading to construction of the power plant in 1970 were done on a reconnaissance basis. The main exploratory technique consisted of costly drilling. Geophysical work was prompted in 1973 by the realization that the subsurface geological characteristics, reservoir size and potential, and other factors affecting producibility were not completely understood. Additional geophysical work was carried out in 1977-78 as a result of the CFE-LBL cooperative agreement. The available geophysical studies are summarized in the following sections.

5.2 LEVANTAMIENTO GRAVIMETRICO DE LA ZONA GEOTERMICA DE MEXICALI, BAJA, CALIFORNIA - Consejo de Recursos Naturales No Renovables [CRNNR] (1963)

Three hundred and forty gravity stations were located in the Cerro Prieto area in order to obtain additional data on the subsurface structure. Interpretation of gravity measurements pointed to the existence of two large sunken blocks near Sierra de los Cucapas, bordered by faults, and covered by Cenozoic sedimentary deposits. The deepest block lies under the area having surface geothermal manifestations. It was concluded that a near-surface intrusive body is possibly located ESE of Cerro Prieto volcano, near the sunken block of the San Jacinto fault.

Figure 5-1. Iso-Resistivity map of the Cerro Prieto region.
(From Manon, et.al., 1978)

5.3 AEROMAGNETIC STUDY OF THE COLORADO RIVER DELTA - de la Fuente (1973)

Results of this study showed the location of a previously unrecognized spreading center in the Colorado River delta, as shown in Figure 5-2. The new spreading center, designated as Panga de Abajo, is concordant with the system proposed by Lomnitz et. al. (1970). Data cross correlation showed that the Cerro Prieto fault is a system of at least two faults.

5.4 MOVEMENT OF GEOTHERMAL FLUIDS AND TEMPERATURE DISTRIBUTION IN THE CERRO PRIETO GEOTHERMAL FIELD - Mercado (1975)

Thermal fluid migration and temperature distribution measurements at Cerro Prieto helped indicate reservoir recharge zones and a probable location of the heat source. Figure 5-3 shows a cross-section of the temperature distribution within the field. The hottest zone lies between wells M-5 and M-8. The sealing of the shallow sandstone layers and an increasing clay content toward the southeast, close to M-51, result in finding high temperatures at greater depth. In the north-western section, there is horizontal movement of hot waters through shallow, permeable sandstone layers. Figure 5-4 shows the temperature distribution within the reservoir. From these measurements it was concluded that: (1) Thermal fluid is ascending in the eastern and central portions of the field and moving in a westerly direction, (2) the gradual temperature increase in the eastern area suggests the location of the reservoir heat source, (3) a recharge zone occurs in the western section, in the area of the alluvial fans of the Sierra de los Cucapas, and (4) another recharge zone is located in the eastern section of the field, where meteoric water from the Colorado River feeds the reservoir.

Figure 5-2. Location of the Panga de Abajo Spreading Center, Baja California, Mexico. The location of the spreading center is related to the idealized system of spreading centers and compensating right-lateral strike-slip faults in the Colorado River delta area. (From de La Fuente, 1973)

Figure 5-3. Subsurface temperature distribution at Cerro Prieto. (From Mercado, 1975)

Figure 5-4. Subsurface temperature distribution at Cerro Prieto. (From Mercado, 1975)

5.5 GEOELECTRICAL STUDY OF THE GEOTHERMAL ZONE AT CERRO PRIETO, BAJA CALIFORNIA, MEXICO - Garcia D. (1975)

In 1972, geoelectrical surveys performed by CFE covered an area of approximately 1600 km². Three exploration techniques were used: (1) Schlumberger soundings using 4 colinear electrodes with separations of $AB/2 = 500$ m and $MN/2 = 40$ m covering a 1600 km² area. This area is characterized by the NW-SE alignment of the iso-resistivity curves which coincide with the San Andreas regional fault system (Figure 5-5). A 70 km² area with resistivities less than 2 ohm-m was delineated around the present exploration zone at Cerro Prieto. Another zone with values less than 2 ohm-m was localized in the area known as Tulecheck. Both zones were believed to be connected with a deep geothermal anomaly. (2) A detailed study of a 140 km² area encompassing the exploited zone consisted of 290 Schlumberger (VES) soundings using a current electrode separation varying from 20 to 4000 m. Figure 5-6 shows the iso-resistivity contours of the area at the maximum calculated depth (1200 m). (3) A dipole-dipole survey performed along the Sonora-Baja California railroad penetrated depths from 1200 to 2000 m. It was concluded that the geothermal field has a NW-SE orientation, following the alignment of regional faults.

5.6 CAMPO GEOTERMICO DE CERRO PRIETO SOBRE LA FALLA DE SAN JACINTO Y SU POSIBLE AMPLIACION HACIA LA FALLA IMPERIAL - Soto, S. (1975)

A careful review of previous geotechnical studies revealed new information relating the geothermal field to major faults. It was concluded that the geothermal reservoir is divided into 2 zones: (1) the area now under exploitation is structurally related to a branch of the San Jacinto fault, and 2) a second, currently unexploited zone, which was discovered from drilling well 53, lies over the San Jacinto fault; its boundary is still unknown.

Figure 5-5. Results from Schlumberger soundings. (From Garcia, 1975)

Figure 5-6. Real resistivity at 1200m depth in the Cerro Prieto geothermal field.
(From Garcia, 1975)

5.7 PRIMER INFORME PRELIMINAR DEL ESTUDIO DE MICROSISMICIDAD DEL SISTEMA DE FALLAS TRANSFORMADAS IMPERIAL - CERRO PRIETO - Centro de Investigacion Cientifica y de Educacion Superior de Ensenada ([CICESE] 1977)

A microseismicity study conducted at Cerro Prieto geothermal field and vicinity produced data which correlated with the fault system in the area. Seismic events were concentrated along the Cerro Prieto and Imperial faults as shown in Figures 5-6, 5-7, and 5-8a and 8b. It was concluded that the Imperial Fault is connected to the right lateral Cerro Prieto Fault by an oblique fault.

5.8 PROSPECCION ELECTRICA DE LA PORCION NORTE DEL VALLE DE MEXICALI Y CAMPO GEOTERMICO DE CERRO PRIETO, BAJA CALIFORNIA - INFORME 6-78 - Razo, A. and Arellano, F. (1978)

A regional geoelectrical survey consisting of 114 Schlumberger vertical electrical soundings (VES) and covering a 580 km^2 area was performed in the Mexicali Valley. Results of this survey outlined areas which merited detailed prospecting, and subsequently, 74 VES soundings were carried out in these zones covering 208 km^2 . Two low resistivity anomalies were identified. A conductive layer was correlated with a layer composed of sands and clays and was defined as the cap rock of the geothermal field. It was concluded that the deeper resistive zone contained the highest temperatures. A second low resistivity area was located 15 km SE of the geothermal field. There are no surface manifestations in this zone, and the sedimentary formations have thicknesses of 1400 to 2300 m, so the high conductivity could be the result of high porosity and salinity in these strata. The anomalies, however, are associated with the Cerro Prieto fault and the area is recommended for exploratory drilling. A high resistivity zone northwest of Cerro Prieto is associated with the horst structure interpreted from gravimetry.

Figure 5-7. Seismic events 1970-1976. (From CICESE, 1977)

Figure 5-8a. Seismicity April 20-22, 1977. (From CICESE, 1977)

Figure 5-8b. Aftershocks of January 17, 1977 event. Focal depth 6 ± 6 km. (From CICESE, 1977)

5.9 SELF-POTENTIAL SURVEY AT THE CERRO PRIETO GEOTHERMAL FIELD, BAJA CALIFORNIA, MEXICO - Corwin, R., Diaz, S., and Rodriquez, J. (1978)

In December 1977, two self-potential survey lines were run across the producing area of the Cerro Prieto geothermal field. Large-amplitude, long-wavelength, self-potential anomalies occur within the field, as shown in Figure 5-9. The inflection points of the anomalies are roughly centered over two major faults believed to act as conduits for the thermal fluids. The shape of the anomalies also indicates that they may be generated by electrical activity extending to a depth of several km along the fault zones. It was concluded that the SP measurements may be helpful in tracing thermally active fault zones in the Cerro Prieto area.

5.10 LBL RESISTIVITY STUDIES AT THE CERRO PRIETO GEOTHERMAL FIELD - Wilt, M., Goldstein, N., and Montiel, R. (1978)

Two long dipole-dipole resistivity surveys were performed by LBL and the results, along with existing Schlumberger data taken by CFE, were used to develop two-dimensional field models. From these it was concluded that (1) the reservoir region within the production zone is not clearly delineated by dc resistivity measurements. (2) The Imperial and Cerro Prieto faults are clearly delineated in the resistivity models; each fault is characterized by a change in the bulk section of resistivity suggesting that they act as aquacludes.

Figure 5-9. Self-potential contours, Cerro Prieto area. Contour interval is 20 mV.
(From Corwin, et.al., 1978)

5.11 CFE SELF-POTENTIAL STUDIES NORTHWEST OF THE CERRO PRIETO VOLCANO -
Diaz, S. (1978)

Self-potential surveys were run along five lines in the Tulecheck area, northwest of the Cerro Prieto field. Surface manifestations in the area suggest the existence of a geothermal reservoir. Results show an SP anomaly associated with the structures and thermal manifestations in the area.

5.12 REFERENCED MAGNETOTELLURICS AT CERRO PRIETO - Gamble, T. et. al.
(1978)

Magnetotelluric (MT) soundings were performed at seven sites throughout the Cerro Prieto area. The results provide a means for checking the accuracy of a two-dimensional field model based on dc resistivity data. Figure 5-10 shows the new model on MT data since the current distribution for this mode of electromagnetic induction is drastically different from the current distribution for the dc resistivity surveys, the good match between models is an indication that the general model is a reasonable representation of the local structure.

5.13 SEISMICITY STUDIES IN THE REGION OF THE CERRO PRIETO GEOTHERMAL FIELD - Albores, A., et. al. (1978)

Results from seismicity studies point to locations of approximately 200 events. The seismic activity consists of swarms of small events, although one swarm had events with magnitude as high as 5.0. The epicenters indicate a broad distribution connecting the Cerro Prieto and Imperial faults. The pattern of seismicity and the composite fault plane solutions suggest that the distribution of tectonic deformation

Figure 5-10. Two dimensional model of the earth's resistivity. (From Gamble, et.al., 1978)

in the Mexicali Valley occurs principally along two tectonic trends: (1) faults parallel to and including the Imperial-Cerro Prieto transform fault system, (2) a system of faults oblique to the Imperial-Cerro Prieto trend with at least some normal faulting. A tectonic model is proposed in which a sigmoidal graben has formed between the Cerro Prieto and Imperial faults. The graben may be controlled by a "leaky transform fault," such as in the geothermal areas north of the border.

5.14 SEISMOLOGICAL STUDIES AT CERRO PRIETO - Majer, E. et. al. (1978)

During the period 14 February to 11 March, 1978 a radio-telemetered 12-station seismographic network was operated in a dense array configuration over the Cerro Prieto field, as shown in Figure 5-11. Seismological data indicates structural complexity associated with the Cerro Prieto geothermal field. Refraction data (GEOCA, 1962) and microearthquakes suggest several major NW striking faults, possibly controlling the field boundaries. The refraction data also suggest high velocity sediments and shallow basement in the production zones. Compared to seismicity in surrounding areas, microearthquake activity is low in the production area. First motion studies indicate right-lateral strike-slip motion for events within the field on NW-SE trending faults. Further micro-earthquake data are necessary to reduce the ambiguity in earthquake source and occurrence properties for comparison to regional values.

High levels of man-made ground noise in the center of the production zone limit the amount of velocity and attenuation data that can be collected. The few data collected suggest P-wave velocity and attenuation anomalies associated with the production region. V_p/V_s values are high; further monitoring may reveal a future change from water domination to vapor domination in the field. Microearthquake data may indicate steam zones if the events are related to large pressure or temper-

Figure 5-11. Regional map showing station locations (triangles) and locations of earthquakes within the field (solid circles) and outside of the field (shaded regions) during February 14 - March 11, 1978. (From Majer, E., et.al., 1978)

ature gradients or to volume changes associated with fluid removal. There is sufficient seismic activity in the production zone to warrant continuous monitoring.

5.15 PRECISION GRAVITY STUDIES AT CERRO PRIETO - Chase, D. et. al
(1978)

Sixty gravity stations were established within and adjoining the Cerro Prieto geothermal field in order to monitor the small temporal changes due to fluid withdrawal and subsidence. Because only one set of data has been obtained, it is too soon to determine whether changes in gravity are occurring with the development of the geothermal field and its environs. A Bouguer anomaly map was prepared, as shown in Figure 5-12.

5.16 SEGUNDO INFORME DE AVANCE DEL ESTUDIO DE MICROSISMICIDAD DEL SISTEMA DE FALLAS TRANSFORMADAS IMPERIAL - CERRO PRIETO - IEE-CICESE
(1977)

Based on preliminary studies of seismic noise and activity, 5 locations were chosen for setting up seismograph stations. Two of these stations were equipped with vertical and horizontal components, which provided optimum data registering of seisms occurring near the Cerro Prieto and Imperial faults. Data from the horizontal component allows for better control of epicenter localization, focal depth estimates and travel times. A total of 200 events, with magnitudes less than 6, were recorded and lying at an average depth of 8 km. Figure 5-13 shows the epicenter distribution for events occurring from 1971 to 1977. This figure also shows the near-parallel correlation of events with the Cerro Prieto fault, and the large occurrence of events between the faults, suggesting the existence of a normal fault in this area.

Figure 5-12. Bouguer anomaly map of the Cerro Prieto geothermal field and its vicinity. Contour interval is 1 mgal. (From Chase, D., et.al., 1978)

Figure 5-13. Seismicity 1971-1977. (From CICESE, 1977)

5.17 PROSPECCION GRAVIMETRICA Y MAGNETOMETRICA EN EL VALLE DE MEXICALI, B.C. - Informe 5-78 - Razon, A. and Fonseca, H. (1978)

In order to understand the structural conditions of the northern Mexicali Valley, 5 cross-sections were drawn based on gravity and magnetic measurements. Two of these lines are shown in Figures 5-14 and 5-15. The inferred faults show the same alignment as the San Andreas fault system. The most important structures, however, correspond to the Cerro Prieto and Imperial faults; the latter one defined as part of a large horst. Between lines 1 and 2, shown in the figures, the Bouguer anomalies indicate the existence of a NE trending transverse fault.

5.18 GRAVIMETRIC, MAGNETOMETRIC AND SEISMIC REFLECTION STUDIES AT THE CERRO PRIETO GEOTHERMAL FIELD - Fonseca, H. and Razo, A. (1979)

Geophysical studies completed in the Imperial Valley not only indicate the shape and regional strike of the basement of the sedimentary series, but gravity anomalies show a close correlation with high temperature gradient areas. This correlation has been explained by densification due to a complex combination of porosity reduction and metamorphism caused by the elevated temperatures and circulating fluids. Similar conditions seem to exist in the Cerro Prieto field and the Mexicali Valley. Based on a comparison of gravimetric, magnetometric and other data, it was concluded that the seismic reflection method gives the best results for developing a regional model. This method has been used to refine the interpretation of basement configuration and faults.

The magnetic and gravimetric anomalies between the Cucapah Range and the Cerro Prieto and Michoacan fault are similar in configuration. The magnetic anomalies are reported to represent a basement which has not undergone material deposition which would change its potential fields or changes or its physical properties.

Figure 5-14. Magnetic and gravimetric interpretation of Line 1. (From Razo and Fonseca, 1978)

Figure 5-15. Magnetic and gravimetric interpretation of Line 2. (From Razo and Fonseca, 1978)

The gravity highs at Cerro Prieto are associated with the high sub-surface temperatures. Local metamorphism seems to have had an influence on both the Bouguer and magnetic anomalies.

5.19 PRECISION GRAVITY MEASUREMENTS IN THE CERRO PRIETO GEOTHERMAL AREA - Grannel, R. et. al. (1979)

A second gravity data set was collected in 1978-1979 and consisted of the reoccupation of approximately 40 stations established in 1977, as well as the initial occupation of 20 additional stations. This year's data were reduced to observed gravity values, and compared to data from the first year. The differences at the stations proved in nearly all cases to lie within the precision of measurement, indicating that mass and/or elevation changes over a year's interval, if any occurred, are not measurable.

5.20 SELF-POTENTIAL AND RESISTIVITY SURVEYS SOUTH OF THE CERRO PRIETO FAULT - Diaz, S. and Arellano, J. (1979)

In order to determine the geothermal possibilities at the southern end of the Cerro Prieto fault, the Comision Federal de Electricidad carried out exploration studies using self-potential and resistivity methods. In the self-potential survey, consecutive potential differences were measured by means of a 200-m dipole along six SE-NW polygon-closing lines. These lines were between 13 and 30 km long and covered an area of about 600 km² in the southeastern part of the Mexicali Valley.

To determine the regional apparent resistivity of this zone, 110 Schlumberger vertical resistivity soundings were made along the six regional lines, perpendicular to the Cerro Prieto fault. The maximum current electrode spacings used was 10 km. The results of the self-potential surveys indicate a 100 mV positive anomaly, with respect to a

reference station. This anomaly covers an area of approximately 100 km², located south of the town of Guadalupe Victoria, Baja California. On the other hand, according to the configuration of the ground water isotherms of the area, two temperature maxima are observed: 35°C and 45°C, one of which can be correlated with the self-potential maximum. This may be explained from the generating mechanisms of self-potential, electrofiltration, and thermo-electric effects associated with zones of anomalous temperatures.

The electric study and its correlation with the geology of the region indicate that the configuration of the apparent resistivities, at different theoretical depths, show a NW-SE alignment indicating the Cerro Prieto fault. This fault acts as a boundary between two large resistivity anomalies which in general terms show a 0.5 to 15 ohm-m resistivity difference in a SE-NE direction, with a steep gradient at the fault zone. In regard to the low resistivity anomaly southwest of the fault, it is assumed to be caused by the characteristic porosity and salinity effects of the alluvial and coastal sands and silts of the Colorado River delta sediments. The resistivity increase northeast of the fault might result from a reduction in subsurface water salinities because of the influence of ground water flow from the Colorado River.

5.21 INTERPRETATION OF SELF-POTENTIAL DATA FROM THE CERRO PRIETO GEOTHERMAL FIELD - Corwin, R. and Fitterman, D. (1979)

The dipolar self-potential anomaly seen at the Cerro Prieto geothermal field can be generated by heat and/or fluid flowing parallel to a vertical contact separating regions of differing cross-coupling coefficients. Using concepts of irreversible thermodynamics, a model that produces a good fit to the Cerro Prieto data has been found. The source of the anomaly consists of a vertical plane that is buried at a depth of 1.3 ± 0.2 km and has a vertical extent of 11 ± 3 km. The strike length of the plane is 9.9 ± 0.4 km, the intensity of the source

voltage is -344 ± 37 mV, and the electrical conductivity to the east of the plane is 80% of that to the west. (The model parameters may change if the dip of the plane is not vertical.)

The plane may represent a fault or fracture zone that could serve as a conduit for geothermal fluids. A similar self-potential anomaly at East Mesa, California, located about 45 km north of Cerro Prieto and in the same Salton Sea geologic setting, also appears to be related to a major fault zone that is thought to serve as a geothermal fluid conduit.

5.22 A DIGITAL SEISMOLOGICAL TELEMETRY NETWORK AT CERRO PRIETO - Medina, M. and Duarte, C. (1979)

This paper describes a digital telemetry network used at Cerro Prieto field for seismological studies. This system was developed by CICESE (see Section 5.17, this report). The seismic system is used in the detection of micro-earthquakes as an aid in the location of geothermal sources. A discussion of the problems that arose during its implementation is included. A detailed description of the system is also presented.

5.23 EARTHQUAKE MONITORING AT THE CERRO PRIETO GEOTHERMAL FIELD - Majer, E. and McEvilly, T. (1979)

A three-week study in the spring of 1978 revealed moderate earthquake activity (one or two events/day, $M_L \geq 1$) in the Cerro Prieto production zone. A plot of these events on a Wadati diagram yielded an estimate a 0.4 Poisson's Ratio for the upper 1 to 2 km of the field. The events were centered near the western edge of the production zone, near well M-6, and indicated strike-slip movement on north-south faults.

To monitor the earthquake activity and propagation characteristics within the production zone, a five-station, semi-permanent array was put into operation in August 1979. The stations are closely spaced (1-2 km). Each station consists of a three-component 4.5 Hz geophone in a 100-meter well connected to a 12-bit triggered-digital cassette recorder. Although each station operates independently, they are interconnected via a third-wire link to a central site. The purpose of this link is two-fold: first, to allow telemetry of any selected station to the central site for visual monitoring; second, to provide an automatic daily time calibration to keep inter-station errors less than five ms. The data from these stations will be used to monitor earthquake activity and wave propagation characteristics associated with fluid withdrawal and/or injection in the geothermal reservoir.

5.24 SEISMIC STUDIES AND ITS CORRELATION WITH POTENTIAL ANOMALIES -
Reyes, A. and Razo, A. (1979)

Seismicity studies in the region of the Cerro Prieto Geothermal Field have provided a unique data set which gives a strong correlation between the fault system outlined by the epicenter distribution and associated focal mechanisms with gravity, magnetics and resistivity anomalies. The data also indicate that the geothermal field is characterized by local tensional stresses, which allow the circulation of hydrothermal fluids from the deep sources to the surface. The fault systems in the region, as interpreted from the gravity anomalies, are corroborated by the epicentral distribution of earthquakes. The faults have high permeability for hydrothermal circulation.

5.25 Preliminary Studies of Attenuation in the Region of the Cerro Prieto Geothermal Field - Albores, A. et. al. (1979)

A preliminary study of seismic wave attenuation using the seismogram code is in progress using data from the Cerro Prieto digitally telemetered seismic array. The results will be especially important to study the Q distribution in the sediments and in the shallow structure of the Cerro Prieto Geothermal Field. They will also provide a unique data set for the regional values of Q, as well as a means to study the source time function as reflected in the spectra for earthquakes occurring along normal and strike-slip faults.

5.26 MAGNETOTELLURIC STUDIES AT CERRO PRIETO - Gamble, W. et. al. (1980)

Ten magnetotelluric soundings were made near the production zone at Cerro Prieto, bringing to 17 the number of stations occupied in and around the geothermal field during 1978 and 1979. The new soundings provide new information on the geometry of the geothermal system. It was concluded that the current production zone is associated with a significant low resistive anomaly. The shape of this anomaly, in conjunction with the geology of the region, suggests a deep source of heat approximately 4 km south-southeast of the present geothermal power plant.

5.27 RESISTIVITY MONITORING AT CERRO PRIETO - Wilt, M. and Goldstein, N. 1980

Data accuracy from dipole-dipole measurements performed in 1979 was improved to where estimated measurement errors were less than 3%. In addition, data coverage on a line over the field was expanded by 40% for greater depth of investigation and more information on the eastern part of the field. Resistivity modeling of the expanded profile indicates that the resistive body associated with the production zone dips

steeply eastward, and may underlie the eastern part of the field. The model also shows a thin, steeply dipping conductor adjacent to the resistivity body that may be associated with faulting and fluid movement. Model perturbation studies have shown that small changes associated with cold-water influx, fault zone migrations, and foundation of a steam zone would all be detectable with precision dipole-dipole measurements.

CHAPTER 6

ABSTRACTS FROM GEOCHEMICAL INVESTIGATIONS

6.1 INTRODUCTION

Extensive geochemical work has been performed at the Cerro Prieto field. The well fluids have been characterized and compared to the surface emanations. General issues like origin of the brine, recharge of the field, and geochemical evidence of drawdown, and specific subjects like silica in the brines and gases in steam have been reported or are in progress. This chapter presents summaries of reported work and preliminary results of current projects.

A number of small hot springs and other surface manifestations are found at the Cerro Prieto geothermal field. These manifestations were first described by A. Calderon in 1958, and that paper is discussed in Chapter 4.

Between 1962 and 1974 the geochemical studies at Cerro Prieto were conducted primarily by S. Mercado of the Comision Federal de Electricidad (CFE). A. Manon is responsible for the geochemical work done by CFE since 1975. In 1977, with the beginning of the International Cooperative Agreement, a number of scientists from the U.S. became involved in specific facets of Cerro Prieto geochemistry. Mercado developed a geochemical model in 1968 and expanded it in the early seventies as the database improved. The joint-papers published from 1975 to the present are abstracted in this report. In addition, several hydrology studies were performed in the Mexicali Valley in the early and mid-seventies and they also are abstracted.

The surface manifestations at Cerro Prieto have decreased in intensity since exploitation of the field commenced. The activity consists of hot springs, large mud volcanoes, muddy bubbling ponds, occasional phreatic eruptions, fumaroles, and pools with little or no flow (Figure 6-1).

6.2 EARLY GEOCHEMICAL INVESTIGATIONS OF S. MERCADO

The first comprehensive chemical study of the field was performed by S. Mercado in 1968. At that time nearly 20 production-exploration wells had been drilled and the fluids were sampled. The spring and pond waters were in general chemically similar to the geothermal reservoir fluids.

Variations in surface manifestation chemistry were considered to be the result of:

- o Evaporation in the ponds,
- o Dilution by meteoric water stored in surface layers, and
- o Recirculation of fluids through very permeable zones.

The flow of most springs ranged between 10 and 80 liter/min and had a fairly uniform chemical composition over the entire field: Cl $\approx$ 8000-9000 ppm, Na $\approx$ 4000 ppm, K $\approx$ 600 ppm, Li $\approx$ 11 ppm, Ca $\approx$ 400 ppm, Mg $\approx$ 50 ppm, and HCO₃ $\approx$ 400 ppm.

Once data were available for the spring and wells, Mercado compared various chemical ratios for the surface and well fluids with measured well temperatures and pressures. When the chemical ratios in the springs were studied it was noted that low Na/K and high Cl/SO₄ ratios corresponded with more intense hydrothermal activity and the distribution of those indicative ratios seemed to outline one north-east-southwest fault and a northwest-southeast structure. The main faults follow this northwest-southeast trend and secondary fractures are generally perpendicular to the major faults. Points of maximum surface activity are located at or near the fault intersections.

Figure 6.1 Location map of the surface emissions of Cerro Prieto geothermal field.

Two zones had intense surface activity, one to the southwest and the other northwest of the field near the Cerro Prieto volcano.

Wells 5, 8, 15, 20 and 21 had the highest pressure and temperature in 1968. These wells also had very high Cl/SO_4 ratios. Two springs just south of these wells were characterized by very high Cl/SO_4 indices.

The 1968 Mercado report contributed further geochemical observations based on gases sampled at the well heads and Na/K ratios of the geothermal fluids (Figure 6.2, $U = \text{Na}/\text{K}$ index). Variations in the composition of the gases indicated zones of maximum geothermal intensity at depth. The $\text{CO}_2/\text{H}_2\text{S}$ index for wells with high and medium pressures were 2 to 3. Fumaroles close to those wells with high and medium pressures were 2 to 3. Fumaroles close to those wells had indices of 3 to 4. The well with the lowest pressure at that time, M-6, showed a high and variable $\text{CO}_2/\text{H}_2\text{S}$ ratio, between 10 and 50, and fumaroles a short distance from that well had $\text{CO}_2/\text{H}_2\text{S}$ indices around 100.

The distribution of Na/K at Cerro Prieto can be related to bottom hole temperature and discharge pressure. An area having Na/K index of 6 had bottom temperatures near 350°C and discharge pressures from 40 to 60 kg/cm^2 . A zone along the southwest edge of the field with an index of 16 had low temperature, 150°C , and low pressure, 3 kg/cm^2 . This observation was based on data from wells 5, 6, 8, 9 and 10 (Figure 6.3).

By 1970 Mercado had more well data and the correlation between low Na/K ratios and high temperatures was considered established. One particular well, M-20, was studied in detail. During the development of the well, chemical and physical changes occurred that were related to changes in size of the discharge orifice. As the orifice diameter increased, the well head pressure and the pressure at the bottom of the well decreased. The decreased pressure in the well allowed cooler fluids with higher density from strata at higher elevations, above the

Figure 6.2 Na/K distribution in underground drill hole flow,
 u = Na/K index (1300 meters maximum depth). (Mercado, 1970)

Figure 6.3 Flow and Na/K distribution. (Mercado, 1968)

slotted liner, to flow down through the annular space between the center pipe and the well wall. The study of M-20 showed a cooler water zone between 800 and 1000 m depth. Most of the wells (M-5, M-8, M-15, M-21 and M-26) produce from strata at 1100 to 1500 m.

The Na/K ratios were derived from calculated enthalpies. The orderly distribution of the Na/K index in the various strata suggested that connections exist between them. These connections were probably fractures between the layers of impermeable shale and porous sandstone. Some later drill holes at Cerro Prieto were located near surface manifestations with low Na/K indices.

In 1974-75 30 wells were considered producers out of 37 drilled. The producing layers varied from well to well between depths of 600 and 900 m, 1300 and 1600 m, and in the deepest well, between 1800 and 2000 m. Two 37.5 MW turbines had been operating for two years in 1975. A newer model of the field included the movement of the fluids and temperature distribution. Mercado (1975) concluded the following:

- o The hot fluid moved horizontally from the eastern and central zones and then ascended to the western part of the field. Fluid migrates through permeable sand and sandstone layers below the thick clay which forms the cap rock.
- o The heat source is probably deep in the eastern part of the field, because of the gradual temperature increase in that direction.
- o There is a zone of recharge west of the field in the saturated, pervious alluvial fans of the Sierra Cucapas.

- o A second recharge area is located toward the eastern part of the field where water from the Colorado River feeds the reservoir. The amount of water is less than the recharge from the Sierra Cucapas because there are only a few layers of moderate permeability in the eastern area.

Mercado noted that a high yield well, MT-53, with a temperature of 340°C at 2000 m depth, had a Na/K index of 4.5 and was apparently closer to the heat source. As the geothermal fluid migrates away from the heat source, the Na/K ratio increases.

He concluded that new exploration-production wells should be sited by considering existing wells and surface manifestations with low Na/K indices.

6.3 COMPLETE HYDROGEOLOGIC SURVEY OF THE AQUIFERS IN THE MEXICALI VALLEY, B.C., AND SAN LUIS MESA, SON. - ARIEL CONSTRUCCIONES, S.A., (1968)

This report presents the regional setting of the Cerro Prieto geothermal area. It is not oriented towards exploration studies of that field, but is a discussion of ground-water resources in an irrigation district in the general region.

The Mexicali Valley is a rift valley, which has been filled mainly by continental sediments deposited by the Colorado River. The Cucapas and El Mayor Sierras are the western boundary of the Mexicali Valley. The Sierras are a mountainous complex of granite, schist, limestone, and quartzite, formed by tectonic upthrust, and bounded by faults on its sides. This complex is considered to be a barrier to the movement of ground water. Basaltic rocks form the Cerro Prieto volcano, which rests discordantly on fine sand and recent silts. Extensive fracturing allows excellent surface infiltration.

Deltaic or flood plain deposits consist mainly of clays, silts, sands, and gravels in the Mexicali Valley. Silt layers alternate with fine quartz sands to the north and south of Cerro Prieto. Wells in and near the Cerro Prieto settlement show fine clastics predominating and alternating with lesser clays and small lenses of sands and gravels. Old alluvial terraces surround the low parts of the Cucapas and El Mayor Sierras. These deposits provide good access to the subsurface for surface infiltration. In addition, old channel and meander deposits are located in the central and southern portions of the valley and have an intermediate capacity for surface infiltration.

Several irrigation wells near the Cerro Prieto field are artesian, and two contain water of higher than ambient temperature.

Ground-water levels for November 1967, March 1968, and November 1968 showed that recharge to aquifers located within the irrigation well zone studied around the Cerro Prieto field was mostly derived from the northeastern region, or from the Pilot Knob and Yuma Mesas, Arizona, and from the San Luis Mesa in the northeastern Mexicali Valley. Ground-water flows to the west in the north part of the valley; another flow direction approximately follows the north-south course of the Colorado River.

6.4 HYDROGEOLOGIC EVALUATION OF THE CERRO PRIETO GEOTHERMAL SYSTEM UTILIZING ISOTOPIC TECHNIQUES - CROSBY, J., CHATTER, R., ANDERSON, J., AND FENTON, R. (1972)

This report describes a detailed study of the hydrology of the Cerro Prieto geothermal field and the Mexicali Valley. The deuterium content of the geothermal fluid indicates the fluid is of meteoric origin, probably from the ancient Colorado River and local precipitation. The principal area of ground-water recharge is related to the location of the channel and distribution of the upper Colorado River in Mexico.

Accelerated discharge from the geothermal field might eventually cause recognizable ground-water declines in the Mexicali Valley Area. The flow regime in the study area is essentially one of lateral flow. The bulk of ground-water recharge is derived from the Colorado River and associated canal system. This may be augmented occasionally by snow-melt or torrential rains which drain into the alluvial plain from adjacent mountains. The latter is decidedly limited in quantity and has little effect upon the general ground-water flow system. Faults on the western part of the valley comprise the principal zones of ground-water discharge and movement of waters toward the geothermal field and their subsequent discharge. Also, near-surface aquifers may be recharged from leakage from irrigation canals or by deep percolation of applied irrigation waters. Ground-water temperature data southeast of the Cerro Prieto field is thought to indicate an extension of the field.

6.5 EXTENSIVE GEOCHEMICAL STUDIES IN THE GEOTHERMAL FIELD OF CERRO PRIETO, MEXICO - A. MANON, E. MAZOR, M. JIMENEZ, A. SANCHEZ, J. FAUSTO AND C. ZENIZO (1977)

This paper presents chemical data on the wells and surface manifestations at Cerro Prieto. Variations in ion concentrations from well to well and time-dependent concentration variations in individual wells are discussed. A working geochemical model of the field was developed as well as a number of conclusions about the chemical nature of the field. The paper contained a summary of geochemical studies at Cerro Prieto performed since the early seventies but most of the information was generated after exploitation commenced in April 1973.

The authors summarized the geology of the field and reported that the thermal waters travelled through sandstone, shale, silt, and volcanic gravel. The common minerals are quartz, feldspars, and mica; calcite is frequently a cementing agent. Pyrite is often disseminated in the

rocks, and chlorite, dolomite, kaolinite, montmorillonite, illite, and epidote were observed by Reed (1975) in drill cores. The geothermal fluid is in contact with these minerals.

Analytical methods and estimated errors in the chemical analyses were considered. Deviations of the individual data points from a regression line were considered to be the result of analytical errors and natural variations. Hence, wells with the best linear fits were considered the most appropriate to use, assuming that natural deviations were minimal and that analytical errors were the same for all wells.

An overall view of the field was obtained by comparing the composition of the most concentrated sample from each well. Chemical data from twenty-seven wells were available at that time (Table 6.1).

The composition of the wells in the main field (i.e. from Well No. 51 to Well No. 3) are approximately the same. The major variations seen were due to a large range of $\text{HCO}_3 + \text{CO}_3$ concentration. Differences in chemical composition for wells away from the main field suggest different tectonic blocks.

The authors noted that diameter changes in the wellhead orifice discharge pipe at the time of sampling produced variations in ion concentrations.

Areal variations in the field were noted for Cl and SiO_2 concentrations and Na/K ratios. The center of the producing field was characterized by high Cl and SiO_2 values and fairly low Na/K ratios. This pattern might be related to higher enthalpy values in the center of the field.

Gas contents in the wells showed a positive correlation between CO_2 and H_2S and between H_2S and the calculated well temperature. These correlations suggested a steam and gas phase existing in the field, occasionally contributing excess steam, CO_2 , and H_2S to some wells

under certain producing conditions. The authors suggested that a likely location for such steam would be above the brine zone but below the sealing cap rock. They reported that Truesdell originally suggested the possibility of a steam cap because of the differences between the SiO_2 geothermometer temperatures and temperatures determined by enthalpy measurements.

TABLE 6.1

WEIGHTED COMPOSITION OF THE MOST
CONCENTRATED SAMPLE OF EACH WELL, mg/l

Well	Na	K	Na/K atomic	Li	Ca	B	HCO ₃ +CO ₃	SiO ₂	Cl
1A	4,400	500	11.5	11.8	230	8.8	50	250	7,700
3	7,500	1,500	7.0	20.0	400	12.0	80	650	12,000
7	6,000	1,400	7.3	15.5	300	13.0	200	500	10,300
6	4,500	470	16.2	17.0	620	7.0	1,000	155	8,200
53	8,300	2,800	5.0	-	350	-	-	1,250	17,300
11	8,600	2,230	6.6	28.0	550	20.0	40	900	16,700
42	6,100	1,470	7.0	17.5	380	-	-	-	11,600
38	8,100	2,000	6.8	23.0	380	17.0	50	850	14,300
39	6,400	1,100	10.0	16.0	420	14.0	50	650	12,100
10	5,500	1,700	5.5	18.0	350	14.5	300	680	10,600
13	8,800	2,400	6.3	26.0	450	18.0	50	1,050	16,200
15	3,200	270	20.0	-	40	-	-	-	5,200
15A	7,400	1,580	8.0	18.0	430	-	20	800	13,500
5	9,900	2,350	7.2	30.0	580	22.0	60	1,000	17,900
19A	8,700	2,180	6.8	24.0	550	-	-	-	17,000
20	8,300	2,000	7.0	26.0	500	14.0	200	950	15,500
25	9,200	2,000	7.8	28.0	600	-	50	950	17,000
21	7,000	2,050	5.7	19.5	300	16.0	100	800	13,000
21A	12,500	3,150	6.7	30.0	760	-	40	960	21,400
26	9,800	2,400	6.9	30.0	850	14.0	50	950	18,700
29	7,100	1,360	8.8	21.0	500	13.0	50	470	13,100
30	9,600	2,500	6.5	30.0	600	-	40	920	17,800
27	9,000	2,600	6.5	-	950	-	-	-	18,000
8	9,900	2,600	6.4	30.0	500	17.0	60	900	16,400
31	8,700	2,200	6.7	29.0	550	14.0	60	900	16,300
35	9,500	2,600	6.2	25.0	550	-	40	1,030	17,100
51	8,500	2,400	5.9	28	420	-	-	1,030	15,900

The authors concluded that the Cerro Prieto chemical data showed regularities and correlations which were not random. The trends produced a "working model" which is summarized here:

- o One type of brine has to be assumed to explain the manifestations encountered in the producing wells and in Wells 1A, 3, and 7, that are located to the north in the same tectonic block.
- o Wells 6 and 53 are located in different blocks, bordering the block of the producing field. Their chemical composition is different, possibly reflecting differences in the chemistry of the brines of each major tectonic block.
- o Modifications in the chemical composition of individual wells in the producing field may be caused by:
 - Steam losses or gains causing concentration or dilution respectively.
 - Production from different temperature zones reflected by lower contents of SiO_2 and K due to reequilibration with aquifer rocks (hence, higher Na/K ratios).
- o Existence of a steam and gas cap at the upper part of the fluid system, below the clay sequence. Various additions of steam and gas to different wells may explain the observed positive correlation between CO_2 , H_2S , and well temperature.
- o The temperature-dependent reactive species, such as K and SiO_2 , reequilibrate to the temperatures prevailing in the various temperature zones of the system, but they have no time to reequilibrate in response to changes caused during ascendance in

the wells. The Na/K geothermometer reflects conditions at the well bottom and is not shifted by steam loss and other production-induced processes.

- o The original brine at depth apparently has a Cl content of around 10,000 mg/liter. The samples with higher chloride content underwent different degrees of steam loss. The few samples with less than 10,000 mg/liter Cl may have been diluted either by shallow fresh water intruding a well or by condensed steam.
- o The brines interact with aquifer rocks as revealed by the occurrence of secondary minerals in the cores and cuttings. These reactions mainly involved the reactive species, e.g., SiO_2 , K, and Ca.

In 1978 a number of papers on geochemistry were given at the First Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico, held in San Diego, California. These papers included a refinement of the field geochemical model (Manon, et al. 1978), isotopic studies of the well fluids (Truesdell, et al. 1978), gas chemistry and helium isotopes (Welhan, et al.), gases in steam (Nehring and Fausto 1978), and geochemical evidence of drawdown (Truesdell, et al. 1978). These studies advanced understanding of the geochemical processes at Cerro Prieto and further characterized the reservoir fluids.

6.6 PRELIMINARY GEOCHEMICAL MODEL OF THE CERRO PRIETO GEOTHERMAL FIELD - A. MANON M., A. SANCHEZ A., J. J. FAUSTO L., M. E. JIMENEZ, S., A. JACOBO R., AND I. ESQUER P. (1978)

This study supported suggestions that there is a cold-water recharge from the north and west of the main producing field at Cerro Prieto. Na-K-Ca values in the center of the field are quite irregular, possibly

due to the effect of downward percolation of colder waters caused by over-exploitation. The temperature distribution in the reservoir aquifer also supports this conclusion, as does the chloride distribution in the hot water aquifer.

The study of temperature distribution in the field indicated a high temperature anomaly from around Well M-45 eastward to Well M-181, coinciding with the fault line shown in geological cross sections. It also coincides with a line of springs, which is interpreted as an area of much fracturing with little vertical displacement. The authors have suggested this anomaly represents recharge to the present field by an ascending flow of hot water.

Changes in aquifer chemical constituents have been observed since exploitation commenced. It was recommended that the production of low enthalpy wells be suspended and be replaced by new wells located in the periphery of the field, preferably to the southwest and northeast. Two aquifers feeding the producing wells were identified in the field. It was also recommended that the deeper aquifer in the center of the field be exploited to prevent the vertical flow of cooler water recognized in some of the wells.

6.7 PRELIMINARY ISOTOPIC STUDIES OF FLUIDS FROM THE CERRO PRIETO
GEOTHERMAL FIELD - A. H. TRUESDELL, R. O. RYE, F. J. PEARSON, JR.,
E. R. OLSON, N. L. NEHRING, M. A. HUEBNER, AND T. B. COPLEN

Oxygen-18 and deuterium have been demonstrated to indicate water origin and the degree of water-rock interaction occurring at high temperatures. The results of these techniques applied to Cerro Prieto were reported in this paper.

Preliminary interpretation of the results has suggested that the Cerro Prieto hot water probably originates from partially evaporated Colorado River water and not from local rainwater or seawater. Recharge to the system also may have occurred along a narrow zone running north from Mexicali, passing just west of the field and curving northeast to Mesa Arenosa on the east. This recharge model agrees with the model of Mercado (1975), and suggests that if recharge is from the part of this zone closest to the field then the thermal fluids are of very local origin and little lateral movement of the fluid has occurred.

The pattern of ^{18}O in well discharge in the field in 1977 showed that water in the central part of the field underwent less oxygen isotope shift than waters at the margins. This pattern is similar to the pattern of change in chloride concentrations observed during 1973-74 and 1977-78. After flashing of fluids from the central part of the field, chloride concentrations are reported to have decreased by as much as 5,000 ppm. The changes could be the result of drawdown of fluids into the production aquifer from a lower temperature, lower salinity aquifer closer to the surface.

Radioactive isotopes in Cerro Prieto waters indicate the average age of the fluid is probably between 50 and 10,000 years. Carbon in CO_2 from the thermal fluids suggests a magmatic or juvenile origin. Some of the CO_2 , however, may result from thermal metamorphism of aquifer carbonates to calc-silicate minerals. Sulfate isotope compositions also suggest a magmatic origin but a mixed sedimentary-organic origin is suggested to be more likely for carbon and possibly sulfur.

6.8 GAS CHEMISTRY AND HELIUM ISOTOPES AT CERRO PRIETO - J. A. WELHAN,
R. POREDA, J. E. LUPTON, AND H. CRAIG, SCRIPPS INSTITUTION OF
OCEANOGRAPHY, LA JOLLA, CA, USA

Gas was analyzed from seven producing wells and seven hot springs. Isotope ratios also were determined.

The geothermal well gases were quite uniform in composition and helium isotope ratios, showing high $^3\text{He}/^4\text{He}$ ratios characteristic of mantle derived helium. Higher than expected N_2/Ar ratios in the wells suggest that the deep gas component in the field becomes diluted with crustal helium and dissolved air as the gas rises to the surface. The gases either re-equilibrate chemically at lower temperatures or are mixed with methane of organic origin near the surface to yield higher CH_4/H_2 ratios.

6.9 GASES IN STEAM FROM CERRO PRIETO GEOTHERMAL WELLS - N. L. NEHRING
AND J. J. FAUSTO I. (1978)

Steam samples were collected for gas analysis in April, 1977. Major gases and gaseous hydrocarbons were determined.

Hydrocarbon gases in Cerro Prieto steam are compared to the hydrocarbons in steam from Larderello, Italy and The Geysers, California. Those reservoirs, although both vapor-dominated, have sedimentary aquifer rocks, although the lithologies are different. Hydrocarbons from sedimentary geothermal aquifers are characterized by the presence of branched C_{4-6} compounds and a lack of unsaturated compounds other than benzene. The authors suggested that high benzene content may be characteristic of high-temperature geothermal systems. All hydrocarbons other than methane probably originate from the thermal metamorphism of organic matter contained in the sediments. Methane was considered to originate mostly from the reaction of hydrogen and CO_2 in the presence of liquid water.

6.10 GEOCHEMICAL EVIDENCE OF DRAWDOWN IN THE CERRO PRIETO GEOTHERMAL FIELD - A. H. TRUESDELL, A. MANON, M. E. JIMENEZ, A. SANCHEZ AND J. J. FAUSTO (1978)

Some producing wells at Cerro Prieto have undergone changes in fluid chemistry which reflect reservoir processes. The producing aquifer has a temperature between 280-300°C with about 9,000 mg/kg chloride. When the fluid flashes to one atmosphere the chloride in the residual brine increases to around 16,000 mg/kg.

Changes in chloride concentration patterns indicated drawdown in the southeastern part of the field. In 1973-74, shortly after the start of production, the field was relatively unaffected by fluid withdrawal. Cl content was fairly uniform at 15,000 to 17,000 mg/kg over an area extending 500 m east-west and 1,500 in north-south. Cl concentrations decreased to 10,000 to 12,000 mg/kg toward the northeast and southwest. By 1977-78 little change had occurred in the wells to the northwest but chloride in wells to the southeast decreased by up to 5,000 mg/kg. This change appears to have been caused by drawdown, with lower salinity brines entering the southeastern part of the producing aquifer from above. In June, 1977 a pattern of excess aquifer steam, as indicated by differences between enthalpy-derived and silica geothermometer temperatures, was similar to the pattern of decreased chloride concentrations (Table 6.2).

Individual wells were studied in the southeastern part of the field for changes in chloride concentration, Na/K ratio and measured enthalpy of fluids from individual wells. It was reported that when excess steam occurs in an aquifer and enters a well, measured enthalpy can increase but Na/K ratios will continue to show the temperature of the brine and steam entering the well bore. Brine flashing in the well and in the separator produces increased chloride concentrations in the residual brine which depends on the enthalpy (and also temperature) of the brine

and not on the enthalpy of the whole fluid. It was tentatively concluded that at Cerro Prieto the Na/K geothermometers are more accurate in indicating aquifer fluid temperatures than enthalpy or silica content.

The authors concluded that pressure decreases due to production in the southeastern part of the field have produced both drawdown of lower chloride fluids from an overlying aquifer and boiling in the aquifer with excess steam reaching the wells. Fluid temperatures were not greatly affected by this drawdown because heat contained in the rock was transferred to the fluid. It was suggested that when this heat is exhausted, fluid temperatures could drop rapidly.

TABLE 6.2

OBSERVED AND CALCULATED AQUIFER TEMPERATURES AND CALCULATED AQUIFER
CHLORIDE CONCENTRATIONS FOR CERRO PRIETO WELLS M-5, M-26, M-21A & M-11
IN 1972-74 AND 1977-78*

Well	Date	Aquifer Temperatures, °C Calculated From					Aquifer Chloride, mg/kg Calculated From			
		measured	enthalpy	SiO ₂	Na/K Mercado	White Ellis	enthalpy	SiO ₂	Na/K Mercado	White- Ellis
M-5	1/74		312	288	316	311	8,660	9,580	8,490	8,980
	6/77	299	281	299	304	301	9,680	9,020	8,550	8,940
M-26	1/74		291	282	314	309	10,600	11,000	9,644	9,870
	6/77	292	285	278	293	292	7,820	7,970	7,532	7,560
M-21A	1/75		362	272	320	314	7,300	12,200	10,000	10,300
	6/77	279	307	280	316	311	9,020	10,100	8,630	8,900
M-11	1/74		276	272	292	291	9,960	10,100	9,380	9,420
	6/77	281	295	287	315	310	9,450	9,750	8,650	8,850

- * Silica and Na/K temperatures were calculated using geothermometer scales from references 4-6. Downhole temperatures are from Eng. F. J. Bermejo (unpublished data, 1977) and were measured in 1976-1977. Data are given for 1/74 and 6/77 except for Well M-21A for which the initial data is from 1/75. Only analyses of fluid samples from production separators were used in calculations although all data are shown in Figures 5-8. Temperatures calculated from enthalpy, Na/K and silica values are from averaged data and are not exactly the same as calculations in reference 4 which were taken from single analyses. (From Truesdell, et al., 1978).

6.11 GEOCHEMICAL INDICATIONS OF BOILING IN THE AQUIFER OF THE CERRO PRIETO GEOTHERMAL FIELD - A. TRUESDELL AND A. MANON (1978)

This study discussed two major points: 1) the recognition of boiling in a thermal aquifer and implications for a producing geothermal field and 2) the detection of aquifer boiling at Cerro Prieto by geochemical methods.

Flashing (boiling) in high temperature, hot-water geothermal fields generally occurs in the well bore and in the surface separators. However, at Wairakei and Broadlands, New Zealand it has been determined that some flashing occurs in the aquifer and a two-phase steam-water mixture enters the well. The primary mechanism for this behavior is drawdown of aquifer pressure which induces boiling in the aquifer and results in the formation of steam and cooling of the remaining water. The transfer of heat from the reservoir rock to the cooled water can produce additional steam. Enthalpy at the well head is increased if phase separation occurs in the aquifer and may differ significantly from the original enthalpy of the liquid water in the reservoir before boiling.

The silica content of wells at Cerro Prieto was used to detect changes in aquifer temperatures. The original silica content of the unflashed liquid in the aquifer was determined and compared with the solubility of quartz in flashed liquid to predict the original aquifer temperature.

Temperatures derived from enthalpy, silica, and downhole measurements were compared. For most of the Cerro Prieto wells these temperatures did not differ significantly or show much excess steam content. However, Wells M-8, M-20 and M-31 had large quantities of excess aquifer steam based on enthalpy-derived subsurface temperatures, which were greater than measured and silica geothermometer temperatures.

Under shut-in or low-flow conditions aquifer pressures may recover enough to prevent boiling and rock near the well may be reheated by hotter water drawn from outside the zone of pressure decrease. However, rock cooled by continued boiling cannot be rapidly reheated because the heat content of the rock is greater than the heat content of the fluid that permeates the rock under most conditions of rock porosity.

6.12 THE ORIGIN OF THE CERRO PRIETO GEOTHERMAL BRINE - TRUESDELL, ET AL.
(1980)

The origin of the Cerro Prieto geothermal fluid and the processes involved in establishing its present composition have been determined by a number of studies. "Conservative" substances, such as deuterium, chloride, and bromide were used because their concentrations are not greatly affected by high temperature interactions with ordinary rocks. Before these tracers could be used at Cerro Prieto it was necessary to determine their concentrations in the geothermal aquifer and in their possible sources.

Based on isotopic data, elemental ratios, and Na-K-Ca geothermometers, the authors believe that the Cerro Prieto waters are a mixture of Colorado River water and a saline brine of marine origin, possibly derived from evaporation in lagoons or sabkhas. This mixture circulated to depth and was heated by conduction from hot rock or magma associated with volcanism at Cerro Prieto.

CHAPTER 7

GEOHERMAL FIELD MODELS

7.1 INTRODUCTION

Conceptual geothermal field models were drawn on completion of various explorative stages in order to obtain a better understanding of processes and structures existing within the Cerro Prieto field. Even though the early models are based almost entirely on results from one specific study such as geology or geochemistry, the latter ones incorporate all previous investigative work along with recently acquired data.

The Cerro Prieto geothermal field subsurface is shown in the included figures, as it was visualized in 1964, 1968, 1974, 1975, 1978 and 1979. The exploration methods used to derive such models, along with other pertinent data, are described in the following sections.

7.2 MODEL 1

This field model was developed by Alonso and Mooser in 1964 from studies of 3 exploratory wells, geological studies concerning volcanism and regional structure, and some gravity, seismic refraction, and geochemical analyses. Tectonic activity in this area of the Mexicali Valley produced block faulting and as a result Sierra Cucapas is 600 m lower than Sierra de Juarez, as shown in the figure. Cerro Prieto volcano is located within a fracture system and is believed to have originated from a fracture intersection. Seismological studies, performed approximately 10 km south of Cerro Prieto volcano, revealed a basement lying at a depth of 1700 m, west of a major fault. The basement was not detected east of this fault. Alluvial deposits overlie the granitic basement, as concluded from the low seismic velocities.

7.3 MODEL 2

This model of the Cerro Prieto field is based on drillhole lithologies, temperatures and Na/K ratios from approximately 20 wells. Mercado (1968) noted that low Na/K ratios correlated with high bottom hole temperatures and high discharge pressures in wells. Lithology and fluid geochemistry from these wells, along with chemistry from surface manifestations, were integrated to form this model. The following conclusions were derived about subsurface processes from this model:

- o The energy supply through magmatic gases is probably located between Wells M-5 and M-10 (low Na/K indices and high temperatures), and may indicate a zone of intense fracturing.
- o A clay layer approximately 700 m thick acts as the cap rock and forces the thermal fluids to migrate horizontally.
- o Thermal fluids migrate toward Well M-6, due to the stratification and high permeability of the sandstones. In the deep, high temperature zone near Well M-10, the permeability is low.
- o Variations in the Na/K index were useful in determining the direction of feed water, which is considered to come from the northwest and probably the Colorado River.

7.4 MODEL 3

This model was developed in 1974 by Soto Pineda. Results from geological investigations, which include subsurface information from 39 wells, were correlated with geochemical and geophysical results. Clays and loose sand prevail to a depth of 700 m; shale and sandstone layers are then observed from this depth down to approximately 1500 m with gravels frequently encountered in the entire section. The Imperial and San

Figure 7-1. Model 3. Geological section and partial view of the Mexicali Valley, B.C. (From Soto, 1974)

Jacinto faults pass through this area, as determined from geophysical surveys. The block structure of the region may influence the movement of thermal fluids. The basement structure and depth were determined from seismic refraction surveys.

7.5 MODEL 4

In 1975 all the available information was interpreted and correlated by Paredes (1975) to obtain a complete picture of the structural geology of Cerro Prieto geothermal field. Data were furnished by geological, geochemical, and geophysical exploration methods, which include temperature logs, electric and combination logs (such as SARABAND*), and drilling records from 30 wells. The resulting field model shows the structure and lithology of the drilled area. It was concluded from this study that:

- o The Cerro Prieto field is part of the Mexicali geothermal province.
- o The area has undergone intense fracturing.
- o The prevailing fault system trends NW-SE.
- o A secondary fault system is related to the San Jacinto fault.
- o Heat, water, and gases from depth are flowing through faults and fractures in the shales and sandstones and affecting the connate water of the sandstone.
- o A large igneous mass probably lies at shallow depth in the Mexicali Valley.

* Trademark of Schlumberger

7.6 MODEL 5

Puente and de la Pena refined the previous field models in 1978 and presented their new model at the First Symposium on the Cerro Prieto Field. Though similar to the model previously drawn by Soto in 1974, this new model differs considerably, especially with the pronounced horst shown under the Laguna Volcano area. From 12 geological cross-sections of the geothermal field correlated with seismic refraction studies, the model shown presents a more accurate location of the granitic basement and the overlying sedimentary formations. These sediments are classified as unconsolidated (upper formation) and consolidated (lower formation). A principal fault system, designated as the Cerro Prieto System, trends NW and parallels major faults such as Imperial, San Jacinto and San Andreas. A secondary fault system, designated as the Volcano System, trends SW, and along with the former system creates a series of the step faults shown in the figure.

7.7 MODEL 6

This model was published in a 1979 CFE report, Field Trip to Cerro Prieto Geothermal Field, by Instituto de Investigaciones Electricas (IIE). The figure resembles the previous models since it is based almost entirely on the same subsurface data used for the other models. One noticeable change, however, is the location of the Cerro Prieto fault, which in this model passes near Cerro Prieto and Laguna Volcano. The sedimentary formations and granitic basement structure is similar to the previous models and merit no further explanation.

Further discussions about geothermal field model components are presented in Chapter 8.

Figure 7-2. Model 5. Geologic cross-section (From Puente and de La Pena, 1978)

CHAPTER 8
CFE/DOE/LBL
GEOTHERMAL FIELD MODEL

8.1 INTRODUCTION

Further concepts and conclusions regarding the Cerro Prieto geothermal field were discussed during an informal DOE/CFE workshop in March 1980 at the Vallambrosa Center, Menlo Park. A review of this information is presented in this section.

8.2 GEOLOGY

The Cerro Prieto fault zone lying on the west side of the field is believed to act as a field boundary rather than one which channels thermal fluids. Well M-6 lies within this fault zone, as shown in Figure 8-1, and appears to be connected to the main production area, east of this fault. Also noticeable in Figure 8-1 are the Hidalgo, Patzcuaro and Delta faults, which constitute the Volcano Fault System. It is this system which acts as the conduit to fluid flow, especially where it intersects the NW-SE fault system. The Morelia fault, shown north of the field, is considered to be part of the northern (leaky) boundary. It was concluded that hot water flows from E-SE to W-NW at some depth while cold water inflow from the Colorado River recharges the reservoir from the northeast.

8.3 GEOPHYSICS

Positive magnetic and coincident gravity anomalies 9 km northeast of Cerro Prieto volcano, shown in Figures 8-2 and 8-3, are caused by a shallow magnetic basement in this area. South of Cerro Prieto volcano,

Legend

- Simplified isotherms (for variable depths).
- Faults, markings on down-dropped side
- Surface manifestations

Figure 8-1. Faults and isotherms map.

Figure 8-2. Magnetic anomaly map of Cerro Prieto area. (Razo and Fonseca, 1978)

Legend

●	Gravity Station		Inferred fault		Highway
	Isogals (in mgals)	+	Gravity high		Railroad
	Geothermal Well	—	Gravity low		

Figure 8-3. Bouguer gravity anomaly map of Cerro Prieto area (Razo and Fonseca, 1978)

the thick sedimentary sequence causes low magnetic and gravity anomalies. Seismic reflection data support this interpretation. A "ridge-like" gravity high extending southeastward from Well M-96 is probably due to densified shales underlying the upper sedimentary formation. LBL scientists have found no clear evidence of the horst structure purported to underlie the existing production area.

A. Self-Potential Surveys

A large dipolar SP anomaly passing through the production area is caused by a combination of fluid flow and a temperature gradient. It was concluded from these surveys that one or more faults of the NE trending Volcano System provide the main conduits for ascending thermal fluids.

B. Electrical Resistivity Studies

Unlike geothermal fields in volcanic terrains, the Cerro Prieto field is best correlated with resistivity highs. Hydrothermal metamorphism due to circulating fluids has reduced porosity of shale units underlying the upper sedimentary formation, thus creating the electrical anomaly. Resistivity lows which occur near the field are explained by (1) marine sediments containing saline pore fluids, or (2) near-surface thermal manifestations, offset laterally from the reservoir. It was concluded that a drilling program based only on tests of low resistivity zones would have incurred costly mistakes.

Interpretation of dipole-dipole surveys show a number of iso-resistivity blocks which cross-cut lithologies and whose distribution is strongly controlled by pore fluid salinity. Colorado River water (high resistivity) at the surface, mixing westward and downward with connate (low resistivity) water in the sediments. Thus, Colorado River water may provide recharge to the deep reservoir.

C. Seismic Reflection Studies

Seismic reflection surveys have not been as helpful as gravity for defining basement configuration but they have provided corroborative data. A combination of factors have contributed to the resolution problems with seismic refraction. They are listed below:

- o Energy scattering due to non-uniform hydrothermal alteration effects.
- o Reduced reflectivity of the densified shales by a vapor phase within.
- o Complex faulting.
- o Energy absorption in the near-surface hydrothermally altered zone over the reservoir.

8.4 GEOCHEMISTRY

Based on isotopic data, zones of recharge and discharge are defined as shown in Figure 8-4. The fluid flow model is quite similar to that envisioned by Mercado in 1968. Hot fluid originates in the eastern part of the field and spreads to the west and southwest, as indicated by the temperature isotherms shown in Figure 8-1. The original waters have 9500 ppm chloride content and 300°C temperature at depth. The reservoir brines appear to result from a mixture of 10% evaporated sea water and 90% Colorado River water. Sediments underlying the upper formation show an increase in secondary porosity caused by destruction of CaCO_3 over SiO_2 . It is therefore concluded that secondary porosity controls the fluid flow in the area east of the railroad track, while fracture porosity prevails in the producing area to the west.

CHAPTER 9

SUMMARY OF EXPLORATION METHODS AND RESULTS

Geothermal potential in the Cerro Prieto area was first determined by drilling in the early 1960's.

Geologic mapping and areal photography studies revealed several major northwest-southeast faults and some minor northeast-southwest structures through the Cerro Prieto volcano (Alonso, 1966). Gravity and seismic refraction surveys were performed between 1961 and 1964. Based on that geophysical information and the initial drilling results, four deep wells were drilled.

Pre-drilling exploration involved surface geologic mapping, air photo studies, and a temperature survey of the thermal manifestations. The first six drill holes explored an area of about 14 km², not including Well M-4 which was 18 km to the northwest.

All wells had extensive down-hole logging, lithologic logging, and microfossils were noted. The water/steam mixture from the wells was sampled and analyzed chemically. Upon completion of these wells, further work was initiated to study the influence of the local tectonic and geologic structure on the migration of the geothermal fluid. Geophysical, geologic, and oceanographic studies were integrated. Alonso (1966) discussed the complexities involved in evaluating the potential of a geothermal area.

No guidelines were established for geothermal exploration in the early 1960's. Wairakei, New Zealand, was the only hot water field under exploitation. Geology and geophysics were used and integrated in the early exploration model of Cerro Prieto, but geochemistry was not yet utilized. At that time, the application of chemical geothermometry to

geothermal fluids was just beginning. However, the well fluids were analyzed, starting the characterization of the reservoir. The first wells served two purposes: exploration for the geothermal aquifer and the establishment of the stratigraphy of the field. Most wells were drilled into the basement even though geothermal fluid was encountered higher in the well. In addition, different horizons identified in the wells were correlated with seismic refraction profiles.

From 1966 to 1968, fifteen exploration-production wells were drilled. Temperature, dip meter, micro caliper and other well logs were run (Dominguez, 1978). During this period Mercado (1968) developed a model of the geothermal fluid flow based on Na/K and Cl/SO₄ ratios. Mercado's work characterized the reservoir fluids and suggested areas in the reservoir influenced by near-surface cool water recharge. It was observed that high temperature, high pressure wells had low Na/K ratios. This information was used to site a few exploration-production wells near surface manifestations with low Na/K ratios (personal communication, Mercado, Sept. 1980). Between 1972 and 1974 six more wells were drilled.

Power generation commenced in April 1973, but the full 75 MW capacity was not realized until the new wells were integrated into the system in February 1974. Before exploitation, downhole temperature and pressure logs were run periodically and many wells flowed simultaneously for long periods. Productivity was measured from well head pressure and output. Preliminary studies indicated that the average well capacity was about 5 MW (Dominguez and Vital, 1975). In April 1979 two more 37.5 MW turbines went on line for a total generating capacity of 150 MW. In 1980, two deep wells (7300 m total) were drilled northeast of the field near Ejido Hidalgo. Both encountered very high pressures and temperatures at depth. In September 1979, twenty-six wells were supplying the 150 MW plant, for an average of 5-3/4 MW per well.

Drilling was the major exploration tool used at Cerro Prieto in the late sixties and early seventies. Fluid and cuttings from each well were analyzed and logged. Three major production blocks became evident as drilling has progressed in the field. Block I corresponds to the zone exploited since 1973, located between the middle and southern end of the evaporation pond and the railroad. Wells in this zone produce between 600 and 1300 m and wells are within 200-300 m of each other. Block II is south of Block I and the depth of the production zone ranges between 1400 and 1700 m. Block III, east of the other two blocks, produces between 1800 and 2500 m. Wells in Block III will replace some wells in Block I for power production, where it is believed some over-exploitation exists.

A hydrologic survey of the aquifers in the Mexicali Valley was undertaken in 1968. This study identified recharge areas to the shallow aquifers in the valley, but did not reveal much about the geothermal field. A more detailed hydrologic evaluation was performed in 1972 utilizing isotopic techniques. The data suggested the geothermal field was of meteoric origin, possibly from the ancient Colorado River. This was the first study at Cerro Prieto that used sophisticated geochemistry.

A resistivity survey was carried out in 1973 that determined a shallow conductive layer over the entire area. A low-resistivity layer was detected at about 1200 m depth, roughly aligned MW-SE following the regional fault system trend. A 1973 aeromagnetic study of the Colorado River delta revealed a previously unrecognized spreading center.

In 1972 Reed studied the cores and cuttings from some of the wells. Petrographic and X-ray analysis showed a number of depth-dependent mineralogical changes. He concluded that metamorphism was initiated after most of the sedimentary section had been deposited. This work was one of the first to investigate the thermodynamic processes involved in

creating the reservoir. The introduction of mineral phase distribution as a function of temperature at depth provided another tool for characterizing the reservoir.

In the mid-seventies CFE initiated more geophysical surveys. They utilized Schlumberger, dipole-dipole, and microseismic surveys. A 70 km² low resistivity zone was delineated around the exploration zone at Cerro Prieto. The major NW-SE fault system was again defined and it was concluded that the geothermal field has a NW-SE orientation.

CFE reviewed all previous geotechnical studies (Soto, 1975) and concluded that the geothermal reservoir was divided into two zones: (1) the area currently being exploited, structurally related to the San Jacinto fault (this is actually the zone between the later identified Cerro Prieto and Michoacan faults) and (2) a zone east of the San Jacinto (Michoacan) fault discovered by Well M-53.

The work performed under the Joint-International agreement included geology, geophysics, and geochemistry. Much effort was devoted to using different geophysical techniques at Cerro Prieto. These techniques included dc-resistivity, self-potential, magnetotellurics, seismicity studies, precision gravity, magnetics, and seismic reflection.

In volcanic terrain, low resistivity layers in geothermal areas often coincide with hot-water producing zones. At Cerro Prieto, low resistivity areas seem to outline the geothermal area (2.0 or less ohms) but the production zone itself has higher (5-10 ohms) resistivity.

Gravity and magnetics have been useful in defining faults and the basement configuration. Gravity anomalies in the Imperial Valley seem to coincide with high temperature gradient areas. At Cerro Prieto there is a prominent gravity high showing a ridge-like structure under the

electrical plant. There is also a higher resistivity (10 ohms) zone in this same general area. These anomalies may indicate the presence of a dike at depth.

A self potential anomaly seems to coincide with the main axis of the producing field, suggesting that self potential measurements may be useful in detecting geothermally active faults. A self potential anomaly found at East Mesa 45 km north of Cerro Prieto may also be related to a fault acting as a conduit for geothermal fluids.

Recent magnetotelluric work (Gamble, et. al. 1980) detected a narrow resistive zone plunging southeastward from the power plant. This zone has been correlated with a zone of hydrothermal metamorphism. This study, in conjunction with the subsurface resistivity model, subsurface geology, and the configuration of the production zone, suggested that the heat source lies at depth, roughly 4 km south-southeast of the power plant.

The geophysical studies by LBL had two purposes: to characterize the structural parameters of the field and define the production zone, and to test which methods were most beneficial. Gravimetrics and seismic reflection worked best to detect the faults and develop a regional geological model. Dipole-dipole resistivity and magnetotellurics defined the same general large-scale features. The precision gravity studies and levelling network served to monitor subsidence in and around the field.

The geological studies at Cerro Prieto by CFE and LBL have included general geology of the area, stratigraphic analysis based on well bore lithologies and geophysical well log correlations, quantitative mineralogic studies of cores and cuttings, and water-rock interaction studies by UC-Riverside. All these methods have been beneficial in characterizing and understanding the geothermal field.

The sedimentation and stratigraphic work has defined the geomorphic regions of the paleo-Colorado River delta. Two main lithologies were identified in the field. A zone related to low-grade metamorphism was identified from the cuttings and this zone, found at variable depths across the field, may be considered the top part of the reservoir.

The hydrothermal mineral zonation and water-rock interaction studies, started by Reed (1972, 1975) and continued by Elders et. al. (1977), 1978A, 1978B, 1979, 1980) have contributed not only to understanding geothermal processes at Cerro Prieto but suggest such studies can be valuable at any geothermal field. Browne (1978) in New Zealand and Bamford (1978), in the USA have conducted similar investigations in geothermal areas in different geologic terrane. Elders et. al. (1980) latest model defines the shape of the reservoir and suggests the pattern of hydrothermal circulation prior to production. They infer that a thermal plume, elongated in a NW-SE direction, inclined 45° to the SW. This plume is recharged from the NE and discharges to the SW. Elders et. al. (1980) has proposed that, if properly understood, hydrothermally altered rocks can indicate temperature, water to rock ratios, f_{O_2} , f_{CO_2} pH of fluids, and duration of heating.

Elders' model and the geophysical model based on resistivity and magnetotellurics are in basic agreement. However, the mechanism for this inclined convective flow needs further investigation. This flow pattern and heat distribution may be a function of both lithology (densified shale zone) and fault or fault-intersection controls.

The fluid geochemistry in the field has been studied primarily by Mercado (1968, 1970, 1975), Manon et. al. (1977), and Truesdell (1978, 1979, 1980). This work characterized the reservoir fluid chemically and developed a model of the field based on temperature distribution and Na/K ratios. Mercado's 1975 model shows a distinct incline of hot fluid flow to the northeast and high temperature zone plunging to the southeast.

Studies by Truesdell et. al. (1978A, 1980) using isotopes, "conservative" substances (deuterium, chloride, and bromide) and Na-K-Ca geothermometry suggest that the Cerro Prieto geothermal brine originated from mixing of Colorado River water with sea water evaporated to around six times its normal salinity.

Truesdell and Manon (1978) have detected aquifer boiling near the well bore of several wells, based on detailed studies of well chemistry. This has serious implications for reservoir management. The boiling occurs in response to a drop in aquifer pressure in the well which produces steam and cools the remaining water. The pressure decrease can also allow cooler fluids to flow into the production zone. Production will decrease in wells where this phenomenon occurs. Truesdell et. al. (1978) recognized evidence of drawdown in some producing wells based on geochemical changes in the fluid over several years. Most of the wells affected are in a small cluster, midway between the power plant and the evaporation pond.

The complicated processes which have created the Cerro Prieto geothermal field are beginning to be understood. All available information was considered in the decisions made - before any drilling began, before deep exploration drilling, during resource assessment and especially in the current, long-term exploration-exploitation phase. Geology and geochemistry investigations have identified and characterized physical parameters of the region and the production zone. Fluid geochemistry studies at Cerro Prieto have proved valuable in both characterizing the reservoir and monitoring changes in reservoir processes. Geophysical studies were first used to define the regional subsurface structure. The latest work has delineated the production zone and suggested new areas for exploration drilling.

Drilling was the main exploration tool at Cerro Prieto. Coupled with extensive geochemical, geologic, and geophysical investigations, it has proved successful in defining the resource and directing subsequent exploration.

Much of the work at Cerro Prieto under the Joint-International Cooperating agreement continues to develop the state-of-the-art in geothermal investigative techniques.

CHAPTER 10

REFERENCES

Abril, A. and Noble, J. (1978): Correlacion de Secciones Transversales en Base a Registros Electricos de Pozos del Campo Geotermico de Cerro Prieto. Proceedings, 1st Symposium, on the Cerro Prieto Geothermal Field, Baja California, Mexico, p. 41-46.

Albores, H., Reyes, C., Brune, J. Gonzalez, J., Garcilazo, L., and Suarez, F. (1978): Estudios de Sismicidad en la Region del Campo Geotermico de Cerro Prieto. Proceedings, 1st Symposium on Cerro Prieto Geothermal Field, Baja California, Mexico, p. 227-234.

_____, H., Rodriguez, M. and Aki, K. (1978): Preliminary Studies of Attenuation in the Region of the Cerro Prieto Geothermal Field. Proceedings - 2nd Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico.

Alonso, E. H. (1966): La zona geotermica de Cerro Prieto, Baja California. Bol. Soc. Geo. Mex. v.29, No. 1, p. 17-45.

_____ and Mooser, F. (1964): El Pozo M-3 del Campo Geotermico del Cerro Prieto, B.C., Mexico. Bol. Asoc. Mex. Geo Petro., V.16, No. 7-8, p. 163-177.

Anderson, D. L. (1971): The San Andreas Fault; in Continents Adrift and Continents Aground, readings from Scientific American, W. H. Freeman and Co., p. 87-102.

Ariel Construcciones, S. A. (1968): Estudio Hidrogeologico Completo de los Acuiferos del Valle de Mexicali B.C. y Mesa de San Luis, Son. CFE Archives.

Atwater, T. (1970): Implication of Plate Tectonics for the Cenozoic Evolution of Western North America. Geol. Soc. Amer. Bull., 81 p. 3513.

Barnard, F. L. (1968): Structural Geology of the Sierra de los Cuap-
pas, Northeastern Baja California, Mexico, and Imperial County, Cali-
fornia. Ph.D. thesis, University of Colorado, 157 p.

Comision Federal de Electricidad (CFE) 1979: Planta Geotermica de
Cerro Prieto, Brochure.

Browne, P. R. L., (1978): Hydrothermal Alteration in Active Geothermal
Fields, Annual Rev. Earth Planet. Sci., 6, p. 229-250.

Chase D., Clover, R., Grannel, R., Leggewie, R., Eppink, J., Tarman,
D., and Goldstein, N. (1968): Precision Gravity Studies at Cerro
Prieto. Proceedings, 1st Symposium on the Cerro Prieto Geothermal
Field, Baja California, Mexico. P. 249-257.

CICESE (1977): Primer Informe Preliminar del Estudio de Microsismici-
dad del Sistema de Fallas Transformadas Imperial - Cerro Prieto. CFE
Archives.

Cobo, J. (1979): Geologia y Mineralogia del Campo Geotermico de Cerro
Prieto. Proceedings - 2nd Symposium, Cerro Prieto Geothermal Field,
Bsja Caifornia, Mexico, p. 103-114.

Corwin, R., Diaz, C., and Rodriguez, B. (1978): Self Potential Survey
at the Cerro Prieto Geothermal Field, Baja California, Mexico, Geother-
mal Resources Council Trans., v.2, p. 115-117.

Cotton, M. L. and Vonder Haar, S. P. (1979): Microfossils from Cerro
Prieto Geothermal Wells, Baja California, Mexico. Proceedings, 2nd Sym-
posium, Cerro Prieto Geothermal Field, Baja California, Mexico.
p. 162-168.

_____, R. and Fitterman, D. (1979): Interpretation of Self-Potential Data from the Cerro Prieto Geothermal Field. Proceedings - 2nd Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico.

Crececius, E., Robertson, D., Fruchter, J., and Ludwick, J. (1976): Chemical Forms of Mercury and Arsenic Emitted by a Geothermal Power Plant. Abstr. University of Missouri - 10th Annual Conference on Trace Substances in Environmental Health.

Crosby, J., Chatter, R., Anderson, J., and Fenton, R. (1972): Hydrogeologic Evaluation of the Cerro Prieto Geothermal System Utilizing Isotopic Techniques. Washington State University, Research Report No. 72/115 of Project No. 13G-3811-1040.

De la Fuente, M. F. (1973): Aeromagnetic Study of the Colorado River Delta Areas, Mexico. M.S. Thesis. University of Arizona.

Diaz, S. and Arellano, J. R. (1979): Self-potential and Resistivity Surveys South of the Cerro Prieto Fault. Proceedings, 2nd Symposium, Cerro Prieto Geothermal Field, Baja California, Mexico. p. 335-345.

Diaz, S. C. (1978): Self-potential Studies Northwest of the Cerro Prieto Geothermal Volcano, Baja California, Mexico. LBL, LBL-7098, p. 202-203.

Elders, W. A., Rex, R. W., Meidav, T., Robinson, Biehler, S., (1972): Crustal Spreading in Southern California. Science, v. 179, p. 15-24.

Fonseca, H. L. and Razo, M. A. (1979): Gravimetric, Magnetometric and Seismic Reflection Studies at the Cerro Prieto Geothermal Field. Proceedings, 2nd Symposium, Cerro Prieto Geothermal Field, Baja California, Mexico.

_____ (1979): The Geological Background of the Geothermal Field of the Salton Trough. Guidebook, Geology and Geothermics of the Salton Trough, Field Trip No. 7, p. 1-19.

_____, Olson, E., Hoagland, J., Barker, C., Johnson, P., and Collier, P. (1977): A Comprehensive Study of Samples from Geothermal Reservoirs: Petrology and Light Stable Isotope Geochemistry of Wells M-48, M-84, M-90, M-91, M-92 and Prian No. 1, in the Cerro Prieto Geothermal Field, Baja California, Mexico. University of California Riverside Report UCR/IGPP-77/37, p. 153.

Gamble, T. D., Goubau, W. M., Goldstein, N. E. , Miracky, R., Stark, M., and Clarke, J. (1979): Magnetotelluric Studies at Cerro Prieto. Proceedings, 2nd Symposium, Cerro Prieto Geothermal Field, Baja California, Mexico. p. 405-413.

Gamble, T., Goubau, W., Goldstein, N. and Clarke, J. (1978): Referenced Magnetotellurics at Cerro Prieto. 1st Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico. LBL, LBL-7098, p. 215-222.

Garcia, D. S. (1973): Geophysical Survey with the Resistivity Method in the Cerro Prieto Geothermal Zone, B. C. Department of Geothermal Resources, CFE Archives.

GEOCA (Geologos Consultores Asociados, S.A.) (1962): Levantamiento Sismologico de Refraccion en la Zona Geotermica de Cerro Prieto, Municipio de Mexicali, Estado de Baja California. CFE Internal Report.

_____, Hoagland, J., and Olson, E. (1978): Hydrothermal Mineralogy and Isotopic Geochemistry in the Cerro Prieto Geothermal Field, Mexico. III. Practical Applications. Geothermal Resources Council Trans., v.2, p. 177-180.

_____, _____, Williams, A. E. (1980): Hydrothermal Alteration as an Indicator of Temperature and Flow Regime in the Cerro Prieto Geothermal Field of Baja California. Geothermal Resources Council TRANS., v. 4, p. 121-124.

Goubau, W., Stark, M., Gamble, T., Goldstein, N., and Miracky, R., (1979): Magnetotelluric Studies at Cerro Prieto. Proceedings - 2nd Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico.

Grannel, R., Aroustan, P., Leggeure, R., Eppink, J., Tarmen, D., Clover, R., Kroll, R. (1979): Precision Gravity Measurements in the Cerro Prieto Geothermal Area. Proceedings - 2nd Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico.

Hamilton, W. (1961): Origin of the Gulf of California. Geol. Soc. Amer. Bull. 72, p. 1307-1318.

Hoagland, J. and Elders, W. (1978): Hydrothermal Mineralogy and Isotopic Geochemistry in the Cerro Prieto Geothermal Field, Mexico. I. Hydrothermal Mineral Zonation. Geothermal Resources Council Trans., v.2, p. 283-286.

Kovach, R., and Monges, J. (1961): Medidas de Gravedad en la Parte Norte de Baja California, Mexico. An. Inst. Geof. UNAM, v.7., p. 10-14.

Larson, R. L., Menard, H. W., Smith, S. M. (1968): Gulf of California: A Result of Ocean Floor Spreading and Transform Faulting; Science, 161, p. 781-784.

_____, (1972): Bathymetry, Magnetic Anomalies and Plate Tectonic History of the Mouth of the Gulf of California; Geol. Soc. Amer. Bull., 83, p. 3345-3360.

Lippmann, M., Wollenberg, H., Manon, A., (1978): The Cerro Prieto Geothermal Field. Unpubl. Report.

_____, M., Dominquez, B., Wollenberg, H., and Witherspoon, P. (1977): Open File Data on the Cerro Prieto Geothermal Field. Lawrence Berkeley Laboratory Report 6321, p. 10.

Lomnitz, C., Mooser, F., Allen, C., Brune, S., Thatcher, W. (1970): Seismicity of the Gulf of California since the late Pliocene. Science, 161, p. 1238-1241.

_____, and McEvilly (1979): Earthquake Monitoring at the Cerro Prieto Geothermal Field. Proceedings - 2nd Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico.

Majer, E., McEvilly, T., Albores, A., and Diaz, S. (1978): Seismological Studies at Cerro Prieto. Proceedings, 1st Symposium on the Cerro Prieto Geothermal Field, Baja, California, Mexico. p. 239-245.

Manon, A., de la Pena, A., and Puente, I. (1978): El Campo Geotermico de Cerro Prieto - Estudios Realizados y Programas Futuros. Paper presented at the OLADE Symposium on Geothermal Exploration in Ecuador.

_____, Mazor, E., Jimenez, M., Sanchez, A., Fausto, J., and Zenizo, C. (1977): Extensive Geochemical Studies in the Geothermal Field of Cerro Prieto, Mexico. Lawrence Berkeley Laboratory Report LBL-7019, 113p.

_____, Sanchez, A., Fausto, J., Jimenez, M., Jacobs, A., and Esquer, P. (1978): Modelo Geoquimico Preliminar del Campo Geotermico de Cerro Prieto. Proceedings, 1st Symposium on the Cerro Prieto Geothermal Field, Baja, California, Mexico. p. 83-90.

Medina, M. and Duarte, C. (1979): A Digital Seismological Telemetry Network at Cerro Prieto. Proceedings - 2nd Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico.

Mercado, S. (1968): Localization of Zones of Maximum Hydrothermal Activity by Means of Chemical Ratios. Cerro Prieto Geothermal Field, Baja, California, Mexico. CFE Archives.

_____, (1975): Migracion de Fluidos Geotermicos y Distribucion de Temperatures en el Subsuelo del Campo Geotermico de Cerro Prieto, Baja California, Mexico. Proceedings, 2nd UN Symposium on the Development and Use of Geothermal Resources, v.1, p. 487-492.

_____, (1977): Geothermal Chemistry of Some Geothermal Fields of Mexico. Paper presented at the Geological Society of America 1977 Annual Meeting, Washington.

Molina, B., and Banwell, C. (1970): Chemical Studies in Mexican Geothermal Fields. Geothermics. Special Issue 2.

Moore, D. G., (1973): Plate Edge Deformation and Crustal Growth, Gulf of California Structural Province. Geol. Soc. Amer. Bull., 84, 1883.

_____, and Buffington, E., (1968): Transform Faulting and Growth of the Gulf of California Since the late Pliocene. Science 161, p. 1238-1241.

_____, (1973): Plate Edge Deformation and Crustal Growth, Gulf of California Structural Province; Geol. Soc. Amer. Bull., 84, p. 1883.

Nehring, N., Fansto, J. (1978): Gases in Steam from Cerro Prieto Geothermal Wells. Proceedings, 1st Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico. U.S. Dept. of Energy and CFE-CECP.

Noble, J., Manon, A., Lippmann, M., and Witherspoon, P. (1977): A Study of the Structural Control of Fluid Flow within the Cerro Prieto Geothermal Field, Baja California, Mexico. Paper presented at the 52nd

Annual Fall Tech. Conf. Soc. Petrol. Engr., AIME, Colorado, Paper SPE-6763, (LBL-7003), 14p.

Olson, D., and Elders, W. (1978): Hydrothermal Mineralogy and Isotopic Geochemistry in the Cerro Prieto Geothermal Field, Mexico II. Isotopic Geochemistry. Geothermal Resources Council, Trans., v.2, p. 513-516.

Paredes, E. A. (1975): Preliminary Report on the Structural Geology of the Cerro Prieto Geothermal Field. Proceedings-2nd UN Symposium on the Developmen and Use of Geothermal Resources, v.1, p. 518-519.

Prian, R. (1978): Correlaciones Litologicas de los Pozos del Campo de Cerro Prieto con Base en la Interpretacion de los Registros Electricos. Proceedings, 1st Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico. p. 49-54.

Puente, C. I. and Pena , L. (1978): Geologia del Campo Geotermico de Cerro Prieto. Proceedings-1st Symposium on the Cerro Prieto Geothermal Field, San Diego, California, September 20-22.

Razo, M. A. (1978): Estudios de Resistividad en Cerro Prieto. CFE Archives.

_____, and Arellano, F., (1978): Prospeccion Electrica de la Porcion Norte del Valle de Mexicali y Campo Geotermico de Cerro Prieto, Baja California. Informe 6-78. CFE Archives.

_____, and Fonseca, H. (1978): Prospeccion Gravimetrica y Magnetrometrica en el Valle de Mexicali, B.C. Informe 5-78. CFE Archives.

_____, Arellano, F., and Fonseca, H. (1978): Estudios de Resistividad Realizados por CFE en Cerro Prieto. Proceedings, 1st Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico, p. 167-175.

Reed, M. (1972): "A Preliminary Report on the Geology and Geochemistry of the Cerro Prieto Geothermal Field", Chapter H in Cooperative Invest. of Geothermal Resources in the Imperial Valley Area and their Potential Value for Desalting of Water and othe Purposes. Inst. of Geophysics and Planetary Physics, Univ. of California, Riverside, California, IGPP-UCR 72-33.

_____, (1975): Geology and Hydrothermal Metamorphism in the Cerro Prieto Geothermal Field Mexico. Proceedings, 2nd U.N. Symposium on the Development and Use of Geothermal Resources, v.1, p. 539-547.

Reyes, A. (1977): Primer Informe Preliminar del Estudio de Microsismicidad del Sistema de Falls Transformadas Imperial - Cerro Prieto. CFE Archives.

_____, and Razo, A. (1979): Seismic Studies and its Correlation with Potential Anomalies. Proceedings, 2nd Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico.

Sharp, R. V. (1972): Tectonic Setting of the Salton Trough, in the Borrego Mountain Earthquake of April 9, 1968. U.S.G.S. Professional Paper, 787, p. 3-15.

Soto, S. (1975): Campo Geotermico de Cerro Prieto Sobre la Falls de San Jacinto y su Posible Ampliacion Hacia la Falla Imperial, CFE Archives.

Truesdell, A., Rye, R. O., Pearson, F. J., Olson, E. R., Nehring, N. L., Huebner, M. A. , and Coplen, T. B. (1978): Preliminary Isotopic Studies of Fluids from the Cerro Prieto Geothermal Field, Baja California, Mexico. Proceedings, 1st Symp. on the Cerro Prieto Geothermal Field, Baja California, Mexico, San Diego, September 1978, LBL Report 7098.

_____, Manon, A. Jimenez, M., Sanchez, A., and Fausto (1978): Geochemical Evidence of Drawdown in the Cerro Prieto, Mexico Geothermal Field, San Diego, September 1978, LBL Report 7098.

_____, Thompson, J. M., Coplen, T. B., Nehring, N. L., and Janik, C. J. (1980): The Origin of the Cerro Prieto Geothermal Brine, LBL Report (in press).

Truesdell, A., and Manon, A., (1978): Geochemical Indication of Boiling in the Aquifer of the Cerro Prieto Geothermal Field. CFE Archives.

Vonder Haar, S. P., and Howard, J. H. (1979): Intersecting Faults and Sandstone Stratigraphy at the Cerro Prieto Geothermal Field. Proceedings, 2nd Symposium, Cerro Prieto Geothermal Field, Baja California, Mexico. p. 118-134.

Wilson, J. T. (1965): A New Class of Faults and Their Bearing on Continental Drift; Nature, 207, p. 343-347.

Wilt, M., Goldstein, N., and Razo, A. (1978): LBL Resistivity Studies at Cerro Prieto. Proceedings. 1st Symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico. p. 179-188.

_____, and Goldstein, N. (1980): Resistivity Monitoring at Cerro Prieto. Proceedings - 2nd symposium on the Cerro Prieto Geothermal Field, Baja California, Mexico.

Witherspoon, P. Alonso, H., Lippmann, M., Manon, A., and Wollenberg, A., (1978): Mexican-American Cooperative Program at the Cerro Prieto Geothermal Field. Report LBL-7095.