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

Agreement No. DE-FC07-79ID 12065

The Momotombo Geothermal Field, Nicaragua:

Exploration and Development Case History Study

Contribution to

Geothermal Model Development Database

July 1982

INTERNATIONAL ENGINEERING COMPANY, INC.
A MORRISON-KNUDSEN COMPANY

DISCLAIMER

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ABSTRACT

This case history discusses the exploration methods used at the Momotombo Geothermal Field in western Nicaragua, and evaluates their contributions to the development of the geothermal field models. Subsequent reservoir engineering has not been synthesized or evaluated.

A geothermal exploration program was started in Nicaragua in 1966 to discover and delineate potential geothermal reservoirs in western Nicaragua. Exploration began at the Momotombo field in 1970 using geological, geochemical, and geophysical methods. A regional study of thermal manifestations was undertaken and the area on the southern flank of Volcan Momotombo was chosen for more detailed investigation. Subsequent exploration by various consultants produced a number of geotechnical reports on the geology, geophysics, and geochemistry of the field as well as describing production well drilling.

Geological investigations at Momotombo included photogeology, field mapping, binocular microscope examination of cuttings, and drillhole correlations. Among the geophysical techniques used to investigate the field sub-structure were: Schlumberger and electromagnetic soundings, dipole mapping and audio-magnetotelluric surveys, gravity and magnetic measurements, frequency domain soundings, self-potential surveys, and subsurface temperature determinations. The geochemical program analyzed the thermal fluids of the surface and in the wells.

This report presents the description and results of exploration methods used during the investigative stages of the Momotombo Geothermal Field. A conceptual model of the geothermal field was drawn from the information available at each exploration phase. The exploration methods have been evaluated with respect to their contributions to the understanding of the field and their utilization in planning further development.

Our principal finding is that data developed at each stage were not sufficiently integrated to guide further work at the field, causing inefficient use of resources.

The opinions expressed in this case history are those of the authors.

CHAPTER 1
INTRODUCTION

The Momotombo Geothermal Field is a liquid dominated field located in the volcanic region of western Nicaragua. The field covers an area of about 2 km^2 and is situated on the north shore of Lake Managua on the lower slopes of the active Momotombo volcano.

Evaluation of this and other areas in western Nicaragua for geothermal potential began in 1966. Exploration and development of the Momotombo field has progressed in various stages from 1970 to the present. Exploration of this field was conducted with limited financial and scientific Nicaraguan national resources, with additional financing and technical personnel from the United Nations, and further financing from the International Bank for Reconstruction and Development (IBRD) and Bank for the International Development (BID). Several different contractors were involved in the geothermal field development and evaluation. This aspect has resulted in a protracted exploration program.

Field development is still in progress and INE should have a 30 MW plant installed in 1982. In 1978 the government of Nicaragua was negotiating for funds for the installation of a 35-MW generating station. Based on short term individual well tests it was calculated that the field could produce up to 105 MWe, but such additional capacity for long term production has yet to be proven. International Engineering Company was monitoring a long term flow test in 1979 but the civil disturbances interrupted that program.

Ahuachapan in El Salvador is the only producing geothermal field in Central America at this time. It also is located in the Pacific Volcanic Belt of Central America. Momotombo may therefore be the second producing field in Central America and will have great significance for Nicaragua, which has considerable geothermal potential, but lacks other energy sources, except for potential hydroelectric capacity. The second closest producing field to Momotombo is Cerro Prieto in Mexico, which has a different geologic setting.

This report is concerned with the geothermal exploration techniques that were utilized at the Momotombo field. An analysis of this work is of interest as an example of geothermal exploration of a liquid dominated field which is associated with Quaternary volcanism and is located in a region in which few previous geothermal studies had been undertaken.

CHAPTER 2
REGIONAL SETTING - WESTERN NICARAGUA

2.1 REGIONAL TECTONICS AND SEISMICITY

The active volcanism and associated geothermal manifestations of western Nicaragua can be understood by considering the relationship of volcanism to plate tectonics in the area. Western Nicaragua, which is part of the Circum-Pacific "Ring of Fire", is a region of intense volcanic and earthquake activity. The Cocos and Caribbean Plates converge in this region, the Cocos Plate being subducted under the Caribbean Plate along the Middle America Trench, which parallels the Nicaraguan Coast 80 to 120 km offshore (Figure 2-1).

Intense seismicity is associated with this subduction zone (Figure 2-2). Epicenters of earthquakes recorded June 1975 to February 1978 cover a wide area, dipping beneath the continent and falling into a well defined band which extends eastward from the Middle America Trench. This map also suggests a few alignments of epicenters along approximately NW-SE directions. These alignments may be related to transverse faults. Figure 2-3 shows a NW-SE cross sectional plot of epicenters which clearly illustrates the relationship between epicenters and the dipping subduction zone. The cross section also shows a second zone of earthquakes associated with the Quaternary Volcanic Range, located about 130 km east of the Middle America Trench. The volcanic activity in this zone is accompanied by shallow-focus earthquakes.

2.2 PHYSIOGRAPHY AND STRUCTURE

Nicaragua can be divided into five physiographic provinces (Catastro, 1972), namely (1) the Pacific Coastal Plain, (2) the Quaternary

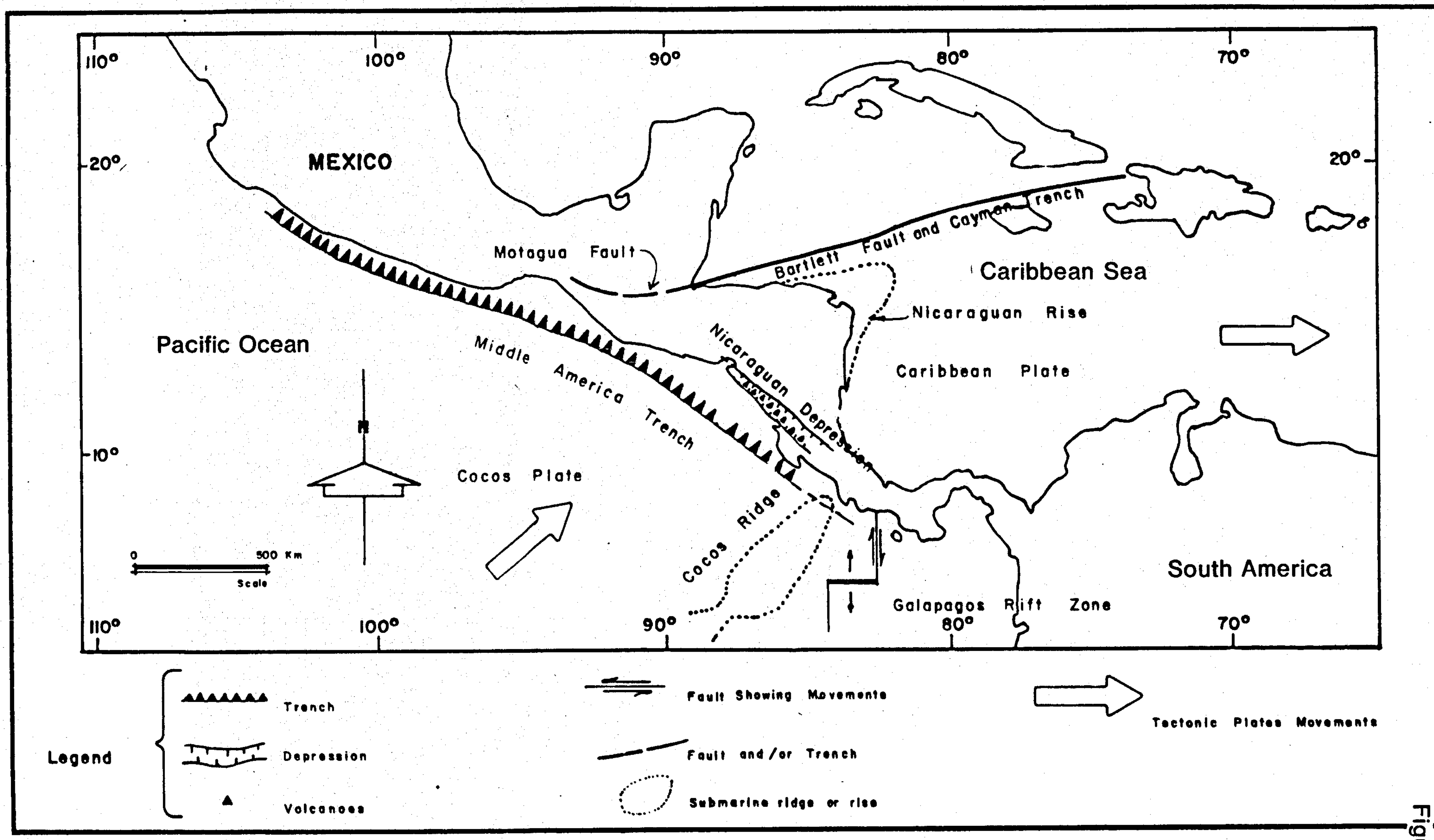
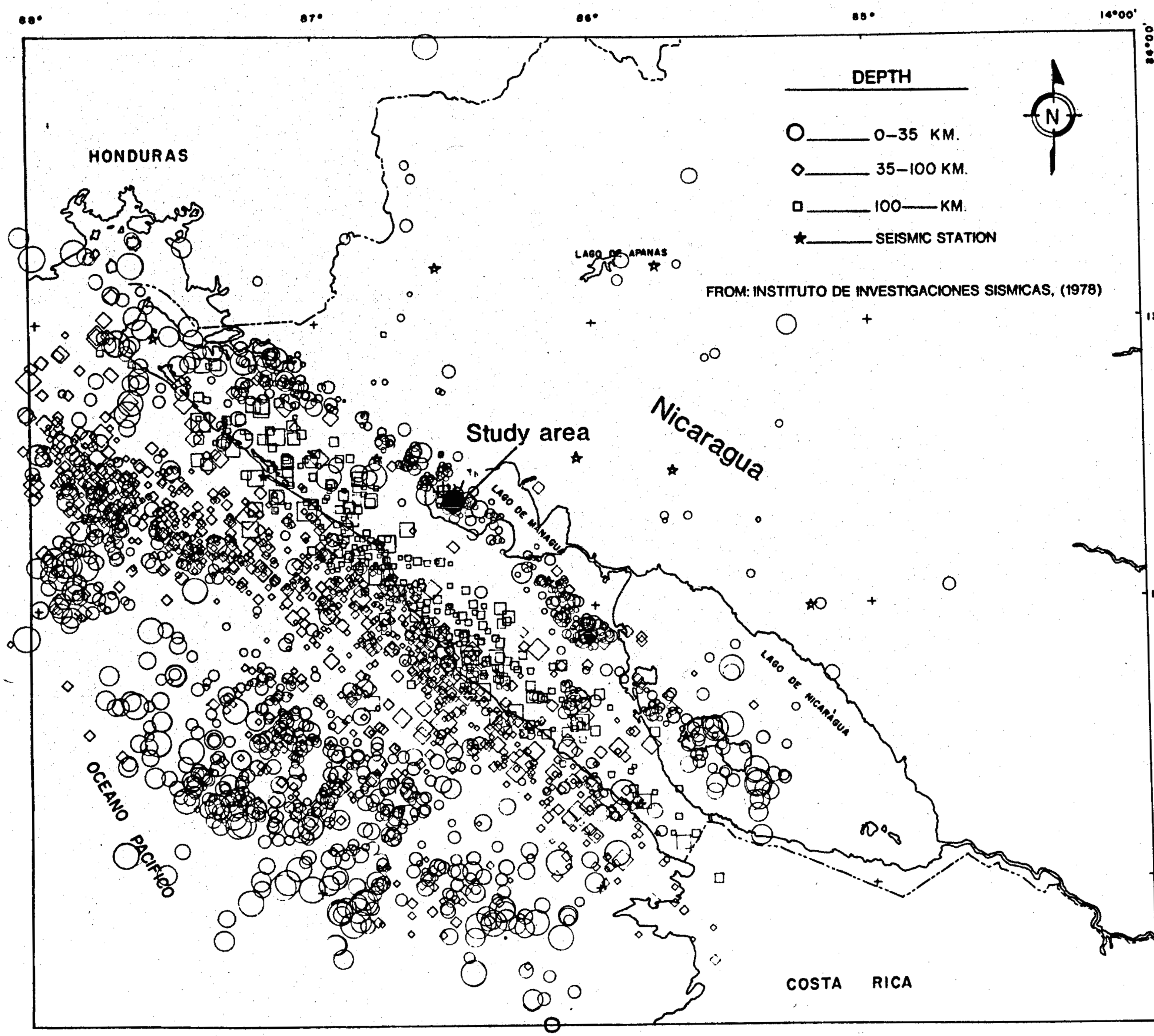


Figure 2-1

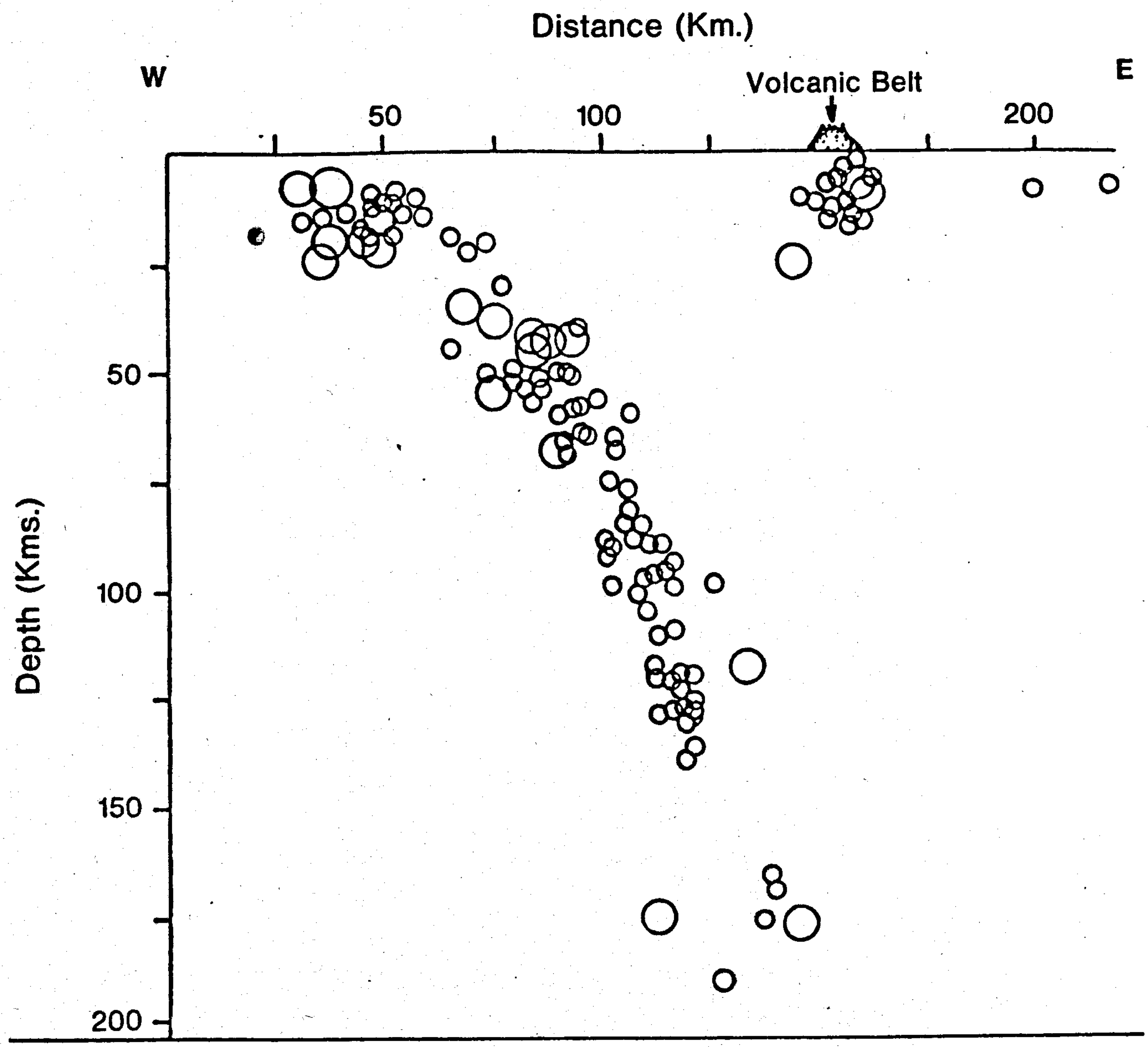
Tectonics of Central America and the Caribbean Region



Map Showing Location of Epicenters from 06/75 to 02/78

Figure 2-2

Figure 2-3



Schematic diagram showing the change in direction of the Nicaraguan volcanic chain. Circles depict hypocenters. Standard error in focal depth is less than 5 Km. for small circles and less than 10 Km. for large circles. Field of view is in a N 56° W direction. (From Instituto de Investigaciones Sismicas, 1975).

Volcanic Chain, (3) the Nicaraguan Depression, (4) the Interior Highlands, and (5) the Atlantic Coastal Plain. Stoiber (1975) includes the Quaternary Volcanic Chain in the Nicaraguan Depression. All these provinces except the Atlantic Coastal Plain, are of interest to the geology of western Nicaraguan (Figure 2-4).

The <u>Pacific Coastal Plain</u> can be divided in two sectors (Catastro, 1972): apart from Cosiguina, the northern sector is characterized by subsidence and the southern sector by emergence. The two sectors are separated by a hinge line passing through Puerto Somoza in a NE direction (Figure 2-5).

This hinge line may be related to the Clipperton Fracture Zone, transverse to the Middle America Trench (Catastro, 1972). Not enough data are available to support this hypothesis, but other examples of oceanic fracture zones continuing across plate boundaries are available, such as the continuation of the Mendocino Fracture zone into the North American Plate.

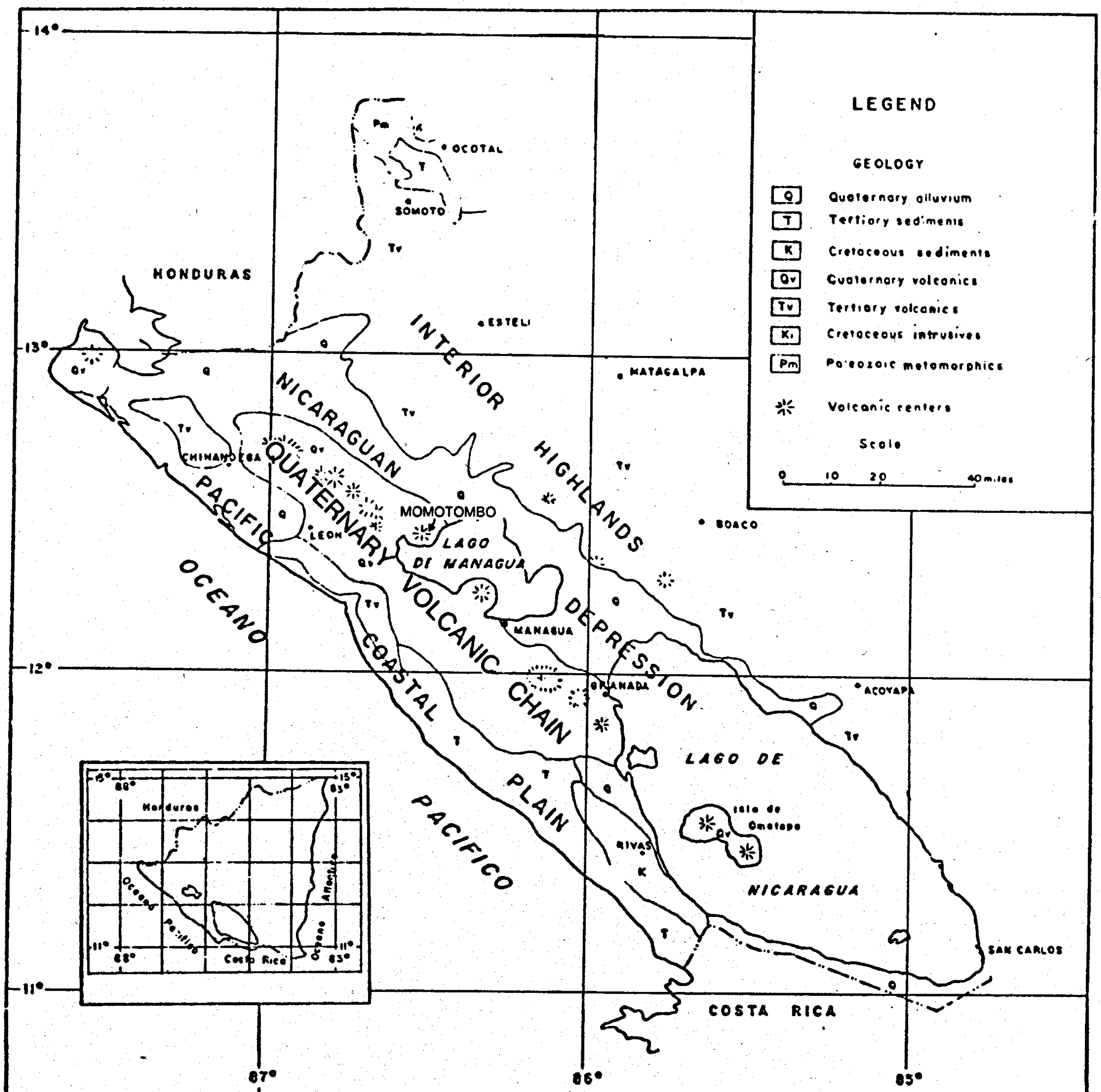
The hinge line is a major structural axis which is aligned with the northwestern shore of Lake Nicaragua west of Momotombo volcano. It not only separates areas of uplift and subsidence on the coast, but also coincides with a break and offset of the coastline and coincides approximately with an offset in the volcanic chain.

The northern portion of the Pacific Coastal Plain is covered by Quaternary volcanic sediments with scattered hills of Tertiary ignimbrites in the north. The southern portion is underlain by Cretaceous and Tertiary sediments which are partially dissected into hills and valleys as a result of intense folding and faulting.

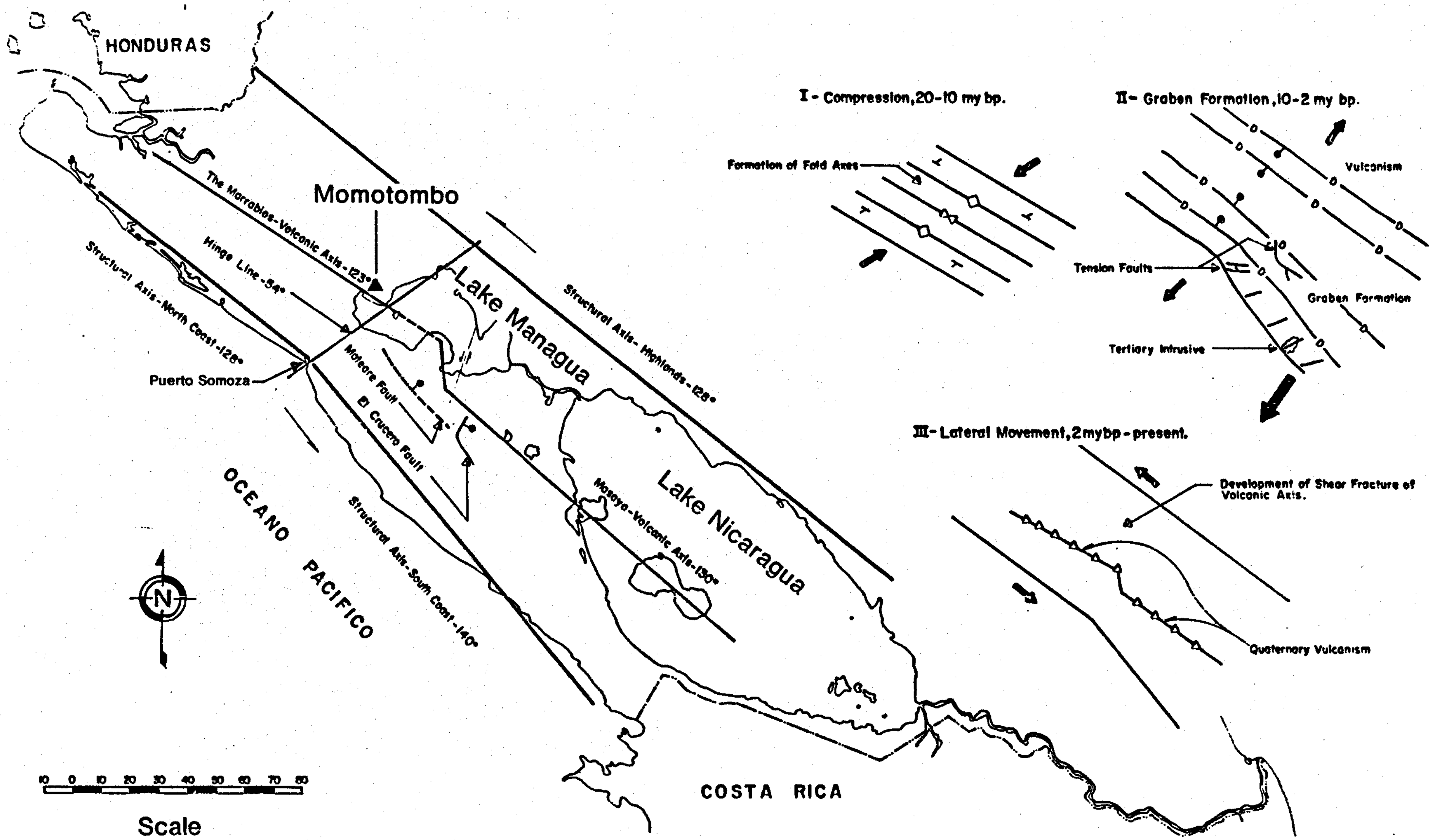
The province with significance geothermal potential is the active <u>Quaternary Volcanic Chain</u>. The Momotombo volcano and its associated geothermal field are located in this province. The northernmost tip of

Figure 2-4

Major Physiographic Provinces of Western Nicaragua



FROM NICARAGUA, NATIONAL INVENTORY OF PHYSICAL RESOURCES (1966)



Tectonic History of Western Nicaragua

Figure 2-5

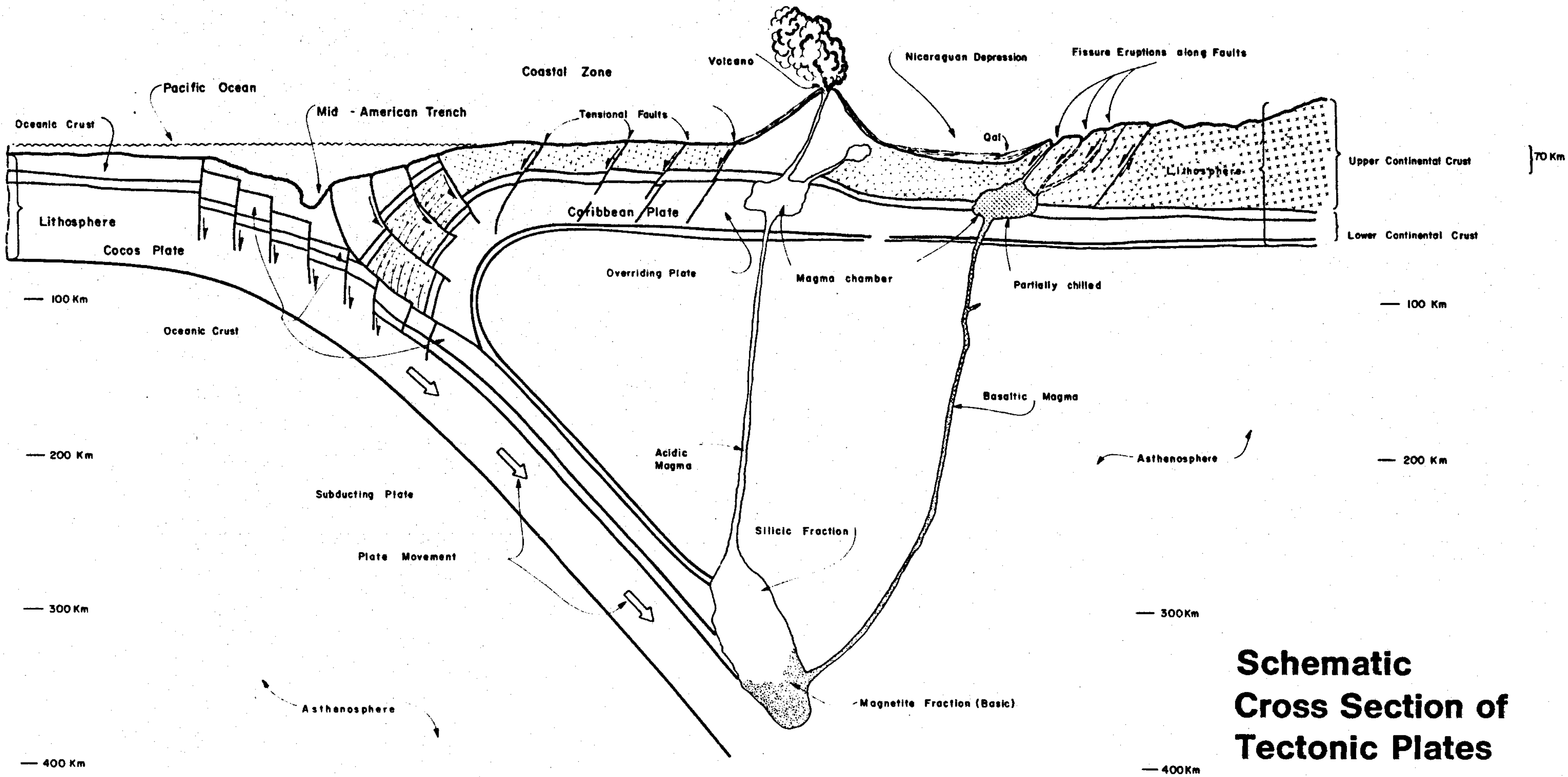
the Volcanic Chain province is Cosiquina volcano which is located on a peninsula, offset to the west, and isolated from the rest of the Quaternary Volcanic Chain (McBirney and Williams, 1965). This volcano had a violent Krakatoan explosion in 1835. Evidence for numerous other explosive eruptions are found in the volcanic range, but the Cosiguina explosion is the only one that is historically documented.

Farther south, the chain continues with the Marrabios Range which extends from El Chonco volcano in the north to Momotombo in the south. Momotombo volcano is located on the north shore of Lake Managua, and a parasitic cone (Momotombito) forms a small island in the lake.

South of Lake Managua, the Quaternary Volcanic Chain continues with a major dislocation and small change in strike, with Masaya, Santiago and Mombacho volcanoes and ends in Nicaragua at Maderas volcano on the island of Ometepe, in Lake Nicaragua.

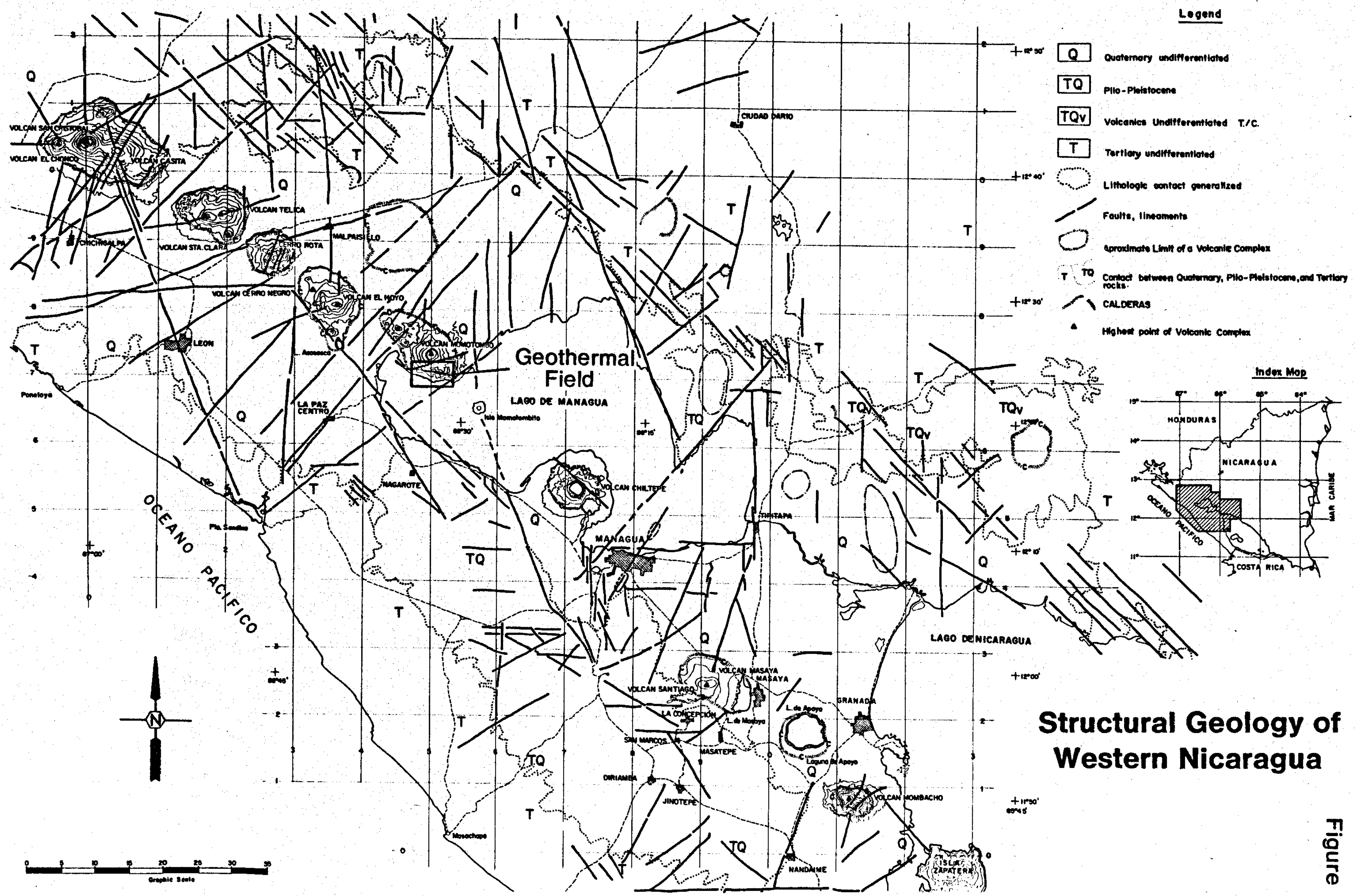
The Volcanic Chain may have begun as an island arc in a submerged Nicaraguan depression. The volcanism of western Nicaragua, like the earthquake activity of the area, is related to the subduction of the Cocos Plate. Figure 2-6 shows a schematic diagram of magmatic activity related to plate movements. The magma is assumed to rise to the surface from above the subducting plate margin, through tension faults, to produce this volcanic chain.

Structural studies based on topography, geologic field mapping, radar imagery and aerial photo interpretation have indicated a number of lineaments and fault trends in western Nicaragua (Figure 2-7). Promising geothermal areas in Nicaragua appear to be located at the intersection of major faults or lineaments. Faults or fractures can influence geothermal activity by permitting passage of fluids into shallow horizons.



Schematic Cross Section of Tectonic Plates

Figure 2-6



Structural Geology of Western Nicaragua

Figure 2-7

The Nicaraguan Depression, which parallels and partly envelops the Quaternary Volcanic Chain is a topographic low between the Pacific Coastal Plain and Tertiary volcanics at the boundary of the Interior Highlands. It extends over a distance of 550 km from the Caribbean coast of Costa Rica through Nicaragua and ends in the Gulf of Fonseca. Lakes Managua and Nicaragua take up almost half of the length of the depression within Nicaragua.

The depression is bounded on the northeast by step faults in the Tertiary volcanic rocks of the Interior Highlands. Faulting postulated for the southwestern margin of the province is not well documented. Faults along this margin include those present in the Tertiary formations of the Pacific Coastal Plain; other fault traces may have been obliterated by volcanics of the Quarternary Volcanic Chain.

The Interior Highlands are comprised mostly of Tertiary volcanic rocks. Some Paleozoic metamorphics, Jurassic and early Tertiary sediments, Cretaceous and Tertiary intrusives, and Quaternary cover have also been mapped in this province.

The Atlantic Coastal Plain consists of Quaternary sediments overlying Tertiary volcanics. Minor lava flows are interbedded with the volcanogenic sediments near the coast, where flat-lying basalt flows form prominent cliffs. Several silicic intrusives have been mapped in the northern section.

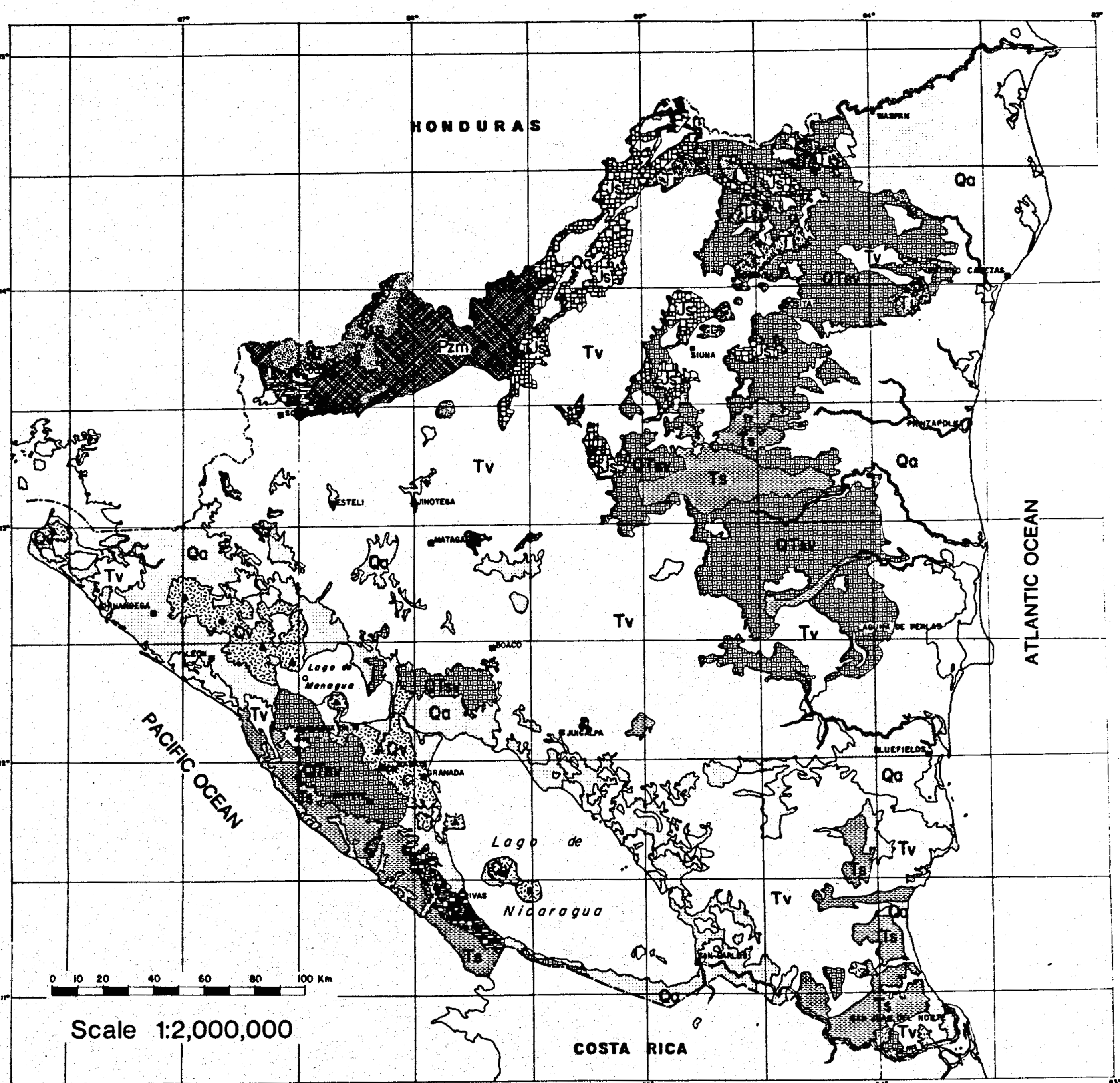
2.3 STRATIGRAPHY

The areal distribution of principal rock units in Nicaragua is indicated on the generalized geologic map (Figure 2-8), and correlated stratigraphic columns for several parts of Nicaragua are shown in Figure 2-9. Tertiary to Recent volcanic rocks predominate in the areas of geothermal interest. Exceptions are the Upper Cretaceous and Tertiary sedi-

Figure 2-8

Geologic Map of Nicaragua

(From McBirney, 1965)



Legend

Quaternary
- Qa — Alluvium, Colluvium and Poorly Consolidated Sediments
- Qv — Volcanic Rocks and Pyroclastic Deposits
- QTsv — Sedimentary Rocks and volcanics

Tertiary
- Tv — Volcanic Rocks; Coyol, Matagalpa and Tamarindo Groups
- Ts — Sedimentary Rocks; Limestone, Sandstone, Siltstone and Shale
- Ti — Intrusive Rocks; Granite, Granodiorite, Monzonite

Cretaceous
- Ks — Sedimentary Rocks: Limestone, Siltstone, Conglomerate
- Ki — Plutonic Rocks, Acidic Intrusives

Jurassic
- Js — Sedimentary Rocks

Paleozoic
- Pzm — Undifferentiated Metamorphic Rocks

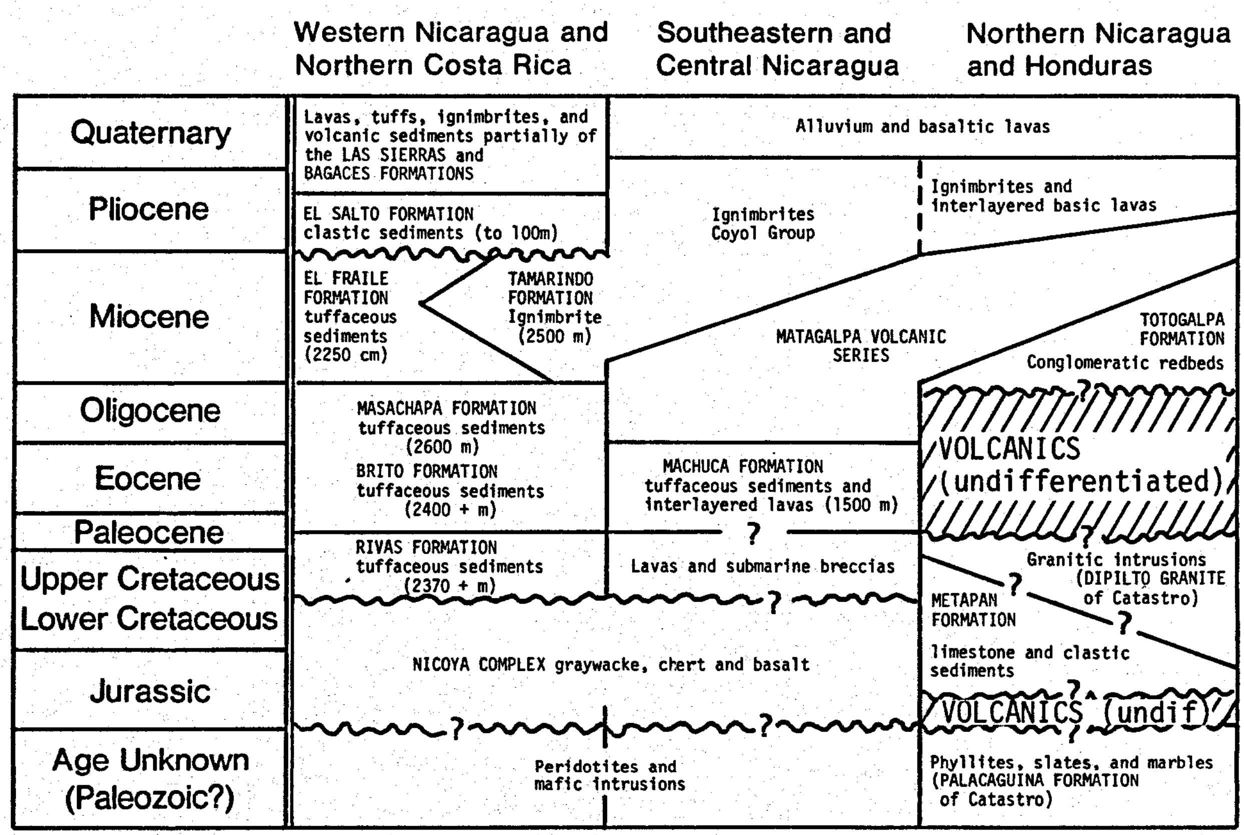
■ Major Cities and Towns

▲ Volcanoes

Note : Map was drawn based on the "Geology Map" of Nicaragua, preliminary edition, published by the Instituto Geologico Nacional, 1974

Figure 2-9

Stratigraphic Relations of Nicaragua and Adjacent Regions



Slightly modified from McBirney and Williams (1965) and Catastro (1972) mentary rocks on the Isthmus of Rivas and probable Paleozoic metamorphic rocks, Cretaceous granitic intrusions, and Miocene sediments in north-central Nicaragua. The marine sedimentary rocks of the Isthmus of Rivas are associated with a broad, northwest-plunging anticline and reach a total thickness of over 10,000 m. The following stratigraphic outline is taken mostly from the Catastro report of 1972 and refers to the area of interest in western Nicaragua.

A. Metamorphic Rocks

The metamorphic rocks of the Northern Highlands, called the Palacaguina Formation, are the oldest rocks exposed in Nicaragua. These rocks are probably of Paleozoic age, although it can only be said with cetainty that they are older than early Cretaceous plutonic rocks which intrude the formation.

At the west and southwest margin of the metamorphic area, marble, quartzite, and slate are found, together with other metasediments and, possibly, metavolcanics. These rocks exhibit low-grade metamorphism. Towards the interior of the metamorphic area, the intensity of metamorphisms increases. Rocks exposed in this area are mostly mica-schists and phyllites.

B. Sedimentary Rocks

The Nicoya Complex, first described in Costa Rica, is assumed to be the oldest sedimentary unit in this region. It consists of weakly metamorphosed graywacke, volcanic conglomerate, siliceous limestone, basalt, agglomerates, and basic to intermediate intrusives. The age of this formation is approximately Jurassic to Lower Cretaceous.

The Nicoya Complex in western Nicaragua is overlain by the Rivas Formation which consists of interbedded tuffaceous shale, siltstone, graywacke, and conglomerate. The base of the formation is formed mostly by volcanic material, and diabase sills are common throughout the formation.

The base of the early Tertiary Brito Formation is a conglomerate which underlies two limestone marker beds. The balance of the formation consists mostly of tuffaceous sandstones and siltstones, graywackes, and shales.

The Masachapa Formation overlies the Brito Formation with a slight angular unconformity. It consists of a monotonous sequence of tuffaceous and occasionally calcareous shales, siltstones, and sandstones.

Along the southwest side of the Quaternary Volcanic Chain, near the coast, the Masachapa Formation is overlain by the sedimentary El Fraile Formation of the Miocene age. Towards the northeast, these beds grade into the volcanic Tamarindo Formation. The base of the El Fraile Formation is a volcanic conglomerate and agglomerate, overlain by interbedded tuffaceous sandstones and siltstones, sandy limestones, and volcanic conglomerates.

The Pliocene El Salto Formation is assumed to be a transgressive facies which decreases in thickness and age from west to east. It overlies the Brito and Masachapa Formation with a pronounced angular unconformity. Since the El Fraile Formation is restricted to the coastal region, it is not in contact with the El Salto beds. Although the El Salto Formation probably covered a large part of the Pacific Coast Province, erosions has left only remnants in the central portion of this province. The formation consists of a basal carbonate unit and overlying clastic beds. The impure limestones and clastics contain basic to intermediate volcanic detritus. The uppermost strata of the El Salto grade laterally into contemporaneous volcanic sediments at the base of the Las Sierras Formation.

The Las Sierras Formation is found in the vicinity of Managua, and its middle part may be correlated with the Bagaces Formation of Costa Rica. The formation consists of pyroclastic rocks of remarkably uniform composition, stemming mostly from mafic eruptions. Some andesitic ejecta are also present, but more silicic components are absent. Texture and structure of the beds are variable, depending on local environments of deposition. The formation is overlain by Holocene pyroclastics and lavas.

According to McBirney and Williams (1965) the Tertiary sediments of the Pacific Coastal Plain exhibit low-grade metamorphism and zeolitization. The rocks of the Rivas Anticline are transitional to zeolite facies while a greenschist facies assemblage is found in northwestern Costa Rica.

C. Tertiary Volcanic Rocks

Most of the Central Highlands region is covered by Tertiary volcanic rocks. The sequence of Tertiary volcanics in this region begins with the Matagalpa Group which consists mostly of andesitic and dacitic lavas with some basaltic lavas, ignimbrites and lahars. Toward the margin of the Nicaraguan Depression, these volcanic rocks become increasingly interbedded with sedimentary rocks.

The Matagalpa Group is overlain by the Coyol Group. The lower portion of the Coyol Group grades upward from andesitic lavas and agglomerates through andesitic ignimbrites to dacitic ash flows. The upper portion of the group repeats this general sequence and is itself overlain by basaltic lavas and agglomerates which form extensive plateaus.

Tertiary volcanic rocks in the northern part of the Pacific Coast Province belong to the Tamarindo Formation. The formation consists of a basal andesitic lava and agglomerates and an overlying ash flow series formed by dacitic tuffs and dacitic or rhyodacitic ignimbrites.

Ignimbrites predominate in the upper part of the formation with minor tuffs underneath. As mentioned in the description of sedimentary rocks, the Tamarindo Formation grades laterally into the marine sediments of the El Fraile Formation found in the southern coastal area.

D. Quaternary Volcanic Rocks

Quaternary volcanic rocks are more closely associated with the Quaternary Volcanic Range and will be described in Section 2.4 of this chapter.

E. Summary of Geologic History

The very complex and active tectonic setting of western Nicaraguan has produced a complex geologic history. The summary presented here is taken from Dames and Moore (1978).

1. Pre-Tertiary - Rocks of Pre-Tertiary age are poorly exposed in western Nicaraguan. The Cretceous rocks of the Rivas Formation are found hundreds of kilometers south near the Costa Rican border. Several hundred kilometers to the north, a metamorphic complex is recognized to be at least partly Paleozoic in age.

An ancient volcanic arc is postulated to have been the source for the regionally extensive Cretaceous volcanic and sedimentary rocks of the Rivas Formation. The Paleozoic metamorphic complex is evidently limited in extent to the northern part of Nicaragua.

2. Tertiary - The great thickness, up to 8000 m, of sedimentary formations deposited from the Upper Mesozoic to the Miocene, indicates a rapidly subsiding trough along the Pacific Coast (Catastro, 1972). The marine tuffaceous sediments of Tertiary Age intertongue with continental volcanic units, modified by various marine fluctuations. Unconformities between various sedimentary members, and renewed volcanism

are evident throughout the record; the latest pulse of volcanic activity was at the end of the Tertiary.

3. Quaternary - The predominant geologic processes in Quaternary time have been volcanism filling the Nicaraguan Depression with pyroclastic debris, and isostatic changes along the graben structure in response to subduction. In the smaller Managua basin, the Quaternary overburden is believed to be 1.4 km thick; however, according to Kuang (1967), Soto (1966), Zoppis Bracci (1966), and Bice (1977), the average depth of the Nicaraguan Depression may not exceed a few hundred meters in other places.

2.4 QUATERNARY VOLCANISM AND THERMAL MANIFESTATIONS

A. Extent of Quaternary Volcanism

Several of the most promising geothermal fields and areas in Central America are associated with the chain of Quaternary Volcanoes which extends from Turrialba in Costa Rica to Tacana in Guatemala (Goldsmith, 1980). These volcanoes roughly parallel the Pacific coast and are marked by frequent eruptions and other volcanic activity. The Quaternary Volcanic Chain of Nicaragua is a part of this volcanic belt. Geothermal fields related to the volcanic chain include Moyuta and Zunil in Guatemala, Ahuachapan in El Salvador, San Jacinto and Momotombo in Nicaragua, and Miravalles in Costa Rica.

In Nicaragua, Quaternary volcanism is concentrated mostly in the Volcanic Chain, however, other Quaternary volcanic centers are found in the Nicaraguan Depression. Those in the northwestern Interior Highlands, and on the Atlantic Coast are small. A detailed description of Quaternary volcanism in Nicaragua is given by McBirney and Williams (1965).

Isolated cones and basalt flows from recent fissure eruptions are found in the Interior Highlands, generally in the region between Esteli and Ocotal. Three Quaternary volcanic centers are present at the eastern margin of the Nicaraguan Depression, east of Lakes Managua and Nicaragua, namely Cerro El Ciguatepe, Cerro San Jacinto and Las Lajas Caldera. They are generally composed of andesitic and basaltic lavas and associated pyroclastic debris. These volcanic centers are older than the present volcanic chain and are minor features developed during the last stages of massive fissure eruptions occurring in this area (Goldsmith, 1980).

B. Quaternary Volcanic Chain

The main area of volcanic activity in Nicaragua and the one in whch the Momotombo volcano and geothermal field are located is the Quaternary Volcanic Chain, the physiography and structure of which are described in this chapter.

The volcanic chain is presently active with plumes of smoke emanating from the San Cristobal, Telica, El Hoyo, and Momotombo volcanoes in the Marrabios Range. At least five volcanoes have had eruptions in the last 15 years, the more recent eruptions having occurred at Cerro Negro volcano in the El Hoyo complex in 1968, 1969 and 1972, and at Volcan Telica in 1977. Cosiguina volcano produced a Krakatoan explosion in recent history and the Masaya caldera and Volcan Concepcion, south of Managua, have vents which emit smoke and hot gases.

Santiago, also south of Managua, is the only Hawaiian-type shield volcano in Nicaragua. Its low, rounded slope formed by basalt upwelling contrasts with the steep, composite volcanic cones built up by the Strombolian eruptions characteristics of the the volcanoes in the Volcanic Chain. A small pool of glowing lava has been visible in the crater for several years.

Basaltic lavas and dacitic pumice are the most common rocks throughout the chain; intermediate compositions are rare in general, and completely absent in the Marrabios Range. The lavas are interbedded with scoriaceous tuff and other pyroclastics. In many instances, the youngest lavas are olivine basalts.

C. Momotombo Volcano

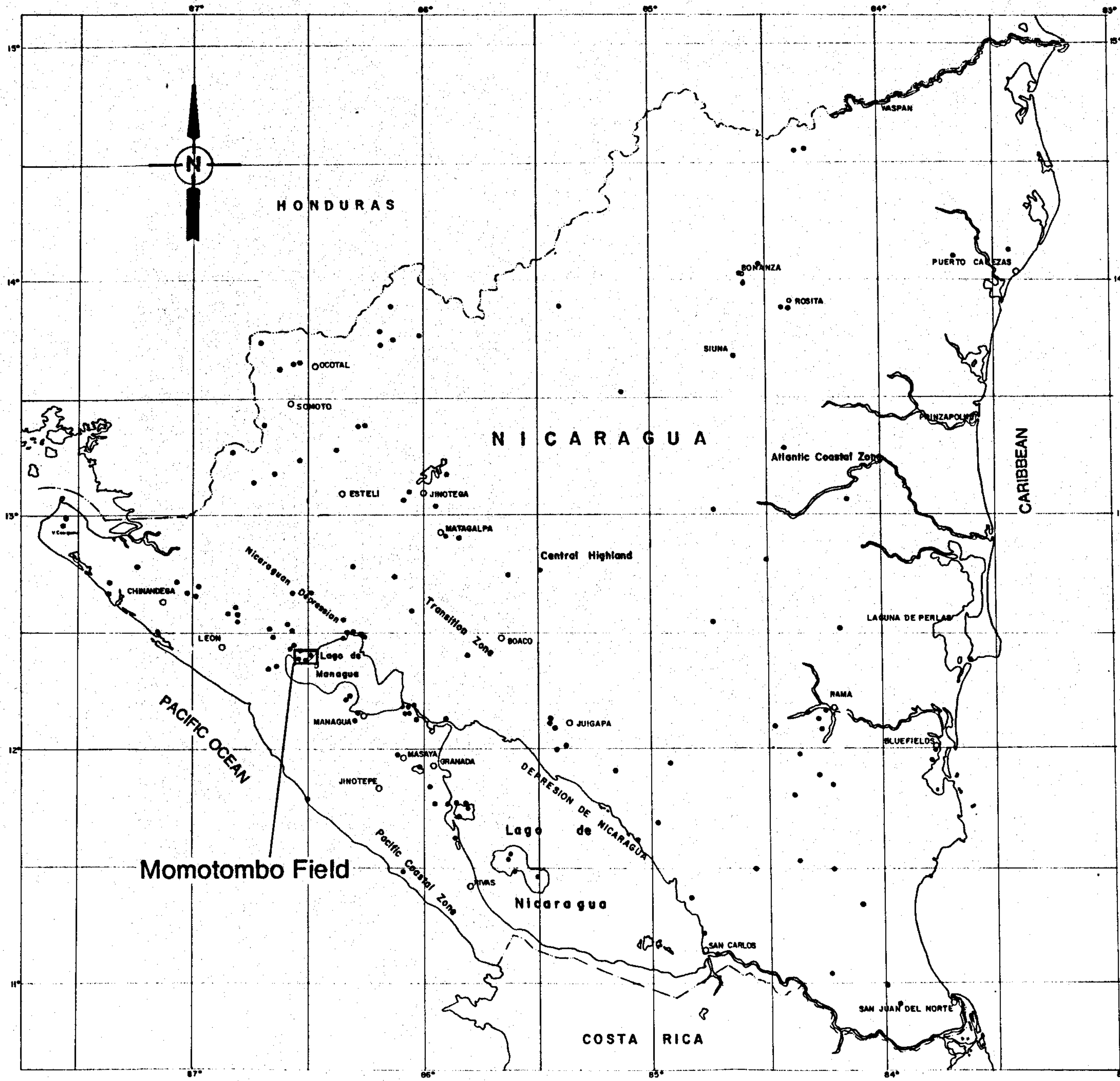
Momotombo, the southernmost volcano in the Marrabios Range, forms a large, symmetrical cone on the northwestern shore of Lake Managua and is one of the most familiar landmarks of Nicaragua. It rises to a height of 1170 m and covers an area of 65 km^2. The Monte Galan caldera is located northwest of the volcano. La Guatusa is a parasitic cone, located on the southeastern flank of Momotombo. Momotombito, another parasitic cone, forms a small island in Lake Managua.

The volcano has a long history of Strombolian activity which includes both explosive and lava eruptions. The last eruption occurred in 1905 and, since then, Momotombo has been in continuous fumarolic activity. The lavas erupted by the volcano are classified as olivine-bearing hypersthene basaltic andesites.

D. Thermal Manifestations

Numerous manifestations of thermal activity are present in Nicaragua, consisting of fumaroles, hydrothermally altered areas, thermal springs, and warm water wells (Figure 2-10). These thermal manifestations are concentrated largely in western Nicaragua, and the majority of them are associated with the Volcanic Chain and the Nicaraguan Depression (Texas Instruments, 1971).

Fumaroles are associated with young volcanoes of the Volcanic Chain. Thermal springs and wells with a wide temperature range from 30° to 96°C are found mostly in the Nicaraguan Depression, although there also



Legend

● Geothermal Manifestation

○ Principal Towns

0 20 40 60 80 100Km.

Scale

Geothermal Manifestations of Nicaragua

Figure 2-10

occurences in the Volcanic Chain. Thermal springs occur at the bottom of Lake Managua and probably in Lake Nicaragua. A very small number of warm springs are found on the coastal plain, ranging up to 50°C.

The Interior Highlands contain a considerable number of hot springs and warm wells ranging in temperature from 28° to 75°C. However, they are scattered over a large area and are more rare in this region.

The thermal manifestations in Nicaragua have been divided into three groups (Texas Instruments, 1971):

1. Fumaroles associated with recent volcanic activity.

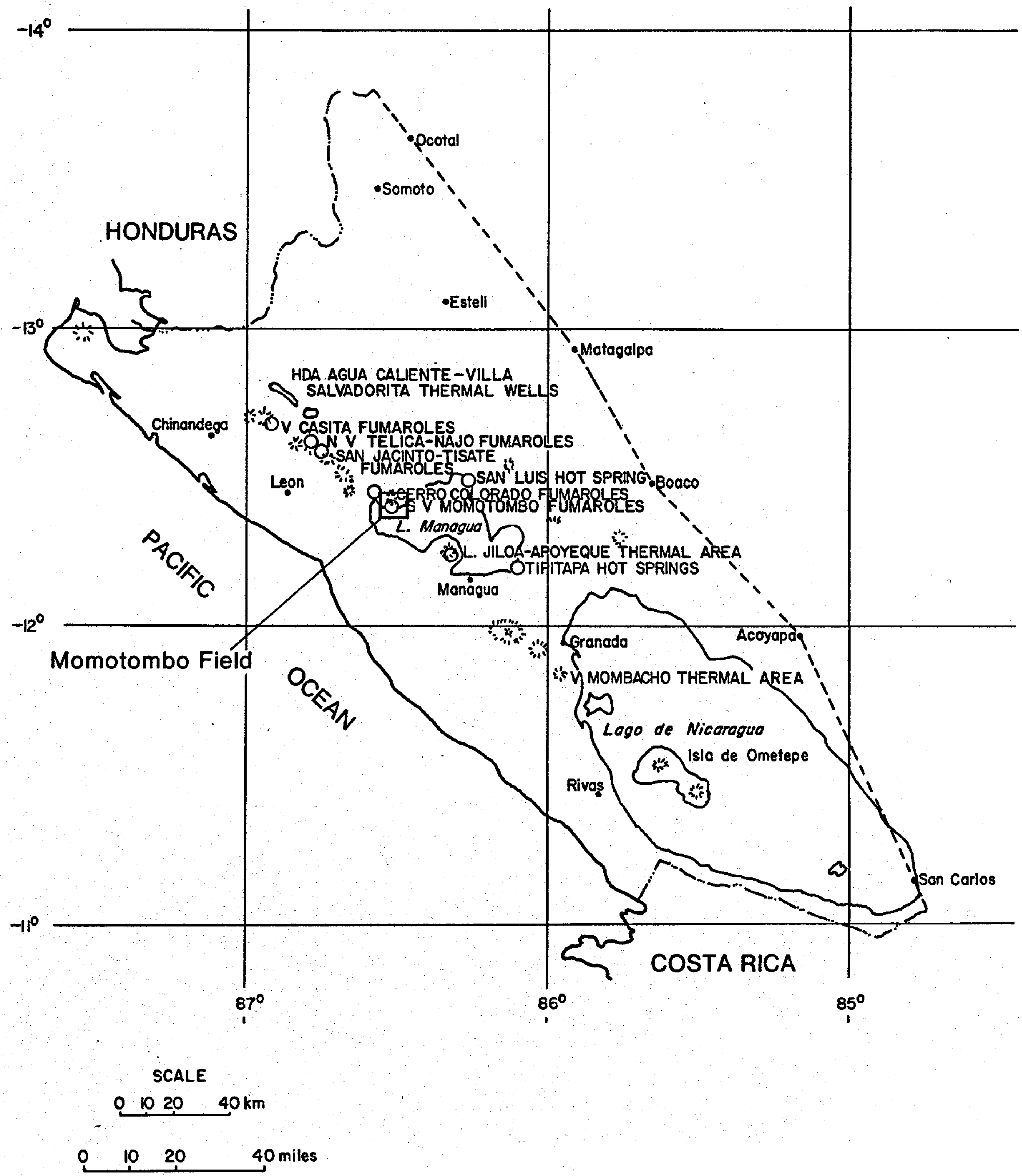
2. Thermal springs associated with postulated magma chambers at moderate depth or with fluid flow through faults and fissures.

3. High or low springs not directly connected with any recent volcanic activity, generally associated with a deep or older magmatic source of heat.

Of these three, Texas Instruments determined that the second type has the highest potential for development of geothermal resources. Surface temperatures are generally less than 100°C but, with increasing depth, higher temperatures and possibly steam may be encountered.

The majority of thermal manifestations are related to faults or fracture zones. These features undoubtedly have acted as conduits permitting hot fluids to reach the surface.

The major thermal areas of the Volcanic Chain and the Nicaraguan Depression are shown on Figure 2-11. The southern slopes of Momotombo have the most extensive area of thermal alteration in Nicaragua. Fumaroles and hydrothermal alteration cover an area of 0.75 km^2 at elevations ranging from 39 m to 340 m. Thermal springs with tempera-



Major Thermal Areas of Western Nicaragua

tures up to 101°C are also present. Further north near Telica Volcano, the San Jacinto thermal area has boiling mud pools and hydrothermally altered areas.

CHAPTER 3
HISTORY OF EXPLORATION

3.1 STRATEGY AT ONSET OF PROGRAM

The Government of Nicaragua originally planned the investigation of geothermal resources in three stages:

STAGE 1 - Location and delineation of a potential geothermal field or fields.

STAGE 2 - Proving of a potential geothermal field or fields by deep exploratory drilling.

STAGE 3 - Design and development of a geothermal power plant.

This report deals with the exploration phases of the Momotombo geothermal area, and is divided into 4 new stages based on exploration strategy. These stages are:

STAGE 1 - Reconnaissance geoscientific studies.

STAGE 2 - Detailed geologic, geophysical, and geochemical investigations.

STAGE 3 - Data accumulation and interpretation during exploration drilling

STAGE 4 - Reservoir engineering studies (not discussed).

3.2 DEVELOPMENT SCHEDULE

Since 1966 the Momotombo area has been considered for further exploration with the purpose of finding an exploitable geothermal reservoir. Figure 3-1 shows the various stages during the investigation of this field and the techniques used in each phase. A summary of all previous work follows:

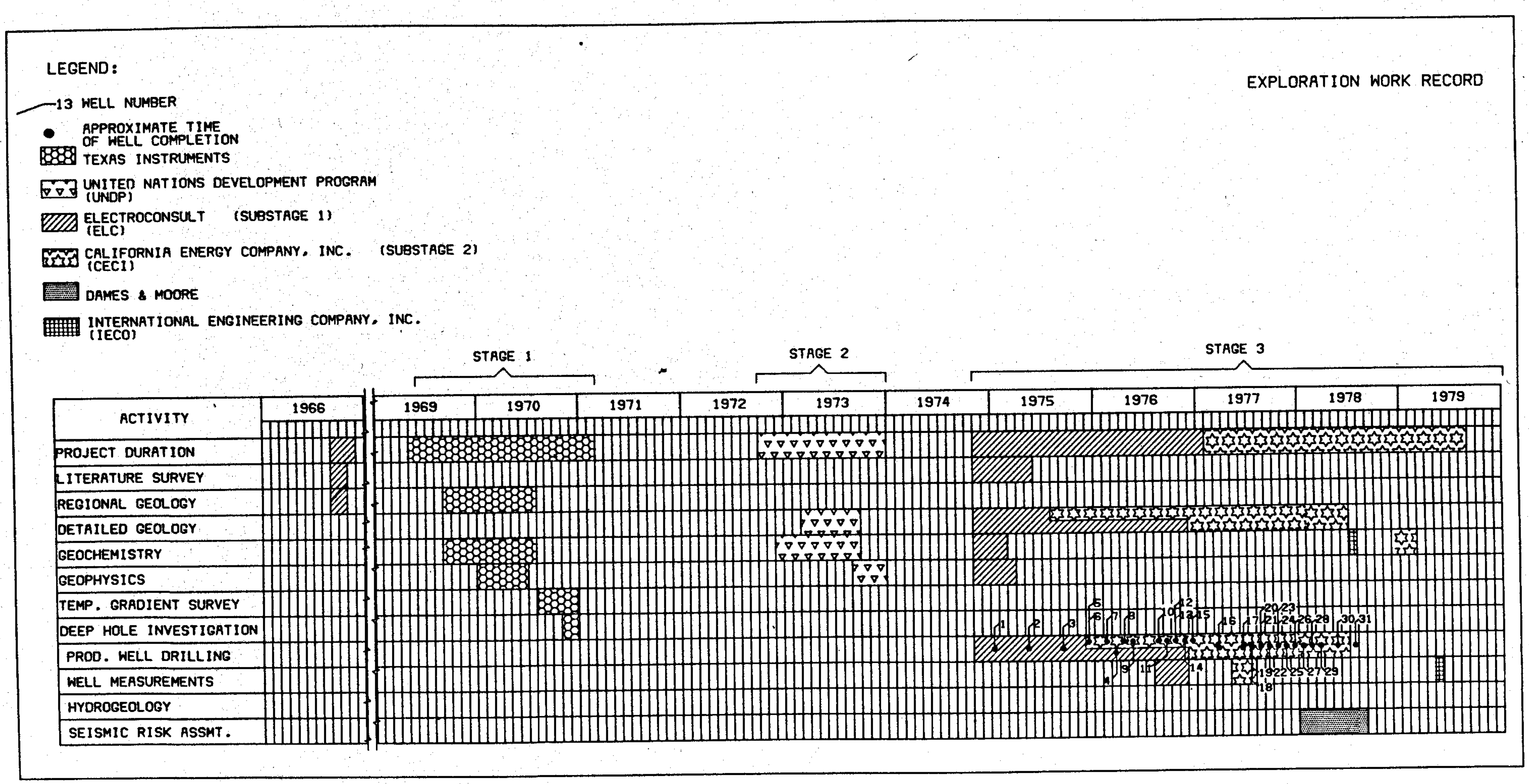
- September to November, 1966 - Electroconsult made a preliminary evaluation of the geothermal potential of Nicaragua.

- June 1969 to February 1971 - Texas Instruments, Inc. completed a reconnaissance exploration program covering an extensive area of western Nicaragua. Its purpose was to locate and delineate a geothermal field or fields. Based on these investigations, Momotombo was chosen as a prime development target.

- October 1972 to December 1973 - The United Nations Development Program (UNDP) continued studies at Momotombo and adjoining areas.

- November 1974 to June 1976 - Electronconsult (ELC) planned and supervised an initial four-well exploration and development program of the Momotombo field. The result of this study was a Feasibility Report which included the first conceptual reservoir model and preliminary power development plans.

- August 1975 to May 1979 - California Energy Company, Inc. continued development of the Momotombo field. Twenty-nine additional production-exploration wells were drilled. Geologic studies, subsurface temperature analyses and production well test were also performed, in addition to temperature gradient hole drilling at other locations.



EXPLORATION WORK RECORD
LEGEND:
13 WELL NUMBER
APPROXIMATE TIME OF WELL COMPLETION
TEXAS INSTRUMENTS
UNITED NATIONS DEVELOPMENT PROGRAM (UNDP)
ELECTROCONSULT (SUBSTAGE 1) (ELC)
CALIFORNIA ENERGY COMPANY, INC. (SUBSTAGE 2) (CECI)
DAMES & MOORE
INTERNATIONAL ENGINEERING COMPANY, INC. (IECO)
STAGE 1
STAGE 2
STAGE 3
ACTIVITY
1966
1969
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
PROJECT DURATION
LITERATURE SURVEY
REGIONAL GEOLOGY
DETAILED GEOLOGY
GEOCHEMISTRY
GEOPHYSICS
TEMP. GRADIENT SURVEY
DEEP HOLE INVESTIGATION
PROD. WELL DRILLING
WELL MEASUREMENTS
HYDROGEOLOGY
SEISMIC RISK ASSMT.

Figure 3-1

- January 1978 to June 1979 - International Engineering Company (IECO) performed a regional geothermal exploration program in Nicaragua, followed by detailed studies at several sites.

- May 1979 to June 1979 - IECO and ENALUF (now INE) initiated a long term flow testing for eight wells. Continuous monitoring and sampling was interrupted from mid-June until late September, when work recommenced.

- August 1979 to Present - Electroconsult was involved with Instituto Nicaraguense de Energia (INE) in continuing the well testing program, reservoir engineering studies, and subsequent plant design. Organizacion Latinoamerica de Energia (OLADE) and their consultants have also contributed technical support to INE at Momotombo. In January 1982 the Geothermal Resources Council Bulletin, Vol. 11, No. 1, reported that Instituto Nicaraguense de Energia (INE) had signed a two million dollar contract with a French firm for further drilling and geophysics at Momotombo. It was reported that a 30 MW plant would be installed in 1982.

CHAPTER 4
EXPLORATION METHODS USED

4.1 STAGE I - Conducted by Texas Instruments Company

A. Geological Methods

The purpose of Stage 1 geological investigations was two-fold: 1) to locate and evaluate all thermal manifestations in western Nicaragua, with emphasis on features indicative of hyperthermal zones with anomalously high subsurface temperatures; 2) to map the surface geology on the south flank of Momotombo volcano in as much detail as possible, and to locate all hydrothermally altered areas as part of an evaluation of the geothermal power possibilities in this zone. The time chart and work plan are shown in Figure 3-1.

1. Surface Investigations

a. Regional Geology - Volcan Momotombo, a semi-active composite volcano and part of the Quaternary Volcanic Chain of western Nicaragua, dominates this area. The range of volcanoes is localized along a northwest-trending, structurally weak zone, probably a major fault, along or near the western side of the Nicaraguan Depression. The Depression has the general surface characteristics of a broad graben but the structure is probably more complicated, involving block faulting or downwarping. Investigations prove that several of the volcanoes in the area have had recent ash or lava eruptions. Pyroclastic rocks dominate the volcanic range with andesitic and basaltic lavas also present in varying amounts.

b. Surficial Geology - Photogeology was extensively utilized in the evaluation of areas around fumaroles. Photogeology, with extensive field work, was used to map and identify the surface geology of the area. The area north of Volcan Momotombo consists primarily of Quaternary pyroclastic rocks including tuff, tephra and dacitic pumice deposits. South of the volcano there are several groups of fumaroles and thermal springs. Within this area two main groups of rocks have been identified and mapped. They include young volcanic deposits referred to as "Volcan Momotombo Rocks" which are predominantly basaltic cinders and ash, forming a tuff of varying degrees of induration. Older layers of volcanic rocks lying below, and forming a low plateau southwest of Volcan Momotombo, consist of lava flows of basalt and andesitic basalt which are erratically distributed vertically and laterally throughout the pyroclastic deposits.

The "Older Volcanic Rocks", possibly of early Quaternary age, form the low plateau southwest of Volcan Momotombo. Here, exposed pyroclastic rocks, mainly well indurated tuff and agglomerate-volcanic breccias, predominate. Less abundant are interbedded lava flows of andesitic basalt and basalt. Hydrothermally altered areas occur in five general groups closely associated with zones of barren vegetation. These zones of alteration vary in intensity from slight to very severe with bleaching, argillization and silicification at the more active or previously more active fumaroles.

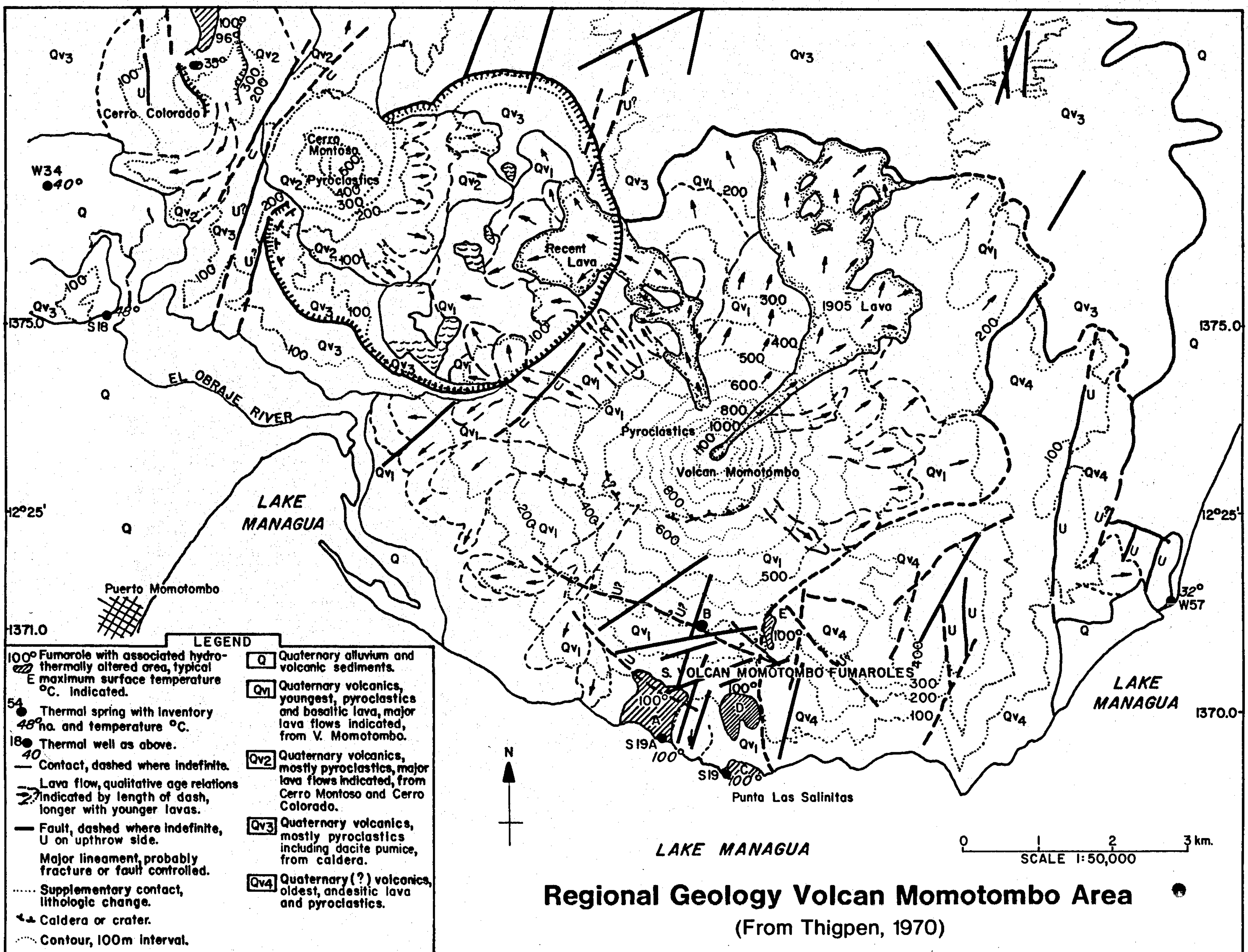
c. Field Mapping - Field mapping was restricted to a few areas, such as Momotombo, since the large area, the limited time, and lack of personnel precluded total coverage of the Quaternary Volcanic Chain. Only one geologist was utilized in the entire geological exploration and this limited the amount of information gathered. Field work was productive in the altered areas where mapping of surface expressions was feasible. The lack of outcrops in the surrounding areas is related to a mantle of variable thickness of recent volcanic cinders (Thigpen, Texas Instruments, 1970). Thick vegetation covered much of the area except for the altered sites.

Thermal areas were delineated and briefly described, and a regional geologic map was produced from these investigations (Figure 4.1). The total area of surface alteration at Momotombo is about .75 km^2, Fumaroles, boiling hot springs, hydrothermally altered ground, and siliceous sinter deposits are present.

d. Structural Geology - With the help of aerial photography, lineaments were located and these were assumed to represent faults and/or fracture zones. The dominant structural feature in the area is a northwest trending probable major fault represented by the alignment of the Volcanic Chain. At the present time the fault is only inferred because all direct evidence is concealed by Quaternary volcanic deposits. There are also several other northwest trending inferred faults and fracture zones (Figure 4.1), two of which are especially significant in the possible control of hydrothermal alterations. Both these faults are normal, steeply dipping and downthrown to the south-east. These and several other inferred faults are mapped as a result of aerial photograph interpretation, based on the apparent alignment of altered areas.

e. Petrology - Identification of surface rocks enabled classification into two main rock groups: Older Volcanic Rocks and Volcan Momotombo Rocks. This division allows some distinction to be made between formations. The Older Volcanic Rocks are possibly of early Quaternary age and are composed of well indurated tuff, andesite, andesitic basalt and basalt. The younger Volcan Momotombo Rocks compose most of the volcanic cone and consist of tephra, basalt, andesitic basalt, and olivine basalt interbedded with pyroclastic deposits. Figure 4.1 shows the surface distribution of the various ejecta and flows on and surrounding the volcano.

Examination of hydrothermally altered rocks by detailed petrographic analysis might have shown zonal distribution of alteration, as was the case in the Matsukawa Geothermal Field in Japan (Sumi, 1968). If this



Regional Geology Volcan Momotombo Area
(From Thigpen, 1970)

Figure 4-1

had been done at Momotombo it would have aided the investigations of delineating the major faults which control fluid flow by: 1) following the alignment of altered areas, and 2) observing the alteration sequence from earliest to most recent.

2. Subsurface Investigations

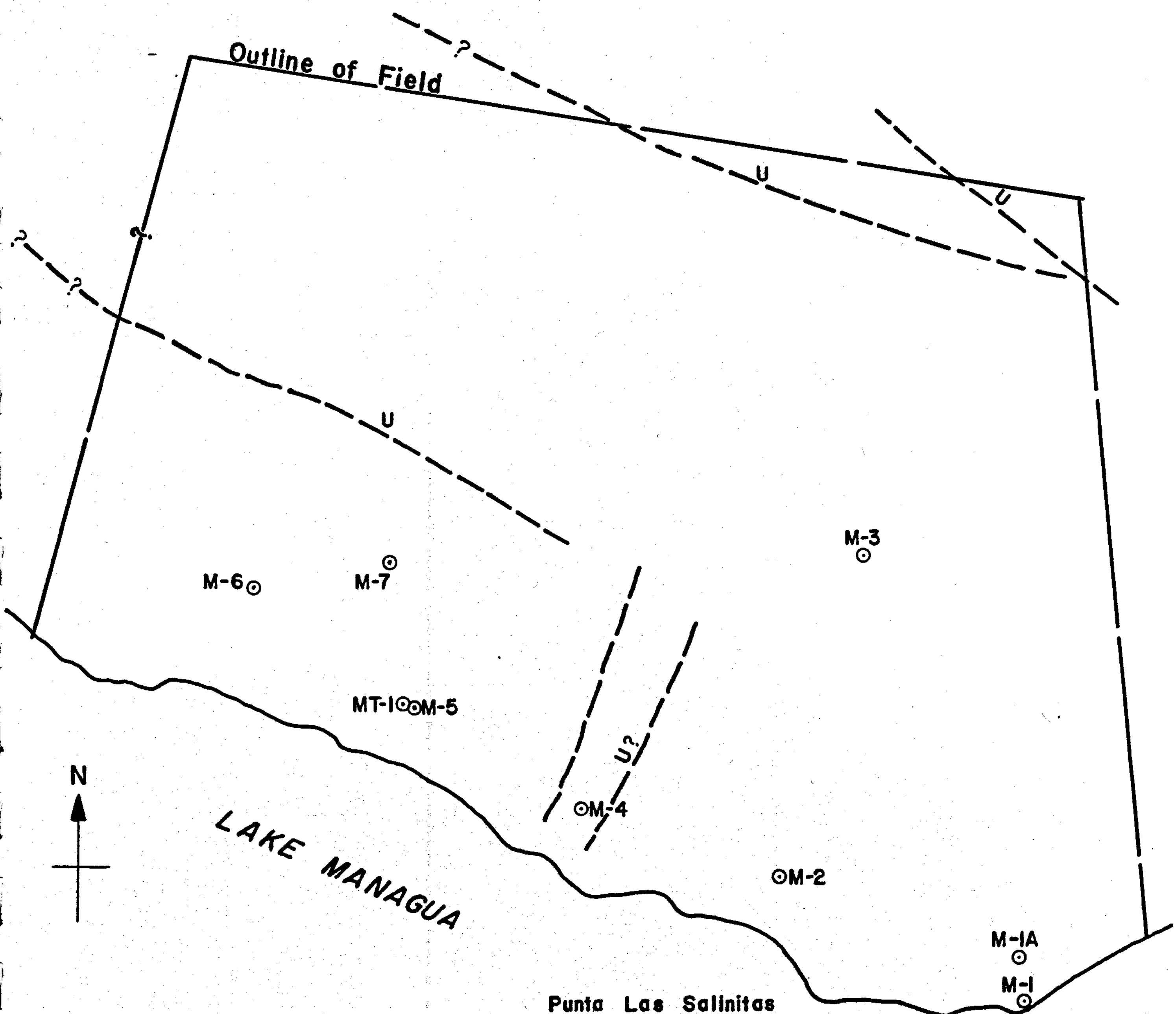
a. Temperature Gradient Hole Drilling - Eight temperature gradient holes were drilled in the Momotombo area with average depth of 55 m and one 608 m deep stratigraphic hole, MT-1. Locations of these holes are shown in Figure 4.2. Some important information on the subsurface geology was obtained from the lithologic descriptions, however, other geological investigations such as petrology and mineralogy, which would encompass hydrothermal mineral alteration studies and fluid inclusion geothermometry, would have increased the amount of data obtained from this field. Figures 4.3 through 4.10 show the information obtained from these holes. The methods used were not adequate to allow the production of a geologic model and to make valuable inferences about the reservoir. Binocular microscope investigation of cuttings from the eight temperature gradient holes concluded that surface layers, having thicknesses of approximately 7 m, consisted of weathered basaltic cinders, tuff, and altered, surrounded fragments. Lower layers consisted almost exclusively of basalts differentiated by color and degree of alteration, occasionally separated by layers of brecciated tuff.

After evaluating the results of MT-1, (the deep test borehole) the lithographic sequence was interpreted to contain basaltic lava flows interlayered with moderately to intensely altered tuff from Volcan Momotombo to a depth of 65.5 m. This substantiates earlier findings. Below 65.5 m the rocks are apparently pre-Volcan Momotombo in origin and consist of pyroclastic deposits, often intensely altered, with minor andesitic and basaltic lava flows.

Figure 4-2

Location of Temperature Gradient Holes

(from Thigpen, 1970)



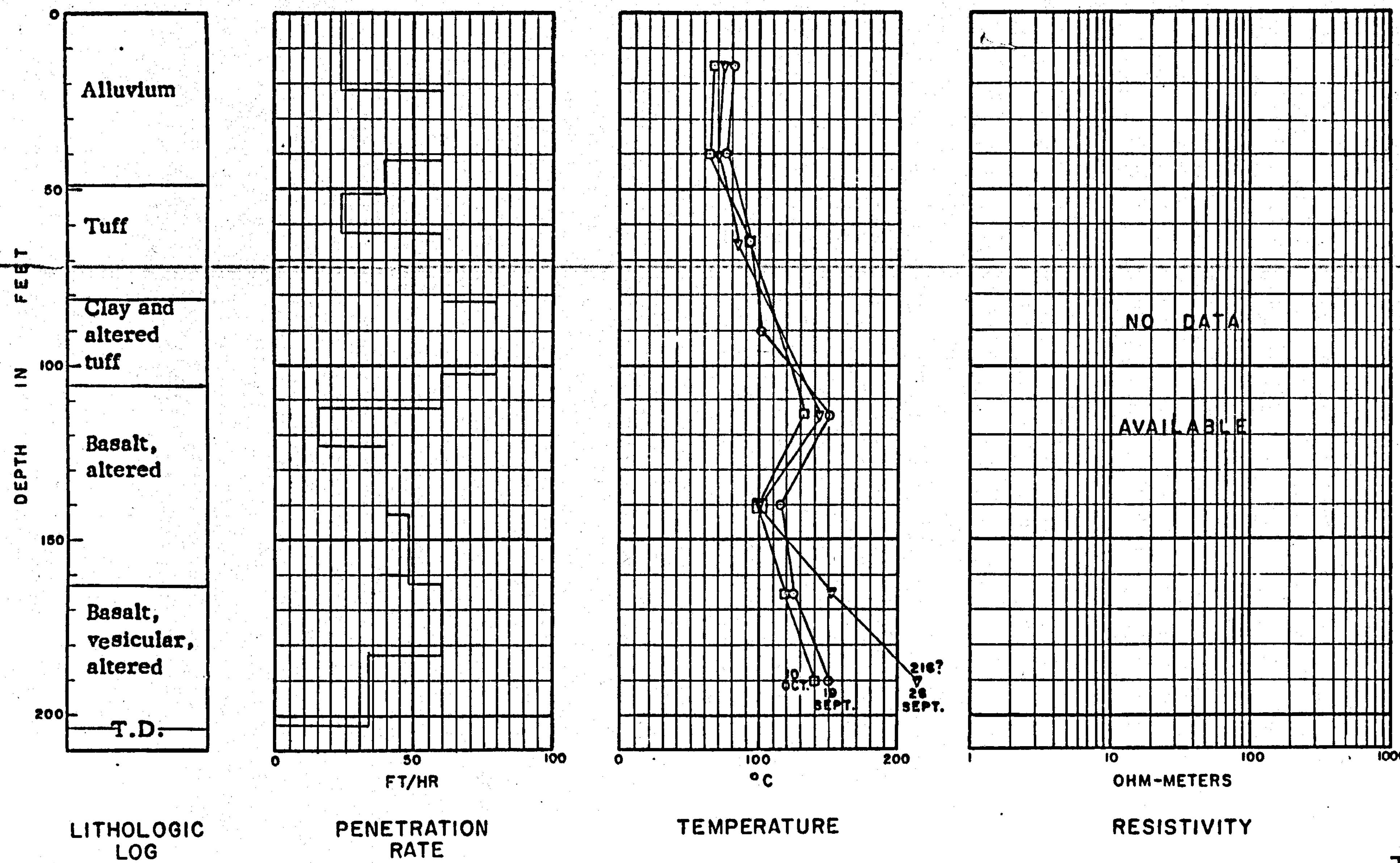
LEGEND

M-3 ⊙ Gradient hole number and location

Inferred fault

MT-1 ⊙ Exploratory well

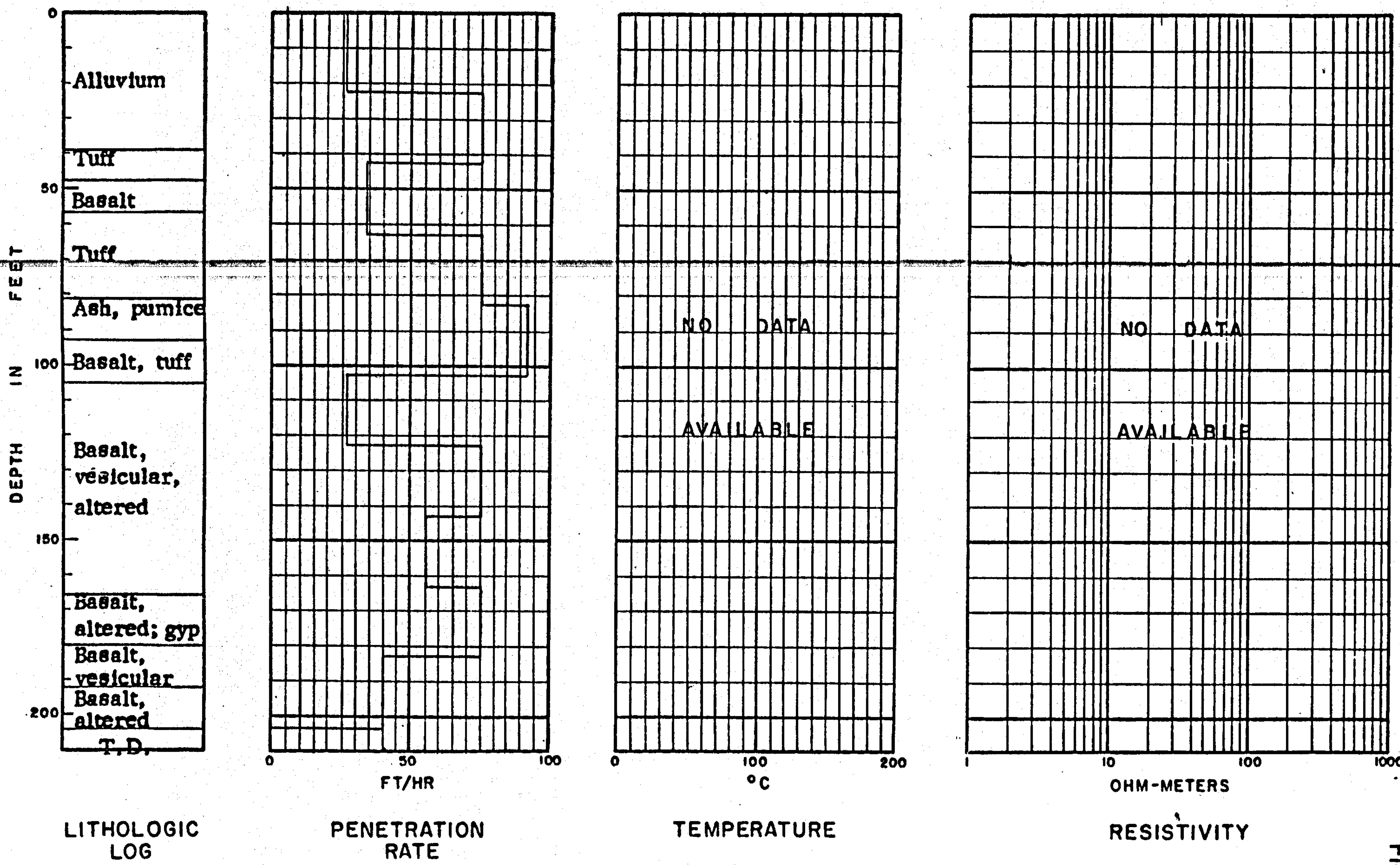
Scale 1:10,000



Gradient Well No. M-1

(From Texas Instruments, 1971)

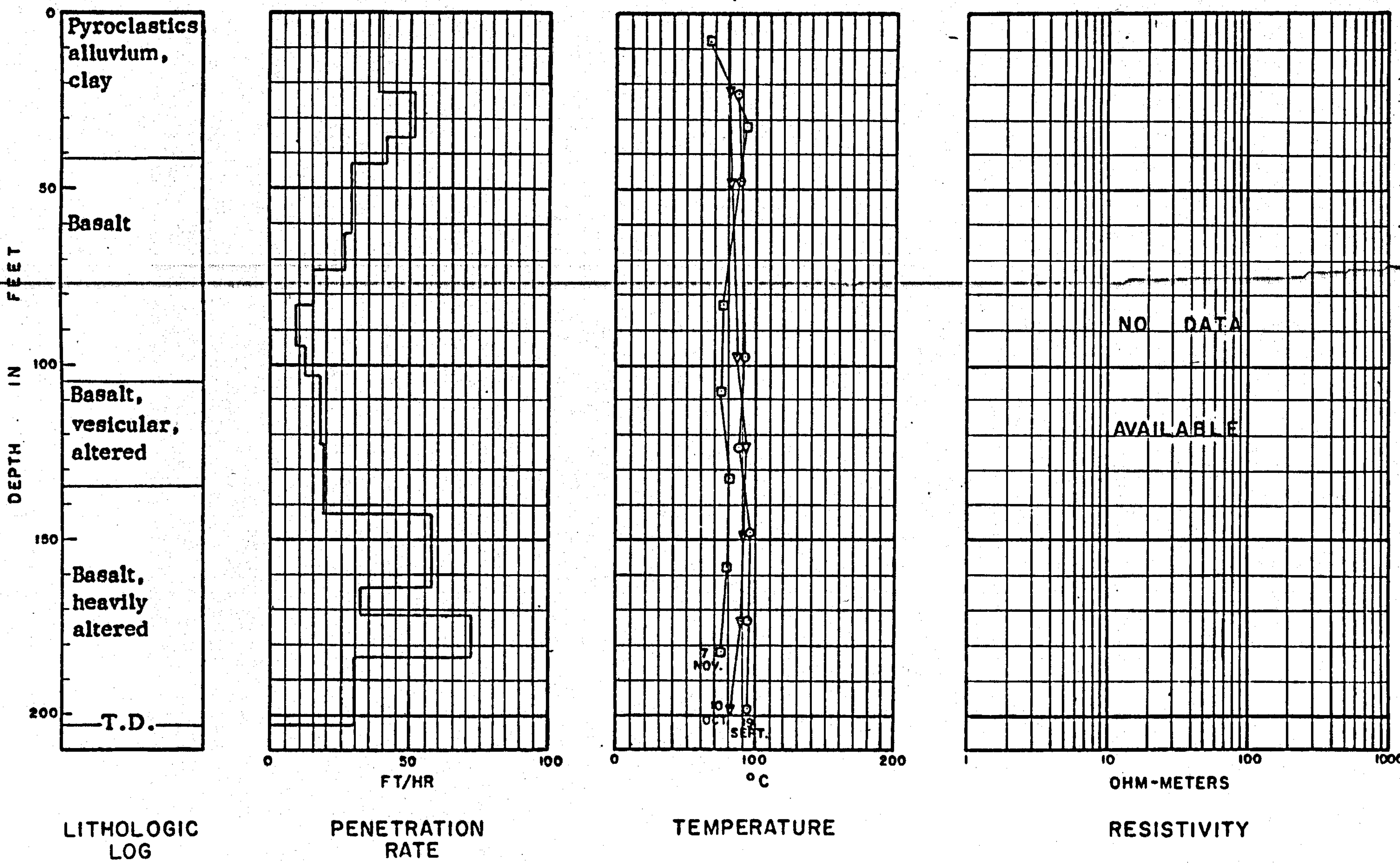
Figure 4-3



Gradient Well No. M-1A

(From Texas Instruments, 1971)

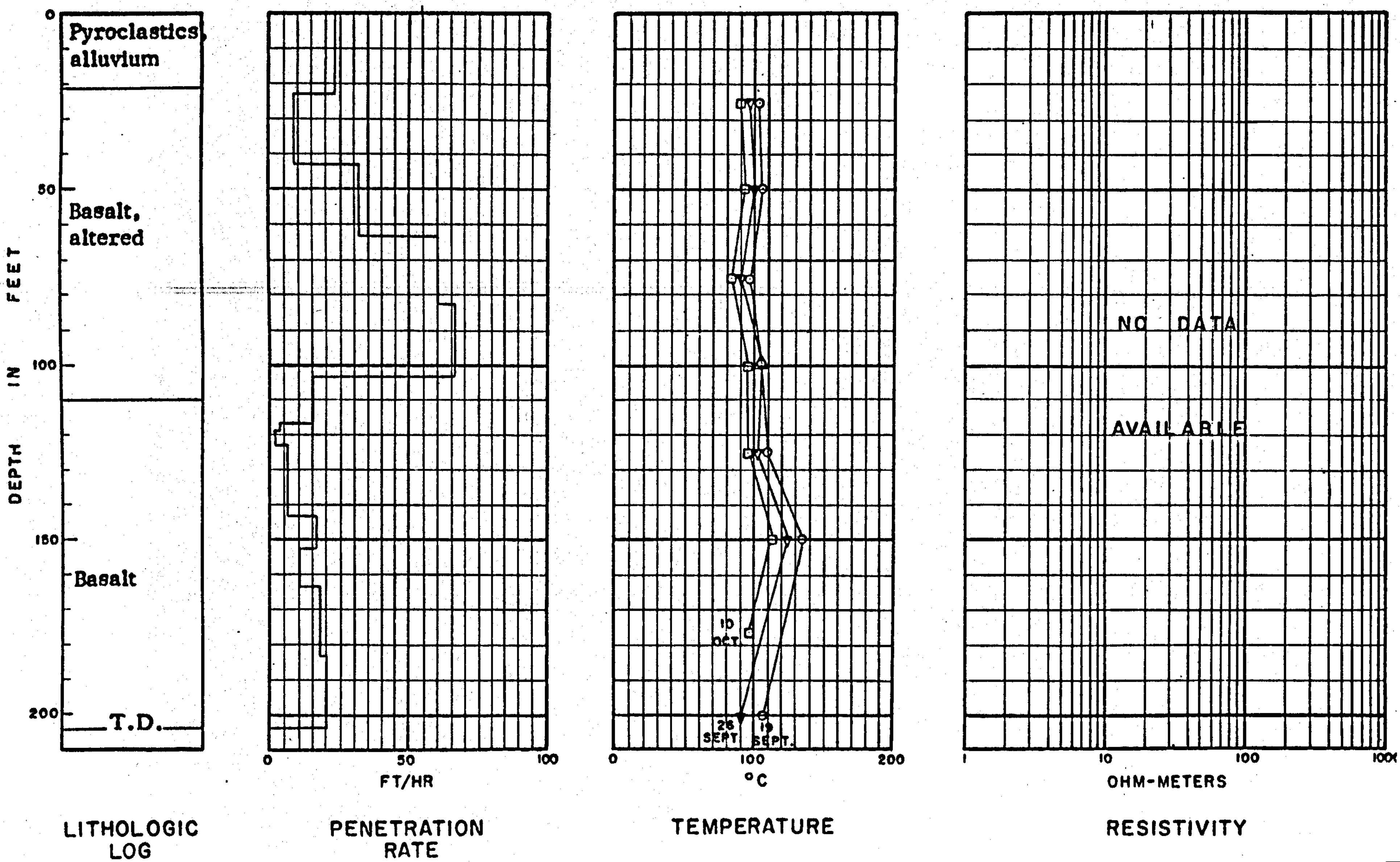
Figure 4-4



Gradient Well No. M-2

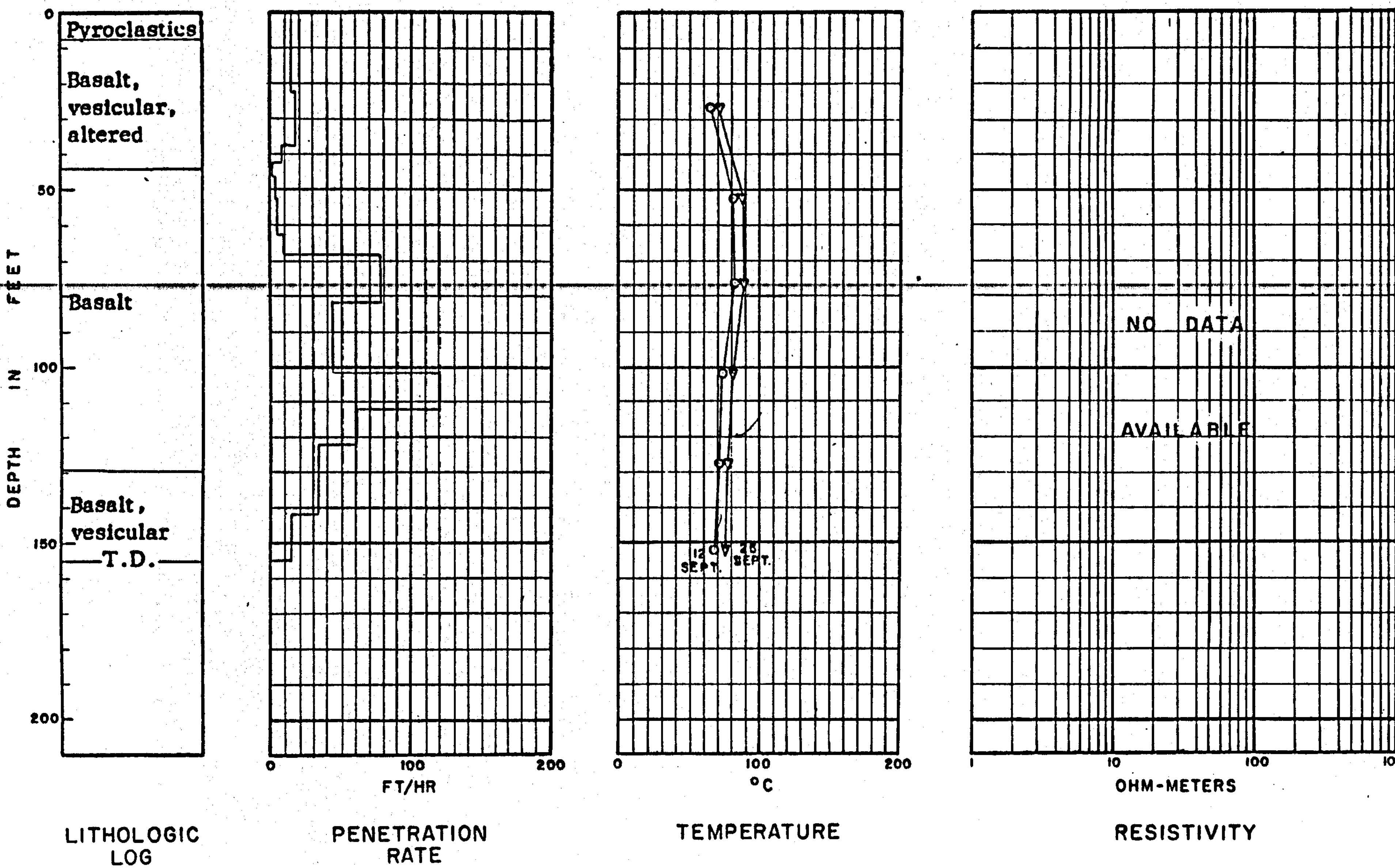
(From Texas Instruments, 1971)

Figure 4-5



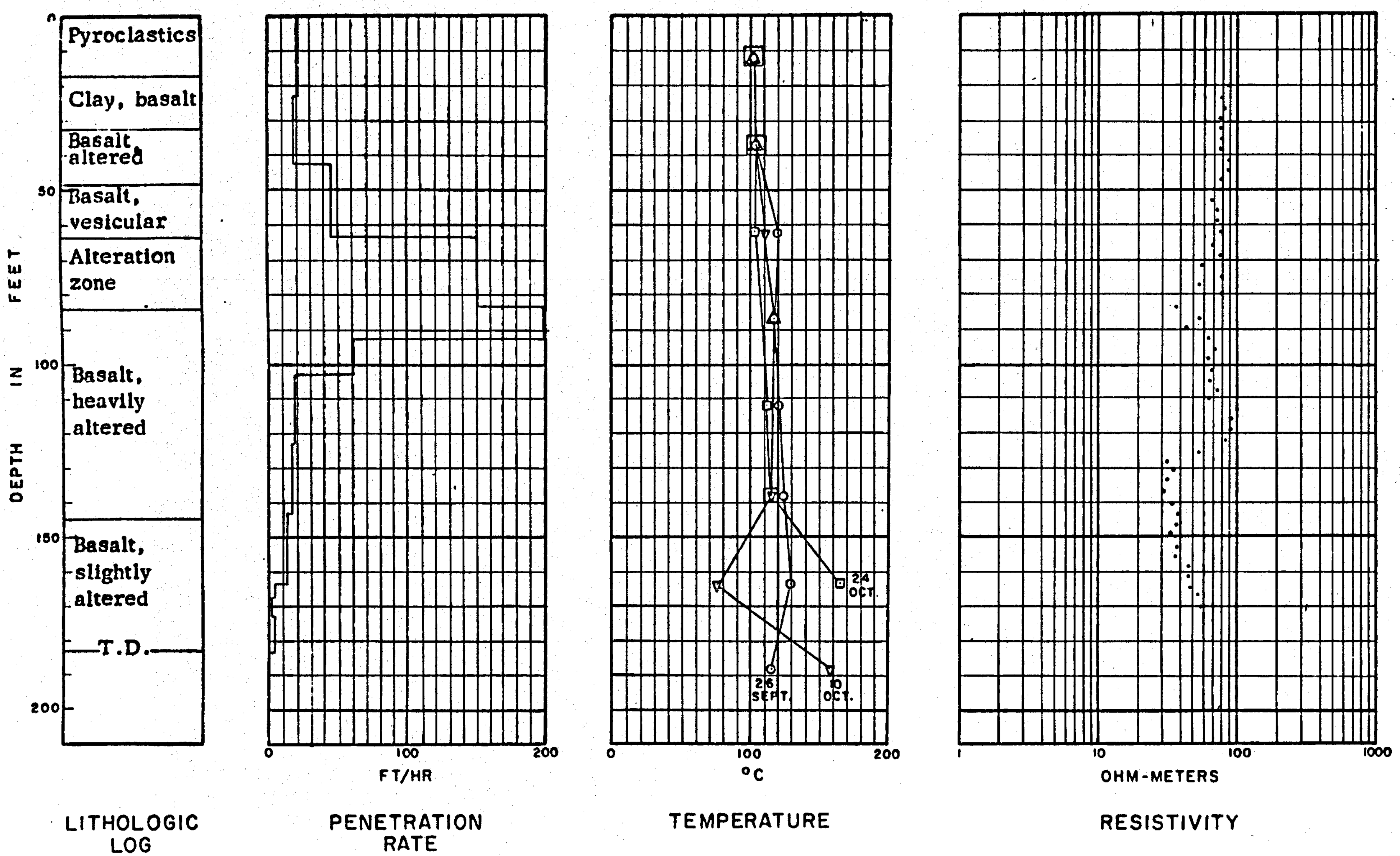
Gradient Well No. M-3
(From Texas Instruments, 1971)

Figure 4-6



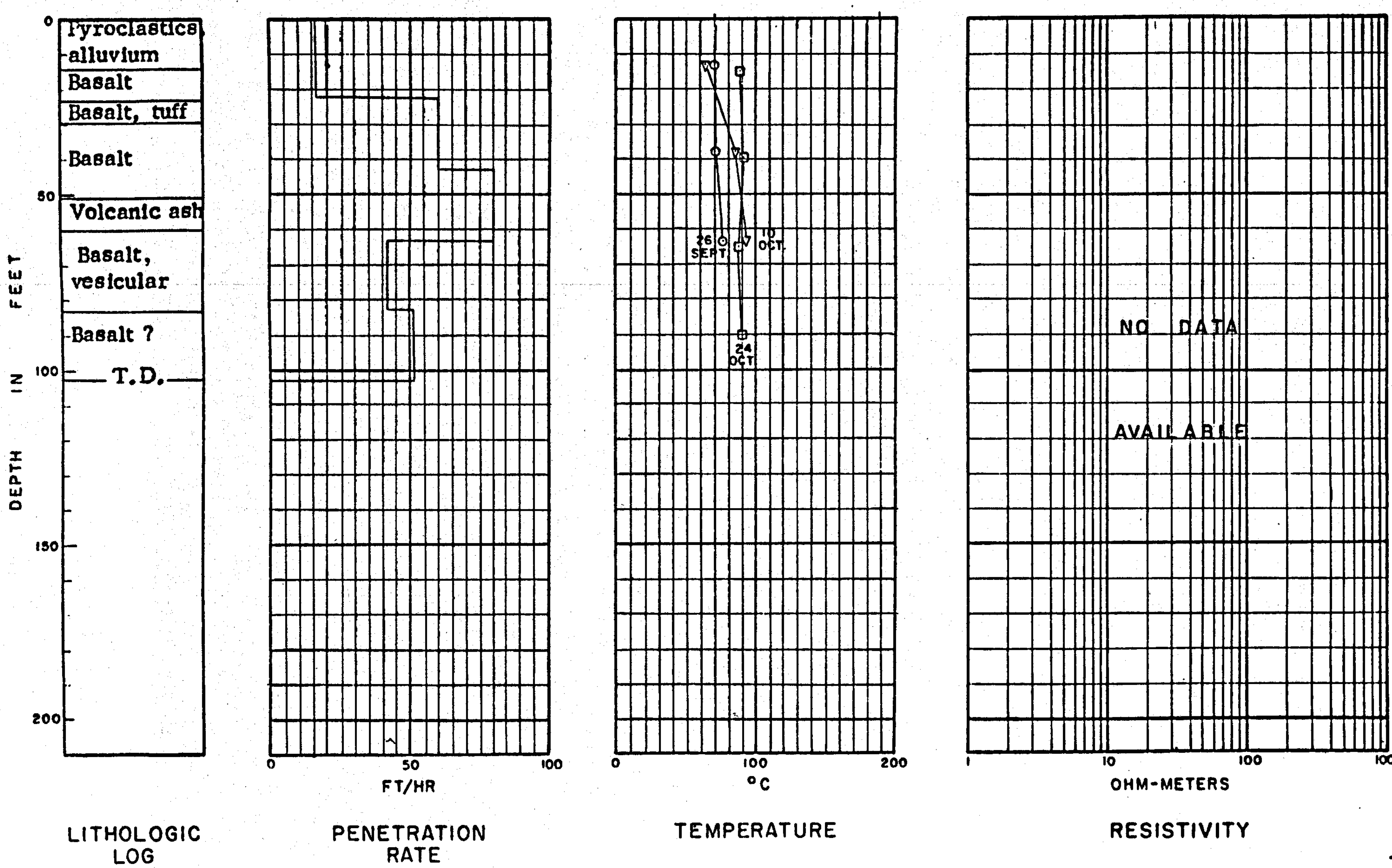
Gradient Well No. M-4
(From Texas Instruments, 1971)

Figure 4-7



Gradient Well No. M-5
(From Texas Instruments, 1971)

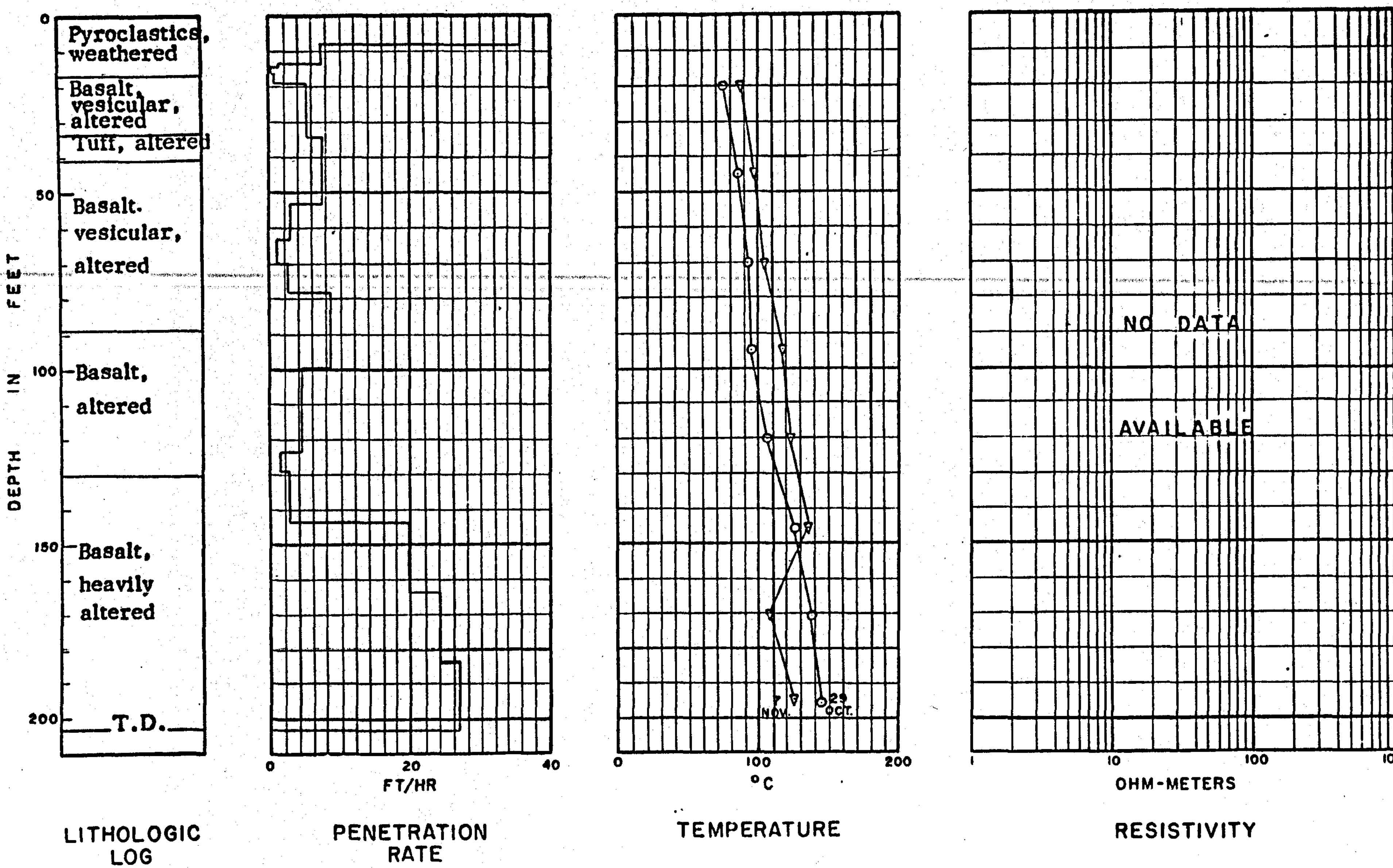
Figure 4-8



Gradient Well No. M-6

(From Texas Instruments, 1971)

Figure 4-9



Gradient Well No. M-7

(From Texas Instruments, 1971)

Figure 4-10

b. <u>Drillhole Correlation</u> - At Momotombo the reservoir rocks consist of lavas and pyroclastics so similar to one another that very detailed petrologic and perhaps geochemical studies are needed. No cross sections, structural contour maps, isopach map or panel diagrams were produced.

c. <u>Petrology</u> - Binocular microscope examination provided only the minimum information for construction of a lithologic column in each hole. Even though some heavily altered rocks were encountered and described, no further steps were taken to examine the hydrothermal rock alteration. The technique of petrographic analysis of altered rocks is widely used (New Zealand, Japan, Iceland and Mexico) to make deductions about reservoir conditions (Browne, 1970; Yamasaki, 1970; Kristmannsdottir, 1975, Elders and Hoagland, 1978). If it had been used at Momotombo it would have provided information about the hydrothermal processes occurring in the reservoir.

d. <u>Subsurface Temperature Distribution</u> - Texas Instruments suggests there are two possible mechanisms for localization of the thermal activity associated with the previously mentioned fumaroles and hot springs. The first is a vertical rise of hydrothermal fluids along fractures; the second is lateral downslope movement of hydrothermal fluids within the more permeable layers of volcanic deposits. The lack of thermal activity in the zone between the two northwest trending inferred faults or fault zones supports the interpretation of vertical flow along fractures, and similarly the occurrence of fumaroles upslope from northwesterly inferred faults tends to support the lateral flow hypothesis. Both types of hydrothermal fluid movement are probably found within the Volcan Momotombo area.

The eight temperature gradient wells were drilled for the following purposes: 1) to determine physical parameters of the rock necessary to quantify and evaluate the areal resistivity survey (discussed in 4.1.B); and 2) to obtain temperature gradients which, with the areal resitivity values, permitted the calculation of the heat flux of the underlying geothermal cells. Temperature gradient graphs were drawn using the data collected from the wells, as shown in Figures 4-3 through 4-10. Generally, measured down hole temperatures ranged from 115° to over 150°C. The results from the temperature gradient wells were encouraging. Data from MT-1, when graphed, showed a gradual increase of temperature from 179°C at 30.5 m to 205°C - 209°C at 221 m. Eleven hours after drilling operations were suspended, water and steam erupted violently from this well. A mixture of water, steam, mud, and small rocks spewed out for 20 minutes until the master valve of the well was closed.

3. Conclusions - The Stage 1 investigations, which included regional and detailed geologic mapping were beneficial in a reconnaissance sense in locating and delineating potential geothermal fields.

However, the omission of detailed petrographic studies, for both surface and drillhole samples, was unfortunate. Planning of future geothermal geologic work in other areas in Nicaragua should include these techniques.

B. Geophysical Methods

The purpose of Stage 1 investigations was to locate and delineate a potential geothermal field or fields in western Nicaragua. Two zones were covered in detail, San Jacinto and Momotombo. At Momotombo, several electrical prospecting methods were used, some already well established in other geothermal areas and some relatively new to geothermal exploration. The techniques used at Momotombo were Schlumberger soundings, dipole mapping surveys, electromagnetic soundings, audiomagnetotelluric surveys, gravity, magnetics, and thermal measurements. Their applicability and usefulness in Stage 1 investigations are discussed in the following sections.

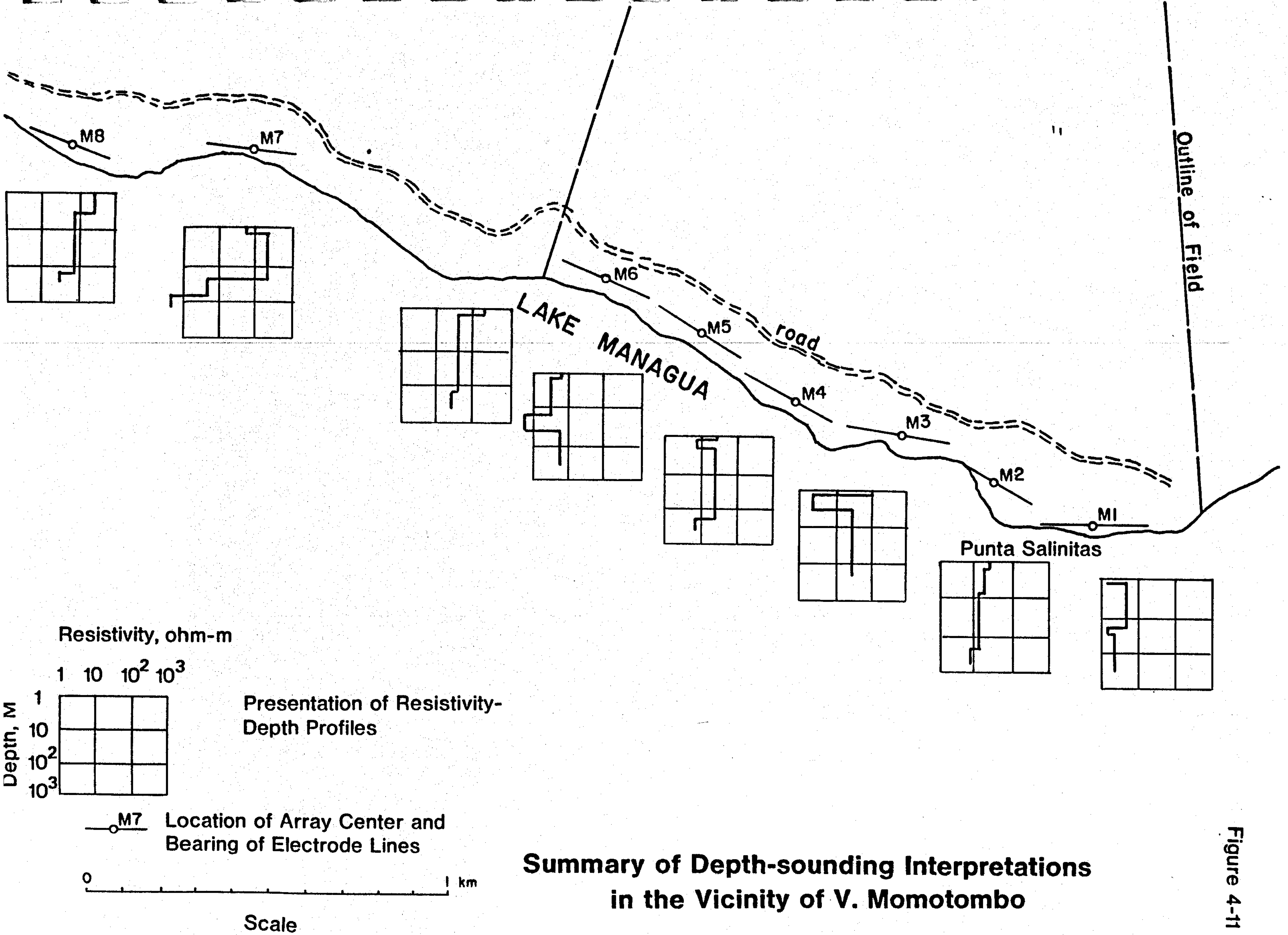
1. Electrical Prospecting Methods

a. Schlumberger Soundings - Eight Schlumberger soundings were performed in the Momotombo prospect. The resultant sounding curves for each point have been interpreted in terms of a sequence of several horizontal layers. This model probably has very little resemblance to the true underground distribution of resistivity in the area (Banwell, 1971) but is the only model which can be used effectively with the theoretical curves then available. There is thus little correlation between the pseudo-layering found in neighboring soundings, or even among the results of soundings taken at nearly the same points. Keller (1971) points out that high surface resistivities in the volcanic rocks lead to erratic measurements of resistivity, and the difficulty in driving sufficient current into the ground probably gave inaccurate measurements.

The maximum depths attained and interpreted from the soundings at Momotombo range between 300 and 400 m. This depth is insufficient to reach the low resistivity formation which lies at 1400 to 1700 m, as indicated by the electromagnetic soundings. Banwell (1971) states that there is no effective check from these soundings on the existence of what are possibly the only structures with sufficient continuity and horizontal extent to make the layer model interpretation meaningful. Two-dimensional and possibly three dimensional earth models would have been more appropriate.

Results of these soundings are shown in Figure 4.11. Low resistivities, less than 1 ohm-meter, were found in the areas where surface geothermal activity is most abundant.

b. Dipole Mapping Surveys - Two dipole mapping surveys were conducted in the Momotombo area with two source dipoles, M1 and M2, located along the shores of Lake Managua. Source dipole M2, having an electrode separation of 2000 m, was located approximately 6 km east of

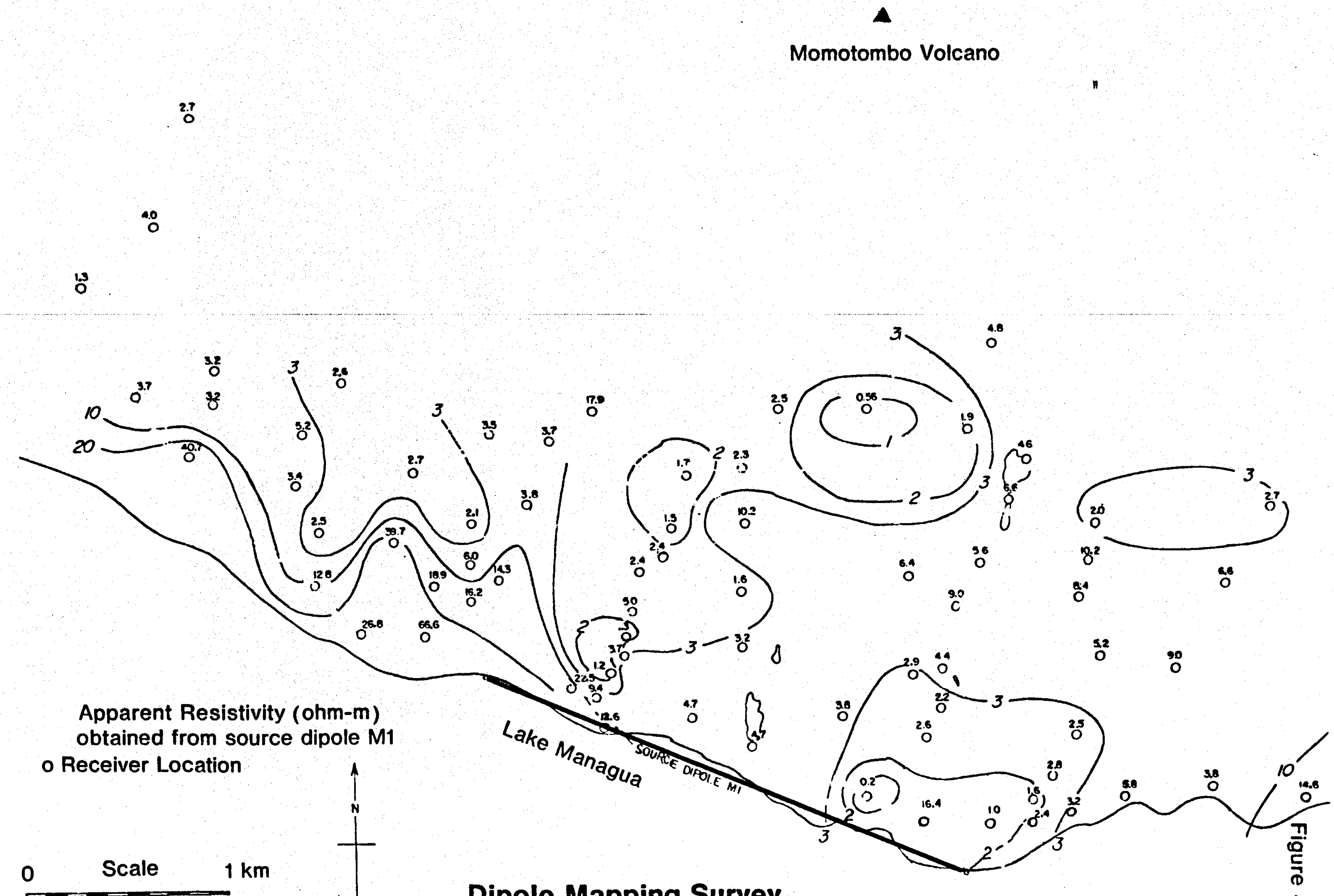


Summary of Depth-sounding Interpretations in the Vicinity of V. Momotombo

Figure 4-11

the Momotombo geothermal area. Because of low resistivity values in this area, signal levels were too low for all readings greater than 4 km from the source dipole (Texas Instruments, 1971). Source dipole M1, with an electrode separation of 2650 m, was then located closer to the geothermal area, as shown in Figure 4-12. Receiver dipole lengths varied between 50 and 300 m depending on the intensity of the signal. The apparent resistivity values obtained from these measurements as well as the isoresistivity contours of this area covered do not overlap sufficiently to provide an effective comparison between the two patterns. Furthermore, the geological map indicates the presence of various faults and fractures in the area surveyed, which have an effect on the apparent resistivity pattern, especially if they are indicative of vertical boundaries with different resistivity. It was also mentioned by Banwell (1971) that the source dipole crossed a pair of these mapped faults and subsequently the interpretation of the isoresistivity contours is suspect.

Two regions of low resistivity were detected: one paralleling the lakeshore and the other lying about 1.5 km up the volcanic slope, parallel to the first. No indication of closure of the low resistivity contours was obtained, and therefore there is no delineation of the thermal activity. This method has the advantage of measuring an average resistivity over a larger volume than Schlumberger soundings, and as such gives more regular resistivity patterns. Previous investigations in Broadlands, New Zealand, show this method can be used effectively for outlining the boundaries of a geothermal field, however, the limited coverage at Momotombo did not produce satisfactory boundary mapping of the area. A greater areal coverage at the Momotombo field, correlated with the geological structure, would have shown better results.



Dipole Mapping Survey
(From Texas Instruments, 1971)

Figure 4-12

c. Electromagnetic Soundings - Although only three electromagnetic soundings were performed in the Momotombo area, the results shown in Figure 4-13 are in general agreement. A hot water reservoir was indicated lying at depths of 1400 to 1700 meters.

The technique used for these soundings is described in Texas Instruments (1971). The electromagnetic field was generated by driving a current step through a grounded length of wire, using the same source equipment that was used in the dipole mapping surveys. The vertical component of magnetic induction was recorded at a measurement site using an induction loop as detector. This loop consisted of one or two 500-meter lengths of 26-conductor wire laid on the ground in the form of a square, with the conductors connected in series to form a continuous loop. The transient voltage induced in this loop by the magnetic induction as the current reversed direction in the grounded wire source was recorded graphically. The essential components of this system are shown in Figure 4-14.

The measurements are interpreted in a similar manner as Schlumberger sounding data. Field recorded signals, however, are not precisely those required for comparison with theoretical curves. The transient coupling, as recorded, is distorted by the response characteristics of the recording equipment. In addition to this problem, extraneous noise added to the recorded signals make recognition of the signals with the desired accuracy difficult. Four stages were required in processing the field data before they were ready for comparison with theoretical curves:

- Synchronous stacking to reduce the level of random noise in relation to signal amplitude.

- Deconvolution to minimize the effect of distortion by the recording equipment.

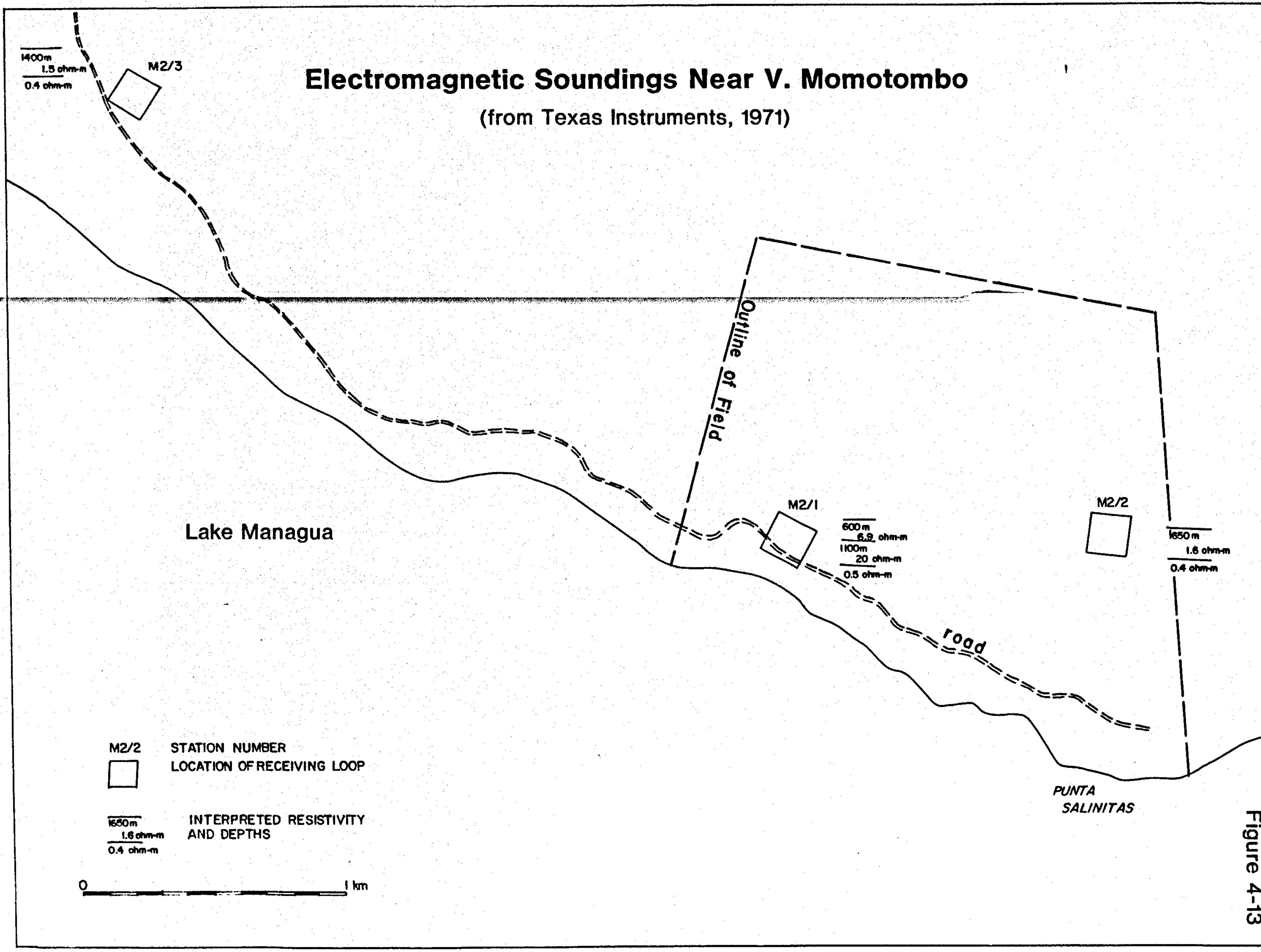
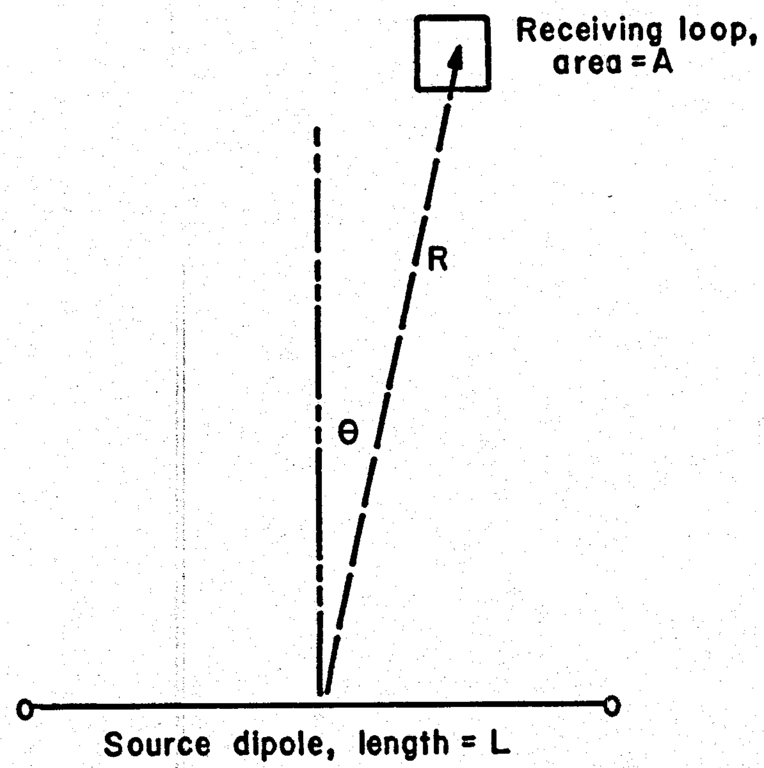

Electromagnetic Soundings Near V. Momotombo
(from Texas Instruments, 1971)
1400m
1.5 ohm-m
0.4 ohm-m
M2/3
Outline of Field
M2/1
600m
6.9 ohm-m
1100m
20 ohm-m
0.5 ohm-m
M2/2
1650m
1.6 ohm-m
0.4 ohm-m
Lake Managua
road
PUNTA
SALINITAS
M2/2
STATION NUMBER
LOCATION OF RECEIVING LOOP
1650m
1.6 ohm-m
0.4 ohm-m
INTERPRETED RESISTIVITY
AND DEPTHS
0
1 km

Figure 4-13

Apparent Resistivity Calculations for EM Soundings



EARLY RESISTIVITY:

$$\rho_a = \frac{2\pi R^4}{3IAL \cos \theta} V$$

LATE RESISTIVITY:

$$\rho_a = \left(\frac{AILR\mu^{5/2}}{40\pi^{3/2} t^{5/2} V} \right)^{2/3}$$

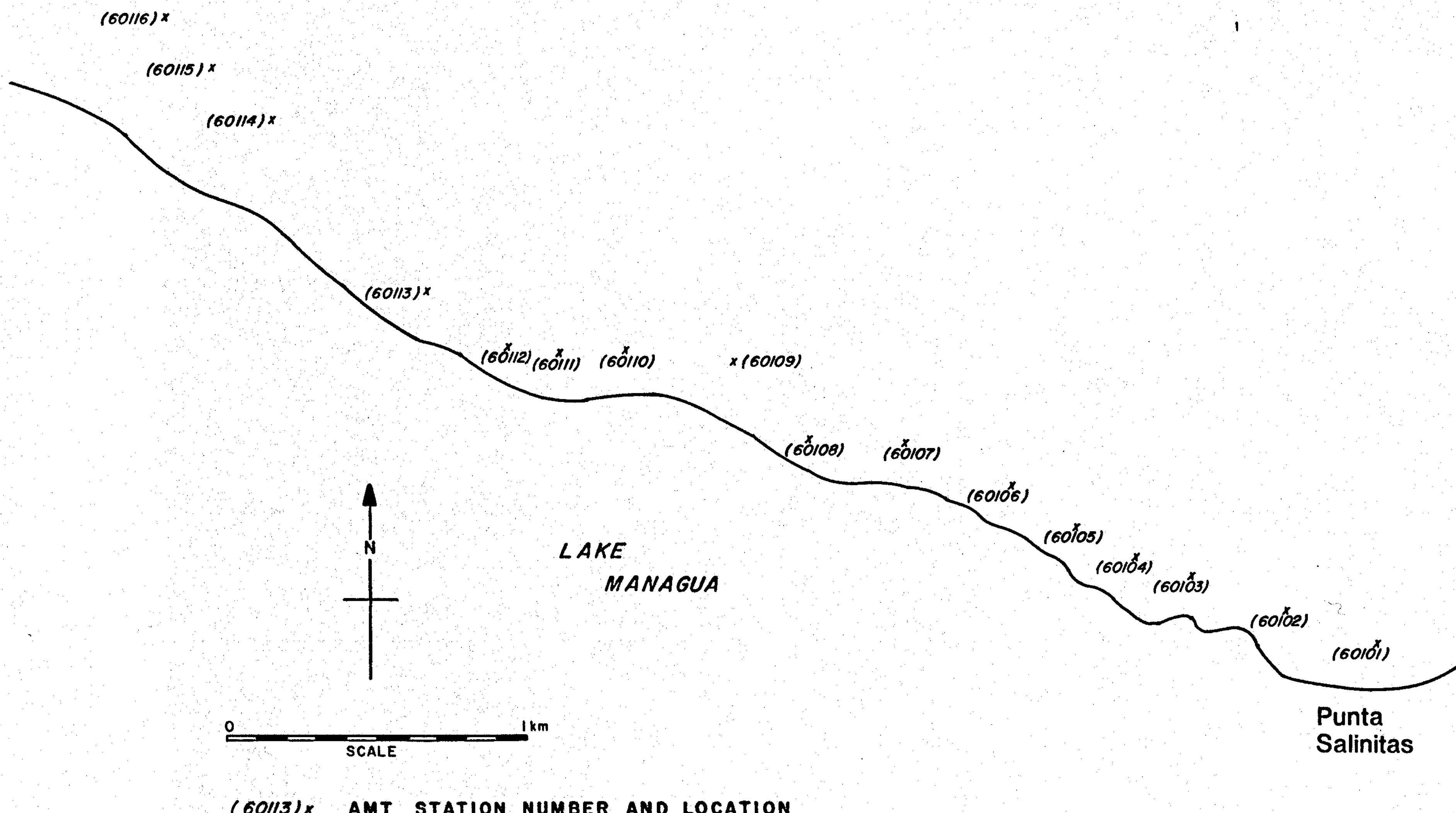
- Smoothing with an exponential time-varying filter to further reduce uncorrelated noise.

- Conversion to values of apparent resistivity using the formulas shown in Figure 4-14.

As already mentioned by Banwell (1971), no verification of these results with other electrical surveys was possible, since their depth of penetration was limited (Schlumberger soundings) or their interpretation too uncertain (dipole). Keller (1971) classifies this technique as superior to resistivity sounding because of the insensitivity to problems caused by resistant surface rocks. The Momotombo data did not define a limit on the size of the conductive zone.

d. Audio-magnetotelluric (AMT) Surveys - A brief survey using this technique was performed at Momotombo at the location shown in Figure 4-15. A comparison between the near-surface resistivities and the distribution of hot ground shows a rough correlation between the high temperature areas and low resistivity. The local variation in structure, however, as noted by Banwell (1971), could readily mask any relationship or explain disagreements. Similarly, the 400 m limitation on the maximum penetration depth does not enable this sounding to check the presence of the suspected reservoir. The main drawback in this method is that the operator has no control of the amplitude and frequency of the source fields.

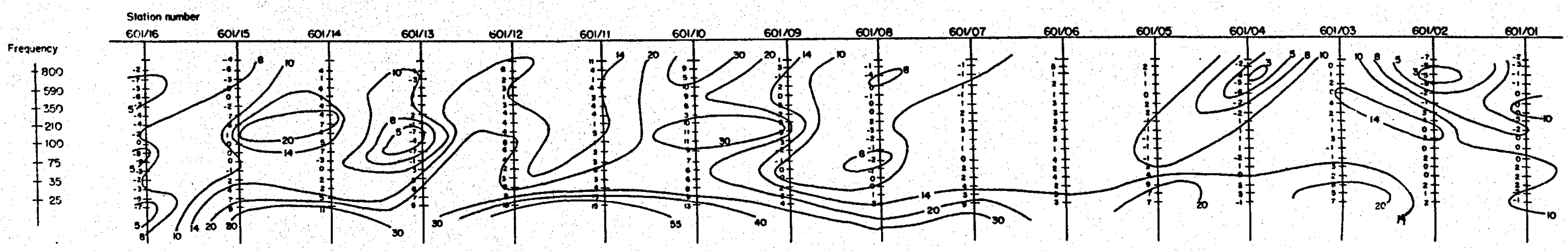
Data from this survey are presented in Figure 4-16. Frequency is plotted as the vertical scale rather than depth, otherwise, the section would be similar to a normal section plot (Texas Instruments, 1971). The observed values of apparent resistivity are contoured. Low resistivity values tend to correspond to low resistivities obtained by the dipole survey (Figure 4-12).



Location of AMT Stations
(from Texas Instruments, 1971)

Figure 4-15

AMT Profile, Momotombo Shoreline of Lake Managua



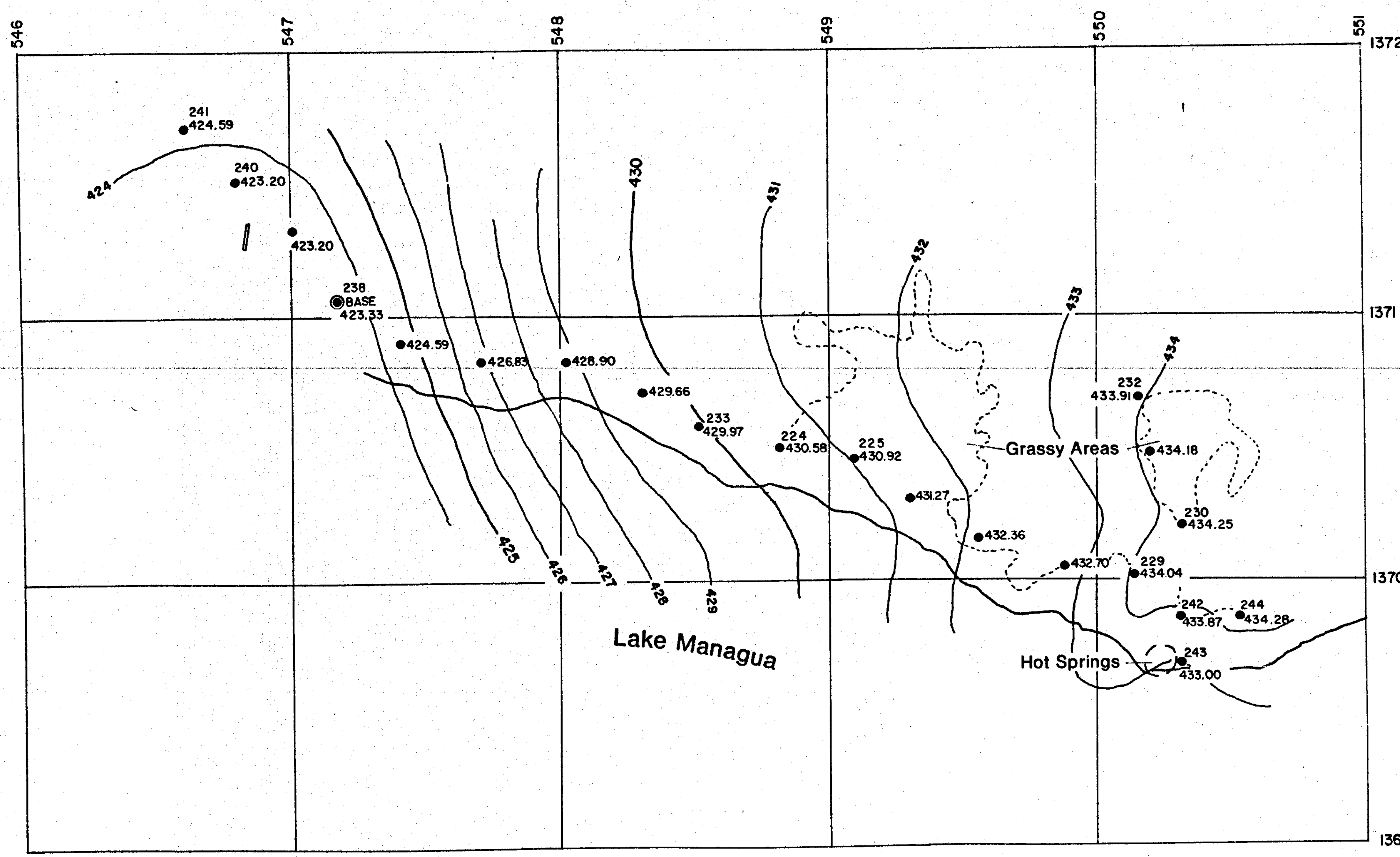
Resistivity values are expressed in db relative to 10 ohm-meters
Contours are in ohm-meters

Figure 4-16

2. Gravity and Magnetic Measurements - A reconnaissance gravity-magnetic survey consisting of 23 stations was made along the shoreline of Lake Managua and extended over some of the thermal areas of Momotombo. The results show a well-defined but weak positive anomaly near the lakeshore, as shown on the Bouguer gravity map (Figure 4.17a). The assumption that altered rocks are of low density, which is employed by Texas Instruments to explain the negative gravity trends on the flanks of the positive anomaly is not supported by work in Broadlands, New Zealand (Banwell, 1971). Also, the lack of a regional gravity map caused problems in the interpretation of the Bouguer anomalies since there is no comparison between site and regional gravity anomalies. Overall, the data have no direct bearing on the geothermal conditions in the area. A broader and more detailed gravity survey would have been beneficial in producing a better Bouguer anomaly map.

Although magnetic methods are used as a secondary exploration tool, broader areal coverage would have produced a better magnetic anomaly map and shown the delineation of surface volcanics, the delineation of demagnetized (by thermal alteration) volcanics, and the delineation of unaltered intrusions within non-magnetic sediments. The vertical intensity map for Momotombo (Figure 4-17b) has negative anomalies which correspond to areas of surface alteration. Correlation with the gravity map was limited to certain areas, and subsequently the magnetic survey only provided a minimum amount of information.

4. Conclusions - The boundaries of the Momotombo geothermal field were not detected by the geophysical methods used in Stage 1 investigations. From the evidence available it appears that the general failings were: insufficient data acquisition, omission of cross checks, and especially, insufficient depth of penetration by most of the electrical techniques. Banwell (op. cit.) pointed out that despite the indications of a low resistivity zone at moderate depth, as suggested by the electromagnetic soundings, no attempt was made to push



Bouguer Gravity Map

(From Texas Instruments, 1971)

Contour Interval: 1 Milligal

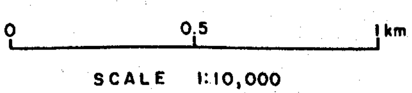
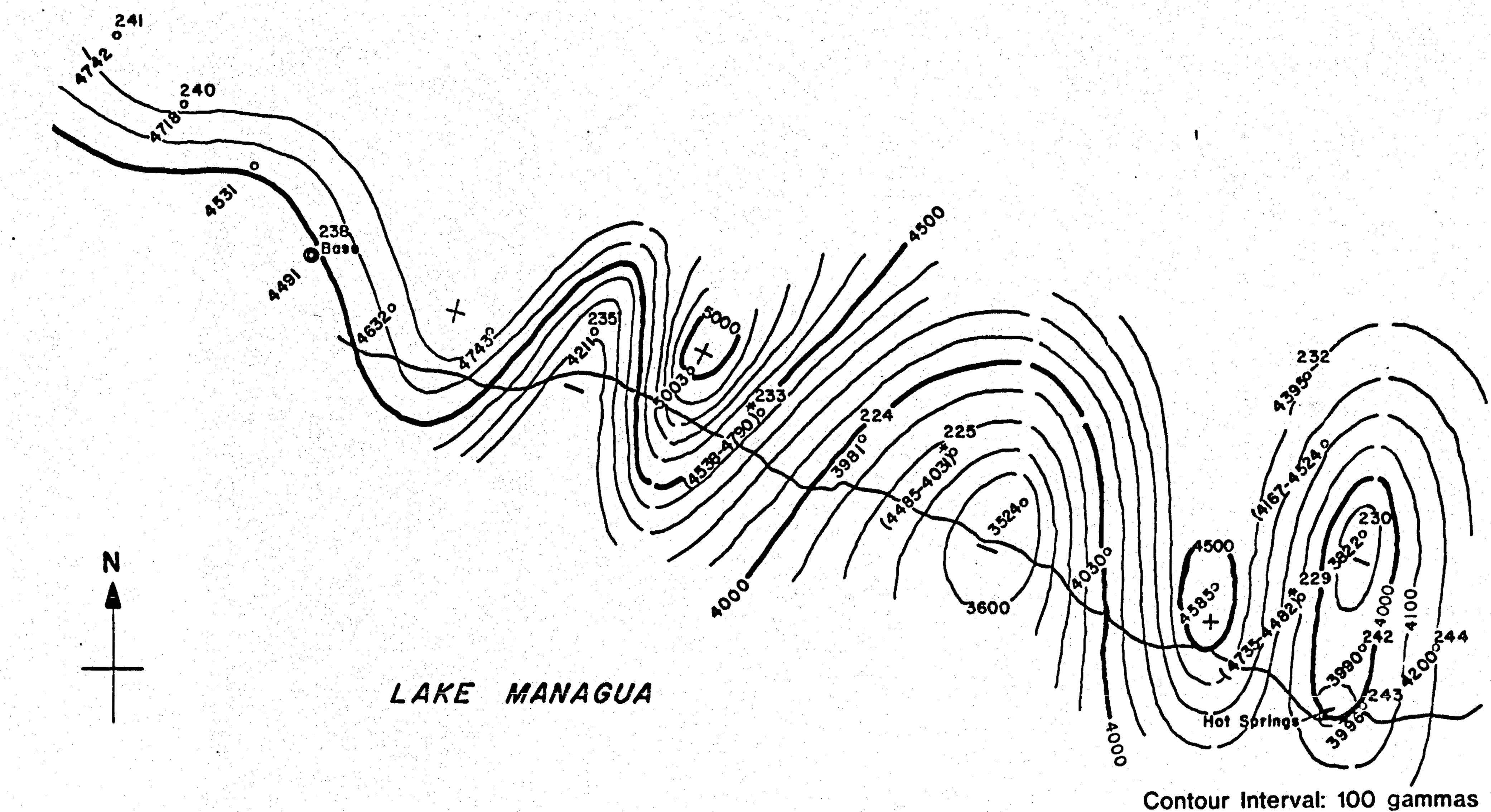


Figure 4-17a



Vertical Intensity Magnetic Map
(from Texas Instruments, 1971)

Figure 4-17b

the Schlumberger soundings or the AMT survey to greater depths in order to confirm the findings, provide more detail, or outline the field.

Previous and concurrent work in geological and geochemical investigations was not taken into account during the electrical prospecting program. The usefulness of the surveys would have increased, especially if the structural geology, faults and lineaments had been considered while performing the dipole mapping surveys. It does not appear that the electrical surveying techniques used in Nicaragua have been subjected to conclusive tests, and none can therefore be condemned as valueless for geothermal exploration in this environment (Banwell, op. cit.)

A variety of electrical prospecting techniques were used, of which the electromagnetic soundings and the dipole mapping surveys proved to be most valuable. Gravity and magnetic measurements were of little value to the geothermal investigations due to the limited areal coverage.

C. Geochemistry

1. Pre-Stage I Information - The thermal manifestations associated with the volcanoes of western Nicaragua have been described by several explorers; Squier, 1851; and Sapper, 1925.

Waring (1915, revised 1965) reports on the fumaroles and hot springs at Momotombo, as well as other manifestations in the country associated with volcanoes in the Volcanic Chain.

A regional geologic mapping program and mineral resource inventory was undertaken in the late 1960's and included a survey and brief description of 53 thermal springs and wells. Samples were taken by Catastro (the Nicaraguan natural resources project); the final report was published in March, 1972.

2. Stage I Information - In 1969, Texas Instruments, Inc., undertook a regional evaluation of thermal manifestations in western Nicaragua. This study covered approximately 38,000 square kilometers. Texas Instruments used the Catastro data and some locations of thermal manifestations supplied by Servicio Geologico Nacional. Further manifestations were located by checking place names on 1:50,000 scale topographic maps. Not all areas having thermal manifestations were visited. Existing data were reveiwed and geologic environments considered favorable for geothermal resources were selected. As a consequence, much of the field work occurred in the Volcanic Chain and the Nicaraguan Depression.

Texas Instruments found some thermal springs and wells in the Volcanic Chain, but they were most abundant in the Nicaraguan Depression where water temperatures up to 96.5°C were recorded, according to their reports. The lesser numbers of thermal manifestations in the Chain is probably due to a deep water table in some areas, favoring the development of fumaroles instead of hot springs.

The thermal manifestations were divided into three broad groups:

- Fumaroles resulting from active volcanism.
- Hot springs deriving fluids from a deep geothermal reservoir.
- Thermal manifestations with no direct relationship to recent volcanism.

The study selected 32°C (90°F) as a minimum temperature for water to be classified as thermal (based on mean annual air temperature in the Nicaraguan Depression.)

Texas Instruments noted that many of the observed thermal manifestations were associated with fractures or faults. They noted that hydrothermally altered areas were devoid of vegetation. The rock or soil in these areas showed bleached or oxidized colors. It was suggested that the alteration around the fumaroles was of recent origin since such deposits are rapidly eroded in the present climate.

Most of the thermal springs and wells were sampled during the dry season. The following regions (ranked by decreasing geothermal interest) were chosen as potential hyperthermal zones warranting further investigation:

- South Volcan Momotombo fumaroles and hot springs
- San Jacinto-Tisate mud pots
- Volcan Casita thermal area
- North Volcan Telica-Najo thermal area
- Lake Jiloa-Apoyeque thermal area
- Volcan Mombacho thermal area
- Cerro Colorado thermal area
- Tipitapa hot springs
- Hacienda Agua Caliente-Villa Salvadorita thermal wells
- San Luis hot springs

This ranking was based on qualitative surface geologic aspects such as size of thermal area, temperature of fluids and degree of alteration. Chemical data were not considered in this listing; those data were specifically discussed in a separate, later report.

a. Surface Alteration - The surface alteration at South Volcan Momotombo is about 0.75 square kilometers. The largest altered zone shown in Figure 4.1 accounts for about half of this total area. The elevation of the altered areas ranges from 39 meters near the lake shore to 340 meters on the higher slopes of the volcano.

Generally, alteration is described as slight to moderate, but it may be severe near the springs and fumaroles where some argillization was observed. The steam has temperatures up to 100°C, occasionally reach-ing 101°C. Sulfur crystals were observed in small amounts around the fumarole orifices.

Boiling hot springs with temperatures of 100-101°C and small flow (5 gpm) occur at Punta Las Salinitas. Siliceous sinter aprons were associated with the springs. No chemical analyses of soil or rock in the altered zones was reported.

b. Water Chemistry - During the course of the regional investigation, 21 hydrothermally altered zones and fumaroles, 83 thermal springs, and 102 thermal wells were located. One hundred and thirty water samples and 52 gas samples were collected and analyzed. The geochemical data resulted in a slight rearrangement of the previously reported list ranked by decreasing geothermal interest:

- South Volcan Momotombo
- San Jacinto-Tisate
- Volcan Casita
- Volcan Telica-Najo
- Lake Jiloa-Lake Apoyeque
- Volcan Mombacho
- Hacienda California
- Tipitapa
- San Luis

The program gave priority to sampling high temperature, high chloride, and high discharge springs. It was considered that those springs would yield more reliable geochemical indicators of subsurface temperature.

The hot spring area at Punta Las Salinitas on the south flank of Volcan Momotombo issued sodium chloride waters with a pH range of 7.1 to 8.2 and TDS ranging from approximately 5000 to 7000 ppm. Silica ranged from 125 to 195 ppm, lithium from .36 to 2 ppm and boron from 3.2 to 13.2 ppm.

c. Geochemical Indicators of High Subsurface Temperatures - The following indicators were used to predict and cross check subsurface temperature predictions:

1) silica (SiO_2) concentrations, used for subsurface temperature predictions

2) sodium/potassium (Na/K) ratios, used for subsurface temperature predictions

3) sodium/lithium (Na/Li), as used for comparison with Na/K; lithium tends to decrease in concentration in rising thermal water systems due to incorporation in alteration minerals, so high Na/Li ratios could indicate high temperatures,

4) magnesium/calcium (Mg/Ca) ratios, used qualitatively because a low value was considered to indicate high subsurface temperature

5) calcium/bicarbonate (Ca/HCO_3) ratios were used for comparison with SiO_2 concentrations and Na/K ratio temperatures, although the Ca/HCO_3 ratio could have a wide range depending on calcite solubility, temperature, pH, and partial pressure of CO_2,

6) sodium/calcium (Na/Ca) ratio was used qualitatively, because a high Na/Ca ratio could indicate high subsurface temperature; however, Texas Instruments noted that if Ca is much greater than HCO_3, the ratio cannot be used,

7) chloride/CO_3 + HCO_3 was used to indicate high temperature environments.

Texas Instruments reported that all geochemical indicators in the Momotombo area water samples predicted high temperatures at depth. Toward the end of the study of surface manifestations, temperature gradient hole drilling commenced at south Volcan Momotombo. Thermal water from well MT-1 also showed high subsurface geochemical indicators. This well blew out shortly after drilling to a total depth of 62M and the discharging fluid was collected and analyzed.

The south Volcan Momotombo water samples had a greater number of indicators of high subsurface temperatures than those of samples from other areas. Silica concentrations and Na/K ratios indicated a reservoir temperature range from 153°C to 200°C. In exploratory well MT-1, SiO_2 and Na/K predicted temperatures of 152°C and 155°C, respectively. Wells M-1 and MT-1 were located about 200 meters east of Punta Las Salinitas hot springs. The geochemically predicted temperatures from M-1A were confirmed by high thermistor readings at 39 m below surface in well MT-1. It was noted that the thermistor cable deteriorated, but several consistent reading of 140°C-152°C were obtained.

The gases collected at the Momotombo fumaroles were characterized by relatively high hydrogen sulfide and carbon dioxide. Hydrogen was not anomalous when compared to other fumarole areas. The non-condensable gas-to-steam ratio at Momotombo ranged from medium to low (from 0.70 in the area near gradient well M-5 to 0.47 in the fumarole area east of M-3). Two different types of gas samples were taken: Drager tubes were used and the gases were analyzed in the field. In addition, 250 ml gas-collecting glass tubes were sent to Rocky Mountain Technology, Inc., in Denver, Colorado, for gas chromatography. Hydrogen in thermal gases is generally regarded as an indicator of high temperature. Field analyses did not detect hydrogen in the gases, but small amounts, approximately 0.1 percent by volume, were identified by gas chromatography.

d. Temperature Gradient Well Water Samples - The gradient wells were drilled with water, 11 to 14 meters of surface casing was set and cemented, and a blowout preventer was installed. Most wells were drilled to total depth of approximately 55 meters. Water samples were taken at 6-meter intervals during drilling. Texas Instruments reported that the analyses were received too late for interpretation and discussion, but they were listed in an appendix. A total of 54 samples were analyzed with 38 samples from the Momotombo temperature gradient wells.

3. Conclusions - The geochemical criteria for predicting high temperatures at depth were routinely used in the geothermal exploration industry at that time. Refinements have since occurred in the use of cation ratios, specifically Fournier and Truesdell's Na-K-Ca geothermometer.

The data from the geochemistry, corroborated by the observed temperature gradients, predicted a minimum reservoir temperature of 200°C. A liquid water-saturated system was indicated by the chemical analyses.

The final report by Texas Instruments concluded that Momotombo was the best prospect in the western part of the country for geothermal development.

Although a general survey of thermal manifestations was conducted in western Nicaragua, Texas Instruments stated that the first prospect list was based on surface alteration and geologic environments. The surface mapping at Momotombo indicated that present or past hydrothermal activity was localized along faults and fractures. The possible existence of geothermal reservoirs with less obvious surface expressions was not considered.

The geochemical indicators used to determine geothermal potential appear to reflect a strategy primarily applicable to the detection of high sodium chloride content, liquid-dominated systems. Little consideration was given to the relationship of site specific geology and geochemistry. The silica and sodium/potassium geothermometers from spring analyses at Momotombo ranged from 153°C to 200°C. Two other areas in western Nicaragua, San Jacinto-Tisate and Hacienda California, showed approximately the same range. A third area, Volcan Mombacho, had temperatures ranging substantially higher. It was concluded that development work should be concentrated at Momotombo and some exploration continued at San Jacinto-Tisate.

4.2 STAGE II - Performed by United Nations Development Program (UNDP)

A. Geological Methods

The objectives of Stage 2 geologic investigations were to map the surface geology of the thermally altered areas, define their areal extent, and map, in a reconnaissance manner, all pertinent structural and volcanic features related to thermal activity. These investigations, when combined with geophysical and geochemical studies, were to provide a preliminary evaluation of the geothermal potential and final selection of deep drilling sites. The methodology consisted of field checking the entire Momotombo area by observing the structure, ground temperature, distribution of altered areas and making inferences about the volcanic evolution. A volcanic risk analysis for plant siting and brief hydrological notes were included in the geologic report.

1. Field Mapping - The area investigated included not only Momotombo volcano, but also the adjacent Monte Galan Caldera, Cerro Montoso and Cerro Colorado cones, and La Guatusa and La Chistata structural features (refer to Figure 4-1). Various lava flows and pyroclastic deposits were briefly described and identified with respect to their source. Since the thermal areas had been previously mapped by Thigpen, Texas Instruments, (1970) during Stage 1 investigations, only

temperature measurements were taken in the steam vents and the ground. The average temperature for the Momotombo thermal areas was 95°C. Jonsson (UNDP 1973), however, suggests there is only one thermal area which is divided superficially by lava flows into a number of smaller areas, based on the fact that thermal alteration occurs almost exclusively at the edge of lava flows, in ravines cut into them by erosion, or in areas between lava flows. If a more extensive survey of ground temperatures had been made, areas of maximum heat flow could have been mapped and a surface isotherm map produced.

Temperature measurements in the volcanic crater revealed a maximum high temperature of 213°C at the southern wall. Several fumaroles were observed along the southern wall of the vent. Other fumaroles were observed on the southern slope of the volcano at an altitude of 1,100 meters.

2. <u>Volcanic Risk Analysis</u> - A selected plant site area on the southern slope of Momotombo was determined to be safe from vent or flank eruptions. The area is outside the trajectory of bombs and blocks thrown from the summit crater (Jonsson, UNDP, 1973). Reviewing the eruptive history of Momotombo, however, the old city of Leon 6 kms away was buried during a 1609 eruption of Momotombo, much like Pompeii. It is therefore unlikely that the southern slope should be considered a safe place. The periodicity of eruptions is uncertain and unknown at Momotombo and the constant danger of a base surge remains a potential volcanic hazard.

The study area appears safe relative to a small pyroclastic eruption, for as Jonsson (1973) mentioned, the prevailing winds are from the east and southeast, thus carrying the tephra toward the west. In the event of another small lava outpouring, the horseshoe-shaped crater opening toward the north would guard the southern slopes.

3. Hydrogeological Notes - Since no systematic hydrogeological investigations had been made in the area, some notes on the hydrology of the area were prepared to help define the reservoir model. Much of it was suggestive and inconclusive, as the author emphasizes.

The high permeability of the lavas and tephra around Momotombo at lower elevation lower the water table considerably. Two types of mineralized thermal waters exist in the subsurface: warm groundwaters and deep, hot, saline waters, with temperatures up to 100°C (Sigvaldason, 1973). The relationship between these waters is obscure, but it was suggested that the deep hot, saline waters reach the surface in the hot area, passing through the fresh groundwater. Additional information on the water chemistry and fluid flow is given in Section 4.1-C.

4. Conclusions - Based on the original scope of work for these investigations, the geological results were successful in fulfilling the objectives. The re-mapping of thermally altered areas and related features which was carried out would have furnished more information if the petrology and mineralogy of hydrothermally altered zones had been investigated. The ground temperature survey had insufficient coverage, precluding the drawing of surface isotherm maps. The hydrogeological study, an addendum, in the final report, should have been expanded and presented as a separate study.

The amount of information obtained did not modify existing data on the Momotombo geothermal field. The program was subsequently stopped because of the 1972 Managua earthquake. The following sections describe the geologic results obtained during this study.

- Area Surface Geology - -The description of the Momotombo area, with few exceptions as noted, repeats in greater detail and adds to the findings of Thigpen carried out in Phase 1. The UNDP report describes the eruptive history of Volcan Momotombo identifying the age and dates of recent lava flows; 1529, 1609, 1764, 1849, 1852, 1886, 1905. The lithology of the flows is described. The Phase 2 report emphasized that from the structure of the volcano, the prevailing winds, and the history of prior eruptions, the production area on the south side of Momotombo, would be somewhat protected in the event of new volcanic activity. The report also describes the vulcanism of Loma La Guatusa.

- o <u>Structural Geology</u> - The description of the structural geology summarized the findings of Phase 1.

- o <u>Thermal Distribution</u> - Thermal activity within the Volcan Momotombo area was also investigated. From those results it was surmised that only one thermal area exists on the southern slope of Volcan Momotombo. The existence of several fumaroles, hot springs and altered areas is explained by stating that the thermal area is superficially divided by lava flows from Volcan Momotombo. Proof of this is given by the fact that the noticeable thermal activity and high temperature thermal alterations occur almost exclusively around or near the edges of the lava flows, in eroded areas and in areas between flows.

Hot water emanates from beneath and between these flows at the shore of Lake Managua. The existence of algae and other vegetation typical of thermal waters, was noted near the shore.

In conclusion, the UNDP report supported and to some extent amplified the findings of the Phase 1 study asserting that the Momotombo geothermal field south of Volcan Momotombo was indeed capable of producing up to 25 MW of electricity.

B. Geophysical Methods

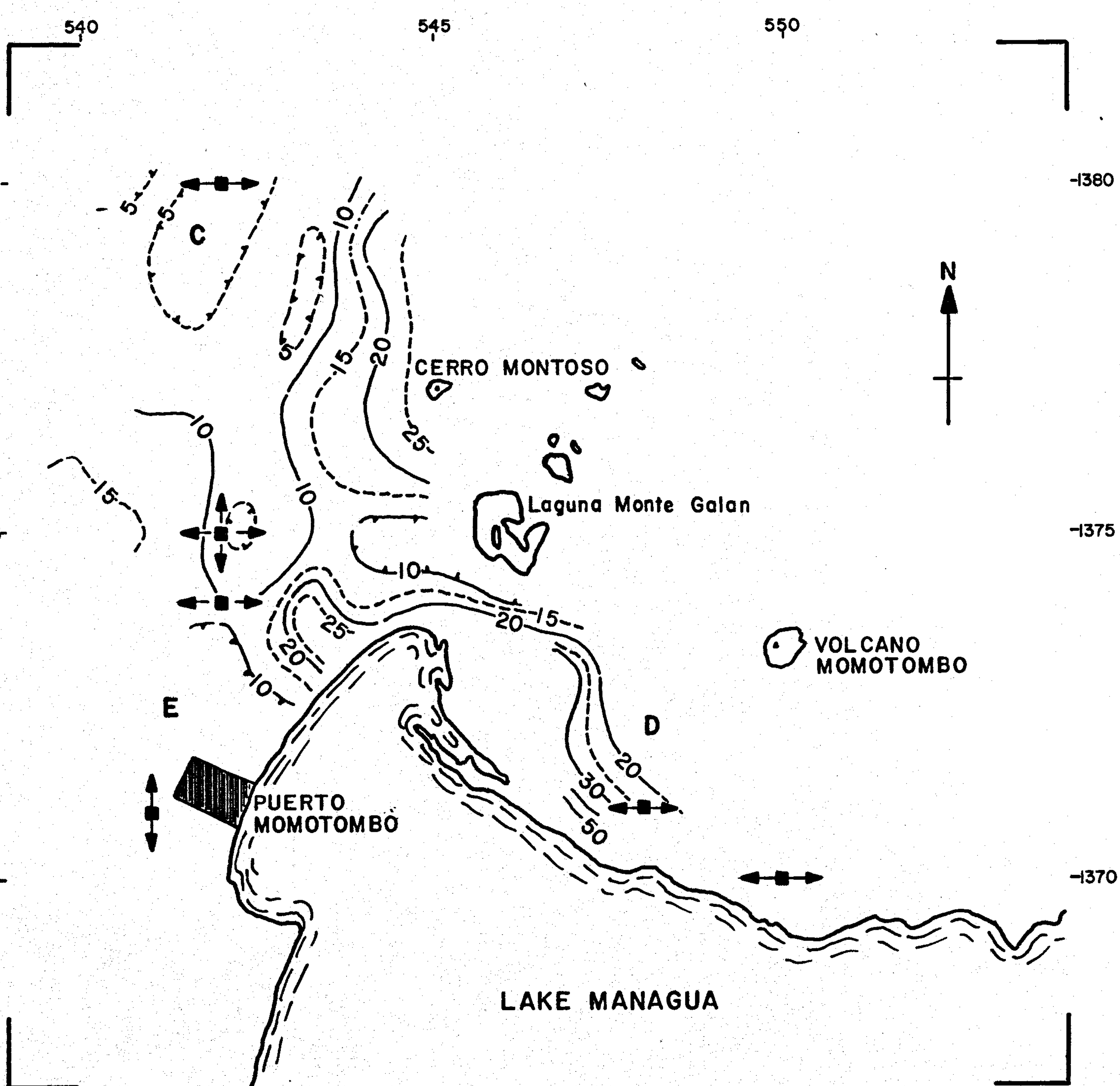
Stage 2 geophysical investigations were carried out at a considerable distance from the surface manifestations of Momotombo, in order to determine the extent of the thermal ground. These investigations were performed almost two years after Stage 1. The area was covered in considerable detail by six different electrical prospecting methods, and these results are of considerable interest as a basis for evaluating these techniques in geothermal exploration. The self-potential method was still a tentative method under investigation as a tool for geothermal exploration and its use at Momotombo was considered experimental. The dipole-dipole method was used on a test basis as well. Other methods included Schlumberger profiling and soundings, roving dipole surveys, and frequency domain electromagnetic soundings. Their applicability and usefulness during Stage 2 investigations are described in the following sections.

1. Electrical Prospecting Methods

a. Schlumberger Constant Depth Profiling (SCDP) - The majority of the survey was done using SCDP with a Lee partition added to detect any lateral inhomogeneities, and to check the validity of the results. The AB/2 separation was 1 km with a potential electrode separation MN of 400 m. The measurements were useful in detecting zones of low resistivity for use in later investigations with vertical electrical soundings (VES). Little contrast in reading was detected in the entire region. Zones C, D and E in Figure 4.18 were found to have the lowest resistivities and warranted further investigation by other methods.

b. Schlumberger VES Sounding - This was the most useful technique in this investigation since it provided subsurface information such as thicknesses of certain conductive layers and the variation in resistivity between adjacent formations. Some irregular results were

Figure 4-18a



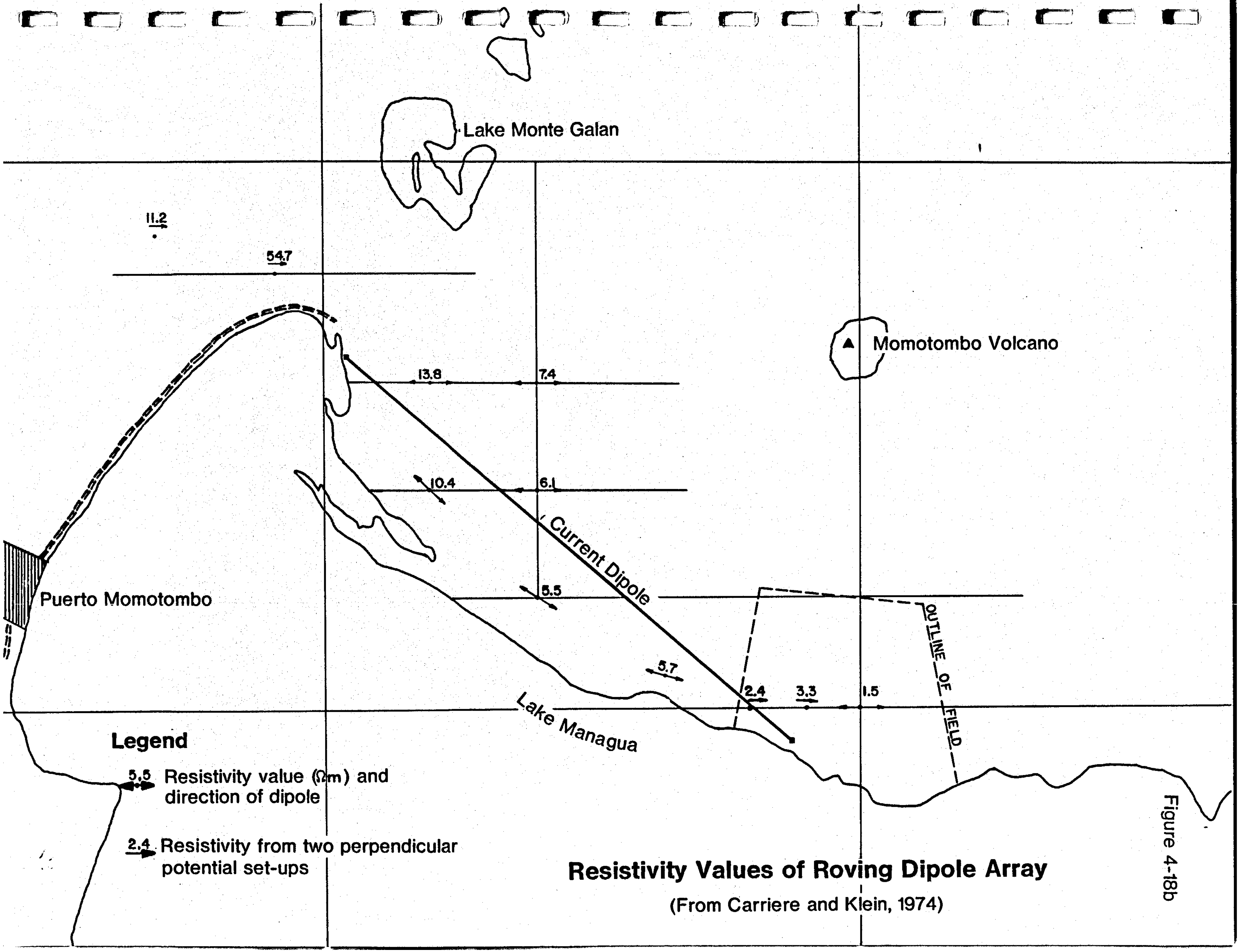
Legend

Location and Direction of Vertical Sounding

Resistivity Contours in Ohm-Meters

Schlumberger Constant Depth Profiling Results

(from United Nations, 1974)



Resistivity Values of Roving Dipole Array

(From Carriere and Klein, 1974)

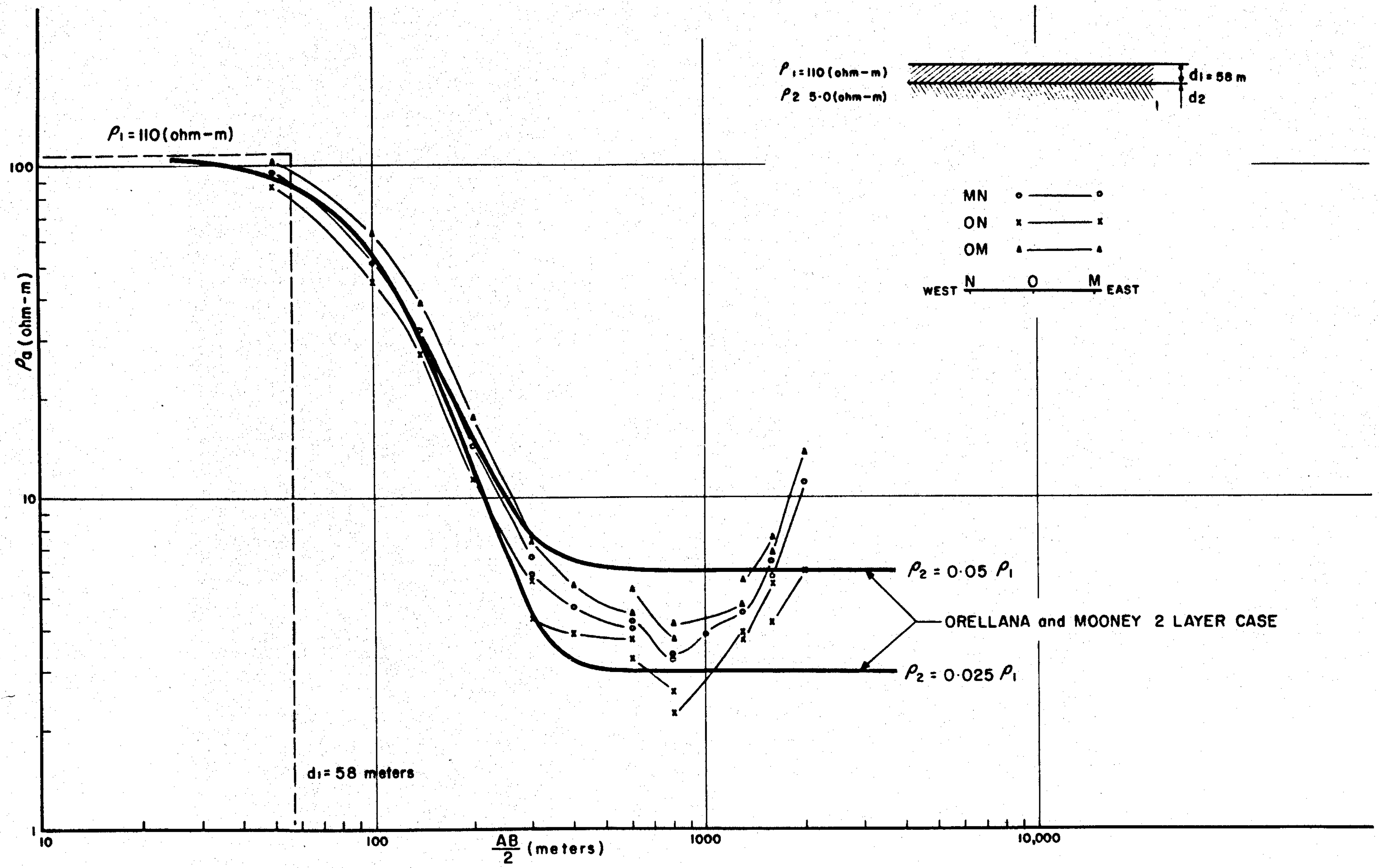
Figure 4-18b

obtained because of dipping formations and lateral and vertical discontinuities. The VES method is of limited value in volcanic regions such as Momotombo, where the layers are irregular and the measured sounding curve cannot be matched to any theoretical layer model curves, thus making interpretation less meaningful. The volcanic debris in some areas resulted in voltages which were too small for accurate and reliable measurements.

The Schlumberger VES soundings used expanding current electrodes (AB/2 = 50, 100, 140, 200, 300, 400, 600, 800, 1000, 1300 and 2000 m). Although the potential electrode separation was kept within 20% of the AB separation, in some cases the voltage recorded was too small and larger MN separations were used (Carriere and Klein, 1974). Results of these measurements are shown in Figures 4-19 to 4-21. Figure 4-18 shows the location of these soundings and the isoresistivity contours of this area.

A VES sounding in zone C of Figure 4.18 was interpreted as a two layer curve with the second layer having an estimated resistivity of less than 5 ohm-meters (Figure 4-19). Vertical discontinuities caused an increase in resistivity for large (AB/2 = 1000 m) electrode spacings. In zone D, which covers a portion of the Momotombo field, VES soundings suggest a low resistivity zone existing at depths greater than 70 m. (Figure 4-20). Results from soundings in zone E, shown in Figure 4-21, are irregular due to the expansion of the electrode array into soils on one side and volcanics in the other (Carriere and Klein, 1974). All three VES soundings correlate with the finding of a 70 m thick surface layer overlying a layer with resistivities of approximately 9 ohm-meters.

c. <u>Roving Dipole</u> - This technique was not used extensively since it showed little depth control and as such some of the results could not be interpreted. Penetration achieved is greater than that of SCDP measurements because of the larger current dipole used (5600 m),



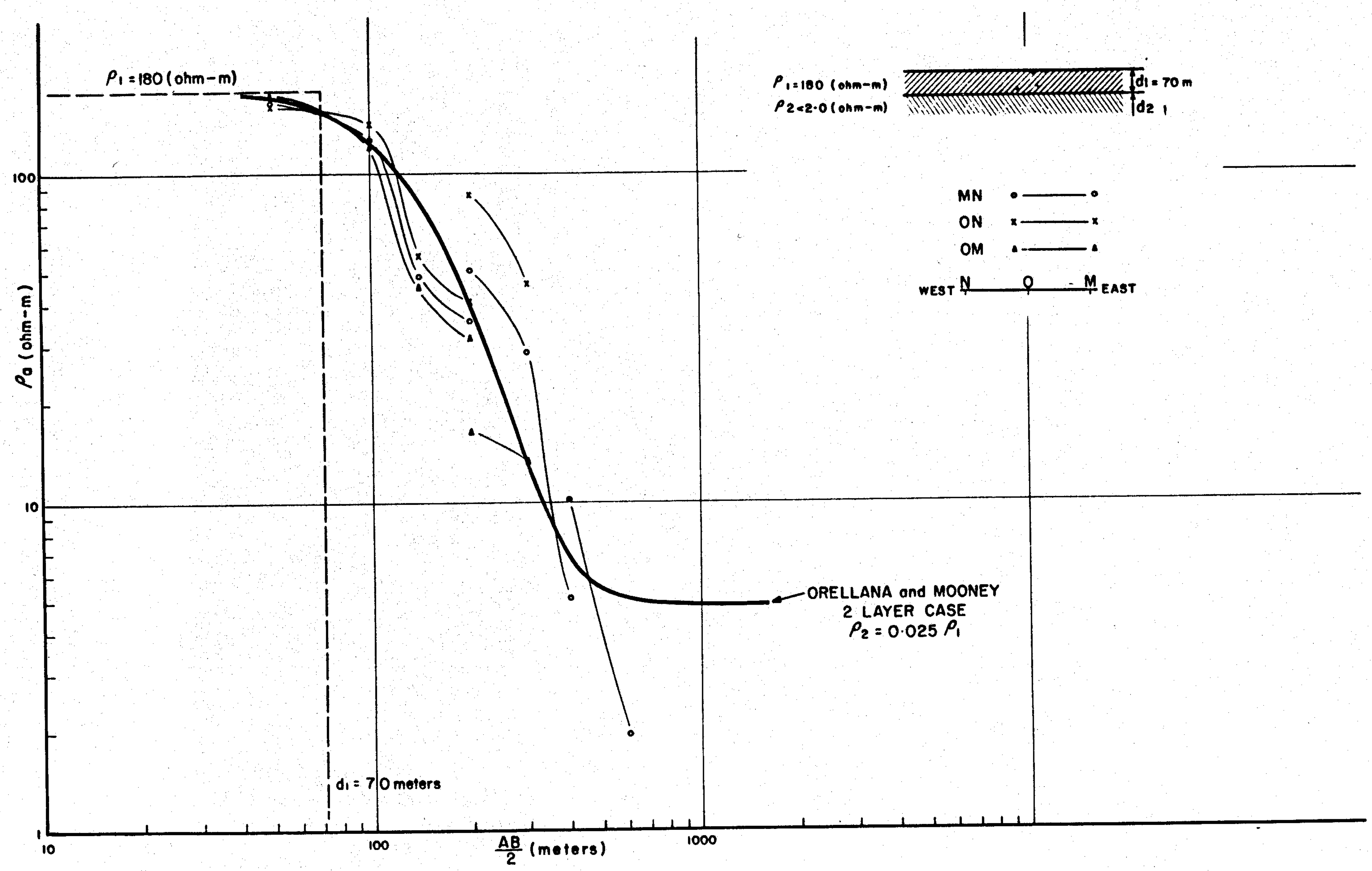
VES at 1380 N, 542 E
ZONE C
in Figure 4-18

UNITED NATIONS
GEOTHERMAL RESOURCES DEVELOPMENT
IN NICARAGUA
(CON. 167/72, NIC-10)

SCHLUMBERGER RESISTIVITY SOUNDING

Figure 4-19

73-9674



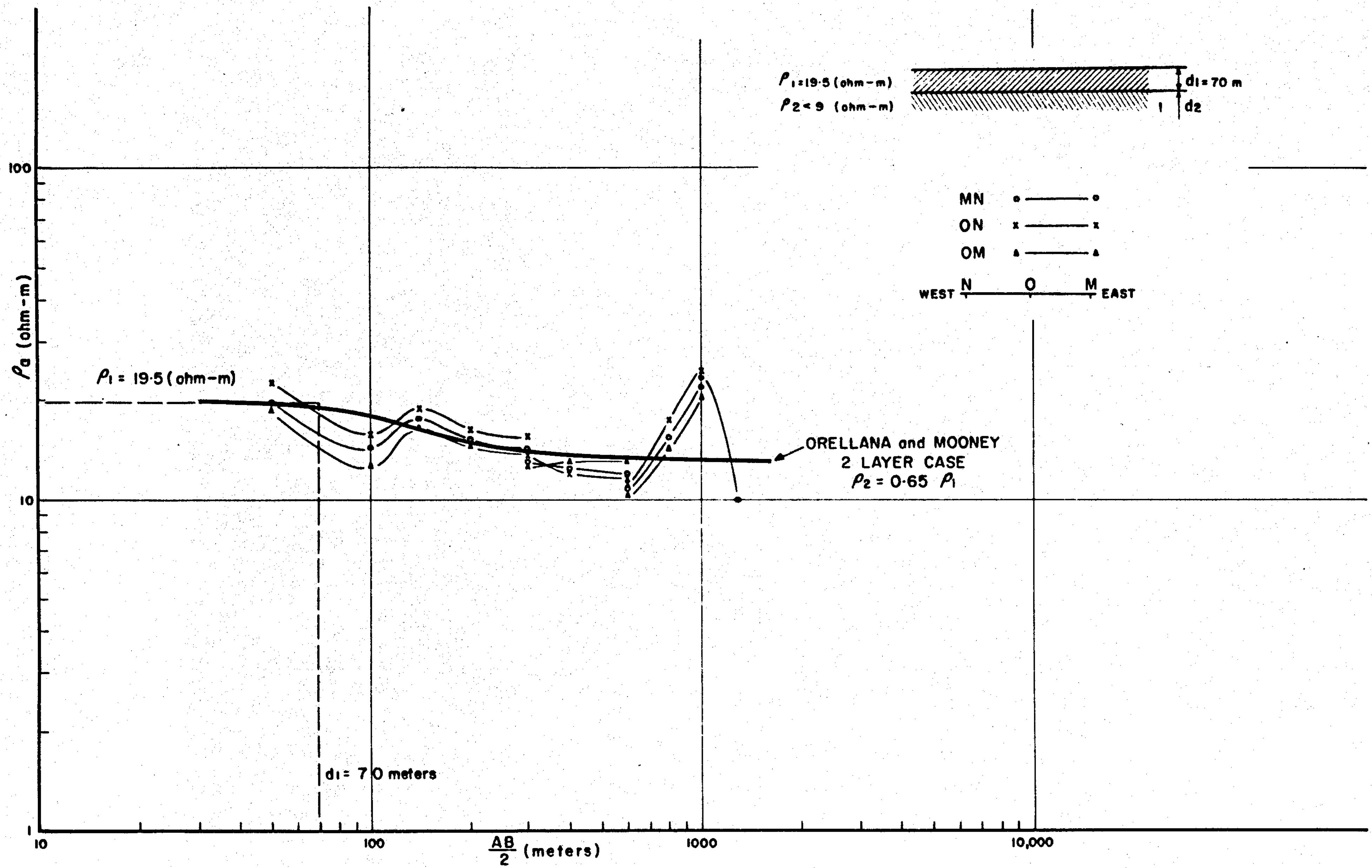
VES at 1370 N, 550 E
ZONE D
in Figure 4-18

UNITED NATIONS
GEOTHERMAL RESOURCES DEVELOPMENT
IN NICARAGUA
(CON. 167/72, NIC-10)

SCHLUMBERGER RESISTIVITY SOUNDING

Figure 4-20

73-9674



UNITED NATIONS
GEOTHERMAL RESOURCES DEVELOPMENT
IN NICARAGUA
(CON. 167/72, NIC-10)

SCHLUMBERGER RESISTIVITY SOUNDING

VES at 1374 N, 542 E
ZONE E
in Figure 4-18

73-9674

Figure 4-21

but measured resistivities may be less reliable because of the nearness of the current electrodes to Lake Managua caused some of the current to flow through the lake, rather than being uniformly distributed through the ground. This caused lower resistivities to be recorded (Carriere and Klein, 1974, refer to Figure 4-18b). Frequencies of 1/64 Hz and 1/32 Hz were used, which are low enough to prevent interference from skin effects.

In a geothermal environment such as Momotombo, measured resistivity variations seldom represent horizontal layers. Vertical boundaries are more likely to be encountered, such as the edge of an upwelling flow of geothermal fluids. In such a case, a boundary is not distinguished if the electric field is parallel. In other cases, lateral changes in resistivity could be interpreted as vertical changes. Since only one survey was performed with one current dipole orientation, the capability for detecting discontinuities was thus limited. It would therefore have been necessary to have more than one survey with various current dipole orientations but this was not done.

The measurements taken in zone D of Figure 4.18 show a decrease in resistivity to the east. A low resistivity of 1.5 ohm-m was measured in 1370 N and 550 E of Figure 4-18.

d. <u>Frequency Domain Sounding</u> - Only one such sounding was performed using the same electrode setup as the roving dipole survey (Figure 4-18b). The potential electrodes had an 800 m separation. The frequencies used were 1/16, 1/32, and 1/64 Hz. Results listed in Table 4-1 show no significant variation in resistivity with changes in frequency. The variations observed were within the reading error of the instrument (Carriere and Klein, 1974).

e. <u>Dipole-Dipole</u> - This technique was tested in the Momotombo area. The array is quite sensitive to lateral changes in resistivity and is greatly affected by near surface inhomogeneities along the survey route. Even with a spacing of 500 m, the high contact resistance caused low signal levels (Carriere and Klein, 1974).

f. Self-Potential Method - Self-potential (SP) measurements have been used in other geothermal fields with little success and the method is still under investigation for suitability in geothermal exploration. Studies by Corwin and Hoover (1979) indicate that great care must be exercised in interpreting SP anomalies. Based on measurements in 13 different geothermal areas, they describe a number of recently discovered factors which affect data quality. These factors were perhaps unknown during the exploration stage at Momotombo, and as such affected the optimum use of the technique at the time. As a result, the SP measurements at Momotombo were of no value. Although the self-potential data may give some information about the near surface hydrothermal system, the anomalies indicated are often small and can be easily confused with other effects. Corwin and Hoover (1979) found some indication that such measurements may be used to locate faults with circulating thermal fluids or areas of elevated heat flow.

2. Conclusions - Resistivity surveys performed during Stage 2 in the Momotombo area identified three zones of low resistivity. Since the increase in resistivities between the zones is not large, these three zones may be part of one body (Carriere and Klein, 1974). The low resistivity areas are shown in Figure 4.18. Zones C and D show resistivities of less than 5 ohm-meters, with resistivities as low as 1.5 ohm-meters in zone D. This area appeared to be most promising for drilling.

TABLE 4-1

FREQUENCY DOMAIN SOUNDING - ROVING DIPOLE ARRAY,

AB = 5.6 Km, MN = 800 m

Frequency (Hz)	Current (A)	Voltage (m,V)	Resistivity (ohm-m)
1/64	3.4	.615	5.5
1/32	3.4	.648	5.7
1/16	3.4	.645	5.7

Although the measurements were accurate, the area which was investigated was west of the original target area, and thus instead of refining previous explorations it outlined another area with resistivity anomalies. More beneficial information would have been obtained if the previously recommended exploration strategy of the Momotombo field had been followed. This would have included the complete review of all previous investigations for any subsequent exploration phase. In this stage, zone D was determined to be the most promising area; Stage 1 investigations had already determined this area to have low resistivities.

C. Geochemical Methods

Geochemical information of the Momotombo area (as described by Sigvaldason, UNDP, 1973) are summarized.

1. Fumarole Gas Samples - Fumaroles at the 100 m, 50 m and lake shore elevation had very low pressure steam and gas emission, and only a faint smell of hydrogen sulfide. The fumaroles at the 300 m elevation emitted gases and water vapor under fairly high pressure; at the 300 m elevation the H_2S smell was reported as quite distinct. Very intense fumarolic activity occurs in the crater. Dense white fumes are given off at low pressure, and incrustations of elemental sulfur are present. In 1973 the fumarole temperature in the crater was 230°C.

Sigvaldason states that activity in the Momotombo crater is reminiscent of basaltic craters during the first weeks after termination of lava activity. The emission of acid gases could indicate a connection with an intrusion of large dimensions. The gases have not been neutralized by reaction with wall rock or absorption in ground water, hence the postulation of a short travel path or an open, permeable connection with the subsurface. In the crater, all gas occurs as SO_2 and elemental sulfur. Neither methane nor hydrogen sulfide was detected; hydrogen content was low and CO_2 was moderate. The gases associated with the hot springs had the same characteristics as gases from the lowest fumarole area (100 m elevation).

The fumarole located at 300 m altitude contains CO_2 as a major component with substantial amounts of H_2S and H_2. The fumarole gases at 100 m altitude showed a trace of H_2, and H_2S decreased markedly, with a corresponding increase of carbon dioxide.

Certain gas mixtures may be associated with specific temperature conditions. Carbon dioxide with some hydrogen sulfide usually indicates high temperature at depth. Hydrogen in excess of 0.5 percent by volume can signify temperatures above 200°C. However, at Momotombo in the hot spring gases, H_2 was 0.13 percent by volume.

Sigvaldason concluded that there was sufficient evidence for a magnetic origin for the hydrothermal gases. He stated: "The differences in gas compositions between the volcanic fumarole and the hydrothermal fumaroles and hot springs would accordingly be the result of:

- reactions between individual gas components upon cooling and pressure release

- reactions with wall rock and thermal water

- o differential boiling resulting in fractional loss of gas species

- o reactions with atmospheric oxygen in near surface layers

- o other factors." (Sigvaldason, 1973)

2. Model for Surface and Near-Surface Thermal Waters - The great change in concentration of hydrogen from fumaroles at the 300 m elevation compared to the hot springs at 39 m was explained in the report by subsurface boiling of upflowing "primary" thermal water, occurring at shallow depth below the fumarole at 300 m elevation. The gases in the lower fumaole and hot spring represent a more advanced state of fractionation resulting from continued boiling and thermal water flow in shall subsurface layers. The behavior of other gas components support this model. H_2S was unusual; it is more common to see a slower release of H_2S. The high amount of CO_2 might have resulted from the low pH of the thermal water, which would facilitate the release of H_2S.

Sigvaldason described the hot springs as typically sodium chloride with characteristics usually observed in high temperature waters. The chloride content was approximately 3600 ppm, Cl/B ratio was 90, and the water was low in calcium and high in sulfate. The model based on the gas compositions provided a basis for interpretation of the thermal water chemistry. Boiling of the fluids occurs at the 300 m level in an upflow zone and water flows toward the south. Hence, substantial chemical changes occur in the thermal water.

The following processes for the observed chemical composition were proposed:

1) Boiling in the upflow zone would have increased the TDS due to loss of vapor. Loss of CO_2 raises the pH and $CaCO_3$ pre-

cipitation results. The low calcium content in the hot springs could have resulted from calcite formation in the upflow zone.

2) Constitutents governed by temperature dependent equilibria would adjust to the new temperature environment as water which cooled by boiling during upflow cools further in shallow subsurface flow.

3) Mixing with cold ground water could lower the temperature of the water and counteract the concentrating effect of the boiling. Dissolved atmospheric oxygen introduced into the system would be used up by reactions with H_2S to form SO_4, explaining the relatively high sulfate in the hot spring water and increased nitrogen content of the gases.

4) Contact with shallow low temperature alteration products (montmorillonite) could affect the temperature indicated by the Na/K ratio.

Sigvaldason (op cit) further stated that because of the potential for re-equilibration in the thermal water no single component or ratio should be used to predict subsurface reservoir temperatures.

3. Conclusions - The conclusion that a geothermal fluid upwell zone exists near the 300 m elevtion fumarole was based on one hard fact: a hydrogen decrease relative to carbon dioxide from the 300 m fumarole to fumaroles at 100 m elevation, 50 m elevation, and the lake shore.

The chemistries of the near surface thermal waters were considered supportive of the 300 m area upwelling hypothesis.

Additionally, some warm wells and springs were sampled 9 km west of the Momotombo. Based on Cl/B ratios and the high content of Li and B in those waters, Sigvaldason concluded there was an admixture of more concentrated thermal water or a combination of mixing and steam heating (high sulfate) in those wells and springs.

IECO observes that the geochemical exploration approach in this stage, by using volatiles and other steam leakage indicators, allowed detection of either liquid or vapor-dominated geothermal systems. The use of steam leakage manifestations to detect apparent emissions from the reservoir expanded the area of geothermal interest away from the south flank of Momotombo.

The UNDP study described the gas sampling apparatus and stated that the sampling train was constructed from locally available parts, with the exception of the gas sampling tubes.

The funnel was described as metal but the type of metal was not mentioned. If the funnel was iron, it is suggested that that material reacted with acid gas in the 300 m elevation fumarole to form some hydrogen. This sample was analyzed in Iceland, and considering the storage time, the high hydrogen value could also result from bacterial activity in the presence of CO_2 and moisture.

The model proposed by Sigvaldason is essentially one for the surface thermal manifestations and shallow, subsurface thermal waters. He considered the hot spring waters re-equilibrated with their near-surface environment. The silica values and Na/K ratios of the hot springs predict subsurface temperatures around 200°C. The report suggests possible dilution by cooler waters and considering the high temperature of 209°C measured at 240 m in MT-1, a temperature range of 230°C - 250°C was assumed in the upflow zone after boiling and hence, higher temperatures in the reservoir.

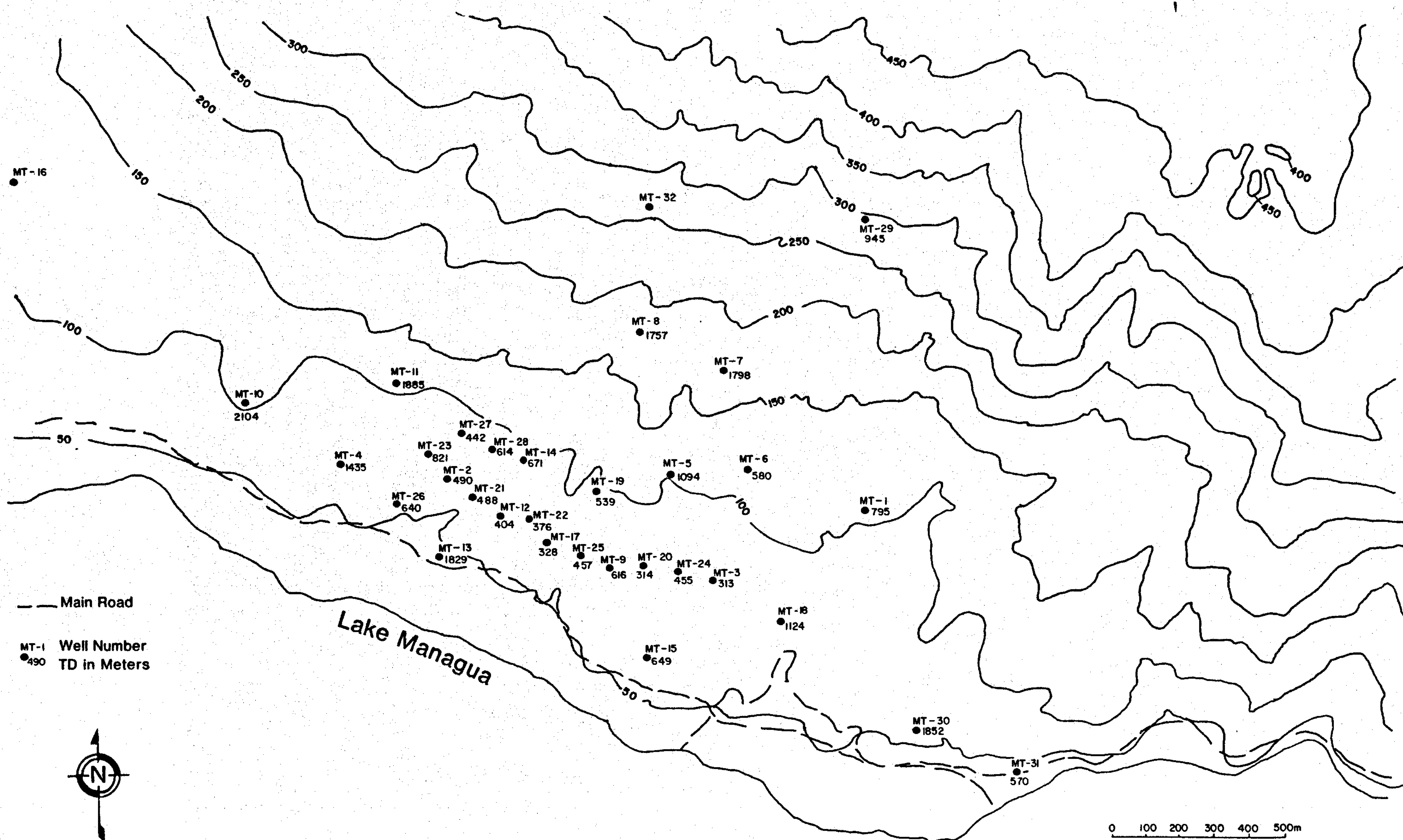
4.3 STAGE III - Performed by Electroconsult (ELC)

A. Substage 1

The objective of this phase of the investigations was the production of a feasibility report for the construction of a geothermal power plant at Momotombo. Detailed geologic mapping combined with other studies allowed the delineation of a preliminary conceptual model of the Momotombo geothermal field. On this basis, and also following Stage 2 recommendations, the first four experimental production wells were sited (MT-1-MT-4). The location of these wells is shown in Figure 4-22. Unfortunately, we were not able to obtain the final geological report of this study and therefore some of the methodology used remains unknown; the petrology and feasibility report, however, summarized the important results. The four production wells gave valuable information on the stratigraphy and a subsurface geological model was presented (Figure 5-4).

1. Geological Methods

a. Petrology - Petrographic analyses of cuttings from the production wells facilitated the elaboration of a lithostratigraphic succession of the formations encountered. The main sequence from top to bottom is: (a) pyroclastic deposits, (b) basaltic flows (rhombic pyroxene), (c) basaltic flows (olivine) (ELC, 1976). Hydrothermally altered minerals were mentioned, but no further mineralogic study was carried out in this field. The omission of this study deprived the petrologist of valuable information as previously discussed. An absolute age determination from samples of well MT-1 revealed an age of about 3.5 million years (Pliocene), confirming pre-Momotombo volcanics at depth (ELC, 1977).



Momotombo Well Location Map

Figure 4-22

b. Conclusions - Based on the geological, hydrological, geochemical, and geophysical investigations, the geological setting of the Momotombo area was described. The block diagrams shown in Figure 5-4.1 depict the subsurface formations and processes occurring in this area. It is believed that two reservoirs are present: the deep reservoir lying at a depth of about 1,200 m, formed by deep heated groundwater moving convectively within the fissured lava flows, and the shallow reservoir found at a depth of about 300 m formed by hot fluids escaping through a shear zone in the deep reservoir cap rock of hydrothermally altered pyroclastics. Cold meteoric water inflow below the shallow reservoir causes a negative temperature gradient, as observed in some of the wells (ELC, 1977). Figures 4.23a and 4.23b show the temperature distribution in the subsurface as plotted from temperature measurements in the wells shown. Geological results follow.

- Area Surface Geology - Faults, fractures and lineations of hydrothermally altered areas were noted by extensive remapping of the area. Few changes or additions were made to what was already known at this point. The study supports conclusions of previous investigations.

- Structure - This report confirms that the Momotombo Geothermal Field is underlain by tuff, tephra, and lava flows derived from the volcanic activity of Momotombo and Loma La Guatusa. The volcanic material of the shallow reservoir is only 200 m thick. Pliocene age flows, related to the Loma La Guatusa activity, underlie the Momotombo volcanics.

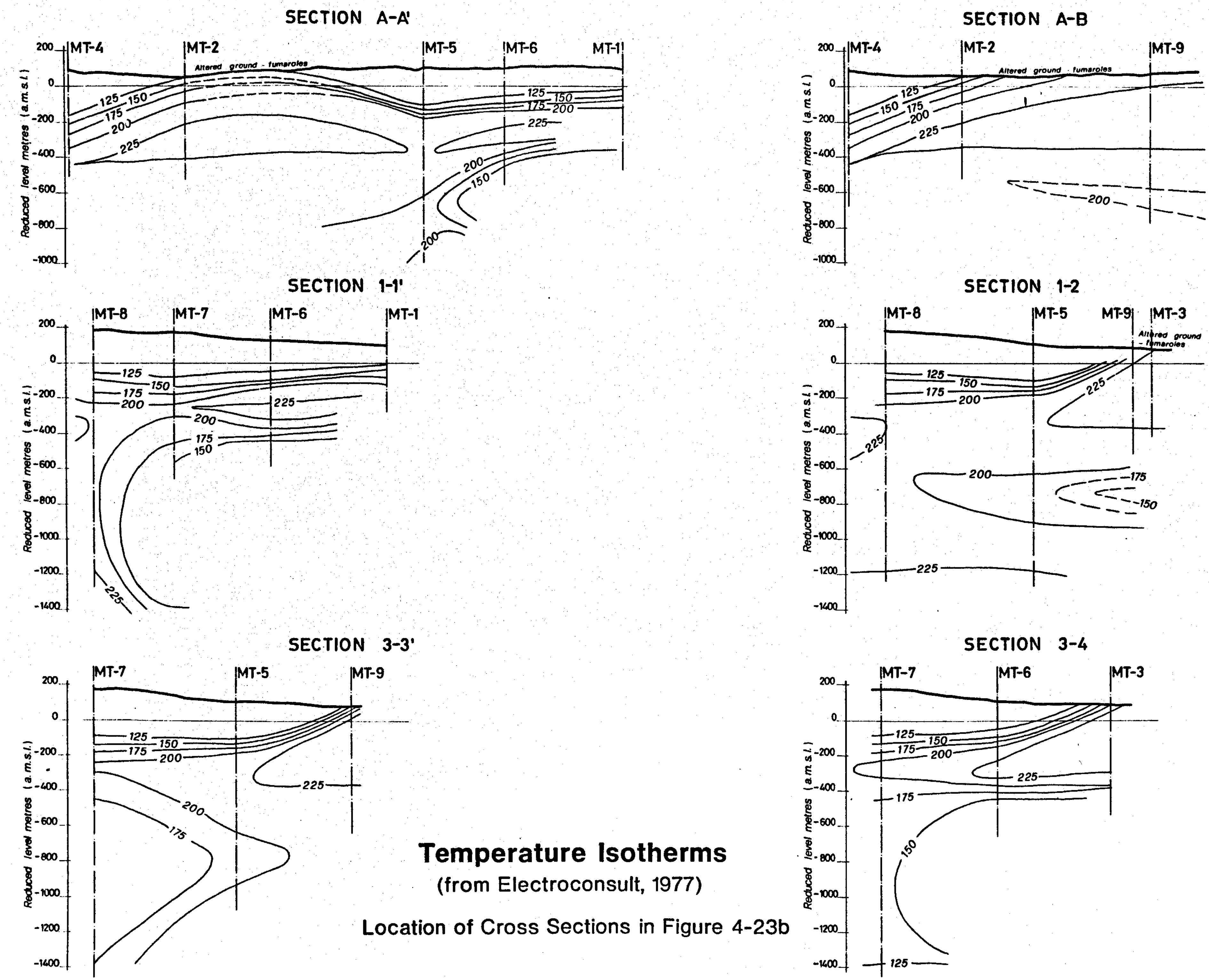
  The Momotombo Field is reported to be located within an uplifted block with its boundary on the west being a NE-SW trending fault, and its boundary on the east being a N-S trending fault. This horst is the structural control for the western extent of the geothermal field.

- **<u>Temperature Distribution</u>** - Temperature profiles were drawn from downhole temperature measurements obtained from geothermal wells MT-1 through MT-10. Almost all wells show temperatures of 220 - 230°C at depths between 230 and 300 m. It is believed that the beginning of this hot zone corresponds to the circulation loss and the collapse zone first encountered in well MT-1.

  MT-4 showed a continuous increase in temperature with depth. This was contrary to results obtained from MT-5, MT-6, MT-7, MT-8 and MT-9 where definite temperature inversions were observed below the productive zone. This temperature inversion seems to be especially marked in wells MT-1, MT-6 and MT-7, suggesting a cold water inflow from the east.

  Based on results of temperature measurements, it was assumed that two reservoirs exist. A "deep reservoir" was believed to be intersected in wells MT-4 and MT-10 at depths of 1200 to 1400 m, and a "shallow reservoir" was intersected by wells MT-2, MT-3 and MT-5 at depths between 300 and 400 m.

  The isotherm maps (Figures 23a, b) are especially important. They indicate cold water entering from the east and southeast below the base of the shallow reservoir. The drawings also indicate that the isotherms seem to align themselves along inferred and/or indicated fault lines. Planes of discontinuity between wells MT-3 and MT-6 and between MT-1 infer westward dipping formations below 300 m. Another plane of discontinuity dipping in a northwesterly direction (affecting shallow formations only) indicates that the shallow reservoir is present in well MT-2 but not in MT-4. ELC concluded that their interpretation was confirmed by the results of MT-4 and MT-10.



Temperature Isotherms

(from Electroconsult, 1977)

Location of Cross Sections in Figure 4-23b

Figure 4-23a

Well Temperature Contour Lines

(from Electroconsult, 1977)

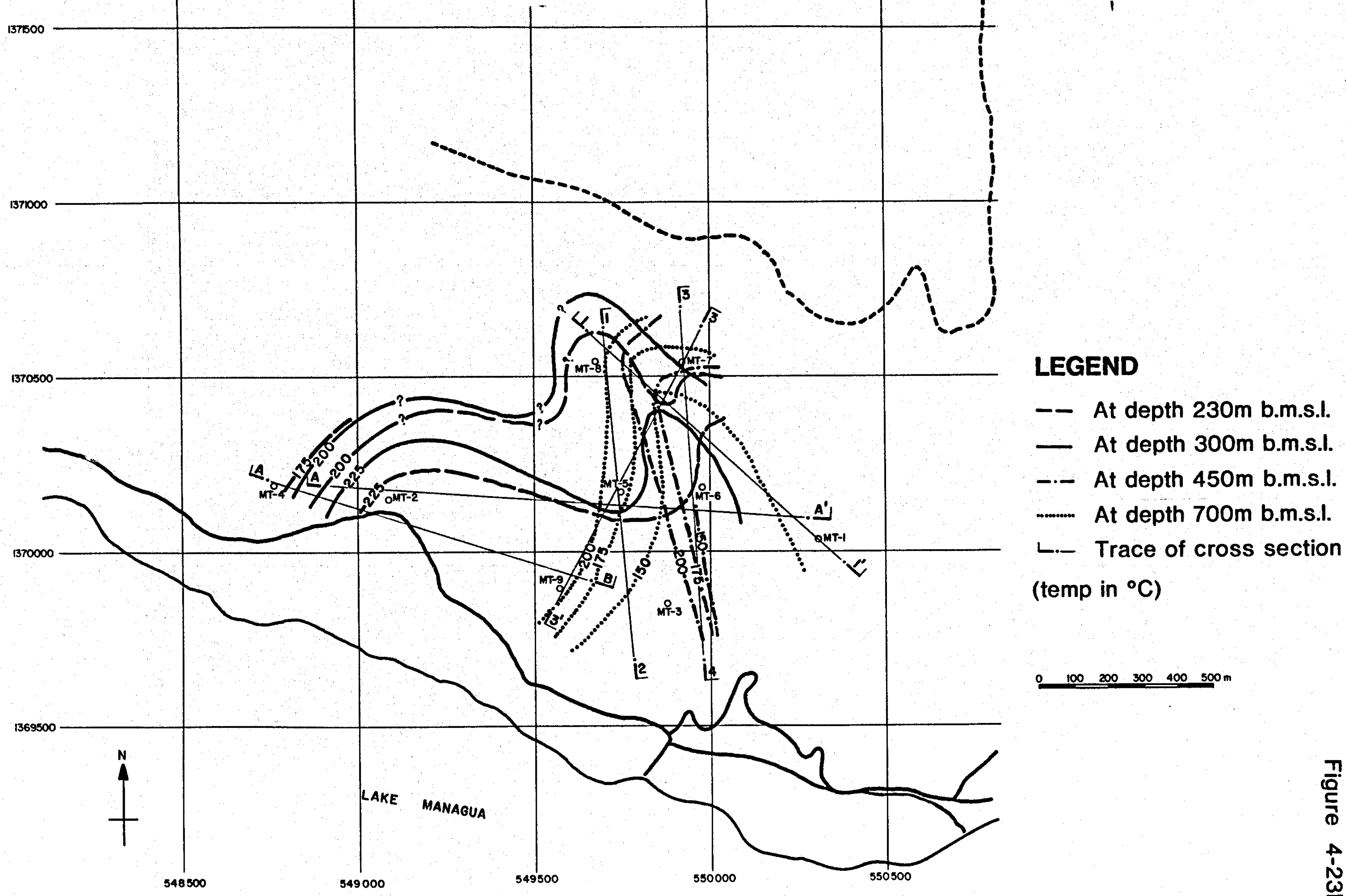


Figure 4-23b

With regard to circulation of hydrothermal fluids it was assumed that the main recharge area of the field is located in the plains north of Managua and in the southern portions of Lake Managua. The fairly shallow magma chamber of Volcan Momotombo heats this deep ground water and creates a convective cell, which develops most prominently in areas of high permeability where the flow makes up the previously mentioned "deep reservoir".

The cap rock for this convective cell is formed within the hydrothermally altered pyroclastics. A shear zone in the cap rock of the deep reservoir allows hot fluids to escape to shallow reservoir located at a depth of 300 to 400 m, where the fluids spread into the shallow reservoir.

In conclusion ELC states that if wells were to be sited at the optimum location, in an area that would be uninhibited by the flow of cold water described earlier, the Momotombo field should be capable of producing up to 30 MWe.

2. Geophysical Methods - Additional geophysical measurements were carried out at Momotombo as required for plant feasibility studies. Schlumberger VES soundings and a gravity survey were to detail the substructure of the field and locate areas of maximum permeability where deep exploratory wells were to be sited. The electrical prospecting encountered various difficulties (ELC, 1976) and the omission of data, procedures and isoresistivity maps in the final report pose problems in the verification of results and conclusions. Gravity measurements appear to have followed correct procedures and a Bouguer anomaly map was presented. The techniques and results are presented in the following sections.

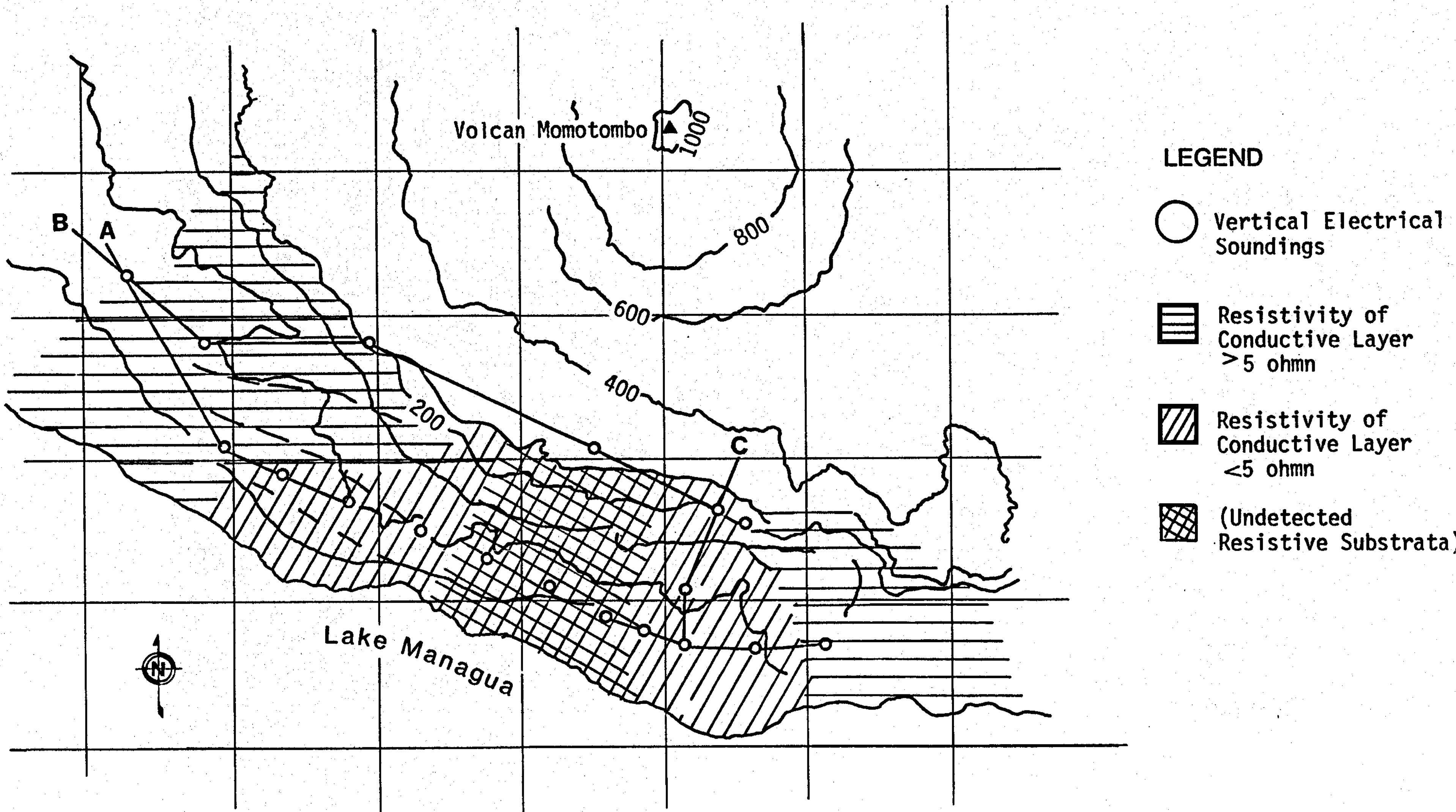
a. Schlumberger VES Soundings - A total of 20 Schlumberger soundings were carried out in the vicinity of Momotombo volcano.

Electrode separations of 2 to 3 km were employed, since larger separations gave inaccurate results due to the high resistivity of the surface layers. These separations allowed exploration to 1000 m depth and are therefore limited since previous results from Stage 2 showed a possible low resistivity zone lying at depths greater than 1200 m. Electrode resistance was high, although up to 500 liters of water were used to water the electrodes at each reading, 8 potential electrodes were necessary for all readings greater than AB/2=300 m. Progress was slow and costly.

Results are shown in Figures 4.24a, b, and 4.25. Three formations which exhibited different resistivities were encountered. The zone in the central portion of the explored area appeared to have resistivities less than 5 ohm-meters, but these findings were already known from Stage 1. The results do not appear to contribute any new data to the Momotombo exploration program, and the geophysical report has no data, curves or isoresistivity maps to verify procedures and results.

b. Gravity Measurements - The gravity survey consisted of 200 readings taken over an area of approximately 300 km^2 including the Momotombo prospect. The usual problems of access and topography affected the distribution of the stations and consequently limited the accuracy of the interpretations. The Bouguer anomaly map shown in Figure 4.26 was incorrectly contoured. A corrected version is presented in Figure 4.27a.

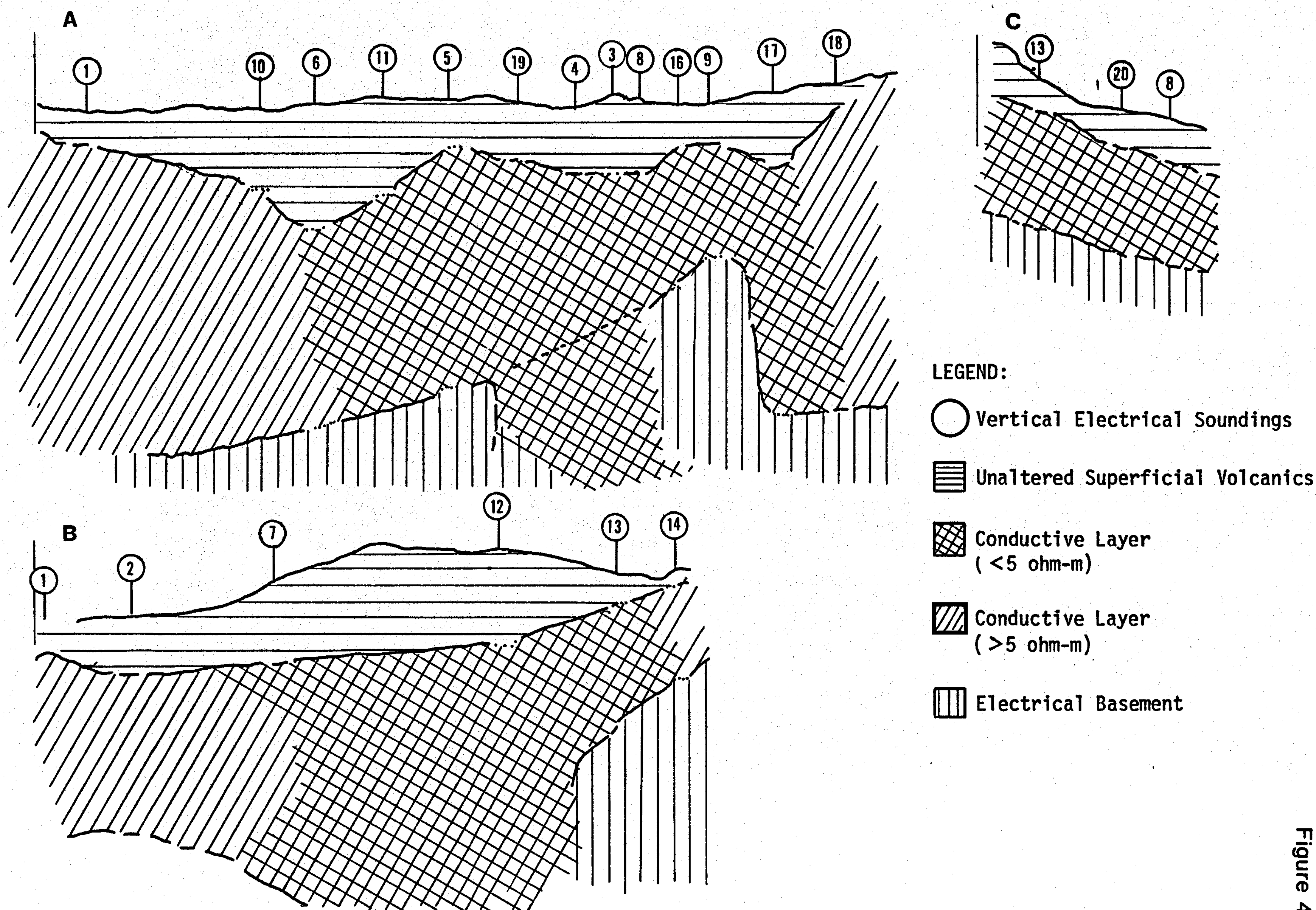
c. Conclusions - The results of the geophysical investigations in Stage 3 remain somewhat unclear due to the omission of data from the report. The reported findings appear to be a recapitulation of Stage 1 results and as such do not contribute any new information pertaining to the geothermal reservoir. The Schlumberger VES soundings were reported to be plagued with problems, but again the omission of procedures, data, and general information on the methodology does not allow for investigation of the problems or for verification of results.



Geophysical Anomalies

(From Electroconsult, 1976)

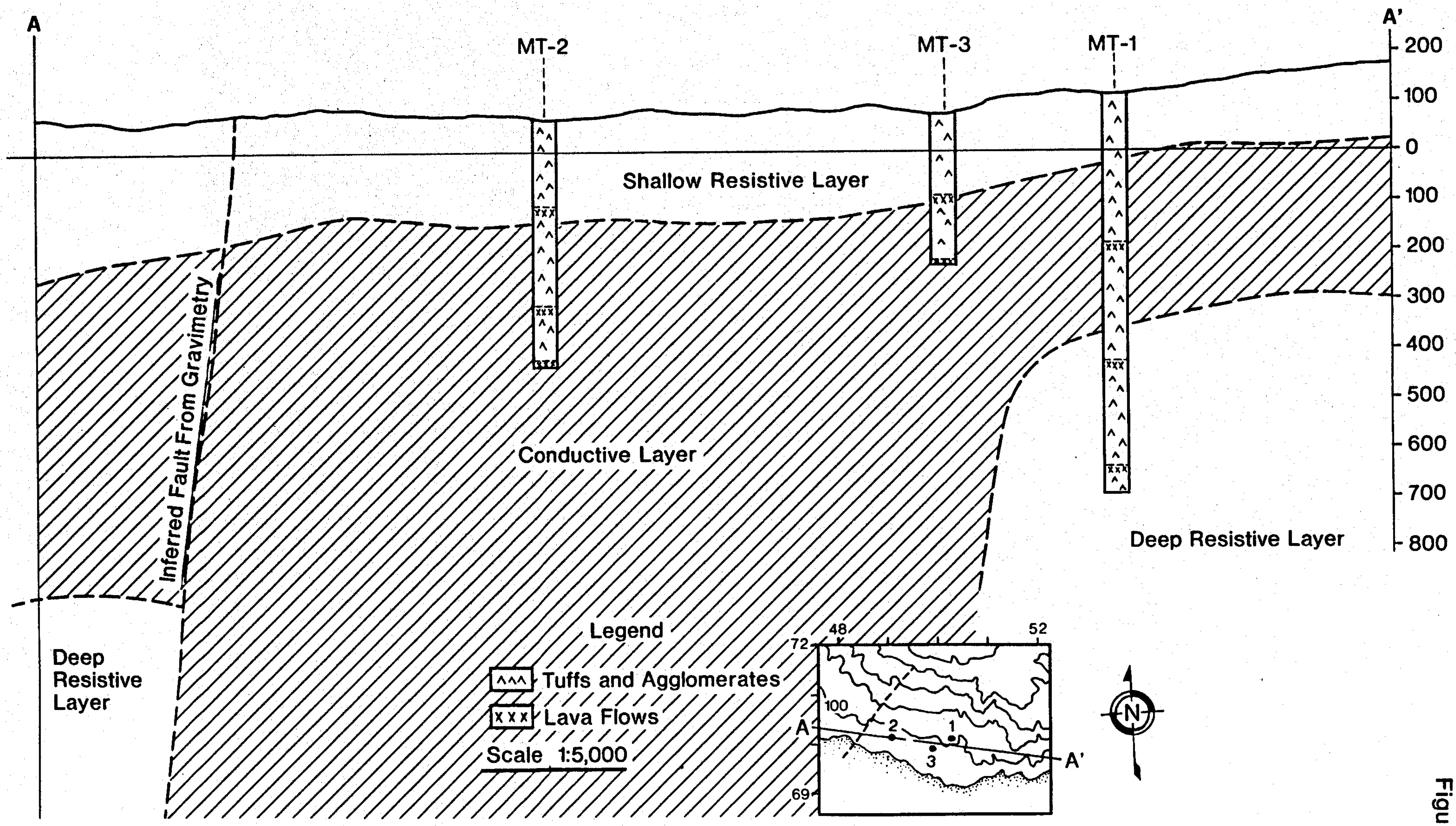
Figure 4-24a



Interpretive Cross Section of Momotombo Anomaly

(From Electroconsult, 1976)

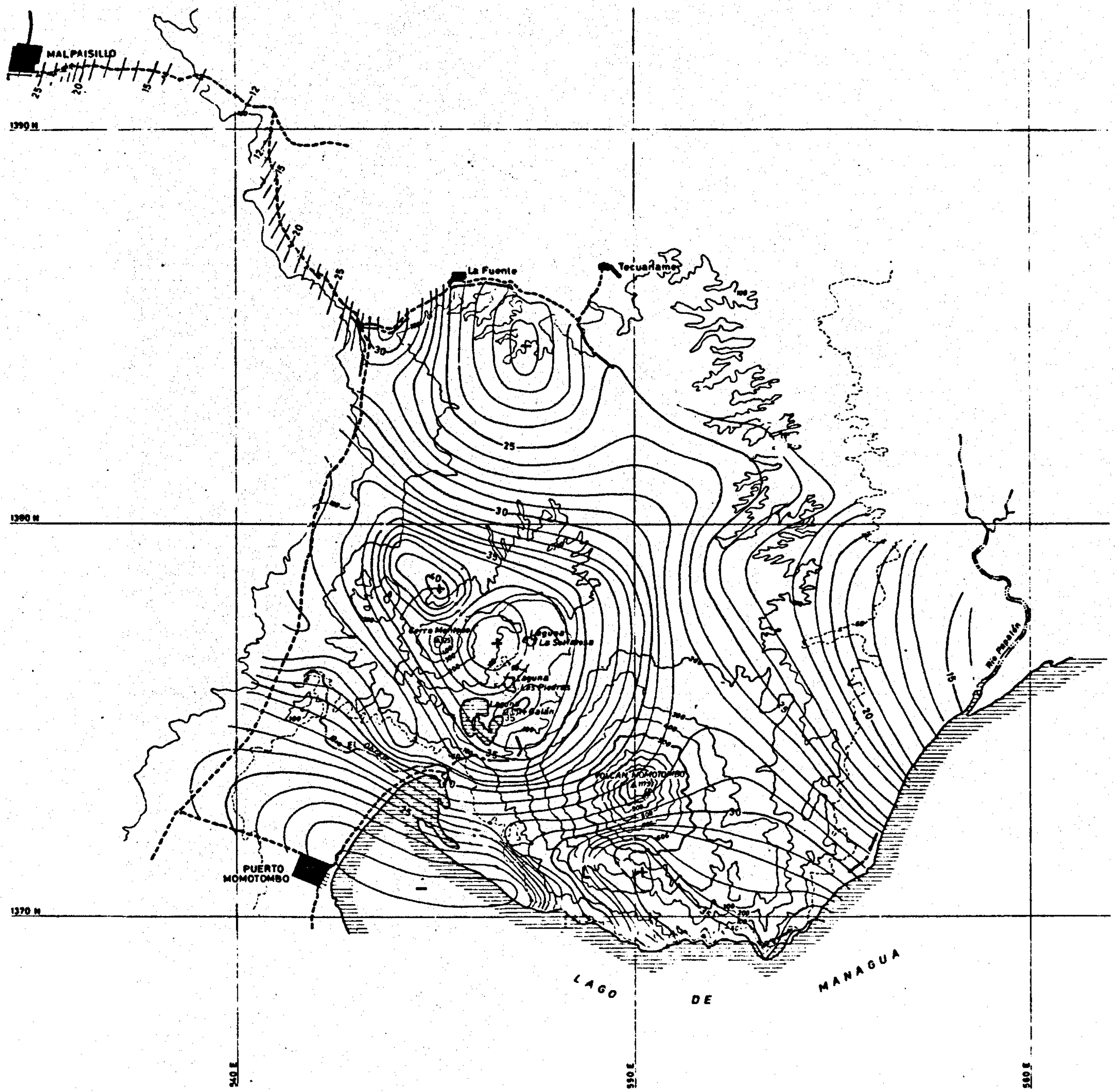
Figure 4-24b



Cross Section A-A'

(From Electroconsult, 1976)

Figure 4-25



LEGEND

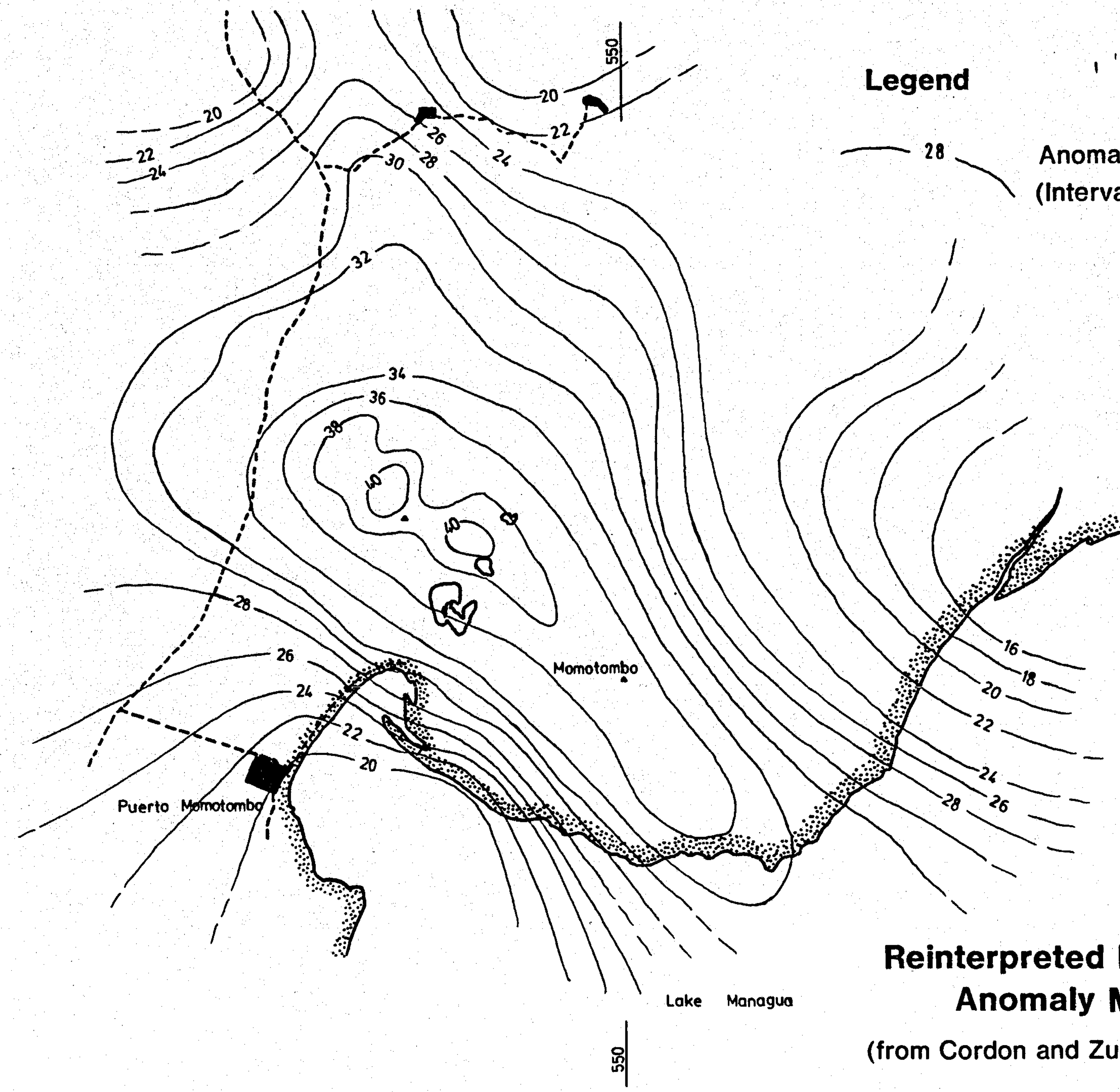
—30—	Anomaly contour line (interval 5 mgals)
——	Anomaly contour line (interval 1 mgal)
+	Gravimetric highs
—	Gravimetric lows

Scale

Original Bouguer Anomaly Map

(From Electroconsult, 1976)

Figure 4-26



Legend

28 Anomaly Contour Line
(Interval 2 mgals)

Reinterpreted Bouguer Anomaly Map

(from Cordon and Zurflueh, 1980)

Figure 4-27a

The incorrect contouring of the Bouguer anomaly map makes subsequent gravity interpretations somewhat dubious.

3. Geochemical Methods

a. Studies Performed - The geothermal field feasibility study performed by Electroconsult included geochemical and isotopic analysis, analyses of regional springs and wells, exploration wells, and a hydrogeologic report.

b. Regional Hydrology - ELC reports that there are major distinctions between the shallow and deep circulation zones in the Nicaraguan Depression.

The shallow circulation zone is in the Quaternary volcanics and flow generally follows the ground morphology. The water is of Na-Ca-Mg carbonate composition, with TDS usually lower than 1000 ppm.

Deep circulation occurs in the lower part of the volcanic complex and in reworked pyroclastic material, probably in the Las Sierras formation. The regional water flow is to the northwest, with the impermeable Tertiary ignimbrites acting as a major aquiclude. The water is reported to be Na-Cl in composition, with TDS ranging between 2,500 and 7,000 ppm. This deeper ground water has a high boron content.

The two water systems may mix along fractures and faults. High sulfate content in the water of either system can occur near volcanoes with fumarolic activity. ELC determined that the existence of two different hydrologic systems has been confirmed by the isotope data, which revealed strong reactions between the waters and the host rock, and a low elevation for the recharge area for the water and the deep system.

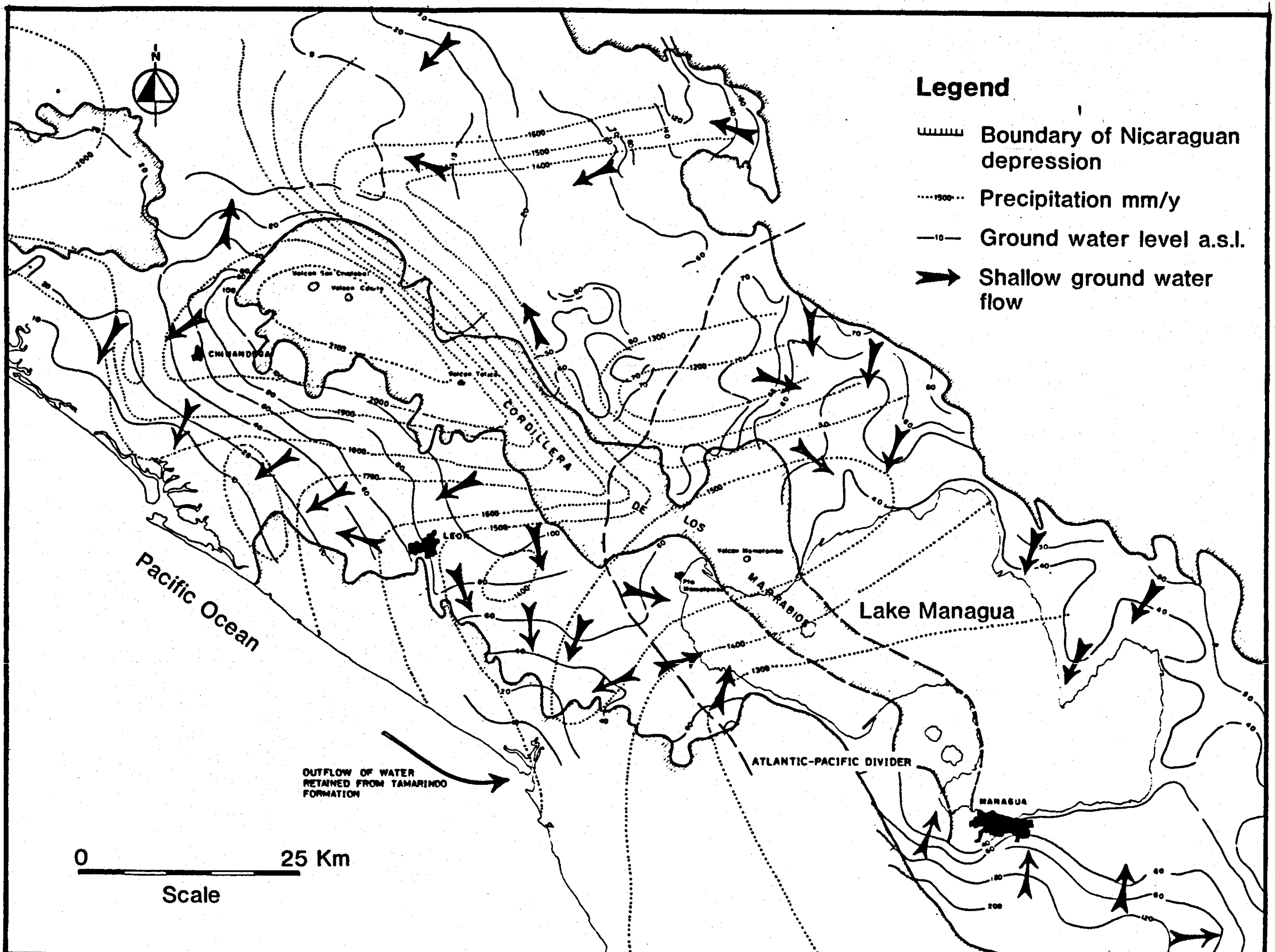
In the Nicaraguan Depression the aquiclude is the Tamarindo Formation, consisting of ignimbrites; the major aquifer is the Las Sierras Formation, composed of pyroclastics and lava flows.

ELC reports that the porosity of the Tamarindo Formation is negligible because of its origin: "...showers of glassy droplets from molten acid rocks, yielding rocks of low permeability and porosity". Alteration of this rock produces clays which further diminish its permeability. The Las Sierras Formation is less consolidated, although solid basic flows do occur.

A general transmissivity for the Las Sierras formation was calculated by ELC, based on data from a 1974 United Nations Development Program study on the groundwater in the Pacific Coastal Belt. This average transmissivity calculated from 47 pumping tests in the study area is: 1.52×10^{-2} m^2/second

The storage coefficients of the free layers varied from 0.30 for the coarse gravels to 0.01 for the fine clayey sands. The confined layers ranged from 0.02 to 0.35. These values indicate that the confined aquifer of the Las Sierras Formation is phreatic or slightly artisian. Information from wells drilled in the Pacific Coastal Belt indicate aquifers in the Las Sierras constitute 35% of the total thickness of the formation.

Rocks with very low or non-existant permeability are found at the base of the Nicaragua Depression. The pumiceous tuffs of the lower Las Sierras Formation, found in the southwestern area of Lake Nicaragua, have good permeability. ELC reports that Tahal Engineering calculated the infiltration rate to be 10-15% of the annual rainfall. The upper part of the Las Sierras Formation, composed of pyroclastics with intercalated lava flows, has intermediate permeability although the fractured zones can be good aquifers (Figures 4-27b and 4-27c).



Hydrogeology and Precipitation

Figure 4-27b

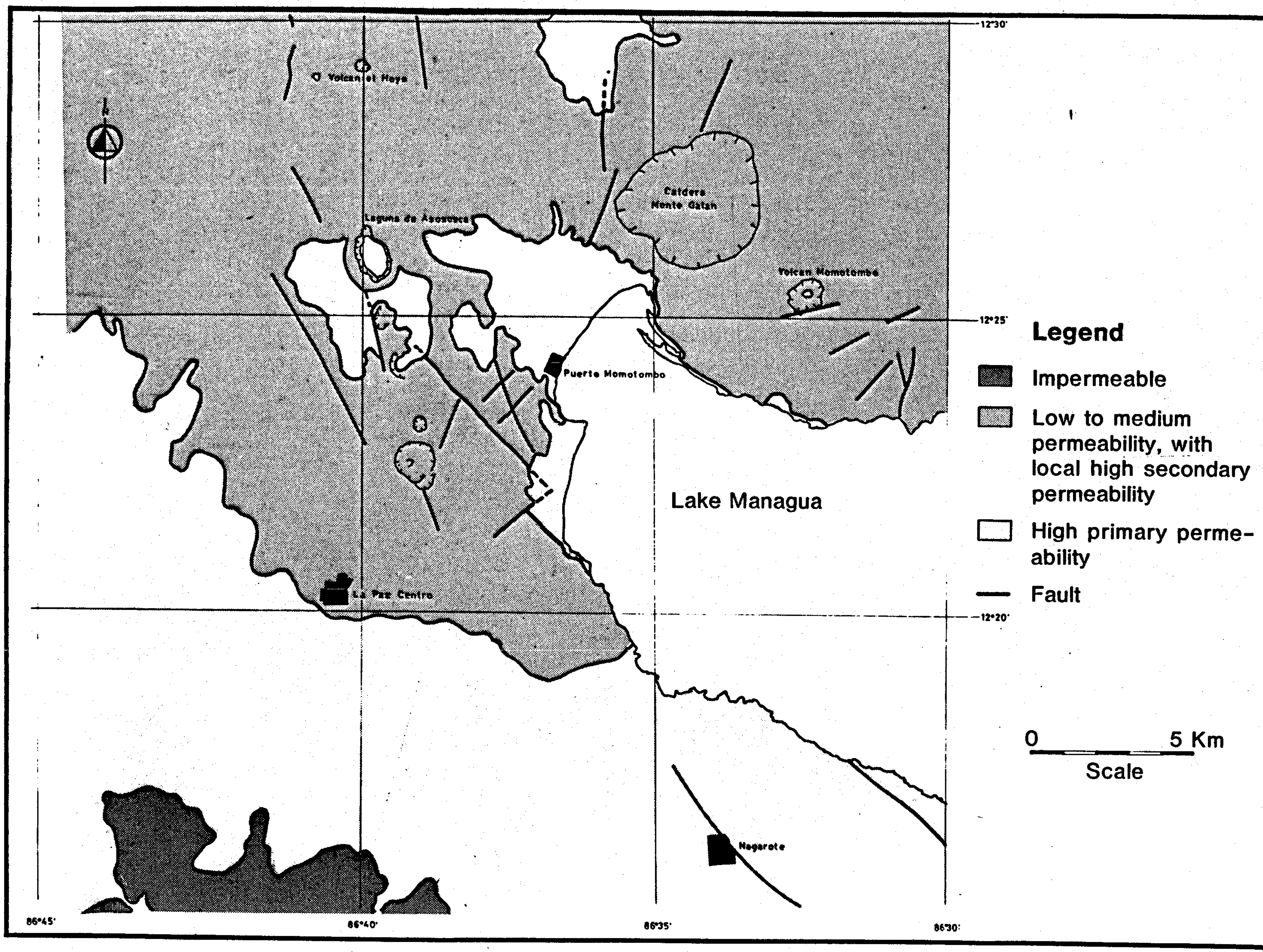


Figure 4-27c

Permeability Map

ELC calculated the hydrogeological balance for the Momotombo area. The orohydrographic basins around the volcano are distributed radially. The equation used was:

$$P = I + R + E_{tr}$$

where P = rainfall, I = infiltration, R = superficial runoff and E_{tr} = evapo-transpiration.

The rainfall, P, for the Momotombo area was taken from a 1971 UNDP report and an ENALUF isohyetal map based on data from 1969-1973. The two reports were in close agreement. The value used was:

$$P = 150 \times 10^{-2} \pm 15 \times 10^{-2} \text{ m/year}$$

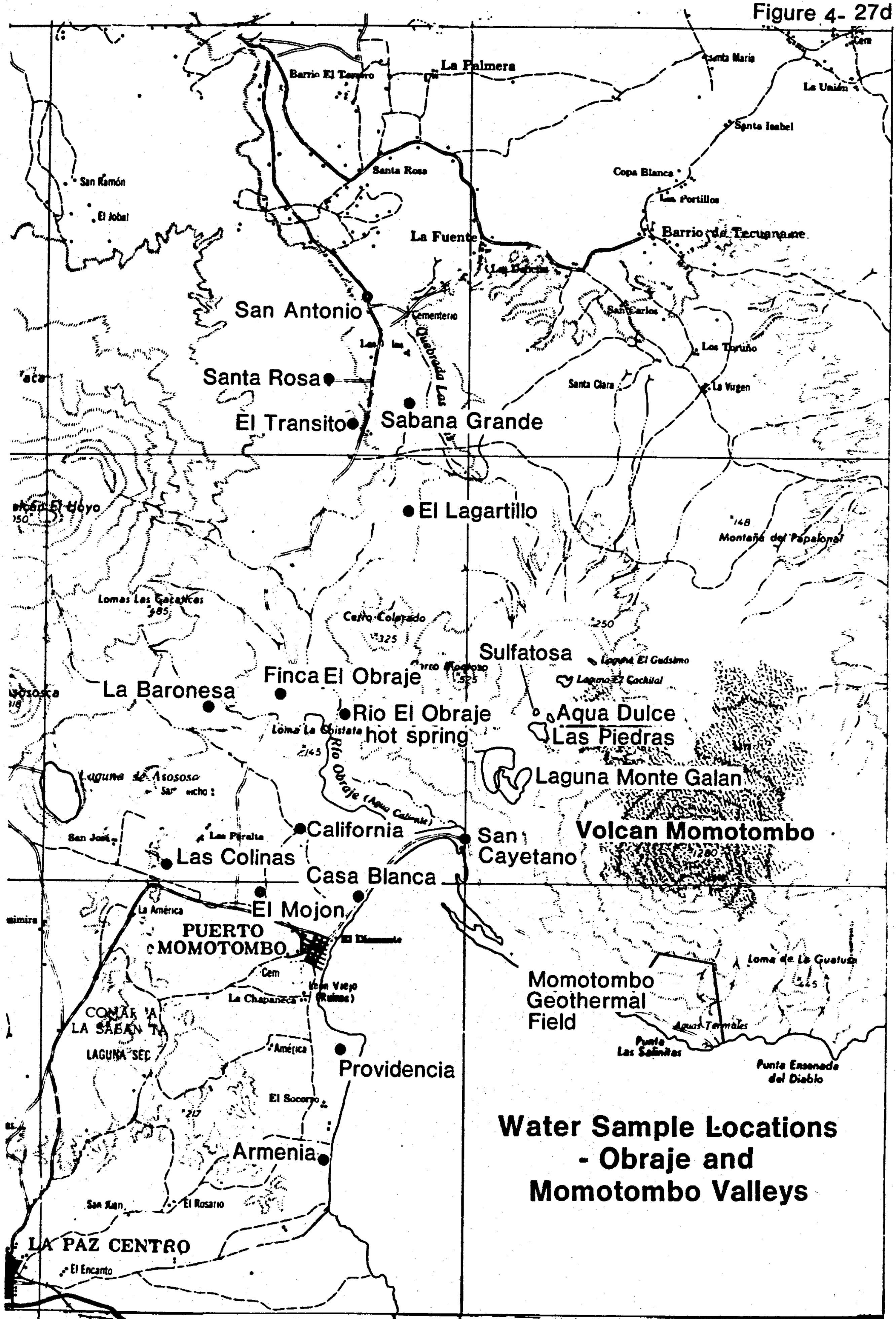
For evapo-transpiration, ELC used the TURC formula which was considered applicable to tropical conditions.

c. Regional Geochemistry - Samples were collected from cold and hot domestic wells, exploration production bore holes, and Lake Managua (Figure 4-27d). Interpretation of chemical data (Tables 4.2 and 4.3) suggested three geochemical groups:

- Waters of geothermal origin around the Obraje-El Hoyo area
- Waters of the Las Sierra aquifer
- Waters of the South Momotombo geothermal field

1) Obraje Area - Several warm wells and a hot spring are located in this area. The spring discharges about 90 liters/sec at a temperature of 50°C. A well at Finca Obraje has a temperature around 40°C. This hot water is encountered 30-35 meters below surface.

Figure 4- 27d



Water Sample Locations - Obraje and Momotombo Valleys

TABLE 4.2

AVERAGE COMPOSITION OF WATERS - RIO OBRAJE AND MONTE GALAN AREAS (All values in ppm)

Locality	Temp. °C	pH	Na	K	Ca	Mg	Li	SiO_2	HCO_3	CL	SO_4	B	TDS	No. of samples
Armenia	Cold	7.3	33	11	104	33	0.003	106	180	160	68	0.3	695	5
Providencia		7.5	34	10	56	26		111	350	25	17	0.3	629	1
Casa Blanca	32	7.5	140	28	85	62	0.05	103	467	137	301	1.92	1325	5
El Mojon		7.6	36	7	26	14		115	221	10	4	0.5	433	4
Las Colinas		6.8	30	7	48	26	0.003	105	271	39	17	0.4	543	2
California	32	7.4	85	24	57	43		90	385	45	139	0.8	868	4
Rio Obraje	46	7.2	154	29	73	51	2.2	148	447	178	206	3.12	1291	10
Finca Obraje	41	7.4	152	26	51	27		139	257	151	165	3.14	971	4
La Baronesa	43	7.3	121	30	133	92	0.2	157	469	203	282	1.48	1489	5
Lagartillo	41	7.0	171	34	55	27		156	430	156	86	2.69	1118	2
El Transito	40	7.9	124	20	49	17		116	428	47	68	1.15	870	4
Sabana Grande	34	7.6	45	10	38	16		122	230	30	30	0.40	521	2
Santa Rosa	40	7.6	93	17	50	25		118	386	36	76	0.75	802	3
San Antonio	34	7.8	76	14	68	33		122	401	25	97	0.54	835	3
Lake Managua		8.9	272	46	9	14	0.4	27	516	181	32	1.1	1098	9
San Cayetano	31	7.8	116	20	75	31	0.07	118	348	145	89	1.38	944	5
Monte Galan	32	7.0	200	30	36	43			124	229	320	1.6	984	1
Las Piedras	40	8.5	405	40	115	140	0.2	56	240	430	910	2.94	2339	1
Agua Dulce		7.8	64	9	57	27			271	65	86	0.65	580	1
Sulfatosa		8.1	800	120	34	460	0.25	94	341	829	3090	4.80	5875	1

TABLE 4.3

AVERAGE ATOMIC RATIOS FOR WATERS - RIO OBRAJE AND MONTE GALAN AREAS

Locality	Cl/B	Cl/SO_4	Cl/HCO_3	Na/K	Na/Ca
Armenia	162	6.4	1.5	5.3	0.6
Providencia	25	3.9	0.1	5.6	1.1
Casa Blanca	22	1.2	0.5	8.5	2.9
El Mojon	6	6.8	0.07	8.8	2.4
Las Colinas	30	6.2	0.25	7.3	1.1
California	17	0.9	0.2	6.0	2.6
Rio Obraje	17	2.3	0.7	9.0	3.7
Finca Obraje	15	2.5	1.0	9.9	5.2
La Baronesa	42	1.9	0.7	6.9	1.6
Lagartillo	18	4.9	0.6	8.4	5.4
El Transito	12	1.9	0.2	10.9	4.5
Sabana Grande	23	2.7	0.2	7.6	2.1
Santa Rosa	15	1.2	0.2	9.3	3.2
San Antonio	14	0.7	0.1	9.2	1.9
Lake Managua	50	15	0.6	10.2	53
San Cayetano	32	4.4	0.7	9.9	2.7
Monte Galan	44	1.9	3.2	11.3	9.6
Las Piedras	45	1.3	3.1	17.2	6.1
Agua Dulce	30	2.0	4.1	11.6	2.0
Sulfatosa	53	0.7	4.2	11.3	41

Northwest of El Obraje are five more wells with high temperatures. The valley in which these wells are located is relatively narrow (3-5 Km). The wells on the north and the wells in the Finca Obraje area are about 7 km apart. There is one hot well located about 4.5 km northwest of the Obraje area.

ELC calls this area the Obraje geothermal field. Boron and chloride concentrations are highest around Finca Obraje, which is also the focal area of a low resistivity anomaly. The concentrations of Cl and B decrease away from the Obraje area towards Puerto Momotombo. Piezometric measurements indicate that ground water flows from El Transito in the north part of the valley southerly towards the Momotombo valley.

ELC suggested two hypotheses based on the observations:

- o The ground waters are contaminated by a chloride-rich thermal water along a northwest-southeast fracture in the Obraje area.

- o The ground water flow from El Transito moves towards Obraje and may encounter a ground water barrier between Obraje and the Momotombo valley.

2) The wells in the valley just north of Puerto Momotombo (El Mojon and Finca California) and south (Armenia, Socorro and Providencia) along the lake shore are fed by an aquifer in the Las Sierras Formation. This water is Na-Ca bicarbonate in character and is quite low in boron and chloride compared to the Obraje waters. The well at El Mojon had a temperature of 28°C.

ELC suggested that the difference in chemistry was due to thermal waters contaminating the ground water in the Obraje area. The ground water flowing southward from El Transito towards the Momotombo valley is impeded by some kind of barrier before this ground water reaches the valley. The thermal spring at Obraje is a major discharge. The thermally mixed water is moving along a northwest-southeast fracture. There is another system of nearly perpendicular fractures which may also channel flow.

3) ELC considers the Rio Obraje valley a separate geothermal entity. The waters feeding this aquifer could be coming from Volcan El Hoyo. The fumaroles at the summit of El Hoyo could be the gaseous phase of the volcanic activity and the hot water emerging at the Rio El Obraje spring may represent the fluid of an El Hoyo geothermal system.

ELC suggests that the hot waters at Lagartillo and El Transito may be separate from the El Hoyo system and might owe their heat to a source associated with the cones northwest of Volcan Momotombo, for example Cerro Montoso and Cerro Colorado.

Just on the northwest edge of Momotombo is caldera Monte Galan. There are four lagoons within this caldera. All but Laguna Agua Dulce have higher than ambient temperatures for the groundwaters in that region. Laguna Sulfatosa has a reported temperature of 40°C and is extremely high in sulfate, 3090 ppm, and TDS, 5875 ppm. The lagoons are aligned along the northeast-southwest fault.

Based on comparisons of chemical constituent concentrations and ratios ELC concluded tha Lagunas Monte Galan, La Piedras, and Sulfatosa contain ground waters mixed with some geothermal fluid, source unknown, but Agua Dulce is fed by surface waters.

d. Geochemical Studies - Momotombo - At the time the ELC geochemistry report for Momotombo was written, July 1976, wells MT-1 through MT-9 had been drilled. By September, 1977, when ELC's Feasibility Study was presented, wells MT-10 through MT-20 had been completed. However, chemical analyses were available only for water samples from well MT-1 through MT-14.

ELC reported in their July 1976 geochemistry study the measured and estimated temperatures from drill holes MT-1 through MT-8.

Subsurface temperatures were estimated using Fournier and Truesdell's Na-K-Ca geothermometer. Estimates for the springs at Punta Las Salinitas ranged from 184-190°C for ELC samples. ELC reports that these estimates are somewhat lower than an estimate from a sample taken by Sigvaldason (1973), which was 227°C. Subsurface temperature calculations for 22 springs at Momotombo from Texas Instruments 1970 data gave a range of 195-230°C. ELC could not state with certainty at that time if the temperature of subsurface water feeding the Punta Las Salinitas springs was dropping or reflected differences in sampling and analytical techniques or even natural temporal changes. They suggested the possibility that the December 1972 Managua earthquake, measuring 6.5 on the Richter scale, could have affected the chemistry of the springs.

The Na-K-Ca geothermometer estimate for the lake waters is 230°C, suggesting that the geothermal reservoir could extend beneath the lake, although ELC reports reservations on this temperature because it is derived from surface lake water samples.

e. Chemical Characteristics of the Wells - ELC reports that chemical composition varies from well to well but some relationships are evident. The differences in chemistry were interpreted to indicate different producing horizons within the field. Well temperatures seemed to correlate with the ionic strength of the fluids. Wells with higher ionic strengths also had higher measured temperatures. MT-4, on the western side of the field, with a total depth of 1450 m, had a measured temperature of 327°C. The Na-K-Ca geothermometer temperature estimate was 313°C with an ionic strength of 0.182. The lowest temperature wells (at the time of ELC's report) were MT-6 and MT-7, with measured temperatures and ionic strengths of 231°C and 0.09 and 214°C and 0.84, respectively.

The geothermal fluid at the field is dominated by Na and Cl. ELC suggested that SiO_2 geothermometer estimates of the reservoir; because some wells were supersaturated with silica, did not reflect the original reservoir temperature. At an "average" temperature of 240°C, the amount of SiO_2 found in solution varied from 400 to 1000 ppm. This variation depends on the nature of the SiO_2; whether it is derived from quartz, cristobalite or amorphous silica.

MT-2, between the middle of the field and the western edge, (total depth 490 m), had a maximum SiO_2 concentration of 740 ppm, a supersaturated condition. ELC postulated this amount of SiO_2 could result if the fluid had cooled 30°C from its original estimated temperature to its measured temperature.

MT-2 was the only well tested for any length of time, more than a year, and some changes in chemistry were noted. The ionic strength increased, as reflected by an increase in Cl content from 3280 to 4090 ppm. Boron was not analyzed in all samples in this well but where available, the Cl/B ratio varied from 24 to 30. The ratio could signify that more vapor was separating from the reservoir and the boron moved preferentially with the vapor, hence a Cl/B ratio increase. Alternatively, a lower ratio could indicate entry of cooler waters into the reservoir. The Na/K ratio also remained fairly constant as did the measured temperature of the fluids.

The Na/Ca ratios for MT-2 varied from a low in July/August 1975 followed by a recovery to close to the original values. The Na/Ca ratio ranged from 23 to 104 for the drill holes. ELC noted that a high ratio could be expected in geothermal waters that have not travelled far from their source. Based on that assumption, MT-4 and MT-8 are closer to the source and cooler waters are entering MT-6 and MT-7. They surmised that the source of the geothermal fluid is west of the area drilled.

f. Hydrology of Momotombo - Based on drilling evidence and chemistry, ELC stated there is a shallow reservoir between 300 and 450 m at a temperature of 225° - 230°C and a deeper reservoir at about 1200 to 1400 m depth. The shallow reservoir, associated with fissured lava flows and fractured tuff, has an areal extent of perhaps 2 km^2. A shallow reservoir steam/water mixture is produced. This reservoir has been intersected by MT-2, MT-3, and MT-9 and possibly by MT-5 and MT-6. The deeper reservoir has been intersected (at that time) by MT-4 and MT-10. Limited production of MT-4 indicated that it was producing a nearly dry steam from 1250 to 1400 m. The maximum measured temperature was 327° at 1430 m. MT-10 (total depth 2104 m) showed a temperature profile similar to MT-4 but offset downward about 200-250 m. The maximum measured temperature in MT-10 was 327°C. However, hydro-fracturing was attempted in the well and two months after that attempt the temperatures had not recovered. ELC suggested the hydro-fracturing caused formation damage because mud and cuttings under pressure plugged the narrow, permeable zones.

Between the two reservoirs is a low temperature pervious zone located between 500 and 800 m depth. There is a pronounced temperature inversion zone in most of the wells below 400 m depth. The negative gradient reaches its maximum at 500 to 600 m. The inversion is most notable in wells located in the eastern part of the field, MT-1, MT-6 and MT-5. The inversion becomes less pronounced and less evident moving to the west and completely disappears at MT-4. This cool water inflow from the east, probably from the Loma Guatusa plateau, moves westerly and roughly follows the upper part of the welded tuff layer. This welded tuff layer is just below the shallow reservoir.

g. Conclusions -

1) Regional Hydrology - The regional flow of ground water was based on piezometric measurements made in the existing wells. In evaluating the connection between the Monte Galan system and Obraje valley hydrologic systems, a knowledge of the water level in the lagoons would have been helpful in determining flow direction. Also, we wonder if there was enough evidence for the distinction of several different aquifers in both the shallow and deep circulation ground water systems.

Hydrological balance studies based on scattered data and data generalized over large areas produce relatively crude estimates. Average annual values of rainfall were used to estimate infiltration apparently without consideration of precipitation variation from location to location, especially variations with elevation. The equation used to calculate hydrological balance neglected the possible contribution of stored water variations.

2) Regional Geochemistry - The ELC study expanded slighty the previous UNDP study by sampling some twenty water points in the Puerto Momotombo and Rio El Obraje valleys. They divided these areas into geochemical zones based on compositional relationships and differences in geothermometer temperatures.

Several new ideas were introduced by this study:

- A water balance sheet was constructed but the reports IECO obtained made no further use of it.

- Waters were classified according to their chemical kinship but the number of samples and limited areal extent precluded meaningful statistical data. "Meaningful" chemical anomalies were considered above "background" waters in small amounts, generally a few percent to ten percent, however, specific error tolerances in analyses for the various constituents were never discussed. Also, "background", or nonthermal waters were never discussed. No type of classification system was discussed in the geochemical reports IECO has seen.

- Geochemical thermometers can contribute to water classification through temperature estimates. This concept may be based on the fact that the geochemical temperatures calculated for the Momotombo wells match the observed temperatures usually with ± 30°C, and sometimes closer. However, IECO review of chemical data in the regional study suggests that geochemical geothermometer temperatures for those waters may be meaningless (Table 4.4). Those surface waters are not in chemical equilibrium with their near-surface environment. Dr. Tonani has calculated the Na/K, Na-Ca, and K-Ca geothermometers for the twenty regional water samples, Punta Las Salinitas (the surface hot springs), and geothermal well MT-3. The hot springs, geothermal wells, and Sulfatosa samples show general internal consistency between geothermometer estimates.

The Rio El Obraje valley may be the site of a geothermal resource but the ELC data have certain ambiguities. The first cause for concern is that although various geothermal geochemists had published what criteria were necessary to apply geothermometers, ELC had no discussion regarding criteria used to establish whether or not a water sample was in equilibrium with its geologic environment. The silica geothermometers were not applied to the regional water samples and there is no discussion about this omission.

GEOTHERMOMETER ESTIMATES FOR RIO EL OBRAJE AND MOMOTOMBO VALLEYS

	Na-K T^oC	Na-Ca T^oC	Ca-K T^oC
1. ARMENIA	389.34	3.49	89.29
2. PROVIDENCIA	389.37	6.6	95.71
3. CASABLANCA	290.41	49.6	122.3
4. EL MOJON	285.14	20.9	96.44
5. LAS COLINAS	317.56	4.98	87.33
6. CALIFORNIA	353.55	37.82	124.25
7. RIO OBRAJE	280.46	56.9	126.6
8. FINCA OBRAJE	265.77	64.22	129.2
9. LA BARONESA	328.41	35.06	117.24
10. LAGARTILLO	289.28	67.88	137.7
11. EL TRANSITO	257.00	56.14	120.53
12. SABANA GR.	308.12	22.05	101.68
13. SANTA ROSA	275.62	43.83	114.52
14. SAN ANTONIO	276.7	30.36	103
15. L. MANAGUA	264.63	144.92	189.4
16. SAN CAYETANO	266.72	44.6	113.22
17. M. GALAN	246.5	85.63	140.96
18. LAS PIEDRAS	26.02	92.09	60.3
19. AGUA DULCE	237.52	27.26	92.19
20. SULFATOSA	246.39	175.8	203.77
21 MT 3 WELL	276.01	229.32	248.50
PUNTA LAS SALINITAS Ti	212.2	218.3	215.65
PUNTA LAS SALINITAS ELC	159.3	193.4	178.0

Mixing cannot be significantly proved by chloride alone. Coincidences cannot be ruled out and specific geologic environment always needs to be considered. The ELC report suggested the possibility of a marine component in the Momotombo geothermal water. Connate waters or local evaporite deposits could also be the source of chlorides or boron. There are fumaroles at Volcan El Hoyo west of the Rio El Obraje valley, Momotombo, and steaming ground is found in the crater of Cerro Colorado. The higher B, and SO_4 in some of the Obraje valley waters could originate from fumarole condensate mixing with local groundwater. A larger data base is needed for the general region before the significance of the higher B and Cl content of the Obraje valley waters can be determined.

3) Momotombo Geochemistry and Hydrology - ELC sampled wells MT-1 through MT-4 fairly consistently. Another contractor was responsible for drilling and testing the additional wells. ELC sampled wells MT-5 through MT-14 when they could but sampling was generally inconsistent. Information about the geothermal fluid at Momotombo was increased but apparently the drill hole siting criteria did not consider well geochemistry. While ELC noted the correlation between highest temperature and highest ionic strength, those parameters did not necessarily correspond with greatest permeabilty or flow rate. ELC also recommended sampling different levels in each well as they believed there were different feeding horizons.

We believe geochemical sampling and modeling of the wells will be critical in reservoir management at Momotombo. There has been some discussion in this report about cooler fluids entering the field from the east. The various temperature profiles across the field show a temperature inversion zone, disappearing towards the western side of the field. However, this fluid has not been chemically defined in any of the wells.

Sampling at different horizons in the wells would help detect the cooler fluid and establish the flow direction.

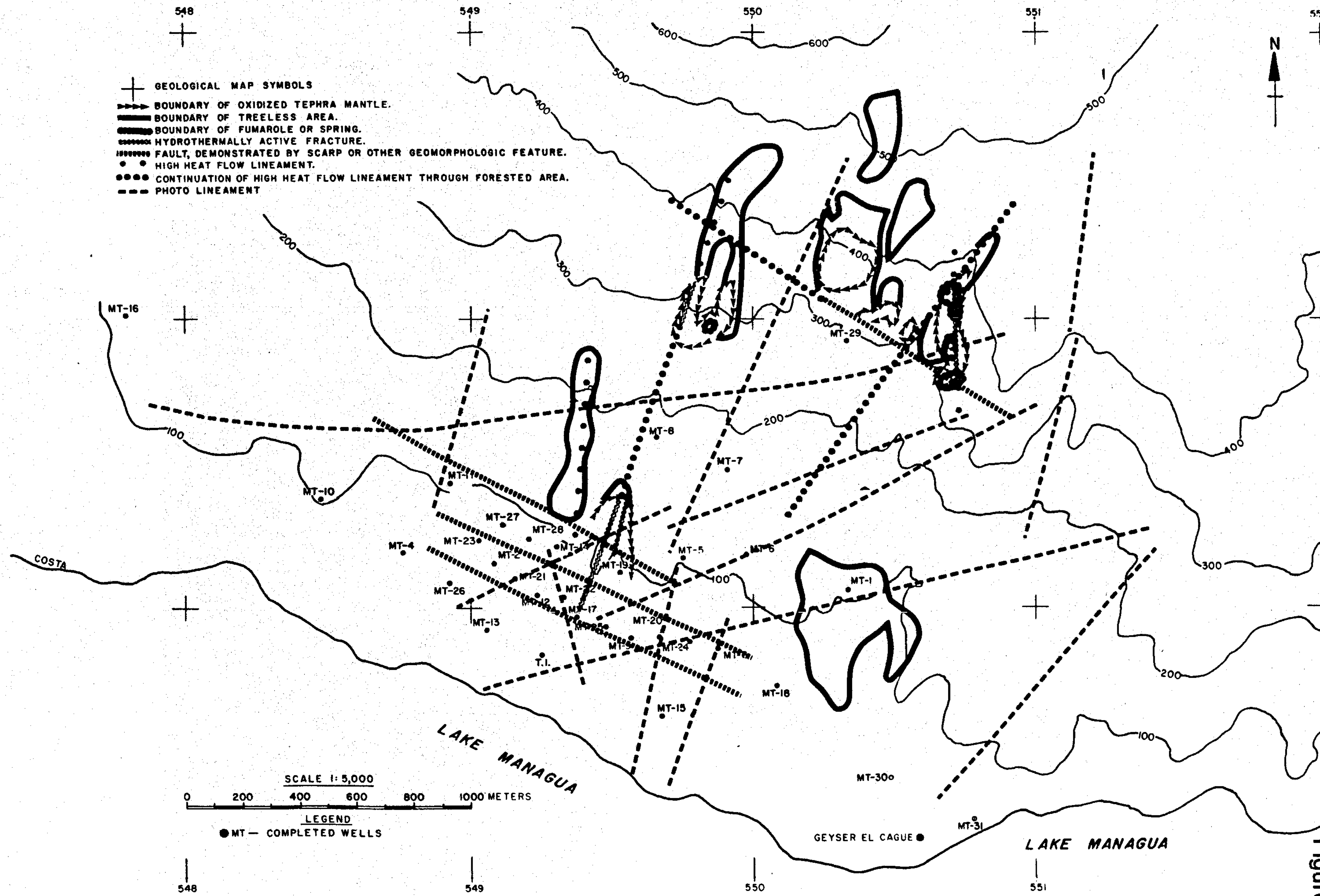
B. Substage 2 - Performed by California Energy Company, Inc. (CECI)

This phase of the geological investigations is a continuation of Stage 3, concurrent with the drilling of exploratory wells MT-5 to MT-32. Well locations are shown in Figure 4-22. Detailed structural mapping, lithologic descriptions from twenty-two wells, and subsurface temperature distribution measurements were included in Substage 2. This information and new data obtained as the field exploration continued were compiled to form a detailed geological report. Some of the techniques used and results obtained are discussed in the next sections.

1. Geological Methods

a. Structural Geology - A detailed structural geology program was conducted after drilling show that productive wells were located in a narrow zone trending NW-SE across the field (CECI, 1977). Previous structural mapping by Thigpen (1970) provided the base map on which a few previously unmapped faults and fractures were added. The new structural map shown in Figure 4.28 locates fracture zones in the area of the wells, indicating new areas which were believed to merit exploratory drillng. These fracture zones were identified partly from cores of wells MT-2 (ELC, 1976) and subsequent well production data indicating flow of fluids in these fractures (CECI, 1978).

b. Stratigraphy - Volcanic rocks of Late Tertiary and Quaternary age were intersected by the Momotombo field wells (CECI, 1978). Figure 4.29 shows a columnar section showing the various compositions and textures of the rocks. The division into eight rock units is based on distinctive lithologies. Most of the stratigraphic section is composed of andesitic ash and lapilli tuffs and tuff-breccias with compositions ranging from basalt to dacite (CECI, 1978). Detailed litholog-



Structural Geologic Map of Momotombo Area

(From CECI, 1977)

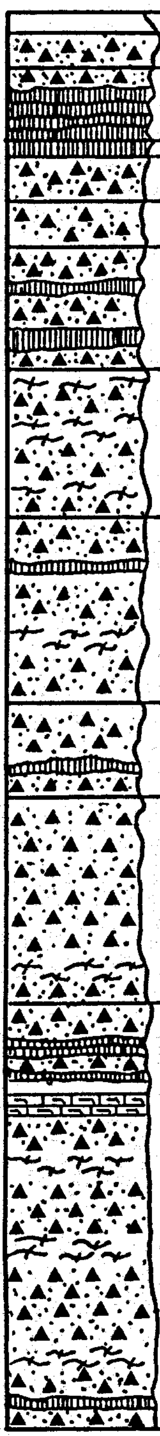
Figure 4-28

Figure 4-29

Preliminary Generalized Columnar Section, Momotombo Field, Based on 28 Well Sections

(From CECI, 1978)

Colum – Thickness (Feet)



Unit	Lithology
Super-ficial	Poorly consolidated, dark gray, vesicular, zeolitic, basaltic crystal ash tuff containing welded boulders of the same material at many places and ocherous lithic ash and lapilli (sand and gravel?) at a few places. Rare, dark gray, vesicular, basaltic lavas.
Ia	Gray, zeolitic, partly vesicular, commonly microporphyritic basaltic andesite lavas (or possibly devitrified, welded tuffs) replaced at places in the section by lithic ash and lapilli tuffs and tuff-breccias. The lithic tuffs are commonly reworked.
Ib	Reddish gray, commonly silicified and argillized crystal vitric ash tuffs and dark gray basaltic* lavas with common, partly reworked interbeds of lithic ash and lapilli tuffs and tuff-breccias.
Ic	Dark gray, indurate, micropophyritic basaltic andesite* lava and associated tuff-breccias and less common, light gray, mottled, devitrified and altered lithic crystal vitric ash tuff.
Id	Variegated, generally deeply argillized and oxidized lithic lapilli tuffs and tuff-breccias and lithic crystal vitric ash tuffs. Unit readily identified in less altered well sections by a marked drilling break.
Ie (28 Wells)	Generally dark reddish gray, altered green and white, generally deeply argillized and oxidized lithic lapilli tuffs and tuff-breccias as well as ash tuff interbeds of various compositions. In several, deeply altered well sections, Ie is practically indistinguishable from Id.
II (25 Wells)	Pink and green to gray, altered lithic crystal vitric ash tuffs, variegated lithic lapilli tuffs and probably agglomeratic tuffs interbedded with dark gray, commonly microporphyritic, glassy-textured, basaltic* lavas. The lavas make up 10-45% of most well sections, but 72-76% of three well sections. Gypsum is locally abundant alteration mineral. Argillization is less common. In several well sections, II tuffs appear much like Ie tuffs.
III (17 Wells)	Reddish gray and gray, indurate, altered, commonly microporphyritic pyroxene andesite* lavas and/or devitrified, commonly felsitic, possibly welded crystal vitric tuff microporphyries with common interbeds of variegated lithic ash and lapilli tuffs. Vein alteration (quartz-feldspar-calcite-chlorite) is generally abundant.
IV (11 Wells)	Dark gray, tinged reddish or brownish commonly, altered green and white lithic crystial vitric ash and lapilli tuffs with subordinate lithic ash to tuff-breccia interbeds and uncommon, r relatively thin flows of dark reddish gray andesitic basalt* lava in upeer 75%. The lower 25% is occupied by reddish gray, altered, cryptocrystalline basaltic andesite* lavas with rare, chloritized pyroxene insetsaand generally, but not always, subordinate lithic crystal vitric ash to lapilli tuffs and uncommon tuff-breccias. Vein alteration is abundant; mineral assemblages range from quartz-feldspar-calcite-chlorite-epidote-sulfide to quartz-chalcedony-calcite-chlorite-gypsum-sulfide to quartz-chalcedony-calcite-chlorite-gypsum-sulfide and rarely argillic.
V (9 Wells)	Dull reddish gray, cryptocrystalline andesitic basalt* lava (40 feet) indicating the top and interbedded, red and gray, mottled green and white, deeply altered, commonly amygdaloidal, rarely welded crystal lithic vitric ash and lapilli tuffs and tuff-breccias with uncommon, deeply altered, gray lavas forming the bulk of the unit. Alteration is as in Unit IV.
VI (7 Wells)	Dull, dark gray, cryptocrystalline, basaltic* lava (20 to 60 feet) indicating the top and inter-bedded, red, gray or green, commonly molted, generally abundantly veined and altered, commonly welded, andesitic* crystal lithic vitric to crystal vitric lithic ash and lapilli tuffs and lithic tuff-breccias forming the bulk of the unit. Lavas are extremely rare. Toward the base the light gray, welded, andesitic to rhyolitic* tuffs commonly occur in cooling units of 40 to 80 feet thickness. Vein alteration is as in Unit IV.
VII (6 Wells)	Light gray, mottled, altered, welded, andestic or dacitic* lithic crystal vitric ash tuff (40 to 120 feet) indicating the top and similar crystal lithic vitric ash to lapilli tuffs and lithic tuff-breccias forming the bulk of the unit. Dark gray fine-grained or glassy-texture basaltic* lavas, hornblende-biotite dacite* lava, gray, cryptocrystalline latite or andesite* lava or welded tuff, fine-grained microgranular diorite or tonalite* diabase, and light gray, fossiliferous (corals (corals and barnacles) marine limestone with basal calcareous tuff form minor parts of the unit. Alteration is as in Unit IV.

*Preliminary rock indentification based on binocular microscope examination.

ic descriptions were made on the basis of binocular microscopic examination of well cuttings. The complexity of the stratigraphy, however, does not allow for broad correlations to be made with confidence from the information at hand, but detailed petrology and perhaps geochemistry would have aided in making correlations. The resulting columnar section and well cross sections are therefore somewhat uncertain. A panel or block diagram would have been useful in visualizing the subsurface lithology.

c. <u>Temperature Distribution</u> - Measurement of subsurface temperatures in the Momotombo Field provided sufficient data for construction of isothermal maps and cross sections (Figures 4.30 through 4.37). A north-south to northeast isothermal trend was detected, open to the south into Lake Managua and to the north toward Volcan Momotombo (CECI, 1978). Data also indicate an increase of temperature with depth in the western part of the field.

d. <u>Conclusions</u> - -The objectives in this stage of the investigation were to increase, upgrade or modify existing geological data. The value of this phase lies in the information gathered from cuttings derived from the drilling of deep wells. The subsurface geology could have been depicted through cross-sections after careful examination of the cuttings. This procedure was not followed, instead more surface geological mapping was done. The omission of hydrothermal alteration studies and detailed petrology deprived the investigators of valuable information. A columnar section was the only apparent improvement in the subsurface data.

The temperature distribution measurements obtained from the deep wells were beneficial in outlining areas of maximum heat flow, as shown in the isothermal map.

- <u>Area Surface Geology</u> - From August 1975 to June 1979, CECI performed the final phase of the three stage study. Thigpen's

(1970) work was reiterated in the description of the surface geology.

Based on these investigations several previously unmentioned NW striking faults appeared to merit exploratory drilling. These consultants concluded that the northern limits of the production zone could extend as much as 200-300m southeast of the units mapped by Thigpen (1970).

- Stratigraphy - The stratigraphy of the area as indicated by deep borehole evidence, is divided into eight separate units based on recognizable lithologic markers. Unit I is divided into 5 sub-units, with rock types determined by binocular microscopic studies of rocks penetrated during drilling. Using these defined units, stratigraphic correlations were made to prepare a cross-section.

Most of the stratigraphic section is composed of ash, tuff, and tuff-breccias, compositions ranging from basaltic to dacitic. Unit VII, however, contained an interbed of fossiliferous marine limestone.

Structural geology is based primarily upon subsurface morphology. A principal fault appears to strike N47°W and dip 86°NE, but can only be traced at depths greater that 275-305 m.

Fractures are evident in cores of indurated lava flows of Unit II in well MT-2. Zones of total or partial loss of circulation are areas of high permeability or fracturing. These zones are believed to be aligned with the N47°W striking fault, and are interpreted as major fracture zones (CECI, 1977). The previous structural map drawn by Thigpen (1970) shows this zone as a highly productive area between two lineaments. Revisions of this map indicated a narrower zone based on the results of deep borehole tests in this area.

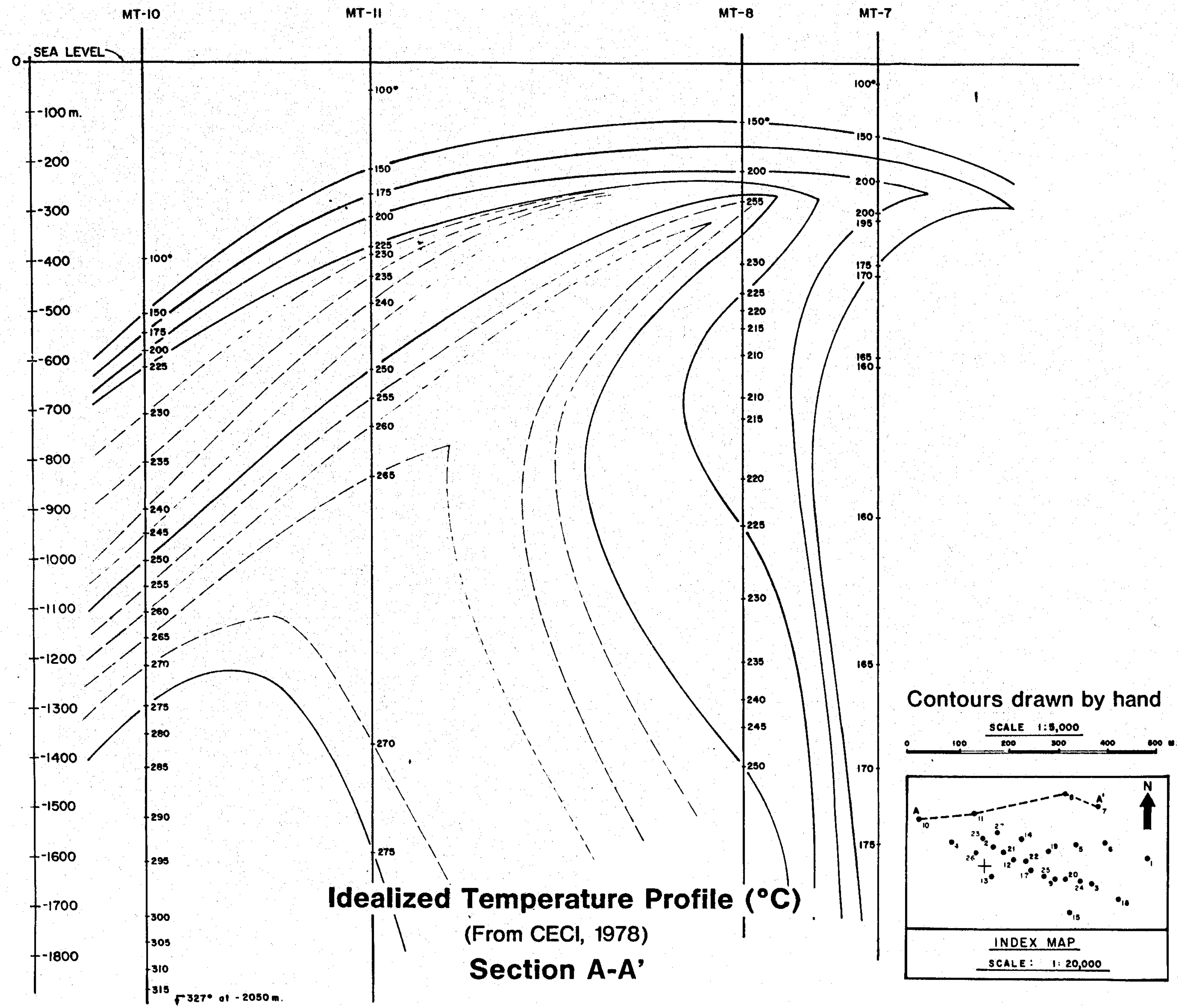
- Temperature Distribution - Using the measured temperature data, seven cross sections showing the isothermal patterns were prepared (Figures 4-30 to 4-37) to illustrate the temperature distribution within the field. The isothermal maps show a definite NS to NE striking trend of the field which is open to the south under Lake Managua and to the north toward Volcan Momotombo.

  Sufficient evidence exists to indicate that distribution of downhole temperatures and zones of high permeability are controlled by geologic structures. It was concluded that hydrothermal fluids are rising along a primary NE trending fault-fracture zone, then moving laterally to the east within the shallow disk-shaped fracture zone of the tephra cone. Earlier reports by the consultants, however, had indicated a northwest-southeast productive zone.

  Results of all information and short-term single-well measurements led CECI's consultants to conclude that the Momotombo field is capable of producing over 105 MW of electricity.

2. Geophysical Methods

a. Dipole-Dipole Survey - This survey was carried out by Phoenix Geophysics (1977) for CECI using 750 m dipoles for reconnaissance work and 250 m dipoles for definition of details. These survey data were not available during the investigations leading to this report. However, the data had been inspected during IECO's previous work for the Nicaragua Master Plan.

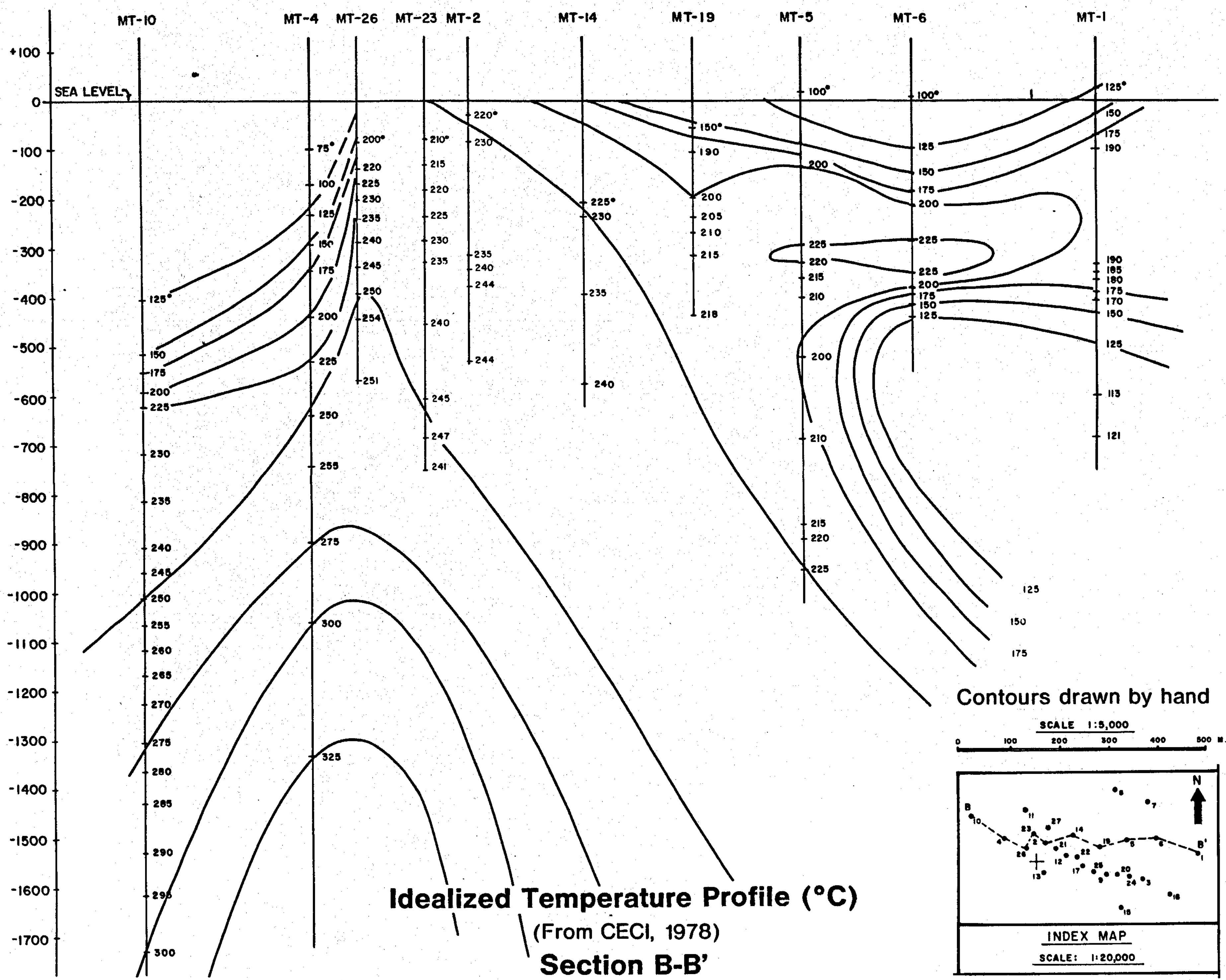


Idealized Temperature Profile (°C)

(From CECI, 1978)

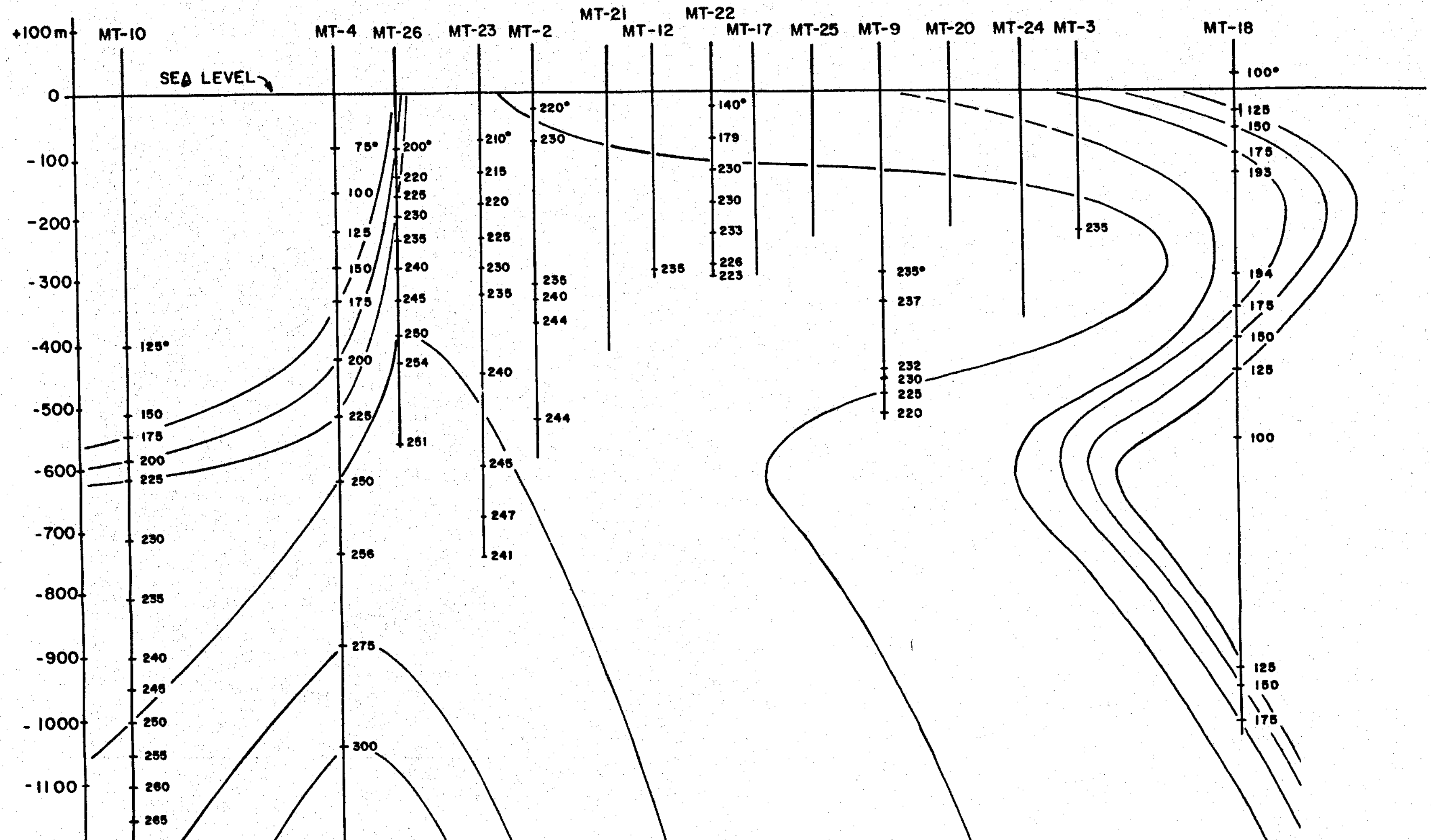
Section A-A'

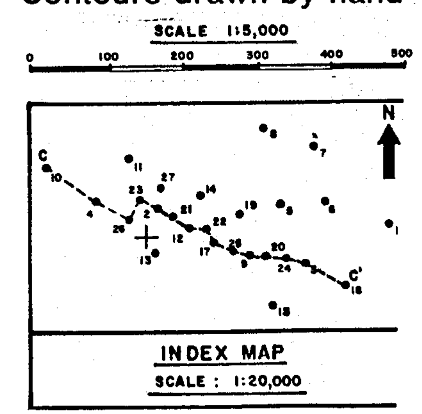
Figure 4-30



Idealized Temperature Profile (°C)
(From CECI, 1978)
Section B-B'

Figure 4-31





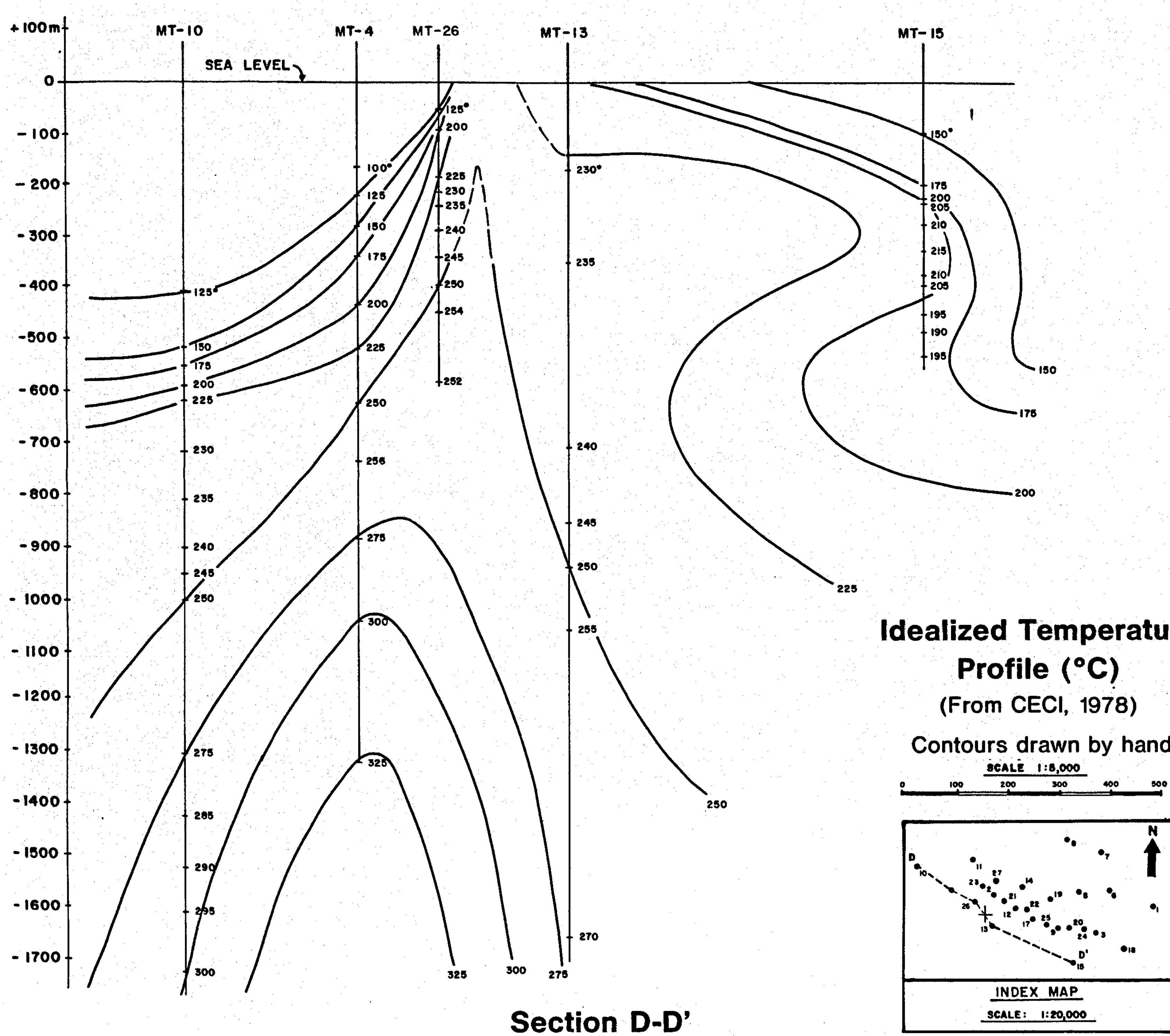
Contours drawn by hand

Idealized Temperature Profile (°C)

(From CECI, 1978)

Section C-C'

Figure 4-32



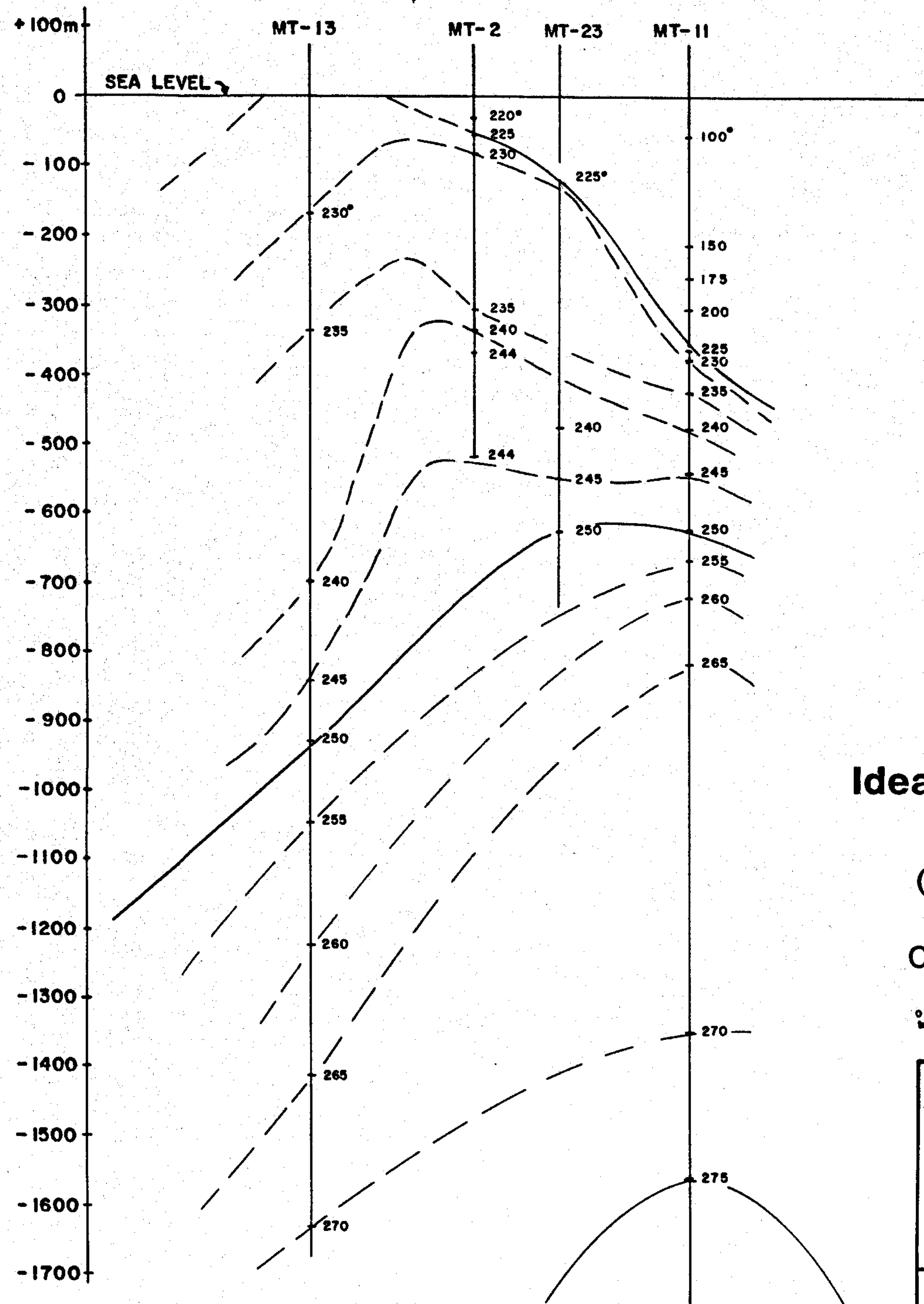
Idealized Temperature Profile (°C)

(From CECI, 1978)

Contours drawn by hand

Section D-D'

Figure 4-33



Section E-E'

Idealized Temperature Profile (°C)

(From CECI, 1978)

Contours drawn by hand

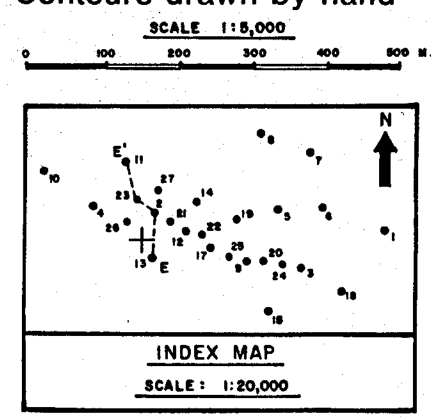
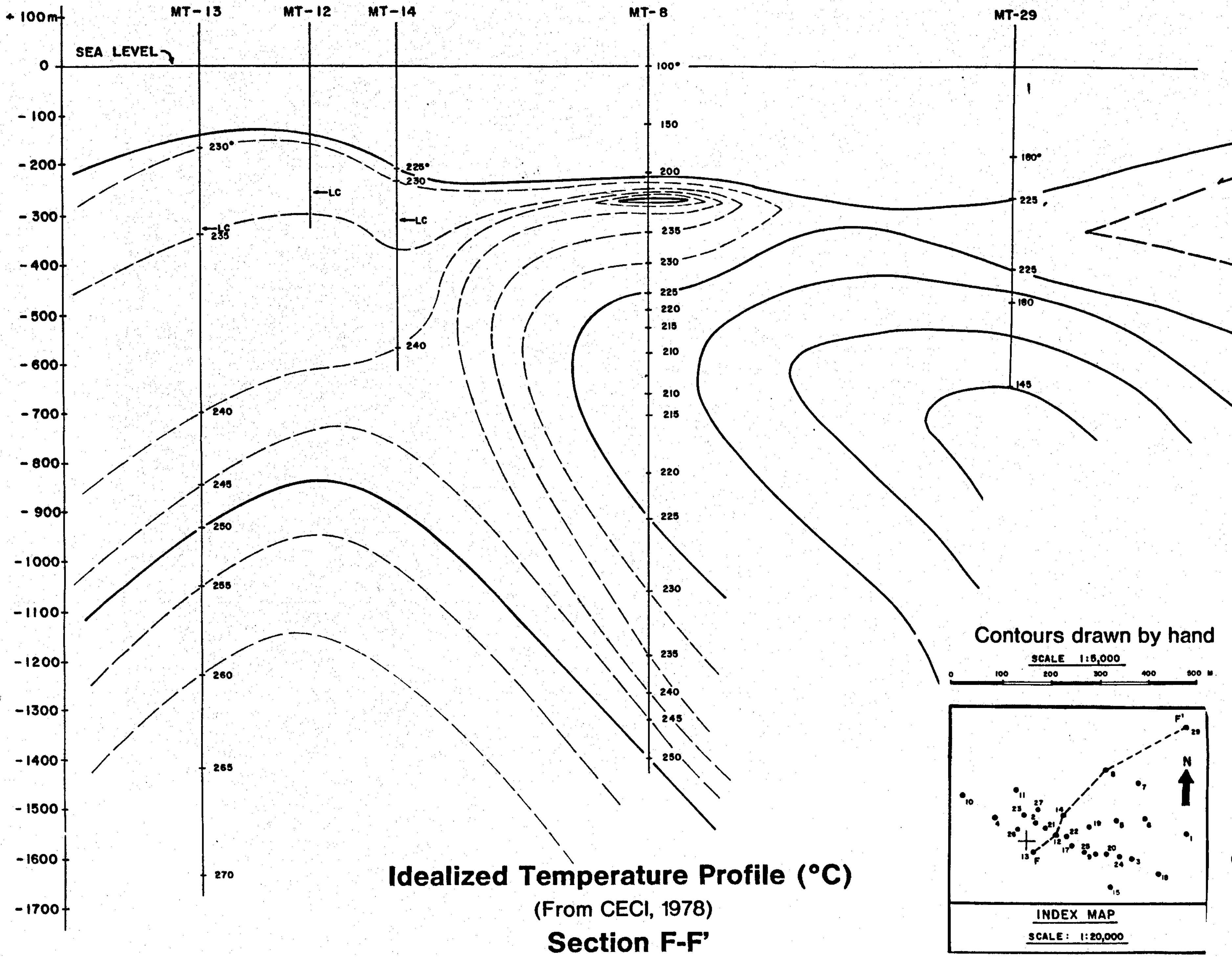


Figure 4-34

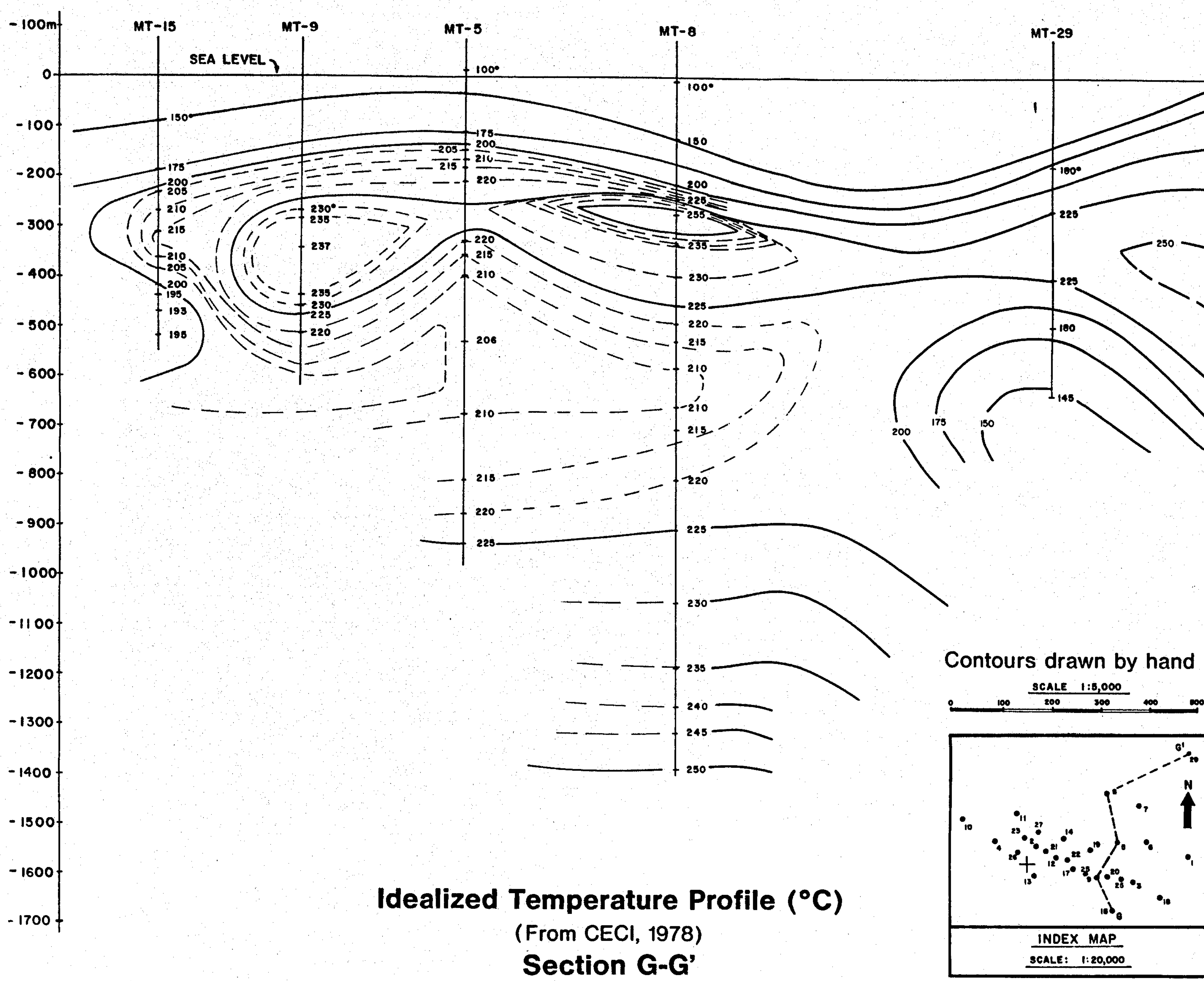


Idealized Temperature Profile (°C)

(From CECI, 1978)

Section F-F'

Figure 4-35

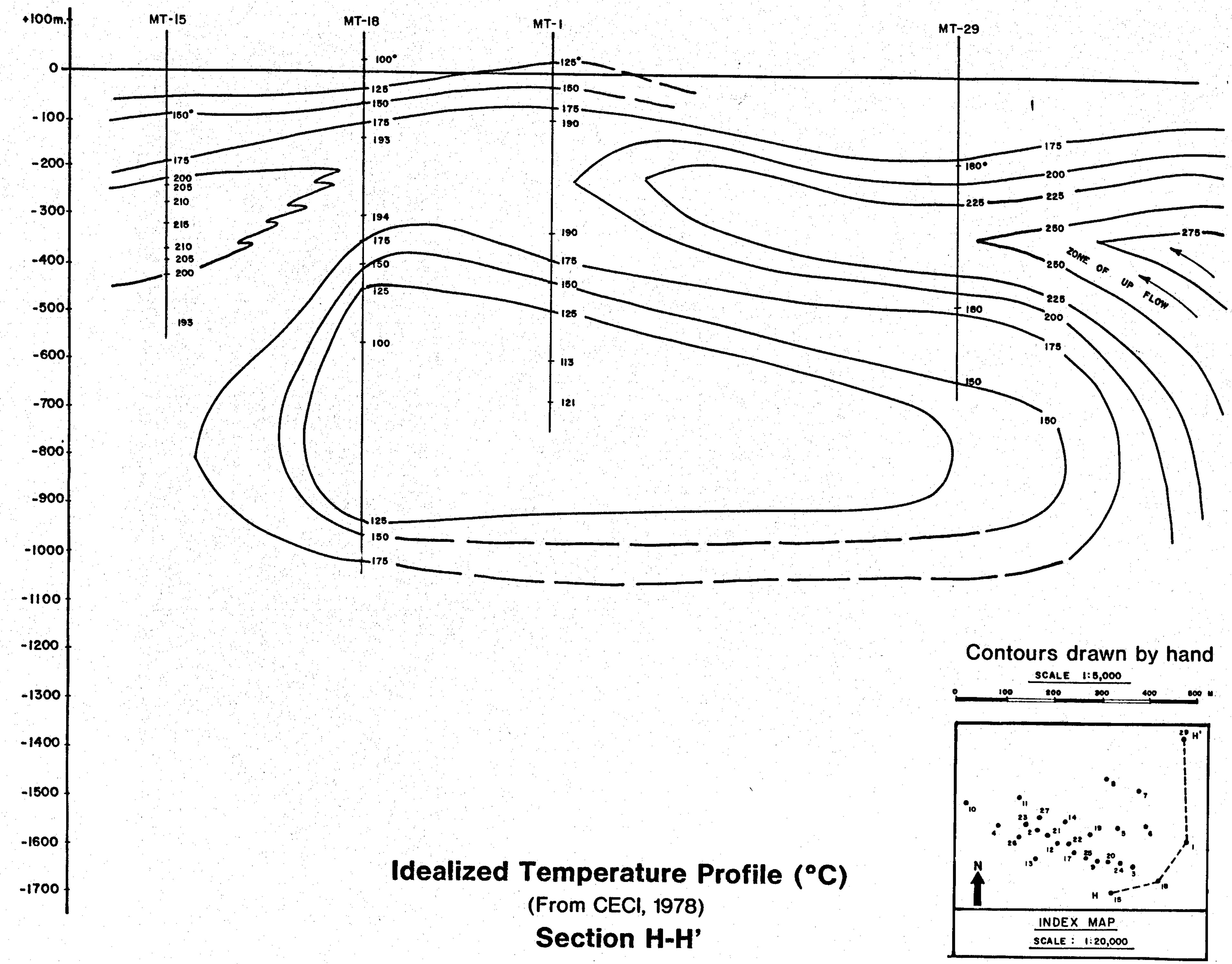


Idealized Temperature Profile (°C)

(From CECI, 1978)

Section G-G'

Figure 4-36



Idealized Temperature Profile (°C)
(From CECI, 1978)
Section H-H'

Figure 4-37

The survey covered the Momotombo geothermal area and adjacent parts of the Obraje valley. The detailed dipole-dipole survey of the Momotombo field shows a less consistent picture than the temperature measurements. However, differences may be due to changes in permeability of the subsurface rocks. With reinterpretation, the low resistivity areas outlined by the survey closely follow the configuration of the shallow hot water reservoir.

b. Conclusions - The dipole-dipole survey was limited in depth penetration, and little information was obtained concerning deeper layers. However, the survey outlines the shallow hot water reservoir and together with temperature data, may be useful in determining zones of high temperature but information on permeability cannot be inferred.

3. Geochemical Methods - Wells MT-16 through MT-33 were drilled during Stage 3, substage 2. Production tests were initiated but fluid samples were rarely collected. The feasibility report written at the end of this period referred to the ELC geochemistry reports and did not reinterpret data or add new information.

4.4 PRELIMINARY INTERPRETATION OF 1979 FLOW TEST DATA

In May 1979, flow tests commenced for wells MT-9, MT-12, MT-19, MT-20, MT-23, MT-24, MT-26, and MT-27. Samples were taken from a discharge pipe at each wellhead. Information from this program is discussed by Tonani and Teilman, 1980.

The sampling program was interrupted at the beginning of June 1979, although the wells continued to flow. Sample collection recommenced in mid-September 1979 under the direction of the reorganized national power company, Instituto Nicaraguense de Energia (INE, formerly ENALUF). The wells were closed at the end of November.

Graphs showing constituent concentration versus time illustrate that in May of 1979 predominantly liquid-phase brine was collected at the sampling points. By the time the wells were closed in November, all but MT-19 and MT-26 were producing dry steam, according to verbal reports. Chemical species which remain in the brine phase and do not fractionate into the steam phase, such as Na, K, Ca, Cl, and SiO_2, greatly decreased in concentration in the wells that showed a flow regime change. However, it could not be determined if the geothermal fluid was flashing in the formation, in the well, or if the steam and brine had separated in some manner that the brine no longer reached the sampling points. Some 1976 data for MT-9 and MT-12 also suggested an increase of the steam fraction in the flow with time.

Tonani calculated the Na-K, Ca-Na, Ca-K, and SiO_2 geothermometers and steam/liquid separation temperatures, which are calculated from the distribution of boric acid between liquid water and steam. These data are presented in Table 4.5.

A review of the well chemistry resulted in several observations:

- Two different waters may be detectable in MT-19, based on correlations between Na, SiO_2, and K. Mg increased (0.2 - 0.7 ppm) and Na decreased (2000-1800 ppm) from May to November, suggesting a 5% admixture of fresh water in May, increasing to 15% in November. This water inflow might be indicative of a casing leak. No change in flow regime occurred.

- Some fresh water may be mixing with the thermal fluid in MT-23. Na, Cl and B contents are low at the beginning of the flow tests and Ca, K, HCO_3 and Mg are high. An increase in Mg correlates with a decrease in thermal constituents. The flow regime changed before October.

AVERAGED MEASURED WELL TEMPERATURES, GEOTHERMOMETERS, AND TEMPERATURE OF LIQUID-STEAM SEPARATION

Well	TD	Slotted Liner Interval	Averaged Measured Temperatures in Slotted Liner Interval[1]		Calculated Temperature °C Na/K	Ca/Na	Ca/K	SiO_2	Temperature of Phase Separation
MT-9	616m	232-615m	232-350m:	215°-225°C					
1976 July-Aug.[2]			350-580m:	225°-205°C	270°	271°	270°	240°	177°C
1979 May					265°	226°	242°	286°	
1979 Oct.-Nov.									
MT-12	402m	234-393m	isothermal-						
1976 July-Aug.[2]			0-393m:	280°C	252°	248°	250°	283°	
1976 Nov.[3]					265°	236°	248°	255°	200°C
1979 mid-May					286°	220°	247°	286°	
1979 end of May					283°	210°	239°	270°	
1979-Sept.-Oct.									
MT-19	536m	271-536m	271-450m:	190°-220°C					
1979 mid-May			450-536m:	200°-270°C	278°	219°	243°	294°	No Phase
1979 late May					259°	214°	233°	274°	Separation
MT-20	310m	260-310m	260-310m:	170°-195°C					
1979 mid-May					261°	217°	235°	272°	
1979 mid/late-May					274°	220°	240°	292°	186°C
1979 late May					261°	215°	234°	250°	
1979 Sept.-Nov.									
MT-23	821m	324-821m	324-600m:	225°-240°C					
1979 mid-May			600-810m:	240°-245°C	284°	226°	250°	314°	
1979 end of May					286°	215°	244°	272°	196°C
1979 Sept.-Nov.									
MT-24	457m	328-455m	200-300m:	200°-210°C					
1979 mid-May			300-440m:	210°-215°C	256°	213°	231°	261°	175°C
1979 late May					245°	210°	225°	272°	
1979 Oct.									
MT-26	640m	365-638m	365-435m:	235°-260°C					
1979 onset of May tests			435-638m:	260°-250°C	276°	233°	251°	324°	No Phase Separation
1979 mid May					274°	238°	253°		
1979 Oct.-Nov.					272°	221°	242°	300°	
MT-27	442m	368-442m	200-430m:	240°-249°C					
1979 May/Oct.					281°	238°	256°	311°	179°C
1979 Nov.									

[1]Downhole temperatures are presented for general comparison. They are averaged measurements of 2 -3 down hole runs taken over several months (1977-1978); runs initiated after well produced; Kuster instruments used; some instrument problems were encountered (J. Moore, California Energy Co., Inc., May 1980, personal communication), data from California Energy Co., Inc., 1978, unpubl.

[2]Electroconsult, 1977, unpubl.

TABLE 4.5

- o Well MT-24 showed a major drop in liquid content in September. This gradual flow regime change was complete in October.

Comparisons between estimated and averaged measured temperatures show that, except for MT-12, the Ca-Na geothermometer produces results closest to the measured temperatures. For MT-23, MT-26 and MT-27, the measured temperatures fall between the Ca-Na and the Ca-K or SiO_2 geothermometer estimates. The average measured temperatures in MT-12 correlate with the Na-K and SiO_2 geothermometer predictions. This high temperature well is unique in the field because it is isothermal for almost its entire length of 400 m. MT-12, MT-19, and MT-24 had the highest measured wellhead temperatures during the flow tests. MT-12 may have intercepted a nearly vertical fault or fracture containing up-flow of thermal fluid from greater depth.

The subsurface contains layers of thin basalt flows interfingered with intermediate to basic tuffs and pyroclastics. The predominance of Ca-and Na-bearing minerals over K-bearing minerals in the subsurface will affect geochemical estimates of temperatures based on cation ratios.

The high silica content relative to the averaged measured temperatures may be the result of various silica and silicate minerals with different solubilities. Because of the observed high silica concentrations, decreasing temperature is likely to cause precipitation, either in the reservoir formation or in the wells and surface pipes, depending on which flow regime prevails.

Although direct measurements of temperatures are generally more reliable than geochemical estimates, at the present stage it cannot be concluded whether the average downhole measurements or the geothermometers are more representative of reservoir conditions at Momotombo. The relative amounts and types of mineral reactants in the subsurface must be considered in evaluating the geothermometry. The suggestion of several feeding horizons and possible casing leaks in some holes make interpretation complex.

Geochemical thermometers at Momotombo are effective in monitoring reservoir behavior. Changes in flow regime were reflected by changes in sample chemistry. These results illustrate that well testing should be accompanied by appropriate sampling. Processes leading to changes in quantity and quality of well flow affect the composition of the produced fluid, e.g., phase separation affects gas and volatile substances, and fluids in different producing horizons are likely to differ in chemical composition.

The change in flow regime in six of the eight wells tested suggests decreasing permeability conditions at Momotombo. The decrease in apparent permeability could be related to a lack of recharge to the system, the precipitation of chemical constituents, or both. More flow data are necessary to evaluate the production capacity of the field and to establish a reservoir management program.

CHAPTER 5
FIELD MODEL DEVELOPMENT

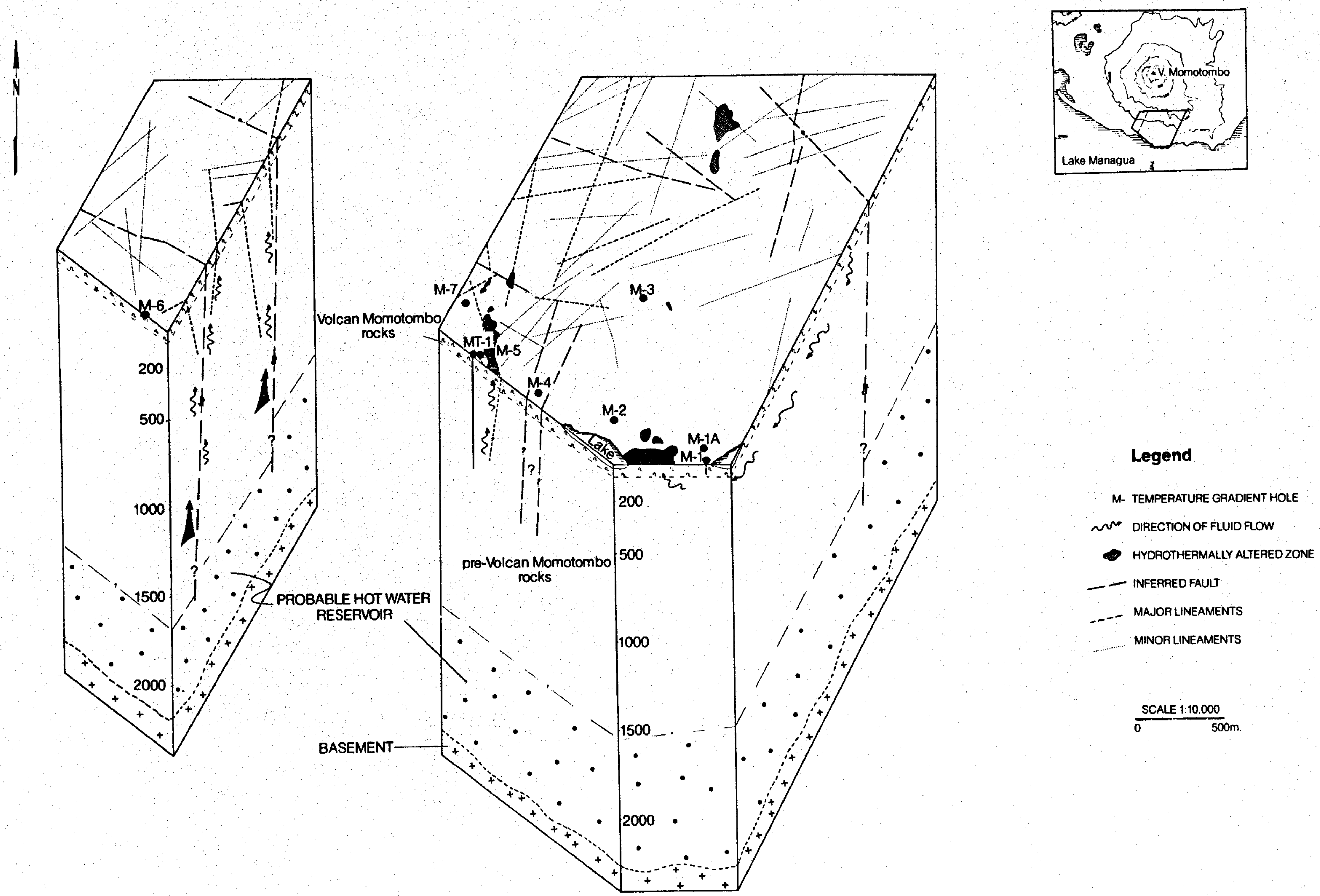
-5.0 GENERAL

International Engineering Company, Inc. (IECO) developed a series of six geothermal field models from data obtained throughout the exploration of the Momotombo field. Each model represents the conceptual view of the field structure and processes at a particular time, usually after an exploration stage when the newly acquired data forms the basis for drawing the model or revising a previous one. The final IECO Model was formed after a thorough review of previous data from geochemical, and geophysical, and geological studies.

5.1 STAGE 1

The first model IECO has constructed of the geothermal field resulted from Stage 1 investigations performed by Texas Instruments (1971) and is shown in Figure 5-1. All exploration carried out in this stage was mainly reconnaissance and consequently the subsurface structure was not investigated in detail. During this stage, the Momotombo area was explored as a possible zone of geothermal potential along with other areas in western Nicaragua; however, the objective was not to explore the field, but to delineate its extent by means of geophysical and geological exploration methods. An area approximately .6 km wide and 2 km long, lying on the southern slopes of Volcan Momotombo, was selected as having the most favorable exploitable geothermal potential. Figure 5-1 shows a section of this area.

Geologic field mapping and photogeology aided in identifying most of the observed major and minor lineaments and inferred faults. The two NW trending faults in the western section of the diagram are believed



STAGE 1 MODEL

(data from Texas Instruments)

Figure 5-1

to control most of the hydrothermal alteration. Both faults are normal, steeply dipping, and downthrown to the southwest. The hydrothermally altered zones covering an area less than 1 km^2, as shown in Figure 5-1, were field checked and mapped. All altered zones show some fumarolic activity with temperatures around 100°C. The lack of thermal activity in the zone between these two faults supports the hypothesis of vertical flow along fractures. Lateral flow was discussed by Thigpen (1970) as existing at relatively shallow depths and probably involved in the hydrothermally altered areas shown in the southern parts of the field.

The drilling of several temperature gradient holes, averaging 55 m deep, not only confirmed the presence of anomalously high temperatures (greater than 90°C), but also provided cuttings for a brief description of nearsurface rocks. One 68 m deep borehole, M-1A, proved the existence of a steam-water mixture at shallow depths and provided a basis for classifying the volcanic rocks into 2 groups: Volcan Momotombo rocks in the upper 50-100 m, overlying pre-Volcan Momotombo rocks. Below 65 m the pre-Volcan Momotombo rocks, consisting of altered pyroclastic deposits with minor andesitic and basaltic lava flows, were believed to be good geothermal reservoir rock. Sparse chemical data indicated a high chloride content, liquid-dominated geothermal system; however, M-1A had a blow-out at 68 m and no production testing was possible.

Geophysical investigations showed the Momotombo system extending southward under Lake Managua and northward under Volcan Momotombo. Electromagnetic soundings indicated a possible hot water reservoir lying at a depth of 1400 to 1700 m over an electrical basement with depth greater than 2000 m.

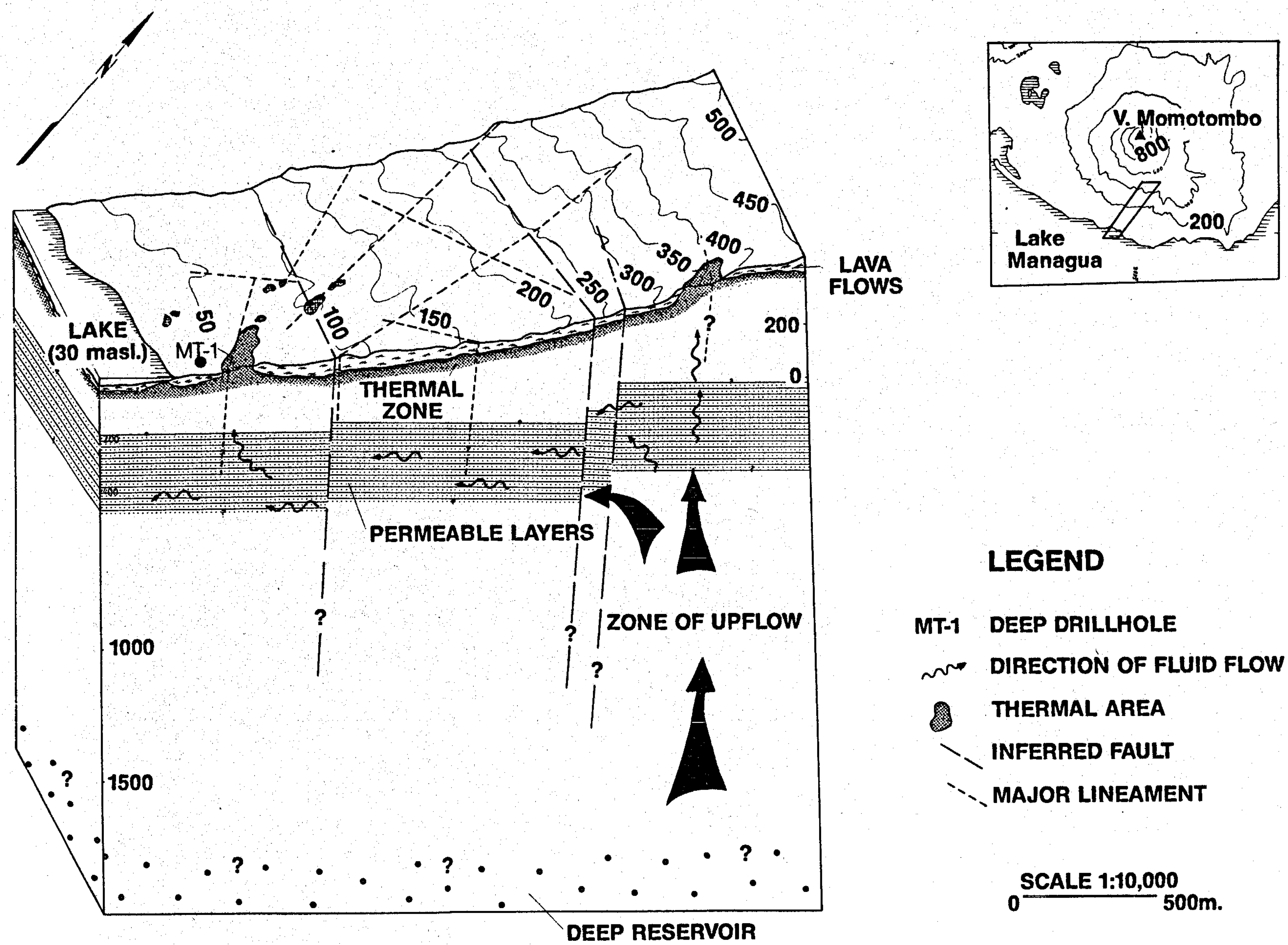
5.2 STAGE 2

Figure 5-2 shows the field model IECO developed from the results of Stage 2 investigations performed by the United Nations Development Program (1974). Geological, geochemical, and a few geophysical measurements contributed to modifying the previous geothermal field model, especially with respect to the flow of thermal fluids.

Even though other areas of interest lying west of the previously selected Momotombo geothermal field were delineated by geophysical methods, there was insufficient geophysical work in this particular zone to define the area exactly. A decrease in resistivity toward this area is noted from a sounding done in the vicinity. No definite conclusions were made from geophysical measurements concerning the substructure of this field.

Reconnaissance geological investigations were performed and did not substantially modify the existing model. The five thermal areas on the southern slopes of the volcano are believed to be outcrops of one large thermal area divided superficially by lava flows. The reasoning behind this belief is that thermal activity occurs almost exclusively at the edges of lava flows, the ravines cut into them by erosion, or in areas between lava flows.

The chemical survey of gases and waters from the Momotombo geothermal area provided a basis for developing a dynamic model of the near-surface thermal waters. This model, shown in Figure 5-2, indicates a deep thermal water reservoir with high temperatures serving as source for the upflow of thermal water below the hydrothermally altered area at 300 m altitude. The water then flows downslope toward the lake in shallow permeable layers. It was suggested that drilling anywhere between the exposed thermal areas shown in the model would encounter thermal water at shallow depth (less than 500 m), with temperatures on



STAGE 2 MODEL

(from United Nations Development program study)

Figure 5-2

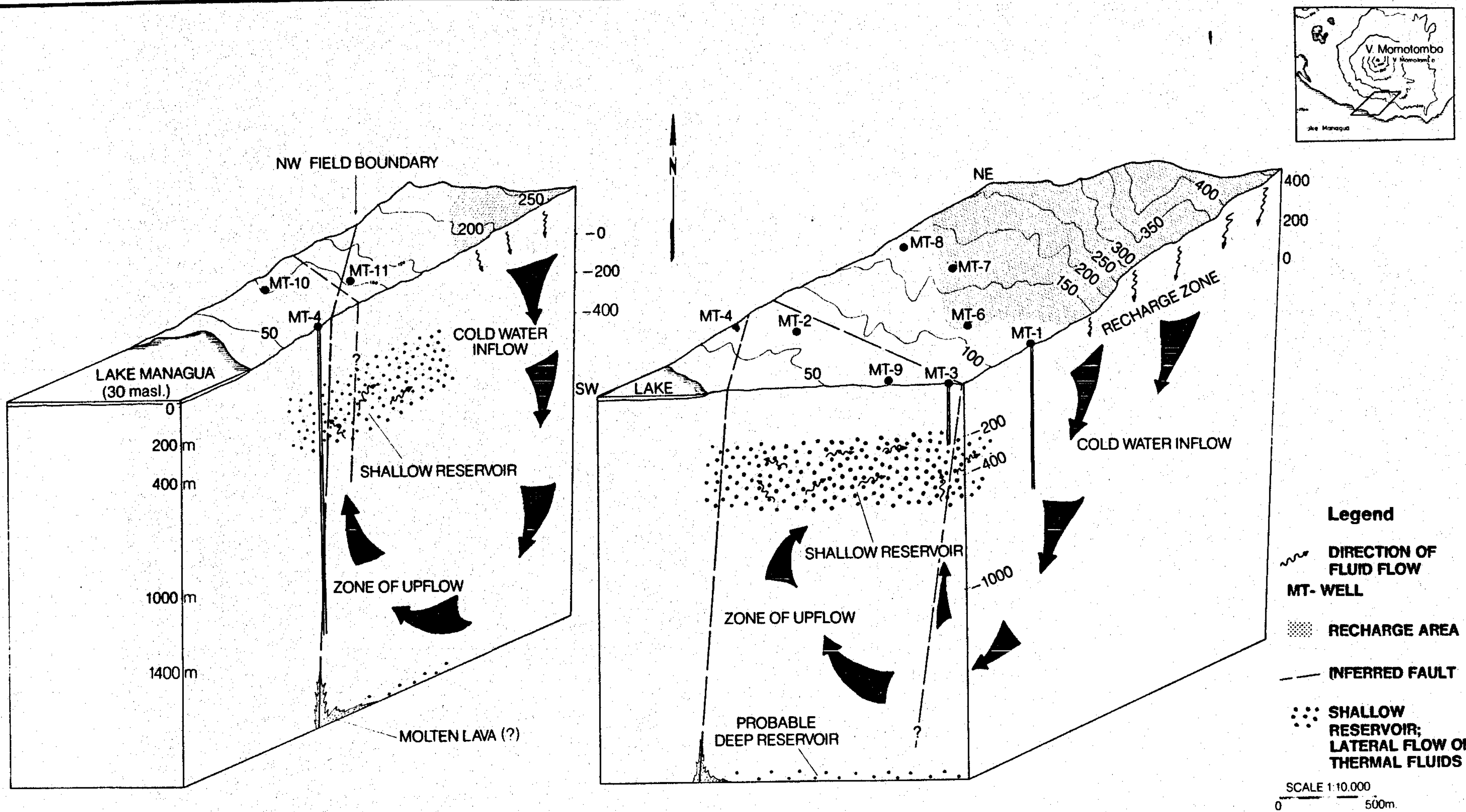
the order of 150° to 200°C; deeper drilling might encounter the reservoir with temperatures exceeding 250°C.

5.3 EINARSSON'S MODEL

Based on the analyses of temperature distribution in the Momotombo geothermal field by Svein S. Einarsson (1977), senior technical adviser for the United Nations, IECO, developed the model shown in Figure 5-3. The heat source is believed to be molten magma which has penetrated a northeasterly trending fault, located on the west side of the field, causing a ridge-shaped high temperature anomaly in the vicinity of MT-4. This fault, shown in the model as the NW field boundary of the hydrothermal system, governs the upflow feeding the shallow, productive reservoir lying at depths of 200 to 500 m. High temperatures were reported below 1000 m in several wells, suggesting a deep hydrothermal system, possibly with limited permeability. However, casing and completion problems prevented these wells from being adequately tested.

A zone of upflow of thermal fluids exists to the east and southeast of this fault. Inflow of water from the east provides the necessary recharge of the reservoir and also serves as the boundary of the system in that area, narrowing the shallow productive horizon north of the lakeshore to approximately 2 km^2. A convective cell is formed as cold water infiltrates from the east, is heated up as it nears the heat source, and is discharged into the shallow reservoir. The steam production potential is therefore limited by the maximum transport of thermal fluids which can be carried by convection to the shallow reservoir.

The field is open to the north toward Momotombo Volcano, and to the south under Lake Managua. High temperatures are encountered with increasing depth toward the west, but low permeability of the formations here is unlikely to favor commercial steam production.



EINARSSON'S MODEL

(data from United Nation's Development programs)

EINARSSON'S MODEL

INTERNATIONAL ENGINEERING COMPANY, INC.
180 HOWARD STREET, SAN FRANCISCO, CALIFORNIA 94105

Figure 5-3

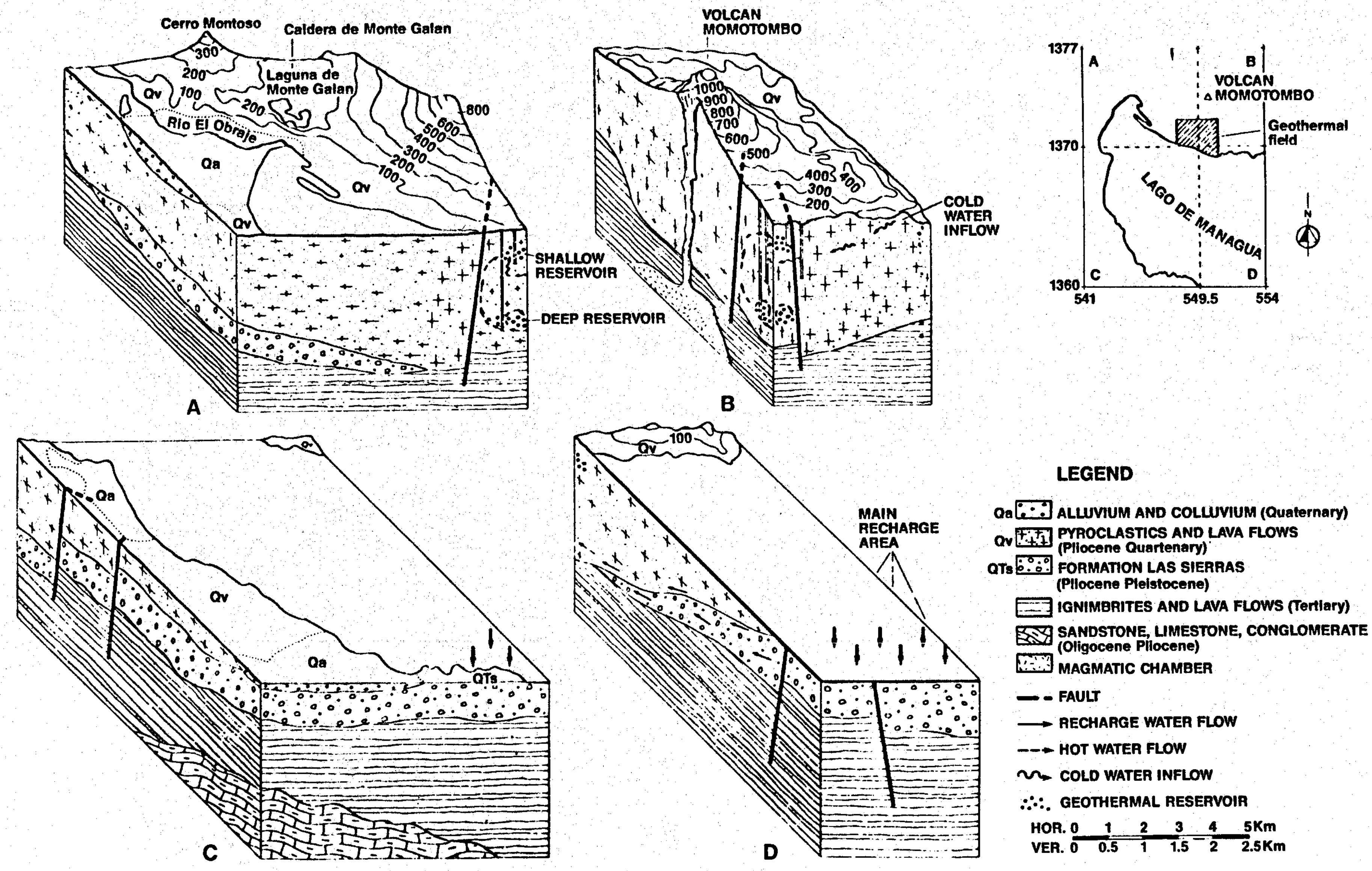
5.4 STAGE 3

A. Substage 1

Figure 5-4 shows the Momotombo geothermal field model developed by Electroconsult (1977) from Stage 3 investigations and modified by IECO. It was concluded from these studies that the dominant regional structure is controlled by a series of northeasterly striking faults, fractures and lineations forming a graben structure. The previously mentioned NW-SE striking fault system intersects the northeasterly system in this area and aids the channelization of thermal fluids. The two primary faults shown in the diagram appear to enclose the hydrothermal area by serving as structural boundaries to the east and west.

The existence of two different hydrological systems was suggested by isotope analyses. Deep circulation occurs in older pyroclastics as water infiltrates some 10 km south of the Momotombo Field and moves in a northwesterly direction following a canal-like feature formed by the Nicaraguan Depression. These waters are gradually heated by the shallow magmatic chamber of Momotombo Volcano and form a convective cell developing within permeable formations and forming the deep reservoir shown in the diagram at depths greater than 1500 m. Its extent and capacity are unknown. Hydrothermally altered pyroclastics act as a cap rock for the convective cell. Fractures in the cap rock serve as channels for thermal fluid flow, feeding the shallow reservoir at 200-500 m depth. Shallow circulation occurs to a depth of 500 m in the Quaternary volcanics and moves approximately parallel to the surface morphology. Cold water inflow from the east, near Loma La Guatusa, flows below the shallow reservoir and follows the welded tuff layer to feed the shallow reservoir.

Another similar model proposed at this time was that of L. H. Goldsmith (1979), consulting geologist for the Momotombo Field. He describes the geothermal field as a shallow extension of the "Plumbing System" asso-



STAGE 3 MODEL

Substage 1

(drawn by Electroconsult (1977))

Figure 5-4

ciated with a larger, deeper primary reservoir located on the northwest shore of Lake Managua, which occurs within the northeasterly trending graben structure shown in Figure 5-4. Thermal fluids in the shallow reservoir originate from large and deep reservoir located 10 km south, in the zone where Electroconsult infers the location of the main recharge area of the system. The fluids rise along this N-S fracture zone and spread out eastward in fracture lava flows in the Momotombo field. Impermeable ignimbrites to the east and west act as the field boundary.

Although the models proposed by Goldsmith (1979) and Electroconsult (1977) have many similar characteristics both in structure and processes, their main difference lies in the location of the deeper reservoir. The model derived from Electroconsult's (1977) investigations was based on data of studies in hydrology, subsurface temperature distribution, cores and cuttings, well-fluid geochemistry, and well tests, which tend to support their conclusions and subsequent model. Goldsmith (1979) bases his interpretation a gravity anomaly centered in an area 10 km south of the field and open toward Lake Managua which is partially supported by resistivity studies performed by Phoenix Geophysics showing the development of a low resistive graben structure near Puerto Momotombo (1977; unobtainable report), and hydrogeologic and geochemical investigations performed for the Nicaraguan government in previous years. Additional detailed investigations such as deep exploratory wells are needed to test this hypothesis.

B. Substage 2

The geothermal field model drawn by IECO as a result of this stage was developed from an analysis of temperature gradient measurements, lithologic correlation between wells, and additional geological observations performed by California Energy Company, Incorporated (1979). Thirty-three wells drilled into the field provided the means for obtaining information on the subsurface conditions of the system.

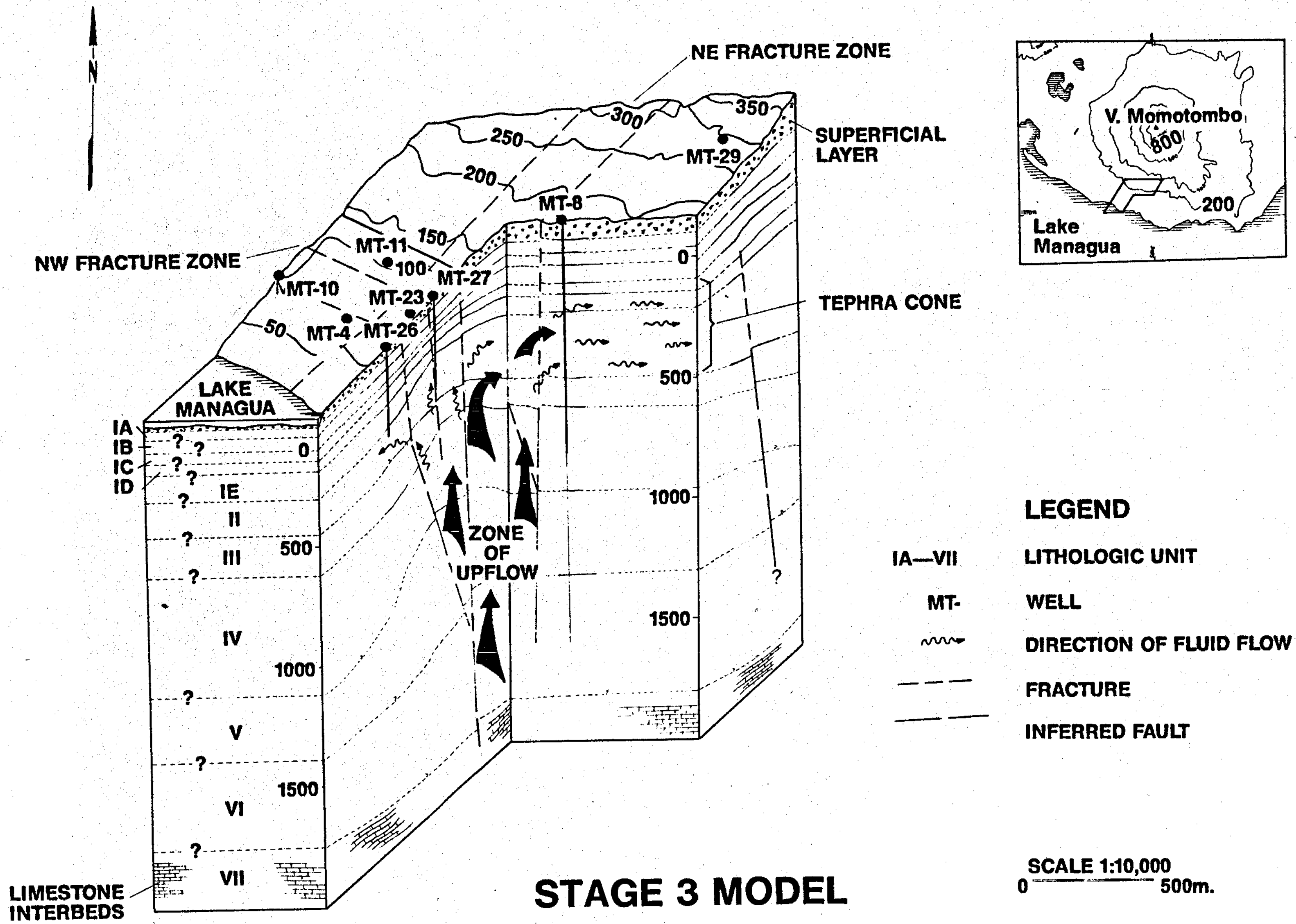
As shown in Figure 5-5 the stratigraphic column is divided into eight informal rock units based on recognizable lithologic markers. Most of the section is composed of basaltic and andesitic ash, tuffs, and tuff-breccias with some interbedded lava flows; only unit VII rocks are of sedimentary origin, containing interbeds of fossiliferous marine limestone.

The two wedge-shaped fault-fracture systems shown in Figure 5-5 are believed to be the near-surface expressions of two deep seated faults serving as major conduits for fluid flow. These fracture zones correspond to primary production zones. The intersection of these NW zones around well MT-23 and especially the NE fracture zone serve as the major zone of upflow. Hydrothermal fluids rise through faults, then fractures, and reach a tephra cone near MT-23 composed of units Id, Ie, and II, previously described in Figure 4-29. This cone serves to channel thermal fluids laterally to the east within a disk-shaped zone under the confines of the more indurate rocks of unit Ic. The lithologic configuration thus appears to play an important role in the lateral flow of the thermal fluids.

Subsurface temperature data indicate a north-south to northeast striking trend through the field, open to the south and to the north, in addition to a marked increase of temperature with increased depth in the western part of the field. A high-temperature peak occurs in the subsurface near wells MT-26 (250°C at 400 m), MT-4 (185°C at 400 m), and MT-11 (225° at 400 m) defines the major source of hot fluids for the Momotombo Field. No deep hot water source was detected in the eastern part of the field as indicated by temperature reversals in the wells.

5.5 IECO MODEL

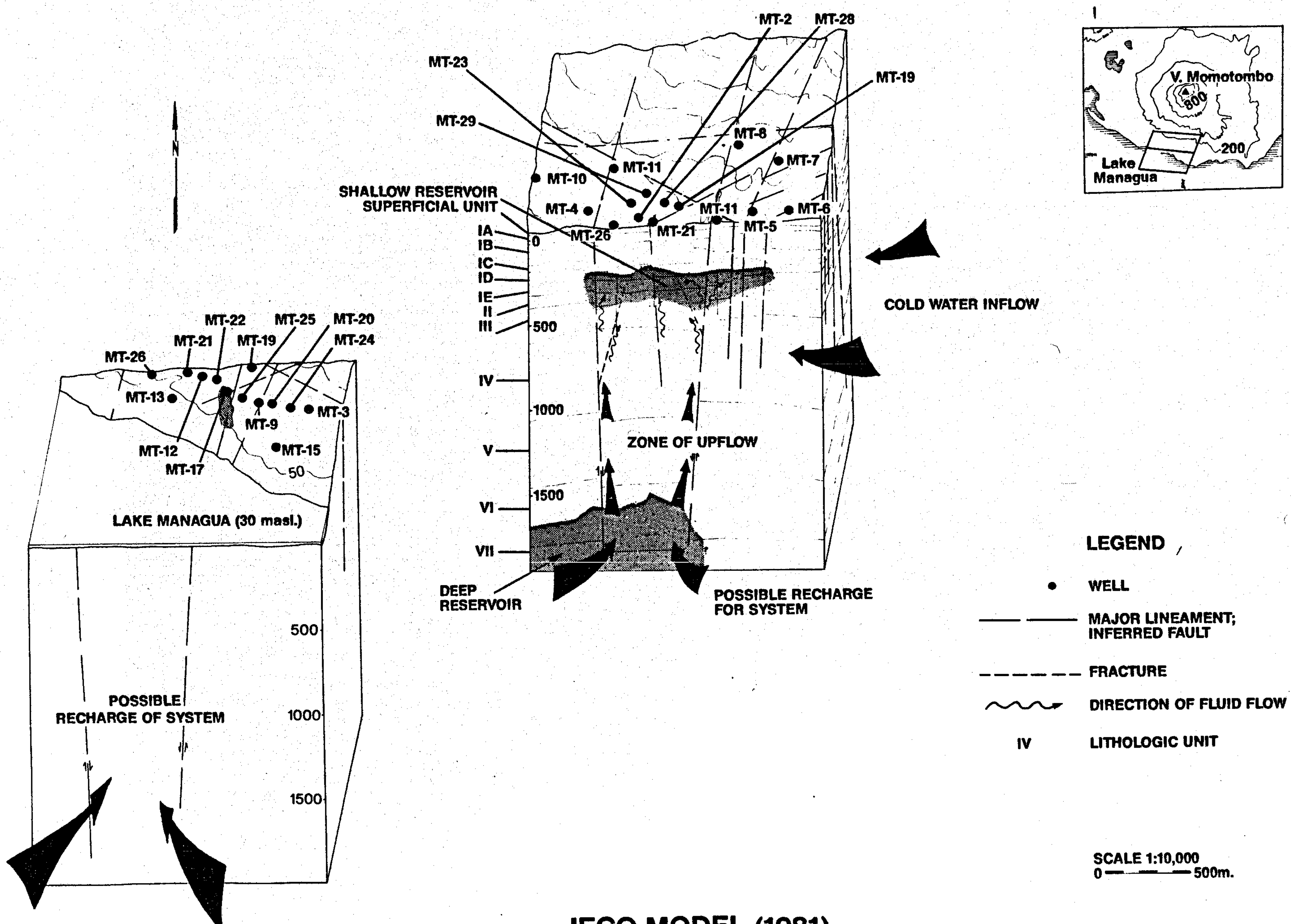
The field model shown in Figure 5-6 was developed by IECO from analysis of data and previous findings by various companies. The model shows



STAGE 3 MODEL
Substage 2

(data from California Energy Company, Inc.; for lithologic units See Figure 4-29.)

Figure 5-5



IECO MODEL (1981)

(based on data from previous studies)

Figure 5-6

the interrelationship of geophysical, geochemical, hydrological, and geological investigations, and the correlation of these data in defining the substructural processes occurring at Momotombo.

A broad, northeasterly trending fault-fracture zone resembling a graben structure controls the fluid flow. A deep reservoir lying at depths greater than 1500 m under the geothermal field heats the fluids which then rise along the fractures to a shallow reservoir controlled by fracture permeability and lying at depths of 200 to 500 m. Probable recharge to the deep reservoir occurs from the south. Thermal fluids move eastward in the shallow reservoir until encountering cold water inflow, which bounds the eastern and probably northeastern portion of the field. The fault defining the western part of the graben serves as the NW field boundary of the hydrothermal system. The deep reservoir, however, increases in depth to the west. The shallow, productive reservoir encompassing an area 1.5 km^2 is thus bounded by faults and by Lake Managua to the south.

CHAPTER 6

EVALUATION OF EXPLORATION STRATEGY AT MOMOTOMBO

6.1 INTRODUCTION

Our case history study has accomplished several goals:

- o The regional setting and physical parameters of the Momotombo geothermal field have been summarized.
- o The history of exploration and development has been discussed.
- o A geothermal field model was constructed for each exploration stage.
- o Data interpretation has been reviewed where possible.

This chapter discusses the strategy and effectiveness of the exploration methods used in the exploration program. The effectivenes of each program is considered in terms of:

- o The technical value of information generated
- o The use made of the information generated at each stage
- o The overall exploration program strategy and program goals.

Exploration techniques and optimum programs have been described by a number of explorationists. Each program should be formulated according to project goal and local environment.

The first purpose of an exploration program is to determine if a viable resource exists. The second purpose is to characterize that resource so that it may be developed economically. A cost effective exploration program contains several milestones where the decision to proceed or to stop may be made with the lowest expenditure for acquisition of the information required for each decision point. Each technique employed in the program must be selected to reduce the level of uncertainty of the resource characteristics.

Cost effectiveness is a major consideration in any exploration program for the identification and development of a resource. However, cost effectiveness is a function of many variables. A total exploration program might be considered cost effective if it leads, through various decisions, to either economic exploitation of the resource, or to abandonment of the program if no economic resource in fact exists, with a minimum expenditure for adequate data. The cost effectiveness of any individual element of an exploration program is much more difficult to define. An exploration technique which provides no useful information in one geologic setting may be extremely important in a different setting. A technique which gives detailed information on some aspect of a geothermal field, such as permeability, would be of very little use in the early stages of exploration where fluid temperature is a critical factor. Also, many techniques only produce useful information when other data are available.

6.2 GEOTHERMAL EXPLORATION METHODS

In this section we discuss a number of techniques which we believe should be used in geothermal resource exploration. No single discipline--geology, geochemistry, geophysics, or hydrology--should be relied on to determine resource potential nor should only one technique within these disciplines be used. Information from each study must be integrated as decisions to proceed or halt are made.

A. Geological Methods

The major cost of geothermal exploration results from drilling deep wells. Consequently, preliminary technical investigations should be aimed at siting wells and obtaining maximum information needed to determine productive areas. Field geology plays an important part throughout investigation and development. The initial purpose is to make reconnaissance evaluations to locate and define likely prospects. Detailed site mapping should be coupled with geophysics and fluid geochemistry in the predrilling evaluation of a field. Once drilling starts the geologist must continue to contribute to the investigations by examining drill cores and cuttings so that the stratigraphy and structure of the field can be understood. These data assist the driller in anticipating depths where drilling problems may be encountered and serve to determine depths for well completion.

1. Photography and Remote Sensing - These methods are especially valuable in the preliminary phases of geothermal exploration when regional studies are performed. Aerial photographs give excellent information on regional structure and faulting. Black-and-white, color, and infrared imagery each emphasize different information. Infrared-color photography improves haze penetration and produces maximum reflectance from vegetation. This helps in identifying areas of high temperature surface alteration marked by an absence of vegetation. Among other remote sensing techniques, thermal infrared scanning and side-looking airborne radar (SLAR) are of special interest in geothermal work. Both methods provide additional structural information. Thermal infrared imagery shows surface temperatures and can be used to map surface and near-surface moisture or areas of surface thermal activity. SLAR images show lithologic and structural variations are particularly suited for identifying faults and lineaments.

2. Detailed Field Mapping - Detailed field geologic mapping must be undertaken after areas of interest have been identified. Basic to

any geothermal mapping program is the identification of faults and fractures which may serve as conduits for geothermal fluids and define field boundaries.

Maps prepared from aerial photos and satellite imagery must be checked in the field to verify the interpretation of geologic features. Field work is essential for more accurate determination of fault displacement and information on thicknesses and attitudes of stratigraphic units.

3. Hydrogeologic Studies - Hydrogeologic studies determine shallow subsurface aquifer levels, their flow directions, possible sources, and chemical quality. Chemical data may indicate leakage of thermal fluids from deeper reservoirs into near-surface aquifers or heating of aquifer waters. Heat flow studies over a large region can help to indicate the more promising geothermal areas. Another crucial purpose of hydrologic studies is to characterize the recharge to the geothermal reservoir.

A rapid reconnaissance of an area of several hundred square kilometers should include measurements of water level and temperature in wells, streams and hot and cold springs. These measurements will establish the hydrologic gradient of the area and may indicate rate and direction of ground-water flow. Temperature measurements coupled with chemical analyses may indicate the heating of such waters by convection or by mixing with thermal waters from a reservoir or other source.

4. Petrologic and Isotopic Analyses - A study of mineral zonation and water/rock interaction in the reservoir will furnish information on subsurface temperature, fluid flow within the reservoir, and reservoir characteristics. Petrologic studies will provide useful information:

- Lithologic descriptions of cores and cuttings to correlate samples from well to well and determine the structural relations of the formations.

- o Hydrothermal alteration data necessary for proper characterization of the reservoir, including temperature and nature of thermal fluid, and fractures traversing or originating in the reservoir which permit upflow of the thermal fluid to the surface.

- o Specific geothermometers using combinations of mineral assemblages, isotopic ratios and fluid inclusion measurements.

Isotopic analyses of mineral and water samples will provide information on the origin of the fluids and the equilibration temperatures of the reservoir.

B. Geophysical Methods

Geophysical methods that have commonly been used in geothermal exploration are electrical, electromagnetic, thermal, gravity, and seismic techniques. These techniques are described in the following sections together with their applications to geothermal exploration. The success of each method depends on the contrast of a set of physical rock variables inside and outside the geothermal system which gives rise to geophysical anomalies. These anomalies can be grouped according to cause:

- o Hot geothermal fluids
- o Lithologic changes in the reservior
- o Structural features
- o Fluid withdrawal
- o Clay, shale, saline waters or mineral deposition.

These anomalies may differ in various types of geothermal systems, and as such the selection of the most suitable geophysical technique is governed by a number of factors involving both the in situ conditions and outside constraints placed upon the exploration program.

The in situ influences upon the exploration program include the type of geothermal system, the regional setting of the system, and the access and terrain. The outside constraints include the availability of equipment and trained staff, the experience of the geophysics team leader, and the availability of data reduction facilities.

No standard approach to planning a geophysical survey of a geothermal prospect exists. The techniques and exploration methodology chosen for any area should follow these guidelines.

- o Use all available geologic maps and other data for exploration planning
- o Start with simple and well established methods
- o Aim for adequate coverage of the whole prospect
- o Use appropriate methods to solve problems identified by geologic studies.

1. <u>Electric and Electromagnetic Methods</u> - Direct-current (DC) resistivity methods are probably the most widely used in geothermal exploration. They are performed by applying a current to the ground through electrodes and measuring the resulting potential at various points on the surface. DC resistivity techniques permit the determination of the distribution of earth resistivities as a function of depth and lateral distance. Liquid-dominated geothermal reservoirs have generally been characterized by relatively low electrical resistivity, on the order of 5 ohm-meters or less, which contrasts sharply with the surrounding higher resistivity host rock (Meidav, 1979).

The resistivity of rock is affected by the following factors:

1. Type and composite
2. Degree of saturation
3. Salinity of the fluid; concentration of dissolved electrolytes
4. Temperature and phase state of the pore water

5. Porosity and permeability; shape, size and interconnection of pores

The depth of current penetration and accordingly the desired depth of the resistivity investigation is a function of electrode spacing and configuration. The larger the electrode separation, the greater the depth of penetration below the surface. A discussion of effective probing depths with different methods is given by Keller and Frischknecht (1968).

There are many different resistivity methods based on different electrode arrangements. A number of surface configurations are used for the current and potential electrodes. The most common electrode arrays are:

- Wenner
- Schlumberger
- Equatorial
- Dipole-Dipole
- Roving Dipole

Extensive descriptions and applications of these and other methods are found in Dobrin (1976), Telford et al. (1976), Meidav (1979), Parasnis (1979), and Keller and Firschknecht (166).

The choice of appropriate method depends on the effective probing depth obtainable by the different arrays. Generally the Wenner array (four equally spaced electrodes in line) is more effective than other methods if the instrument being used is limited in either the voltage it can detect or the current it can produce. The Wenner array, however, is greatly affected by lateral variations and therefore the resultant relation between apparent resistivity and depth may be irregular reflecting lateral variations rather than depth effects. The advent of more powerful voltage receivers and current transmitters which can better discriminate against random noise has decreased the use of the Wenner array in geothermal exploration. In addition, resistivity systems are now available with signal averaging which give extended penetration depth.

The Schlumberger array is one of the most widely used electrical methods. This method consists of two current and two potential electrodes symmetrically arranged on a line with the distance between current electrodes much greater than the spacing of the potential electrodes. The Schlumberger array has a number of advantages over the Wenner array: (1) the effect of lateral variations is reduced because of the smaller number of moving electrodes, (2) contact resistance problems can be minimized, and (3) less manpower is required (Meidav, 1979).

Many arrays and procedures exist for either horizontal profiling (constant depth profiling) or depth sounding, or combinations of both. The dipole-dipole method offers a combination of depth probing and horizontal profiling. This method has become popular recently in geothermal exploration. Horizontal profiling yields an iso-resistivity map at an approximately constant depth. If the probing depth has been properly selected, the constant depth profiling method can quickly locate the area of greatest interest. The vertical depth probing method provides a profile of apparent resistivities versus spacing, whch gives information on the variation of resistivity with depth; however, lateral resistivity changes may affect this method.

A major problem with the DC electrical resistivity method lies in the interpretation of measured anomalies. Other methods are required to verify results and determine the relationship between the resistivity anomaly and the in situ geologic section.

Electromagnetic methods have been used in geothermal exploration only in the last 5 years. These methods involve the generation of a time-varying magnetic field, and the detection of either the resulting electric or magnetic field arising from currents induced in the earth (Keller and Frischknecht, 1966).

Electromagnetic methods may use artificial or natural sources. Artificial sources do not, in general, provide sufficient depth of penetration. Among the methods using natural sources, the magnetotelluric (MT) and audio-magnetotelluric (AMT) methods are among the most effective. They use natural currents related to ionospheric currents induced by radiation of charged particles from the sun. These earth currents penetrate to great depth, so that magnetotelluric measurements can provide resistivity estimates to depths of several thousand meters. The effective depth of penetration depends on resitivity and frequency. Also, the depth of penetration is greater in resistive strata, which offers an advantage over DC resistivity methods.

Magnetotelluric methods are particularly suited to reconnaissance surveys because the field equipment is easily portable. However, DC electrical resistivity methods often provide better resolution of subsurface features.

Electrical and electromagnetic measurements determine apparent resistivity as related to electrode spacing or frequency. This information must be interpreted to derive a measure of actual rock resistivity versus depth and location. As with other potential field methods, data from both electrical and electromagnetic methods should be compared to other geological and geophysical information to arrive at an improved interpretation.

The self potential (SP) method is an electric technique that employs natural electrical sources. The potentials may be caused by electrokinetic coupling as thermal fluids flow through porous media or fractures, thermoelectric effects, bioelectric activity, and varying electrolyte concentrations in ground water. Anomalies measured in geothermal areas may range from 50 millivolts to over 2 volts (Corwin and

Hoover, 1979). The primary application to geothermal resources is in the location and tracing of faults which control the flow of thermal fluids. The method however, can not distinguish between normal ground water flow and the flow of hot (geothermal) water.

Equipment is simple, consisting of a pair of nonpolarizing electrodes connected by a wire to a millivoltmeter. Where possible, traverses are performed normal to the strike of suspected SP anomalies. One or two electrode spreads may be used; either both electrodes are moved with a fixed spacing between them or one electrode is fixed at a base station while the other is move to successive locations along the line. The advantages of maintaining a base station electrode are that the potential is measured with respect to a fixed point and zero errors between the electrodes do not accumulate. The disadvantage is that a long cable that is necessary, with a resultant slowdown in measurements.

2. Thermal Methods - Thermal methods require the measurement of temperature, and the calculation of geothermal gradient, heat flow, and heat budget.

The geothermal gradient is calculated from the vertical variation of temperature, usually measured in a borehole. Care must be exercised in obtaining the correct temperature at a specified depth, and not an average temperature. Heat flow calculations also require the measurement of thermal conductivity of the rocks. Heat flow is the product of the geothermal gradient and the thermal conductivity. Heat budgets may be obtained from the measurement of temperatures and flow rates of surface springs.

Hydrologic conditions also must be taken into account. Ideally, temperature gradient holes are drilled to a depth below the level where ground water circulation affects the thermal gradient. Gradient measurements are usually taken at depths in the range of 30 to 150 m.

3. Gravity, Magnetic, and Active Seismic Methods - Gravity, magnetic, and seismic refraction and reflection surveys are also used in geothermal exploration. These are all indirect methods and have not been successful by themselves in locating specific geothermal systems.

These methods are useful in determining the structure and nature of rocks or aquifers. Gravity and magnetic surveys are not very useful by themselves but used in conjunction with other exploratory techniques, they become excellent tools for studying regional tectonics, including faulting and other lineaments.

Gravity surveys measure lateral variations in gravity due to density variations in the subsurface. These density changes could be the result of lithology or of leaching or mineral constituents from rocks heating a geothermal reservoir. Biehler (1979) suggested that ambiguity in gravity interpretation can be reduced by combining the gross structural features of seismic refraction surveys with gravity modeling.

The objectives of a gravity survey are: to locate faults, to determine basement structure, to establish the lower limits of potential reservoirs, to estimate the thickness of volcanic or alluvial cover, and to aid in the determination of drilling targets.

Magnetic surveys are a potential field method similar to gravity and employ similar interpretation schemes. Magnetic surveys measure the local magnetic field intensity (Dobrin, 1976: Telford et al., 1976), and may be either airborne or ground based. Regional surveys are performed using airborne methods. The many factors that influence the character of the magnetic map, especially in volcanic terrain, make it difficult to interpret the results in terms of the geothermal resource. Another factor that must be taken into account is the time-varying nature of the earth's magnetic field.

Magnetic measurements can provide information on the tectonic framework of an area by locating regions of contrasting magnetic susceptibility. Magnetic survyes may give excellent indications of lineaments which can supplement other information relating to faults and fractures.

Curie isotherm studies, in some cases, permit outlining of geothermal areas directly by the magnetic method. The Curie temperature is the temperature above which rocks lose their ferromagnetic properties and become practically non-magnetic. Increased heat flow in a geothermal area will raise the level in the subsurface at which the Curie temperature is reached and a corresponding magnetic anomaly may be detected. Gravity may also give direct indications of geothermal activity via density changes produced by elevated temperatures.

The interpretation of gravity and magnetic data should be upgraded and altered as additional information becomes available from other techniques.

4. Microseismic Methods - Microseismic measurements consist of recording and analyzing acoustic signals that originate in and travel through the subsurface. There are two types of methods: rock noise monitoring and microseismic measurements.

Rock noise monitoring detects subaudible noise resulting from stress conditions or mass movements in the subsurface. Locations at which sounds originate can be determined by analyzing recordings made with detectors distributed over an area. In geothermal exploration, this method has been used extensively to monitor ground noise often associated with geothermal reservoirs, caused by thermal stress or circulation of water or steam in the reservoir formation.

Microseismic measurements, or microearthquake measurements are performed by placing sensitive seismographs in various locations around the area to be investigated. The instruments are designed to record small earthquakes (less than magnitude 3) occurring in the area.

With a sufficient number of microseismographs, earthquakes can be determined. Movements producing small earthquakes often occur along faults and local fractures. Given a sufficient recording time, locations many microearthquake foci will define the location and attitude of faults or fracture planes.

The applicability of these techniques to geothermal exploration is currently under investigation. Further studies are needed to understand the concepts which could be applied to a fast, mobile, and economic method of investigation for geothermal areas, using a combination of geologic and geophysical techniques.

C. Geochemical Methods

Geochemistry can provide extremely useful information in all phases of exploration and exploitation of a geothermal active region. However, geochemistry is frequently under-applied and misunderstood in geothermal exploration. Water sampling and analysis is always recommended in the first phase of regional exploration for geothermal targets. Careful professional interpretation of water chemistry can tell the explorationist if a geothermal resource exists, and the probable temperature of that resource can be estimated by using geochemical geothermometry. There are two types of geothermal systems: liquid and vapor-dominated. Geochemistry can indicate which system is present. The following discussion of geochemical exploration methods includes data accumulation and interpretation approaches as well as a discussion of chemical indicators of high temperatures.

1. What Geochemistry Can Do - A resource can be directly detected by a drill hole penetrating a reservoir. Geochemistry is a less direct detection method and is more cost effective than drilling during the

initial stage of exploration. A critical parameter that can be estimated is resource temperature. Geothermometry is empirically based on the concentrations of chemical constituents resulting from the equilibrium between the fluid and the surrounding rock under the existing pressure and temperature conditions. Geothermometry is a valuable method in exploration but numerous physical variables must be considered before estimated subsurface temperatures can be considered indicative, as discussed by Fournier, White and Truesdell (1974). However, once water samples meet the criteria necessary for application of geothermometers, the explorationist will know if the supposed resource temperature is sufficient to warrant a larger commitment of funds and manpower to assess the target.

During regional and target exploration geothermal chemical indicators in sampled waters can be used to roughly outline areas of interest. Interpretation of fluids sampled in all types of holes (including temperature gradient holes) can refine geothermometry and determine the amount of mixing between thermal and non-thermal waters, and indicate the chemical nature of the geothermal system. Any fluids encountered during temperature gradient hole drilling should be sampled. We believe this basic principle is overlooked by many practioners in geothermal exploration. Knowledge of the brine chemistry is crucial in designing geothermal plant equipment. Once a field is in production, and during well testing, continued sampling and analysis can monitor changes in the field. A field's response to continued exploitation also may be predicted by long term chemical monitoring.

2. Hot-Water and Vapor-Dominated System - There are major differences in chemical characteristics between hot-water and vapor-dominated systems (Tonani, 1970; White, et al., 1971; Truesdell, 1976; and Ellis and Mahon, 1977). Chloride content is commonly used to discriminate between the two types of systems. Springs waters associated with vapor-dominated systems generally contain less than 20 ppm chloride, while high chloride content thermal waters (>2000 ppm) are generally

associated with liquid-dominated systems. There are exceptions, such as the low chloride, high temperature systems at Beowawe, Nevada; Carboli, Italy; and Kizildere, Turkey.

The presence of high chloride waters does not necessarily indicate the existence of a hot water geothermal system at depth. A knowledge of the rocks in the subsurface is necessary to determine if the chloride is an indication of a geothermal system.

Table 6-1 summarizes many of the distinctions between the two systems, as described by the authors listed above.

The two systems are not always distinguishable in the early stage of exploration at the surface. Hot water systems mixing with ground water below the surface will typically produce steaming ground, fumaroles, and acid-sulfate springs. Volatile elements will be carried in steam when a phase separation occurs in a geothermal system. Approximately the same volatiles, B, NH_3, Hg, Li, F, and As, depending on geologic environment, are found in fumarole or steaming ground condensates and shallow ground water whether the steam has come from a vapor or liquid-dominated system. These volatiles may be considered the common denominator for detecting both systems in geochemical exploration for geo-

TABLE 6.1

HYDROLOGICAL AND GEOCHEMICAL CHARACTERISTICS
OF GEOTHERMAL SYSTEMS

Hot Water Systems	Vapor-Dominated Systems
High chloride contents of thermal thermal springs or wells relative to nearby cold surface and groundwaters.	Low chloride content in springs.
High temperature hot water system will be higher in SiO_2, Cl, B, Na, K, Li, Rb, Cs, and as relative to surrounding groundwaters.*	Condensed steam or spring water will be higher in B, NH_4, Hg, SO_4, F, and CO_2 relative to surrounding ground waters.
Siliceous sinter ($T>180°C$) or travertine ($CaCO_3$) ($T<150°C$) may be precipitated by hot springs.	Pyrite and cinnabar may be abundant around the border zones of condensing steam.
True geyser activity.	Major vent areas are characterized by fumaroles and mud pots.**
Thermal springs may have a large volume of discharge (depending on ground water supply) at near-neutral pH.	Springs will have low discharge and low pH.
Argillic alteration from neutral reactions will produce typically, montmorillonite and illite.	Argillic alteration of silicic rocks can produce kaolinite, dickite, or halloysite.

* If steam is leaking from a low pressure zone in a hot water reservoir into surface or ground waters, B, NH_3, Li and F content will be higher relative to surface and ground water away from th leakage area.

** Hot water systems discharging in low water table areas also have fumaroles, mud pots and acid-sulfate springs (White, 1970).

thermal resources. Vapor-dominated systems are rare compared to the number of hot water systems recognized around the world, but both types must be considered in exploration.

-A wide area around thermal waters must be sampled because of local variations in water chemistry that may produce false geothermal signatures. Apparent chemical anomalies can result from near-surface effects such as salt evaporation and solution, sulfate reactions, and contributions of ammonia and boron from decaying organic matter in sediments.

3. Geothermometry - One of the biggest pitfalls in geothermal geochemistry is the misuse of geothermometers.

Geochemical geothermometers are based on the relationships between chemical species in solution. Constituents such as Na, K, and Ca are strongly affected by temperature-dependent water-rock interactions. SiO_2 in solution also strongly depends on subsurface interaction between water and silica minerals and silicates. The solubilities of these minerals generally change as functions of temperature and water pressure. The basic assumption is that, given an adequate supply of all reactants, constant values are produced for water-rock equilibrium at any particular temperature. Temperature-dependent reactions "fix" the amount or amounts of dissolved "indicator" constituents in the water. The critical condition for valid geothermometry is the water-rock equilibrium occurs at the resource temperature, and that delution from other waters has not occurred.

Transient ground water is not likely to have attained geochemical equilibrium with the minerals in its environment. Therefore, temperatures predicted from chemical concentrations in shallow ground waters do not usually yield meaningful data. We have demonstrated this in Chapter 4, Section 4.3-A-3 with a recalculation of the geothermometers for the Rio El Obraje valley water samples. The Na-K-Ca geothermometer was the only geothermometer calculated for the samples by the contractor. This geothermometer is used widely, along with the SiO_2 geothermometer, for subsurface temperature estimates.

Tonani (1980) has suggested that one method of checking internal consistency, and therefore equilibirum of sample water, is the simultaneous use of separate geothermometers, Na/K, Ca/Na, and Ca/K, based on the following formulas:

$$\text{NaK } t = \frac{833.3}{\log \text{Na/K} + 0.55} - 273$$

$$\text{CaK } t = \frac{1930}{\log \frac{\text{Ca}}{\text{K}} + 2.92} - 273$$

$$\text{CaNa } t = \frac{1096.7}{\log \frac{\text{Ca}}{\text{Na}} + 2.37} - 273$$

Table 6.2 shows discrepancies between the various geothermometers calculated for shallow, nonequilibrated waters and general agreement for the hot springs and geothermal wells at Momotombo.

An additional benefit in the simultaneous use of three separate geothermometers is that the available reactants in the reservoir rock can be considered. The available minerals vary between different reservoir types. It appears that at Momotombo the Na-Ca geothermometer gives temperature estimates closest to measured temperatures. This may occur because sodic-calcic feldspars are more abundant in the subsurface than potassic feldspars.

TABLE 6.2- Geothermometer Calculations

	Na/K	Na/CA	K Ca	Na-K-Ca*	Location
Lake Shore Hot Springs, 60°C	297.2	52.3	126.3		West of Fumarole Area
San Cayetano	254.74	55.65	116.35	95°C	Cold
Casablanca	309.71	36.71	115.2	105°C	Field Camp-Puerto Momotombo Shore
El Diamante	302	29.6	107.37		Cold, Puerto Momotombo Finca Well
Puerto Momotombo	352	26.85	113.71		House Well, NW Corner of Village
Finca California	308.9	23.4	103.02	80°C	Cold, 200 M from Main Road on Road to Finca
Finca California	280.4	29.9	103.46		Cold, 500 M from Farm
Finca California	268.9	65.3	130.83		Warm River 1 km North of Finca California
Finca California	377.5	42.9	133.08		Cold Well Farmhouse
Las Colinas	334.05	4.24	89.2	40°C	Cold Well
Armenia	353.0	4.9	92.7	58°C	Cold Well
Volcan Momotombo Hot Springs	210.43	216.96	214.1		Exact Locations Unavailable
Volcan Momotombo Hot Springs	210.43	217.45	214.1		Exact Locations Unavailable
Volcan Momotombo Hot Springs	442.13	65.47	165.1		Exact Locations Unavailable
Volcan Momotombo Hot Springs	209.85	215.08	212.8		Exact Locations Unavailable
Volcan Momotombo Hot Springs	185.73	202.56	192.13		Exact Locations Unavailable
Punta Salinitas SIGV	210.43	215.76	214		Punta Las Salinitas Hot Springs
Punta Salinitas ELC	159.7	192.36	177.7	210°C	Punta Las Salinitas Hot Springs
Punta Salinitas Ti	257.2	147.95	189.05	210°C	Punta Las Salinitas Hot Springs
MT 1	212.3	203.2	207.1		Geothermal Wells
MT 2	289.15	234.6	256.8	260°C	Geothermal Wells
MT 3	276.01	229.3	248.5		Geothermal Wells
MT 4	290.76	225.2	254.0		Geothermal Wells
MT 5	283.7	233.5	254.0		Geothermal Wells
MT 5	289.1	221.1	248.3		Geothermal Wells
MT 6	113.7	187.1	152.3		Geothermal Wells
MT 7	133.8	204.5	171.2		Geothermal Wells
MT 8	267.9	243.1	253.5		Geothermal Wells

D. Conclusions

The techniques we have discussed should be combined to suit specific exploration goals. The main point we wish to emphasize is that data from each study must be integrated in the model for the geothermal area or field and this model should be constantly revised as new data are generated.

6.3 Summary of Momotombo Exploration Program Evaluation

The Momotombo field was initially chosen for investigation on the basis of fumaroles, hot springs and surface alteration. The San Jacinto field was also selected for investigation, but was designated as a secondary prospect due to absence of fumaroles. Although a geologic map of the immediate area of interest was prepared, no attempt was made to place the field within the framework of regional structure. The Momotombo volcanic complex consists of 5 recognizable events and calderas over a distance of 12 kilometers. All of these volcanic manifestations form a linear feature, part of a longer alignment to the south, marking the tension fracture which gave the rising magma access to the surface. The relationships of this fracture and intersecting major fault lineaments and the volcanic features could have furnished valuable clues regarding the possible location of a magma chamber heat source. A study of the vulcanism of the area should have noted the 2.5 kilometer westward offset of the volcanic axis, from the vent of Cerro Colorado. This offset created the Obraje valley and is of major significance in regard to the magma chamber location and hence the primary geothermal reservoir feeding the Momotombo field. Readily mappable is a north-northwest striking lineation of several hot springs over a distance of more than 30 kilometers. A study of the regional volcanology and structure may have pointed out that the area of thermal manifestations at Momotombo was not necessarily the optimum exploration target.

An analysis of the physical location of the Momotombo field, lying on the steep flanks of the volcano and truncated to the south by Lake Managua, would have indicated that field development was restricted to an area less than 3 km^2.

The small geophysical anomaly delineated in Stage I and III Substage 1 investigations clearly showed the small areal extent of the field. The failure to extend the geophysical survey beyond the limited area south of Momotombo precluded locating the source reservoir of the thermal fluids.

Geochemical investigations during Stage II investigations showed the thermal fluids sampled in the Obraje Valley and at Momotombo to have similar chemistries, possibly with a common reservoir origin.

Failure to construct a viable model incorporating all data developed throughout Stages I through III prevented development of a more rational regional exploration strategy and resulted instead on concentration of effort in the restricted, clearly indicated shallow Momotombo field.

Location of temperature gradient holes over the geophysical anomaly delineated in Stage I exploration did not furnish data on temperature gradients in the general area. The holes were subject to convection currents, and were isothermal with a few exceptions which showed hot and cooler thin intervals of flow. Consequently, heat flow at the site was equated with a geothermal anomaly reflecting a reservoir at depth.

The initial four wells clearly showed that the east-west extent of the field did not exceed 1,200 meters. As mentioned above, the north-south extent was even more restricted. The hot springs and fumaroles at this site dried up when two wells were permitted to discharge. This clearly demonstrated that the shallow resource was small and that all areas within this productive interval were interconnected. The deeper productive zone on the west side of the field, detected by geophysics and confirmed by several wells, should have been the main exploration and modelling target.

During Phase III a total of 29 additional wells were drilled and completed within an area of approximately 2 km^2, therefore all wells are closely spaced. Several wells drilled within the productive zone penetrated the temperature inversion zone and were completed, connecting these two zones. Others were drilled outside of the boundary faults of the productive zone and failed to encounter fracture or permeability within the ignimbrites.

Wells testing was undertaken generally on a single well, short term test basis. No adequate tests were performed to determine well interference nor were any long term production tests performed. Although well temperature data were available, failure to interpret and consider this information throughout the course of drilling resulted in failure to recognize the zone of the thermal fluid upwelling. These data could have been recognized early in the program. Well temperature profiles did not show an inversion zone in the west, but clearly demonstrated its presence in wells drilled toward the east.

Sustained productivity of the field could have been greatly enhanced by drilling into or near the thermal fluid upwelling zone. Such drill holes would have permitted close well spacing without producing adverse well interference.

D. Conclusions

We believe there were several major deficiences in the Momotombo development program, which were discussed in Chapter 4.

- Data generated in each stage were not integrated in successive stages, nor was each data set integrated with other data sets within the same stage.

- There was no program continuity.

- Production drilling was the primary exploration method. A true exploration program could have improved the efficiency of resource development.

- More information could have been generated from the work that was performed. Downhole geophysics, hydrothermal alteration studies and more consistent geochemical sampling from the holes drilled would have contributed greatly to an understanding of the resource.

- The area explored by drilling was about .8 km x .7 km, suggesting that the strategy was to develop a few MW or that the field was considered to have an unprecedented concentration of energy over less than 2 sq. km of area.

In the summer of 1980, the national power company, Instituto Nicaraguense de Energia, was planning to construct a 30 or 35 megawatt plant at Momotombo. Five wells were opened in August 1980 for further flow tests. We suggest that integration of the data during each exploration survey and from one exploration stage to the next would have greatly improved the cost-effectiveness of the program and enabled economically important decisions to be made on the basis of the best possible information.

CHAPTER 7

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APPENDIX A

AVAILABILITY SITE EXPLORATION

BEFORE SITE EXPLORATION OF

THE MOMOTOMBO FIELD

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