GL01462

CASE HISTORY STUDY OF EXPLORATION METHODS USED AT MOMOTOMBO, NICARAGUA, GEOTHERMAL FIELD

Draft of a study by International Engineering Co., Inc. of San Francisco. Study is under contract to DOE/ID and is portion of the Geothermal Exploration and Assessment Technology Program.

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SUMMARY

A geothermal exploration program was started in Nicaragua in 1969. Its objective was to discover and delineate potential geothermal reservoirs.

This report presents a description, evaluation and results of geothermal exploration methods used during the investigative stages of the Momotombo geothermal field. Geologic, geophysical and geochemical techniques furnished all the data for the evaluation of the field.

CHAPTER 1

INTRODUCTION

A geothermal exploration program conducted in areas where little previous work has been undertaken should be sequentially structured into reconnaissance and detailed investigation phases to permit continuous evaluation of results for decision making. The techniques and methodology used during these phases in the Momotombo area of Nicaragua (Figure 1.1) are presented in this report, along with their results and evaluations.

Geoscientific information necessary for the investigation of the Momotombo field includes geologic, hydrologic, geochemical and geophysical data. Evaluation of data from each discipline will permit decision making for continued investigations during all stages. Integration of data obtained is essential, since no single technique is sufficiently definitive to establish confidence adequate to permit the interpretation of an anomaly as a geothermal reservoir. A summary of the various investigation studies is diagrammatically presented in Figure 1-2.

1.1 PURPOSE AND SCOPE

The purpose of this report is two-fold. First, it is to present in summarized form the results of the various exploration techniques used during the investigative phase of the Momotombo Geothermal Field. Second, it is to assess each technique with regard to its reliability, accuracy measurement limitations, and research and development needs. In this report, three categories of geotechnical measurements are treated:

- Geologic, Hydrologic
- Geophysical
- Geochemical

The text also presents introductory discussions of the various exploration methods for each category. These discussions list the methodology which can be used to assess geothermal fields. Also included, where applicable, are evaluations of the reliability of the technique and if research and development are needed.

The scope of work conforms to the objective given in the specific contract for each stage. The workplan generally includes geoscientific studies such as:

- A geological survey, reconnaisance and detailed, leading to the preparation of a geologic map of the area.
- A geochemical survey of all springs and waters with their respective analysis to give information on existing temperatures in the subsurface.
- Shallow well drilling to determine temperature gradients.
- A brief hydrologic study to determine the origin and flow of waters which supply the reservoir.
- Report preparation on each of the aforementioned subjects.

1.2 STRATEGY AT ONSET OF PROGRAM

The Government of Nicaragua originally planned the investigation of geothermal resources in the following 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 for steam and power production.

This report deals with the exploration phases of the geothermal area, stages 1 and 2, and as such is divided into 3 new stages based on the required exploration strategy. These are:

STAGE 1 - Reconnaissance geoscientific studies.

STAGE 2 - Detailed geologic, geophysical and geochemical investigations.

STAGE 3 - Geoscientific data accumulation during exploration drilling.

1.3 DEVELOPMENT SCHEDULE

Since 1966 the Momotombo area was considered for further exploration studies with the purpose of finding an exploitable geothermal reservoir. Figures 1.2 and 1.3 show 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 - A group of experts under Electroconsult made a preliminary evaluation of the geothermal potential of Nicaragua.

- June 1969 to February 1971 - Texas Instruments, Inc. performed an 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.

- November 1974 to June 1976 - Electroconsult (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 including 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-eight production wells were drilled and measurement tests, geological studies and temperature gradient hole data was accumulated.

- August 1979 to Present - The Nicaraguan National Institute for Electrification (INE) continues a well testing program at Momotombo. – need to reference ELC's work – reserv. [illegible] study in progress by Knesp(?), and plant design by another Italian firm.

AVAILABILITY OF INFORMATION
BEFORE SITE EXPLORATION OF
THE MOMOTOMBO FIELD

The following information was available and extensively used during Stage 1 - Geothermal Resources Project in 1970:

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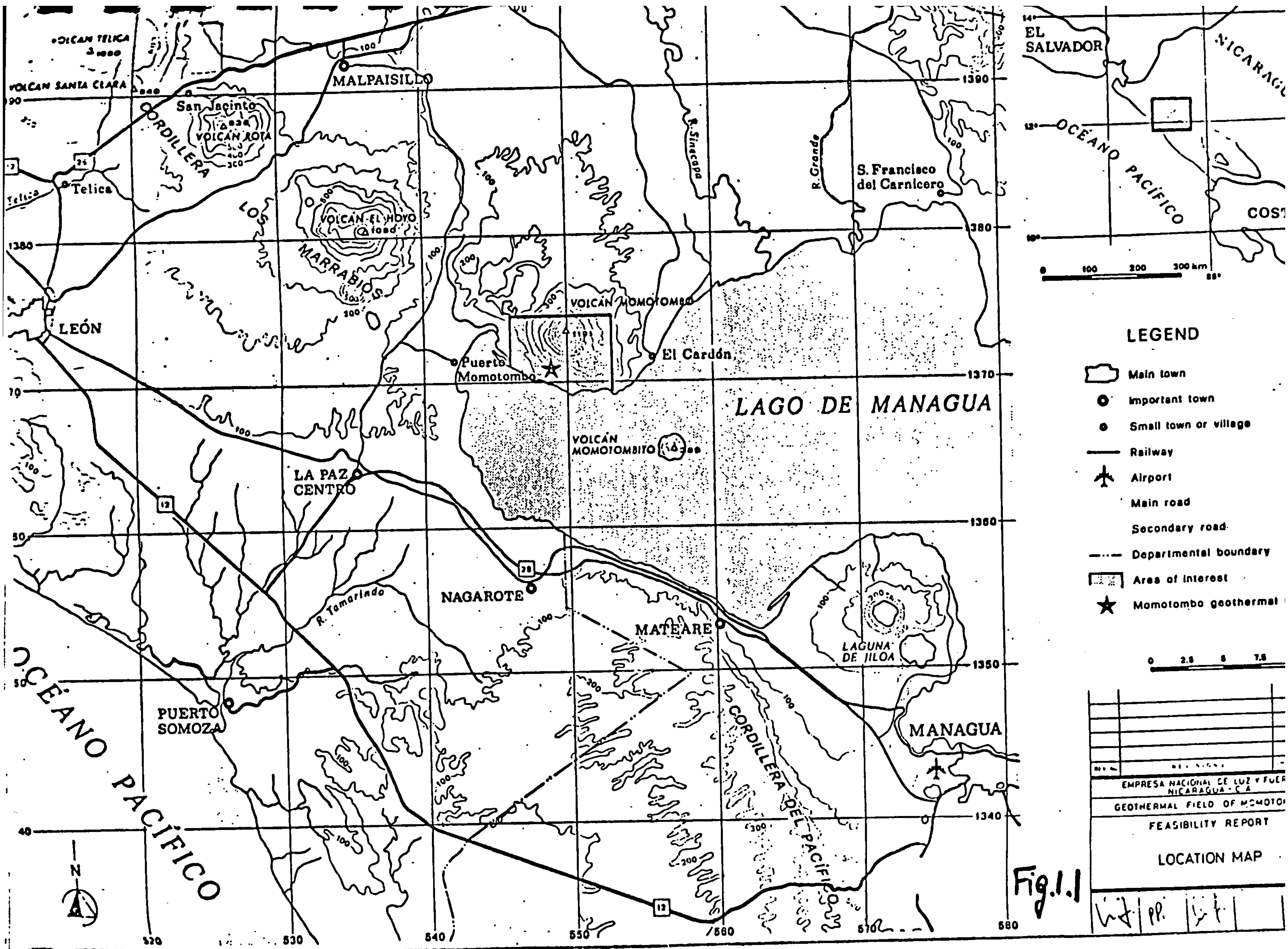
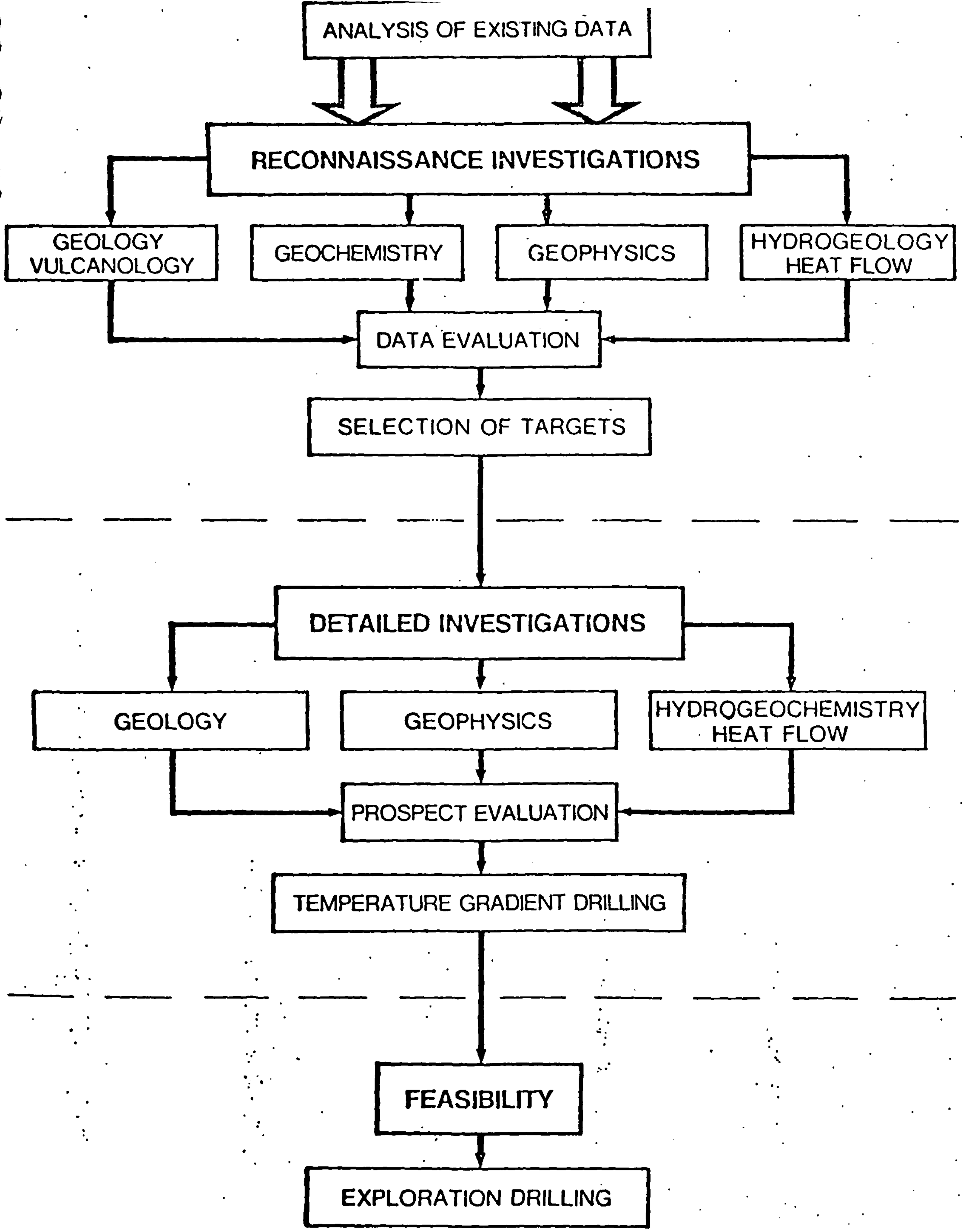

VOLCAN TELICA
VOLCAN SANTA CLARA
MALPAISILLO
San Jacinto
VOLCAN ROTA
CORDILLERA
LOS MARRABIOS
VOLCAN EL HOYO
Telica
LEÓN
R. Sinecapa
R. Grande
S. Francisco del Carnicero
VOLCAN MOMOTOMBO
Puerto Momotombo
El Cardón
LAGO DE MANAGUA
VOLCAN MOMOTOMBITO
LA PAZ CENTRO
NAGAROTE
R. Tamarindo
MATEARE
LAGUNA DE JILOA
PUERTO SOMOZA
MANAGUA
OCÉANO PACIFICO
CORDILLERA DEL PACIFICO
N
EL SALVADOR
NICARAGUA
OCÉANO PACIFICO
COST
0 100 200 300 km
LEGEND
Main town
Important town
Small town or village
Railway
Airport
Main road
Secondary road
Departmental boundary
Area of interest
Momotombo geothermal
EMPRESA NACIONAL DE LUZ Y FUER
NICARAGUA - C.A.
GEOTHERMAL FIELD OF MOMOTO
FEASIBILITY REPORT
LOCATION MAP

Fig.1.1

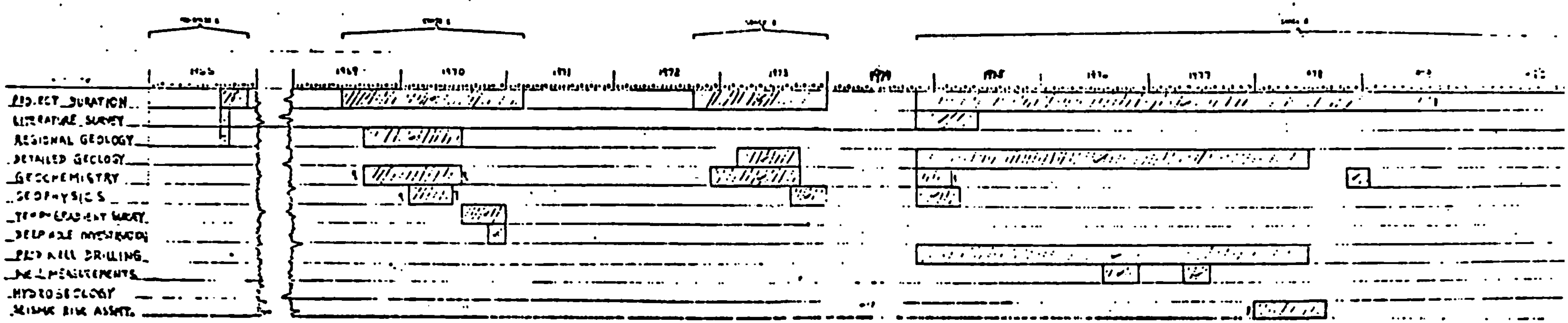


SCHEMATIC DIAGRAM
GEOTHERMAL EXPLORATION PROGRAM

Fig. 1.2

FIG. 1.[redacted]3

EXPLORATION WORK RECORD



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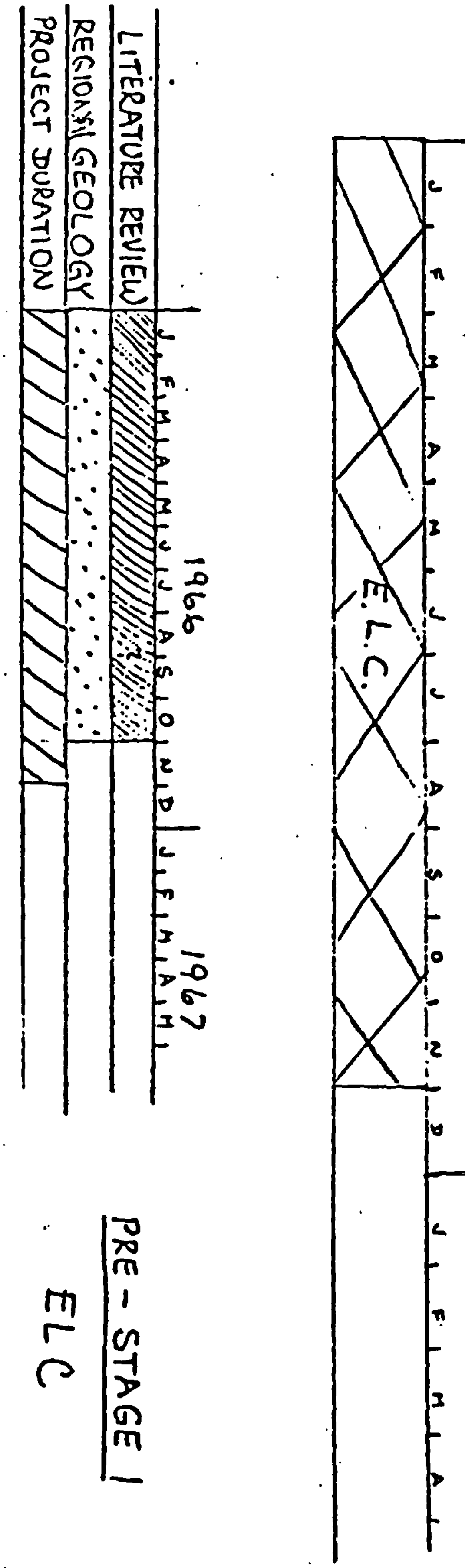

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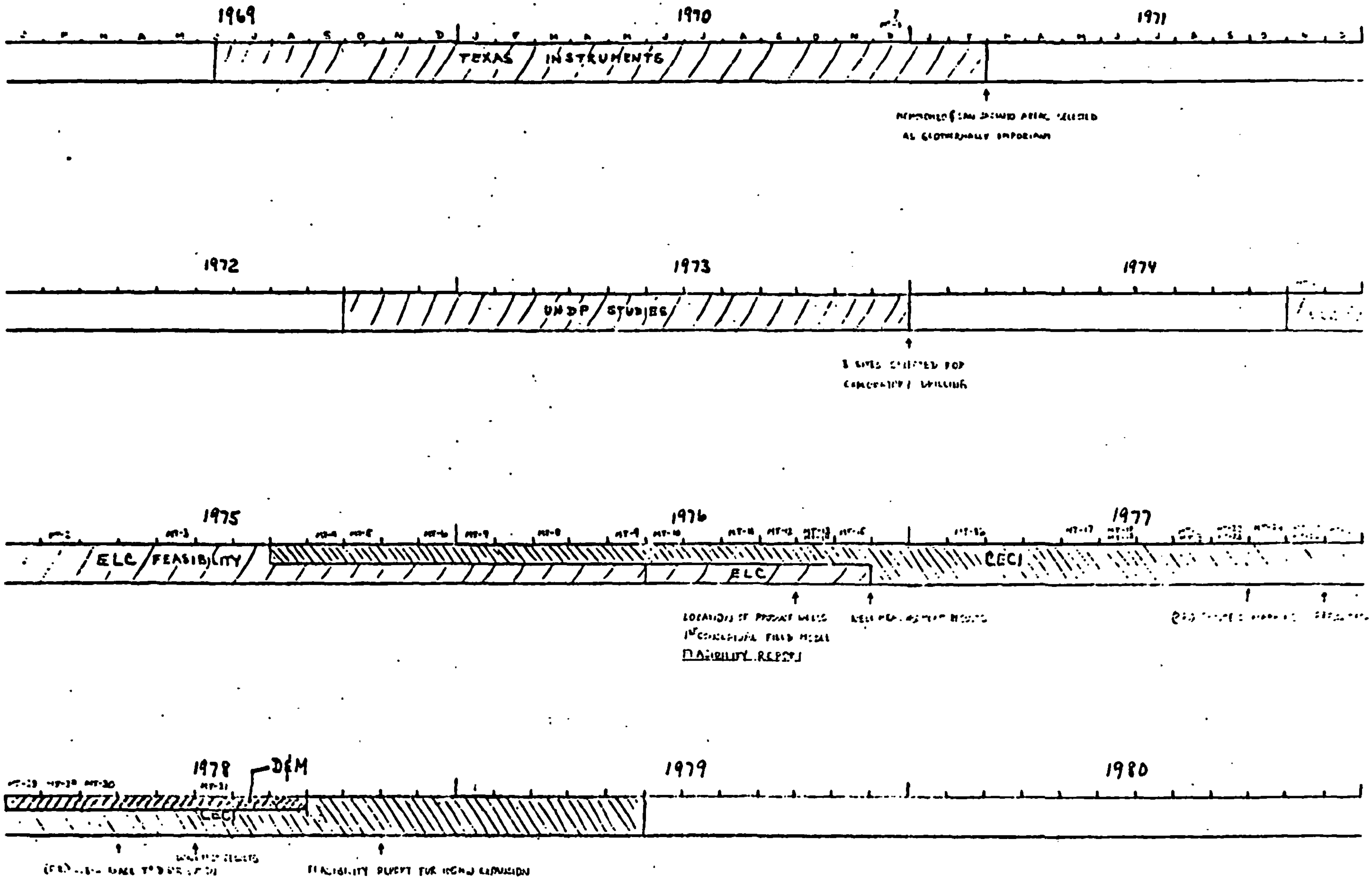
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INTERNATIONAL ENGINEERING COMPANY, INC.

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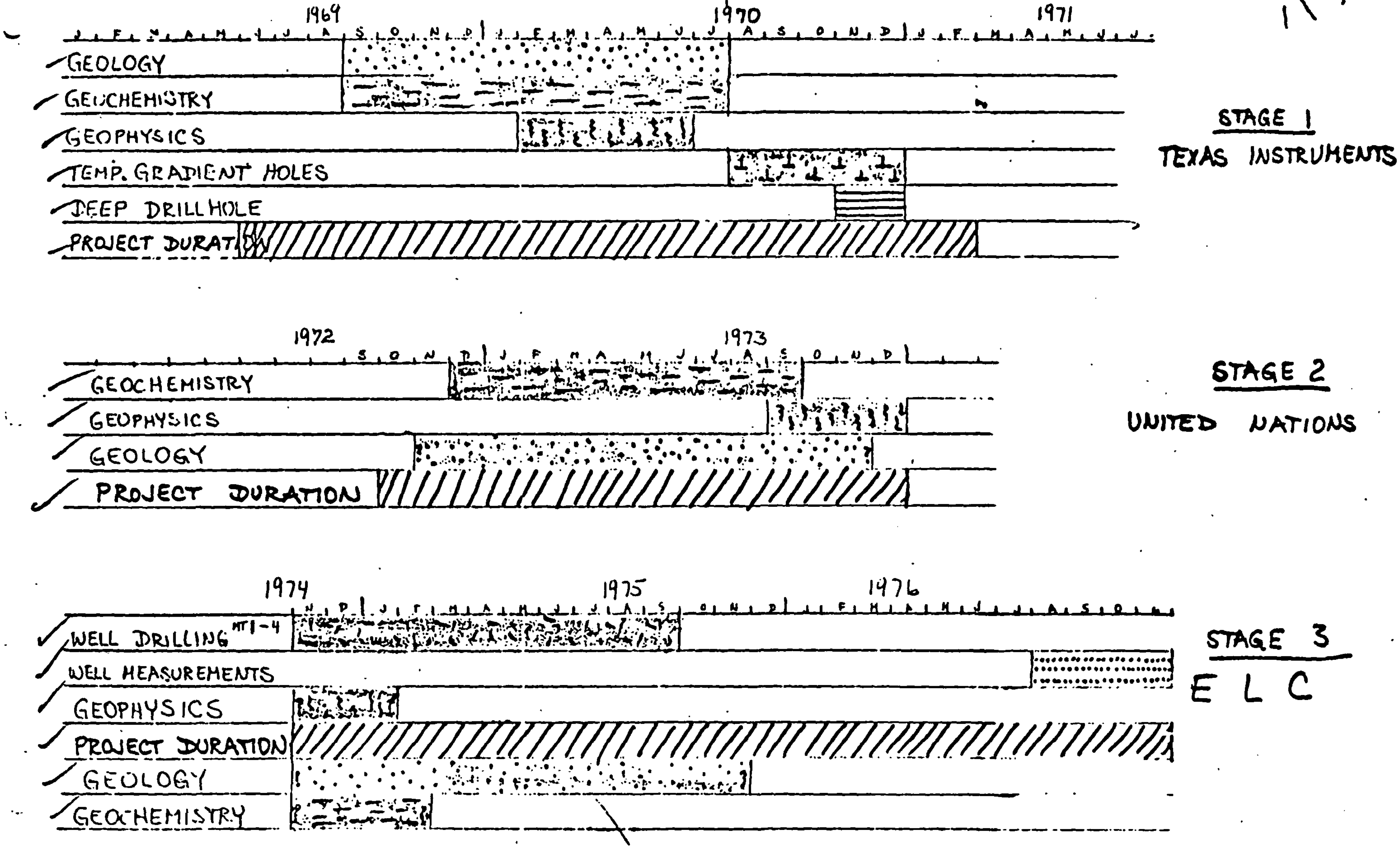

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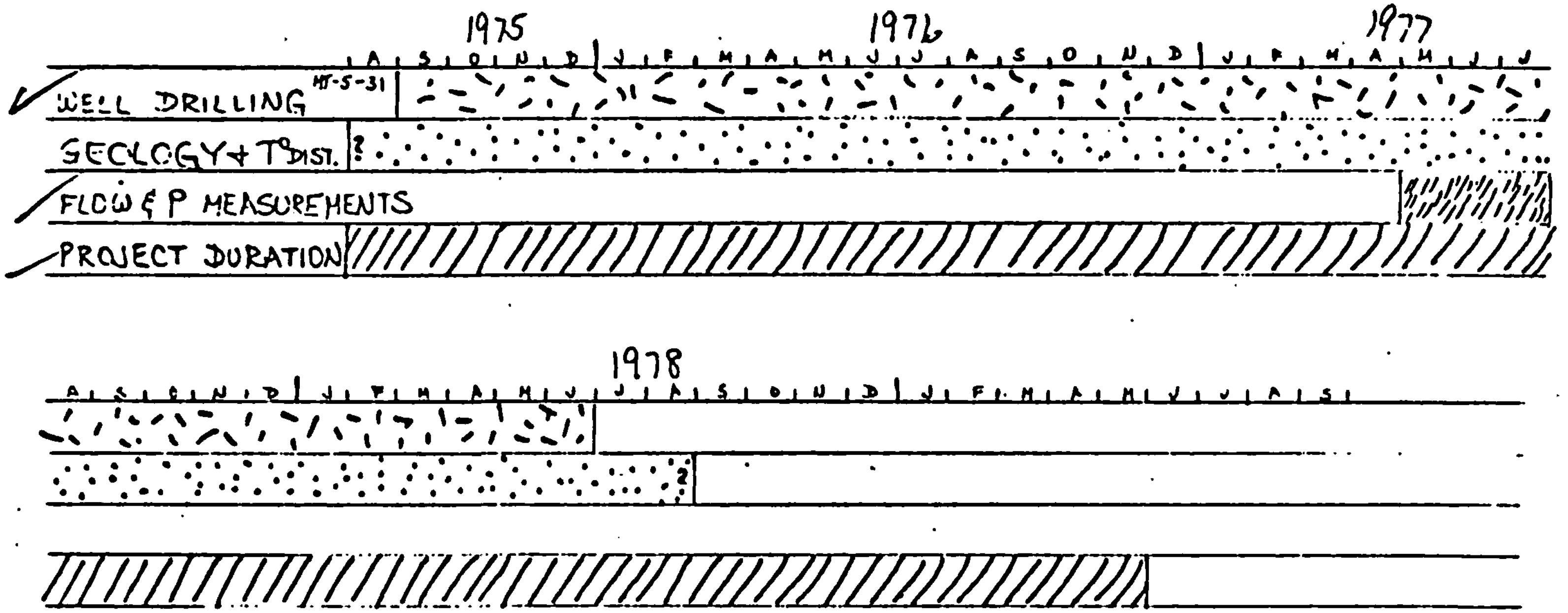

STAGE 3
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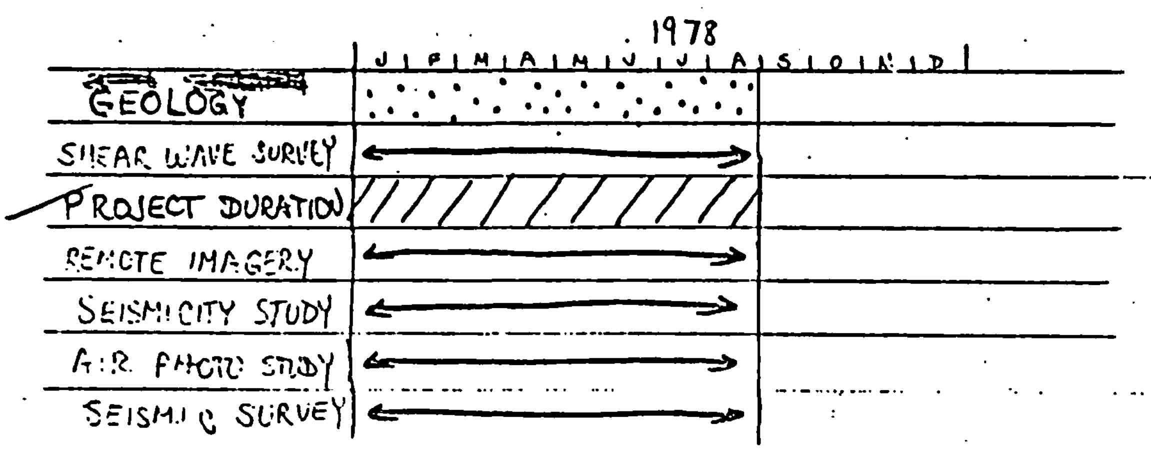


Dames & Moore
(seismic risk assessment)

2.1 GEOGRAPHICAL LOCATION

The region of Western Nicaragua is dominated by the Nicaraguan Depression, a northwest-trending graben formed by periods of extension and compression (Figure 2.1) and paralleling the Pacific coastline. The northeast margin of this graben is outlined by the parallel northwest-trending step faults in the Tertiary volcanic rocks at the edge of the depression. The faulted southwest margin is largely covered by Quarternary volcanics. The depression extends to the northwest 550 km from the Caribbean coast of Costa Rica, crossing Western Nicaragua (Figure 2.1), passing through Southern Honduras, and barely entering El Salvador. The width ranges from 25 km near Malpaisillo to 70 km at Lake Nicaragua. Almost half the length of this depression in Nicaragua is filled by Lake Managua and Lake Nicaragua.

Momotombo volcano lies within the Marrabios Range, a series of young volcanoes aligned near the western boundary of the Nicaraguan Depression. The range forms a northwest trending chain flanked by plains to the northeast and southwest; structurally these plains are valleys filled with alluvium and pyroclastics. The major physiographic provinces of Western Nicaragua are shown in Figure 2.1. Figure 2.2 presents a general geologic map of Nicaragua.

2.2 VULCANISM AND TECTONIC SETTING

The volcanic chain in Nicaragua is part of the Circumpacific Earthquake Belt which passes through Western Nicaragua. The relationship of this chain to the Nicaraguan Depression is shown in Figure 2.1. In Lake Nicaragua to the southeast the volcanic chain appears as isolated volcanic islands within the depression. This volcanic chain in Nicaragua may have begun its volcanic activity as a series of volcanoes forming an offshore island arc in the interoceanic zone, now expressed as the Nicaraguan Depression. Island arcs are usually associated with continental plate movement.

About 50 km offshore in the Pacific, the oceanic Cocos Plate is being subducted toward the northeast, sliding under the southwest-moving continental Caribbean Plate and developing part of the Middle America Trench at their offshore junction. The Nicaraguan coast roughly parallels the zone of subduction where the two plates meet. The underthrusted Cocos Plate partially melts due to the intense heat generated by friction, pressure, and the normal geothermal gradient. The molten rock then rises through fractures to the surface and forms the chain of volcanoes parallel to the offshore trench, here known as the Quaternary Volcanic Chain.

The volcanic chain in Nicaragua is active. In the Marrabios Range, volcanoes Santiago, Momotombo, El Hoyo, San Cristobal, and Telica are constantly emitting plumes of smoke from their craters. At least five volcanoes have had minor eruptions in the last 15 years. The chain is broken into three structural blocks, of which the Marrabios Range Block and the Managua Structural Block have most of the geothermal potential. The limits of these blocks are based upon distinctive volcanic features, by changes in the Pacific shoreline, and by changes in direction of the volcanic axes (Figures 2.3 and 2.4).

2.3 REGIONAL SEISMICITY

Figure 2.5 shows the seismic events greater than four (Richter scale) between 1898 and 1979. The concentration of seismic epicenters along the Pacific coastline illustrates the activity of plate tectonics in this region. The high levels of seismicity, representing two different source mechanisms, are directly or indirectly associated with the underthrusting process; an inclined zone of shallow to intermediate activity along the downwarping crustal boundary, the Benioff Zone, and a zone of very shallow activity associated with the volcanic chain known as the shallow-focus volcanic terrain zone (Dames and Moore, 1978). This relationship between plates, volcanoes, and seismic zones is illustrated in Figures 2.6 and 2.7.

2.4 THERMAL MANIFESTATIONS

A regional evaluation of thermal manifestations in Western Nicaragua by IECO revealed numerous fumaroles, hydrothermally altered areas, thermal springs and warm water wells. There is a notable concentration of thermal manifestations along the Nicaraguan Depression and specially near the volcanic chain.

2.5 GENERAL GEOLOGY

2.5.1 Physiography

Western Nicaragua can be divided into four principal physiographic provinces as shown in Figure 2.1 (Catastro, 1969).

The Pacific Coastal Plain is covered by alluvium and volcanic sediments with scattered hills of Tertiary ignimbrite in the north. The southern portion is underlain by Cretaceous and Tertiary sedimentary rocks, partially dissected into hills and valleys.

The Volcanic Range composed of Quaternary volcanoes was described in section 2.2.

The Nicararaguan Depression east of and parallel to the Volcanic Range was described in section 2.1.

The Interior Highlands cover most of Central Nicaragua. Tertiary volcanic rocks underlie the area along with a few small igneous intrusions and small areas of Quaternary volcanics. Plateaus, mesas and cuestas are the dominant land forms.

2.5.2 Stratigraphy

The age relationships and age distribution of the principal rock units of Nicaragua and adjacent regions are shown in Figure 2.8 (Mc Birney and Williams, 1965). Tertiary to Recent volcanic rocks predominate in the areas of geothermal interest, as shown by the map in Figure 2.2. Exceptions are the Upper Cretaceous and Tertiary sedimentary rocks on the Isthmus of Rivas and probably Paleozoic metamorphic rocks, Cretaceous granitic intrusions, and Miocene sediments in the northern extremity.

The following information is summarized from McBirney and Williams (1965).

Tertiary volcanic rocks cover most of Central Nicaragua. These rocks are mostly andesitic and dacitic lavas with some basaltic lavas, and lahar and ignimbrite deposits, named the Matagalpa Series (McBirney and Williams, 1965). These rocks are generally overlain by andesitic and dacitic ignimbrites and minor mafic lavas and volcanic sediments, with this upper series forming extensive plateaus. Differentiation of the two series is not feasible over the entire area.

Tertiary volcanic rocks are also exposed along the northwest coast of Nicaragua, where they are known as the Tamarindo Formation. Silicic ignimbrites predominate but silicic tuffs, lahars, mafic lavas, and shales are common to the south, where the Tamarindo Formation interfingers with the marine El Fraile Formation.

Quaternary volcanic rocks, including important Recent volcanic outporings are associated with the volcanic range. Pyroxene andesite, andesitic basalt, and basaltic lavas are interbedded with scoraceous tuff and other pyroclastic deposits. Pumice, usually dacitic, is associated with some of the volcanoes, particularly the calderas. In many instances the youngest lavas are olivine basalts.

Quaternary volcanic rocks are also present to a limited extent in and east of the Nicaraguan Depression. The Quarternary volcanic centers of Cerro El Ciguatepe, Cerro San Jacinto, and the Las Lajas Caldera along the eastern boundary of the depression are in general 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, 1979).

Marine sedimentary rocks of Late Cretaceous and Tertiary age with more than 10,000 meters total thickness are exposed on the Isthmus of Rivas in association with a broad, northwest-plunging anticline. According to McBirney and Williams (1965) these rocks are mainly graywacke, sandstone, and shale but considerable volcanic material is included in some beds. Minor continental to marine sedimentary rocks of probable Miocene age are exposed near Ocotal.

2.6 GEOLOGIC HISTORY

The very complex and active tectonic setting of Western Nicaragua has produced a similarly complex and extensive geologic activity. A summary of the geologic history is presented from Dames and Moore, (1978).

2.6.1 Pre-Tertiary

Due to lack of exposures older than Tertiary, very little is known about the Pre-Tertiary in this portion of Nicaragua. The nearest Cretaceous rocks of the Rivas Formation are found some hundreds of kms 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.

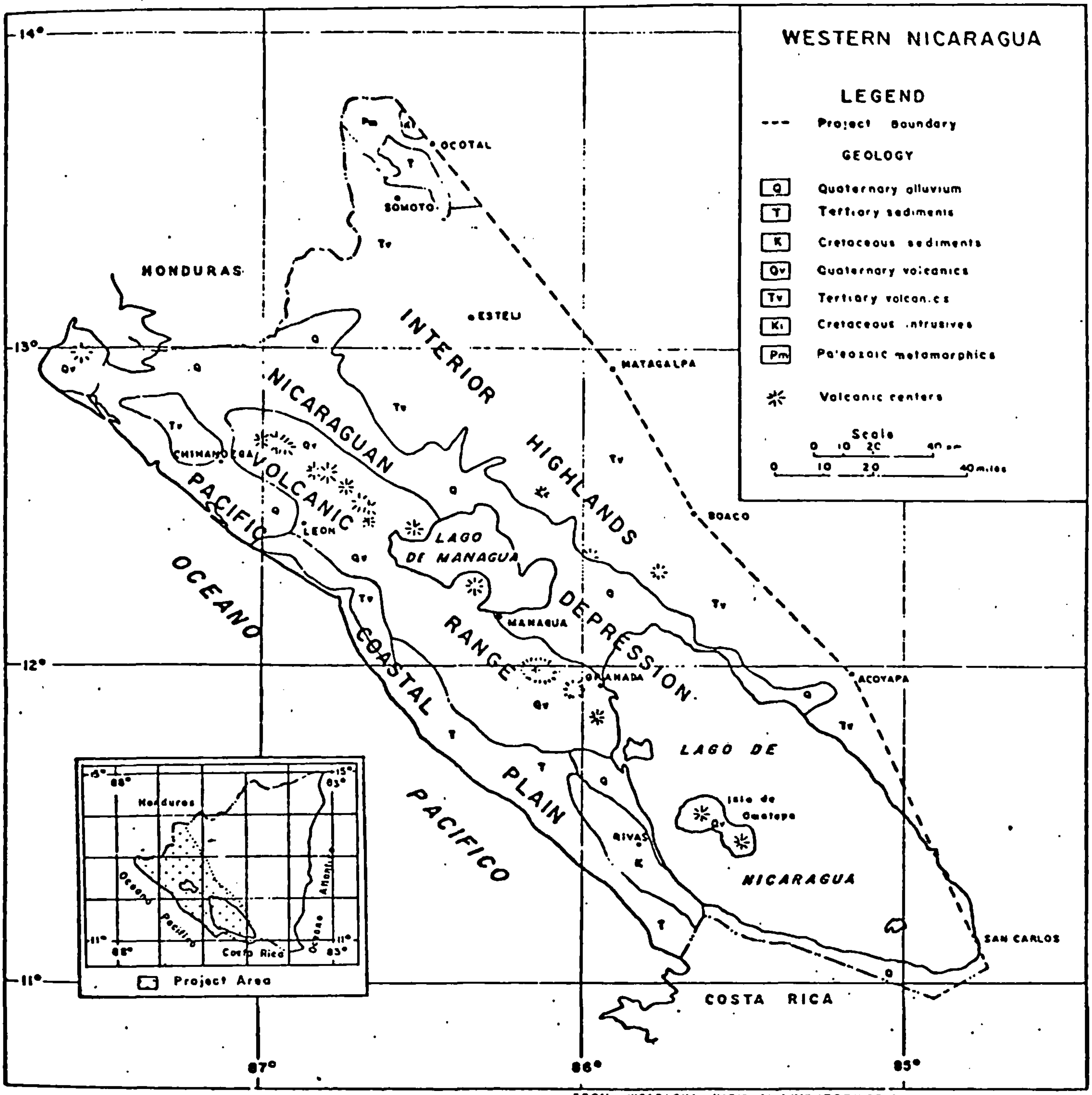
An ancient volcanic arc is postulated by many to have been the source for the regionally extensive Cretaceous volcanic and sedimentary rocks of the Rivas Formation. Allowing for a more continental facies based upon scarce evidence of open water facies to the east of the Rivas Formation and Nicoya complex the Rivas Formation may be postulated to extend underneath the study area. The Paleozoic metamorphic complex is evidently limited in extent to the northern part of Nicaragua.

2.6.2 Tertiary

The great thickness, some 8000 meters, of sedimentary formations from Upper Cretaceous to the Miocene, indicates a strongly subsiding trough along the Pacific Coast (Parsons, 1972). The marine tuffaceous sediments of the Tertiary intertongue with continental volcanic units, modified by various marine fluctuations. Unconformities between various sedimentary members, and renewed volcanism is evident throughout the record, the latest peak of volcanic activity being at the end of the Tertiary.

2.6.3 Quaternary

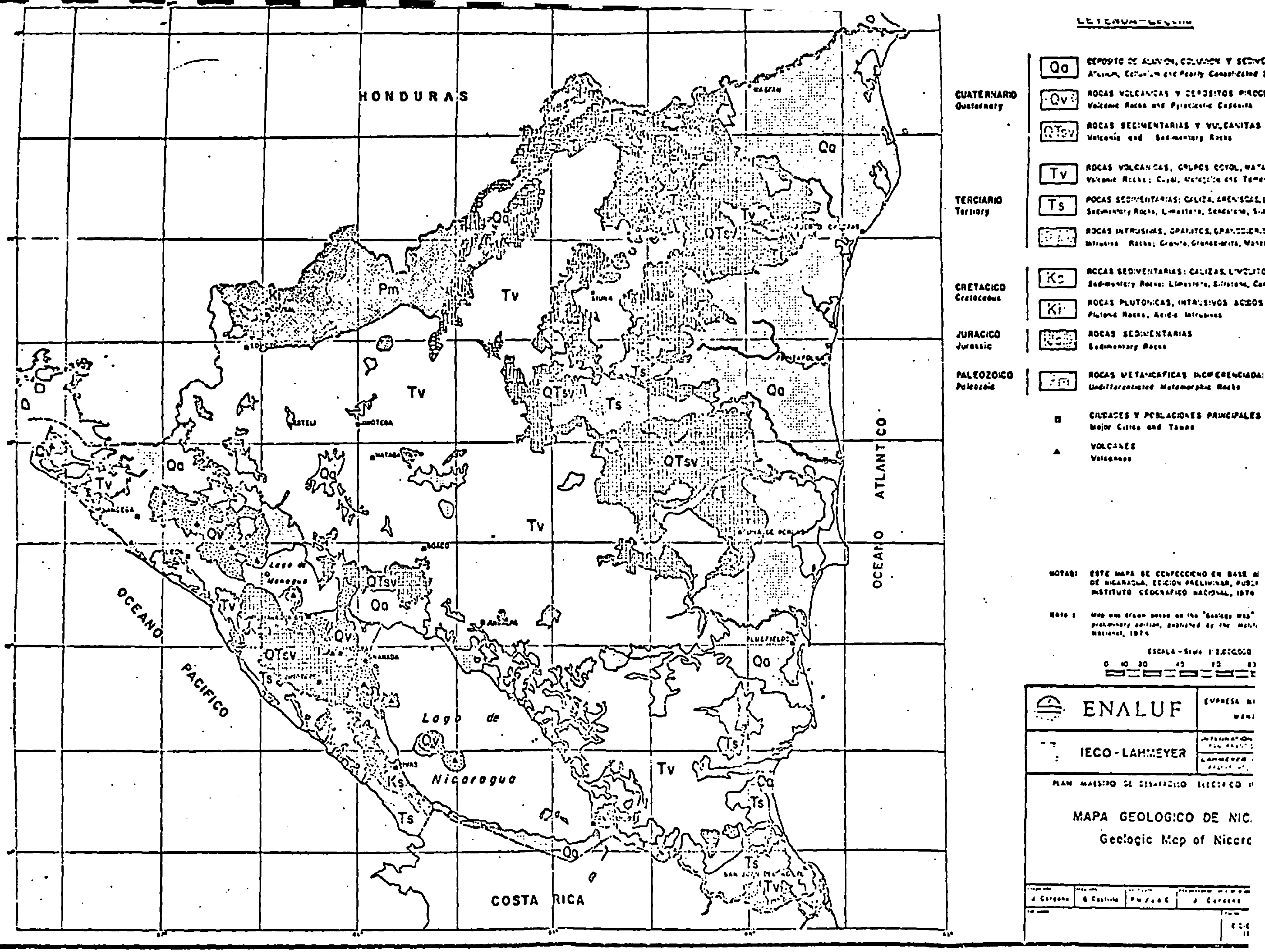
The predominant geologic processes in the Quaternary have been volcanic eruptions, filling of the Nicaraguan Depression by pyroclastic debris, and isostatic changes along the graben structure in response to tectonic subduction. In the smaller Managua basin, the Quaternary burden is believed to be 1.4 kms thick; however, generally the average depth of the Nicaraguan Graben may not exceed a few hundreds of meters in other places (Kuang, 1967, Soto, 1966, Zoppis B, 1966, Bice, 1977).



FROM NICARAGUA, NATIONAL INVENTORY OF PHYSICAL RESOURCES (1966)

~~FIGURE 1 Project Area Index~~

Figure 2.1



HONDURAS
COSTA RICA
OCEANO PACIFICO
OCEANO ATLANTICO
Lago de Managua
Lago de Nicaragua
Qa
Qv
QTsv
Tv
Ts
Ks
Ki
Pm
CUATERNARIO
Quaternary
ROCAS VOLCANICAS Y DEPOSITOS PIROCL
Volcanic Rocks and Pyroclastic Deposits
ROCAS SEDIMENTARIAS Y VULCANITAS
Volcanic and Sedimentary Rocks
TERCIARIO
Tertiary
CRETACICO
Cretaceous
ROCAS PLUTONICAS, INTRUSIVOS ACIDOS
Plutonic Rocks, Acidic Intrusives
JURACICO
Jurassic
ROCAS SEDIMENTARIAS
Sedimentary Rocks
PALEOZOICO
Paleozoic
Undifferentiated Metamorphic Rocks
CIUDADES Y POBLACIONES PRINCIPALES
Major Cities and Towns
VOLCANES
Volcanoes
ENALUF
IECO-LAHMEYER
MAPA GEOLOGICO DE NIC.
Geologic Map of Nicara

Figure 2.2

Preparado	Dibujado	Verificado	Recomendado - Jefe de grupo	Aprobado	Archivo Nº	Fecha
I. Jamieson	E. Pernudi M.	L.H. Goldsmith	L.H. Goldsmith	R.F. Kilmartin	3281 - 4	Abril, 1979

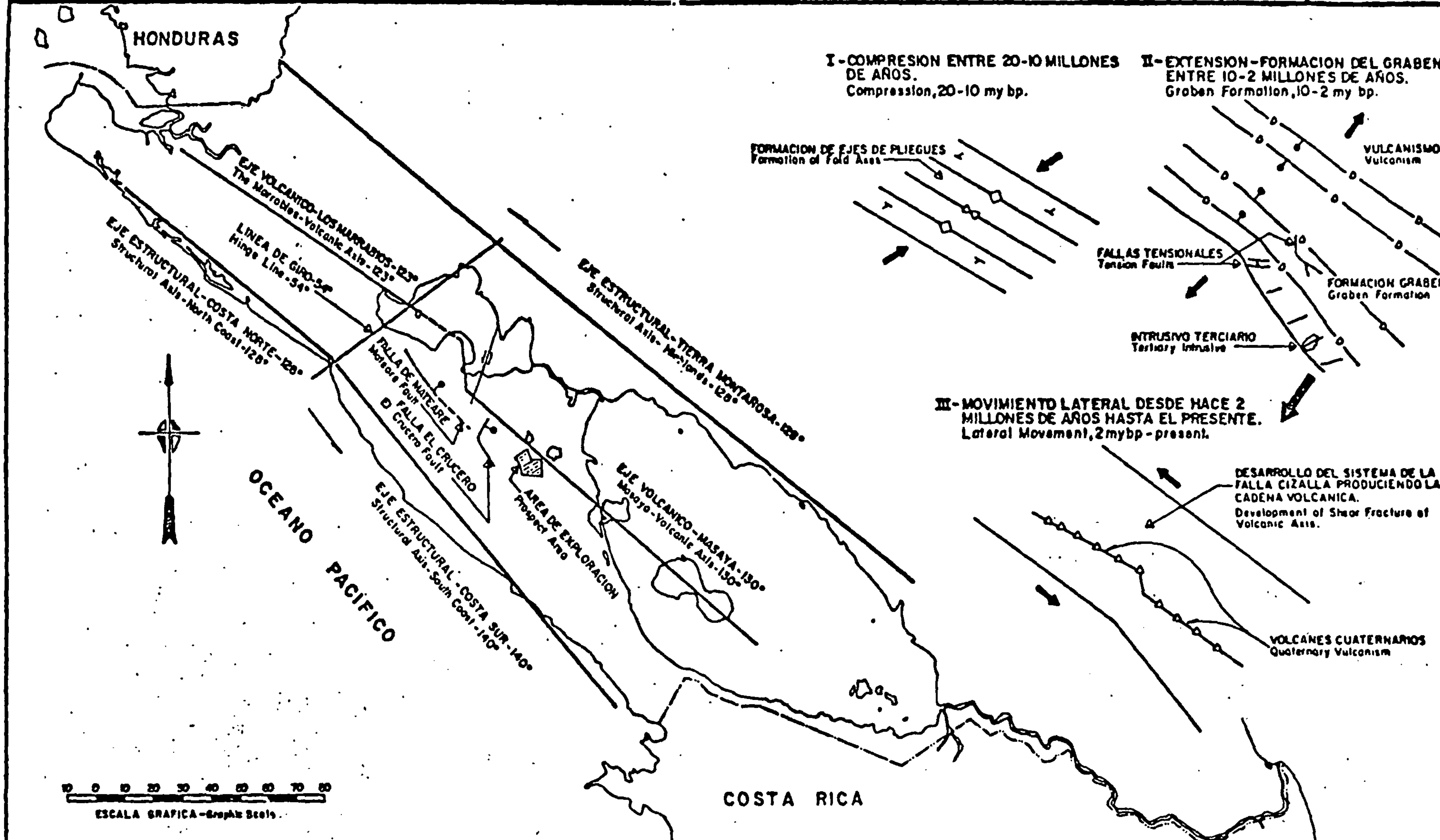
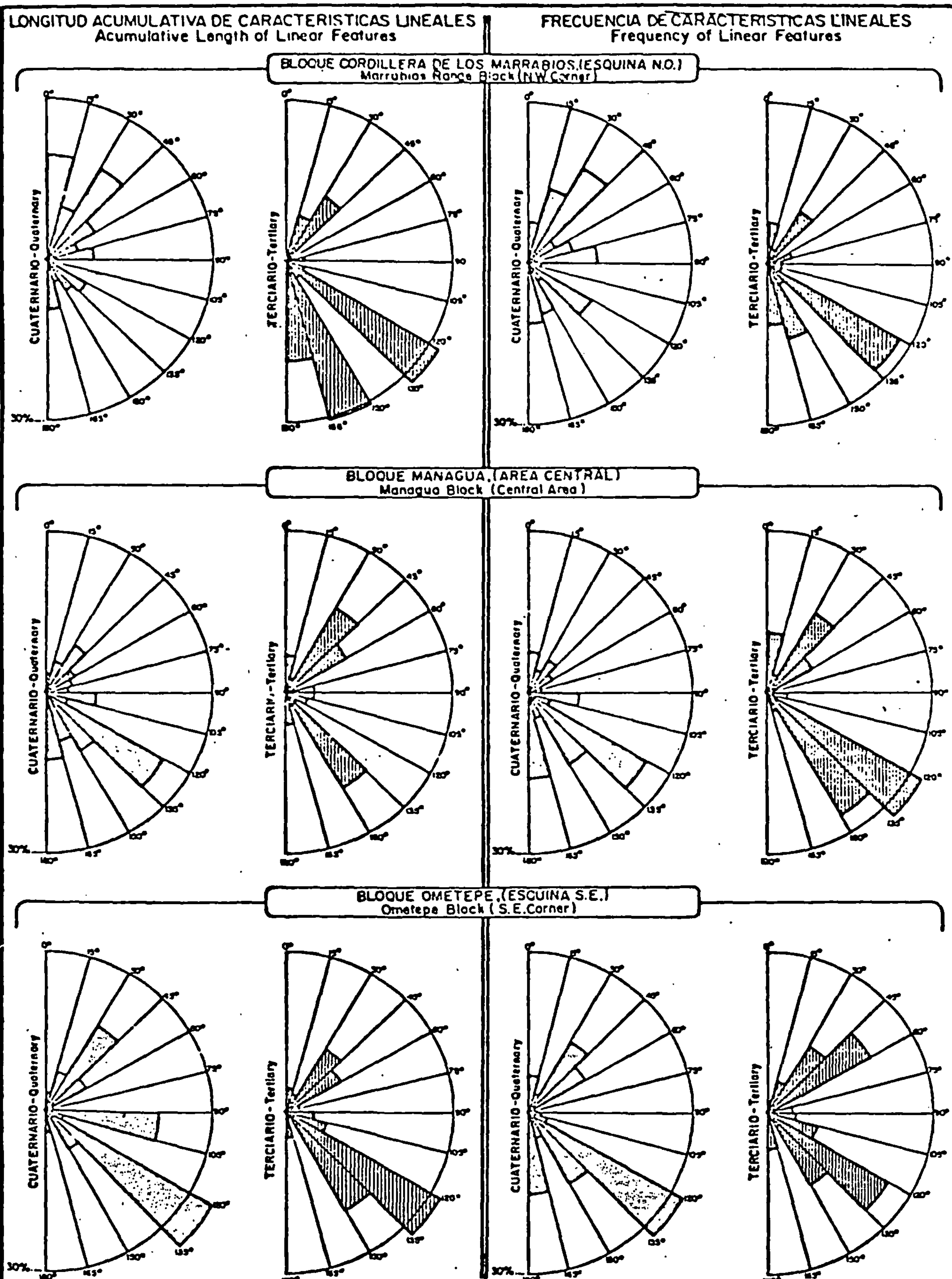


Fig. Nº		
4-1	EMPRESA NACIONAL DE LUZ Y FUERZA	PLAN MAESTRO DE DESARROLLO ELECTRICO 1977-2000 NICARAGUA
	Consorcio IECO - LAHMEYER	HISTORIA TECTONICA DEL OESTE DE NICARAGUA Tectonic History of Western Nicaragua
	Managua, Nicaragua	

Figure 2.3

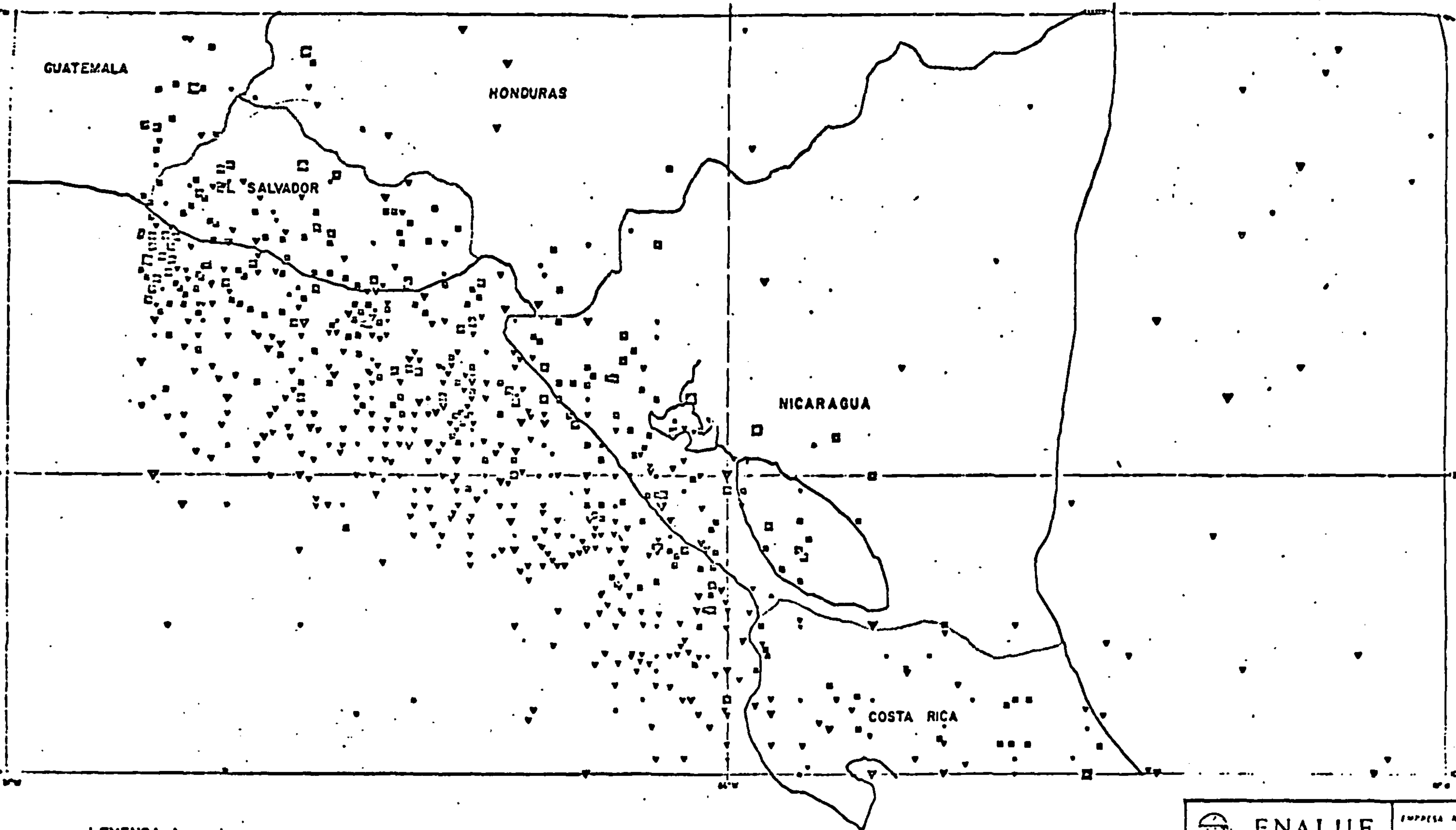


Fecha	Abril, 1979
Archivo Nº	3281-5
Aprobado	R.F. Kilmartin
Recomendado - Jefe de grupo	L.H. Goldsmith
Verificado	L.H. Goldsmith
Dibujado	E. Pernudi M.
Preparado	T. Jamieson

EMPRESA NACIONAL DE LUZ Y FUERZA	PLAN MAESTRO DE DESARROLLO ELECTRICO 1977 - 2000 NICARAGUA	Fig. Nº
Consorcio IECO - LAHMEYER	DIAGRAMA DE DIRECCIONES EN LA ESTRUCTURA GEOLOGICA EN EL OESTE DE NICARAGUA	4 - 2
Managua, Nicaragua	Rose Diagrams of Geologic Structure in Western Nicaragua	

Figure 2.4

Figure 2.5



LEYENDA - Legend

MAGNITUDES - Magnitudes			PROFUNDIDAD - Depth (Km)	
4	•	▪	0 – 70	▼
5	▼	■	70 – 300	◘
6	▼	◘		
7+	▽	□		

NO EXISTEN EPICENTROS A MAS DE 300 Km. DE PROFUNDIDAD

No epicenters are interpreted deeper than 300 Km.

NOTAS: INFORMACION SISMICA ABARCA EVENTOS DESDE 1898 a 1978 CUYAS MAGNITUDES SON MAYORES DE 4

Notes: Sismic information covers events recorded between 1898 and 1978 whose magnitudes are greater than 4

LOS LIMITES GEOGRAFICOS ESTAN DIBUJADOS POR COMPUTER Y NO SON PRECISOS (EXCEPTO EL LAGO DE MANAGUA)

Geographic boundaries are drawn by computer and are not precise (except for Lake Managua).

LOS DATOS SE OBTUVIERON DEL SERVICIO SISMICO DE NOAA, BOULDER COLORADO Y DE LOS INFORMES DEL INSTITUTO SISMICO DE NICARAGUA

Data were obtained from NOAA, Earthquake Service, Boulder Colorado and Instituto Sismico de Nicaragua.

ENALUF	EMPRESA NACIONAL DE … MANAGUA, NICARA…
IECO - LAHMEYER	

PLAN MAESTRO DE DESARROLLO ELECTRICO 1977-2000 …

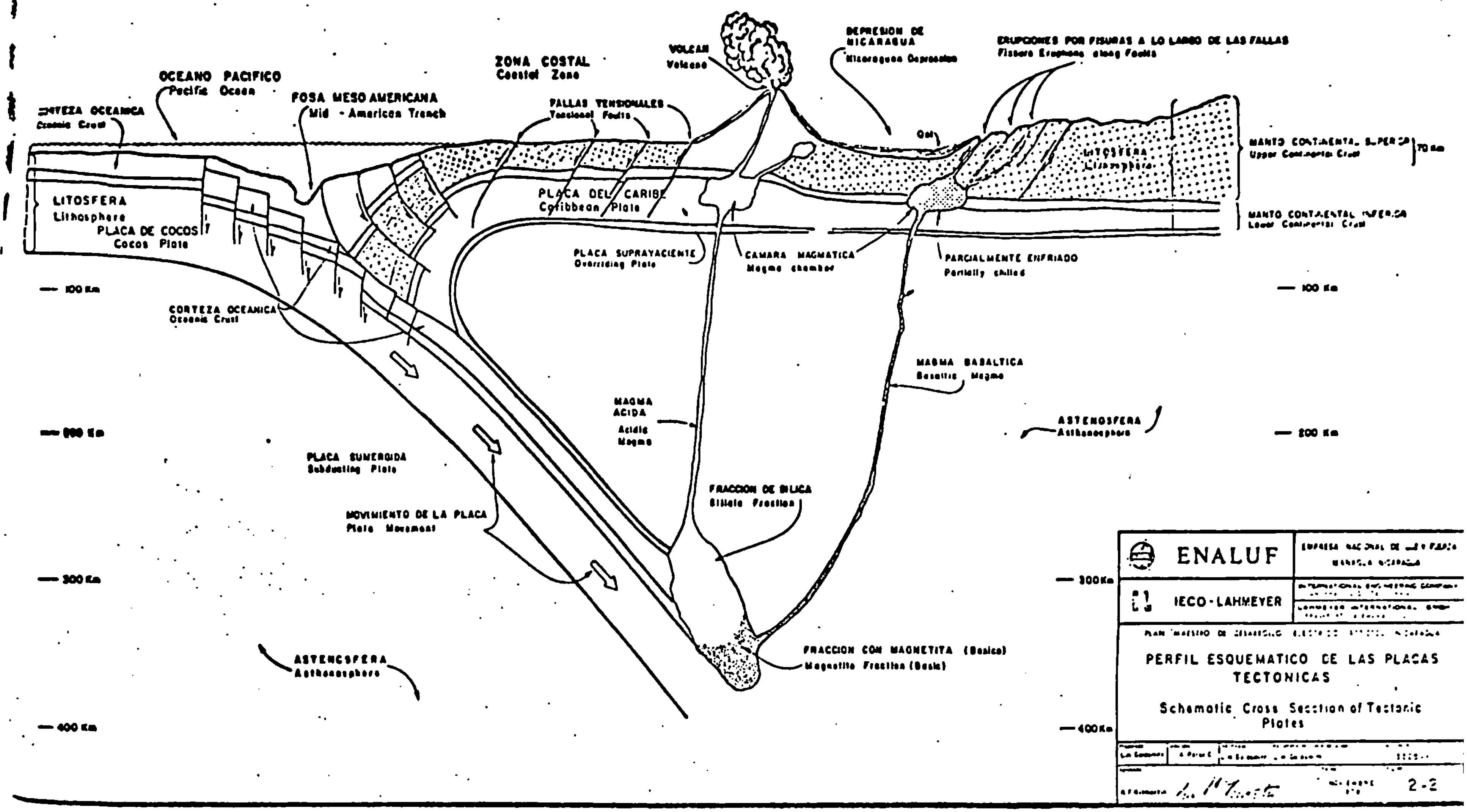
MAPA DE EPICENTROS SISMICOS DE NICARAGUA Y ALREDEDORES

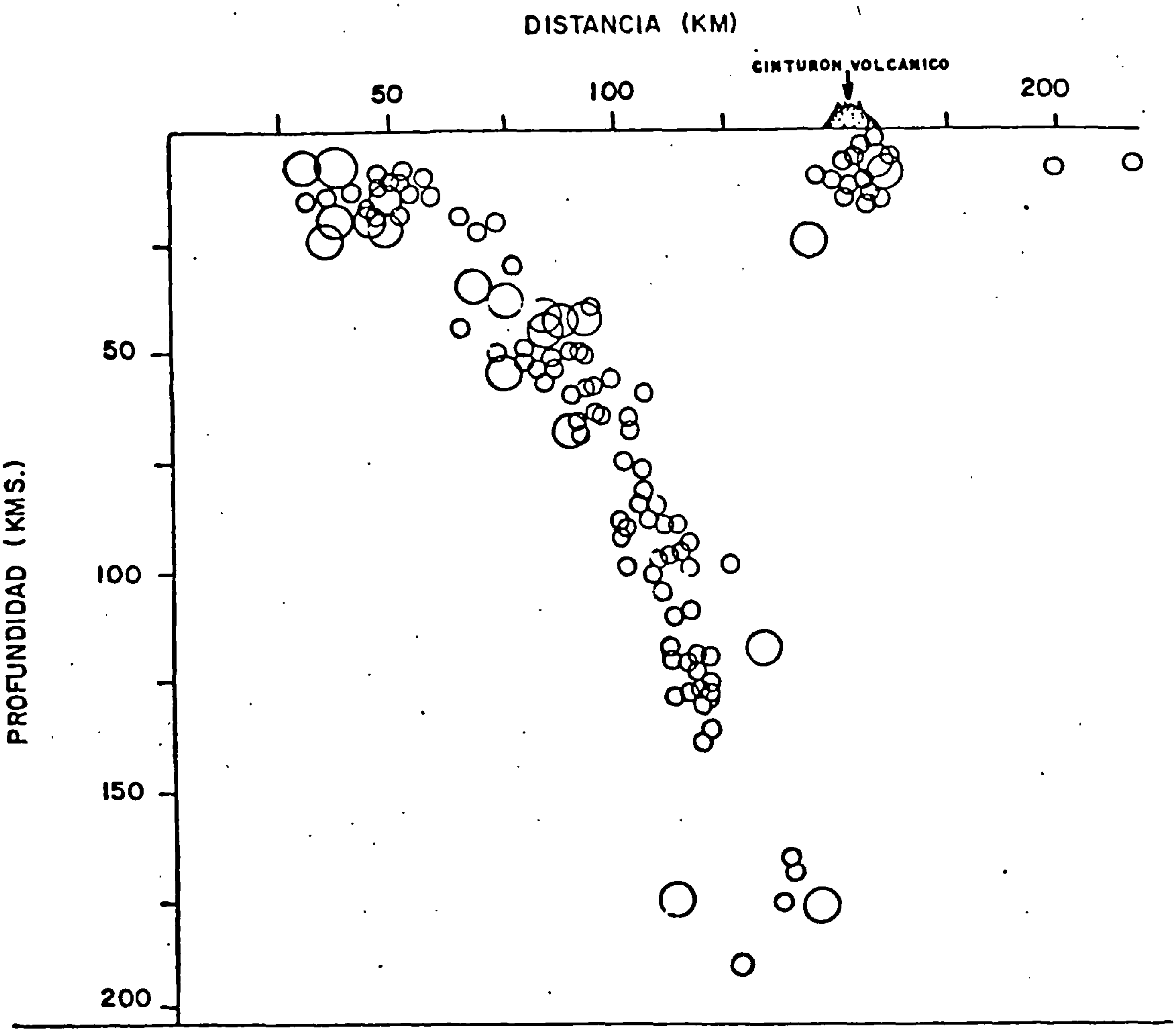
Map of Sismic Epicenters of Nicaraq… and Adjacent Areas

Dr E Zurflueh	J Castillo

DICIEMBRE 1978

Figure 2.6


OCEANO PACIFICO
Pacific Ocean
FOSA MESO AMERICANA
Mid - American Trench
ZONA COSTAL
Coastal Zone
VOLCAN
Volcano
DEPRESION DE NICARAGUA
Nicaraguan Depression
ERUPCIONES POR FISURAS A LO LARGO DE LAS FALLAS
Fissure Eruptions along Faults
FALLAS TENSIONALES
Tensional Faults
LITOSFERA
Lithosphere
PLACA DE COCOS
Cocos Plate
PLACA DEL CARIBE
Caribbean Plate
PLACA SUPRAYACIENTE
Overriding Plate
CAMARA MAGMATICA
Magma chamber
PARCIALMENTE ENFRIADO
Partially chilled
CORTEZA OCEANICA
Oceanic Crust
MAGMA BASALTICA
Basaltic Magma
MAGMA ACIDA
Acidic Magma
ASTENOSFERA
Asthenosphere
PLACA SUMERGIDA
Subducting Plate
MOVIMIENTO DE LA PLACA
Plate Movement
FRACCION DE SILICA
Silicic Fraction
FRACCION CON MAGNETITA (Basica)
Magnetite Fraction (Basic)
100 Km
200 Km
300 Km
400 Km
ENALUF
IECO-LAHMEYER
PERFIL ESQUEMATICO DE LAS PLACAS TECTONICAS
Schematic Cross Section of Tectonic Plates
2-2



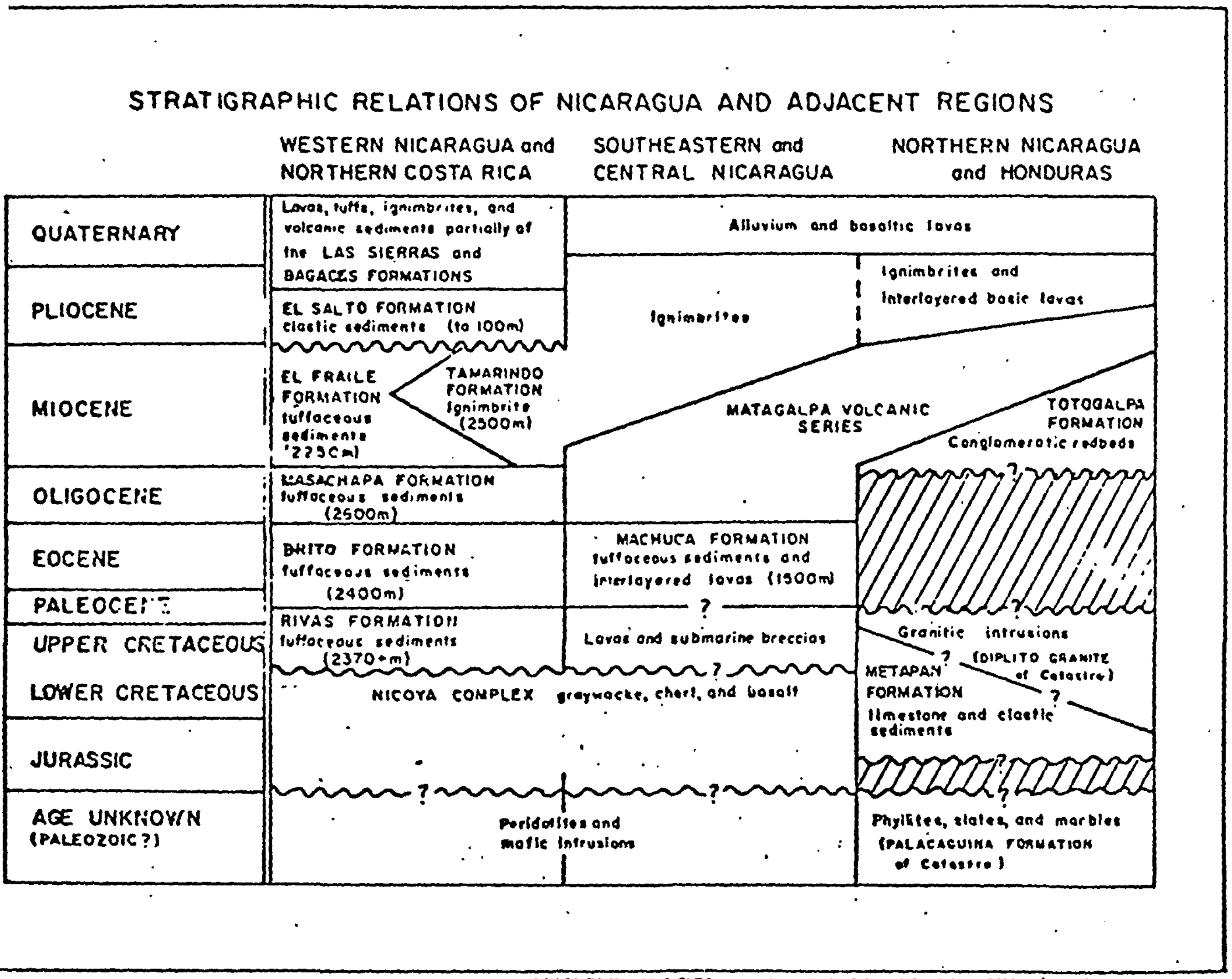
Corte vertical transversal del cambio de rumbo de la cadena volcánica de Nicaragua. Las profundidades hipocentricas se muestran en círculos. Error estandard de la profundida de foco es menor que 5 Kms. para los círculos más pequeños y menor que 10 Kms. para los círculos más grandes. La vista tiene un rumbo N 56 ° W.

Fig. 2.7

TOMADO DE: INSTITUTO DE INVESTIGACIONES SISMICAS, 1975

CORTE VERTICAL ESQUEMATICA CON TERREMOTOS

DAMES & MOORE



SLIGHTLY MODIFIED FROM MCBIRNEY AND WILLIAMS (1965)

[ ] EXPOSED IN PROJECT AREA

FIGURE 2.8

9081-101
Momotombo

CHEMICAL ANALYSES OF MOMOTOMBO WATER SAMPLES (ppm)

	K	Ca	Mg	Cl	SO_4	HCO_3	SiO_2	B	T°C	pH	Electrical Conductivity
	0.2	0.117	.007	10.97	2.2	28.51	8.56	0.8	nd	6.13	1.02 E-4
	0.42	0.130	.005	11.99	2.2	39.83	nd	0.7	nd	6.59	1.19 E-4
.0	11.0	2.3	0.004	62.84	0.6	31.63	nd	2.05	181	7.59	4.48 E-4
.435	0.15	0.055	0.006	4.27	nd	36.86	nd	0.76	180	7.51	7.89 E-5
.910	0.205	0.091	0.004	5.02	nd	37.1	1.07	.72	181	7.52	9.23 E-5
	2.0	0.45	.023	19.97	0.1	37.88	4.28	1.23	nd	7.3	1.46 E-4
	0.11	0.092	.01	9.32	nd	40.74	nd	1.0	nd	6.19	9.67 E-5
.485	0.11	0.07	0.0015	9.14	nd	22.94	nd	1.2	171	7.3	9.51 E-5
.9	0.575	0.125	0.006	7.61	nd	36.39	nd	1.3	172	7.57	9.72 E-5
.09	0.325	0.15	0.004	5.37	nd	39.64	nd	1.27	173	7.65	8.82 E-5
	275	72.5	0.022	3617	62.6	35.93	45.6	37.0		7.83	9.44 E-3
	250	72.5	0.014	3519	62.0	36.17	43.0	36.8		7.83	9.34 E-3
	240	57.5	0.066	3121	56.5	29.7	41.7	31.5		7.21	8.26 E-3
	0.155	0.057	.005	1.25	7.3	34.73	8.5	0.44	nd	7.0	8.55 E-5
	0.075	0.065	.008	4.76	nd	35.27	nd	.78	nd	6.01	9.64 E-5
57	0.25	0.10	0.006	6.03	nd	34.42	nd	0.91	174	7.59	9.65 E-5
225	0.05	0.05	0.017	3.95	nd	40.98	nd	1.36	174	7.67	8.32 E-5
265	0.07	0.075	0.003	8.00	nd	26.26	nd	1.06	196	7.43	9.35 E-5
	0.775	0.195	.007	9.06	nd	23.65	2.14	.74	nd	6.43	1.07 E-4
	0.235	0.125	.011	4.10	nd	28.02	nd	.86	nd	6.29	7.76 E-5
552	0.17	0.11	0.004	8.95	nd	15.5	nd	0.76	171	7.01	8.19 E-5
5	4.5	0.875	0.011	54.64	nd	19.28	nd	1.34	171	7.3	2.15 E-4
7	1.255	0.215	0.004	11.44	nd	24.46	1.07	1.00	171	7.36	1.03 E-4
40	1.0	6.5	0.056	249.23	4.1	37.0	3.42	3.22	162	7.56	7.88 E-4
1	10.8	3.3	0.014	142.02	17.5	22.28	2.14	1.97	160	7.3	4.94 E-4

2 Sept 89

90

CHEMICAL ANALYSES OF MOMOTOMBO WATER SAMPLES (ppm)

SAMPLE			Na	K	Ca	Mg	Cl	SO_4	HCO_3	SiO_2	B
P-9	(11-9)	4.9	1.1	0.2	0.117	.007	10.97	2.2	28.51	8.56	0.8
	(13-9)	18.10	1.6	0.42	0.130	.005	11.99	2.2	39.83	nd	0.7
P-MT-9,	14-9	23.10	60.0	11.0	2.3	0.004	62.84	0.6	31.63	nd	2.05
	15-9	30.10	0.435	0.15	0.055	0.006	4.27	nd	36.86	nd	0.76
	16-9	7.11	0.910	0.205	0.091	0.004	5.02	nd	37.1	1.07	.72
P-12	(12-12)	5.9	10.7	2.0	0.45	.023	19.97	0.1	37.88	4.28	1.23
P-MT-12	(13-12)	19.10	0.5	0.11	0.092	.01	9.32	nd	40.74	nd	1.0
P-MT-12	14-12	24.10	0.485	0.11	0.07	0.0015	9.14	nd	22.94	nd	1.2
	15-12	30.10	1.9	0.575	0.125	0.006	7.61	nd	36.39	nd	1.3
	16-12	17.11	1.09	0.325	0.15	0.004	5.37	nd	39.64	nd	1.27
P-19	14-19	24.10	2050	275	72.5	0.022	3617	62.6	35.93	45.6	37.0
	15-19	1.11	2050	250	72.5	0.014	3519	62.0	36.17	43.0	36.8
	16-19	8.11	1810	240	57.5	0.066	3121	56.5	29.7	41.7	31.5
P-20	(12-20)	4.9	0.4	0.155	0.057	.005	1.25	7.3	34.73	8.5	0.44
	(13-20)	18.10	0.4	0.075	0.065	.008	4.76	nd	35.27	nd	.78
P-MT-20	14-20	23.10	0.57	0.25	0.10	0.006	6.03	nd	34.42	nd	0.91
	15-20	30.10	0.225	0.05	0.05	0.017	3.95	nd	40.98	nd	1.36
	16-20	7.11	0.265	0.07	0.075	0.003	8.00	nd	26.26	nd	1.06
P-23	(13-23)	9.10	3.1	0.775	0.195	.007	9.06	nd	23.65	2.14	.74
	(14-23)	18.10	0.9	0.235	0.125	.011	4.10	nd	28.02	nd	.86
P-MT-23	15-23	24.10	0.652	0.17	0.11	0.004	8.95	nd	15.6	nd	0.76
	16-23	29.10	22.6	4.5	0.875	0.011	54.64	nd	19.28	nd	1.34
	17-23	6.11	9.7	1.255	0.215	0.004	11.44	nd	24.46	1.07	1.00
P-24	14-24	24.10	.40	1.0	6.5	0.056	249.23	4.1	37.0	3.42	3.22
	15-24	1.11	178.4	10.8	3.3	0.014	142.02	17.5	22.28	2.14	1.97

CHEMICAL ANALYSES OF MOMOTOMBO WATER SAMPLES (ppm)

SAMPLE			Na	k	Ca	Mg	Cl	SO_4	HCO_3	S_iO_2	B	T^oC	pH	Electrical Conductivity
P-24	(12-24)	4.9	2.1	0.52	0.175	.010	5.42	10.9	29.42	16.47	.62	nd	6.87	1.14 E-4
	16-24	8.11	70.6	8.5	2.5	0.014	103.95	12.9	17.89	1.93	1.7	181	7.29	3.89 E-4
	15-26	22.10	2300	400	75.0	0.056	4105	26.2	36.64	60.9	48.2	144	7.53	1.08 E-2
	16-26	29.10	2270	450	77.5	.066	4066	25.0	38.93	59.9	47.4	143	7.73	1.09 E-2
	17-26	6.11	2150	410	72.5	.053	3750	26.5	33.61	59.9	45.6	196	7.47	9.85 E-3
P-MT-27	15-27	22.10	2210	365	82.5	.037	3831	34.3	41.13	52.4	48.6	146	7.41	1.05 E-2
	16-27	29.10	2200	375	82.5	.048	3769	30.4	42.42	57.99	46.8	144	7.44	9.72 E-3
	17-27	6.11	5.5	1.31	0.23	.015	9.49	nd	30.14	1.28	0.8	183	7.40	1.12 E-4

CHAPTER 3

GEOLOGICAL EXPLORATION METHODS

3.1 INTRODUCTION

Since the major cost of geothermal exploration comes from drilling deep wells, the preliminary scientific surveys should be aimed at siting wells and obtaining the maximum information on the substructure of the system. Field geology is involved from the first stages of an investigation and its initial purpose is to make reconnaissance evaluations to locate and define some likely prospects. Later, detailed ground mapping usually with the aid of aerial photographs, and specialist assistance helps contribute, along with geophysics and fluid geochemistry, to the predrilling evaluation of a field. Once drilling starts the geologist can contribute to the investigations in several ways: he examines drill cores and cuttings so that the stratigraphy and structure of the field can be worked out. Many of the sub-branches of geology shown in Table 3.1 aid in this.

3.2 DETAILED FIELD MAPPING

Detailed field geologic mapping must be undertaken after areas of interest have been identified, based on structural and/or thermal manifestations. Basic to any geothermal mapping program is the identification of major structural elements that result from vulcanism, intrusions and major faulting responsible for present land surface configuration.

Maps prepared from aerial photointerpretation and satellite imagery must be checked in the field to verify the interpretation of geologic features. Field geology also permits more accurate determination of fault displacement, favorability of faults or fractures which act as fluid conduits, information on thickness of stratigraphic units, and of strike and dip. Graben structures, which frequently serve as hosts for primary geothermal reservoirs, will be identified, thus helping to localize the most favorable areas.

Briefly restated, the objectives of geological mapping would be to map with some precision the various structural stratigraphic elements of the prospect areas and to prepare geologic maps and cross sections. Hydrothermal alterations and associated mineral assemblages are indicative of thermal activity in the volcanic rocks and their suitability of hosting a thermal reservoir should be examined. Vulcanology frequently is an important phase of the geologic program to help determine the magmatic heat source. The study of volcanoes and knowledge of their state of development furnish information on the heat source, its potential extent, and activity. Caldera structures indicate magma withdrawal and collapse, curving faults, fissure fillings, graben structures and lineaments. All are associated with volcanic features and give information on favorable areas for reservoir formation.

The information obtained by the geology team serves as a guide for further exploration utilizing other techniques. Geologic cross sections prepared in conjunction with geologic maps furnish subsurface data of importance in understanding the geothermal reservoir.

3.3 HYDROGEOLOGIC STUDIES

Hydrogeologic studies have a threefold purpose. The first of these is to determine shallow subsurface aquifers and water tables, their possible source and the chemical quality of such waters. Such data may indicate leakage of thermal fluids from deeper reservoirs into the aquifers. The second is the study of heat flow over areas to indicate those specific areas of major importance in geothermal studies. The third purpose is to determine the availability of deeper subsurface waters for recharge of the geothermal reservoir. This latter study should be done after a geothermal reservoir has been confirmed.

A rapid reconnaissance of an area embracing several hundred square kilometers should be undertaken, consisting of measurements of water level and temperature in wells, in streams, and in hot or cold springs, together with collection of water samples. These measurements will establish the hydrologic gradient of the area and indicate probable direction of movement of subsurface water. Analyses of chemical constituents may indicate the mixing of subsurface waters with water escaping from a geothermal reservoir which data aid in the determination of the presence of a reservoir. Temperature measurements, when coupled with chemical analysis, may indicate the possible heating of such waters by convection or by mixing with thermal waters from a reservoir or other source.

Metereologic data such as temperature, humidity, precipitation, etc. should not be neglected, for these are important in planning future geophysical and drilling programs.

3.4 PETROLOGIC AND ISOTOPIC ANALYSES

A description of mineral zonation and water/rock interaction in the reservoir will supply information on the subsurface temperature, fluid flow within the reservoir, and reservoir characterization. Petrological studies will provide the following information.

- Lithologic descriptions of cores and cuttings in order to correlate samples from well to well and determine the structural relations of the aquifers.
- Hydrothermal alteration data necessary for proper characterization of the reservoir, its temperature, permeability, and porosity.
- Development of specific methods of geothermometry using a combination of mineral assemblages, isotopic ratios and fluid inclusion measurements.

Isotopic analyses of mineral and water samples will determine the origin of the fluids and the temperatures at which they equilibrated with the reservoir.

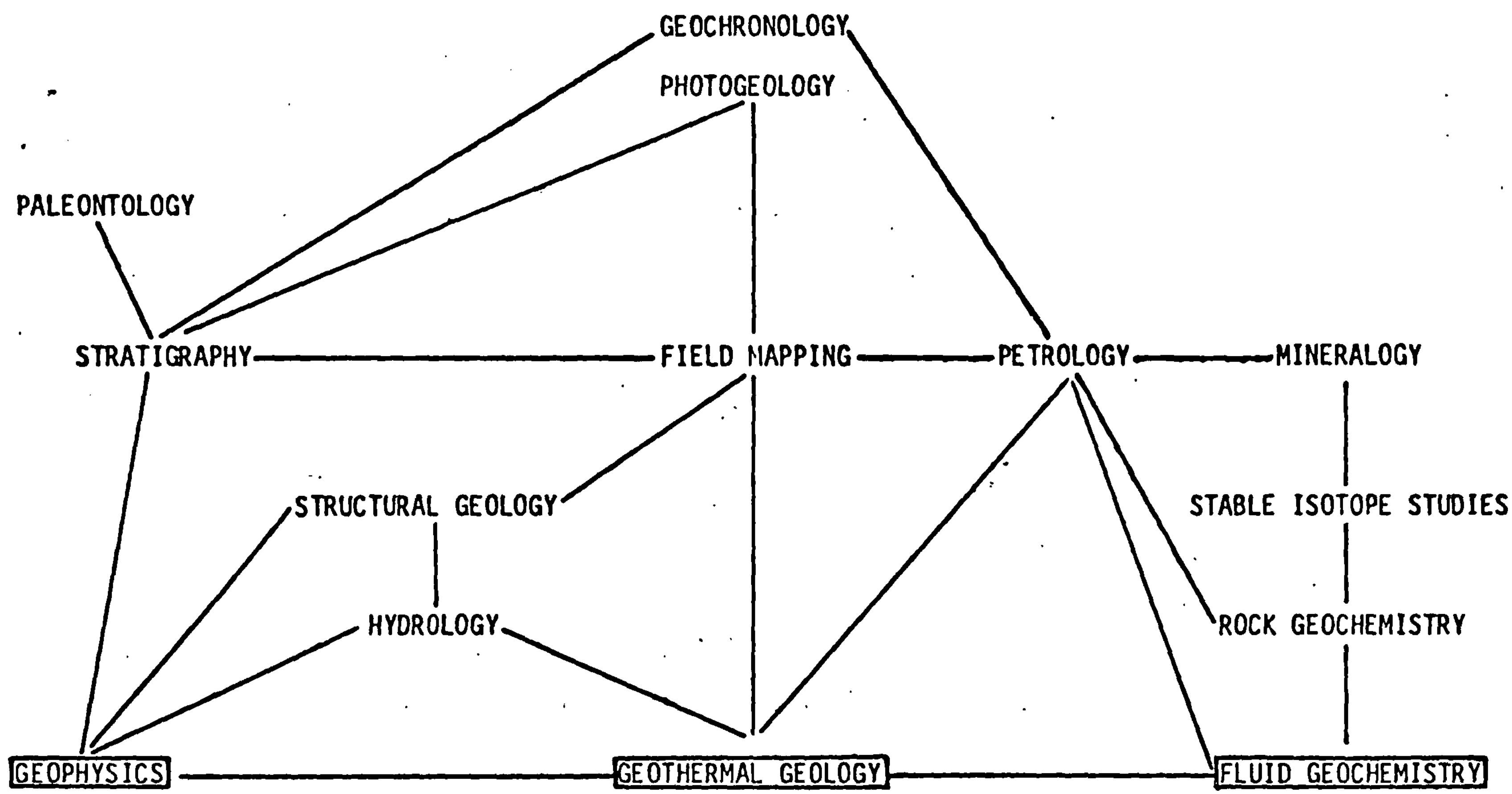

GEOCHRONOLOGY
PHOTOGEOLOGY
PALEONTOLOGY
STRATIGRAPHY
FIELD MAPPING
PETROLOGY
MINERALOGY
STRUCTURAL GEOLOGY
STABLE ISOTOPE STUDIES
HYDROLOGY
ROCK GEOCHEMISTRY
GEOPHYSICS
GEOTHERMAL GEOLOGY
FLUID GEOCHEMISTRY

TABLE 3.1

CHAPTER 4

ADEQUACY OF GEOLOGICAL METHODS

USED IN THE VARIOUS EXPLORATION STAGES

STAGE I

4.1 INTRODUCTION

The purpose of Stage I geological investigations was two-fold: to locate and evaluate all thermal manifestations in Western Nicaragua, with emphasis on features indicative of hyperthermal zones with anomalously high subsurface temperatures, and to map the surface geology south 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 methodology used comprised various geological exploratory techniques but relied mainly on analysis of existing data, photogeology and field geology. The usefulness and results of these methods are described in the following sections.

4.2 SURFACE GEOLOGY EXPLORATION METHODS

4.2.1 Photogeology

Interpretation of few available air photographs was helpful in locating hydrothermally altered areas throughout the volcanic range. The limited amount of air photograph coverage, however, was a very pronounced problem, resulting in an incomplete evaluation of the project area. South of Momotombo volcano, photogeology and some field checking were relied upon to map the surrounding area in a reconnaissance manner. Several lineaments were located from the air photos and classified into major or minor, depending on the degree of expression on the photos.

4.2.2 Field Mapping

The extent of field mapping was restricted to certain areas, such as Momotombo, due to the large coverage, limited time, and availability of personnel. Only one geologist was in charge of the entire geological exploration and this limited the amount of information gathered. Field work was productive in the altered areas where outcrops are clearly visible; the lack of outcrops in the surrounding areas is related to a mantle of variable thickness of Recent volcanic cinders (Thigpen, 1970). Thick vegetation covered much of the area apart from the altered zones.

Thermal areas were delineated and briefly described, and a regional geologic map was produced from these investigations ~~Refer to~~ (Figure 4.1) The total area of surface alteration is about .75 km^2. Fumaroles and boiling hot springs with temperatures of 100°C are associated with the altered ground and siliceous sinter deposits. Possibly a more careful examination of surface manifestations would have proven useful in making certain inferences about (a) the nature of the altering fluid and (b) the duration of the thermal activity. This would have also aided in a detailed petrographic study of the thermally altered rocks.

4.2.3 Structural Geology

Much of the structural geology study is derived from photogeology and field mapping of faults and lineaments. Two northwest trending and steeply dipping faults were inferred to be controlling the hydrothermal alteration south of Momotombo volcano (Figure 4.1). Other fracture controlled lineaments were also mapped but the mantling effect of young lava covered most of them (Thigpen, 1970). The dominant structural feature is the fault zone represented by the alignment of the volcanic range, however, in the Momotombo area it was concealed by Quaternary volcanics.

4.2.4 Petrology

Identification of surface rocks enabled the classification of two main rock groups: Older Volcanic Rocks and Volcan Momotombo Rocks, allowing for 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 basalt, andesitic basalt and olivine basalt interbedded with pyroclastic deposits. Figure 4.1 shows the surface distribution of the various formations around the volcano. Surficial deposits were also analyzed.

Additional examination of hydrothermally altered rocks could have lead to a detailed ~~to a detailed~~ petrographic analysis which might have shown zonal distribution, as was the case in the Matsukawa Geothermal Field in Japan.

4.3 SUBSURFACE GEOLOGY EXPLORATION METHODS

Eight temperature gradient holes with average depths of 200 feet and one 2,000 foot deep drillhole, MT-1 , were drilled in the Momotombo area. Some important information was obtained on the subsurface geology from the lithologic descriptions, however, the omission of other geological techniques such as petrology and mineralogy, which would encompass hydrothermal mineral alteration studies and fluid inclusion geothermometry, narrowed the amount of data which was obtained from this field. The methods used failed to produce a geologic model and to make valuable inferences about the reservoir. Some of the techniques which would have been valuable in this stage of the study are described in the next sections.

4.3.1 Drillhole Correlation

In volcanic areas such as Momotombo the reservoir rocks consist of lavas and pyroclastics so similar to one another that very detailed petrology and perhaps geochemistry are needed before firm correlations can be made, such as was done at Kawah Kamojang, Indonesia, and other fields. Due to the omission of petrographic analysis from cuttings, well defined rock types and formation boundaries were not identified. No cross sections, structural contour maps, isopach map or panel diagrams were produced.

4.3.2 Petrology

Binocular microscope examination provided only the minimum information for construction of a lithologic column for each hole. Even though some heavily altered rocks were encountered and described, no further steps were taken to examine the hydrothermal rock alterations. The technique of analyzing petrographically the altered rocks is widely used (New Zealand, Japan, Mexico, U.S., ...) to make deductions about reservoir conditions. If it had been used at Momotombo it would have provided the first view of processes occurring in the reservoir.

4.3.3 Mineralogy

This branch of geology was not used in Stage 1. Careful mineralogical examination of the cuttings would have provided clues to the reservoir conditions, since hydrothermal minerals depend on 1) temperature, 2) pressure-mainly depth of boiling, 3) parent rock type, 4) reservoir permeability, 5) altering fluid composition, and 6) duration of activity. Studies performed by Hoagland and Elders at Cerro Prieto, Mexico, (1978) showed the effect of increasing temperature on hydrothermal mineral zonation, and subsequently, the section of maximum heating in the reservoir was delineated. Fluid inclusion geothermometry, a very inexpensive method, would have proven most useful in determining the local reservoir temperature.

4.4 CONCLUSIONS

Based on the purpose of Stage 1 investigations, which included regional and detailed geologic mapping, the results were beneficial as a reconnaissance phase in locating and delineating potential geothermal fields. Unfortunately no emphasis was placed on the petrology and mineralogy of hydrothermally altered rocks which would have enhanced further detailing of the reservoir geology. This could have resulted in the first overview of reservoir conditions and processes.

Since Stage 1 studies were conducted in 1970 and many of the petrological advances in geothermal geology have been active only since 1968, the omission of these techniques might have been caused by the lack of information and knowledge in these matters at the time. Planning of future geothermal geologic work in similar fields, however, will include these techniques, and current mineralogical advancements will be considered.

4.5 INTRODUCTION

The objectives of Stage 2 geological investigations were to map the surface geology of the thermally altered areas, define their areal extent, and map all pertinent structural and volcanic features related to thermal activity in a reconnaissance manner. These investigations, when combined with geophysical and geochemical studies, were to provide a preliminary evaluation of the geothermal potential and a 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 and brief hydrological notes were included in the geologic report.

4.6 FIELD MAPPING

The area investigated not only included Momotombo volcano, but also the surrounding Monte Galan Caldera, Cerro Montoso and Cerro Colorado cones, and La Guatusa and La Chistata structural features (Jonsson, 1973). Various lava outflows and pyroclastic deposits were briefly described and identified with respect to their source of origin. Since the thermal areas had been previously mapped by Thigpen (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 95ºC. Jonsson (1973), however, suggests there is only one thermal area which is turn divided superficially by lava flows into a number of other areas. This reasoning is 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 temperature isotherm map produced.

Temperature measurements near the volcanic crater revealed a maximum high temperature of 213°C at the southern wall. Several fumaroles were observed on the southern wall. Other fumaroles were observed on the southern slope down to an altitude of 1,100 meters, and with these included as part of the thermal area, the areal extent of the high temperature area was estimated to be about 15 km^2.

4.7 VOLCANIC RISK ANALYSIS

The thermal area on the southern slope of Momotombo was determined to be safe from central or flank eruptions. The area is outside the reach of bombs and blocks thrown from the summit crater (Jonsson, 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 can be considered a safe place. The periodicity of eruptions is uncertain and unknown in Momotombo and the constant danger of a base surge remains a potential volcanic hazard.

For a small pyroclastic eruption, the study area appears safe, 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 lava outpour, the horseshoe-shaped crater opening toward the north would guard the southern slopes.

4.8 HYDROGEOLOGICAL NOTES

We have Eckstein's report

Since no systematic hydrogeological investigations had been made in the area, some notes on the hydrology of the area were prepared in order to aid in defining the reservoir model. Much of it is suggestive and inconclusive, as the author emphasizes.

The high permeability of the lower part of the lavas around Momotombo lower the water table considerably. Two types of mineralized thermal waters exist in the subsurface: warm groundwaters and hot, saline waters with up to 100°C temperatures (Sigvaldason, 1973). The connection between these waters is obscure, but it was suggested that the hot, saline waters reach the surface in the hot area, passing through the fresh groundwater.

4.9 CONCLUSIONS

Based on the original scope of work for these investigations, the geological results were successful in fulfilling the objectives, however, the planning and requirements of the geologic investigations were unsatisfactory. A second mapping of thermally altered areas and related features seem superfluous at this stage of the program. A detailed investigation should have been required, especially on the petrology and mineralogy of hydrothermal altered zones. The ground temperature survey was incorrectly outlined by excluding a detailed coverage which would have produced a surface isotherm map. The hydrogeological study, an extra in the final report, should have been a study by itself.

Briefly, only a minimum amount of information obtained serves to adequately define or modify existing data on the Momotombo geothermal reservoir.

4.10 INTRODUCTION

This phase of the investigations had the objective of producing a feasibility report. 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 experimental production wells were sited. Unfortunately, the final geological report was unobtainable and as such, some of the methodology used remains unknown; the petrology and feasibility report, however, summarize the important results. The four production wells drilled gave valuable information on the stratigraphy and a subsurface geological scheme was presented (Figure 4.2).

4.11 PETROLOGY

The 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 report, 1977). A brief mention of hydrothermally altered minerals was made, but no further studies were carried out in this field. The omission of this study deprived the petrologist of valuable information previously mentioned in 3.4. An absolute age determination from samples of well MT-1 revealed an age of about 3.5 million years (Pliocene), suggesting pre-Momotombo volcanics at depth (ELC report, 1977).

4.12 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 4.2 depict the subsurface formations and processes occurring in this area. It is believed that two reservoirs are present: the deep reservoir lying at depths of about 1,200 mts. and formed by deep heated groundwater moving convectively within the fissured lava flow, and the shallow reservoir found at depths of about 300 mts. and formed by hot fluids escaping through a shear zone of the cap rock formed by hydrothermally altered pyroclastics. Cold meteoric water inflow runs below the shallow reservoir and causes a negative gradient, as noted from the wells. (ELC Report, 1977).

4.13 INTRODUCTION

This phase of the geological investigations is a continuation of Stage 3, but performed by another company and concurrent with the drilling of exploratory wells. The methodology consisted of detailed structural mapping, lithologic descriptions from twenty-two temperature gradient holes drilled, and temperature distribution measurements. This and new information obtained as the field exploration continued were compiled to form a detailed geological report. Some of the techniques and results obtained are presented in the subsequent sections.

4.14 STRUCTURAL GEOLOGY

A detailed structural geology program was carried out after drilling showed the productive wells were lying in a narrow zone trending NW-SE across the field. Previous structural mapping by Thigpen (1970) provided the base map on which few faults and new fractures were added. The new structural map shown in Figure 4.3 locates fracture zones within the area of the wells, indicating to areas which merit exploratory drilling. These fracture zones were identified partly from cores of well MT-2 (ELC report, 1975) and subsequent well production data indicates flow of fluids in these fractures (CECI report, 1977).

4.15 STRATIGRAPHY

Volcanic rocks of Late Tertiary and Quaternary age were intersected by the Momotombo Field wells (CECI report, 1978). Figure 4.4 shows a columnar section showing the various compositions and textures of the rocks. The division of the eight rock units is based on distinctive lithologies. Most of the stratigraphic section is composed of andesitic ash and lapilli tuffs and tuff-breccias, although compositions range from basaltic to dacitic (CECI report, 1978). Detailed descriptions of lithologies were made on the basis of binocular, plain light, microscopic examination of well cuttings. The complexity of the stratigraphy, however, does not allow for broad correlations to be made with confidence, but instead detailed petrology and perhaps geochemistry were necessary before firm correlations could be made. On this basis , the resulting columnar section and well cross sections remain somewhat dubious. If the petrology and subsequent lithologic descriptions were reliable, a panel or block diagram would have been useful in visualizing the subsurface lithology.

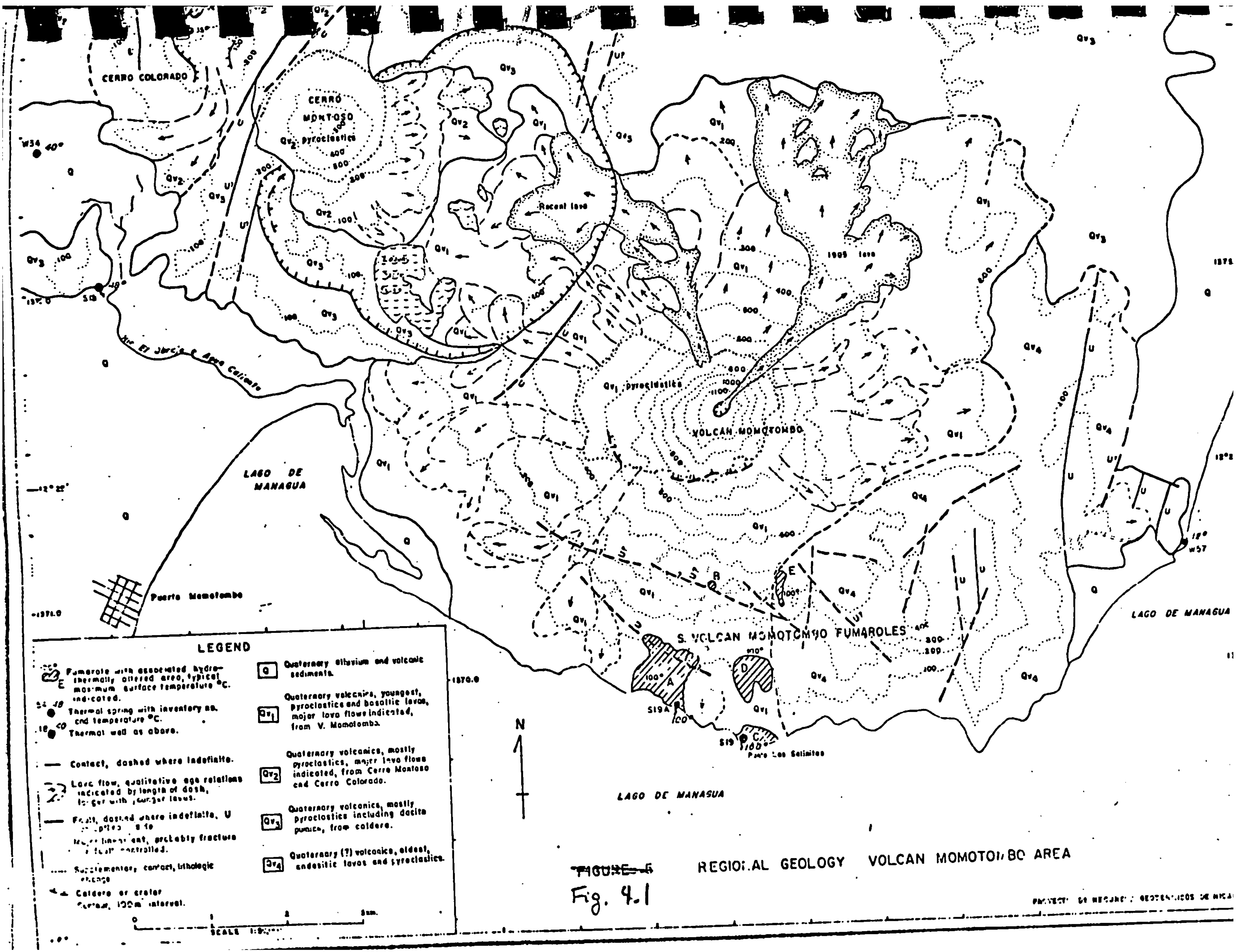
4.16 TEMPERATURE DISTRIBUTION

Measurements of subsurface temperature in the Momotombo Field provided sufficient data for the making of isothermal maps and cross sections. A north-south to northeast isothermal trend was detected and being open to the south into Lake Managua and to the north toward Momotombo Volcano (CECI report, 1978). Data also indicates an increase of temperature with depth in the western part of the field (Figure 4.5).

4.17 CONCLUSIONS

The objectives of this stage of the investigations were to increase, upgrade or modify existing geological data. The advantage of the geologist in this phase was in the information gathered from cuttings derived from the drilling of deep wells. The subsurface geology could now be depicted through diagrams after careful examination of the cuttings. Unfortunately, this procedure was not followed, but instead more surface geological mapping was carried out. Again, the omission of hydrothermal alteration studies, detailed petrology, mineralogy and a more comprehensive subsurface geological study deprived the investigators of valuable information. A dubious columnar section was the only apparent improvement in the subsurface data. It appears that the importance of cuttings from deep wells was not fully recognized.

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



~~FIGURE 6~~ REGIONAL GEOLOGY VOLCAN MOMOTOMBO AREA

Fig. 4.1

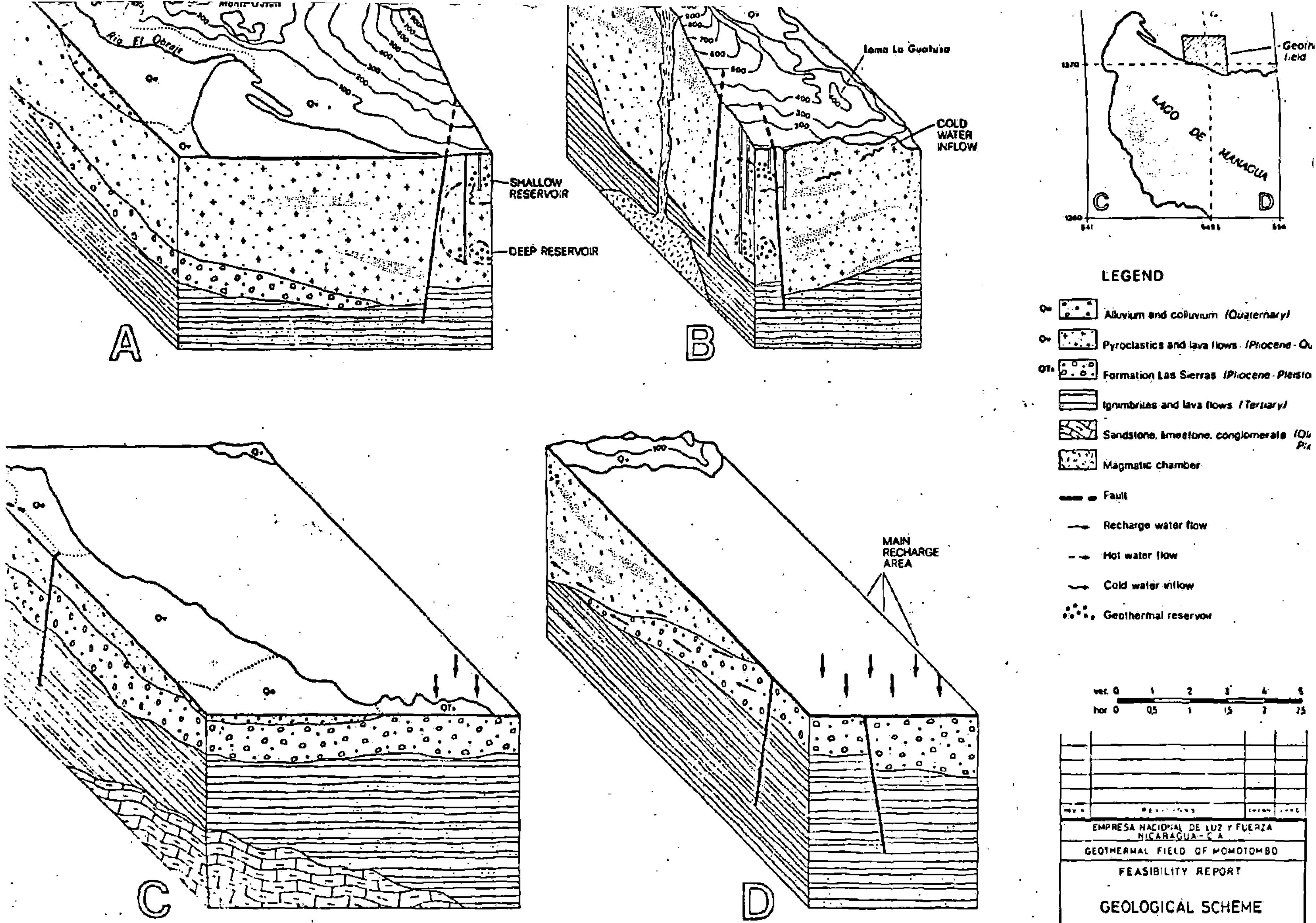
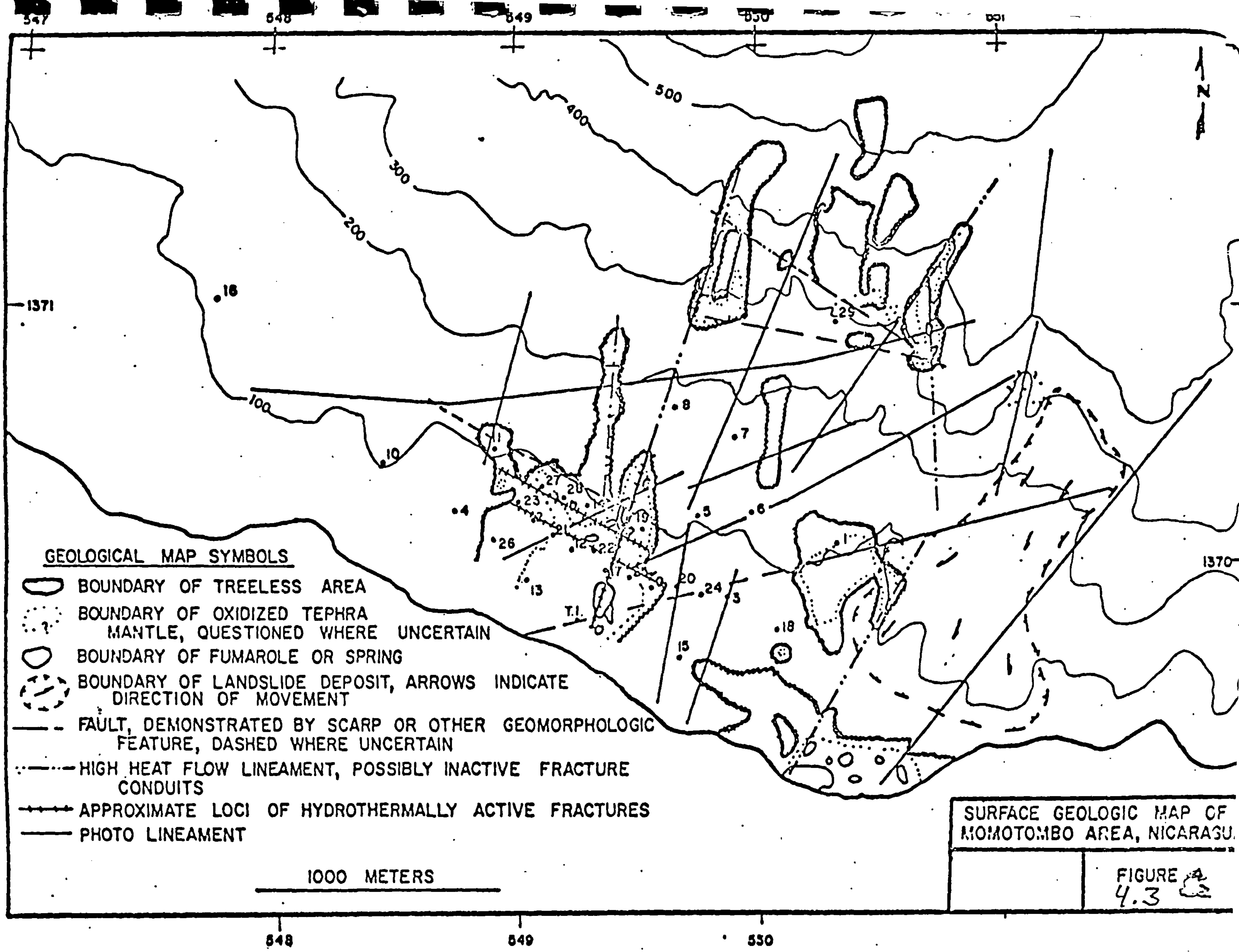

Rio El Obraje
SHALLOW RESERVOIR
DEEP RESERVOIR
A
Loma La Guatusa
COLD WATER INFLOW
B
LAGO DE MANAGUA
C
D
MAIN RECHARGE AREA
C
D
LEGEND
Alluvium and colluvium (Quaternary)
Pyroclastics and lava flows (Pliocene - Qu
Formation Las Sierras (Pliocene - Pleisto
Ignimbrites and lava flows (Tertiary)
Sandstone, limestone, conglomerate
Magmatic chamber
Fault
Recharge water flow
Hot water flow
Cold water inflow
Geothermal reservoir
vet. 0 1 2 3 4 5
hor 0 0,5 1 1,5 2 2,5
EMPRESA NACIONAL DE LUZ Y FUERZA NICARAGUA - C.A.
GEOTHERMAL FIELD OF MOMOTOMBO
FEASIBILITY REPORT
GEOLOGICAL SCHEME

Fig. 4.2

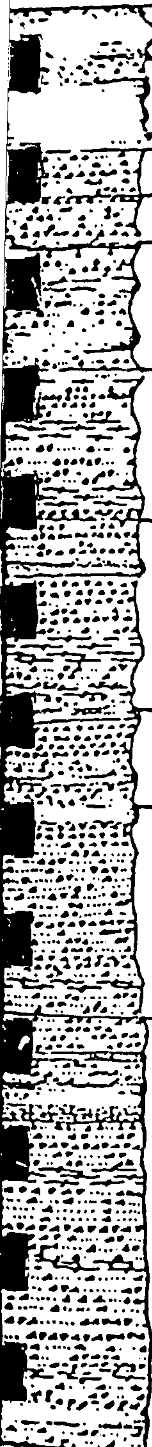


SURFACE GEOLOGIC MAP OF MOMOTOMBO AREA, NICARAGU.

FIGURE 4.3

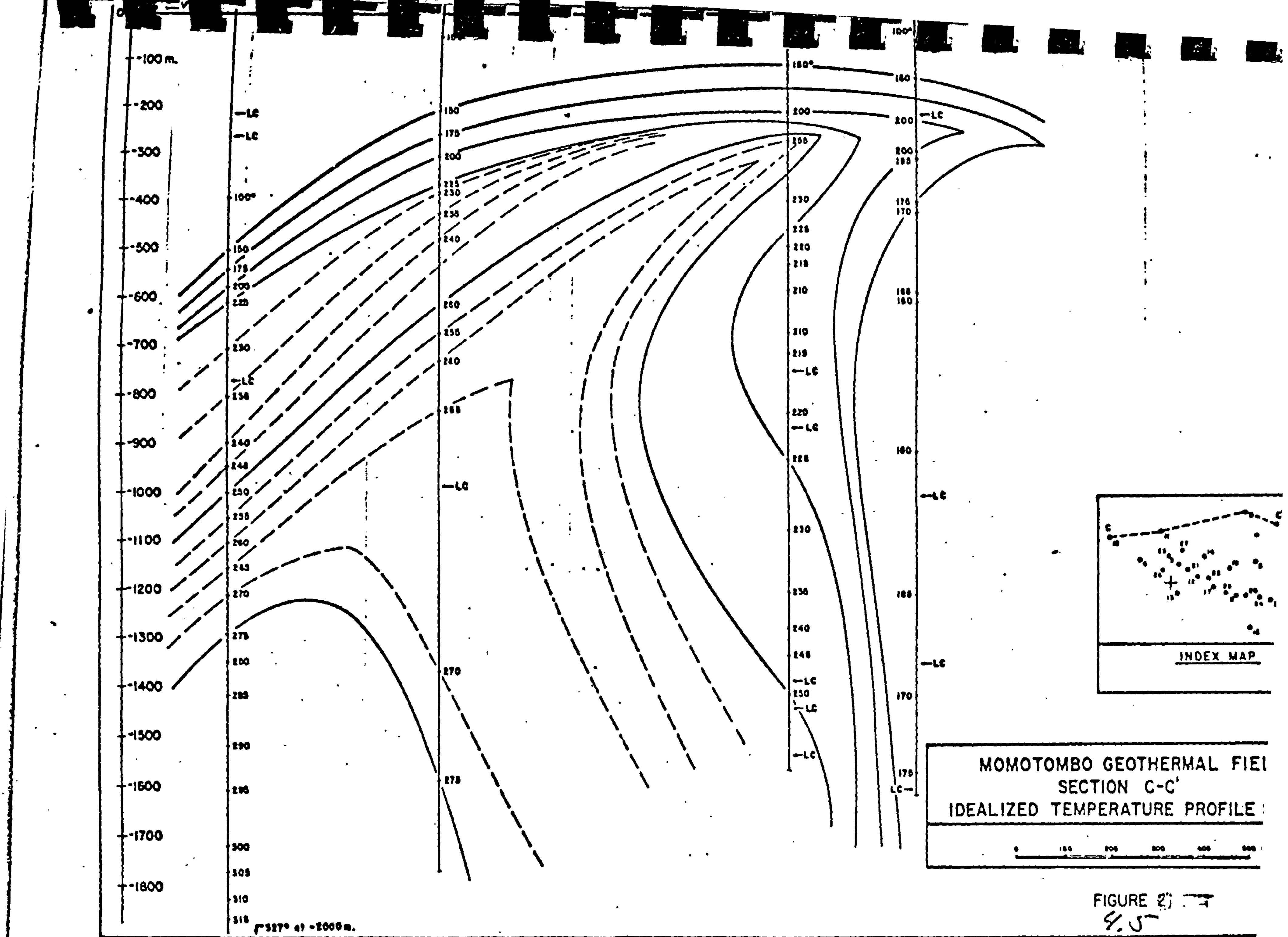
FIGURE 24.9

PRELIMINARY GENERALIZED COLUMNAR SECTION, MOMOTOMBO FIELD, BASED ON 28 WELL SECTIONS (CECI Report, 1978)



COLUMN	THICKNESS (Feet)	UNIT	LITHOLOGY
	24-144 (but 304 in 1 well) 80-280 (possibly 340)	Superficial	Poorly consolidated, dark gray, vesicular, zeolitic, basaltic* crystal vitric 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.
	220 - 540	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.
	[illegible] 120 - 340	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.
	120 - 340	Ic	Dark gray, indurate, microporphyritic basaltic andesite* lava and associated tuff-breccias and less common, light gray, mottled, devitrified and altered lithic crystal vitric ash tuff.
	400 - 860	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.
	580 - 920	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.
	700 - 1210	IV (11 Wells)	Dark gray, tinged reddish or brownish commonly, altered green and white lithic crystal vitric ash and lapilli tuffs with subordinate lithic ash to tuff-breccia interbeds and uncommon, relatively thin flows of dark reddish gray andesitic basalt* lava in upper 75%. The lower 25% is occupied by reddish gray, altered, cryptocrystalline basaltic andesite* lavas with rare, chloritized pyroxene insets and 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 and rarely argillic.
	420 - 560 (but 1680 in one well)	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 altored, gray lavas forming the bulk of the unit. Alteration is as in Unit IV.
	920 - 1200	VI (7 Wells)	Dull, dark gray, cryptocrystalline, basaltic* lava (20 to 60 feet) indicating the top and interbedded, red, gray or green, commonly mottled, 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.
	2180	VII (6 Wells)	Light gray, mottled, altered, welded, andesitic 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-textured 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 and barnacles) marine limestone with basal calcareous tuff form minor parts of the unit. Alteration is as in Unit IV.

* Preliminary rock identification based on binocular microscope examination.


MOMOTOMBO GEOTHERMAL FIEl
SECTION C-C'
IDEALIZED TEMPERATURE PROFILE
INDEX MAP
327° at -2000 m.
-100 m.
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
-1500
-1600
-1700
-1800

FIGURE

5.1 INTRODUCTION

The most useful geophysical methods for geothermal exploration are: temperature gradient surveys, heat flow determinations, electrical resistivity surveys, seismic, magnetic and gravity surveys, and some passive seismic methods. The first three methods are the most widely used for delineating the geothermal reservoir and furnishing data on subsurface conditions; the others are used mainly to refine the subsurface structure.

Almost all geophysical methods have been used for exploring various types of geothermal systems. The success of each method depends on the contrast of a set of physical rock constants inside and outside the geothermal system which give rise to certian geophysical anomalies. These anomalies can be grouped as follows:

- Geophysical anomalies caused by hot geothermal fluids
- Geophysical anomalies caused by changes in the reservoir rocks
- Geophysical anomalies caused by structural features
- Geophysical anomalies caused by fluid withdrawal

These anomalies may differ between various types of geothermal systems, and as such the selection of the most suitable geophysical technique is governed by:

Funds
Organization of exploratory program
Availability of equipment
Trained staff
Experience of geophysical team leader
Data reduction and interpretation facilities
Access and terrain
Type of geothermal system
Setting of system

The geophysical methods outlined in Table 1.1 have been used for geothermal exploration in various parts of the world.

It is obvious that there is no well defined approach as to the planning of a geophysical survey of a geothermal prospect. The techniques and exploration methodology chosen for any area should follow the following guide lines.

- o starting with simple and well established methods
- o aiming for an adequate coverage of the whole prospect
- o using as many locally available resources
- o staying within the budget.

5.2 DC ELECTRICAL METHODS

These methods are probably the most widely used for geothermal exploration today. DC resistivity methods are preferred to AC methods because of skin effects present at large spacings with AC methods. The various DC resistivity techniques permit the determination of resistivity zones as a function of depth and subsequently they are sometimes used with controlled depth of exploration. The resistivity of rocks is affected by six factors:

- Inherent resistivity of the rock matrix
- Conductive rock components
- Amount of water present
- Salinity of fluid
- Temperature
- Influence of steam

Since geothermal systems give distinctive and measurable discontinuities in resistivity, the reservoir can be inferred from indirect measurements at depth. Numerous case histories suggest that liquid-dominated geothermal reservoirs, such as Momotombo, are characterized by a resistivity of less than 5 ohm-meters, regardless of the resistivity of the host rock (Meidav, 1979).

The depth of current flow is a function of the inter-electrode distance; the larger the current electrode distance, the deeper the current penetrates into the ground. Consequently, a large variety of electrode arrays exist. The most common are:

- Wenner array
- Schlumberger array
- Equatorial array
- Dipole-Dipole array
- Roving-Dipole array
- Constant depth profiling

Further descriptions or applications of these or other methods may be found in Dobrin (1976), Telford, et. al. (1976), Meidav (1979), Parasnis (1979).

The major problem with all these techniques lies in the interpretation of the measured resistivity anomalies, especially since the resistivity may be a function of the aforementioned factors. Whenever a low resistivity anomaly is detected, another exploratory method should be used to determine the causal relationship.

5.3 ELECTROMAGNETIC TECHNIQUES

Electromagnetic methods have been used in geothermal exploration only in the last 5 years. They involve the generation of a magnetic field that varies with time, and the detection of either the electrical or the magnetic field arising from currents induced in the earth (Keller, 1970). Although instrumentation and interpretation are complex, electromagnetic (inductive) methods have two theoretical advantages over electrical methods: (1) signal size increases with decreasing resistivity, making measurements easier and more accurate in geothermal areas, and (2) inductive methods are not adversely affected by near surface high resistivity zones. Some of the EM methods which have been used in geothermal areas are:

- The two-loop method
- Audio-frequency magnetotellurics (AMT) and MT
- Telluric current methods
- Frequency domain soundings

Additional information on the use and implications of these methods may be found in Keller (1970), Pritchard (1979), Telford, et. al. (1976), and Parasnis (1979).

As with electrical methods, the major problem lies in the interpretation of the measured resistivity anomalies, and other methods are required to verify results.

5.4 GRAVITY AND MAGNETIC STUDIES

These methods are used mainly to investigate the structure of the subsurface rocks in geothermal areas; they can detect basement and aquifer structures with limited success. Gravity and magnetic surveys as single data sets are therefore not very useful and must be used in conjunction with other exploratory techniques.

Gravity surveys have been used to delineate anomalies related to geothermal systems and to outline structural features. A variety of factors such as density, topography, and the many corrections contribute to the misinterpretation of gravity data. Biehler (1979) suggested that the ambiguity of gravity interpretation can be reduced by combining the gross structural features of seismic refraction surveys with gravity modeling.

Magnetic surveying is probably the least useful tool in geothermal exploration. The many factors which influence the character of the magnetic map, especially in volcanic terrain, makes it difficult to interpret it in terms of geothermal resources. Almost all regional surveys are done using airborne methods. Highly detailed ground surveys may be useful in particular cases (Biehler, 1979). The interpretation of gravity and magnetics data should constantly be upgraded and altered as additional information becomes available from other investigative techniques.

5.5 OTHER GEOPHYSICAL TECHNIQUES

Passive seismic techniques such as microearthquake studies or seismic noise detection in geothermal systems is presently under investigation. The location of microearthquakes and seismic noise may aid in delineating permeable or fractured zones in geothermal areas. Fault movements may give rise to microearthquakes and factors such as flashing at depth may be the cause for geothermal-noise detection. Further studies in these fields are necessary in order to understand the concepts which could be applied for a fast, mobile and economical investigation of a geothermal area.

TABLE 5.1

Geophysical Method	Anomaly Detected	Remarks
a) Emissive (airborne) infrared	Slightly elevated surface temperatures	Available only through contractor
b) Temperature gradient holes	Anomalous temperatures at shallow depths	Costs increase significantly for deeper holes
c) Electromagnetic (EM) surveys (audio-frequencies)	Near surface low resistivities	Rarely used
d) Audiofrequency magnetotelluric surveys (AMT)	Near surface low resistivities	Only available through contractors
e) Self potential methods	Anomalous (negative) surface potentials	Experimental but helpful if used in connection with f.)
f) DC - Resistivity traversing with 1) linear arrays 2) non-linear arrays	Low apparent resistivity over upper reservoir and outflows	Costs usually include data analysis
g) Magnetotelluric (MT) surveys and soundings	Low apparent resistivity in the subsurface	Only available through contractors
h) DC-resistivity soundings	Variations of resistivity with depth	Extensively used
i) Transient methods	Variations of resistivity with depth	Experimental; only available through contractor

5.1

TABLE ~~1.1~~

(Continued)

Geophysical Method	Anomaly Detected	Remarks
j) Recording of seismic noise (surface waves)	Enhanced ground noise anomalies over reservoirs with 2 phase flow	Surveys offered only by contractors
k) DC-resistivity traversing with dipole-dipole arrays	Deeper apparent resistivity anomalies	Extensively used
l) Telluric surveys	Deeper apparent resistivity anomalies	Rarely used
m) Gravity survey	Gravity anomalies	Costs include surveying
n) Airborne magnetic survey	Magnetic anomalies	Available only through contractor
o) Seismic reflection and refraction	Seismic velocity structure of reservoir and basement rocks.	Costs may include shothole drilling
p) Ground magnetic survey	Magnetic anomalies	Usually used as an aid for m) and h)

ADEQUACY OF GEOPHYSICAL TECHNIQUES AND METHODS IN THE VARIOUS EXPLORATION STAGES

STAGE 1

6.1 INTRODUCTION

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, namely San Jacinto and Momotombo. At Momotombo, several distinct electrical prospecting methods were used; some already well established in other geothermal areas and some relatively new for geothermal exploration. The exploration results provide a way to evaluate these methods, from the point of view of their utility for geothermal exploration, their applicability with subsurface geology, topography, and their relationship to other geophysical methods used. The exploration techniques used at Momotombo were: Schlumberger Soundings, Dipole Mapping Surveys, Electromagnetic Soundings, and Audio-Magneto-Telluric Surveys. Their applicability and usefulness in Stage 1 investigations are described in the following sections.

6.2 ELECTRICAL PROSPECTING METHODS

6.2.1 Schlumberger Soundings

Eight Schlumberger soundings were performed in the Momotombo prospect. The resulting sounding curves for each point have been interpreted in terms of a sequence of several horizontal layers, which is the only model which can be used effectively with the theoretical curves currently available, but which probably has very little resemblance to the true underground distribution of resistivity in the area (Banwell, 1971). There is thus little evidence of correlation between the pseudo-layering found in neighboring soundings, and not much similarity between the results of soundings taken at nearly the same points. Keller, (1971) points out that high surface resistivity 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 which were interpreted from the soundings at Momotombo, range between 300 and 400 meters. 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) thus 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.

Results of these soundings are shown in Figure 6.1. Low resistivities less than 1 ohm-meter were found in the areas where surface geothermal activity is most abundant.

6.2.2 Dipole Mapping Surveys

Two dipole mapping surveys were carried out in the Momotombo area with two source dipoles located along the shores of Lake Managua. Due to the extremely low resistivities in the area, signal levels were not high enough to permit accurate detection beyond 4 km. from the source dipole. Also, as noted by Banwell (1971), the areas 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 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.

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 that this method can be used effectively for outlining the boundaries of a geothermal field, however, the limited coverage at Momotombo did not produce a satisfactory boundary mapping of the area.

Results of this survey are shown in Figure 6.2. 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 as such there is no delineation of the thermal activity.

6.2.3 Electromagnetic Soundings

T1, Group7

Even though only three electromagnetic soundings were performed in the Momotombo area, the results are in general agreement. A hot water reservoir was indicated and lying at depths of 1400 to 1700 meters. As already mentioned by Banwell (1971), no verification of these results from other surveys was available, since their depth of penetration was limited (Schlumberger soundings) or their interpretation too uncertain (dipole). The geochemical data, however, supports the findings. Keller (1971) classifies this technique as superior to the resistivity soundings because of the insensitivity to problems caused by resistant surface rocks. The Momotombo data did not permit any limits to be set as to the size of the conductive zone.

6.2.4 Audio-Magneto-Telluric Surveys

A brief survey using this technique was performed at Momotombo. 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 limitation on the maximum penetration depth to 400 meters 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. This technique was shown to be successful when used as a reconnaissance tool, as demonstrated during the Nicaragua Master Plan study by IECO.

6.3 GRAVITY AND MAGNETIC MEASUREMENTS

A reconnaissance gravity-magnetic survey consisting of 23 stations was made along the shoreline of Lake Managua and extending over some of the thermal areas of Momotombo. The results show a well-defined but weak positive anomaly near the lakeshore. The assumption that altered rocks are of low density, which is employed to explain the negative gravity trends on the flanks of the positive anomaly is not supported by recent 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 the 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 more beneficial in producing a better Bouguer Anomaly map and enhancing further gravimetric measurements.

Even though magnetics is used as a secondary exploration tool, a broader aereal coverage would have produced a better magnetic anomaly map and shown a) the delineation of surface volcanics b) the delineation of demagnetized (by thermal alteration) volcanics, and c) the delineation of unaltered intrusions within non-magnetic sediments. The vertical intensity map for Momotombo 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.

6.4 TEMPERATURE GRADIENT HOLES

This technique for detecting nearsurface anomalous heat flux is used worldwide. At Momotombo this method was successfully used in finding temperatures greater than 90°C in all eight gradient holes. Four holes had temperatures greater than 140°C. The findings contribute to the geothermal system model by delineating areas of anomalous heat flux and inferring the depths at which a certain temperature is liable to exist. Gradient extrapolation in four holes gave depths of 500, 300, and 240 feet for temperatures of 200°C (Berry, 1971). They provided little information, however, as to the size, location, or depth of the geothermal reservoir.

The drilling of one 700 foot deep hole produced satisfactory results with respect to temperature measurements. A maximum temperature of 209°C was measured at 700 feet, thus establishing with certainty a base temperature at least as high as the 200°C value that is required for successful geothermal reservoirs (Berry, 1971). No valid results were obtained as to the nature of the reservoir fluids, productivity rates, pressure, etc. The validity of this deep drillhole was not properly recognized and subsequently lots of valuable information was not accumulated.

6.5 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 (1971) pointed out that despite the indications of a low resistivity zone at moderate depth, as suggested by the electromagnetic soundings and supported by the geochemical data, no attempt was made to push 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, 1971).

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 useless to the geothermal investigations, due to the limited areal coverage.

6.6 INTRODUCTION

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

6.7 ELECTRICAL PROSPECTING METHODS

6.7.1 Schlumberger Constant Depth Profiling (SCDP)

The majority of the survey was done using a SCDP with a Lee partition added to detect any lateral inhomogeneities, and to check the validity of the results. The measurements were useful in detecting zones of low resistivity to be later investigated with VES soundings. Little contrast was detected in the entire region.

The results of these measurements are shown in Figures 6.3 and 6.4. Zones C, D and E were found to have the lowest resistivities and warranted further investigation by other methods.

6.7.2 Schlumberger VES Soundings

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 obtained as a result of dipping formations, and lateral and vertical discontinuities. These are caused by the limitation on the applicability of the VES method in volcanic regions such as Momotombo, where the layers are irregular and the measured sounding curve cannot be matched to any theoretical model, thus making any interpretation somewhat meaningless. The volcanic debris in some areas caused voltages which were too small for accurate and reliable measurements.

A VES sounding in zone C of Figure 6.4 was interpreted as a two layer curve with the second layer having an estimated resistivity of less than 5 ohm-meters. Vertical discontinuities caused an increase in resistivity values for large (AB/2 = 1000) electrode spacings. In zone D, VES soundings also point to a low resistivity zone existing at shallow depths (greater than 70 m.) to the east. Results from soundings in zone E are irregular due to the expansion of the array into soils on one side and volcanics in the other (Carriere, et. al., 1974). All three VES soundings correlate with the finding of a 70 m. thick surface layer overlying a second layer with resistivities around 9 ohm-meters.

6.7.3 Roving Dipole

This technique was not extensively used since it showed little depth control and as such some of the results remained unclear. The penetration is greater than the SCDP measurements because of the larger current dipole used, but the measured resistivities may be less reliable than the SCDP results because 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, et al., 1974).

In a geothermal environment such as Momotombo, resistivity is seldom that of horizontal layers. Vertical boundaries are more likely to be encountered such as the edge of an upwelling flow of geothermal fluids. Subsequently, when the electric field is parallel to a boundary, there is zero contrast and the boundary is not distinguished. Since only one survey was performed with one current dipole orientation, the detection of discontinuities was thus limited. It was therefore necessary to have more than one survey with various current dipole orientations.

The measurements taken in zone D of Figure 6.4 show a decrease in resistivity to the east. Results are shown in Figure 6.5.

6.7.4 Frequency Domain Sounding

Only one such sounding was performed and using the same electrode setup as the roving dipole survey. Results showed no variation in resistivity with changes in frequency.

6.7.5 Dipole-Dipole

This technique was used as a test in the Momotombo area. The array is quite sensitive to lateral changes in resistivitity and is greatly affected by near-surface inhomogeneities along the survey route. Even with a spacing of 500 m, the high contact resistance caused too low signal levels for the n=3 and 4 spacings. Since this method was not extensively used in this investigation, the valid results from n=1 and 2 spacings suffice its limited use.

6.7.6 Self-Potential Method

Self-potential measurements have been used in other geothermal fields with little success and the method is still under investigation. Studies by Corwin and Hoover (1979) indicate no consistent pattern to the anomalies caused in 13 different geothermal areas, and a number of recently discovered factors which affect data quality. These factors were perhaps unknown during the Momotombo exploration stage and as such affect the use~~lessness~~ of the technique at the time. Although the self-potential data may give some information about the near surface hydrothermal system, the anomalies are small and can be easily confused with other effects. The results at Momotombo were meaningless, although there is some indication that such measurements may be used to locate faults in this area.

6.8 CONCLUSIONS

From the resistivity survey performed during Stage 2 in the Momotombo area, three zones of low resistivity were located. Since the increase in resistivities between the zones is not large, these three zones may form part of one body (Carriere, et al. 1974). The low resistivity areas are shown in Figure 6.4. Zones C and D show resistivities of less than 5 ohm-meters and as low as 2 ohm-meters in zone D. This area appears to be the most promising one for drilling.

Even though 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 original 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, but Stage 1 investigations had already determined this area to contain low resistivities as shown in Figure 6.2.

6.9 INTRODUCTION

Additional geophysical measurements were carried out at Momtombo as a requirement for the 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 phase encountered various difficulties (ELC report, 1975) and the omission of data, procedures and isoresistivity maps in the final report poses problems in the verification of results. 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.

+ dipole by Phoenix Geophysics (CECI ?)

6.10 ELECTRICAL PROSPECTING METHODS

6.10.1 Schlumberger VES Soundings

A total of 20 Schlumberger soundings were carried out in the vicinity of the Momotombo volcano.. Electrode separations of 2 to 3 kms. were employed, since larger separations gave inaccurate results due to the high resistivity of 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. Contact resistance was high and even though up to 500 l. 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. The progress was eventually slow and costly.

Results are shown in Figures 6.6 and 6.7. 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 Momtombo exploration program, and the geophysical report has no data, curves or isoresistivity maps to verify or investigate procedures with results.

6.11 GRAVITY MEASUREMENTS

The gravity survey consisted of 200 readings taken over an area of approximately 300 km^2 and including the Momotombo prospect. The usual problems of access and topography affected the distributiion of the stations and consequently limited the interpretation accuracy. The Bouguer anomaly map (Figure 6.8), however, appears fairly accurate from the data presented and shows the basement lying at a depth of 500 to 700 m. the geothermal field and gently dipping in a southwesterly direction.

6.12 CONCLUSIONS

The results of the geophysical investigations in Stage 3 remain somewhat unclear due to the omission of data from the report. The suggested findings appear as 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 used does not allow for investigation of the problems nor for verification of results. The gravity survey proved more beneficial in finding the depth and dip of the basement in the prospect area.

Phoenix Geophysics: outlines low resistivity thermal area, shallow plume + deeper low res. near fault.

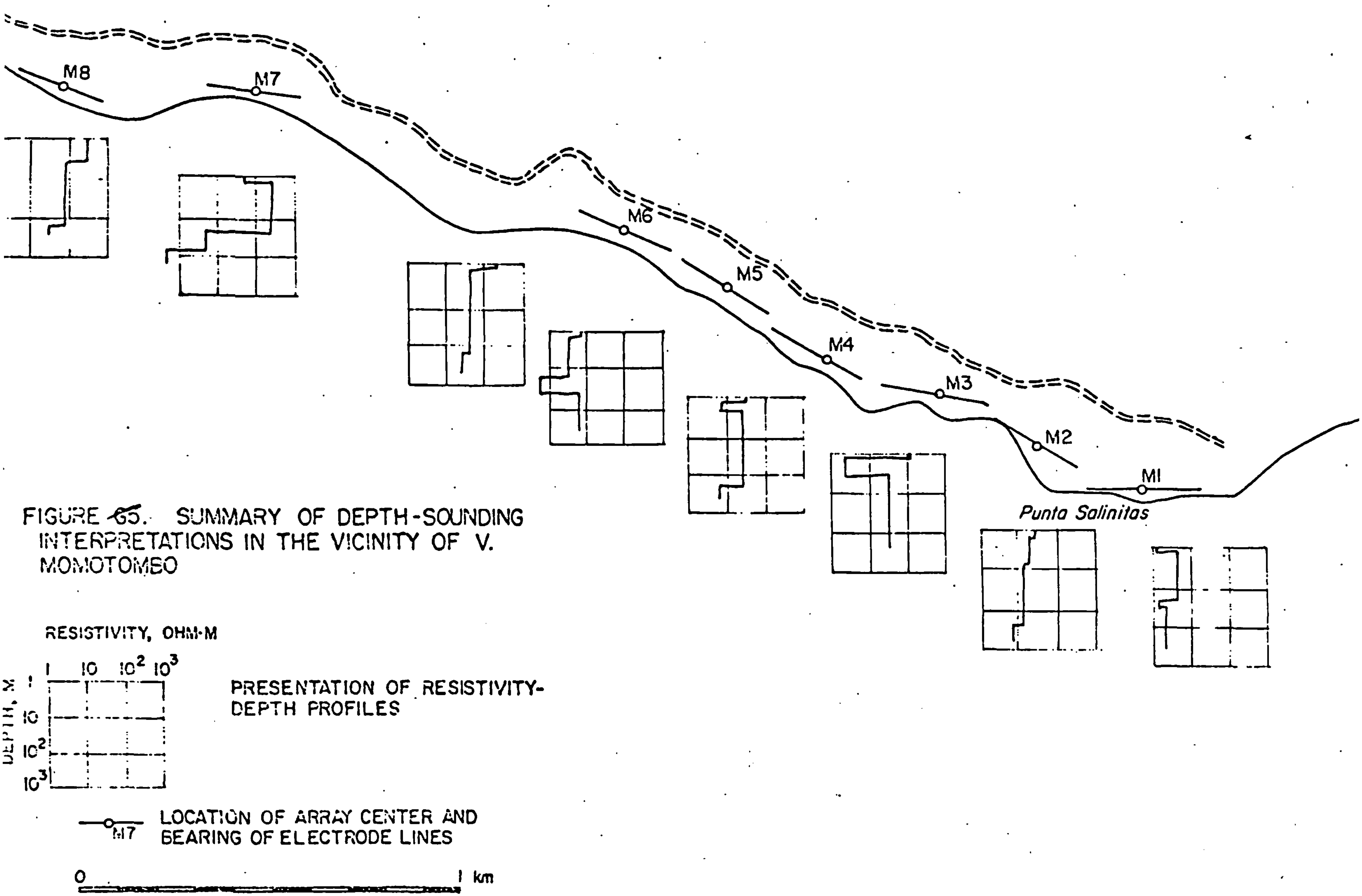
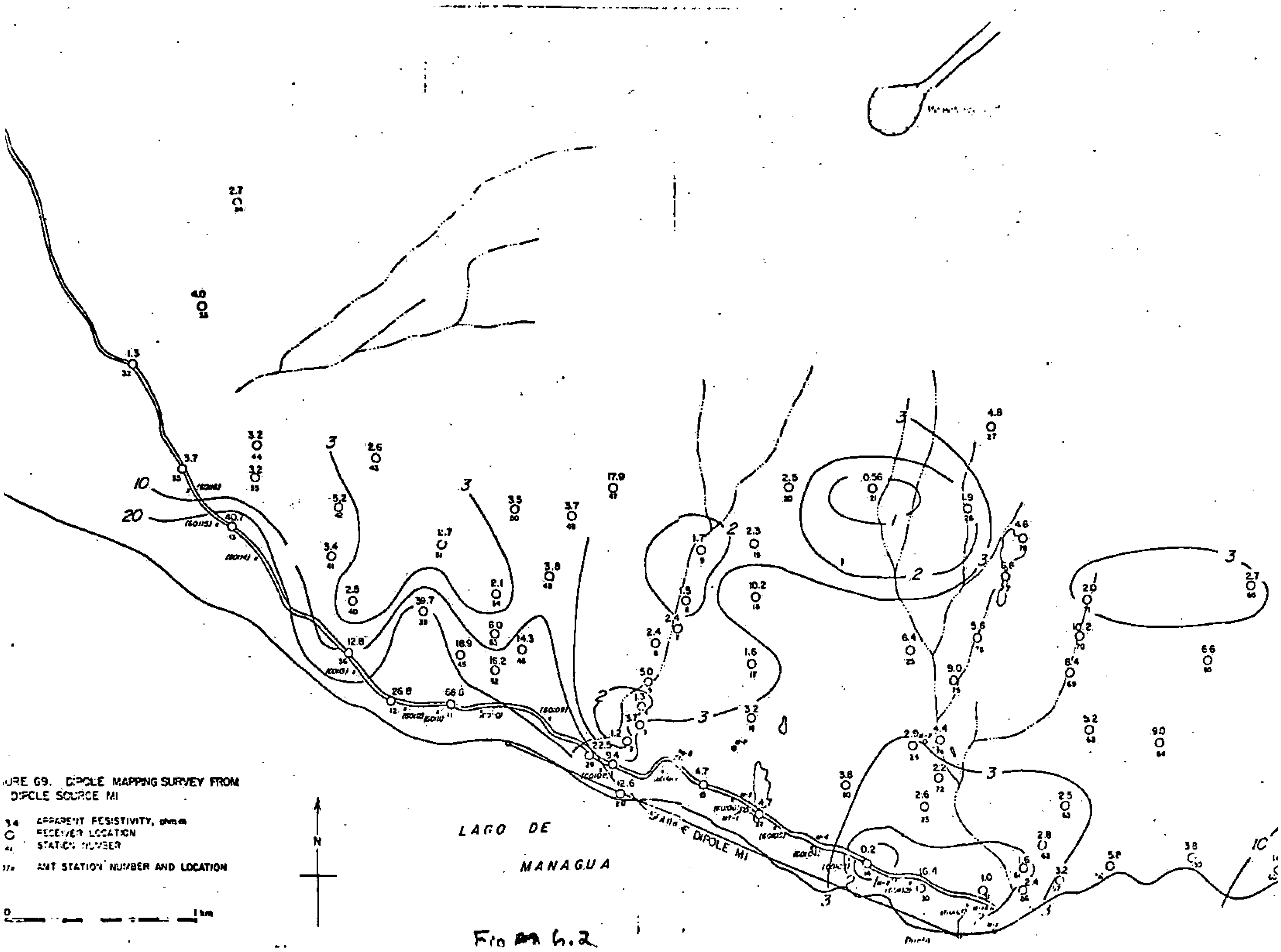


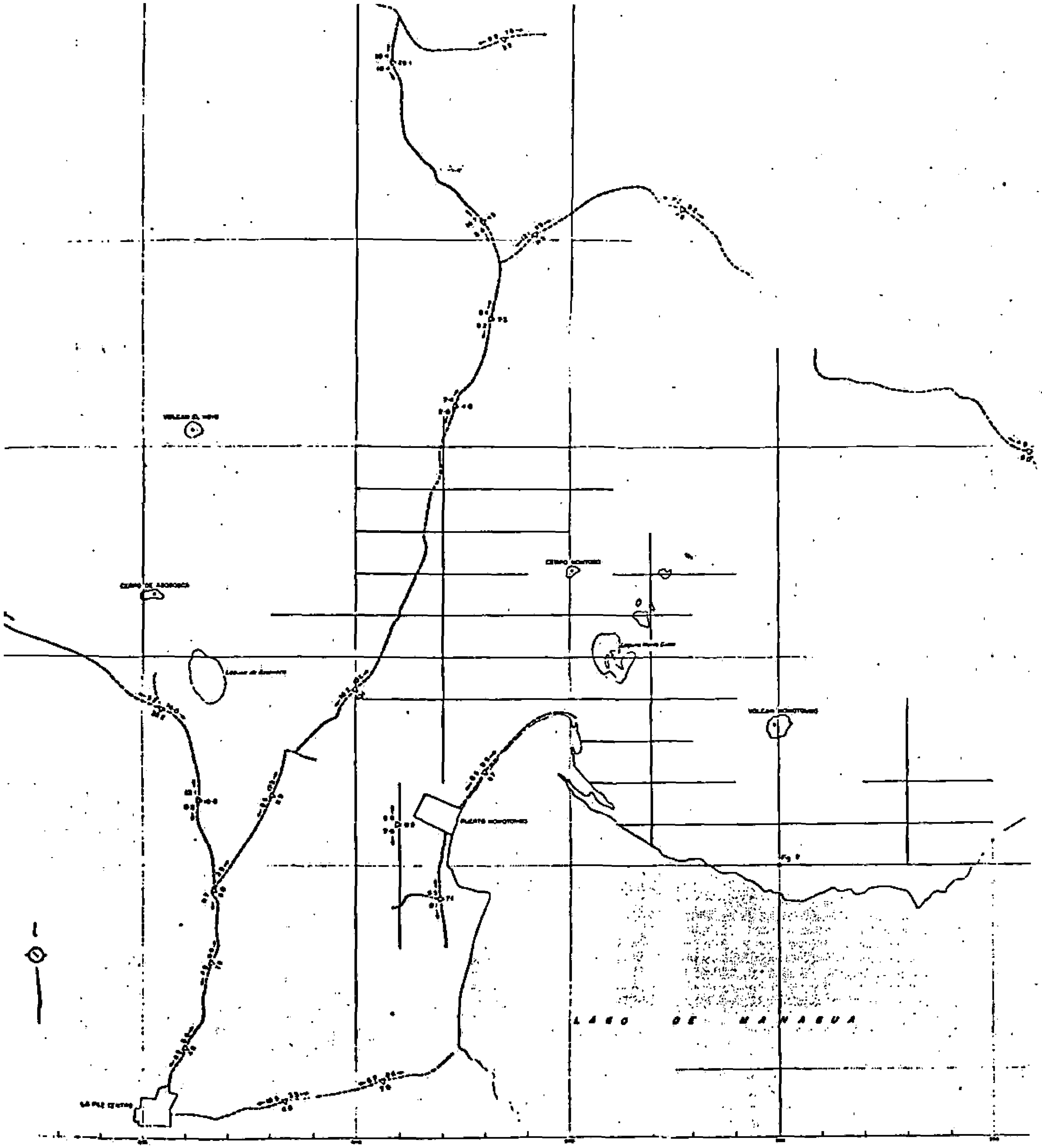
FIGURE ~~65~~. SUMMARY OF DEPTH-SOUNDING INTERPRETATIONS IN THE VICINITY OF V. MOMOTOMBO

Fig. 6.1



URE 69. DIPOLE MAPPING SURVEY FROM DIPOLE SOURCE M1

Fig 6.2



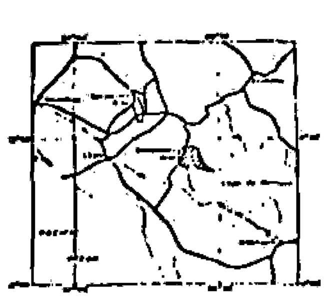


Fig. 6.3

PLATE 8

UNITED NATIONS
GEOTHERMAL RESOURCES DE
IN NICARAGUA

MOMOTOMBO, AREA, NIC

GROUND GEOPHYSICA

RESISTIVITY VALUES OF I

SCALE 1 50,00

SURVEY BY
SCINTREX SURVEYS LTD

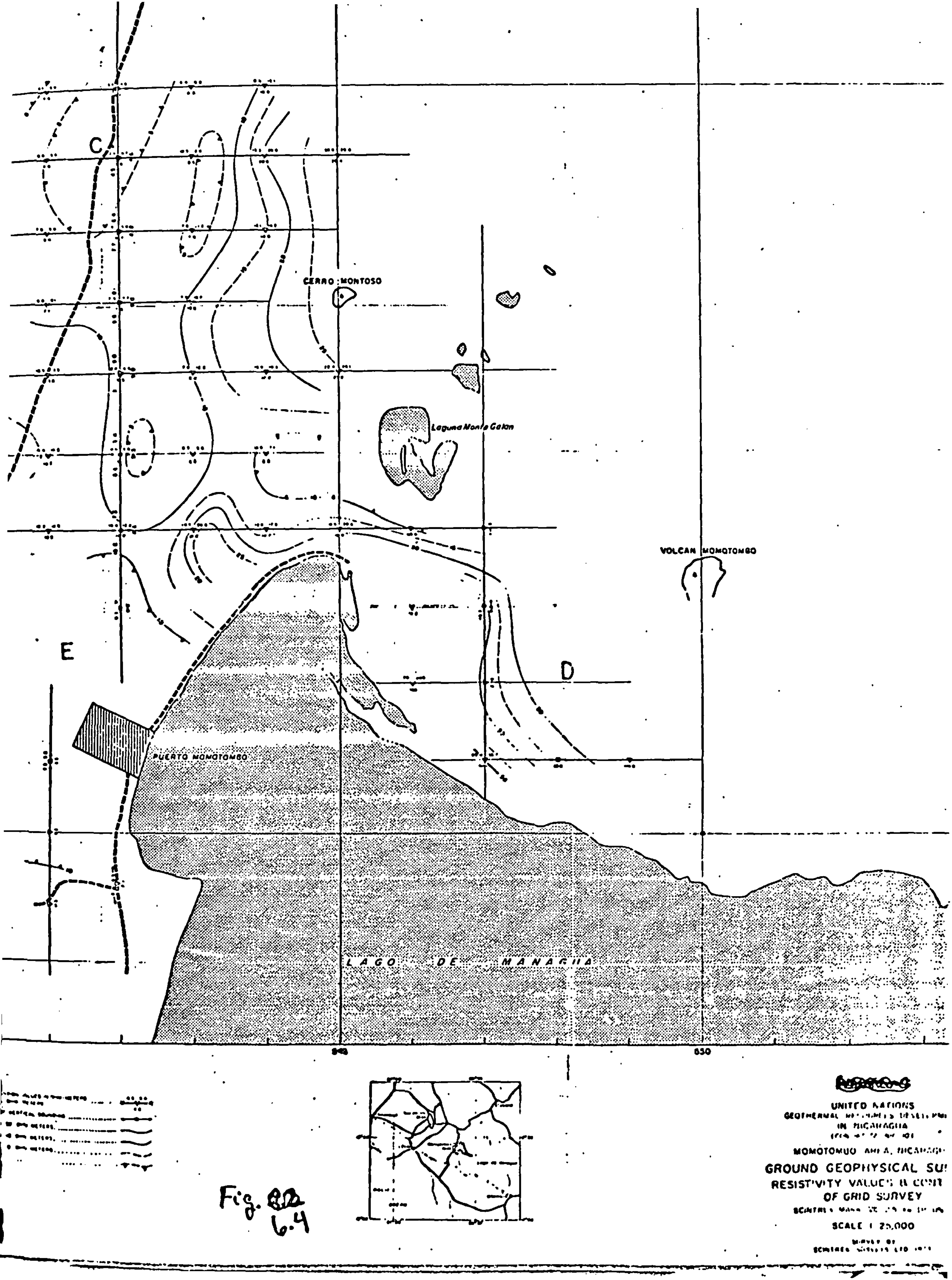

C
CERRO MONTOSO
Laguna Monte Galan
VOLCAN MOMOTOMBO
E
D
PUERTO MOMOTOMBO
LAGO DE MANAGUA
UNITED NATIONS
IN NICARAGUA
MOMOTOMBO AREA, NICARAGUA
GROUND GEOPHYSICAL SU
RESISTIVITY VALUES & CONT
OF GRID SURVEY
SCALE 1:25,000

Fig. 6.4

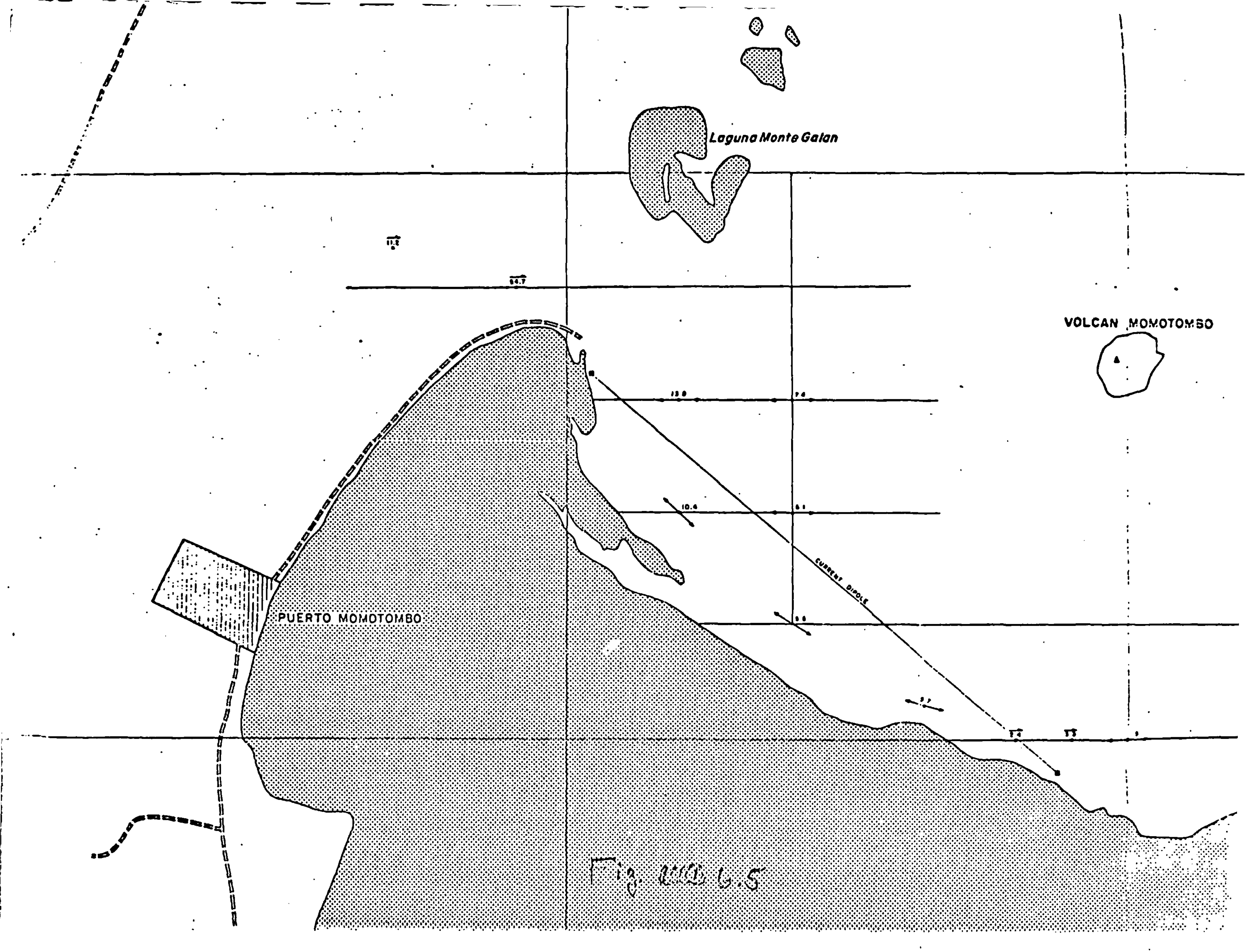

Laguna Monte Galan
VOLCAN MOMOTOMBO
PUERTO MOMOTOMBO
CURRENT DIPOLE
10.4

Fig. [illegible] 6.5

ANEXO 3

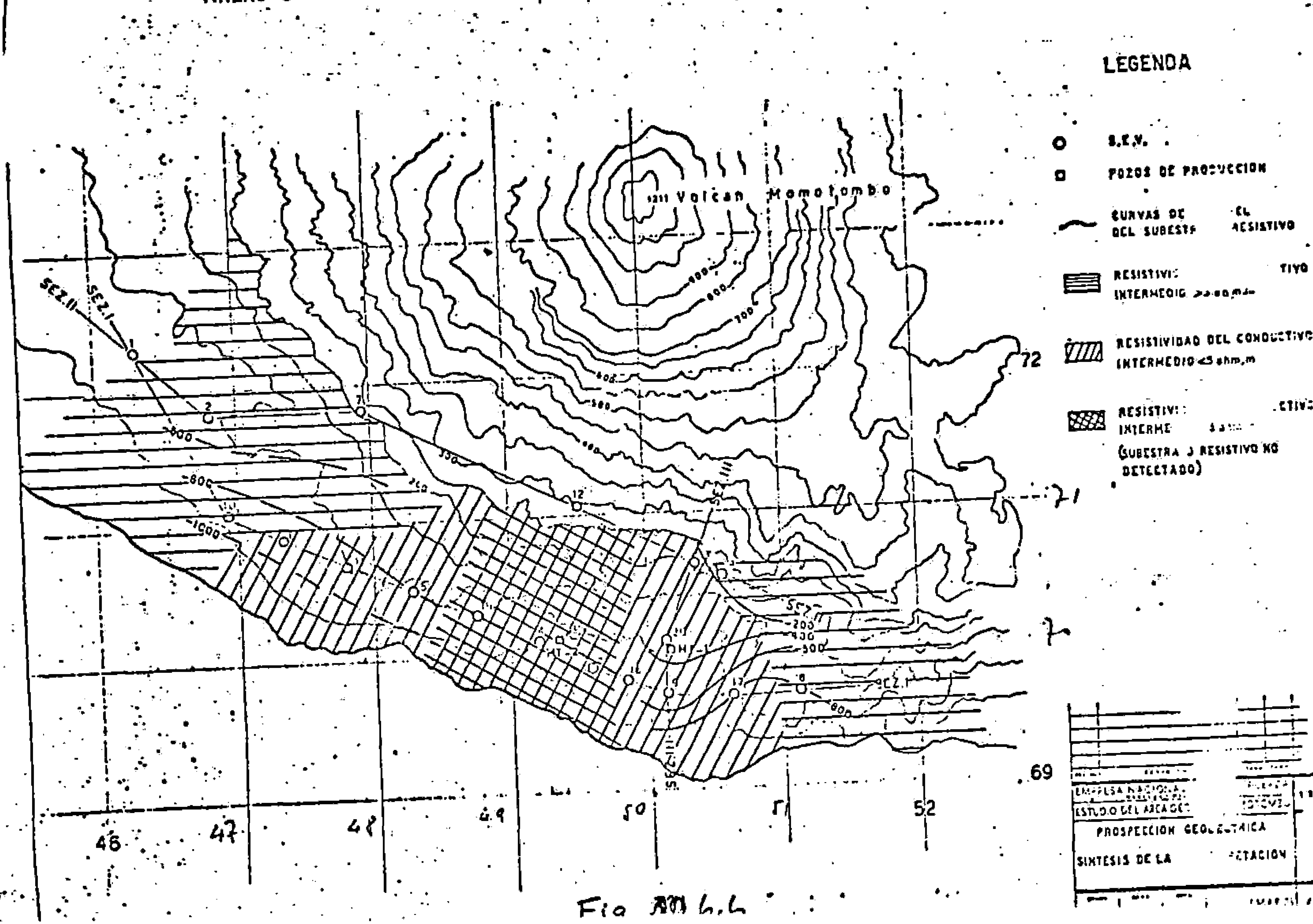


Fig AM 6.6

ANEXO 2

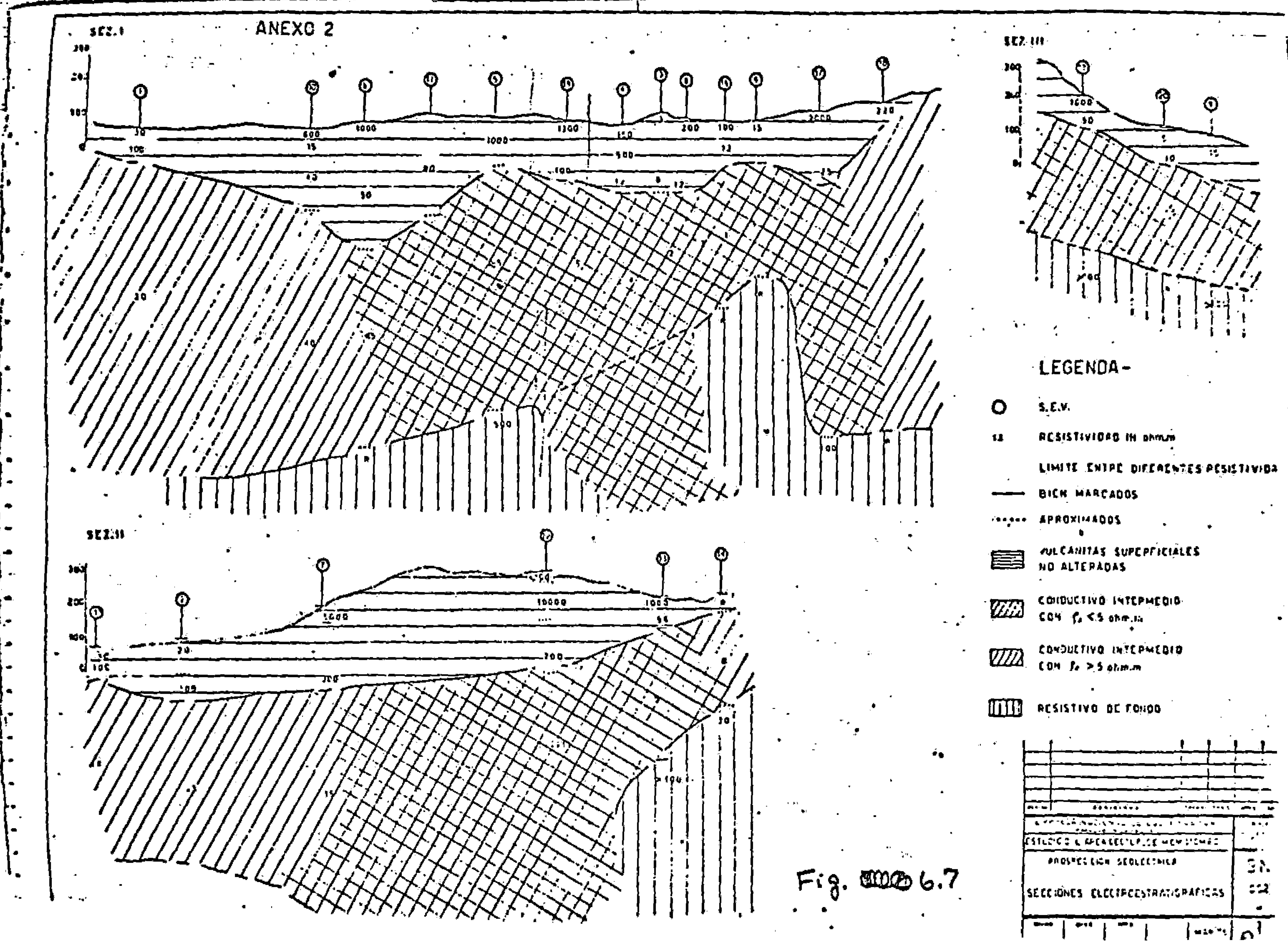
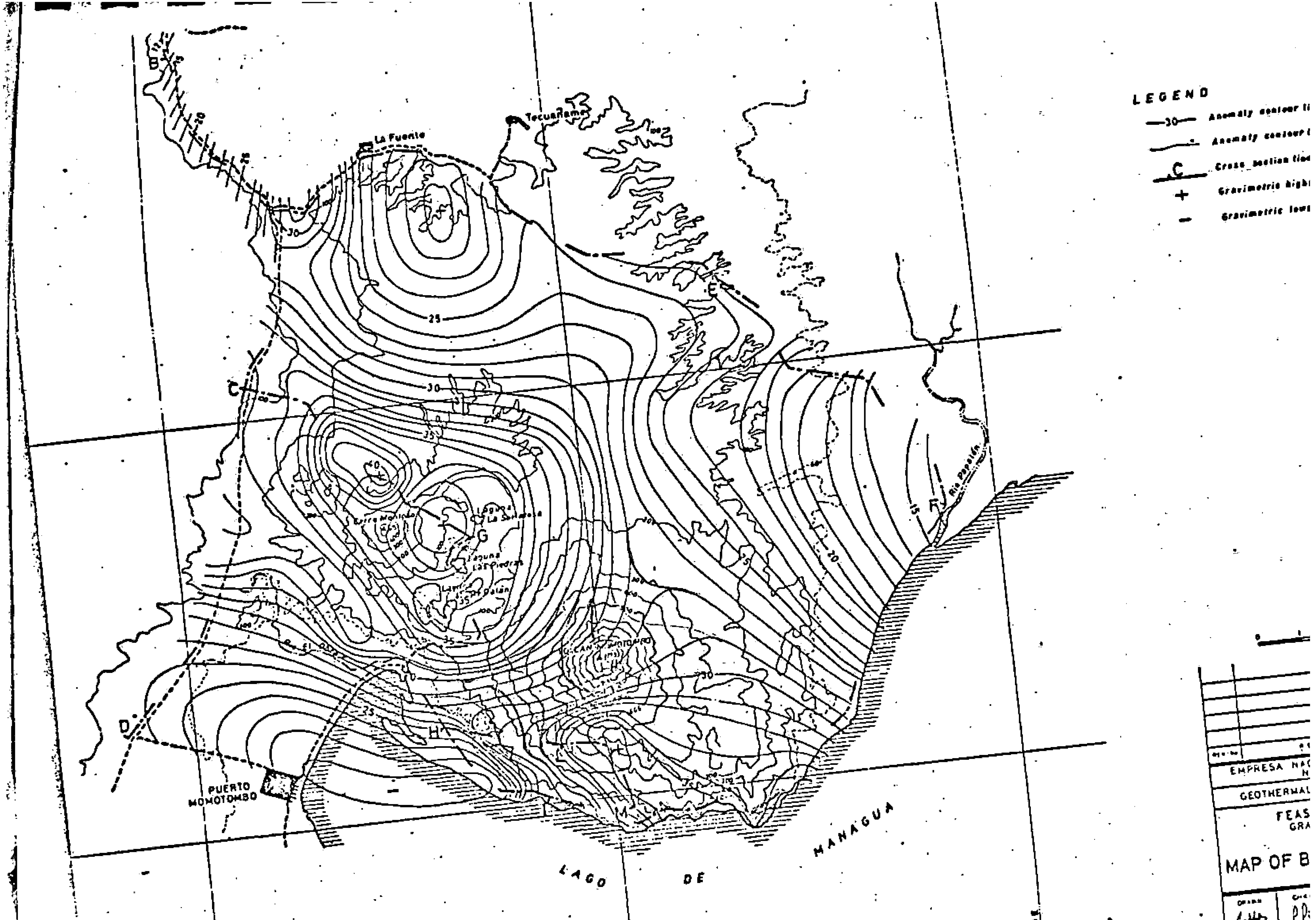


Fig. 6.7


LEGEND
Anomaly contour li
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Gravimetric high
Gravimetric lows
La Fuente
Tecuanamé
Laguna La Sandoval
Laguna Las Piedras
Río Papalón
PUERTO MOMOTOMBO
LAGO DE MANAGUA
EMPRESA NAC
GEOTHERMAL
FEAS
GRA
MAP OF B

Fig. 6.8

CHAPTER 7

GEOCHEMICAL EXPLORATION METHODOLOGY

CHAPTER 8

ADEQUACY OF GEOCHEMICAL EXPLORATION METHODS IN THE VARIOUS EXPLORATION STAGES

PRODUCTION DRILLHOLE SITING CRITERIA

9.1 INTRODUCTION

The unavailability of reports related to deep drillhole siting, limits the information needed for a thorough evaluation of the siting decisions. Data was obtained on only the first 4 deep holes drilled. Of the 31 total wells drilled, 22 were productive and the remaining will probably be used for reinjection.

Geological and geochemical recommendations concerning drill sites were presented in the UNDP report by Jonsson and Sigvaldason (1973). None of the three recommended sites based on geological studies were considered. The geochemical recommendations were of no benefit since it was suggested that drilling be carried out in the area "between the lakeshore and the fumarole at 300 mts" (Sigvaldason, 1973). This area covers almost the entire Momotombo prospect into which all wells were drilled.

9.2 WELLS MT-1 TO MT-4

ELC report (1977) mentions the siting of well MT-1 based on the UNDP study (1974). Its location is 150 mts. east of the recommended site by Jonsson (1973), based on geology studies. The well is not productive. The basis for choosing this location was probably solely on geology, since previous geophysical data (Carriere, et. al., 1974) outlined other nearby areas with lower resistivities than this location. Geophysical results from the ELC report (1975) show a stratigraphic section of this area (Figure 6.7) with subsurface resistivities greater than 5 ohm-meters and also indicating nearby areas with lower resistivities.

Wells MT-2 and MT-3 locations were based on the results of geophysical investigations (ELC report, 1977). Both wells intersected a productive horizon at 300 to 400 mts. depth, and have a first stage power production of 5.9 MW and 6 MW respectively (SAI Engineers report, 1978). The location of MT-2 lies within the low resistivity boundary outlined ~~and~~ by both Texas Instruments (1974) and ELC (1975), however, MT-3 lies only 500 mts from the non productive well MT-1 and within the same resistivity anomaly.

Well MT-4 was sited on the basis of results from MT-2 and MT-3 (ELC report, 1977). No explanation was given with respect to the nature of these results nor the reasoning behind the siting of MT-4. The well has a small first stage power productivity of 2.3 MW (SAI Engineers report, 1978).

9.3 <u>REMAINING WELLS</u>

No information was available on the siting of the remaining 27 wells, however, by examining their locations it is noted that well MT-9 lies exactly in one of the locations recommended by Jonsson (1973). This well has a first stage power productivity of 4.3 MW (SAI Engineers report, 1978). The location of all wells is shown in Figure 9.3. The transparencies indicate whether any well location lies within the low resistivity anomaly or in a major geologic feature.

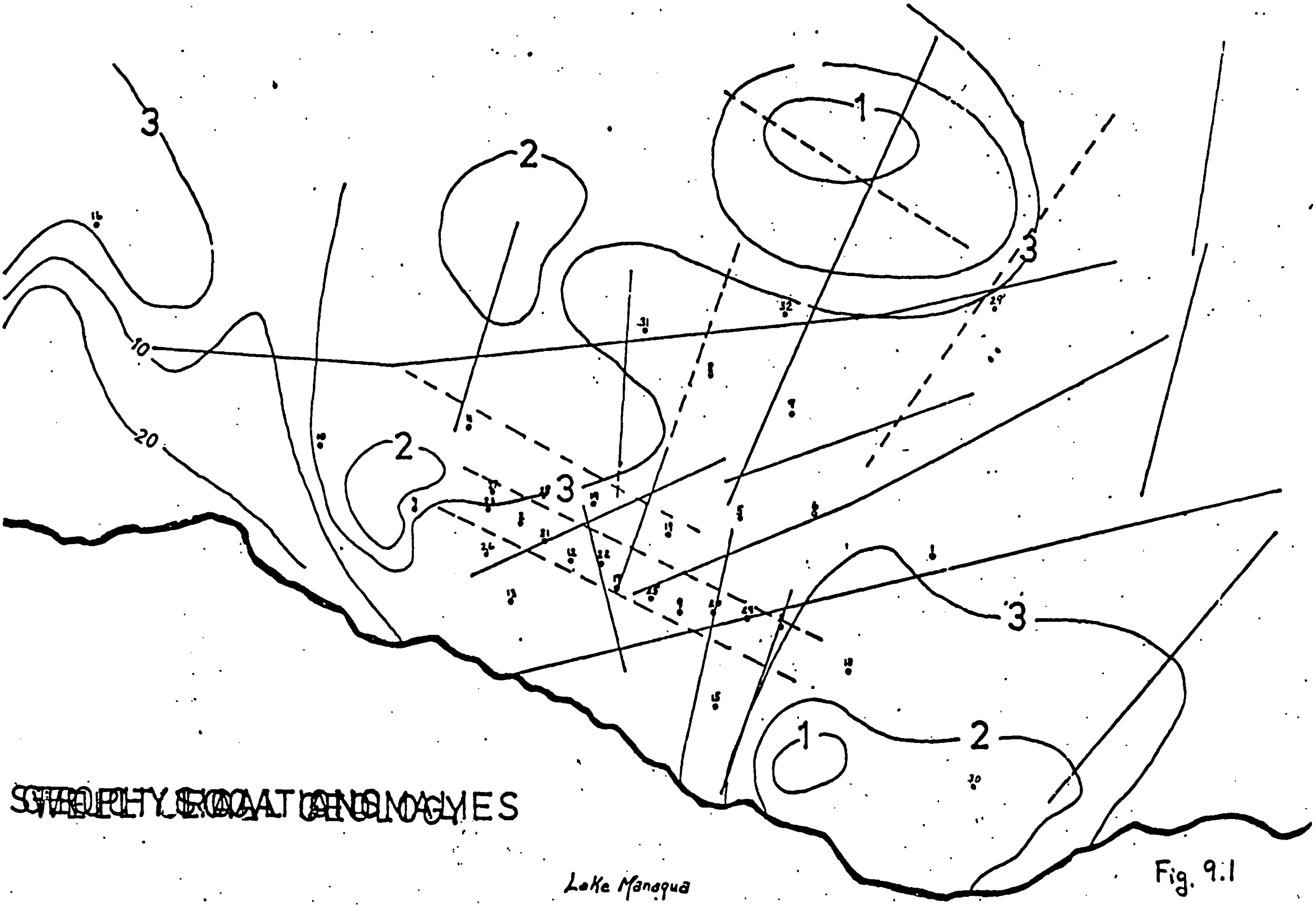

Fig. 9.1

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Exploration for Geothermal Energy in Nicaragua—Summary[1]

JOHN B. THIGPEN[2]

INTRODUCTION

A geothermal exploration project was conducted in 1969–70 over an area of about 38,000 km² in the Cenozoic volcanic zone of western Nicaragua (Fig. 1). The project included a regional geological and geochemical evaluation of the geothermal potential of the area and more detailed geological, geophysical, and borehole studies at two geothermal prospects—San Jacinto–Tisate and Momotombo.

Western Nicaragua is a region of widespread late Cenozoic volcanism, with activity locally continuing to the present (McBirney and Williams, 1965; McBirney, 1958). Tertiary acidic ash-flow tuffs predominate east of the Nicaraguan depression (Fig. 1), whereas Quaternary andesites and basalts are present to the west. An impressive chain of Quaternary volcanic centers is localized along the southwestern margin of the Nicaraguan depression, which is a regional structure of probable volcano-tectonic origin (McBirney and Williams, 1964). This geologic setting is very favorable for development of hyperthermal conditions and, thus, geothermal potential.

Relatively little was known about Nicaraguan thermal activity until recently, when brief descriptions were given by McBirney (1958) and Del Giudice (1959). An inventory, with temperature and some chemical data, of most of the water wells and many of the springs in the project area, by the Catastro i Inventario de Recursos Naturales de Nicaragua project was helpful as a preliminary indication of several thermal manifestations.

REGIONAL EVALUATION OF THERMAL MANIFESTATIONS

The initial phase of the project was an inventory and evaluation of all thermal manifestations, including thermal springs, wells, and fumarolic areas. Expectably, all the fumaroles and most of the higher temperature thermal waters are associated with the area of Quaternary volcanism. Additionally, higher silica concentrations and lower Na/K ratios, both suggesting high subsurface temperatures, are present in thermal waters near the Quaternary volcanic zone. A detailed inventory of all thermal manifestations of western Nicaragua has been prepared by the writer (Thigpen, 1970a; 1971).

Several of the more significant thermal manifestations have been grouped together as thermal areas (Fig. 2). A brief synopsis of each area is presented in Table 1. Thermal activity at the designated areas ranges from moderately intense fumarolic activity and boiling thermal water at Momotombo to relatively low-temperature water at Agua Caliente.

Based on geological and geochemical data, the designated thermal areas are ranked from best to poorest in probable geothermal potential as follows: Momotombo, San Jacinto–Tisate, Jiloa-Apoyeque, Mombacho, northeast Telica–Najo, Casita, Tipitapa, Agua Caliente, Cerro Colorado, and San Luis.

SAN JACINTO–TISATE GEOTHERMAL PROSPECT

Geology—Two small fumarolic areas and several thermal springs (32–66°C) are localized along a north-south-trending fault. Quaternary andesitic-basaltic lava flows and pyroclastic deposits have piled up against a probable fault-line escarpment of older volcanic rocks. Reservoir permeability and recharge potential appear favorable.

Moderately intense thermal activity, including fumaroles (100°C), mudpots, and thermal ground, is present at San Jacinto in a local zone of intense hydrothermal alteration. The current thermal activity at Tisate, 2.5 km north, is restricted to a few feeble fumaroles, but considerable hydrothermal alteration exists. Geophysical data indicate that San Jacinto and Tisate are probably connected at depth.

The only previous geothermal investigations in Nicaragua were made at Tisate in 1953, when three holes were drilled to a maximum vertical depth of 94.2 m and a maximum temperature of

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FIG. 1–Index map of western Nicaragua. Numbered volcanoes are: *1*, Casita; *2*, Telica; *3*, San Jacinto; *4*, Santa Clara; *5*, Rota; *6*, Momotombo; *7*, Apoyeque; and *8*, Mombacho.

142°C was recorded (A. R. McBirney, written commun., 1953). The investigations were terminated when the mining-type drilling equipment proved unsuitable (D. E. Spencer, oral commun., 1969).

Geochemistry—The small (0.3 l/sec) 66°C spring southeast of Tisate is the only significantly mineralized spring in the area. That spring is displaced from the probable locus of thermal activity suggested by the dipole resistivity-mapping survey.

The 140 ppm of SiO_2 and the Na/K ratio of 13.3 from that spring are both favorable, indicating possible reservoir temperatures of about 155°C and 215°C, respectively (after curves of Fournier and Truesdell, 1970; Ellis, 1970). The chemical data are inconclusive, but a hot-water geothermal system is suggested.

Chemical analyses of fumarolic gases were not particularly diagnostic.

Geophysics—Several types of geophysical surveys were conducted over the San Jacinto–Tisate area. Much of the following discussion is after Keller and Harthill (1970).

Resistivity profiling and depth soundings with a Schlumberger array were not very effective because of difficulties in penetrating the highly resistive surficial lavas. A dipole resistivity-mapping survey was much more effective in defining the areal extent of apparently lower resistivity rocks. The survey suggests that a geothermal cell, about 3.0 km long by 0.5–1.5 km wide at the 6-ohm-m contour, may be localized in the San Jacinto area. The contour pattern indicates a north-northeast elongation of the lower resistivity zone, with the 9-ohm-m contour extending to just northeast of Tisate. The southern extent was incompletely defined. Extended depth-sounding calculations suggest that the near-surface zone of relatively high resistivity is about 100 m thick; beneath this zone, resistivities decrease to a few tens of ohm-meters outside the area of thermal activity and to 2–3 ohm-m within. A possible electrical basement is present at a depth of 1.0–1.5 km.

Temperature-gradient boreholes—Six boreholes drilled near the San Jacinto thermal area to obtain temperature-gradient (Table 2) and geologic data penetrated alternating lavas and pyroclastic deposits with minor hydrothermal alteration except for moderate alteration in hole 3.

Momotombo Geothermal Prospect

Geology—Five areas of fumarolic activity and thermal ground are located on the lower southern slopes of Momotombo Volcano (Fig. 3A). This part of Momotombo is an older volcanic structure, separated from the presently active Momotombo cone by a somma ridge, which together with an eastward breach in the summit crater has served to deflect recent lava flows. The last significant eruption of Momotombo was the 1905 lava flow down the northern flank (McBirney, 1958), but high-temperature fumarolic activity continues

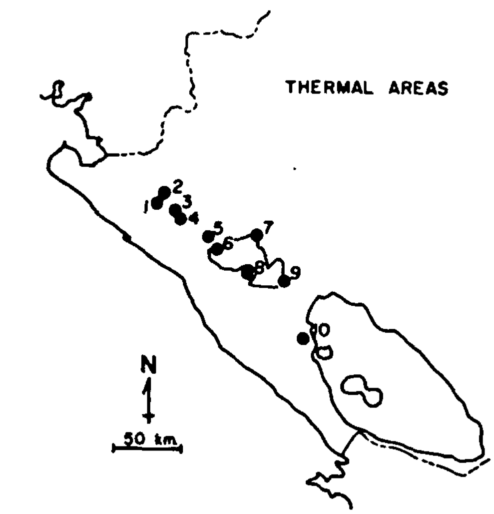

FIG. 2–Index map of designated thermal areas: *1*, Casita; *2*, Agua Caliente; *3*, NE Telica-Najo; *4*, San Jacinto-Tisate; *5*, Cerro Colorado; *6*, Momotombo; *7*, San Luis; *8*, Jiloa-Apoyeque; *9*, Tipitapa; and *10*, Mombacho.

Table 1. Summary of Thermal Areas

Area	*Thermal Activity and Geology*	*Size*	*Elev.*	*Remarks*
Casita	Fumarolic areas localized along faults in pyroclastic deposits on upper slopes of dormant Casita Volcano. Much alteration, locally severe.	0.4 km^2 within overall 3 X 4 km	650-1200 m	Poor potential, unfavorable chemistry, gases mostly H_2O; probable synvolcanic origin, altitude and access unfavorable.
Agua Caliente	Thermal water (max. 55°C) in numerous wells and a few springs. Quaternary alluvium and volcaniclastic sediments in Nicaraguan depression.	3 X 10 km overall	40	Poor to fair potential; perhaps involves deep circulation of meteoric water from volcanic slopes.
NE Telica-Najo	Small, scattered fumarolic areas, often localized along faults in pyroclastic deposits on middle slopes of San Jacinto Volcano.	0.04 km^2 active in overall 1.5 X 3 km	290-500	Fair potential, more study needed.
San Jacinto-Tisate	Vigorous fumaroles, mudpots, and thermal ground with intense alteration in 0.02 km^2 area at San Jacinto. Few feeble fumaroles in moderately altered 0.06 km^2 at Tisate. Localized along N-S fault, with thermal springs, on lower eastern slopes on San Jacinto and Santa Clara Volcanoes.	0.08 km^2 two active areas 2.5 km apart	160-190	Good potential, favorable surface display, chemistry from one spring, and geophysics. Environmental problems due to adjacent village.
Cerro Colorado	Weak fumarolic activity with widespread alteration in eroded cinder cone tephra. Thermal spring (48°) 3.5 km SW.	0.2 km^2	160	Poor potential at synvolcanic fumaroles. Favorable spring chemistry.
Momotombo	Five areas of strong fumarolic activity; prevalent alteration, locally severe on lower southern slopes of "older" Momotombo Volcano in lava-tephra overlying pyroclastics. Strong fault control. Boiling springs and seeps along Lake Managua shoreline.	0.8 km^2 active in overall 2 X 2.3 km	40-360	Best potential of sites investigated. Favorable geology, chemistry, geophysics, with few environmental problems.
San Luis	Numerous thermal springs (max. 89°C) in fracture or fault controlled alignments. Several associated travertine mounds. In Quat. alluvium near Tert. volcanics.	1 X 3 km overall	40	Poor potential; travertine is a qualitative indicator of low temperature at depth (White, 1970), but favorable SiO_2.
Jiloa-Apoyeque	Very small fumarolic area and several thermal springs near summit crater and lateral phreatic crater of eroded and inactive Apoyeque Volcano.	2 X 5 km overall	40	Fair potential; favorable chemistry. Close to major city of Managua.
Tipitapa	Several localized thermal springs (max. 96°C) in Quat. alluvium and pyroclastics perhaps on concealed fault.	Small, other nearby springs	40	Poor to fair potential; silica and boron favorable, but Na/K ratio unfavorable (?).
Mombacho	Very small fumarolic area and small thermal springs near top of Quat. Mombacho Volcano. Other thermal springs (max. 55°C) around base.	Small, but with basal springs 8 X 10 km	30-1000	Fair potential. Synvolcanic(?) features on the volcano are less favorable than those around base.

to the present in the summit crater. The thermal areas are in andesitic-basaltic pyroclastic deposits and lavas, whereas the younger lavas from Momotombo are basalts. Suitably permeable reservoir rocks are present in the sequence and recharge potential is good.

The surface thermal manifestations—extensive fumarolic-solfataric and thermal-ground areas—have the most activity of any site in Nicaragua. Hydrothermal alteration ranges from moderate to severe, locally resulting in a siliceous residue within the fumarolic areas. Minor boiling springs (101°C) discharge about 5 l/sec from permeable alluvium-pyroclastic layers at the southeastern site. The presence of minor siliceous sinter at some of these springs is a qualitative indicator of

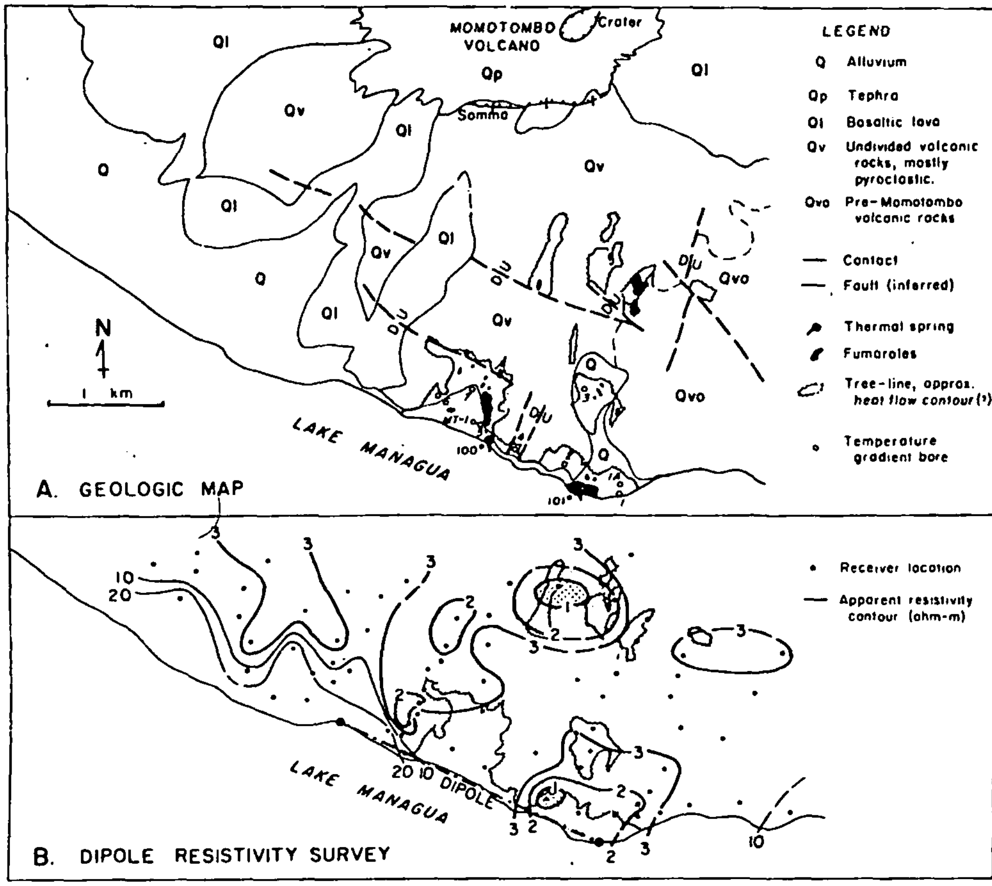

FIG. 3—Momotombo thermal area: A. Geologic map (Thigpen, 1970b); B. Dipole resistivity survey (after Keller and Harthill, 1970).

temperatures above 180°C (White, 1970). Boiling thermal seeps occur at the southwestern site and, especially in the wet season, numerous thermal springs and seeps occur nearby in the waters of Lake Managua.

Several faults, partly inferred, are interpreted by the writer to exert strong control on the localization of thermal activity by serving as the conduits from depth. The two northern thermal areas are adjacent to an east-west fault system (Fig. 3A), and the three southern thermal areas are, for the most part, either adjacent to or downslope from another east-west fault system.

The thermal manifestations are thought to represent late-stage solfataric volcanic activity, perhaps originating at considerable depth from a cooling magma intrusion.

Geochemistry—Thermal waters from the boiling springs are relatively highly mineralized. Although chemical data are inconclusive, a hot-water geothermal system is suggested.

The thermal water contains an average of 145 ppm SiO_2, with a maximum of 180 ppm, and an average Na/K ratio of 16.7. These values suggest subsurface temperatures of 170°C and 185°C, respectively (Fournier and Truesdell, 1970; Ellis, 1970). A higher temperature of 209°C was measured in a deep borehole. The discrepancy could be due to chemical inequilibrium and/or geographic separation (Fig. 3A).

Geophysics—Dipole resistivity-mapping surveys revealed an extensive area of apparently low-resistivity rocks with much lower values than at San Jacinto (Fig. 3B). Part of the following discussion is after Keller and Harthill (1970). Closure of the low-resistivity contours was not attained, either northward toward Momotombo or, in the southeastern part of the area, southward underneath

Table 2. Temperatures Measured Near San Jacinto Thermal Area

Hole	Total Depth (m)	Max. Temp. (°C)	Depth (m)	Temp. Gradient (°C/10 m)
1	13.1	No data	—	—
1A	12.2	No data	—	—
2	61.9	50	60.9	5.9
3	61.9	105	60.9	9.5
4	61.9	30	15.2	Isothermal
5	61.9	30	Uniform	Isothermal

Lake Managua. The resistivity contour pattern suggests two separate zones trending generally east-west. The northern zone practically coincides with the previously mapped fault system to the west, but not to the southeast. The incomplete 3-ohm-m contour encloses a minimum area of about 4 km^2.

Extended depth-sounding calculations and electromagnetic-sounding data show high resistivity in the near-surface rocks and, in the underlying rocks, low resistivities apparently extending to considerable depth (at least 2 km). There was no strong indication of electrical basement.

Temperature-gradient boreholes—Eight holes penetrated an alternating sequence of predominantly lavas and lesser pyroclastic deposits. Hydrothermal alteration ranges from slight to severe, but is more intense than at San Jacinto.

Temperature data, obtained with a thermister array, revealed favorable temperature gradients. These data, with maximum credible temperatures and highest gradients from several observations, are summarized in Table 3.

Deep borehole—One nominal 14.3-cm hole (MT-1) was drilled with a slim-hole drill rig to a depth of 608.2 m (Fig. 3A). A sequence of basalt flows with minor tuff intercalations was penetrated to a depth of 65 m. Below that depth the apparently pre-Momotombo lithologic sequence is mostly tuffs and other pyroclastic deposits with minor andesitic and basaltic lava flows. Hydrothermal alteration ranges from moderate to locally severe; severely altered zones occur at 150–195 m, 225–260 m, and in most of the section from 460 to 608.2 m. Much of this pyroclastic sequence appears to have good reservoir potential.

A maximum temperature of 209°C was measured at a depth of 213 m where a cave-in prevented deeper wire-line temperature measurements. That temperature confirmed predictions from thermal gradients as in nearby hole 5 and showed a favorable correlation between low resistivity and high temperature at depth. No production tests were attempted.

Summary and Conclusions

Western Nicaragua has very good geothermal potential. Ten prospects were defined during this evaluation. Most geothermal prospects and other thermal manifestations are associated with the Quaternary volcanic zone, where hyperthermal conditions appear to be widespread. Other hidden or "blind" geothermal reservoirs are likely to be present in the Quaternary zone and possibly scattered through the Tertiary volcanic zone.

The San Jacinto–Tisate and Momotombo geothermal prospects both show very favorable potential after detailed preliminary evaluation. The Momotombo prospect shows more positive indications of geothermal potential, particularly in larger size and higher temperature. Geochemical

Table 3. Temperature Data for Momotombo Thermal Area

Hole	Depth (m)	Max. Temp. (°C)	Depth (m)	Temp. Gradient (°C/10 m)	Remarks
1	61.9	152	57.9	13.8 av., 27.5 max.	
1A	61.9	—	—	—	No data, hole erupted
2	61.9	96	60.2	2.6	Near isothermal
3	61.9	140(?)	53.4	7.7 av., 23.0 max.	
4	47.2	84	23.5	7.5	Inversion below 23 m
5	55.8	165	49.2	9.8	Hole later erupted
6	31.4	92	19.2	17.0	Shallow data only
7	61.9	150	59.5	11.8	Inversion below 44 m, later erupted

and geophysical data are moderately favorable at San Jacinto–Tisate and very favorable at Momotombo.

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