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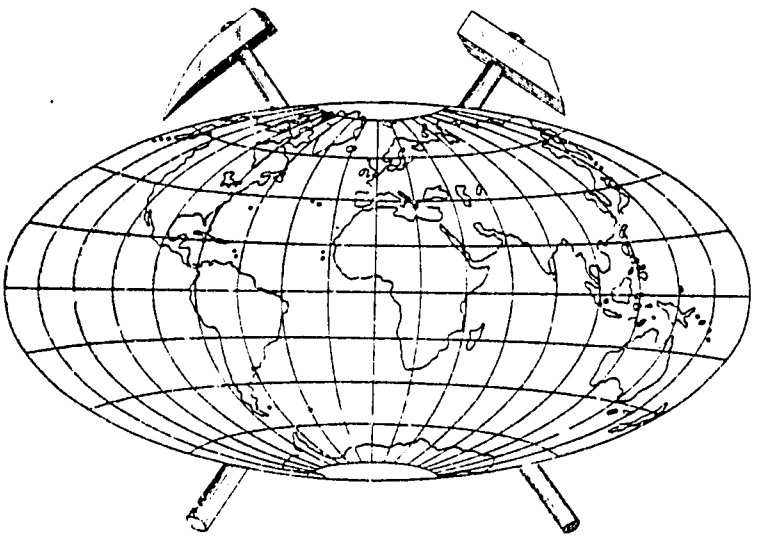
REPORT ON THE FEASIBILITY OF A GEOTHERMAL RESOURCES ASSESSMENT FOR CENTRAL AMERICA



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REPORT ON THE FEASIBILITY OF A GEOTHERMAL RESOURCES ASSESSMENT FOR CENTRAL AMERICA

by

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The Project Report series presents information resulting from various kinds of scientific, technical, or administrative studies. Reports may be preliminary in scope, provide interim results in advance of publication, or may be final documents.

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EXECUTIVE SUMMARY

The emerging nations of Central America are verging on an energy shortage which could severely hinder their economic and industrial development. Faced with ever increasing costs to import oil as a source of energy, the Central American nations are anxious to exploit their own natural energy sources and thus improve their balance of payments. Combined with hydropower, the region's potentially abundant geothermal resources could produce enough electricity to alleviate, if not eliminate, the need to import oil as a fuel for electrical generation.

The purpose of this report is to advise on the feasibility of performing a regional assessment of the geothermal resources of Central America and to recommend an appropriate course of action to accomplish an assessment. A review of the literature and reports on the geothermal resources of Central America indicates that there is not enough data to execute a credible assessment at this time. Furthermore, discussions with officials of the Organización Latinoamericana de Energia (OLADE) and national scientists in Costa Rica, Guatemala, and Panama indicate that the nations of Central America generally do not have the civil employees with the necessary background to undertake an assessment on their own. Thus, technical support would have to be provided by an outside organization or agency with geothermal-assessment capabilities.

The goals of the assessment should be threefold: (1) document and quantify the region's geothermal energy resources using a systematic and consistent methodology; (2) provide a supportable basis for planning national energy policy and for funding geothermal projects; and (3) transfer technology and knowledge on state-of-the-art geothermal assessment/evaluation methods to Central American scientists.

To accomplish these goals and provide the most immediate benefit to the region, the geothermal assessment must be practical in nature. Therefore, it is recommended that the assessment (1) be conducted in three graduated stages (only stages 1 and 2 are recommended at this time), (2) concentrate on assessing the more commercially important geothermal systems (hydrothermal convection and igneous-related), and (3) use a standard, but flexible, set of procedural steps throughout each stage to insure consistency.

The transfer of up-to-date technology and knowledge will be one of the assessment's chief contributions to the nations of Central America. National scientists are expected to participate directly in the assessment and thereby gain experience and confidence in geothermal assessment methodologies. They in turn will provide a strong foundation of geothermal expertise within their respective national agencies. Once practiced in assessment methodology and data interpretation, the national scientists should be in a position to perform future geothermal assessments and evaluations with little outside technical assistance. They also should be able to evaluate and judge better the soundness of consultants' work, and have a better appreciation for the types of data needed for various geothermal projects.

REPORT ON THE FEASIBILITY OF A GEOTHERMAL RESOURCES ASSESSMENT OF CENTRAL AMERICA

By Charles Brook

INTRODUCTION

The successful economic and industrial development of emerging nations is strongly dependent upon the availability of reliable and relatively inexpensive energy sources. Developing countries that must import oil as a major energy source are particularly vulnerable to the adverse economic impacts caused by increasing oil prices and fluctuating supply. The rapid increases in the price of oil during 1973-74 and 1979-80, which impacted the world economy as a whole, have had severe repercussions on the financial stability of many oil-importing countries. Much of their oil expenditure now must be financed through borrowing of foreign exchange rather than through increased exports (Munasinghe, 1984). This has led to a significant deterioration in the balance of payments for many of these countries.

The countries of Central America (Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panamá) are not immune to the adverse financial and developmental impacts caused by high oil prices. Although many of these countries are developing their hydropower resources, hydroelectricity alone will not be enough to supply all of the region's future energy demands[1]. And unless new indigenous sources of energy are identified

[1]Most damable sites already have been utilized, and many hydroplants are subject to reduced output during periods of drought. Run-of-the-river hydroplants are an option for the future, but these are even more subject to seasonal fluctuations in rainfall and river discharge (R.O. Fournier, personal commun., 1984).

and developed, many of the Central American nations may be facing an energy crisis in the near future. An energy crisis in this part of the world would not only impact the economic and industrial growth of the region, but also could have far reaching political ramifications.

The wealth or dearth of a region's mineral and energy resources is a function of its geology. Fortunately, much of Central America is located in a geologic environment that is favorable for the development of geothermal resources. All of the nations of Central America, except for Belize and perhaps Honduras, have a high potential for geothermal resources capable of generating electricity. Two nations--El Salvador and Nicaragua--already have demonstrated the practicality of exploiting their geothermal resources for electrical production; El Salvador's 95-MWe plant at Ahuachapán produces about 25 to 44 percent of the country's electricity, and Nicaragua's 35-MWe plant at Momotombo provides about 12 percent of that country's electricity (Cunningham and others, 1984). The successful development of Central America's geothermal resources would effectively complement the hydropower developments, and with the completion of the proposed electrical grid system between the nations, could do much to make the whole region more energy self-sufficient. Furthermore, the cost of generating electricity in geothermal plants in Central America is significantly less, perhaps as much as 15 percent (Bethancourt, 1983), than the cost of generating electricity in thermal plants using petroleum for fuel. Thus, development of the region's geothermal resources would favor a foreign-exchange savings owing to lesser oil imports.

Energy problems can not be meaningfully separated from national development issues, and unless both issues are resolved, the effects of higher energy costs will continue to reduce real incomes and living

standards, increase unemployment, and fuel inflation in the developing, oil-importing nations of Central America. Accordingly, effective energy planning and management are imperative for their economic and political stability. Before policy makers in Central American governments can enact wise energy-management decisions, they must have an inventory of their indigenous energy resources and a quantification of the resource potential. A resource assessment, which can be defined as "the broad-based estimation of future supplies of minerals and fuels" (Muffler, 1981), affords government officials a tool for planning national energy policy and priorities. A resource assessment also can be used by financial institutions to make funding decisions for specific projects.

PURPOSE OF REPORT

The purpose of this report is to advise on the feasibility of conducting a geothermal resource assessment for Central America. As such, this report fulfills the committments of item 8, Reconnaissance of the Geothermal Resources Potential of Central America, in the U.S. Agency for International Development's (AID) S&T/EY Resources Support Services Agreement STB-5724-R-TC-2050 with the U.S. Geological Survey. This investigation was funded by AID at the request of the Organización Latinoamericana de Energia (OLADE), which has given top priority to a geothermal resource assessment for Central America.

SCOPE OF WORK PERFORMED

This section briefly describes the schedule of work leading to the conclusions and recommendations presented in this report. The work was divided chiefly into two parts: (1) a review of the literature on the

geothermal resources of Central America, and (2) meetings and discussions with geoscientists in the United States and Central America who are familiar with geothermal-related activities in the region. Much of this work was carried out at the U.S. Geological Survey facility in Menlo Park, California (headquarters of the Geothermal Research Program), and during a trip to OLADE headquarters in Quito, Ecuador, and to the national electrical agencies in Panamá, Costa Rica, and Guatemala.

Literature Review

A review of the pertinent geothermal literature was necessarily limited to those reports published in the scientific and technical journals available in U.S. Geological Survey and personal libraries. Unpublished, and in some cases proprietary, reports held in various personal and official files were also reviewed. Most of the proprietary reports consist of studies performed by international consultants under contract to the individual national electrical agencies. A selected bibliography of geothermal resources-related literature for Central America is given at the end of this report.

Meetings and Discussions

Discussions with geoscientists in the United States were held primarily to identify sources of information and to review past and present geothermal projects. Contacts in the U.S. Geological Survey included Robert Christiansen, Robert Fournier, Patrick Muffler, John Sass, and Don White, whose combined personal knowledge and files proved a source for much information. Academicians contacted included David Blackwell (Southern Methodist University) and David Chapman (University of Utah) for information on regional heat flow (there are essentially no heat flow data on a regional scale). Sveinn Einarsson of the United Nations' Division of Natural

Resources and Energy provided a review of United Nations geothermal projects in Central America. Except for William Isherwood of GeothermEx, Inc., no effort was made to contact industry or private geothermal consultants; studies and data generated by these groups are generally maintained in a confidential status and are released only with the written permission from the contracting agency.

Meetings at OLADE were held mostly with Gustavo Cuéllar, Chief of OLADE's geothermal program. Topics of discussion centered around identifying an appropriate methodology for geothermal resources assessment, clarifying the types and quality of data required for the applicable assessment methodology, and establishing procedures and reasonable options to implement the assessment.

Meetings with scientists and officials of national electrical agencies in Central American included the following: Vicente Rios and Arturo Ramirez, Instituto Recursos Hydráulicos y Electrificación (IRHE), Panamá; Manuel Corrales, Instituto Costarricense de Electricidad (ICE), Costa Rica; and Edgar Tobias and Rolando Bethancourt, Instituto Nacional de Electrificación (INDE), Guatemala. As with other national electrical agencies in Central America, these agencies are responsible for the exploration and development of the geothermal resources within their nation's borders. These meetings were held primarily to open channels of communication, to determine each agency's interest in conducting a geothermal assessment, and to explain assessment methodology and implementation procedures. Inquiries were also made regarding the availability of data, support personnel, and equipment.

SUMMARY OF GEOTHERMAL INVESTIGATIONS IN CENTRAL AMERICA

This section reviews the history of geothermal investigations in Central America and the present stage of exploration and development in each country. National agencies, private consultants, and foreign participants who have conducted geothermal studies in the region are identified; references to their reports can be found in the Selected Bibliography.

Belize

Belize has no reported geothermal resources and apparently has never undertaken any geothermal investigations.

Costa Rica

Beginning in 1975, the Instituto Costarricense de Electricidad (ICE) and its prime consults, Rogers Engineering Company and GeothermEx, began a concentrated study along a 30-km zone on the southwest flank of the volcanic cordillera in Guanacaste Province, northwestern Costa Rica. A report prepared by Rogers Engineering Company (1976) details the geology, gravity, geohydrology, electrical resistivity, geochemistry of thermal waters, and heat flows and temperature gradients from 35 boreholes in the zone.

The study of the Guanacaste zone led to the selection of an area on the southern slope of Miravalles Volcano for additional investigations (Electroconsult, 1983) and the proposed siting of a geothermal power plant. Electroconsult (of Italy) is ICE's prime consultant for this phase of the project, which is planned to result in a 55-MWe plant. The Miravalles project is being financed by the Interamerican Development Bank (IDB); a five-member panel consisting of Robert Christiansen and Robert Fournier (U.S. Geological Survey), Franco Barberi (University of Pisa), Ronald DiPippo (Southeastern Massachusetts University), and Roland Horne (Stanford University) is advisory to ICE on the project.

With funding from the United Nations, ICE recently awarded a contract to Italy's Ente Nazionale per l'Energia Elettrica (ENEL) to conduct a geothermal reconnaissance study of the entire volcanic chain in Costa Rica (Manuel Corrales, ICE, oral commun., 1984). The study will cover approximately 20,000 km^2 and is projected to begin in early 1985. Other than the Guanacaste study, little useful information is available on the geothermal resources of Costa Rica.

El Salvador

The first geothermal studies in El Salvador were begun in 1953 in the Ahuachapán area by the Geological Survey of El Salvador and the Comisión Ejecutiva Hidroeléctrica del Rio Lempa (CEL; Ramos, 1983). Additional geothermal studies were conducted in the early- to mid-1950's by Italian, British, and German consultants. Investigations of geothermal resources on a national level were begun in 1965 with financial aid and technical assistance from the United Nations Development Program; detailed studies were conducted in the areas of Ahuachapán, Berlin, San Vicente, Chinameca and Chipilapa. Much of this work was completed by 1970 and reported to CEL in a series of documents prepared under the auspices of the United Nations Development Program (1970). The United Nations also assisted in the feasibility study of developing the Ahuachapán field, which ultimately led to the construction of the first power plant. Commercial operations began in 1975, and Ahuachapán now supports three geothermal power plants with a combined capacity of 95 MWe. CEL is continuing studies at Berlin, San Vicente, Chinameca and Chipilapa.

A considerable volume of information has now been published on the Ahuachapán field. However, the overall picture of geothermal resources in El Salvador is still incomplete. Several thermal springs are known, but

many remain to be sampled. Obtaining additional data to complete a geothermal resources inventory may be difficult or impossible owing to the inaccessibility of some of the springs and guerrilla activity in the country's northeast quadrant.

Guatemala

The Instituto Nacional de Electrificacion (INDE) began geothermal investigations in 1972 with studies of the Moyuta area; studies in the Zunil area began shortly thereafter in 1973 (Bethancourt, 1983). A contract was awarded to Electroconsult in 1975 to complete the surface studies initiated by INDE in the Moyuta field and to drill one deep exploration well to determine the commercial feasibility of the reservoir. Temperatures measured in the first well and an additional deep exploration well proved too low to support electrical generation, and activities at Moyuta have been suspended.

Studies at Zunil were carried out sporadically between 1973 and 1977 with technical assistance from the Japan Overseas Technical Cooperation Agency. INDE began a prefeasibility study of Zunil in 1977, and the field continues to receive most of the geothermal interest in Guatemala.

Preliminary studies of Amatitlán were briefly carried out jointly by Electroconsult and INDE in early 1977; OLADE is now supporting additional studies in the field. In 1982 the French Bureau de Recherches Géologique et Minières (BRGM) completed a regional reconniassance study, supported by OLADE, of the geothermal resources in the volcanic cordillera and in adjacent volcanic areas in southeastern Guatemala. Although data gaps are recognized, the BRGM report contains a significant amount of information that could be used in a geothermal assessment. The U.S. Geological Survey (R.O. Fournier, personal commun., 1984) has conducted detailed

geochemical studies at Zunil and San Marcos.

Honduras

Geothermal exploration in Honduras began in 1976 with technical assistance from the United Nations (Flores and Mass, 1983). In 1977 the Empresa Nacional de Energía Eléctrica (ENEE) contracted Geonomics, Inc., to do preliminary investigations in selected areas; however, this work was not completed owing to financial difficulties in the company. Assistance was again acquired from the United Nations in 1978, and in 1979 GeothermEx was hired to conduct a hydrogeochemical reconnaissance of the country. This study resulted in the inventory of 128 hydrothermal manifestations and 111(?) water analyses. However, none of these data has been released. The geothermal project in Honduras was placed in abeyance in 1980 due to lack of financing.

Nicaragua

The search for possible geothermal fields in Nicaragua was begun in 1966 by Electroconsult (Tiffer and Lacayo, 1983). In 1969 the Government of Nicaragua awarded a contract to Texas Instruments, Inc., to conduct a reconnaissance study of the geothermal resources in western Nicaragua with the objective of identifying a field or fields with commercial potential. Thigpen (1976) summarizes the Texas Instruments' work. Completed in 1971, these studies identified Momotombo as the most likely target for commercial geothermal production. The San Jacinto-Tizate area was also identified as a geothermal target.

The Government continued the geothermal exploration program in 1972-73 with prefeasibility studies of the Momotombo and San Jacinto-Tizate areas; financial and technical assistance was provided by the United Nations Development Program. At the end of 1973, the Empresa Nacional de Luz y

Fuerza (ENALUF), which is now the Instituto Nicaraguense de Energia (INE), was placed in charge of the geothermal program. In 1974 ENALUF contracted the services of Electroconsult to test the Momotombo prospect by deep drilling and to make technical and economic feasibility studies for a geothermal power plant (Electroconsult's final report was submitted in 1976). The drilling company Foramines was also contracted in 1974 to drill four dual-purpose (exploration/production) wells. In 1975, ENALUF contracted California Energy Company, Inc., to plan and supervise the drilling of 12 production wells with Energetics S.A. as the drilling contractor. The first Momotombo unit, rated at 35 MWe, became operational in August 1983. A large volume of data on Momotombo is available in the published literature.

In 1980, INE and OLADE undertook a prefeasibility study in the area between the volcanoes of El Hoyo-Momotombo and San Jacinto-Tizate, and in 1981 OLADE completed a reconnaissance study of the geothermal resources in the volcanic cordillera of western Nicaragua. INE conducted prefeasibility studies in the area between the cities of Granada, Massaya, and Nandaime in 1982. No data have been released yet.

Panamá

A detailed chronological summary of the numerous geothermal studies conducted in Panamá is given in Rios and Ramirez (1983). Investigations of the hydrothermal manifestations in the country were initiated in 1971. In 1974 the Panamanian Government assigned the primary responsibility for geothermal investigations in Panamá to the Corporación de Desarrollo Minero-Cerro Colorado (CODEMIN). CODEMIN's objective was to identify a geothermal site that could support electrical generation for use in the electrolytic recovery of copper from the ores mined in Chiriqui Province.

Consequently, most of the geothermal studies in Panamá were concentrated at Cerro Pando volcano in western Chiriqui Province. Several outside organizations, including the United Nations, the French Bureau de Recherches Géologiques et Minières, the Comisión Ejecutiva Hidroeléctrica del Rio Lempa (CEL) of El Salvador, and the Institute of Geological Science (of England), were contracted for various geoscientific studies at Cerro Pando (see Rios and Ramirez, 1983, for details). In 1980 geothermal investigations in Panamá became the exclusive responsibility of the Instituto de Recursos Hydráulicos y Electrificación (IRHE), which completed in that year an updated survey of Panamá's known thermal manifestations; 37 thermal areas were identified.

A reconnaissance study of the Baru-Cerro Colorado geothermal complex, which includes the Cerro Pando area, in western Chiriqui Province was completed by OLADE in 1981. Following OLADE practice, this report compiles in detail the known geologic, volcanologic, geochemical, geophysical, and hydrogeological information on the area and interprets that information within the context of geothermal resources. On the basis of the recommendations made by OLADE, IRHE has obtained funding from the Inter-american Development Bank (IDB) for a national geothermal reconnaissance and for an advanced prefeasibility study of the Baru-Cerro Colorado complex. The prefeasibility study will be overseen by an advisory group that includes Robert Fournier of the U.S. Geological Survey.

AVAILABILITY AND QUALITY OF INFORMATION

The types of data required for the kind of regional geothermal resources assessment that will be proposed later in this report are generally those data generated by reconnaissance and prefeasibility

studies, as defined in OLADE's geothermal exploration methodology (Organización Latinoamericana de Energia, 1983). Some of the more important data for a regional geothermal assessment include:

- An inventory and characterization of all thermal springs and hydrothermal manifestations.
- Water chemistry of the thermal springs and a description of their geologic settings.
- An inventory and characterization of all volcanoes and volcanic structures less than one million years old.
- The ages, volumes, and lithologies of the youngest volcanic eruptions.
- Some geophysical data, such as gravity, temperature gradient, or electrical resistivity, to establish the subsurface areas and thicknesses of potential geothermal reservoirs.

Although these are minimum essential data, information gathered from shallow and deep boreholes, from well tests and production monitoring, and even from nongeothermal wells is useful. In fact, all available geothermal resources-related information is considered and integrated during the assessment process. The types of data that should be collected for the assessment are elaborated in the data sheets given in the Appendix.

The literature review revealed that most of the published information is concentrated on those areas presently undergoing extensive exploration and development, such as Ahuachapán in El Salvador and Momotombo in Nicaragua; this information generally is excerpted from the numerous unpublished reports prepared by the various contractors for the national electrical agencies. Although the information on these few areas is relatively extensive and complete, sufficient data to perform a geothermal resources assessment on a regional scale is sorely lacking. Even

those reports which have attempted an inventory and characterization of geothermal resources on a national or regional scale have significant gaps in the geologic, geochemical, and geophysical data required for an assessment. In summary, systematic investigations designed to inventory and characterize the region's geothermal resources have not been undertaken.

Three subregional reconnaissance reports recently prepared either by or under the auspices of OLADE for the national electrical agencies of Guatemala, Nicaragua and Panama are noteworthy. These reports, which are confidential, compile all existing data relative to geothermal resources on the geology, volcanology, hydrogeology, geochemistry, and geophysics for the areas of southern Guatemala (Bureau de Recherches Géologiques et Minières, 1982), western Nicaragua (Organización Latinoameriocana de Energia, 1981a), and western Chiriqui Province, Panama (Organización Latinoamericana de Energia, 1981b). The data are interpreted within the context of geothermal concepts to select target areas for prefeasibility studies. Although some critical data gaps (mostly insufficient water chemistry and ages of volcanic rocks) were identified, the reports generally contain sufficient information to begin compiling a geothermal data base and attempt preliminary assessments on a subregional scale.

Discussions with officials at OLADE and at IRHE, ICE, and INDE indicated that all unpublished, proprietary reports related to geothermal resources would be made available (at least to the U.S. Geological Survey) for assessment activities. Some information, such as topographic maps of Guatemala which are militarily sensitive, would have to be maintained in individual countries on a confidential basis, but apparently could be used by an independent "third party" for data interpretations.

CONCLUSIONS

Much of Central America occurs in a geologic setting that is favorable for the development of geothermal resources. A narrow chain of some 80 active and dormant Quaternary (less than 1.6 million years old) volcanoes stretches along the Pacific margin of Central America from the Mexican border to western Panamá (fig. 1). These volcanoes result from the enormous heat generated by the subduction of the Cocos tectonic plate beneath the Caribbean plate. The nature and history of the volcanism--many volcanic structures show evidence of silicic eruptions and multiple caldera collapse--indicate repeated intrusion of magmas into the upper crust, thus providing relatively long-lived heat sources for the development of geothermal systems. Areas of hydrothermal activity are associated with many of the volcanoes; these areas offer the most promising potential for commercial geothermal development.

Although Central America has high geothermal potential, few studies have been conducted on a national or regional level to inventory and characterize the thermal manifestations. The review of the published literature and accessible confidential reports indicates clearly that sufficient data are <u>not</u> available at this time to conduct a credible geothermal resource assessment of Central America on a regional scale. Because most of the geothermal investigations in Central America have been limited to those few areas with impressive surface manifestations, attempting an assessment using the existing data would result only in an incomplete--and therefore unrealistic and perhaps misleading--evaluation of the geothermal potential. Such an exercise would have little benefit or value and is not an acceptable approach.

Any geothermal assessment conducted on a regional scale would require

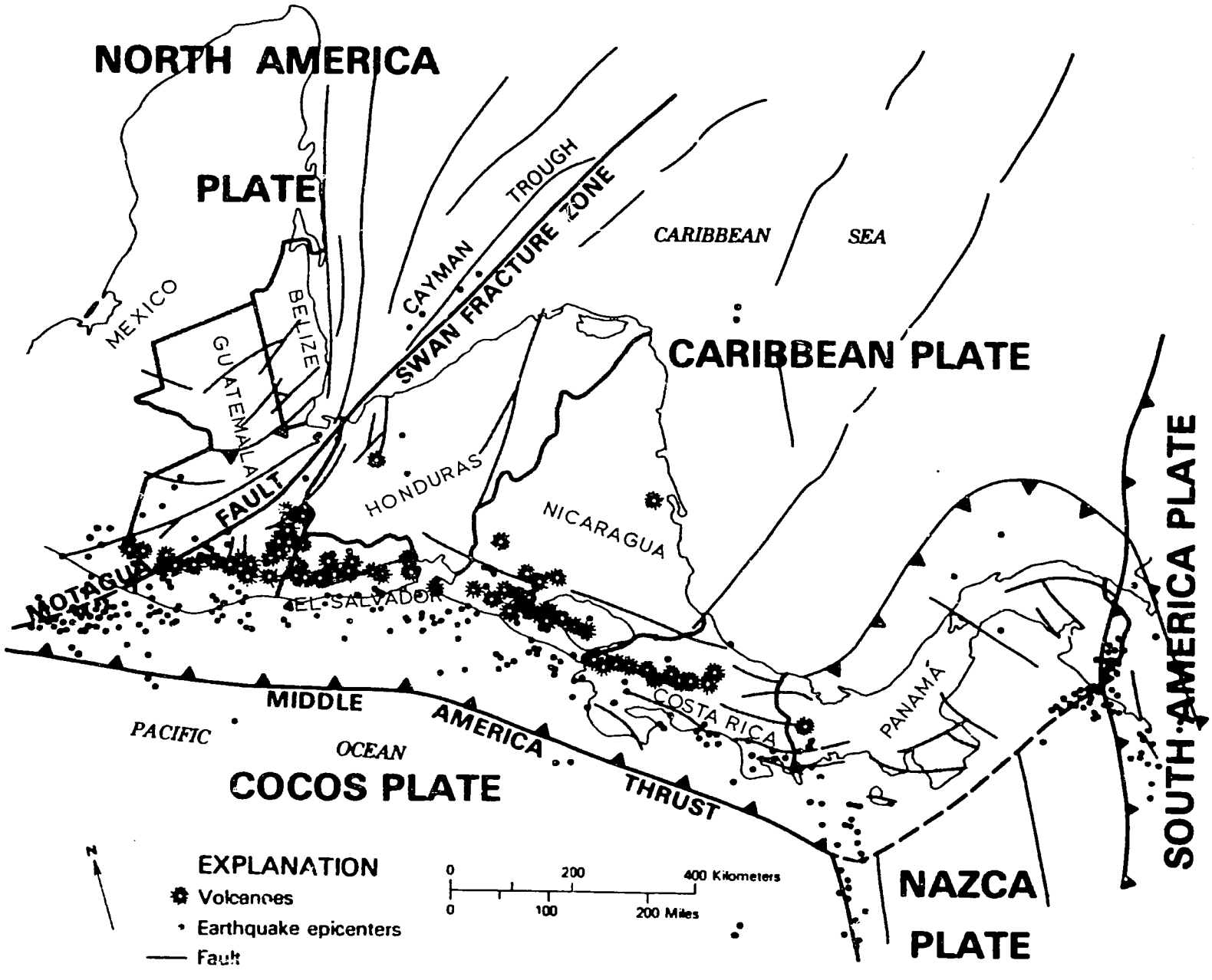

Figure 1. Simplified tectonic map of Central America (Cunningham and others, 1983, figure 2). Line of volcanoes along Pacific margin corresponds to zone of highest geothermal potential.

a consistent and systematic methodology for gathering, analyzing, and interpretating data. Uniform procedures must be used in every country to insure consistently reliable--and, equally important, supportable--results. To insure that consistent procedures are effectively initiated and maintained during the assessment, a single agency or team familiar with assessment methods must assume a leadership role and directly participate in the assessment activities. Because none of the Central American nations apparently has the technical personnel with the combined experience and expertise to effect a regional geothermal assessment, technical assistance would be required from an outside agency or agencies. Outside agencies also would likely have to fund an assessment because of the unfavorable financial situation of many Central American nations.

The support and participation of national scientists are essential to the assessment because of their familiarity with their nations' geology and geothermal occurrences. Accordingly, the technical capabilities and knowledge of the national scientists must be updated to state-of-the-art levels so that they can functionally assist in the assessment. Although several international consultants have conducted geothermal studies in Central America, the national geothermal personnel have not always benefited from these studies owing to the absence of direct participation. As a result, many Central American countries now sorely lack the geothermal specialists with the necessary experience to perform independent geothermal investigations or even to judge the quality of the consultants' work. Accordingly, one of the primary objectives of the geothermal assessment should be the transfer of technical knowledge to both OLADE personnel and to the national scientists. Geothermal technology can be effectively transfered only through direct "hands-on" participation and tutelage.

If maintained, the knowledge gained by the national scientists during the course of the assessment should help assure the success of future geothermal programs in Central America.

In summary, a geothermal assessment in Central America should accomplish three basic goals: (1) document and quantify the region's geothermal energy resources using a consistent and systematic methodology; (2) provide a supportable basis for national energy planning and project funding; and (3) effect a technology transfer on state-of-the-art geothermal assessment/evaluation methods.

RECOMMENDATIONS

Sufficient data must be collected and personnel trained before a geothermal assessment can be successfully achieved. Furthermore, the assessment must be practical in nature to afford the most benefit to the Central American region. In order to satisfy this counsel, it is suggested that the assessment effort (1) be conducted in graduated stages, (2) concentrate on quantifying the thermal energies of the more commercially important geothermal systems, and (3) use a standard set of procedural steps throughout each assessment stage.

Assessment Stages

The three assessment stages recommended here are sequentially graduated in order to initiate the needed technology and knowledge transfer and at the same time begin accomplishing a reliable and useful quantification of geothermal resources. The advantages of a staged approach are manifold in terms of technology transfer, the benefits gained, and funding; the emphasis here is that the knowledge and experience acquired in earlier stages can be applied to the later, more complex stages, and indeed to

future geothermal projects.

Stage 3 would produce the ideal regional assessment of geothermal resources in Central America. However, this stage is not realistic at this time owing to the excessive lack of data. Stages 1 and 2, on the other hand, are designed to produce more immediate--and practical--results, although a considerable amount of data will have to be gathered to complete stage 2. Stages 1 and 2 therefore are recommended to accomplish the principal goals of the assessment.

Stage 1: Perform preliminary "subregional" assessments on those areas reported in the detailed reconnaissance studies of OLADE (1981a,b) and the Bureau de Recherches Géologique et Minières (1982), or where sufficient information may exist in national files (Gustavo Cuéllar of OLADE suggested choosing two areas). This stage would be conducted primarily as a training exercise to familiarize OLADE personnel and scientists from the involved nations with the assessment methodology. It is particularly important that OLADE personnel become proficient with the assessment methodology as they will be jointly responsible for maintaining the continuity of the assessment and solely responsible for conducting the assessment in those countries where the presence of certain foreign agencies may be a political issue. These preliminary assessments would provide an opportunity to test the methodology and refine it as needed; participants would gain experience in the procedure and confidence in interpreting the data before attempting the more complex and time-comsuming stages of the assessment.

Stage 2: Assess the geothermal resources of the volcanic cordillera. The volcanic cordillera is the critical area for geothermal resources in Central America; it likely contains all of the high-temperature resources

and most of the commercially utilizable thermal energy in the region. Although this stage would require considerable additional studies and data gathering--performed jointly by a qualified outside organization, OLADE, and the national energy agencies--to fill existing data gaps, it would be of most immediate benefit to the Central American nations. The completion of this stage would essentially satisfy the chief goal of the assessment by providing a documented and supportable analysis of Central America's more significant geothermal resources.

Stage 3: Fill all remaining data gaps and assess the entire region accordingly. This stage would lead to the ideally complete regional assessment of geothermal resources in Central America. However, most of the geothermal resources outside the volcanic cordillera are probably of the low-temperature/low-enthalpy variety and occur as relatively small, isolated systems. Such systems likely have little interest or value for commercial development at this time, and their contribution to the regional geothermal potential is probably minor. Furthermore, the gathering of additional field data likely would be difficult because of funding and manpower constraints, insurgent activities in parts of some of the countries, and the remoteness and poor accessibility of some of the thermal occurrences. Accordingly, a comprehensive assessment on a regional scale presently is neither realistic nor practical. Although this stage is not recommended at this time, it could be completed at some future time by the individual nations on an as-needed basis. The training gained by OLADE and the national scientists during Stage 2 assessments should provide them with the necessary experience to conduct future assessments with only a minimum of outside technical support.

Assessment Methodology

Any geothermal resources assessment conducted now or in the near future in Central America should concentrate on determining the thermal energies in hydrothermal convection systems. These systems are the most attractive for commercial development; given the proper reservoir conditions of permeability and water storage, they are easily producible using present-day drilling technology. This approach is the most realistic under existing circumstances and would afford the most immediate benefit to the individual nations and to the region as a whole.

Thermal energies in hydrothermal convection systems should be quantified using the volume method (e.g., Brook and others, 1979). This method involves the calculation of the thermal energy in given volume of rock and water--the geothermal reservoir--at a specified temperature, and then an estimation of the amount of thermal energy recoverable at the surface and thus available to do work. Although other assessment methods--such as surface thermal flux, planar fracture, and analogy (see Muffler, 1981, for summary)--may be locally applicable, the volume method can be consistently applied and supported using the types of data (mostly reconnaissance) presently available or reasonably attainable during the course of an assessment. The volume method has been successfully used in three regional assessments in the United States (White and Williams, 1975; Muffler, 1979; Reed, 1983) and in a subregional assessment in Italy (Cataldi and others, 1978). In fact, Muffler and Cataldi (1978) have concluded that the volume method is probably the most useful for geothermal assessments because it is applicable to almost any geologic environment, the required parameters can be measured or estimated, and errors are in part compensating. The recovery factor, which is the most uncertain parameter in volumetric

calculations, should be evaluated separately to reflect the geologic conditions present in Central American hydrothermal reservoirs.

The determination of thermal energies associated with young igneous-related geothermal systems also should be attempted. Igneous-related systems, together with hydrothermal systems, are the dominant geothermal systems in Central America, especially in the volcanic cordillera. Although much of the thermal energies in igneous-related systems is not commercially extractable at this time, the estimates would provide an indication, at least of magnitude order, of the total heat storage in the region.

The method of magmatic heat budget as used by Smith and Shaw (1975) is recommended for the quantification of thermal energies associated with igneous-related systems. This method involves the calculation of thermal energies remaining in young (generally less than one million years) igneous intrusions and surrounding country rocks, as a function of emplacement temperature, age, volume, and cooling mechanism. This method has been used in two regional geothermal assessments in the United States (White and Williams, 1975; Muffler, 1979). Recoverable thermal energies are not calculated for igneous-related systems because of the large uncertainties inherent in estimating the required parameters.

An assessment of thermal energies associated with conduction-dominated regimes or possible geopressured systems should not be attempted because of insufficient data and minimal benefit.

Implementation: The Assessment Program

This section discusses the recommended program for initiating and successfully completing a geothermal assessment. The program was worked out in collaboration with Gustavo Cuéllar of OLADE and is designed to accomplish the fundamental objectives of the assessment.

The overall coordination of the assessment project would be the responsibility of OLADE. All of the nations in Central America that would be involved in the assessment are members of the OLADE organization, thus giving OLADE officials diplomatic access to the information collected by the national electrical agencies. Accordingly, OLADE would represent the programmatic and universally consistent authority throughout the course of the assessment.

Technical leadership necessarily would be provided by an outside organization selected to conduct the assessment. That organization would be responsible for providing technical assistance during field investigations, providing laboratory support, and insuring that sampling and analytical procedures are consistently followed. The procedures for sampling thermal waters particularly must be standardized, and laboratories must be calibrated to insure consistent results within analytical error. Isotopic determinations and radiometric dating likely would have to be performed in the outside organization's own or contracted laboratories. Data reduction and interpretation also would be the responsibility of the outside organization to insure consistent results. Overall, the outside organization must insure that the assessment methodology is closely followed and therefore must participate directly in all assessment activities. Perhaps most importantly, the outside organization would be charged with the effective transfer of technology to OLADE and national scientists.

The outside organization that accepts the leadership role must have the necessary support facilities and the personnel with the proper disciplines to provide the above services and perform its obligated duties. OLADE officials have expressed their desire that the U.S. Geological Survey

take on the technical leadership. Having completed three regional assessments of the geothermal resources of the United States, the Geological Survey would be a logical choice to conduct the assessment. However, any involvement of the Geological Survey must be viewed within the context of funding, domestic priorities, and staffing limitations.

Once an outside organization has been selected and a team of geothermal specialists has been assembled to conduct the project, the assessment program can be divided into distinct, but slightly overlapping, procedural steps. Of course, these steps may have to be modified to accommodate individual stages; the steps outlined below are intended primarily for stage 2. Steps 1 and 2 are more or less administrative, whereas steps 3 through 7 are actual working procedures.

Step 1: Identify a technical counterpart(s) in each country. The technical counterpart(s)--geologist, geochemist, and(or) geophysicist--in each country would act as liaison between the assessment team and other scientists and technical organizations in his country, coordinate logistical support, and provide geoscientific expertise and information. He would work directly with the assessment team in evaluating the geothermal resources in his country and therefore would be the direct beneficiary of the technology transfer.

Step 2: Conduct training seminars. One or two training seminars of not fewer than three days each and divided among the participating nations should be conducted to introduce the counterparts to the assessment methodology, define terminology, explain the types of data required, present thermal energy equations, and discuss the counterparts' responsibilities. Basic assumptions and parameters that would be held constant--such as reference temperature, base depth of reservoirs, and recovery factor--

would be specified during these seminars. These seminars should be designed to acquaint the participants with the basic concepts of the assessment project, but should not be conducted with the idea that the participants will become instantly proficient in quantifying geothermal resources. Proficiency will only be gained from the experience of performing the assessment directly with the assessment team.

Step 3: Prepare a geothermal data base and identify data gaps. The data base would consist of a compilation of all existing, pertinent geothermal information on hydrothermal convection systems and igneous-related systems in each country. The counterpart and his associates in each country would have the primary responsibility of preparing the data base and insuring its accuracy. Data gaps and needs would be identified in collaboration with the assessment team during the course of the assessment.

Sample data sheets that should be used to compile data for each of the hydrothermal convection and igneous-related geothermal systems in each country are given and explained in the Appendix of this report. These forms will provide a documented inventory of geothermal systems and their characteristics for easy reference. Although most of the data requested on the data sheets is critical to the interpretation of parameter values used in resource calcuations, it is realized that not all of these data are attainable. Nonetheless, every effort should be made to complete the data sheets as they will provide important reference documents for the assessment team. These forms will be maintained by the counterpart's agency with duplicate sets maintained at OLADE headquarters.

Step 4: Collect additional data where needed. One of the primary functions of preparing the data base is to identify areas where additional

critical data are needed. Activities to gather the additional information might include the location and sampling of thermal springs for chemical analysis, aerial photo and ground reconnaissance of volcano-tectonic structures and zones of hydrothermal alteration, collection of volcanic rock samples for radiometric dating, and planning and executing selected geophysical surveys. Steps 3 and 4 would be done concurrently and in collaboration with the assessment team. These two steps would also require the most time to complete. Geophysical surveys may have to be contracted and funded separately because of their expense.

Step 5: Interpret data. The interpretation of data will be the responsibility of the assessment team in order to insure consistent results. The assessment team will be working jointly with OLADE personnel and counterparts in each country during this step; the degree of participation by the counterparts will have to be negotiated by OLADE. Data interpretation will consist of estimating the parameter values (such as reservoir area, thickness and temperature) used in the thermal energy calculations; details of this procedure are given in U.S. Geological Survey Circular 790 (see Brook and others, 1979, p. 20-23). The assessment team also must prepare documentation giving the bases for their estimates.

Step 6: Resource calculations. The volumetric methodology as applied to hydrothermal convection systems allows calculation of the following quantities: the identified accessible resource base, the resource (recoverable geothermal energy), electrical power potential, and beneficial heat. The methods, equations, and factors used in the computations are given in Circular 790 (see Brook and others, 1979, p. 20-26). Although the calculations are fairly straightforward, a micro-computer will be useful to perform statistical operations and calculate standard deviations.

The recovery factor (the fraction of thermal energy theoretically producible at the wellhead) is considered to be a major uncertainty in the volume method; it should be evaluated within the context of the geologic settings of the hydrothermal systems and their known reservoir characteristics. The factor for volumetric specific heat likewise must be evaluated in terms of the geologic settings, particularly the reservoir lithologies. For simplicity, both factors should be held constant for all resource calculations. They therefore must be representative of the reservoirs for the majority of the hydrothermal systems.

The amount of thermal energy remaining in igneous-related systems should be calculated using the method of Smith and Shaw (1975) in U.S. Geological Survey Circular 726. This method provides an order of magnitude estimation of the thermal energies expected in volcanic terrains, but cannot be easily translated into geothermal resources (Muffler, 1981, p. 186) because of large uncertainties in the estimates and because much of the resource is not recoverable. Therefore, recoverable resources, electrical power potential, and beneficial heat are not calculated for igneous-related systems.

Step 7: Estimation of undiscovered resources. Although the "resource calculations" step essentially completes the assessment, an effort should be made to establish the amount of undiscovered accessible resource base associated with hydrothermal convection systems. As discussed by Renner, White, and Williams (1975), this undiscovered component consists of additional thermal energy due to upward revisions of volume and/or temperature estimates, and thermal energy in systems that have not yet been identified.

ESTIMATED MANPOWER AND FUNDING REQUIREMENTS

An assessment requires a fill-time committment by its participants. Manpower requirements for stages 1 and 2 can be estimated with a fair degree of confidence; estimates of the manpower required for stage 3 will not be attempted because this option is not recommended in terms of the realistic objectives of the assessment. Funding requirements, on the other hand, cannot be easily estimated at this time because too many unknowns are involved regarding the operating costs and salaries of outside organizations that are qualified to undertake the assessment. Also, the financial arrangements for the travel and salaries of the counterparts and for the use of national laboratories are unknown. The funding estimates given below are crude at best and should be used only as general guides. The actual funding of the assessment, especially for stage 2, may require negotiation.

Stage 1

Because stage 1 is designed as a training exercise on a seminar basis, only two instructors from the outside organization would be required. The instructors should be disciplined in geology, geochemistry and geophysics as related to geothermal resources, and have a complete understanding of the assessment methodology. It is important that the instructors have the experience and qualifications for this task as it will be the first step in the technology transfer. This stage would take four or five weeks (8-10 manweeks) to complete. Estimated costs, including salaries and benefits, travel (airfare and per diem), computer use, report publication expenses, and a minimal amount for indirect costs, range from $33,000 to $40,000, depending on the level of effort required by the personnel involved.

Stage 2

The comprehensive nature of this stage requires a considerable allocation of manpower and funding. The assessment team should consist of a minimum of a geologist, a geochemist, and a geophysicist; a volcanologist, chemist, one or two computer specialists, and a reservoir engineer should be available to directly support the assessment team. Much of the time and expense required to complete stage 2 will likely involve the field investigations and various laboratory analyses needed to gather the additional required data. Geophysical surveys, if conducted, would be particularly expensive and may have to be funded separately. For example, an audio-magnetotelluric (AMT)[2] survey covering 50 km^2 may cost on the order of $10,000-12,000. Total manpower for the assessment team and support personnel is likely on the order of 4 to 8 manyears. Estimated costs, including salaries and benefits, travel (airfare and per diem), computer use, laboratory analyses, report publication expenses, and a minimal amount for indirect costs, but not including any geophysical surveys, range from $600,000 to $1,000,000, depending mainly on the level of effort required by the personnel involved.

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[2]Audio-magnetotelluric (AMT) surveys are recommended for the assessment; the equipment is easily portable and these electrical techniques are effective for reconniassance exploration, and thus gathering the kinds of information needed for the assessment.

APPENDIX

Data Base and Data Sheets

The preparation of a useful data base is the first working step in conducting the geothermal assessment. The data base serves four main purposes: (1) It provides an inventory of the resource occurrences; (2) it documents the resource characteristics; (3) it exposes critical data gaps; and (4) it is a first-line reference for the assessment team during the data interpretation step. The data base therefore must be comprehensive in scope. To insure completeness, data sheets such as those presented here are recommended to compile the data base. Separate data sheets should be prepared for each hydrothermal convection system (e.g., each isolated, single thermal spring or group of closely-spaced springs) and igneous-related system (e.g., each volcano or caldera complex). Examples of data sheets and explanations of the types of data required are given on the following pages; some data are self-explanatory and will not be discussed.

CENTRAL AMERICA GEOTHERMAL RESOURCES DATA
Hydrothermal Convection Systems

Thermal spring/area:_____ Country:_____
Province/Department:_____

Location: Lat._____°_____.___' N., Long._____°_____.___' W.
UTM_____
Other_____
Topographic maps (Scale)_____

Elevation:

Surface manifestations:

Thermal springs: Number_____ Temperatures_____ Flows_____

Wells: Number_____ Depths_____ Temperatures_____
Flows_____

References:

Water Chemistry: Date collected_____

Spring: Temperature_____ Flow_____ Conductivity_____ pH_____

Well: Surface flowing temp._____ Sample temp._____; depth_____
Max. downhole temp._____; depth_____ pH_____
Bottom-hole temp._____; depth_____ Flow_____
Total depth_____

Analytical units_____ Separation pressure_____

Na_____	SiO_2_____	Cl_____	Other:
K_____	HCO_3_____	F_____	
Ca_____	CO_3_____	B_____	
Mg_____	SO_4_____	Li_____	Charge balance: _____ percent

Gases: Analytical units_____ Isotope ratios:

CO_2_____	H_2_____	D/H_____
H_2S_____	NH_4_____	O^{18}/O^{16}_____
CH_4_____	Other:	Other:

References:

Geology:

Maps:

References:

Geophysics:

References:

Hydrothermal Convection Systems

Thermal spring/area: The name(s) of the thermal spring or area of thermal manifestations.

Location: Latitude and longitude coordinates are preferred, but can be converted from UTM coordinates if unavailable. "Other" refers to a narrative description of the physical setting of the spring or area (e.g., on hillside 20 m above and to the north of sharp bend in stream). Accurate locations are important for depiction on maps and for reoccupation of sites should additional investigations be needed.

Surface manifestations: Thermal springs, fumaroles, travertine, sinter deposits, hydrothermal alteration, mercury deposits, etc.

Thermal springs: The number of active springs and their ranges of temperatures and flow rates. Additional sheets may be attached if data from individual springs are necessary for interpretations.

Wells: The number of thermal wells in the area and their ranges of depths, temperatures, flows, and pressures. Cite reference(s) if compiled from literature. [Only author(s) and year are needed for the reference citation; complete bibliographic citations should be maintained separately.] Additional data sheets may be attached if data from individual wells are necessary for interpretations.

Water chemistry: Chemical, gas, and isotopic analyses of spring or well sampled. Additional sheets may be required if more than one spring or well in a group is sampled or if more than one analysis is available for the same spring or well. Cite reference(s) if compiled from literature.

Geology: Narrative description of the local geologic setting, including any structures (e.g., faults, joints, bedding planes) that might be controlling the location of the thermal manifestations and especially

the lithology at the site. Note if the hydrothermal occurrence is assoc- with an igneous-related system and name the system for cross reference. Geologic maps and cross sections are useful for interpreting the subsurface.

Geophysics: Reference any geophysical surveys that have been conducted in the area, giving a brief narrative if a particular survey identifies a critical resource parameter (e.g., area of reservoir, depth, stratigraphic unit).

References: List only the author(s) and year(s); maintain complete bibliographic citations separately.

CENTRAL AMERICA GEOTHERMAL RESOURCES DATA
Igneous-related Systems

Name of volcanic structure or field: _____ Country: _____
Province/ Department: _____

Type of volcanic structure: _____

Location: Lat. _____ ° ____ . ___ ' N.; Long. _____ ° ____ . ___ W.
UTM _____
Other:
Topographic maps (Scale): _____

Volcano or volcanic complex: Area of edifice _____

Eruptive sequence (oldest to youngest)

Type	Lithology	Volume (km^3)	Age (m.y. B.P.)

Caldera:

Eruptive sequence (oldest to youngest)

Type	Lithology	Volume (km^3)	Area of collapse (km^2)	Age (m.y. B.P.)

Associated hydrothermal manifestations:

Geophysical surveys:

References:

Miscellaneous:

Igneous-related Systems

Name of volcanic structure or field: Formal or geographic name of volcano, caldera, volcanic complex, or volcanic (generally basalt) field.

Type of volcanic structure: Shield, stratovolcano, dome, cone, caldera, etc.

Location: Location of center of volcano, volcanic complex, caldera, or field.

Volcano or volcanic complex: Briefly describe the eruptive sequence from oldest to youngest, listing the types of eruptions, lithologies, volumes of material erupted, and ages of eruptions (annotate method of age determination).

Caldera: Same as above, except the areas of caldera collapses also should be listed.

Associated hydrothermal manifestations: List types of hydrothermal manifestations associated with the volcano, volcanic complex, caldera, or volcanic field. Briefly describe their spatial relationship to the volcanic structure or to an eruptive sequence. Separate data sheets should be prepared for each of the hydrothermal occurrences.

Geophysical surveys: Note the types of geophysical surveys conducted in the area and reference the sources of information.

References: Cite author(s) and year(s) of references. Complete bibliographic citations should be maintained separately.

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